ROBERT L. SHRADER

# Electronic Communication

# ELECTRONIC COMMUNICATION

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ELECTRONIC COMMUNICATION

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IX

# PREFACE

Here, in one book, are the electronics theory and practical information required to pass all radio licenses, commercial and amateur. It includes both commercial radiotelephone and radiotelegraph license material, the relatively simple Novice Class Amateur license information, and the more advanced General Class Amateur license information.

This book presents a fundamental but wide coverage of the field of electronic communication for both commercial and amateur operators. While commercial and amateur operators are subject to somewhat different rules and regulations, the electronic theory required by both for proper operation of equipment is closely related.

Operating, installing, and maintaining commercial and amateur radio transmitting and receiving equipment require personnel with more than a minimum of technical background and ability. The goal of this book is to put into as simple language as possible the basic theory of electricity and electronics, as well as to include the fundamentals of good operating.

This book covers basic electrical theory, basic electronic circuits incorporated in radio transmitters and receivers, applications of the basic circuits in communication equipment, and finally, simplified rules and regulations pertaining to radio operation.

For those interested in working in areas of electronics other than radio, this book should form an excellent grounding for later specialization. In many cases, the possession of a commercial or amateur license is a valuable recommendation for an applicant for employment in these fields.

Basically, this book was written for junior college or technical school students, but it is suitable for a general coverage of electronics for pre-engineering students. It is within the grasp of senior high school classes. For those unable to attend a school, thorough study of this book alone should enable them to learn sufficient theory to pass satisfactorily any of the FCC licenses mentioned above, as well as the radar endorsement on a commercial-grade license.

Mr. Emery L. Simpson, educator, as well as commercial and amateur operator, served as consultant and proofreader for this book. His pertinent suggestions and corrections as well as uncounted hours of work are gratefully acknowledged. The Mackay Radio and Telegraph Company, particularly Mr. W. R. Taggart and Mr. G. G. Thommen, and the Radio

Corporation of America, through Mr. C. D. Pitts, Mr. G. P. Aldridge, and Mr. Ralph Scott, aided materially in compilation of some of the text. I should also like to acknowledge the invaluable help of the many students who have aided in simplifying and clarifying the wording of the text during the past few years. Last, and far from least, were the many contributions made by my wife Dorothy and the cooperation of Patricia and Douglas in giving up many hours of recreation that this book might be finished.

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# HOW TO USE THIS BOOK

The Federal Communications Commission requires persons who are in direct control of transmitting equipment to pass license examinations. As a guide to what they believe necessary background for commercial radio operators, the FCC publishes a list of sample questions. From these questions, or others similar in content, the FCC makes up its license examinations. This book was written with these same sample questions as the basis for a comprehensive electronics course for prospective radio operators or communication technicians.

FCC commercial license examinations are given in sections under the heading Commercial License Information. The higher the grade of the license, the more elements are included in the examination. There are six elements included in commercial license examinations. The FCC elements included in this book are:

1. Questions on basic law (Chapter 30)
2. Basic operating practice (Chapter 31)
3. Basic radiotelephone
4. Advanced radiotelephone
5. Radiotelegraph operating practice (Chapters 17 and 32)
6. Advanced radiotelegraph
8. Ship radar techniques (Chapter 29)

Element 8 is a special radar operator's *endorsement*, which may be added to any commercial license.

Element 7 is a special aircraft operator's endorsement, complete material for which is not included because of the relatively few calls for it.

The questions and material for Elements 3, 4, and 6 make up the bulk of the book.

The commercial-grade licenses and required elements for which this book will prepare the reader are:

*Radiotelephone Second Class* (Elements 1, 2, and 3).

*Radiotelephone First Class* (Elements 1, 2, 3, and 4).

*Radiotelegraph Second Class* (Elements 1, 2, 5, and 6). This license also requires an International Morse Code test, sending and receiving, at 16 code groups per minute, the equivalent of 20 words per minute plain language.

*Radiotelegraph First Class.* Requires no written test, but an International Morse Code test, sending and receiving, at 20 code groups per minute, 25 words per minute plain language. The applicant must have one year of authenticated marine experience on a valid Radiotelegraph Second Class license.

More detailed information pertaining to commercial licenses and permits is given in Chapter 30.

The amateur licenses for which this book will prepare the reader are:

*Novice Class.* Requires a simple written test and a plain-language International Morse code test, sending and receiving, at 5 words per minute.

*Technician Class.* Requires the same written test as a General Class license and a plain-language code test, sending and receiving, at 5 words per minute.

*General or Conditional Class.* Requires a theory test and a plain-language sending and receiving code test, including numbers and punctuation, at 13 words per minute.

*Extra Class.* Requires an extensive theoretical examination covering much of the commercial radio theory in this book and a sending and receiving code test at 20 words per minute. (It confers no additional privileges over those enjoyed by the holder of a General or Conditional Class license at this writing.)

The recommended procedure for the use of this textbook for home study is as follows:

1. Determine the FCC elements required for the license desired.
2. Check the end of the first chapter to see if there are questions in it for the required elements or test.
3. Read the chapter through rapidly, including all the questions pertaining to the required elements or test.
4. Return to the beginning of the chapter and study it carefully, working any problems required. As soon as all the FCC questions can be answered, move on to the next chapter.
5. Before taking a license examination, review all FCC questions on the required elements.

It is recommended that all chapters be read by all prospective commercial operators to acquaint the reader with the communications field as a whole, even if the material is not indicated as necessary in the desired license test.

Code practice can be obtained by listening on a short-wave communications receiver, by renting or buying automatic code tape machines, by sending and receiving with a practice code oscillator with another interested person, by joining a local radio club, or by attending a night-school code class if one is available in the locality.

# CONTENTS

# CHAPTER 1

# CURRENT, VOLTAGE, AND RESISTANCE

**1.1 Electricity.** In this day and age it would be unusual to find anyone in the United States who has never experienced the simple marvel of flipping a switch and seeing an electric light start to glow. An everyday occurrence such as this is accepted by everybody, but how many understand why it occurs? It is a simple thing to pass it off with a general statement that "The switch connected the light to the power lines." What does connecting the light to the power lines do? How does energy travel through solid wires? What makes a radio play? What is behind the dial that makes it pick out one radio station and not several thousand others on the air at the same time?

There is no one simple single answer to any of these questions. Each question requires the understanding of many basic principles. By adding one basic idea to another, it is possible to answer, eventually, most of the questions that may be asked about the intriguing subjects of electricity and radio.

When the light switch is turned on at one point in a room and the light suddenly glows, energy has found a path through the switch to the light. The paths used are usually copper wires, and the tiny particles that do the moving and carry the energy are called *electrons.* These little electrons are important to anyone studying radio since they are usually the only particles that are considered to move in electric circuits.

To explain what is meant by an electron, it will be necessary to investigate more closely the make-up of all matter.

The word *matter* means, in a general sense, anything that can be touched. It includes substances such as rubber, salt, wood, water, glass, copper, air, and so on. The whole world is made of different kinds of matter.

Water is one of the most common of the many items in the category of matter. If a drop of water is divided in two, then divided again and again until it can be divided no longer *and still be water*, this smallest particle is known as a *molecule* of water. The water molecule can be broken down into still smaller particles, but these new particles will not be water.

Physicists have found that there are three particles making up a molecule of water, two *atoms* of hydrogen (H) and one *atom* of oxygen (O) (Fig. 1.1). Oxygen, at normal temperatures, is one of several gases that constitute the air we breathe. Hydrogen is also a gas in its natural state. It is found in everyday use as part of the gas used for heating or cooking. If a gaseous mixture containing two parts of hydrogen and one part of oxygen is ignited, a chemical reaction in the form of an explosion takes place. The residue of the explosion will be water ($H_2O$) droplets.

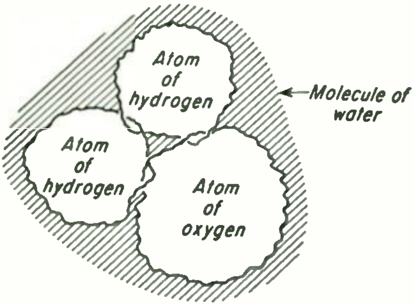

FIG. 1.1. Two atoms of hydrogen and one atom of oxygen interlocked to form one molecule of water.

It has been determined that an atom is also divisible. An atom is made up of two types of particles, *protons* and *electrons*. Both are electrical particles and are not divisible. *All* the molecules that make up *all* matter of the universe are composed of these electrical proton-electron pairs.

**1.2 Electrons and Protons.** Electrons are the smallest and lightest of particles. They are said to have a *negative* charge, meaning that they are surrounded by some kind of an invisible *field of force* (Fig. 1.2) that will react in an electrically negative manner on anything that is electrically charged and brought within the limits of the field. The electric field is represented pictorially as being composed of outward-pointing *lines of force*. Whether lines of force actually exist is not known. However, they are used for explanatory purposes.

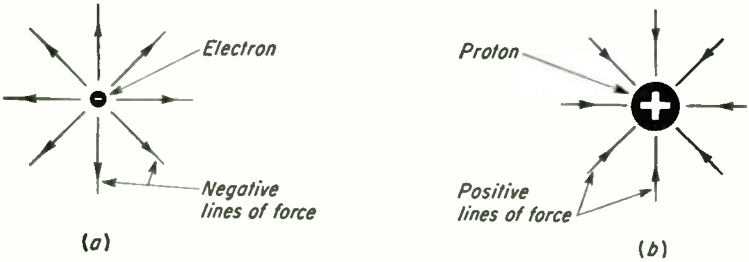

FIG. 1.2. Electrostatic lines of force, directed outward by the negative charge (*a*) and inward by the positive (*b*).

Protons are about 1,800 times as massive as electrons and have a *positive* electric field surrounding them. The positive field is represented by inward-pointing lines. Theoretically, an electron has exactly as many outward-pointing lines as a proton has inward-pointing lines. The proton is just exactly as positive as the electron is negative, each having a *unit* electric charge.

In theory, negative lines of force will not join other negative lines of force. In fact, they repel each other, tending to push each electron away from every other electron (Fig. 1.3*a*). Positive lines of force do the same, as shown in Fig. 1.3*b*.

When an electron and proton are far apart, as illustrated in Fig. 1.4, only a few of their lines of force join and pull together. The contracting pull between the two charges is therefore small. When brought closer together, the electron and proton are able to link more of their lines of force and will pull together with more force. If close enough, all the lines of force from the electron are joined to all the lines of force of the proton and there is no external field. They form a *neutral*, or uncharged, group. Such a neutral group is known as a *neutron* and exists in the nucleus of heavier atoms.

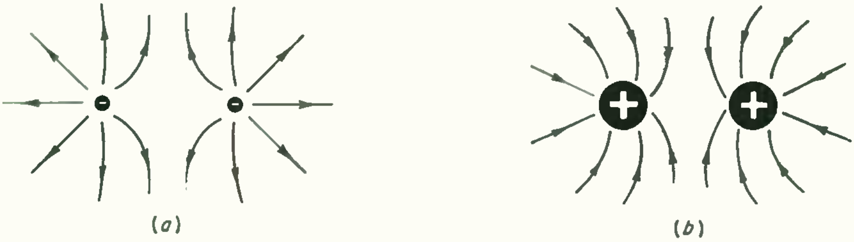

FIG. 1.3. Lines of force in similar directions repel one another.

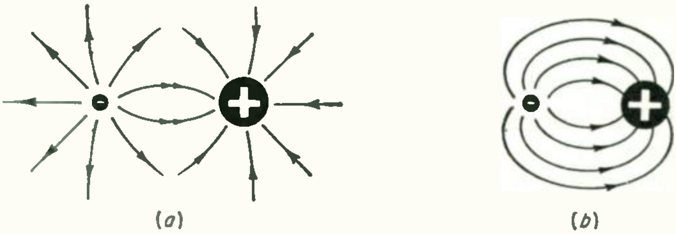

FIG. 1.4. (*a*) Remote dissimilar charges have relatively little field interlinkage; both charges are still capable of attracting other charged particles. (*b*) When close together, all lines interlink, leaving none external, resulting in a neutron or neutral charged group.

Electrons repelling other electrons, protons repelling other protons, but electrons and protons attracting each other follows the basic physical law, *Like charges repel, unlike attract.*

Because the proton is about 1,800 times heavier than the electron, it seems reasonable to assume that when an electron and a proton attract each other it will be the tiny electron that will do most of the actual moving. Such is the case. It is the electron that moves in electricity.

Regardless of the difference in apparent size and weight, the negative field of an electron is just as strong negatively as the positive field of a proton is positive. As small as it is physically, the field near the electron is very strong. If the field strength around an electron at a distance of one-millionth of an inch is a certain amount, at two-millionths of an inch it will be one-quarter as much; at four-millionths of an inch it will be one-sixteenth as much; and so on. Notice that when the distance is doubled, the field strength is not halved, as might possibly be expected, but is one-half squared $[(\frac{1}{2})^2]$, or one-quarter as much. Because the field *decreases* as the distance *increases*, the field is said to vary *inversely* with the distance. Actually, it varies inversely with the distance *squared*.

When an increase in something produces an increase in something else, the two things are said to vary *directly*, rather than inversely. Two million electrons on an object produce twice as much negative charge as one million electrons would. The charge is directly proportional to the number of electrons.

Since the electric-field strength of an electron varies inversely with the distance squared, the field strength an inch or so away will be very weak.

The fields surrounding electrons and protons are known as *electrostatic* fields. The word "static" means, in this case, stationary, or not caused by movement.

When electrons are made to move, the result is *dynamic* electricity. The word "dynamic" indicates motion is involved.

To produce a movement of an electron it will be necessary to have either a negatively charged field to push it, a positively charged field to pull it, or, as normally occurs in an electric circuit, a negative and positive charge (a pushing and pulling pair of forces) between which electrons travel.

**1.3 The Atom and Its Free Electrons.** In this atomic age the atom deserves more mention. There are over 100 different kinds of atoms, or *elements*, from which the millions of different forms of matter found in the universe are composed. The heaviest elements are radioactive and unstable, decomposing into lower-atomic-weight atoms spontaneously.

The simplest and lightest atom is hydrogen. An atom of hydrogen consists of one electron and one proton, as shown in Fig. 1.5. In one respect this atom is similar to all others: the electron whirls around the proton, or *nucleus*, of the atom, much as planets rotate around the sun. In fact, electrons whirling around the nucleus are often termed *planetary*, or *orbital*, electrons.

The second, and next heavier, atom is helium, basically with two protons and two electrons. The third atom is lithium, basically with three electrons and three protons, and so on.

Some of the common elements, in order of their atomic weights, are:

1. Hydrogen
2. Helium
3. Lithium
6. Carbon
8. Oxygen
13. Aluminum
26. Iron
28. Nickel
29. Copper
79. Gold
82. Lead
88. Radium
92. Uranium

Most atoms have a nucleus consisting of all the protons of the atom and also one or more neutrons. The remainder of the electrons (always equal in number to the number of nuclear protons) are whirling around the nucleus in different layers. The first layer of electrons outside the nucleus can accommodate only two electrons. If the atom has three electrons (Fig. 1.5), two will be in the first layer and the third will be in the next layer. The second layer is completely filled when eight electrons are whirling around in it. The third is also filled when eight electrons are in it. Actually, both helium and lithium have neutrons in their nuclei, although this is not indicated in the simplified illustration.

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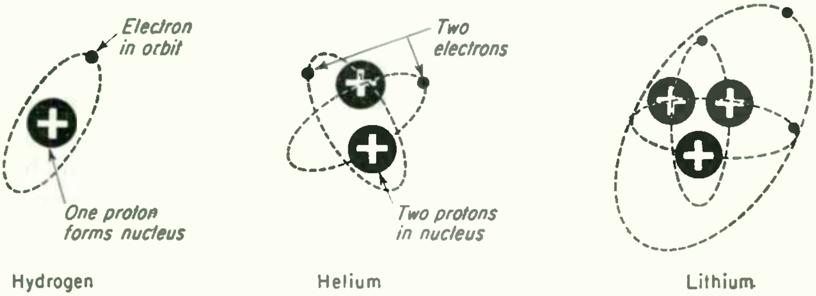


Fig. 1.5. Simplified picture of hydrogen atom with one proton as the nucleus and one rotating orbital electron. Helium is shown with a two-proton nucleus and two orbital electrons; lithium with a three-proton nucleus, two electrons in the inner layer and one in the second layer.

Some of the electrons in the outer orbit, or shell, of the atoms of many materials such as copper or silver can be dislodged easily. These electrons travel out into the wide open spaces between the atoms and molecules and may be termed *free electrons.* Other electrons in the outer orbit will resist dislodgment and may be called *bound electrons.* Materials consisting of atoms (or molecules) having many free electrons will allow an easy interchange of their outer-shell electrons, while atoms with only bound electrons will hinder any electron exchange.

When a substance is heated, greater energy is developed in the free-moving electrons. The more energy they contain, the more they resist an orderly movement of electrons through the material. The material is said to have an increased *resistance* to the movement of electrons through it.

**1.4 The Electroscope.** An example of electrons and electric charges acting on one another is demonstrated by the action of an *electroscope,* shown in Fig. 1.6. It consists of two very thin gold or aluminum leaves attached to the bottom of a metal rod. To prevent air currents from damaging the delicate metal-foil leaves, the electroscope is usually encased in a glass flask, with the rod projecting out the top, through a rubber cork.

To understand the operation of the electroscope, it is necessary to recall these facts: (1) Normally an object has a neutral charge. (2) Like charges repel, unlike attract. (3) Electrons are negative. (4) Metals have free electrons.

Normally the electroscope rod has a neutral charge, and the leaves hang downward, parallel to each other, as shown in Fig. 1.6. Rubbing a piece of hard rubber with wool causes the wool to lose electrons to the rubber, charging the rubber negatively. When such a negatively charged object is brought near the top of the rod, some of the free electrons at the top are repelled and travel down the rod, away from the negatively charged object. Some of these electrons will force themselves onto one of the leaves, and some onto the other. Now the two leaves are no longer neutral, but are slightly negative and repel each other, moving outward to the position shown by the dotted lines. When the charged object is removed, electrons return up the rod to their original areas. The leaves again have a neutral charge and hang down parallel.

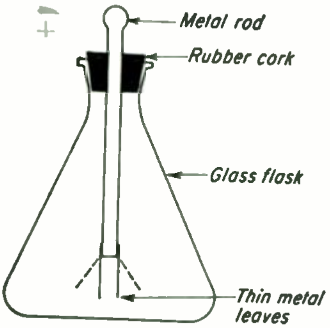


Fig. 1.6. Electroscope used to indicate presence of either a negative or positive charge.

Since the charged object did not touch the electroscope, it neither placed electrons on the rod nor took electrons from it. When electrons were driven to the bottom, making the leaves negative, these same electrons leaving the top of the rod left the top positive. The over-all charge of the rod remained neutral. When the charged object was withdrawn, the positive charge at the top of the rod pulled the negative electrons up to it until all parts of the rod were neutral again.

If a positively charged object, such as a glass rod vigorously rubbed with a piece of silk, is brought near the top of the electroscope rod, some of the free electrons in the leaves and rod will be attracted upward toward the positive object. This charges the top of the rod negatively because of the excess of free electrons there. Both leaves are left with a deficiency of free electrons and are positively charged. Since both leaves are similarly charged again, they repel each other and move outward.

If a negatively charged object is *touched* to the metal rod, a number of excess electrons will be deposited on the rod and will be immediately distributed throughout the whole electroscope and the leaves will spread apart. When the object is taken away, an excess of electrons remains on the rod and leaves and the leaves stay spread apart. If the negatively charged electroscope is touched to any large object that can accept the excess free electrons, such as a person, a large metal object, or the earth, the excess electrons will have a path by which they can leave the electroscope and the leaves will collapse as the charge returns to neutral. The electroscope has been *discharged*.

If a positively charged object is touched to the metal rod, the rod will lose electrons to it and the leaves will separate. When the object is taken away, the rod and leaves still lack free electrons and the leaves remain apart. A large neutral body touched to the rod will lose some of its free electrons to the electroscope, discharging it, and the leaves will hang down once more.

The electroscope demonstrates the more or less free movement of electrons that can take place through metallic objects or conductors when electric pressures, or charges, are exerted on the free electrons.

**1.5 The "Big Three" in Electricity.** Without calling them by name, the discussion so far has touched on the three elements always present in all operating electric circuits:

I *Current.* A progressive movement of free electrons along a wire or other conductor.

E *Electromotive Force.* The electron-moving force in a circuit that pushes and pulls electrons (current) through the circuit. X

*Resistance.* Any opposing effect that hinders free-electron progress through wires when an electromotive force is attempting to produce a current in the circuit.

Changes in the values of any one of these "big three" will produce a change in the value of at least one of the others. The basic functioning of these in a simple electric circuit will be discussed briefly.

**1.6 A Simple Electric Circuit.** The simplest of electric circuits consists of some sort of an electron-moving force, or *source,* such as is provided by a dry cell, or battery, a *load,* such as an electric light, and connecting wires. A method of both picturing and diagraming the connections of such a circuit is shown in Fig. 1.7.

It can be seen that the schematic diagram is simpler to draw and actually easier to read than the picture diagram. For this reason, schematic diagrams are used by radiomen as much as possible. It will pay you to observe closely the diagrams that are given and practice drawing them until they can be reproduced rapidly and correctly. Note, for example, that the negative terminal (−) on the symbol representing the cell in the schematic diagram is made with a short line, while the positive terminal (+) is made with a longer line. This is an important point to remember when drawing diagrams, since correct battery polarity is required in many circuits if the equipment is to work properly.

Although the wires connecting the source of electromotive force to the load may have some resistance, it is usually a very small amount in comparison with the resistance of the load and is ignored in most cases. A straight line, then, in a schematic diagram is considered to connect parts electrically, but does not represent any resistance in the circuit.

In the simple circuit shown, the cell produces the electromotive force that continually pulls electrons to its positive terminal from the lamp's filament and pushes them out the negative terminal to replace the electrons that were lost to the load by the pull of the positive terminal. The result is a continual flow of electrons through the lamp filament, connecting wires and source. The special wire of the lamp filament heats when a current of electrons flows through it. If enough current flows, the wire becomes white-hot and the lamp glows.

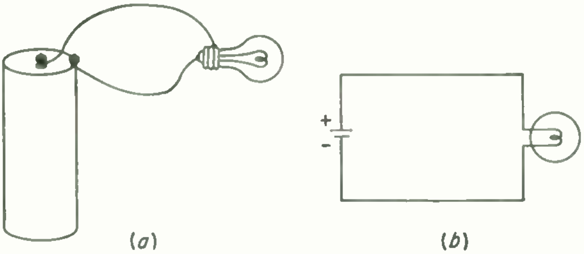


FIG. 1.7. (a) A lamp connected to a dry cell. (b) Schematic diagram of the same circuit.

The addition of a switch in series with one of the connecting wires of the simple circuit affords a means of controlling the current in the circuit, as shown in Fig. 1.8. When the switch is closed, electrons find an uninterrupted path in the circuit and they flow through the lamp. When the switch is opened, the electromotive force developed by the battery is normally insufficient to cause the electrons to jump the switch gap in the form of a spark, and the electron flow in the circuit is interrupted. The lamp cools and no longer glows.

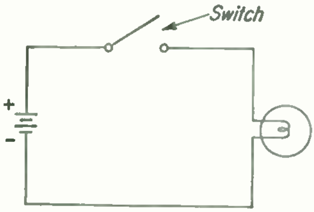


FIG. 1.8. Simple circuit consisting of a battery as the source, the lamp as the load, and a switch to control operation.

Since the only duty of the switch is to interrupt or close the circuit, it may be inserted anywhere in the circuit. It is shown in the upper connecting wire, but will give the same results if placed in the lower. In either case it controls the flow of the electrons.

**1.7 Current.** A stream of electrons forced into motion by an electromotive force is known as a *current*. The atoms in a good conducting material such as copper are more or less stationary. However, one or more of the outer-ring free electrons are constantly flying off at a high rate of speed. Electrons from other nearby atoms fill in the gaps. Apparently there is a constant aimless movement of billions of electrons in all directions at all times in every part of the conductor.

When an electric force is impressed across the conductor (from a battery) it drives some of these aimlessly moving free electrons away from the negative force toward the positive. It is unlikely that any one electron will move more than a fraction of an inch in a second. However, an energy flow takes place along the conductor at approximately 186,000 miles per second. A simple analogy of energy flow can be illustrated with automobiles parked in a circle, as shown in Fig. 1.9.

All the automobiles are parked, bumper to bumper, except cars 1 and 2, which are separated by a few feet. Nothing is happening in the circuit. The driver in car 1 steps on the gas for an instant, produces mechanical energy, and his car is propelled forward, striking car 2. The force of the impact transfers energy to car 2, which in turn transfers energy to car 3, and so on. An instant later the energy is transferred to the back bumper of car 17, and it is propelled forward, striking the back of car 1. Energy has traveled completely around the circuit in a very short space of time, and yet none of the cars except cars 1 and 17 may have moved more than a fraction of an inch. In an electric circuit the electrons are somewhat similar to the cars. By moving suddenly in one direction, electrons can repel other electrons. These repel others farther along, and so on. The energy transfer (current) of a single impulse is very rapid, but the *drift* of the electrons themselves is relatively slow.

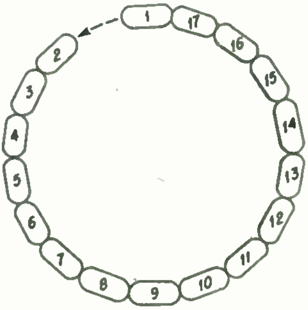


FIG. 1.9. Transmission of energy, similar to that occurring in electric circuits. In this case, automobiles are parked in a circle, bumper to bumper. If car 1 is propelled forward to strike car 2, the force of the impact will travel from car to car until car 17 receives the energy. It will then move forward and strike car 1.

A source of electric energy does not increase the number of free electrons in a circuit; it merely produces a concerted pressure on loose, aimlessly moving electrons. If the material of the circuit is made of atoms or molecules that have no freely interchanging electrons, the source cannot produce any current in the material. Such a material is known as an *insulator*, or *nonconductor*.

The amount of current in a circuit is basically measured in *amperes* (abbreviated amp). An ampere is a certain number of electrons passing or drifting past a single point in an electric circuit *in one second*. Therefore an ampere is a rate of flow, similar to gallons per minute in a pipe.

The quantity of electrons used in determining an ampere (and other electrical units) is the *coulomb*. An ampere is one coulomb *per second*. A coulomb is 6,280,000,000,000,000,000 electrons. This large number is more easily expressed as $6.28 \times 10^{18}$, which is read verbally as "6 point 28 times 10 to the eighteenth power." "Ten to the eighteenth power" means the *decimal place* in the 6.28 is moved 18 places to the *right*. This method of expressing numbers is known as the *powers of 10* and is handy to use when very large or very small numbers are used. An example of a small number is $42.5 \times 10^{-7}$. The $10^{-7}$ indicates the *decimal point* is

X
$6.28 \times 10^{18}$
elec

to be moved seven places to the *left*, making the number 0.00000425. When very large and very small numbers are multiplied, the powers of 10 are added algebraically; that is, if both are negative numbers, they are added and the sum is given a negative sign. If both are positive numbers, they are added and the sum is given a positive sign. If one is negative and the other positive, the smaller is subtracted from the larger and given the sign of the larger. For example, multiply $3.2 \times 10^{14}$ by $4.5 \times 10^{-12}$. When multiplied, 3.2 times 4.5 equals 14.4. The powers of 10, $10^{14}$ and $10^{-12}$, together equal $10^2$. The answer is then $14.4 \times 10^2$, or 1,440.

Just as the unit of measurement of current is the ampere, the unit of measurement of electrical *quantity* is the coulomb.

**1.8 Electromotive Force.** The electron-moving force in electricity, variously termed electromotive force (emf, e.m.f.), electric potential, potential difference (PD), difference of potential, electric pressure, and voltage, is responsible for the pulling and pushing of the electric current through a circuit. The force is actually the result of an expenditure of some form of energy to produce it.

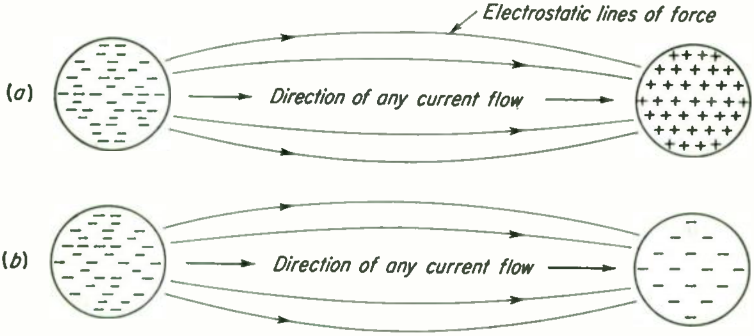


FIG. 1.10. Direction in which energy or current will flow between (*a*) a negative and a positive body and (*b*) a highly negative and a less negative charged body.

An emf exists between two objects whenever one of them has an excess of free electrons and the other has a deficiency of free electrons. This is illustrated in Fig. 1.10*a*. Should the two objects be connected together with a conductor, a current will flow from the negative to the positive.

An emf also exists between two objects whenever there is a difference in the number of free electrons per unit volume of the objects. This is illustrated in Fig. 1.10*b*. If the two objects are both negative, current will flow from the more negatively charged to the less negatively charged when they are connected together.

There will also be an electron flow from a less positively charged object to a more positively charged object.

The electrostatic field, the strain of the electrons trying to reach a positive charge, or to move from a more highly negative to a less negative charge, or to move from a less positive to a more positive charge, *is* the emf in electricity. When a conducting material is placed between two points under electric strain, current flows.

The unit of measurement of electric pressure, or emf, is the *volt*. A single flashlight dry cell produces about 1.5 volts. A wet cell of a storage battery produces about 2.1 volts.

A volt can also be defined as the pressure required to force a current of one ampere through a resistance of one ohm. (The *ohm* is the unit of measurement of resistance, to be discussed later.)

An emf can be produced in many ways. The following is a list of some of the more common methods, with examples of the application of each principle:

1. Chemical (batteries)
2. Electromagnetic (generators)
3. Thermal (thermocouple junctions)
4. Piezoelectric (piezo-oscillator crystals)
5. Magnetostriction (filters and oscillators)
6. Static (laboratory static-electricity generators)
7. Photoelectric (light-sensitive cells)

**1.9 The Battery in a Circuit.** In the explanations so far, "objects," either positively or negatively charged, have been used. A common method of producing an emf is by the chemical action in a battery. Without going into the chemical reactions that take place inside a cell, a brief outline of the operation of a battery is given here. For a more detailed explanation, refer to the chapter on Batteries.

Consider a flashlight *cell*. Such a cell (two or more cells form a battery) is composed of a zinc can, a carbon rod down the middle of the cell, and a black, damp, pastelike *electrolyte* between them (Fig. 1.11).

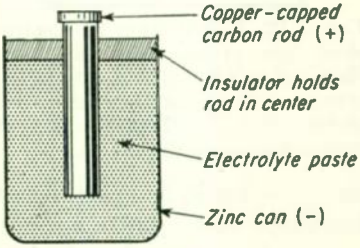


FIG. 1.11. Simple cross section of the common dry cell.

The zinc can is the negative terminal. The carbon rod is the positive terminal. The active chemicals in the cell are found in the electrolyte.

The materials in the cell are selected of such substances that electrons are pulled from the outer orbits of the molecules or atoms of the positive carbon terminal chemically by the electrolyte and deposited on the zinc can. This leaves the carbon positively charged and charges the zinc negative. The number of electrons that move is dependent upon the types of chemicals used and the relative areas of the zinc and carbon electrodes. If the cell is not connected to an electric circuit, the chemicals can pull a certain number of electrons from the rod over to the zinc. The massing of these electrons on the zinc produces a *backward* pressure of electrons, or an electric strain, equal to the chemical energy of the cell, and no more electrons can move across the electrolyte. The cell remains in this static, or stationary, 1.5-volt-charged condition until it is connected to some electric load.

If a wire is connected between the positive and negative terminals of the cell, the 1.5 volts of emf starts a current of electrons flowing through the wire. The electrons flowing through the wire start to fill up the deficient outer orbits of the molecules of the positive rod. Electrons move away from the zinc into the wire. This begins to neutralize the charge of the cell. The electron backward pressure on the zinc, which held the chemical action in check, is decreased. The chemicals of the electrolyte can now force electrons to the zinc can from the positive rod in a continuous stream, maintaining a current of electrons through the wire and battery as long as the chemicals hold out.

Note that as soon as the wire begins to carry electrons, the electrolyte also has electrons moving through it. This motion produces an equal amount of current throughout the whole circuit at the same time. This point is a very important one to understand. There are no bunches of electrons moving around an electric circuit like a group of race horses running around a track. It is more like the race track with a single lane of automobiles, bumper to bumper. Either all must move at the same time, or none.

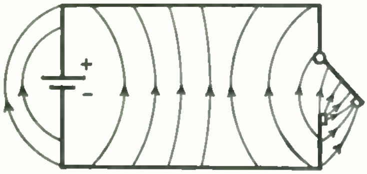


FIG. 1.12. Distribution of electrostatic lines of force across an open-circuited switch. The greatest concentration occurs at the sharp point at the switch, but the field is present everywhere along the circuit.

In an electric circuit, when electrons start flowing in one part, it can be considered that all parts of the circuit have the same value of current flowing in them instantly. Most circuits are so short that the velocity of energy flow, 186,000 miles per second, may be disregarded for the present.

When a circuit is broken by the opening of a switch, electron progress comes to a sliding halt at all points of the circuit at the same time. In this case the chemicals keep pumping electrons until the wire on the negative terminal attains a 1.5-volt charge of electrons when compared with the positive terminal. When this occurs, the electron charge, or strain, across the open switch equals the chemical strain produced in the cell again and all electron progress in the circuit ceases. The circuit is charged, and electrostatic lines of force are developed as illustrated in Fig. 1.12.

It will be noticed that more lines of force per square inch appear at the sharpest point of the switch. The sharper this point, the more concentrated the lines of force and the more likely it is that the relatively strong field will pull free electrons from the point. Electrons pulled out at this point form a *corona*, or *brush discharge*. In high-voltage circuits, care must be taken to make sure that no sharp points occur to produce such discharges. Several thousand volts is usually required to produce a corona discharge.

If electrons leave a sharp point, as described, in such quantities that the air is heated and becomes *ionized*, a spark of electronically heated air will be visible. A constant spark between two points is called an *arc*.

**1.10 Ionization.** When an atom loses an electron, it lacks a negative charge and is therefore positive. The electronless atom in this condition is a *positive ion*.

In most metals the atoms are constantly losing and gaining free electrons. They may be thought of as being constantly undergoing ionization. In this condition the metal is a good conductor.

Atoms in a gas are not normally ionized to any great extent, and therefore a gas is not a good conductor under low electric pressures. However, if the emf is increased across an area in which gas atoms are present, some of the outer planetary electrons of the gas atoms will be attracted to the positive terminal of the source of emf, and the nucleus of the atom toward the negative. When the pressure increases enough, one or more free electrons may be torn from the atom. It is then ionized. If this happens to enough of the atoms in the gas, a current flows through the gas. For any particular gas at any particular pressure, there is a certain voltage value that will produce ionization. Below this value, the number of ionized atoms is small. Above the critical value more atoms are ionized, producing greater current flow, tending to hold the voltage across the gas at a constant value. In an ionized condition the gas acts as an electric conductor.

Examples of ionization of gases are lightning, neon lights, and fluorescent lights. Ionization plays an important part in radio and electricity.

**1.11 Types of Current and Voltage.** There are different types of currents and voltages dealt with in electricity. In this book the following nomenclature will be used:

*Direct Current* (d-c). No variation of the amplitude (strength) of the current or voltage. Obtained from batteries, d-c generators, power supplies. (See Fig. 1.13*a*.)

*Varying Direct Current* (vd-c). The amplitude of the current or voltage varies, but never falls to zero. Found in many tube circuits. (See Fig. 1.13*b*.)

*Pulsating Direct Current* (pd-c). The amplitude drops to zero periodically. Produced in rectifier circuits. (See Fig. 1.13*c*.)

*Interrupted Direct Current.* Current or voltage starts and stops abruptly. Produced by vibrators, choppers, and special circuits. (See Fig. 1.13*d*.)

*Alternating Current* (a-c). Electron flow reverses (alternates) periodically and usually changes amplitude in a more or less regular manner. Produced in a-c generators, oscillators, some microphones, and radio in general. It is the usual house current. (See Fig. 1.13*e*.)

*Damped a-c.* Alternating current which dies out in amplitude. Produced by spark-type oscillators and inadvertently in many circuits. (See Fig. 1.13*f*.)

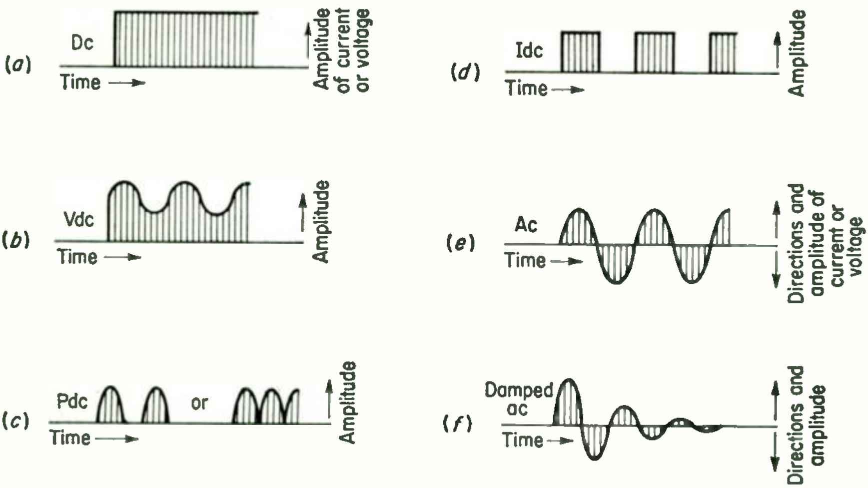


FIG. 1.13. Different forms of voltage or current. (*a*) Direct current. (*b*) Varying d-c. (*c*) Pulsating d-c. (*d*) Interrupted d-c. (*e*) Alternating current. (*f*) Damped a-c.

**1.12 Resistance.** It was previously pointed out that certain metals, such as silver and copper, have many free electrons flying aimlessly, at high rates of speed, at all times, through the spaces between the atoms of the material. Other metals, such as nickel and iron, have fewer free electrons in motion. Still other materials, such as glass, rubber, porcelain, mica, quartz, etc., have practically no interatom free-electron movement. When an emf is applied across opposite ends of a copper wire, many free electrons progress along the wire and a relatively high current results. Copper is a very good conductor of electric current. When the same emf is applied across an iron wire of equivalent size, only about one-sixth as much current flows. Iron may be considered a fair conductor. When the same emf is applied across a length of rubber or glass, no electron drift results. These materials are insulators. Insulators are used between conductors when it is desired to prevent electric current from flowing between them.

Silver is the best conductor, and glass is one of the best insulators. Between these two extremes are found many materials of intermediate conducting ability. While such materials can be catalogued as to their conducting ability, it is more usual to think of them by their resisting ability. Glass completely resists the flow of current. Iron resists much less. Silver has the least resistance to current flow.

The resistance a wire or other conducting material will offer to a current depends on four physical factors:

1. The type of material from which it is made (silver, iron, etc.)
2. The length (the longer, the more the resistance)
3. Cross-section *area* of the conductor (the more area, the less resistance)
4. Temperature (the warmer, the more resistance, except for carbon)

A piece of silver wire of given dimensions will have less resistance than an iron wire of the same dimensions. It is reasonable to assume that if a 1-ft piece of wire has 10 ohms (the unit of measurement of resistance), 2 ft of the same wire will have 20 ohms.

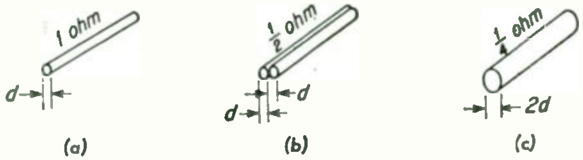


FIG. 1.14. (*a*) Single wire with a certain cross-section area and 1 ohm resistance. (*b*) Two similar wires together have twice the cross-section areas and half the resistance. (*c*) Doubling the *diameter* quadruples the cross-section area, reducing the resistance to one-fourth.

On the other hand, if a 1-ft piece of wire has 10 ohms, two pieces of this wire placed side by side will offer twice the cross-section *area*, will conduct current twice as well, and therefore will have half as much resistance. (The cross-section area is the area seen when a wire is cross-sectioned, or cut in two.) A wire having *twice* the *diameter* of another wire will have *four* times the cross-section area (area = $\pi$ times radius *squared*), and therefore one-fourth the resistance. These relationships are illustrated in Fig. 1.14.

A round wire of 0.001 in. diameter is said to have one *circular mil* (abbreviated cir mil) of cross-section area. The word mil means one one-thousandth of an inch. A round wire of 2 mils diameter has twice the radius and, by the formula for the area of a circle, above, has four times the cross-section area, or 4 cir mils. A 3-mil-diameter wire has 9 cir mils, and so on. The number of circular mils in any round wire is equal to the number of thousandths of an inch of diameter *squared.*

The number of circular mils is considered when determining how much current a wire may pass safely. When current flows through *any* wire, heat is produced in the wire. If too much heat is produced, the insulation on the wire may be set on fire, or the wire may even melt.

It has been found that a copper wire having a diameter of 64 mils, or $(64)^2 = 4{,}100$ cir mils, will allow 4.1 amp to flow through it in a confined area without excessive heating. This represents 1,000 cir mils/amp. Therefore it may be assumed that any copper wire may carry 1 amp for every 1,000 cir mils of cross-section area. In some applications, when a highly heat-resistant insulation is used, it may be possible to use wire with 750 cir mils or less per ampere. The wire will heat considerably more than it would with 1,000 cir mils/amp, but cannot destroy the improved insulation at the temperature that will be developed. However, the same 64-mil wire may carry safely 15 amp or more if it is in free air where it can rapidly dissipate the heat developed in it.

The unit of measurement of resistance is the *ohm*. For practical purposes an ohm may be considered to be the resistance of a round copper wire, 0.001 in. in diameter, 0.88 in. long, at 32° Fahrenheit (32°F). It is common practice to use the Greek letter omega (Ω) to indicate the word ohms in problems and on diagrams where resistance values are given. For example, 100 ohms may be written: 100 Ω.

The *specific resistance* of a conductor is the number of ohms in a 1-ft long 0.001-in.-diameter round wire of that material. The specific resistance of several common materials is listed in Table 1.1.

Table 1.1

| *Conductor* | *Specific resistance, ohms* |
|---|---|
| Silver | 9.75 |
| Copper | 10.55 |
| Aluminum | 17.30 |
| Nickel | 53.00 |
| Iron | 61.00 |
| Lead | 115.00 |
| German silver | 190.00 |
| Nichrome | 660.00 |

An aid in remembering the order of resistance of five of the more common materials used as conductors is to remember how they go down the "scail" (misspelling of the word "scale"), where the letters of "scail" indicate Silver, Copper, Aluminum, Iron, and Lead.

Materials such as german silver and nichrome are alloys of two or more metals and are used in the construction of resistors. When wire made of these substances is wound on a tubular ceramic form, the result is a *wire-wound resistor*, as shown in Fig. 1.15. These resistors are usually covered with a hard, vitreous protective coating.

A carbon resistor may be made from powdered carbon mixed with a binding material and baked into small hard tubes with a wire attached to each end. Other carbon resistors consist of a glass or ceramic rod coated with a carbonized layer, which in turn is covered with a ceramic nonconductive coating. A connector wire projects from each end, as shown in Fig. 1.16. The value of the resistance depends on the percentage of carbon in the mixtures used. Such resistors range in value from a few ohms to several million ohms. The physically larger resistors of this type may be 1 to 2 in. long and about ⅜ in. in diameter and are usually 2-*watt* resistors. The smallest normally used are ¼-*watt* resistors, being less than ⅛ in. in diameter and about ½ in. in length. Other carbon resistors are made in ⅒-, ½-, and 1-watt sizes.

The symbol used in radio diagrams for a *fixed*, or nonvariable, resistor, either wire-wound or carbon, is shown in Fig. 1.17. The symbol used for one variable type of resistor, called a *rheostat* (ree-oh-stat), is shown in Fig. 1.18. The rheostat has two connections, one to an end of the resistor and the other to a sliding arm that moves along the length of the resistor. Rheostats may be either wire-wound or carbon.

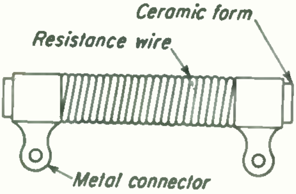


FIG. 1.15. Wire-wound fixed resistor.

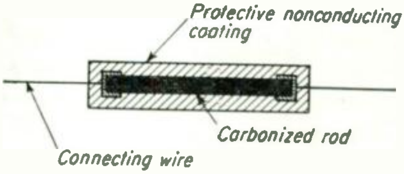


FIG. 1.16. Construction of fixed carbon resistor.

FIG. 1.17. Symbol of any fixed resistor.

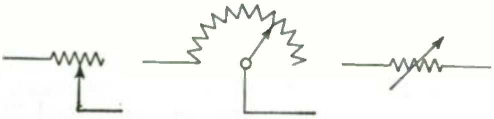


FIG. 1.18. Various symbols used to indicate a rheostat.

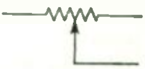


FIG. 1.19. Symbol of a potentiometer.

The symbol for a *potentiometer* (po-ten-she-om-itr), which is a rheostat with connections at both ends of the resistance, plus a connection to a sliding contact, is shown in Fig. 1.19. Potentiometers are used in most cases to select a desired proportion of the total voltage across the potentiometer. They are used as *voltage dividers.*

An *adjustable* resistor is a wire-wound resistor with a sliding contact on it that can be locked into position when the desired value of resistance is determined experimentally. It can be made in the form of a rheostat, but may take the form of a cylindrical potentiometer, except that its moving contact can be tightened by a machine screw to make it immobile, as shown in Fig. 1.20. Extreme care must be exercised when adjusting these resistors to make sure that the machine screw is loose enough to allow the movable contact to be moved without damaging the fine resistance wires with which they are often wound. These resistors may be partly covered with a vitreous coating, but part of them will be bare wire to allow the slider to make contact on the resistor.

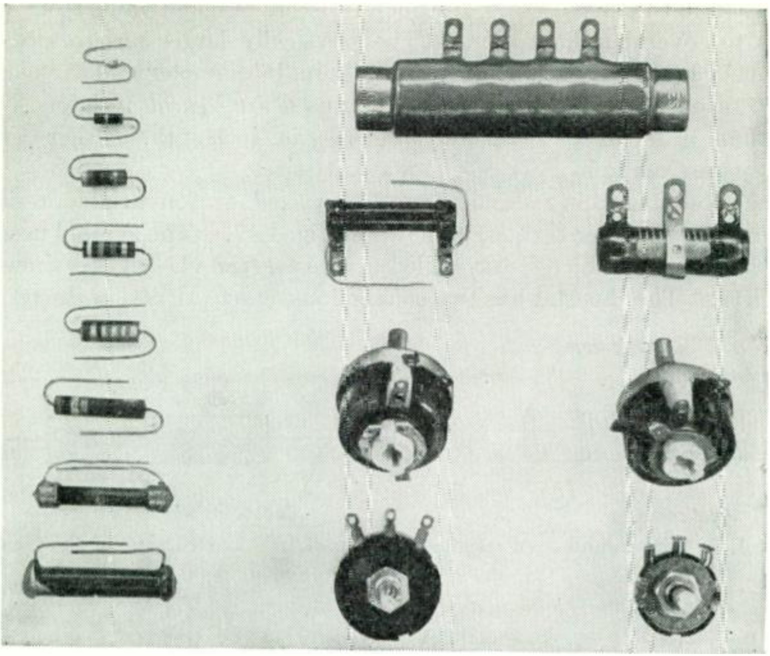


FIG. 1.20. Resistors. Left, top to bottom, carbon types, 1⁄10-watt, ½-watt, five 1-watt, and one 2-watt. Right, top to bottom and left to right, tapped wire-wound 100-watt, fixed wire-wound 10-watt, adjustable wire-wound 25-watt, wire-wound potentiometer, wire-wound rheostat with arm at the "off" position, 1-watt and ½-watt carbon potentiometers.

**1.13 Color-coded Resistors.** In many cases resistors do not have their resistance values printed on them. They are painted with color-coded markings. It is necessary that radiomen be familiar with this code, as these same colors will have the same values when other types of parts are color-coded. There have been two methods used to color-code resistors. One is the three-stripe method; the other is the body-end-dot method. The body-end-dot resistors are no longer used, but existing equipment may contain some of these resistors. In both methods, the same color code is used. The colors and their meanings are given in Table 1.2.

Table 1.2

| *Color* | *Number* |
|---|---|
| Brown | 1 |
| Red | 2 |
| Orange | 3 |
| Yellow | 4 |
| Green | 5 |
| Blue | 6 |
| Purple or violet | 7 |
| Gray | 8 |
| White | 9 |
| Black | 0 |

To read the resistance of a three-stripe color-coded resistor, start with the stripe nearest the end of the resistor. The first stripe is the first number. The second stripe is the second number. The third stripe is the *number of zeros* following the second number. Figure 1.21 illustrates how a three-stripe color-coded resistor can be deciphered.

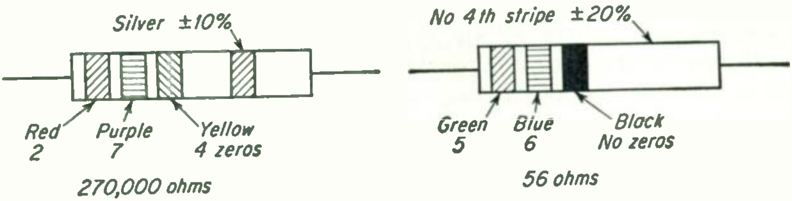


FIG. 1.21. Three-stripe color-coded resistors.

If no other stripes are on the resistor, it indicates the color-coded-resistance value is correct within a tolerance of 20 per cent. If a fourth stripe is used, the tolerance is as shown in Table 1.3.

**Table 1.3**

| *Fourth-stripe color* | *Tolerance, %* |
|---|---|
| Silver | 10 |
| Gold | 5 |

Sometimes a resistor will be found with a third stripe of gold or silver. The gold indicates that the first two numbers are to be multiplied by 0.1 to determine the resistance. The silver indicates that the first two numbers are to be multiplied by 0.01.

The body-end-dot coding is read in that order. If no dot is visible, the dot and body number are assumed to be the same. Figure 1.22 illustrates a body-end-dot–marked resistor.

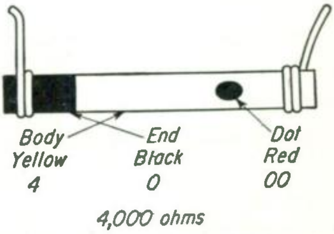


FIG. 1.22. Body-end-dot resistor. Resistance = 4,000 ohms.

**1.14 The Metric System.** Rather than use the more cumbersome measurement systems of the United States and Great Britain (1 ft = 12 in., 3 ft = 1 yd, etc.), radio and electronic engineers tend to use the *metric* system, which divides weights and measures into units with multiples of 10, similar to the cent, dime, and dollar system.

The *meter* is the unit of length measurement in the metric system and is roughly similar to a yard, being 39.37 in. (approximately *three* feet, *three* and *three*-eighths inches long).

For shorter lengths, the *centimeter*, or one-hundredth of a meter, is used. A centimeter (abbreviated cm) is 0.3937 in. long. An inch is 2.54 cm, or slightly more than 2½ cm. For still smaller lengths, the *millimeter* (abbreviated mm), or one-thousandth of a meter, is used.

**For greater lengths the kilometer (kill-uh-mee-ter).** or one thousand meters, is used. The kilometer (abbreviated km) is approximately 0.64 mile.

*Kilo*, *milli*, and *centi* appear repeatedly in all radio work, as do *mega* and *micro*. These five prefixes must be understood and memorized:

X

*Kilo* means "1,000 times."
*Mega* means "1,000,000 times."
*Centi* means "0.01 times," or "1/100 of."
*Milli* means "0.001 times," or "1/1,000 of" (*not* one million).
*Micro* means "0.000001 times," or "1/1,000,000 of."

Examples of some common uses of these word elements are *milliampere*, *kilovolt*, *megohm*, *microampere*, and *micromicroamperes*.

Hz
HERTZ
for
CYCLES

Abbreviations for these units are k for *kilo*, m for *milli*, M for *mega*, and the Greek letter mu, or $\mu$ (mew), for *micro*. Thus, 100 kilohms is 100,000 ohms; 25 kc is 25,000 cycles; 4 mh is 0.004 henry; 65 $\mu$f is 0.000065 farad; 144 Mc is 144,000,000 cycles.

**1.15 Wire Sizes.** Most wire used in electricity and radio is made of copper. It may be either *hard-drawn* (stiff) or *soft-drawn* (pliable). It is manufactured in various sizes, with or without insulation coating the wire. Some of the insulating materials used are enamel, silk, glass fibers, cotton, fiber, rubber, varnish, and various plastics.

Table 1.4 lists some of the more commonly used copper-wire sizes and information regarding them.

Table 1.4

| Gage no. | Diameter in mils | Ohms per 1,000 ft, room temp | Current-carrying capacity at 1,000 cir mils/amp, as in transformers* | Approximate current for open wiring, rubber-insulated |
|---|---|---|---|---|
| 0 | 325 | 0.1 | 90 amp | 125 amp |
| 8 | 128 | 0.641 | 16.5 amp | 35 amp |
| 10 | 102 | 1.02 | 10.4 amp | 25 amp |
| 12 | 81 | 1.62 | 6.5 amp | 20 amp |
| 14 | 64 | 2.58 | 4.1 amp | 15 amp |
| 16 | 51 | 4.09 | 2.6 amp | |
| 18 | 40 | 6.51 | 1.6 amp | |
| 20 | 32 | 10.4 | 1.0 amp | |
| 22 | 25 | 16.5 | 640 ma* | |
| 24 | 20.1 | 26.2 | 400 ma | |
| 26 | 15.9 | 41.6 | 250 ma | |
| 28 | 12.6 | 66.2 | 160 ma | |
| 30 | 10.0 | 105 | 100 ma | |
| 32 | 7.95 | 167 | 63 ma | |
| 34 | 6.3 | 265 | 40 ma | |

* "Cir mils" means circular mils; "ma" means milliamperes.

**1.16 Making Low-resistance Connections.** When less current flow is desired in an electric circuit, a resistor may be connected into one of the lines carrying the current. When it is desired to maintain as much current as possible, it is necessary that no extraneous resistance be added to the circuit.

Loose or oxidized (rusted) electrical connections may act as resistances in a circuit. Such poor connections are often the source of improper operation of a circuit. When radio equipment is constructed, repaired, or revamped, the radioman must make sure that *all* connections are tight.

There are four types of electrical connections: (1) those held together with nuts and bolts, (2) those held together with twisted wires, (3) crimped connections, and (4) soldered connections.

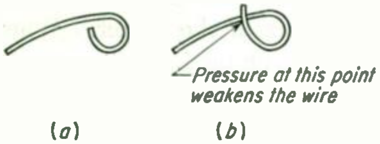


FIG. 1.23. (*a*) Properly looped wire to fit around a machine screw and under a nut. (*b*) Improperly looped wire.

FIG. 1.24. (*a*) Properly made splice between two ends of wire. (*b*) Very poor method of splicing two wires.

When a wire is scraped *clean* and looped around a machine screw and a nut is tightened down on it, a reasonably good connection is made between wire and machine screw. The harder the nut presses, the more the wire is flattened. This presents more contacting surface between wire and nut and less resistance, or more current-carrying ability, for the connection. It is usually desirable to insert a flat metal washer between wire and nut to prevent excessive chafing of the wire by the rotating nut as it is tightened. The wire should not be overlapped on itself, as shown in Fig. 1.23*b*, as pressure exerted on the two pieces of wire where they overlap may squeeze them each to half thickness and greatly weaken the wire at the connection. The looped end of the wire should be fitted snugly around the screw or bolt (Fig. 1.23*a*) and in such a direction that the tightening of the nut tends to close the loop rather than open it. This is particularly important when no washer is used at the connection.

Two wires may be scraped or sanded clean and then twisted together. It is imperative that they be tightly twisted, preferably by using pliers to assure a tight twist. Figure 1.24*a* illustrates a common twisted connection used with two wires. It will withstand considerable strain. (If it is covered with a layer of solder, its strength is considerably increased.) Over a period of time the wires may corrode and a resistance joint can result.

It is generally considered poor practice to use a figure-eight, or bowline, knot to connect wires, since sharp bends in a wire tend to crystallize the metal and weaken the wire. Figure 1.24*b* illustrates a highly undesirable method of connecting two wires. It produces a loose connection that can cause interference in nearby receiving equipment, even if it is not being used to carry electric current.

There are special wire-connecting tools that will twist wires around a square terminal so tightly and so rapidly that such connections are considered the equal of soldered joints, and may be superior if the joint is subject to vibration.

Crimped connections are produced with a pressure tool that crimps the wire and lug together physically.

For most radio equipment, a soldered connection is considered to be the best and most practical. Many *clean* metal surfaces will take a coating of solder. Some materials, such as aluminum, stainless steel, etc., will not. *Solder* (sod-r) is a mixture of about 50 per cent lead and tin, having a relatively low melting point. For radio work it usually comes in 1/8-in. hollow-wire form, with a rosin-core flux in the center. When heated with a hot soldering iron, the solder can be made to flow over a clean *heated* metal surface. The solder flows into surface depressions, and apparently into the spaces between the surface molecules of the metal. This interlocking of metal and solder molecules produces an extremely tight connection between solder and metal when the solder cools and hardens.

When two wires are to be soldered together, (1) *both* wires should be heated before solder is applied and (2) the surfaces of both wires must be clean.

To heat both wires, the hot soldering iron is laid so that both wires receive heat simultaneously. Solder is then held against the point where the two wires touch. As hot solder flows over the hot metal surfaces, the iron and the solder are taken away. The solder on the joint cools rapidly and solidifies. Unless care is taken not to move the wires until the solder is thoroughly solidified, a crystallization of the solder occurs, weakening the joint materially.

Adequate cleaning of the surfaces to be soldered is one of the most important requirements for good soldered connections. Most of the metals used in radio work will take a coating of solder if they have been filed, scratched clean with a knife, or sanded. Solder will not stick to oxidized or rusted surfaces, however. Aluminum will not solder because it oxidizes as fast as it is scratched clean. When a large wire is to be soldered, a little *soldering paste* may be spread on its surface. When heated on the wire, the acid in the paste cleans the surface and allows it to take solder. Rosin and other *flux* materials will do the same thing, provided the oxidation is light. However, the acid in soldering pastes can eat away the wire, eventually weakening it or producing a voltage-generating cell between the solder, acid, and metal. Acid joints can produce noises and rectification in radio equipment and should therefore not be used. In some radio establishments, anyone using acid flux on connections is fired. Either rosin or some other noncorrosion flux should be used.

*Hookup* wire that has been *tinned* is available. It has a light coating of tin or solder on it. Unless exposed to the air for a long period of time, it requires no cleaning when it is being soldered.

Tinning the soldering iron is very important. Copper is used as the working surface of a soldering iron (Fig. 1.25). The copper tip is cleaned by filing it smooth. When the iron is turned on, it will heat and the shiny copper surface will become a dull reddish color. As it dulls, it is becoming oxidized and will not tin. It is necessary to bring the tip up to a temperature that will melt solder but will not oxidize the copper. At this temperature, if solder is applied, a thin coating will spread over the cleaned tip and the iron is tinned. The tinned portion will melt solder quickly when heated sufficiently. From time to time it is necessary to cool the iron, lightly file the working surface clean, and re-tin it.

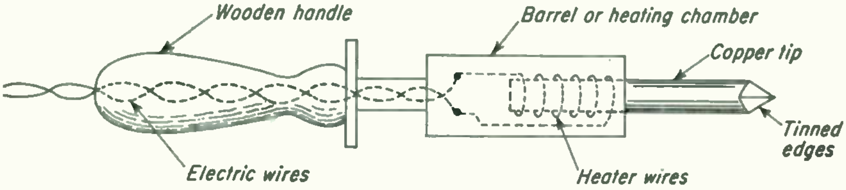


FIG. 1.25. A soldering iron.

A soldering iron requires about five minutes to come to operating temperature. When one or two joints are to be made, this is usually an undesirable delay. In the last few years a quick-heating iron has been developed. It is called a *soldering gun*, resembling a pistol in shape. When the trigger switch is pulled, its heavy copper-wire tip heats in a few seconds and can be used to solder wire connections. When large metal areas are to be soldered, a heavier soldering iron is more desirable.

Solder that has been heated and cooled several times oxidizes and crystallizes and will not solder to tinned surfaces properly. It should be melted off the connection, and new solder used.

To make good soldered connections, it is usually necessary that a reasonably good physical connection be made between wires, or between a wire and a terminal. The solder holds the connection immovable and prevents oxidation of the contacting surfaces. For most connections it is usually only necessary to twist the wire enough so that it will remain steady while it is soldered to assure a satisfactory connection. It is not necessary that it be woven or tied around a terminal. For high-current circuits, the more terminal area and wire area making contact, the better. The solder should not be relied upon to carry the current in such cases. It should be considered more as a weatherproof and physical, or mechanical, holding coat rather than as a conductor of current.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

1. What is an electron? (1.2) An ion? ionization (1.10) [3 & 6]

2. Does the resistance of a copper conductor vary with variations in temperature, and if so, in what manner? (1.3, 1.12) heat ↑ R ↑ except carbon [3 & 6]

3. By what other expression may an electric current flow be described? (1.7) Coulomb [3 & 6]

4. Define the term coulomb. (1.7) 6.28×10' electrons [3 & 6]

5. By what other term may a difference of potential be described? Volt (1.8) [3 & 6]

6. With respect to electrons, what is the difference between conductors and nonconductors? (1.12) con ors have more free electrons [3 & 6]

7. What is the unit of resistance? (1.12) R [3 & 6]

8. Name four conducting materials in their order of conductivity. [illegible] (1.12) [3 & 6]

9. If the diameter of a conductor of given length is doubled, how will the resistance be affected? (1.12) 1/4 resistance [3 & 6]

10. Explain the factors which affect the resistance of a conductor. (1.12) [3 & 6]

11. What effect does the cross-section area of a conductor have upon its resistance per unit length? (1.12) [3 & 6]

12. Explain the meaning of *kilo*, *micro*, *meg*, and *micromicro*. (1.14) [3 & 6]

13. Why is rosin used as soldering flux in radio construction work? (1.16) [3 & 6]

14. List at least two essentials for a good soldered connection. (1.16) [3 & 6]
well soldered good " mechanically

## AMATEUR LICENSE INFORMATION

Applicants for Novice Class License examinations should be able to answer questions prefaced by a star. Applicants for General, Conditional, and Technician licenses should be able to answer all questions.

★1. What is electric current? In what unit is it measured? (1.7)

★2. What is electric potential? In what unit is it measured? (1.8)

★3. What is electric resistance? In what unit is it measured? (1.12)

★4. What are the meanings of the prefixes *kilo*, *micro*, and *meg*? (1.14)

5. What is the name of the unit of electrical quantity used in determining an ampere? (1.7)

6. What are the essentials for making good soldered connections? (1.16)

7. Why is rosin used as soldering flux in radio construction work? (1.16)

# CHAPTER 2

# DIRECT-CURRENT CIRCUITS

**2.1 Ohm's Law.** Wherever electric circuits are in use, whether in a simple flashlight, in motors or generators, or in radio and television circuits, the "big three" of electricity—voltage, current, and resistance—are present. It is interesting to see how the theory of more complex circuit operation unfolds by starting with a simple circuit and slowly adding one step to another. To the beginner, each step may appear understandable enough, but remembering it and, more important, learning when to apply it is the secret to success in the study of electrical circuitry. Once the reader comprehends something of the physical nature of current, voltage, and resistance, he is ready to use this knowledge to learn when, where, how, and most of all *why* it may be applied to electric circuits.

It was previously explained that a change in current can be produced by changing either the voltage or the resistance in the circuit. An *increase* in voltage will produce an *increase* in current. Therefore voltage and current are directly proportional to each other.

An *increase* in resistance in a circuit produces a *decrease* in current. Therefore resistance and current are inversely proportional to each other.

These two facts can be condensed into one statement, which is known as *Ohm's law*:

*Current varies directly as the voltage and inversely as the resistance.*

Ohm's law is a simple statement of the functioning of an electric circuit. It can be expressed mathematically as

$$I = \frac{E}{R}$$

where $I$ is the intensity of the current in amperes; $E$ is the emf in volts; and $R$ is the resistance in ohms. Ohm's law might also be expressed as

$$\text{Amperes} = \frac{\text{volts}}{\text{ohms}}$$

Multiplying both sides of the equation by $R$, the formula becomes

$$E = IR$$

Dividing both sides of this last equation by $I$, the formula becomes

$$R = \frac{E}{I}$$

These three variations of the Ohm's-law formula enable one to determine the current value if the voltage and resistance are known, or the voltage in the circuit if the current and resistance are known, or how much resistance is in the circuit if the voltage and current are known.

An understanding of this law and an ability to use it are quite important. License examination questions are certain to involve the operation of Ohm's law in several different ways.

The ability to rearrange formulas as shown above is another requirement for the radio operator. If you are not familiar with the indicated divisions and multiplications, pay particular attention to the section dealing with the fundamentals of this type of mathematics (Sec. 2.3). If you are unable to comprehend the briefly outlined steps, you should study a basic algebra book.

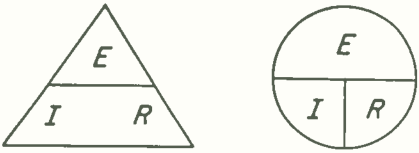


FIG. 2.1. Aids to remembering Ohm's-law formulas.

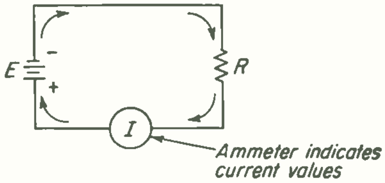


FIG. 2.2. Current is directly proportional to emf and inversely proportional to resistance.

The so-called "magic triangle," or "magic circle" (Fig. 2.1), may help in learning the three formulas of Ohm's law. If the desired symbol is covered, the mathematical method of solving for this letter is shown by the position of the other two symbols. For example, cover the $I$; it is necessary to divide $E$ by $R$. Cover the $E$; it is necessary to multiply $I$ times $R$. Cover the $R$; it is necessary to divide $E$ by $I$.

**2.2 Using Ohm's Law.** The following examples illustrate the use of Ohm's-law formulas in determining the functioning of simple electric circuits:

In the circuit of Fig. 2.2, if the voltage $E$ of the battery is 10 volts and the load resistance $R$ is 20 ohms, what is the value of the current $I$ in the circuit?

Solution, using Ohm's law:

$$I = \frac{E}{R} = \frac{10}{20} = 0.5 \text{ amp}$$

In the same type of circuit, if the ammeter reads 4 amp and the resistance is known to be 30 ohms, what value of emf must the source have?

Solution:

$$E = IR = 4(30) = 120 \text{ volts}$$

In the same type of circuit, the ammeter reads 3 amp, and the source voltage is known to be 150 volts. What is the load-resistance value?

Solution:

$$R = \frac{E}{I} = \frac{150}{3} = 50 \text{ ohms}$$

An electric shock due to more than 15 ma (0.015 amp) flowing through the body is considered dangerous to human life. What current will flow through a person having 2,200 ohms if connected across 110 volts?

$$I = \frac{E}{R} = \frac{110}{2{,}200} = 0.05 \text{ amp, or } 50 \text{ ma}$$

### Practice Problems

1. A lamp connected across 120 volts is found to have 2 amp flowing through it. What is its resistance? 60 Ω

2. A relay coil having 35 ohms resistance is made to operate when connected across 6.3 volts. How much current will it draw? .18 amps

3. A 5,000-ohm resistor in a receiver has 5 ma flowing through it. How much voltage is developed across it? (NOTE: Milliamperes must be changed to amperes before Ohm's law is used.) 25V

4. The resistance of a circuit remains the same, but the current through the resistor suddenly triples. What has happened to the voltage of the circuit? ×3

5. If the voltage applied to a circuit is doubled and the resistance remains unchanged, what will be the final current value? ×2

6. If the voltage applied to a circuit is doubled and the resistance of the circuit is increased to three times its former value, what will be the final current value? ×.67

**2.3 Mathematics for Ohm's-law Problems.** This is not intended to be a textbook on mathematics. It may be well, however, to point out some basic mathematical operations that can be used in working electrical problems involving formulas similar to Ohm's law. These operations are a form of simple algebra. Only a few of the simplest will be given. You should undertake an outside study of algebra if you are weak in this subject.

When you work with algebraic formulas, such as the Ohm's-law equation $I = E/R$, there are certain operations to remember. These are as follows:

1. The sign for addition is +. The sign for subtraction is −. The sign for multiplication is × or parentheses ( ).

$$+2 + 2 = +4 \qquad +5 - 2 = +3$$
$$-3 - 4 = -7 \qquad +3 - 5 = -2$$
$$3 \text{ times } 4 = 3 \times 4 = (3)(4) = 3(4) \qquad (A)(B) = A(B) = AB$$

2. Any number (or letter) multiplied by 1 is unchanged, and therefore the 1 may be dropped.

$$1(3) = 3 \qquad 1(A) = 1A = A$$

3. Any number (or letter) divided by 1 is equal to the number (or letter), and therefore the 1 may be dropped.

$$\frac{4}{1} = 4 \qquad \frac{A}{1} = A$$

4. Any number (or letter) when multiplied by itself is equal to the number (or letter) squared.

$$2 \times 2 = 2^2 \qquad E(E) = E^2 \qquad EE = E^2$$

5. Any number (or letter) divided by itself is equal to 1.

$$\frac{4}{4} = 1 \qquad \frac{F}{F} = 1 \qquad \frac{XQZ}{ZXQ} = 1$$

6. If *both sides* of an equation are multiplied by the same number (or letter), the equation will still be correct.

$2 = 2$ If multiplied by 4: $4(2) = 4(2)$ or $8 = 8$
$6 = 2(3)$ If multiplied by 4: $4(6) = 4[2(3)]$ or $24 = 24$
$X = AC$ If multiplied by $B$: $BX = BAC$

7. If *both sides* of an equation are divided by the same number (or letter), the equation will still be correct.

$6 = 2(3)$ When divided by 2: $\frac{6}{2} = \frac{2(3)}{2}$ or $3 = 3$
$E = IR$ When divided by $R$: $\frac{E}{R} = \frac{IR}{R}$ or $\frac{E}{R} = I$

8. If *both sides* of an equation are squared, the equation will still be correct.

$6 = 2(3)$ $6^2 = [2(3)]^2$ or $6^2 = 2^2 3^2$ or $36 = 36$
$A = BC$ $A^2 = (BC)^2$ or $A^2 = B^2 C^2$

9. If the square root is taken of *both sides* of an equation, the equation will still be correct.

$16 = 2(8)$ $\sqrt{16} = \sqrt{2(8)}$ or $4 = 4$
$A = BC$ $\sqrt{A} = \sqrt{BC}$
$4^2 = 2(8)$ $\sqrt{4^2} = \sqrt{2(8)}$ or $4 = 4$
$E^2 = PR$ $\sqrt{E^2} = \sqrt{PR}$ or $E = \sqrt{PR}$

10. A negative number on one side of the equation becomes a positive number when moved to the other side. (No sign in front of a number or letter indicates it is positive.)

$7 + 2 = 9$ $B + C = A$ $B - C = A$
$7 = 9 - 2$ $B = A - C$ $B = A + C$

When rearranging formulas involving simple fractions, a first step may be to *cross-multiply.* This means to multiply the top of the fraction on one side of the equation by the lower number of the fraction on the opposite side of the equals sign. The same is done to the other halves of the fractions. These two answers are set as equal to each other.

$$4 = \frac{8}{2} \qquad \text{may be written} \qquad \frac{4}{1} = \frac{8}{2}$$

When cross-multiplied,

$$\frac{4}{1} \times \frac{8}{2} \qquad \text{becomes} \qquad 2(4) = 1(8) \qquad \text{or} \qquad 8 = 8$$

Using a letter formula,

$$I = \frac{E}{R} \qquad \text{or} \qquad \frac{I}{1} = \frac{E}{R}$$

When cross-multiplied,

$$\frac{I}{1} \times \frac{E}{R} \qquad \text{becomes} \qquad 1E = IR \qquad \text{or} \qquad E = IR$$

By cross-multiplying it has been determined what $E$ equals. A further possible step is to determine what $R$ equals. To do this, divide out the *unwanted* letters on one side of the equation, leaving only the desired letter.

$$E = IR$$

To find what $R$ equals, divide out the $I$ from both sides:

$$\frac{E}{I} = \frac{IR}{I}$$

The $I$'s on the right-hand side cancel each other, leaving

$$\frac{E}{I} = R \qquad \text{or} \qquad R = \frac{E}{I}$$

These two operations, first, cross-multiplying, and second, dividing out the unwanted from one side, can be used in a surprising number of electrical problems. If you are trained in mathematics, you may know other methods, but if you are not a mathematician, these operations will be well worth knowing and using.

**2.4 Finding the Square Root.** To determine the answer to many electrical problems it is necessary to find the square root of some number. Often this can be done by referring to a mathematical table of square roots, by using a slide rule, or by using logarithms. If neither the slide rule nor the desired tables are handy, it will be necessary to use the long-division-like method of finding square roots.

The square root of a given number is the number which when multiplied by itself equals the given number. The square root of 9 is 3; the square root of 16 is 4; the square root of 100 is 10; and so on. With many simple numbers such as these, the square root may be easily determined. But what is the square root of a number like 2,168? To find the square root of such a number, it should first be written out in groups of two numbers, *starting at the decimal point.*

2,168 is written as: 21 68.00 00

Next, a line is drawn above the number.

$$\overline{21\ \ 68.00\ \ 00}$$

Above the first group of two numbers (21) a number is placed which, when multiplied by itself, will come close to equaling, but will not exceed, the number 21. This number is 4.

$$\begin{array}{rl} 4 & \\ \hline 21 & 68.00\ \ 00 \end{array}$$

The number 4 multiplied by itself is 16. The 16 is placed below the 21, and the difference is indicated below the 16.

$$\begin{array}{rll} 4 & & \\ \hline 21 & 68 & .00\ \ 00 \\ 16 & & \\ \cline{1-2} 5 & & \end{array}$$

The next two numbers, 68, are brought down next to the 5, making the problem read

$$\begin{array}{rll} 4 & . & \\ \hline 21 & 68 & .00\ \ 00 \\ 16 & & \\ \cline{1-2} 5 & 68 & \end{array}$$

As the next step, the number above the main line, 4 in this problem, is *doubled* to 8 and placed in front of the 5 68, as shown. A space is left for another number after the 8.

$$\begin{array}{rrll} & 4 & . & \\ \cline{2-4} & 21 & 68 & .00\ \ 00 \\ & 16 & & \\ \underline{8\ \ }\big/ & \overline{5} & \overline{68} & \end{array}$$

Above the main line and over the second group of two numbers, the 68 in this case, another number is now required. This number, when multiplied by itself with the 8 in front of it, must be equal to or slightly less than the figure 568 in the problem. By trial, the largest possible number is found to be 6. This is placed above the line and also after the 8. The

86 thus produced is then multiplied by the 6, and the problem now reads

```
          4   6.
        ____________
        21  68.00 00
        16
   86/  5 68
        5 16
        ____
          52
```

The difference between 568 and 516 is determined, and the next group of two numbers, 00, is brought down. As before, the number above the line, 46, is doubled to 92 and placed in front of the 5,200.

```
          4   6.
        ____________
        21  68.00 00
        16
   86/  5 68
        5 16
 92 /     52 00
```

Above the main line and above the next group of two numbers, 00, another number is required. The 92 in front of this number forms a group which when multiplied by this number must be equal to, or less than, 5,200. By trial the number is found to be 5. The 5 is placed above the line and also after the 92. The 925 is now multiplied by 5, and the problem reads

```
          4   6.  5
        ____________
        21  68.00 00
        16
   86/  5 68
        5 16
  925/    52 00
          46 25
          ________
           5 75 00
```

The number above the line, 46.5, is doubled and brought down as before. The next required number, 6, is placed above the next group of double numbers, and also placed after the 930, and multiplied.

```
          4   6.  5   6
        ____________
        21  68.00 00
        16
   86/  5 68
        5 16
  925/    52 00
          46 25
 9306/     5 75 00
           5 58 36
           _______
             16 64
```

The square root of 2,168 is 46.56. For proof, the answer is multiplied by itself. It should equal the original number if the answer is carried out far enough; that is, $(46.56)^2$ should equal 2,168. However, since there was a remainder in the example problem, the 46.56 when squared is only 2,167.8336, which is close enough to 2,168 for most purposes. (In most of your work, figures need be used correct only to the third significant figure. This would make 2,168 equal to 2,170.)

The important points when working square roots are: First, start marking off in double numbers *from the decimal point*. To find the square root of 325, it is marked off as 03 25, and not 32 50. Second, when the numbers to be multiplied are brought down from one step to the next, the number above the line is always *doubled*. Third, the multiplying number must be added after the last-mentioned doubled number.

Take another example in finding the square root of a number: What is the square root of 97,344?

$$\begin{array}{r|l} & \;\;3\;\;\;1\;\;\;2. \\ \hline & 09\;73\;44. \\ & \;\;9 \\ \underline{61} & \overline{\;\;0\;73} \\ & \;\;\;\;\;\;61 \\ \underline{622} & \overline{\;\;\;\;12\;44} \\ & \;\;\;\;12\;44 \end{array}$$

Proof: $(312)^2 = 97{,}344$

### Practice Problems

1. $P = EI$ $E = ?$ $\frac{P}{I}$ $I = ?$ $\frac{P}{E}$
2. $Q = \frac{X}{R}$ $X = ?$ $QR$ $R = ?$ $\frac{X}{Q}$
3. $Z = \frac{X^2}{R}$ $R = ?$ $\frac{X^2}{Z}$ $X = ?$ $\sqrt{RZ}$
4. $FL = \frac{1}{FC}$ $1 = ?$ $FLFC$ $C = ?$ $\frac{1}{F^2L}$ $L = ?$ $\frac{1}{F^2C}$ $F = ?$ $\sqrt{\frac{1}{LC}}$
5. $(3 - A) = \frac{L}{X}$ $X = ?$ $L = ?$ $A = ?$

   HINT: $(3 - A)$ is $1(3 - A)$, or $+3 - A$, or is a unit $(3 - A)$.

6. $2(B - C) = \frac{Q}{Z}$ $Q = ?$ $Z = ?$ $B = ?$ $C = ?$

   HINT: $2(B - C)$ is 2 times $B$ and 2 times $-C$, or $+2B - 2C$.

7. What is the square root of 525?
8. What is the square root of 10,000?
9. What is the square root of 1,000?
10. What is the square root of 10?
11. What is the square root of 0.05?

**2.5 Power and Energy.** Electric pressure, or emf, by itself can do no work. A battery develops an emf, but if there is no load connected across it, no current flows and no electrical work is accomplished.

When a conductor is connected across a source of emf, a current of electrons is developed. The current represents movement. The product of the pressure and the movement (volts and amperes) does accomplish work. The unit of measurement of the rate of doing work, or the unit of measurement of power, is the *watt*. One volt causing one ampere to flow in a circuit produces one watt of power. In formula form,

$$P = EI$$

where $P$ is power in watts; $E$ is emf in volts; and $I$ is current in amperes.

*Example:* What is the power input to a transmitter having a plate voltage of 2,000 volts and a plate current of 0.5 amp?

$$P = EI = 2{,}000(0.5) = 1{,}000 \text{ watts}$$

The Ohm's-law formula states: $E = IR$. By substituting $IR$ for the $E$ in the power formula,

$$P = IR(I) \qquad \text{or} \qquad P = I^2R$$

where $R$ is the resistance in ohms.

*Example:* What is the heat dissipation, in watts, of a resistor of 20 ohms having a current of ¼ amp passing through it?

$$P = I^2R = (0.25)^2 \times 20 = 0.0625(20) = 1.25 \text{ watts}$$

From Ohm's law again, $I = E/R$. By substituting $E/R$ for the $I$ in the basic power formula,

$$P = E\left(\frac{E}{R}\right) \qquad \text{or} \qquad P = \frac{E^2}{R}$$

*Example:* What is the minimum power-dissipation rating of a resistor of 20,000 ohms to be connected across a potential of 500 volts?

$$P = \frac{E^2}{R} = \frac{(500)^2}{20{,}000} = 12.5 \text{ watts}$$

These three formulas for determining the power in an electric circuit are undoubtedly as important for the radioman to know as the three Ohm's-law formulas.

When a current of electrons flows through a conductor, the conductor always becomes warmer than when no current was flowing through it. Some of the power in the circuit is converted to heat and is lost. If a perfect conductor could be found, it would be possible to carry current without such a heat loss. However, even the best of conductors have some resistance and there will always be some heat loss in electric circuits. Note that the main factors in the conversion of electric power to heat are the current and the resistance. The power formula $P = I^2R$ can always be depended upon to give true power indications as far as heat alone is concerned. This is discussed further in circuits involving alternating currents.

All power in electricity is not converted into heat. In the case of a radio receiver, some power is converted into sound waves, although considerable heat will be developed in the radio in the process of this conversion. With transmitters, power is changed into radio waves in the air. When current flows through the resistance-wire filament of an electric light, the filament becomes so hot that it glows brightly. The wire is hot and is radiating heat energy, but it is also radiating energy in the form of light. The power formula will give the total amount of power being consumed. The light energy is a small percentage of the total, however. Fluorescent lights, in many modern installations, utilize a method of producing light energy other than by using a hot filament, and less heat is used to produce the same amount of light. Such lights are more efficient because of their lower percentage of heat loss.

The basic unit of measurement of power is the watt. For smaller quantities the *milliwatt*, or 1/1,000 of a watt, may be used. For larger quantities, the *kilowatt*, or 1,000 watts, may be used. Another unit of power is represented by 746 watts, called *one horsepower*. If an electric motor were 100 per cent efficient, 746 watts of power fed to it would produce the equivalent of one mechanical horsepower of twisting force, called *torque* (pronounced **tork**).

746 W -
1 HP

The terms *power* and *energy* have been used somewhat synonymously. Actually, these two terms do not mean the same thing, although there are many occasions when they may be used interchangeably. Power is the ability to do work and is measured in watts. Energy is usually computed by multiplying the amount of power by the length of time the power is used. One watt of power working for one second is known as a *wattsecond*, or as a *joule* (**jool**, or **jowl**) of energy.

Energy

JOULE =
1 watt second

If a 100-watt lamp is turned on for one second, it uses 100 joules of energy. During the time it was working it was dissipating 100 watts of power. If the light is left on for 10 sec, it dissipates 1,000 joules of energy, but while it was working it was still dissipating only 100 watts of power. Electric power companies may produce power, but they sell energy. Instead of using wattseconds, they use the larger basic units, the watthour (number of watts times the number of hours) or the kilowatthour (number of watts times the number of hours *divided* by 1,000). Every establishment buying electric "power" has a kilowatthourmeter measuring how many kilowatthours (abbreviated *kwhr*) of energy flows in the power lines. If electricity costs 5 cents per kilowatthour, a one-kilowatt lamp may be operated for one hour for 5 cents, or a 100-watt lamp may be operated for 10 hr for the same amount of money.

Actually, power, by the formula $P = EI$, implies time, since the ampere

($I$) in the formula is a coulomb per *second.* This can be expressed as

$$A = \frac{Q}{T}$$

where $Q$ is the quantity of electrons called a coulomb; $T$ is time in seconds; and $A$ is current in amperes.

For example, if 10 coulombs move through a circuit in 2 sec, the average current is 5 amp.

If power equals volts times amperes and amperes equals $Q/T$, then power must equal volts times $Q/T$. In formula form,

$$P = E\left(\frac{Q}{T}\right) = \frac{EQ}{T}$$

This formula expresses power as equal to volts times coulombs per second.

The unit of energy was given as the wattsecond, or joule, and is usually computed as power times time. This brings up an interesting fact. If energy equals power times time, and the power formula $P = EQ/T$ is multiplied by time to give energy, the equation then reads $E_n = EQT/T$, and time cancels out. Therefore energy is actually something that may do work if given a chance and has no reference to time itself. Although normally measured for convenience as power times time, energy as such is timeless. The energy formula with the time canceled is $E_n = EQ$, or joules equals volt-coulombs. The power company actually sells volts of pressure times the number of coulombs it delivers, irrespective of how long it takes the consumer to accept the energy.

Pressure times quantity (volt-coulombs) equals the energy that is available. Pressure times movement (volt-amperes) equals work done, or power.

In practical problems involving energy, the wattsecond or watthour is usually used. For example, to determine the number of watthours of energy consumed by a radio receiver drawing 60 watts of power for 20 hr, the power-times-time formula is employed, using *hours* as the time unit. In this case, 60 watts times 20 hr equals 1,200 watthr of energy. This is also equal to 1.2 kwhr, or 4,320,000 wattsec, or joules.

*Example:* It is desired to know how many kilowatthours are consumed by a receiver drawing 75 watts operating for a period of 24 hr. The number of watthours will be 75 times 24, or 1,800 watthr, or 1.8 kwhr.

**2.6 Using the Power Formulas.** The power formula $P = EI$ states in mathematical form, "The power is directly proportional to both voltage and current." Since the current increases if the voltage increases, doubling the voltage will normally double the current, and the power will increase fourfold.

The power formula $P = I^2R$ states in mathematical form, "The power is directly proportional to the resistance and also to the *current squared.*" If the current is doubled, the power dissipation is equal to *two squared,* or four times as much.

The power formula $P = E^2/R$ states in mathematical form, "The power is directly proportional to the *voltage squared* and inversely proportional to the resistance." If the resistance is kept constant, doubling the voltage will produce four times the power. If the voltage is kept constant, doubling the resistance will halve the power and halving the resistance will double the power.

When the resistance in a circuit is doubled and the voltage remains the same, the power *loss* in the circuit will be halved. On the other hand, if either the voltage or the current in a circuit is known to double, the power loss in the circuit will be *four* times as much.

From these three basic power formulas, other useful formulas involving power can be derived. From the formula $P = EI$, it is possible to solve for $E$ by dividing both sides of the equation by $I$. This results in the formula

$$E = \frac{P}{I}$$

where $E$ is the emf in volts; $P$ is the power in watts; and $I$ is the current in amperes.

*Example:* A resistor rated at 50 watts and a maximum current of 100 ma (0.1 amp) will stand how much voltage without becoming excessively hot? From the formula $E = P/I$, the maximum voltage is equal to 50/0.1, or 500 volts.

From the same power formula $P = EI$, when both sides are divided by $E$, the result is the formula

$$I = \frac{P}{E}$$

*Example:* How much current will flow in a television set that is rated at 240 watts when connected across mains carrying 120 volts? From the formula $I = P/E$, the current is equal to 240/120, or 2 amp.

From the formula $P = I^2R$, dividing both sides by $R$ and then taking the square root of both sides results in the formula

$$I = \sqrt{\frac{P}{R}}$$

*Example:* What is the maximum rated current-carrying capacity of a resistor marked "5,000 ohms, 200 watts"? From the formula $I = \sqrt{P/R}$, the current is equal to $\sqrt{200/5{,}000}$, or $\sqrt{0.04}$, or 0.2 amp.

From the formula $P = I^2R$, dividing both sides by $I^2$ results in the formula

$$R = \frac{P}{I^2}$$

*Example:* A radio receiver rated at 55 watts draws 2 amp from the line. The effective resistance is $R = P/I^2$, or $55/2^2$, or 13.75 ohms.

From the formula $P = E^2/R$, multiplying both sides by $R$ and then taking the square root of both sides results in the formula

$$E = \sqrt{PR}$$

*Example:* What is the maximum voltage that may be connected across a 10-watt 1,000-ohm resistor? From the formula $E = \sqrt{PR}$, the voltage is equal to $\sqrt{10(1{,}000)}$, or $\sqrt{10{,}000}$, or 100 volts.

From the formula $P = E^2/R$, cross-multiplying (or by multiplying both sides by $R$) and then dividing both sides by $P$ results in the formula

$$R = \frac{E^2}{P}$$

*Example:* What is the resistance of a 3-watt 6-volt lamp? The resistance is equal to $6^2$ divided by 3, or 36/3, or 12 ohms.

**2.7 Power Dissipation of Resistors.** Resistors, whether they are the carbon type or wire-wound, have a resistance and a power rating. The power rating indicates how much heat the resistor is capable of dissipating under normal circumstances. If cooled by passing air across it, the resistor may be capable of considerably greater power dissipation. If enclosed in an unventilated area, it may become excessively hot and burn out when dissipating its rated power or less. Usually, the power rating required is computed by one of the power formulas, and a resistor of twice the computed rating is used. Thus, if it is computed that a resistor in an operating circuit must be capable of dissipating at least 5 watts, a 10-watt resistor would be used. If tightly enclosed, a rating three or four times the computed value may be required.

Instead of rating resistors by power dissipation they might be rated in current-carrying ability. In fact, some wire-wound resistors carry a resistance, a power dissipation, and a current rating. When the current rating is not given, the rearranged power formula $I = \sqrt{P/R}$ can be used. For example, a 100-ohm 1-watt resistor will carry safely

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{1}{100}} = 0.1 \text{ amp, or } 100 \text{ ma}$$

### Practice Problems

1. A receiver is connected across a 120-volt power line, and 0.75 amp flows through it. How much power is being used?
2. A 420-ohm resistor has 30 ma flowing through it. How much power is producing heat in the resistor?
3. An electric iron has 36 ohms resistance. How much power is produced when it is connected across a 120-volt power line?
4. How many milliwatts in a kilowatt?

**5.** How much energy is used in 30 days by an electric clock having 5,000 ohms resistance if it is connected across a 120-volt power line?

**6.** If electricity sells for 4 cents a kilowatthour, how much does it cost to run a television receiver for one whole day if it draws 2 amp when connected across a 120-volt power main?

**7.** If ½ coulomb passes one point in a circuit in 0.01 sec, what is the average current value?

**8.** When 100 volts can force 80 coulombs through a point in a circuit in ½ sec, how much power is being used? $160\,A \times 100 = 16{,}000\,W$

**9.** In question 8, how much energy does this represent? 8000 Joules in ½ second

**10.** How much energy is being used by a transmitting station drawing 40 amp from a 440-volt power line in 2 hr of operation? $2.04 \times 10^6$ Joules

**11.** Across how many volts must a 600-watt heater be connected if it is drawing 5 amp? $P = \frac{E}{I}$ $E = \frac{P}{I} = \frac{600}{5} = 120V$

**12.** A 25-watt emergency light draws how many amperes from a 6.3-volt storage battery?

**13.** How much current will a 1-watt 2,500-ohm resistor safely pass?

**14.** A 100-watt lamp draws 0.9 amp. How much resistance does it have?

**15.** A 25-watt 500-ohm resistor can be safely connected across how much voltage?

**16.** How many ohms resistance does the ordinary 75-watt house lamp have when operating?

**17.** A 1,700-ohm cathode resistor must stand 8 ma. What power-rating resistor should be used?

**2.8 Fuses.** To protect circuits from damage caused by accidental *short circuits*, fuses are installed in series with the lines carrying current from the source to the load. The first duty of a fuse is to carry the circuit current with little or no voltage loss to the circuit. This requires a fuse of relatively low resistance in circuits carrying high current. Lower-current circuits may have higher-resistance fuses.

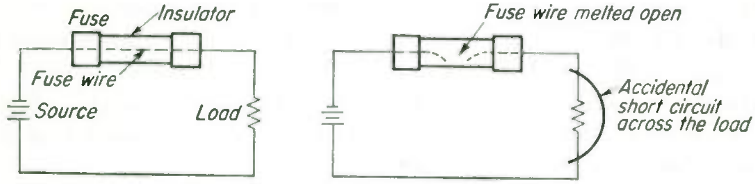


FIG. 2.3. Fuse wire melts open if excessive current is made to flow in the circuit.

A fuse is placed in such a position that all the current flowing through the circuit to be protected must flow through the fuse, as shown in Fig. 2.3. If a short circuit develops across the load, as shown, the current from the source flows through the fuse and through the low-resistance short circuit. This produces a high current. The heavy current will produce enough heat to melt the special low-melting-point fuse wire, interrupting the current flow and protecting the source from damage due to overload and excessive current flow. With no fuse, a "short" may cause the connecting wires of a circuit to become hot enough to ignite the insulation on the wires and start a fire.

Fuses are rated by their current-carrying ability and also by the maximum voltage of the circuit in which they are used. High-current fuses use relatively heavy fuse wire and are recognizable by their relatively large diameter. Lower-current fuses may be made quite small with delicate fuse wire.

Low-voltage-circuit fuses may be physically short, but fuses for high-voltage circuits are quite long. This is to prevent the high voltage that appears across the burned-out section of the fuse from jumping the gap and striking an arc of current, preventing the fuse from open-circuiting. The greater length results in better insulating properties of the fuse *after* it has burned out.

Fuses are available in such ratings as 100 amp, 30 amp, 15 amp, 1 amp, ½ amp, ¼ amp, 1⁄32 amp, etc.

"Slow-blow" fuses are made to withstand short-duration overloads due to current surges, but will burn out after a short interval of time. They are not suitable for some types of circuits.

**2.9 Meters.** The five types of meters in general use are the voltmeter, ammeter, wattmeter, watthourmeter, and the ohmmeter. They are explained in more detail in the chapter on measuring devices. At this point they will only be shown in their usual positions in simple electric circuits. The symbol of a meter is a small circle with the proper letter in it to indicate the type of meter.

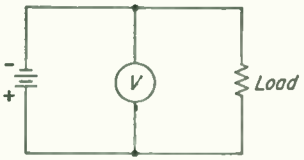


FIG. 2.4. Voltmeter is connected *across* the circuit to be measured.

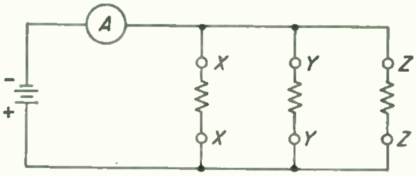


FIG. 2.5. Ammeter in series with circuit reads total of all three branch currents.

The voltmeter measures the difference of potential, or the emf, *across* a circuit. It is always connected *across* the difference of potential to be measured, as shown in Fig. 2.4.

The ammeter is always connected *in series* with the line carrying the current to be measured. The ammeter indicates the number of electrons, in coulombs, flowing through it per second. The meter in Fig. 2.5 is measuring the total current of the circuit. To measure the current in any one of the three branches, the meter must be moved to point *X*, *Y*, or *Z* shown. Since an ampere is a relatively large current value in radio circuits, *milliammeters* are frequently used. In some cases, *microammeters* are used. A milliampere is a thousandth of an ampere, and a microampere is a millionth of an ampere.

The wattmeter measures electric power. It can be considered a voltmeter and ammeter combined in such a way that it gives the product of the voltage and current on its scale. It is therefore connected across the difference of potential and also in series with the line carrying the current. It may have three or four terminals, whereas most other meters have only two. Figure 2.6 shows a three-terminal wattmeter, with the necessary connection when the fourth terminal is used shown in dotted lines.

In many practical applications a voltmeter and an ammeter are used instead of a wattmeter. The voltmeter value multiplied by the ammeter value gives the power value in watts. Figure 2.7 illustrates how a voltmeter and ammeter may be connected to obtain power values.

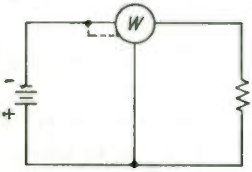


FIG. 2.6. Wattmeter connected in series and across circuit.

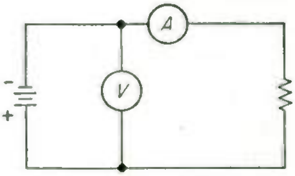


FIG. 2.7. Voltmeter and ammeter readings when multiplied together give power in watts demanded by load.

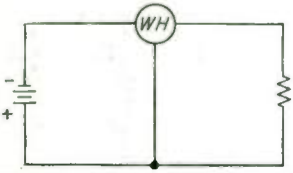


FIG. 2.8. Watthourmeter connected in series with and across load.

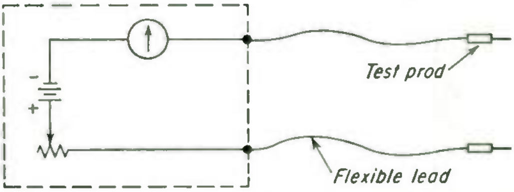


FIG. 2.9. Ohmmeter consists of a milliammeter calibrated in ohms, a battery, and test prods.

The watthourmeter measures electric energy. It is actually an electric motor geared to an indicator needle similar to the hand of a clock. How far the indicator rotates depends on the current flowing through the meter and load and the length of time the current flows. Figure 2.8 shows how a watthourmeter is connected in a simple circuit.

The ohmmeter is a sensitive ammeter plus an internal battery, both contained in a small bakelite case. It can be used only when the resistance being measured is in a dead circuit; that is, when the resistance being measured has *no current* flowing through it. It is usually a portable meter with flexible leads, as indicated in Fig. 2.9.

**2.10 Types of Circuits.** The remainder of this chapter will deal with solving for the current, voltage, resistance, or power in various types of circuits. The circuits diagramed below illustrate the terminology used for the different methods of connecting one or more loads to a source.

A source of emf with a single load, as shown in Fig. 2.10, is a *simple circuit.*

A source of emf with two or more loads connected across it in such a way that there is only one current path through the whole circuit, as shown in Fig. 2.11, is called a *series circuit.*

A source of emf with two or more loads connected across it in such a way that each load has only its own current flowing through it independent of the other load or loads, as shown in Fig. 2.12, is termed a *parallel circuit.*

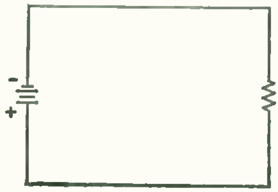


FIG. 2.10. Simple circuit.

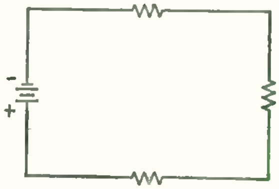


FIG. 2.11. Series circuit (loads in series).

When there is a group of loads connected in a more or less mixed and complex group of series and parallel circuits, the whole group may be said to be connected in *series-parallel.*

When we speak of paralleling resistors or loads, it is sometimes said that they are connected in *shunt.* When something is connected across the terminals of something else, it may be said that the first is *shunted* across the second.

**2.11 Series Circuits.** The diagrams in Fig. 2.13 show two series circuits. In series circuits the same current flows through *all* parts of the circuit. (More electrons can never flow into a resistance than flow out the other end. The electrons forming the current may lose energy in the form of heat while moving through a resistor, but electrons themselves are not lost.)

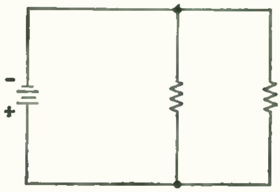


FIG. 2.12. Parallel circuit (loads in parallel).

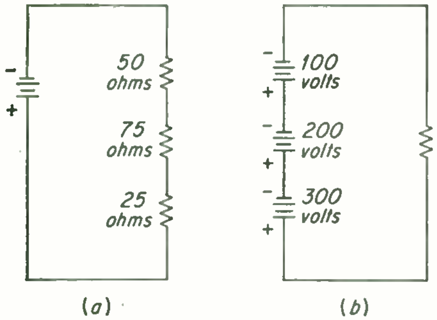
In working with series circuits, the sums of the unit values are simply added. For example, Fig. 2.13 shows a series-resistance diagram with a total resistance of 150 ohms. It also shows a series of batteries with a total voltage of 600 volts.

Resistors can be connected in series when it is desired to have a greater resistance and thereby a smaller current.

Batteries are connected in series when it is desired to produce the highest possible voltage. However, a battery can have only a certain value of current flowing through it. By connecting batteries in series, the sum of all the voltages of all the batteries is obtained. The maximum current possible through the circuit is no greater than the greatest current that the weakest battery can pass. If one of the batteries in Fig. 2.13 is capable of passing 1 amp through it, another 2 amp, and the third 3 amp, the maximum current the three batteries in series can pass without damage to any is only 1 amp. The series combination shown will result in 600 volts with a maximum current capability of 1 amp. According to

Ohm's law $I = E/R$, if the resistor across the three batteries has 600 ohms resistance, the current in the circuit will be 1 amp. If *less* than 600 ohms is used, the weakest battery will be overworked and damage to it may result.

In Fig. 2.14, the voltage of the battery is 100 volts and each of the resistors has a value of 100 ohms. Note the voltage distribution in the three circuits and how the sum of the voltage drops of the resistors always equals the battery voltage of 100 volts.



(a) (b)

FIG. 2.13. (a) Resistors connected in series total 150 ohms. (b) Batteries connected in series total 600 volts.

If the emf across each resistor is considered to be a *voltage drop*, or loss of voltage, then the sum of all the voltage drops (negative values) around the circuit, when added to the source voltage (a positive value), gives an algebraic sum (positive and negative sum) of zero volts in the circuit. This is stated in *Kirchhoff's voltage law:*

*The algebraic sum of all the voltages in a series circuit is always zero.*

*Kirchhoff's current law* states:

*The total current flowing into a point in a circuit will always equal the current value flowing out of the point.*

To find the total resistance of a group of series resistors the formula is

$$R_{\text{total}} = R_1 + R_2 + R_3 + \cdots$$

If all the resistors are *equal* in value, the value of any one can be multiplied by the number of resistors to give the total. Five 25-ohm resistors in series present 125 ohms.

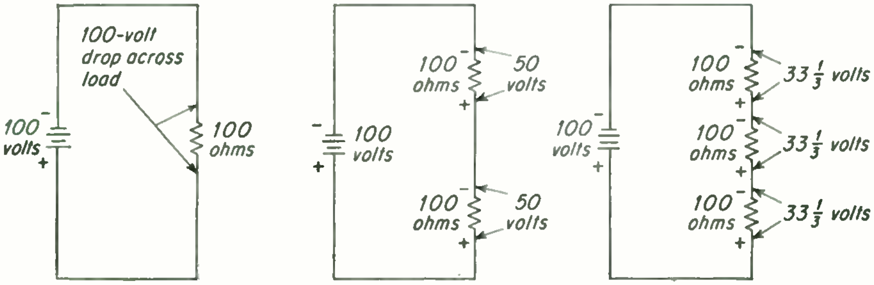


FIG. 2.14. Voltage-drop distribution in series circuits.

**2.12 Ohm's Law in More Complex Circuits.** The use of Ohm's law was previously discussed as it applied to a circuit made up of a source of emf and a load. If two of the three elements making up the Ohm's-law formula ($E$, $R$, and $I$) are known, the third can be computed.

When more complex circuits are used, Ohm's law may still be used but additional factors must be considered. Complex circuits, in this instance, means either parallel, series, or series-parallel types.

There are three important rules regarding the use of Ohm's law when working problems:

*Voltage Rule:* It is possible to determine the voltage across *any particular known R* in a group of resistances, if the current through *that particular R* is known, by $E = IR$.

*Current Rule:* It is possible to determine the current through *any particular known R* in a group of resistances, if the voltage across *that particular R* is known, by $I = E/R$.

*Resistance Rule:* It is possible to determine the resistance of *any one part* of a circuit, if the voltage across *that part* and the current flowing through *that part* are known, by $R = E/I$.

These seem simple rules, but one of the most difficult things for a student to determine is when Ohm's law can and when it cannot be used properly. Consider the following *impossible* problems.

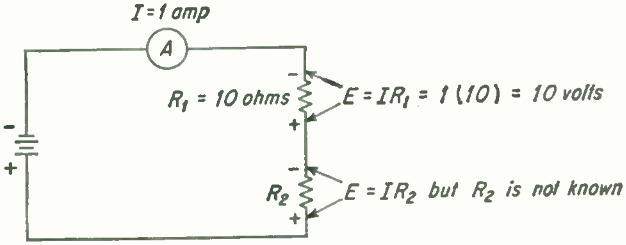


FIG. 2.15. Insufficient data given to compute unknown circuit values.

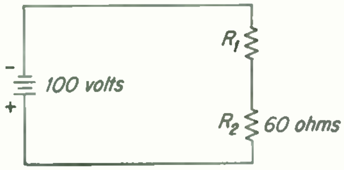


FIG. 2.16. Insufficient data given to compute unknown circuit values.

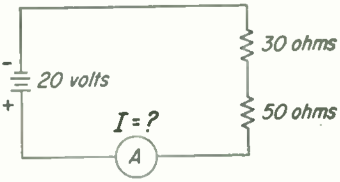


FIG. 2.17. Sufficient data given to compute all circuit values.

In Fig. 2.15 it is impossible to find the *voltage* across the second resistor since none of the above rules can be applied to *any one part* of the circuit.

In Fig. 2.16 it is impossible to determine the resistance of $R_1$ since none of the rules can be applied to *any one part* of the circuit. The source voltage is not across $R_2$, but across $R_1$ and $R_2$ in series.

A problem that *can* be computed is shown in Fig. 2.17. Being a series circuit, the current value in all parts must be equal. Since the total resistance in a series circuit is equal to the sum of all the resistors in the circuit, the total resistance is equal to 30 plus 50 ohms, or 80 ohms across the battery. (In such a case it may be said that the source "sees" an 80-ohm load.)

Once the total resistance is known, the current value in the circuit can be found by Ohm's law:

$$I = \frac{E}{R} = \frac{20}{80} = 0.25 \text{ amp}$$

The voltage drop, or difference of potential, across either of the resistances alone can be found by applying Ohm's law to that part.
For the 30-ohm resistor,

$$E = IR = 0.25(30) = 7.5 \text{ volts}$$

For the 50-ohm resistor,

$$E = IR = 0.25(50) = 12.5 \text{ volts}$$

The voltage drops across the resistances are considered as voltage losses. The voltage of the source is considered a gain voltage. The sum of $-7.5$, $-12.5$, and $+20$ equals zero volts (Kirchhoff's law). This can be used as a method of checking whether the current value has been correctly computed or not. If not, the sum of the voltage drops will not equal the source voltage.

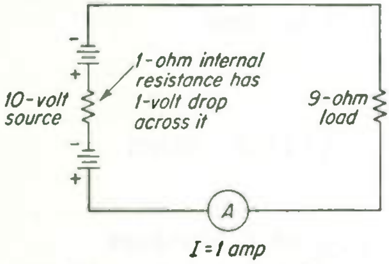


FIG. 2.18. Internal resistance in the source may have to be considered.

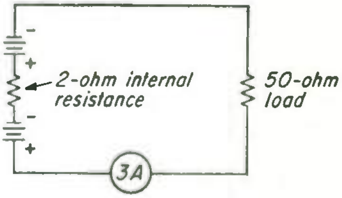


FIG. 2.19. The source has an output of 150 volts with the 50-ohm load; with no load, 156 volts.

In some cases, where the source has internal resistance, the voltage loss across the internal resistance must be considered. Suppose a 10-volt source has 1 ohm internal resistance and is connected across a 9-ohm load, as shown in Fig. 2.18. With 10 ohms and 10 volts the current is 1 amp. One ampere through the 1-ohm resistance produces a 1-volt loss. Therefore the 10-volt source actually produces only 9 volts across its terminals and across the 9-ohm resistance load. The other volt of pressure is lost inside the source. However, if no current is flowing through the source, there is no voltage loss developed across the internal resistance and the terminal voltage is 10 volts. This is important to understand!

If a circuit passing a current of 3 amp has an internal resistance of 2 ohms in the source and has a 50-ohm load, what is the terminal voltage of the source? This can be analyzed and worked in two ways. The diagram of this circuit is shown in Fig. 2.19.

The simplest solution is to consider that the terminal voltage of the source is the voltage drop across the 50-ohm resistor since the two are directly connected together. From the information given, the voltage across the 50-ohm resistor when 3 amp flows through it is equal to $E = IR$, or 3(50), or 150 volts.

The other analysis of this problem is to consider the total resistance in the circuit as equal to 50 plus 2 ohms, or 52 ohms. The current is 3 amp. From Ohm's law, the total voltage in the circuit is $E = IR$, or 3(52), or 156 volts. However, the voltage drop developed across the 2-ohm internal resistance is $E = IR$, or 3(2). Thus, 6 volts does not appear outside the source and must be subtracted from the total voltage present in the circuit. This gives 156 volts less 6 volts, or 150 volts across the terminals of the source, the same answer as above. It indicates that if the 50-ohm resistor is disconnected, the source will have a terminal voltage of 156 volts.

FIG. 2.20. Circuit in which internal resistance is negligible.

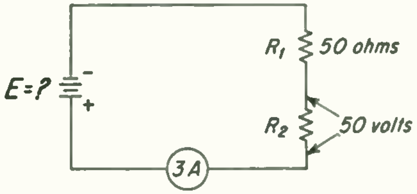


FIG. 2.21. The sum of the voltage drops across $R_1$ and $R_2$ will be the source voltage.

As another example of internal resistance: If a 6-volt storage battery has an internal resistance of 0.01 ohm, what current will flow when a 3-watt 6-volt lamp is connected across it? This circuit is illustrated in Fig. 2.20.

It is assumed that the storage battery has 6 volts with no load connected across it. The resistance of the lamp is determined by using the rearranged power formula $R = E^2/P$, or $6^2/3$, or 12 ohms. The total resistance of the circuit is the load plus the internal resistance of the source, or 12.01 ohms. The current, according to Ohm's law, is $I = E/R$, or 6/12.01, or 0.4996 amp. (The loss of voltage across the internal resistance is only 0.004996 volt.)

It is possible to solve for missing values in some series problems. For example, two resistors are connected in series, as shown in Fig. 2.21. The current through them is 3 amp, while $R_1$ has a value of 50 ohms. $R_2$ is unknown but has a voltage drop of 50 volts across it. What is the total impressed emf across the whole circuit?

Two factors regarding $R_1$ are known: its resistance, 50 ohms, and the current through it, 3 amp. The voltage across it can therefore be determined as $E = IR$, or 3(50), or 150 volts. This voltage is in series with the 50 volts across $R_2$, resulting in a total of 200 volts across the two resistors, and therefore across the source.

As an example of a somewhat similar series-circuit problem, a vacuum tube has a filament rated at ¼ amp and 5 volts and it is to be operated from a 6-volt battery. What is the value of the necessary series resistor? This circuit is illustrated in Fig. 2.22.

The "filament" can be considered as a resistor requiring ¼ amp flowing through it to develop 5 volts drop across it. A 6-volt battery directly across the filament will cause too much current to flow. To prevent this, a resistance with a value sufficient to drop 1 volt across it when ¼-amp flows is required. According to Ohm's law, its resistance should be $R = E/I$, or 1/0.25, or 4 ohms. The minimum power dissipation for this resistor is equal to $P = EI$, or 1(0.25), or ¼ watt. A 4-ohm ½-watt resistor should be used. Actually, a 1- or 2-watt resistor would be just as satisfactory but would be physically larger and more expensive.

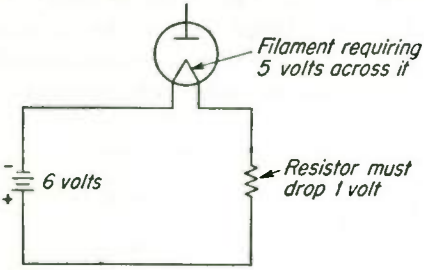


FIG. 2.22. Circuit required to drop the voltage of the source to a usable value across the filament.

As another example, a keying relay coil has a resistance of 500 ohms and is designed to operate on 125 ma. If the relay is to operate from a 110-volt d-c source, what value of resistance should be connected in series with the relay coil? The circuit is shown in Fig. 2.23.

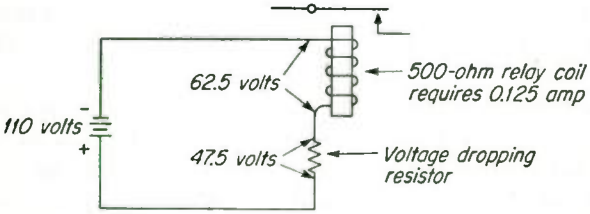


FIG. 2.23. Voltage-dropping resistor required to prevent excessive voltage across a relay coil.

The relay coil can be considered as a resistor in this problem. A current of 125 ma equals 125/1,000 amp, or 0.125 amp. The voltage required to produce this current value through the coil is found by Ohm's law $E = IR$, or 0.125(500), or 62.5 volts. The emf available is 110 volts, or 47.5 volts too much. To drop 47.5 volts, a resistance of $R = E/I$, or 47.5/0.125, or 380 ohms, is required. The minimum power dissipation is $P = EI$, or 47.5(0.125), or 5.94 watts. Any 380-ohm resistor with a power rating of 12 or more watts would be satisfactory.

If two 10-watt 500-ohm resistors are connected in *series*, what are the power-dissipation capabilities of the combination? Since they are similar resistors, they will stand the same amount of current. With the maximum current for their rating, $I = \sqrt{P/R}$, or 0.141 amp, each will produce 10 watts of heat, resulting in 20 watts maximum safe dissipation from the two.

On the other hand, if one is a *20-watt* 500-ohm resistor and the other is a 10-watt 500-ohm resistor, when in series the 10-watt resistor will have a maximum safe current of 0.141 amp and the 20-watt resistor will have a maximum safe current of $I = \sqrt{P/R}$, or $\sqrt{20/500}$, or 0.2 amp. The limiting factor in the circuit is the 0.141 amp. The 10-watt resistor will dissipate 10 watts, but the 20-watt resistor will be held to 10 watts of dissipation because only 0.141 amp should be flowing through it. The total safe power dissipation for the two resistors in series is 20 watts.

When resistors are considered in *series*, the maximum safe current for each must be determined before the limiting current can be judged. The highest wattage rating does not always indicate the greatest safe current rating. For example, a 20-watt 2,000-ohm resistor has a maximum current value of only 0.1 amp, which is lower than the 0.141-amp capability of a 10-watt 500-ohm resistor.

**2.13 Suggestions for Working Complex Problems.** Be neat and orderly in problem working. The tried and proven method explained will help in thinking out the problems in an orderly, complete way.

1. Read through the whole problem carefully, *twice*. Determine what is wanted.
2. At the top left-hand part of the work paper, sketch a diagram of the circuit, if any is involved, and label the parts with the values given in the problem.
3. Directly below the diagram, jot down any other information that may be necessary to use (such as formulas) which does not have a place on the diagram. Draw a line under this information.
4. State what is to be found at the top right-hand part of the page.
5. Beneath the information, write out the first formula used in the first operation in the problem. Do any miscellaneous computations at the right side of the page if possible, rather than on another piece of paper. Keep formulas and computations close together to simplify any later rechecking of the work.
6. Continue solving the formulas down the left side of the page, using the right side for incidental mathematics. The last line on the left side should contain the final answer. It often helps to encircle subanswers, if any, and answers.

## Practice Problems

1. Four 37.5-ohm resistors are connected in series across a 120-volt line. What is the voltage drop across one of the resistors? 30V

**2.** A 30-ohm, a 60-ohm, and a 150-ohm resistor are connected in series across a 24-volt battery. How much potential difference appears across the 60-ohm resistor? 6V

**3.** In question 2, how much current flows through the 150-ohm resistor? 15 ✓

**4.** A 50-ohm resistance, a 90-ohm resistance, and a resistance of unknown value are connected in series across a 60-volt generator. If ⅓ amp is flowing through the generator, what is the voltage drop across the unknown-value resistor? 15V

**5.** In question 4, what is the value of the unknown resistance? 70Ω

**6.** A 12.6-volt automobile battery is connected across a 1.5-ohm headlight lamp. If the battery has 0.14 ohm internal resistance, what is the current in the circuit?

**7.** In question 6, what is the terminal voltage of the battery under loaded conditions?

**8.** A relay with a coil resistance of 500 ohms is designed to operate when 0.2 amp flows through the coil. What value of resistance must be connected in series with the coil if operation is to be made from a 110-volt d-c line?

**9.** A mobile receiver operating across a 6-volt storage battery draws 36 watts. If it is to operate from a 12-volt battery, what is the value of the resistance that must be connected in series with it to maintain the power consumption of 36 watts for the receiver?

**10.** A 5,000-ohm 20-watt resistor and a 1,000-ohm 5-watt resistor are in series. What is the maximum voltage that can be applied across this combination that will not exceed the wattage rating of either resistor?

**11.** A filament of a vacuum tube requires 6.3 volts across it and a current of 300 ma flowing through it. What is the value of series resistance required if it is to be operated across a 110-volt power line?

**12.** In question 11, what is the power being dissipated in heat in the resistance?

**2.14 Conductance.** An interesting point regarding the study of electricity is the necessity, at times, of observing the same thing from two viewpoints in order to obtain a better understanding of the whole. One example of this is the resistance versus the conductance of a circuit.

In an operating electric circuit there must always be a source of emf and a load. In the simplest circuit the load may be a single resistor. As explained before, the greater the resistance in the load, the less the current in the circuit. However, the very fact that some current is flowing indicates that the resistance is not "infinite" ("immeasurable," or "endless") but is actually a conductor of sorts. It may be a very poor conductor, or it may be a fairly good conductor. In any event, the greater its conducting ability, or "*conductance,*" the less its resistance value. Conversely, the less its conductance, the greater its resistance. Conductance and resistance refer to the same thing, but from opposite viewpoints. They are said to be *reciprocals* of each other.

The meaning of reciprocal is, roughly, "mathematically opposite." In stating that something is the reciprocal of the other, or that it varies inversely as the other, the two are placed on opposite sides of an equals sign and one of them is expressed as a fraction by putting a 1 over it. Thus:

$R$ stands for resistance in ohms.

$G$ stands for conductance in "*mhos.*" (Mho, the unit of conductance, is the word ohm spelled backward.)

Since $R$ and $G$ have opposite meanings, they may be expressed in the following manner:

$$R = \frac{1}{G} \qquad \text{or} \qquad G = \frac{1}{R}$$

If a resistance has a value of 2 ohms, then its conductance value is 1 over 2, or ½ mho. If the $R$ value is raised to 3 ohms, the conductance value becomes ⅓ mho. As the resistance is increased from 2 to 3, the conductance value decreases from ½ to ⅓ mho.

Since $R = 1/G$, Ohm's law can be expressed in terms of conductance by using $1/G$ in place of $R$ in the three formulas:

$$E = IR = I\left(\frac{1}{G}\right) = \frac{I}{G}$$

$$I = \frac{E}{R} = \frac{E}{1/G} = E\left(\frac{G}{1}\right) = EG$$

$$R = \frac{E}{I} \qquad \frac{1}{G} = \frac{E}{I} \qquad GE = I \qquad G = \frac{I}{E}$$

*Example:* What is the conductance of a circuit if 6 amp flows when 12 volts d-c is applied to the circuit? Using the last formula above, $G = I/E$, the problem is solved:

$$G = \frac{I}{E} = \frac{6}{12} = \frac{1}{2}\ \text{mho}$$

(Note that if $R = E/I$, then $G$ is equal to the reciprocal, or mathematical opposite, $G = I/E$.)

**2.15 Parallel Resistances.** The subject of conductance is a fitting preliminary to the subject of parallel resistors. Understanding conductance makes it possible to see that when two 10-ohm resistors are connected in parallel, as shown in Fig. 2.24, across a source of emf, the conductance of the circuit is greater, and therefore the resistance must be less. Two such 10-ohm resistors provide a conductance value twice that of one, and therefore a resistance value of one-half of 10, or 5 ohms, and not 20 ohms as in series circuits. This apparent adding resistances to a circuit and obtaining a resultant resistance less than any of the resistances may be confusing unless it is seen from the conductance viewpoint.

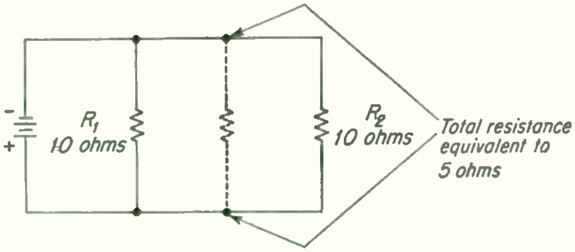


FIG. 2.24. Two 10-ohm resistors in parallel present an equivalent resistance of 5 ohms to the source.

The total conductance of a circuit is equal to the sum of all the conductances connected in parallel across the circuit. This may be expressed in formula form as

$$G_t = G_1 + G_2 + G_3 + \cdots$$

Since any single conductance value is equal to the reciprocal of its resistance value, the formula for the total conductance ($G_t$) of a parallel circuit may also be expressed as

$$G_t = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

Substituting the reciprocal of the total resistance ($R_t$) for the total conductance gives the formula

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

If this equation is made into a pair of fractions by placing a 1 over both sides, it becomes

$$\frac{1}{1/R_t} = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

The rule for simplifying compound fractions is: "Invert the lower fraction and multiply it by the upper." In this case the left-hand part of the equation,

$$\frac{1}{1/R_t} \quad \text{becomes} \quad \frac{R_t}{1} \times 1, \text{ or } R_t$$

The complete formula to solve for the total resistance of any number of parallel resistances is

$$R_t = \frac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3}}$$

This formula can be solved in one of two ways, by using fractions or by using decimals. This can be explained by the following problem:

If resistors of 5, 3, and 15 ohms are connected in parallel, what is the total resistance? First, the substitution of the known values in the formula:

$$R_t = \frac{1}{1/5 + 1/3 + 1/15}$$

To add fractions such as $1/5$, $1/3$, and $1/15$, they should be expressed in their lowest common denominator: $1/5$ equals $3/15$, and $1/3$ equals $5/15$. Substituting the fractions expressed in their lowest common denominator and then adding the fractions, the problem becomes

$$R_t = \frac{1}{3/15 + 5/15 + 1/15} = \frac{1}{9/15} = \frac{15}{9} = 1\,2/3 \text{ ohms}$$

The same problem can be solved by expressing the original fractions $\frac{1}{5}$, $\frac{1}{3}$, and $\frac{1}{15}$ as decimal equivalents. This is accomplished by dividing 5 into 1 (0.2), then 3 into 1 (0.3333), and then 15 into 1 (0.0667). Substituted in the formula this becomes

$$R_t = \frac{1}{\frac{1}{5} + \frac{1}{3} + \frac{1}{15}} = \frac{1}{0.2 + 0.3333 + 0.0667} = \frac{1}{0.6} = 1.67 = 1\tfrac{2}{3} \text{ ohms}$$

In the special case where all the resistances in parallel are equal in value, such as five 100-ohm resistances, the total resistance is simply determined by dividing the resistance value of one resistor by the number of resistors. Therefore five 100-ohm resistors in parallel present $\frac{100}{5}$, or 20 ohms resistance to the source.

When there are only two parallel resistances, the formula used above can be algebraically rearranged to read

$$R_t = \frac{R_1 R_2}{R_1 + R_2}$$

*Example:* What is the total resistance of a parallel circuit consisting of one branch of 10 ohms resistance and one branch of 25 ohms resistance? Using 10 ohms as $R_1$ and 25 ohms as $R_2$, the problem is solved:

$$R_t = \frac{R_1 R_2}{R_1 + R_2} = \frac{10(25)}{10 + 25} = \frac{250}{35} = 7.14 \text{ ohms}$$

If there are three resistances in parallel, the total of two of them can be computed by this formula and the answer considered as a resistance value. Using this resistance value and the third resistance, the formula can be used to solve for the total of the three resistances. The same procedure can be used to determine the value of any number of parallel resistances.

A quick check on answers to problems involving parallel resistances is possible by noting that the answer must always be a lower value than the lowest of the parallel resistances. Also, when one resistance is about 10 times another and the two are in parallel, the total resistance will be about 10 per cent less than the lower. If one resistance is 100 times a second resistance, it may often be possible to disregard the first entirely, since it will affect the total resistance by less than 1 per cent.

When two 10-watt 500-ohm resistors are connected in parallel, the total power-dissipation capabilities of the combination is equal to the sum of the two, or 20 watts. Since they have similar power and resistance ratings they will stand the same maximum value of voltage across them, $E = \sqrt{PR}$, or $\sqrt{10(500)}$, or 70.7 volts. With the two resistors in parallel across 70.7 volts, each will dissipate 10 watts, giving the total of 20 watts of heat.

In parallel circuits the controlling and limiting factor is the voltage, whereas in series circuits it is the current. With parallel resistors it is necessary to determine what maximum voltage each will stand to produce enough current through it to make it dissipate its maximum rated power.

The *lowest* maximum voltage of a group of resistors will determine the highest voltage that may be applied across the parallel group.

*Example:* A 10,000-ohm 100-watt resistor, a 40,000-ohm 50-watt resistor, and a 5,000-ohm 10-watt resistor are connected in parallel. What is the maximum *voltage* that may be applied across the circuit, and with this voltage what is the maximum total value of current through this parallel combination which will not exceed the wattage rating of any of the resistors? Figure 2.25 shows the diagram of the circuit.

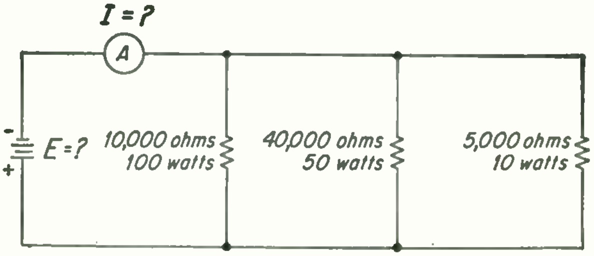


FIG. 2.25. To determine the maximum allowable current flow, first determine the maximum safe source voltage.

For the 10,000-ohm 100-watt resistor:

$$E = \sqrt{PR} = \sqrt{100(10{,}000)} = \sqrt{1\ 00\ 00\ 00} = 1{,}000 \text{ volts}$$

For the 40,000-ohm 50-watt resistor:

$$E = \sqrt{PR} = \sqrt{50(40{,}000)} = \sqrt{2\ 00\ 00\ 00} = 1{,}414 \text{ volts}$$

For the 5,000-ohm 10-watt resistor:

$$E = \sqrt{PR} = \sqrt{10(5{,}000)} = \sqrt{5\ 00\ 00} = 224 \text{ volts}$$

The maximum allowable voltage across the circuit must not exceed 224 volts or the 10-watt resistor will be drawing more than its rated current.

With 224 volts the 10,000-ohm resistor draws

$$I = \frac{E}{R} = \frac{224}{10{,}000} = 0.0224 \text{ amp}$$

With 224 volts the 40,000-ohm resistor draws

$$I = \frac{E}{R} = \frac{224}{40{,}000} = 0.0056 \text{ amp}$$

With 224 volts the 5,000-ohm resistor draws

$$I = \frac{E}{R} = \frac{224}{5{,}000} = 0.0448 \text{ amp}$$

The total current value in the circuit is the sum of the three separate branches, or 0.0728 amp.

**2.16 Batteries in Series and in Parallel.** As indicated previously, if two 45-volt batteries, each capable of 0.1 amp maximum safe current through them, are connected in series, as shown in Fig. 2.26, the circuit will be capable of producing 90 volts at 0.1 amp and 9 watts of power.

If the same two 45-volt batteries are connected in parallel, as shown in Fig. 2.27, they are capable of only 45 volts output, but each will allow 0.1 amp to flow through them, permitting the load to draw a total of 0.2 amp of current from the two. The maximum safe power output is still 9 watts.

To produce maximum *voltage* output, batteries must be connected in series, negative to positive, as shown.

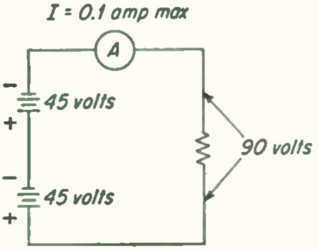


FIG. 2.26. Two 45-volt 100-ma batteries in series are capable of 90 volts at 100 ma.

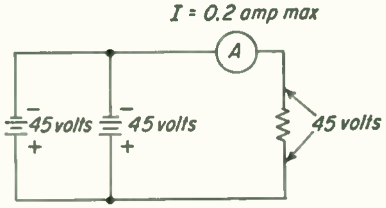


FIG. 2.27. Two 45-volt 100-ma batteries in parallel are capable of 45 volts at 200 ma.

To produce maximum *current* output, batteries must be connected in parallel, *but* all such batteries must have the same voltage; that is, a 40-volt battery cannot be paralleled with a 45-volt battery or the higher-voltage battery will soon run down, discharging through the lower-voltage battery. Care must be taken to connect the negative terminal to negative and positive terminal to positive when connecting in parallel.

## Practice Problems

1. What is the conductance of a circuit having two 300-ohm resistors and a 500-ohm resistor all in parallel?

2. What is the conductance of a circuit having 250 volts and a current of 50 ma? $2 \times 1^{-}$

3. What is the lowest common denominator of the fractions 2⁄30, 7⁄60, and 11⁄90? 90

4. What is the lowest common denominator of the fractions 8⁄25, 9⁄15, and 3⁄10? 25

5. What is the effective resistance of three parallel resistors of 1,000 ohms, 2,000 ohms, and 3,000 ohms?

6. A 240-ohm resistor and a 180-ohm resistor are in parallel across a 100-volt source. What is the total circuit current?

7. A 55-ohm and a 23-ohm resistor are in parallel in a circuit. The current through the source is 2.5 amp. What is the voltage of the source?

8. A 4,000-ohm resistor and a 3,672-ohm resistor are in parallel across a 500-volt power supply. How much current flows in the 4,000-ohm resistor?

9. In question 8, how much current flows in the 4,000-ohm branch if the 3,672-ohm branch is disconnected from the circuit?

10. A 75-ohm and a 100-ohm resistor are in parallel. The total current through the combination is 3 amp. How much current will flow through the 100-ohm resistor if the 75-ohm resistor is disconnected?

11. A 400-ohm 10-watt resistor and a 1,500-ohm 50-watt resistor are connected in parallel. What is the maximum voltage that can be applied across this circuit without exceeding the wattage rating of either of the resistors?

**12.** In question 11, what is the maximum total current that can flow in the combination and not exceed the wattage rating of either resistor?

**13.** The filament circuit of a 12.6-volt tube and the filament circuit of a 6.3-volt 0.3-amp tube with a dropping resistor in series with it are connected in parallel across a 12.6-volt battery. What is the value of the dropping resistor?

**14.** Draw a simple schematic diagram showing the method of connecting three resistors of equal value so that the total resistance will be one-third of one unit.

### 2.17 Complex D-C Circuits.

There are countless circuit configurations involving resistors in series and in parallel. To attempt to give examples covering all is obviously impossible. However, by applying the basic principles involved in series circuits and in parallel circuits, it should be possible to solve most circuits.

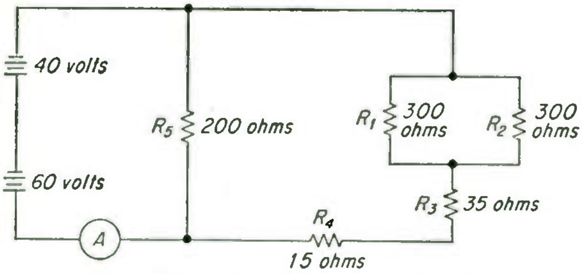


FIG. 2.28. A relatively complex circuit.

Two important points to remember are: (1) All parts connected in series have the same current flowing through them. (2) All parts in parallel have the same voltage across them.

A relatively complex circuit is shown in Fig. 2.28. By examination it can be rationalized into a single resistance value.

Resistors $R_1$ and $R_2$ are connected in parallel. Two 300-ohm resistors in parallel present 150 ohms of total resistance. In series with this 150-ohm resistance are two other resistances, $R_3$ and $R_4$, totaling 50 ohms. Across the source, this one branch presents a total of 150 plus 50, or 200 ohms.

There are two branches across the source, one made up of $R_5$ alone and the other made up of $R_1$, $R_2$, $R_3$, and $R_4$. Both branches present 200 ohms of resistance each and are in parallel with each other. Two 200-ohm parallel resistances present 100 ohms. Therefore the source of 40 plus 60 volts, or 100 volts, sees a total load resistance of 100 ohms. With a total emf of 100 volts and a total resistance of 100 ohms, the current through the ammeter will be $I = E/R$, or 100/100, or 1 amp.

The current through the series-parallel branch is equal to $I = E/R$, or 100/200, or ½ amp.

With ½ amp flowing through $R_4$, it will have a voltage drop across it equal to $E = IR$, or 0.5(15), or 7.5 volts. Similarly, the drop across $R_3$ will be 17.5 volts. The voltage drop across $R_1$ will be the voltage drop across $R_1$ and $R_2$ in parallel, or the voltage drop produced by ½ amp flowing through 150 ohms, or 75 volts. Note that the voltage across both $R_1$ and $R_2$ is one and the same voltage, and not merely equal voltages. The current through $R_1$ (or $R_2$) is $I = E/R$, or 75/300, or ¼ amp.

Take a somewhat similar problem: Two resistors of 18 and 15 ohms are connected in parallel. In series with this combination is connected a 36-ohm resistor. In parallel with this total combination is connected a 22-ohm resistor. The total current through the combination is 5 amp. What is the current value in the 15-ohm resistor? The circuit illustrating this problem is shown in Fig. 2.29.

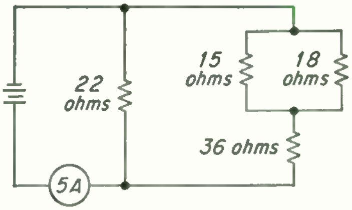


FIG. 2.29. To find the current value in the 15-ohm resistor, first determine the source voltage.

The current through neither branch is known, nor is the source voltage known. However, by determining the resistance of the series-parallel branch, both of these unknowns can be determined.

The 15-ohm and 18-ohm resistances are in parallel. By using a parallel-resistor formula, together they are found to equal 8.18 ohms, or 8.2 ohms for simplicity. The total resistance of the series-parallel branch is 8.2 plus 36, or 44.2 ohms.

The resistances of the two parallel branches are now known to be 22 ohms and 44.2 ohms. When computed in parallel, they are found to equal 14.7 ohms. If 5 amp flows through 14.7 ohms, the voltage across the whole combination must be $E = IR$, or 5(14.7), or 73.5 volts.

If there is 73.5 volts across the series-parallel branch with its 44.2 ohms, the current through it must be $I = E/R$, or 73.5/44.2, or 1.66 amp. With 1.66 amp flowing through the 8.2-ohm parallel group, the voltage across it must be $E = IR$, or 1.66(8.2), or 13.6 volts. This is the voltage across the 15-ohm resistance. With the voltage and resistance known, the current through the 15-ohm resistor must be $I = E/R$, or 13.6/15, or 0.907 amp.

In this particular problem it is necessary to solve almost all the circuit values in order to finally apply the Ohm's law formula $I = E/R$ to the single resistance in question. Had the source voltage been given, the 22-ohm branch could have been disregarded as it has no effect on the current flowing through the series-parallel branch.

The circuit shown in Fig. 2.30 is an example of an apparently highly complex circuit. However, closer observation will show that relatively simple steps can be taken to solve the problem. Actually, the current through the ammeter should be determinable without pencil and paper. The method is as follows:

1. $R_3$ and $R_4$ can be computed as a parallel group.
2. The answer in step 1 can be computed with $R_5$ as a series group.

3. $R_7$ and $R_8$ can be computed as a parallel group.
4. The answers in steps 2 and 3 can be used to compute a parallel group.
5. The answer in step 4 can be added to $R_6$ as a series circuit.
6. The answer in step 5 can be computed with $R_2$ in parallel.
7. The answer in step 6 and $R_1$ can be computed in series, which is the effective resistance seen by the source.
8. The current is 2 amp.

The diagrams in Fig. 2.31 illustrate four methods of connecting three similar resistors to produce various total-resistance combinations. Three 1-ohm resistors in series, as in diagram *a*, result in a total resistance of 3 ohms. Three 1-ohm resistors in parallel, as shown in diagram *b*, result in a total resistance of ⅓ ohm. Two in series shunted across the third, as in diagram *c*, results in two-thirds the resistance of one alone. Two parallel resistors in series with the third, diagram *d*, results in a total resistance of 1½ times the resistance of one alone.

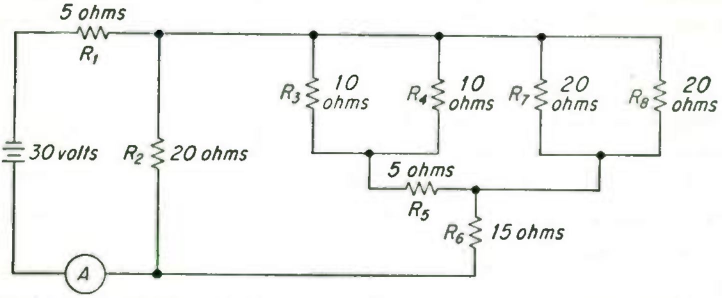


FIG. 2.30. Complex-looking circuit that may be computed mentally.

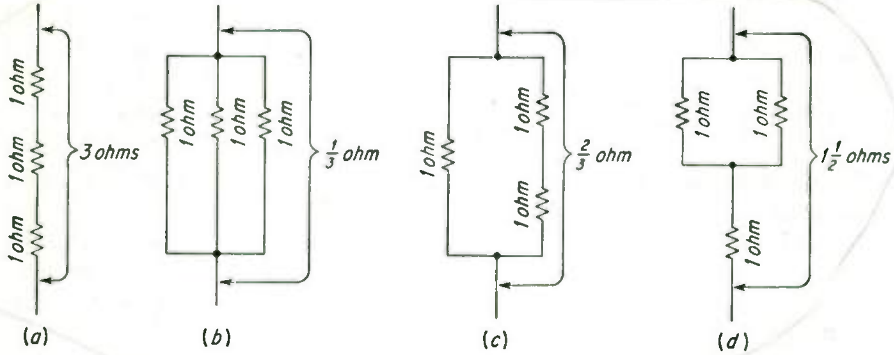


FIG. 2.31. Four circuit configurations for similar resistances.

## Practice Problems

1. Two resistors of 200 and 300 ohms are in parallel. In series with them is a 180-ohm resistor. The whole combination is across a 50-volt generator. (*a*) What current flows through the generator? (*b*) What current flows through the 180-ohm

resistor? (*c*) What current flows through the 200-ohm resistor? (*d*) What voltage appears across the 300-ohm resistor?

**2.** A 40-ohm and a 60-ohm resistor are in parallel. In series with these resistors are two other resistors of 20 and 30 ohms. The whole combination is connected across a 1.5-volt dry cell. (*a*) What is the current in amperes flowing through the dry cell? (*b*) What is the current in milliamperes flowing through the 60-ohm resistor? (*c*) What is the voltage drop across the 20-ohm resistor?

**3.** A filament (may be considered as a resistor) of a vacuum tube requires 6.3 volts across it, with a current of 0.3 amp. Another tube has a filament requiring 12.6 volts at 0.15 amp. The two tubes are connected in series. (*a*) What is the value of the resistor that must be connected across the 12.6-volt filament to allow it to operate properly when in series with the 6.3-volt tube? (*b*) What is the value of the resistance that must be connected in series with the combination to allow operation if the source is 110 volts?

**4.** A 6BQ6 tube requires 6.3 volts at 1.2 amp for its filament. A 6C4 requires 6.3 volts at 0.15 amp. A 6SN7 requires 6.3 volts at 0.6 amp. A 12BE6 requires 12.6 volts at 0.15 amp. (*a*) Draw a diagram of the most economical method of connecting these four tubes across a 12.6-volt battery. (*b*) What are the value and the wattage rating of the required resistor?

**2.18 Matching Load to Source.** Ranking high among the important concepts for the radioman to understand is the requirement of matching the load to the source. To produce maximum power in the load, it is necessary that the load resistance equal the internal resistance of the source.

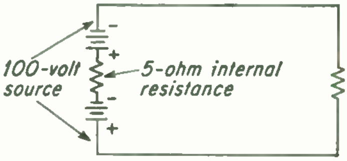


FIG. 2.32. Load resistance matches the resistance of the source.

The diagram in Fig. 2.32 shows a 100-volt source with 5 ohms internal resistance and a load with a resistance of 5 ohms also.

With the load and internal resistance equal, the voltage in the circuit is 100 volts, the total resistance is 10 ohms, and the current is

$$I = \frac{E}{R} = \frac{100}{10} = 10 \text{ amp}$$

The power delivered to the *load* in this case is

$$P = I^2R = 10^2(5) = 500 \text{ watts}$$

If the load resistance mismatches the source and is 15 ohms, the current in the circuit is

$$I = \frac{E}{R} = \frac{100}{20} = 5 \text{ amp}$$

The power delivered to the *load* with this mismatch is only

$$P = I^2R = 5^2(15) = 375 \text{ watts}$$

If the load resistance mismatches the source and is 3 ohms, the current in the circuit is

$$I = \frac{E}{R} = \frac{100}{8} = 12.5 \text{ amp}$$

The power delivered to the *load* with this mismatch is only

$$P = I^2R = (12.5)^2(3) = 468.75 \text{ watts}$$

These figures can also be used to demonstrate an important fact. When the load matches the source, half the power is dissipated in the source and half in the load. The total in the example above is 1,000 watts. The *efficiency* of the circuit, the ratio of output to input powers, is equal to 500/1,000, or 0.5, usually expressed as 50 per cent.

With the 15-ohm load, the power dissipated in the source is 125 watts. The total power is 125 watts in the source and 375 watts in the load, or 500 watts. This results in an output efficiency of 375/500, or 75 per cent.

With the 3-ohm load, the power dissipated in the source is 781.25 watts. The total power is 781.25 watts in the source and 468.75 watts in the load, or 1,250 watts. This results in an output efficiency of 468.75/1,250, or only 37.5 per cent.

Matching the source to the load may produce the maximum power output in the load, but mismatching with the higher resistance in the load gives better output *efficiency*. Theoretically, 100 per cent efficiency can only occur with an infinite resistance load.

Later, when speaking of circuits involving a-c, it may be said that the *impedance* of the load must match the *impedance* of the source, where impedance is the resisting effect of the load and source to alternating currents.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** How much energy is consumed in 20 hr by a radio receiver rated at 60 watts? (2.5) **[3]**

**2.** What is the difference between a milliwatt and a kilowatt? (2.5, 2.8) **[3]**

**3.** What instrument measures electric energy? (2.9) **[3]**

**4.** What is the sum of all voltage drops around a simple d-c series circuit, including the source? (2.11) **[3]**

**5.** A relay with a coil resistance of 500 ohms is designed to operate when 0.2 amp flows through the coil. What value of resistance must be connected in series with the coil if operation is to be made from a 110-volt d-c line? (2.13) **[3]**

**6.** What is the conductance of a circuit if 6 amp flows when 12 volts d-c is applied to the circuit? (2.14) **[3]**

**7.** What method of connection should be used to obtain the maximum no-load output voltage from a group of similar cells in a storage battery? (2.16) **[3]**

**8.** What method of connection should be used to obtain the maximum short-circuit current from a group of similar cells in a storage battery? (2.16) **[3]**

**9.** State the three ordinary mathematical forms of Ohm's law. (2.1) **[3 & 6]**

**10.** If the voltage applied to a circuit is doubled and the circuit resistance increased to three times its former value, what will be the final current value? (2.2) **[3 & 6]**

**11.** What is the unit of electric power? (2.5) **[3 & 6]**

**12.** What is the formula for determining the power in a d-c circuit when the current and voltage are known? (2.5) **[3 & 6]**

**13.** What is the formula for determining the power in a d-c circuit when the current and resistance are known? (2.5) **[3 & 6]**

**14.** What is the formula for determining the power in a d-c circuit when the voltage and resistance are known? (2.5) **[3 & 6]**

**15.** What will be the heat dissipation, in watts, of a resistor of 20 ohms having a current of ¼ amp passing through it? (2.5) **[3 & 6]**

**16.** What should be the minimum power-dissipation rating of a resistor of 20,000 ohms to be connected across a potential of 500 volts? (2.5) **[3 & 6]**

**17.** What is the difference between electric power and electric energy? (2.5) **[3 & 6]**

**18.** If the value of resistance, across which a constant emf is applied, is doubled, what will be the resultant proportional power dissipation? (2.6) **[3 & 6]**

**19.** If the value of a resistance to which a constant emf is applied is halved, what will be the resultant proportional power dissipation? (2.6) **[3 & 6]**

**20.** What is the maximum rated current carrying capacity of a resistor marked "5,000 ohms 200 watts"? (2.6) **[3 & 6]**

**21.** Show by a diagram how a voltmeter and ammeter should be connected to measure power in a d-c circuit. (2.9) **[3 & 6]**

**22.** What instrument measures electric power? (2.9) **[3 & 6]**

**23.** If a vacuum tube having a filament rated at ¼ amp and 5 volts is to be operated from a 6-volt battery, what is the value of the necessary series resistor? (2.12) **[3 & 6]**

**24.** If resistors of 3, 5, and 15 ohms are connected in parallel, what is the total resistance? (2.15) **[3 & 6]**

**25.** What is the total resistance of a parallel circuit consisting of one branch of 10 ohms resistance and one branch of 25 ohms resistance? (2.15) **[3 & 6]**

**26.** Indicate by a diagram how the total current in three branches of a parallel circuit can be measured by one ammeter. (2.15) **[3 & 6]**

**27.** If two 10-watt 500-ohm resistors are connected in parallel, what are the power-dissipation capabilities of the combination? (2.15) **[3 & 6]**

**28.** Show by a diagram how to connect battery cells in series (2.16) **[3 & 6]**

**29.** Show by a diagram how to connect battery cells in parallel. (2.16) **[3 & 6]**

**30.** Draw a simple schematic diagram showing the method of connecting three resistors of equal value so that the total resistance will be three times the resistance of one unit. (2.17) **[3 & 6]**

**31.** Draw a simple schematic diagram showing how to connect three resistors of equal value so that the total resistance will be one-third of one unit. (2.17) **[3 & 6]**

**32.** Draw a simple schematic diagram showing the method of connecting three resistors of equal value so that the total resistance will be two-thirds the resistance of one unit. (2.17) **[3 & 6]**

**33.** Draw a simple schematic diagram showing the method of connecting three resistors of equal value so that the total resistance will be 1½ times the resistance of one unit. (2.17) **[3 & 6]**

**34.** If the power input to a radio receiver is 75 watts, how many kilowatthours does the receiver consume in 24 hr of continuous operation? (2.5) **[6]**

**35.** A circuit is passing a current of 3 amp. The internal resistance of the source is 2 ohms. The total external resistance is 50 ohms. What is the terminal voltage of the source? (2.12) **[6]**

**36.** A 6-volt storage battery has an internal resistance of 0.01 ohm. What current will flow when a 3-watt 6-volt lamp is connected? (2.12) **[6]**

**37.** Two resistors are connected in series. The current through these resistors is 3 amp. Resistor 1 has a value of 50 ohms; resistor 2 has a voltage drop of 50 volts across its terminals. What is the total impressed emf? (2.12) **[6]**

**38.** If two 10-watt 500-ohm resistors are connected in series, what is the total power-dissipation capability? (2.12) **[6]**

**39.** A certain keying relay coil has a resistance of 500 ohms and is designed to operate on 125 ma. If the relay is to operate from a 110-volt d-c source, what value of resistance should be connected in series with the relay coil? (2.12) **[6]**

40. A 10,000-ohm 100-watt resistor, a 40,000-ohm 50-watt resistor, and a 5,000-ohm 10-watt resistor are connected in parallel. What is the maximum value of total current through this parallel combination which will not exceed the wattage rating of any of the resistors? (2.15) [6]

41. Two resistors of 18 and 15 ohms are connected in parallel; in series with this combination is connected a 36-ohm resistor; in parallel with this total combination is connected a 22-ohm resistor. The total current through the combination is 5 amp. What is the current value in the 15-ohm resistor? (2.17) [6]

## AMATEUR LICENSE INFORMATION

It is recommended that applicants for Novice Class license examinations be able to answer questions prefaced by a star. Applicants for General, Conditional, and Technician Class licenses should be able to answer all questions.

★1. What is the unit of measurement of electric power? (2.5)

★2. What is the unit of measurement of electric energy? (2.5)

★3. What instrument is used to measure electric potential? (2.9)

★4. What instrument is used to measure electric current? (2.9)

★5. State the three Ohm's-law formulas. (2.1)

★6. State the three power formulas. (2.5)

★7. What current flows when an electric pressure of 10 volts is across a resistance of 20 ohms? (2.2)

★8. What is the power input to a transmitter having a plate voltage of 2,000 volts and a plate current of 500 ma? (2.5)

★9. If a person touches the two sides of a 110-volt circuit and he has 2,200 ohms resistance, what current flows through him? (2.2)

10. What instrument is used to measure electric resistance? (2.9)

11. What is the reciprocal of resistance? (2.14)

12. What is the unit of measurement of conductance? (2.14)

13. What is the formula used to compute resistances in series? (2.11)

14. What is the formula used to compute resistances in parallel? (2.15)

# CHAPTER 3

# MAGNETISM

**3.1 Magnetism and Electricity.** In the study of electricity, magnetism must be considered. Electricity (emf, current, and resistance) and magnetism are inseparable. Any wire carrying a current of electricity is surrounded by an unseen area of force, a *magnetic field.*

At one time or another almost everyone has had experience with a magnet or a pocket compass. A magnet attracts pieces of iron but has little effect on practically everything else. Why does it single out the iron? A compass, when laid on a table, swings back and forth, finally coming to rest pointing toward the north pole of the world. Why does it always point in the same direction?

These and other questions about magnetism have puzzled scientists for hundreds of years. It is only comparatively recently that theories have been developed that seem to answer the many puzzling questions that arise when magnetism is investigated.

Radio and electronic apparatus such as relays, circuit breakers, earphones, loudspeakers, transformers, chokes, magnetron tubes, television tubes, phonograph pickups, tape and disc recorders, microphones, meters, vibrators, motors, and generators depend on magnetic effects to make them function. Every coil in a radio receiver or transmitter is utilizing the magnetic field that surrounds it when current is flowing. But what is meant by the term magnetic field?

**3.2 The Magnetic Field.** An electron at rest has a negative electrostatic field of force surrounding it, as explained previously. When energy is imparted to it to make it move, apparently a new type of field develops around it, at right angles to its electrostatic field. Whereas the electrostatic lines of force are considered as radiating outward from the electron, the *electromagnetic* field of force develops as a ring around the electron, at right angles to the path taken (Fig. 3.1).

It is also believed that the proton, besides having an electrostatic positive field, also develops an electromagnetic field around itself *when moving.*

Electrons whirling around the orbits of an atom or molecule produce electromagnetic fields around their paths of motion. These magnetic fields are either balanced or neutralized by the magnetic effect of any proton movement in the nucleus, or the movement of one orbital electron is counteracted by another orbital electron whirling in an opposite direction. In almost all substances the net result is little or no external magnetic field.

In the case of an electric conductor carrying current, the concerted movement of electrons along the wire produces a magnetic field around the conductor. The greater the current, the more intense, or concentrated, the magnetic field.

Under normal circumstances, the field strength around a current-carrying conductor varies inversely as the distance squared from the conductor. At twice the distance from the conductor the magnetic-field strength is one-quarter as much; at five times the distance the field strength is one twenty-fifth; and so on. At a relatively short distance from the conductor the field strength may be quite weak.

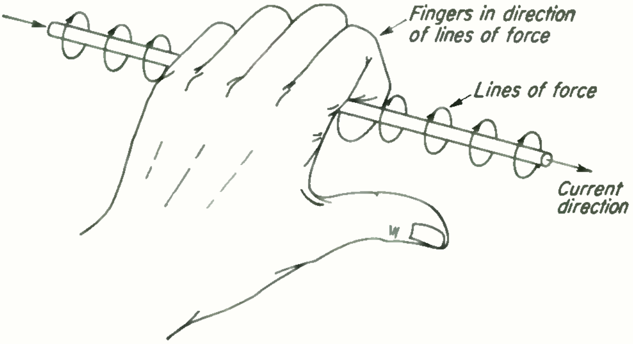


Fig. 3.1. Left fingers indicate magnetic-field direction if the thumb points in the current direction.

To indicate the presence of a magnetic field around a wire, circular lines are used, as shown in Fig. 3.1. Note that the *lines of force* are given direction by arrowheads drawn on them. The arrowheads do not mean that the lines of force are moving in this direction, but only that a relative polarity is present in them. The direction of these lines is determined in relation to the direction of the electron movement, or current flow. In the illustration the electron flow is indicated to be from left to right. If the *left hand* grasps a current-carrying conductor with the thumb extended in the direction of the current, the fingers will indicate the accepted field direction of the magnetic lines of force. This is known as the *left-hand magnetic-field rule.* If the current flows in the opposite direction, the left hand must be turned over so that the thumb points in the direction of the current, and the direction of the lines of force will be opposite to that shown.

If the direction of the lines of magnetic force is known, the same rule indicates the current direction and is known as the *left-hand current rule.*

When the current in a conductor is increased, more electrons flow, the magnetic-field strength near the wire increases, and the whole field extends farther outward.

In many electric circuits the current flows through a coil of several turns of wire. Figure 3.2 illustrates the magnetic field as it might be set up around a single turn. Note that the indicated field direction conforms to the left-hand rule and that the greatest concentration of lines of force appears at the center, or the *core*, of the turn.

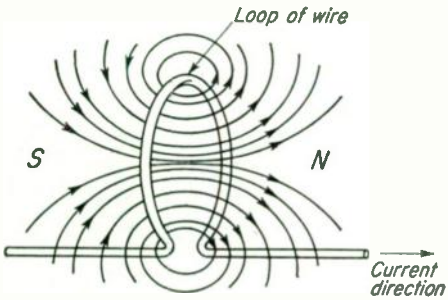


Fig. 3.2. Looping a wire concentrates the magnetic lines of force.

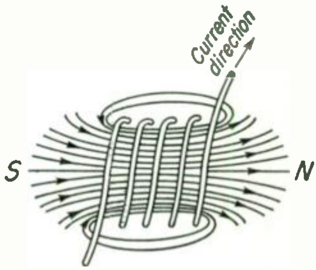


Fig. 3.3. Increasing the number of turns increases the magnetic-field concentration.

When several turns of wire are formed into a coil, the lines of force from each turn add to the fields of the other turns and a more concentrated magnetic field is produced in the core of the coil, as indicated in Fig. 3.3. The more current and the more turns, the stronger the magnetic field produced.

At one end of the coil the indicated field direction is outward. At the opposite end it is inward. At any time that lines of force have a direction outward from either a coil or from a piece of metal, that end of the coil or metal is said to have a *north* polarity. Conversely, the end of a coil or piece of metal having lines of force pointed inward is the *south* pole. Magnetic polarity uses the terms north and south, whereas electrostatic polarity uses the terms *positive* and *negative.* These polarity terms are not interchangeable. The negative end of a coil can only mean the end connected to the negative terminal of the source and does not refer to either a north or south magnetic pole. Note that a line of force surrounding a current-carrying wire has no north or south pole.

A second, and different, left-hand rule may also be illustrated by Fig. 3.3. If a coil is grasped by the left hand, with the *fingers* pointing in the direction of the current flow, the thumb indicates both the direction of the lines of force in the core and the north end of the coil.

If the direction of the lines of force through the core is known, the same left-hand rule can be applied to determine the current direction in the coil.

All magnetic lines of force are complete loops and may be considered as somewhat similar to stretched rubber bands in their action. They will contract back into the circuit from which they came as soon as the force that holds them out ceases to exist.

Magnetic lines of force never cross each other. When two lines have the same direction, they will oppose mechanically if brought near each other. This is illustrated in Fig. 3.4, which shows a cross-section view of two wires with current flowing in opposite directions in them. Where adjacent, the lines from both wires have a similar and upward direction and repel each other. The two wires try to push apart. The little cross in the wire represents the rear view of a current-indicating arrow, with the current flowing away from the viewer. A dot represents the point of the current-indicating arrow approaching the viewer.

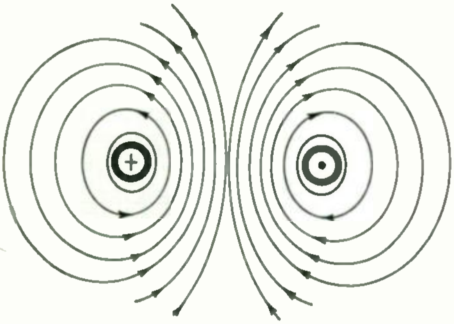


FIG. 3.4. Similar-direction magnetic lines repel.

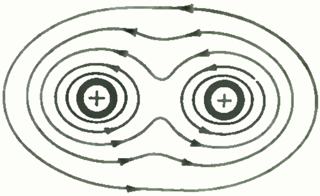


FIG. 3.5. Opposite-direction magnetic lines attract and join.

Magnetic lines of opposite direction or polarity are attracted to each other. The loops surrounding wires carrying current in the same direction are opposite in polarity where they are adjacent, as shown in Fig. 3.5. Such loops may join into single large loops encircling both of the wires carrying the current. The two wires will now be subjected to a common contracting force that tends to pull them together physically.

**3.3 Flux Density.** The complete magnetic field of a coil is known as the *flux* and is usually denoted by the Greek letter $\phi$ (phi). If a current flowing through a certain coil produces 100 lines of force in the core of the coil, it may be said that the core has a flux of 100 lines ($\phi = 100$ lines).

$\phi$

The *flux density* of a magnetic field is the number of lines per square inch and is indicated by the letter $B$. In the example above, in which the core has a total of 100 lines, if the cross-section area of the core is 2 square inches, the flux density is $^{100}\!/_{2}$, or 50 lines per square inch ($B = 50$ lines/in.$^2$).

B lines/inch

**3.4 Field Intensity.** The energy that produces magnetic lines of force is contained in the movement of electrons, or in current. The *magnetomotive force* (mmf), the force that will produce the flux in a coil, may be computed by multiplying the current in amperes by the number of turns, or

# turns

Ampere turns $$F = NI$$ Current

where $F$ is the force in ampere-turns; $N$ is the number of turns in the coil; and $I$ is the current in amperes.

Out past the ends of the coil, the magnetic field starts spreading and the flux density begins decreasing. Within the core itself, however, the lines of force are relatively straight and parallel and present a constant flux density. The most practical unit of measurement of the magnetizing force working on the column of material forming the core of the coil is determined by dividing the total mmf by the core length in inches. This reduces the total mmf to a unit for comparison and computation. Thus, a 3-in. coil having 60 amp-turns has a standardized magnetizing force, or field intensity, of $^{60}/_{3}$, or 20 amp-turns/in. This magnetizing force is represented by the letter $H$. In the example above, $H$ = 20 amp-turns/in.

Summarizing, flux, $\phi$, indicates a total number of lines as at the end of the coil. Flux density, $B$, is the number of lines per square inch as at the end of the core. The total magnetizing force, mmf, or $F$, is in ampere-turns. The magnetizing force, or field intensity, $H$, for a standard unit length of the core is the *ampere-turns per inch.*

**3.5 Permeability.** When a coil of wire is wound with air as the core, a certain flux density will be developed in the core for a given value of current. If an iron core is slipped into the coil, it will be found that a very much greater flux density will exist in the iron core than was present when the core was air, although the current value and the number of turns have not changed.

With an air-core coil the air surrounding the turns of the coil may be thought of as pushing against the lines of force, tending to hold them close to the turns. However, with an iron core, the lines of force find a medium in which they can exist much more easily than they can in air. As a result, lines of force that were held close to the turns in the air-core coil are free to expand into the highly receptive area afforded by the iron. This frees more lines of force that otherwise would have been so close to the surface of the wire as to be lost as far as the flux of the air core is concerned. These lines of force in the iron core produce a greater flux density, $B$, for the iron core, although there might have been as much total magnetizing force produced in the air-core coil. The iron core merely brings the lines of force out where they can be more readily used.

When comparing the ability of different materials to accept or allow lines of force to exist in them, air may be considered as the standard of comparison. A magnetizing force $H$ of 20 amp-turns/in. will always produce a flux density $B$ of 20 lines/in.$^2$ in an *air-core* coil. Substituting a core of fairly pure iron, the same 20 amp-turns/in. may produce a flux density of perhaps 200,000 lines/in.$^2$ in the core.

The ratio of $B$ to $H$, or $B/H$, expresses the ability of a core material to accept, or be *permeated* by, lines of force. The *permeability* of most substances is very close to that of air, which may be considered as having a value of 1. Other materials, such as iron, nickel, and cobalt, are very permeable, having permeabilities of several hundred to several thousand times that of air. (Note that the word "permeability" is a derivation of the word permeate, meaning "to pervade," or "saturate," and is not related to the word "permanent.")

Permeability is represented by the Greek letter $\mu$. In formula form X it may be expressed as

$$\mu = \frac{B}{H}$$

flux density

where $\mu$ is permeability (no unit); $B$ is flux density; and $H$ is magnetizing force.

In the example above, the iron has a permeability equal to $B/H$, or 200,000/20, or 10,000. In practice this is not particularly high. Pure iron approaches a permeability of 200,000. Special alloys of nickel and iron may have a permeability of 100,000. Alloying iron makes it possible to produce a wide range of permeabilities. Cast iron can be made that has almost unity (1) permeability. Stainless steel also exhibits practically no magnetic effect.

The permeability of magnetic materials is somewhat analogous to conductance in electric circuits. It indicates the ease with which a material will accept lines of force or allow them to move into or through it.

In electric circuits the reciprocal of conductance is resistance. In X magnetic circuits the reciprocal of permeability is *reluctance*. The symbol for reluctance is $\mathcal{R}$, and $\mathcal{R} = 1/\mu$. A material with high reluctance is reluctant to accept lines of force. If an iron has a permeability of 2,700, it may be said to have a reluctance of 1/2,700. Air has a reluctance of 1. Neither permeability nor reluctance has a unit of measurement assigned to it.

**3.6 The Atomic Theory of Magnetism.** The discussion here will be a considerably condensed version of the atomic theory of magnetism.

From atomic theory it is known that an atom is made up of a nucleus of protons, surrounded by one or more electrons encircling the nucleus. The rotation of electrons and protons in most atoms is such that the magnetic forces cancel each other. Only the atoms of the elements iron, nickel, and cobalt arrange themselves into magnetic entities. Such atoms form into special atom groups. These groupings are known as *domains* and are magnetic.

Groups of domains form crystals of the magnetic material. The crystals may or may not be magnetic, depending on the arrangement of the domains in them. Investigation may show that many of the domains are fully magnetized but the external resultant of all the domains in a crystal may be a neutral field.

Each domain has three directions of magnetization. These are the direction of *easy* magnetization, the direction of *semihard* magnetization, and the direction of *hard* magnetization.

If an iron crystal is placed in a weak field of force, the domains begin to line up in the easy direction. As the magnetizing force $H$ is increased, the domains begin to roll over and start to align themselves in the semihard direction. Finally, as the $H$ is increased still more, the domains are lined up in the hard direction. When all the domains are lined up in the hard direction the iron is said to be *saturated*, because an increase in magnetizing force will produce no more magnetic change in the material.

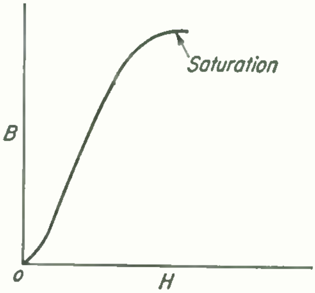


FIG. 3.6. Simplified magnetization ($BH$) curve for iron.

The result of this action can be seen in the $B$-$H$ curve for a piece of iron, as shown in Fig. 3.6. The graph shows that an increase of $H$ produces an increase of $B$. At low values of magnetizing force the iron produces relatively little flux density. The permeability, or $B/H$, is relatively low under this condition. As the magnetization is increased, the flux density increases rapidly in respect to the increase of magnetizing force, resulting in a large $B/H$ ratio, or a high value of permeability. As saturation is approached, further increase in $H$ produces little increase in $B$. This general curve form is to be expected of all magnetic materials, although the steepness of the curve changes with different permeabilities.

**3.7 Ferromagnetism.** Substances that can be made to form domains are said to be *ferromagnetic*, which means "iron-magnetic." The only ferromagnetic *elements* are iron, nickel, and cobalt. However, it is possible to combine properly two or more nonmagnetic elements and form a ferromagnetic substance. For example, in the proper proportions, copper, manganese, and aluminum, each by itself being nonmagnetic, form an alloy, or mixture, which is similar to iron magnetically.

Materials made up of nonmagnetic atoms, when placed in a magnetic field, may attempt either to line up in the field or to turn at right angles to the field. If they line themselves in the direction of the magnetic field, they are said to be *paramagnetic*. If they try to turn from the direction of the field, they are called *diamagnetic* materials. There are only a few diamagnetic materials. Some of the more common are gold, silver, copper, zinc, and mercury. All materials which do not fall in the ferromagnetic or diamagnetic categories are paramagnetic. The greatest percentage of substances are paramagnetic.

Ferromagnetic substances will oppose being magnetized by an external magnetic field to a certain extent. This opposition, mentioned previously, is reluctance.

Once magnetized, ferromagnetic substances may also tend to oppose being demagnetized. They are said to have a certain amount of *retentivity*, or *remanence*, which is the ability to retain magnetism when an external field is removed.

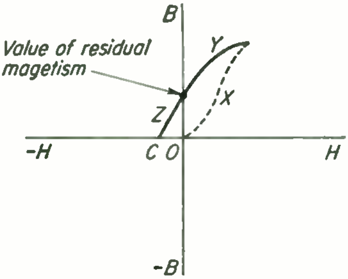


FIG. 3.7. Magnetization of iron when subjected to a magnetizing force, dotted line $X$. Partial loss of magnetism when the magnetizing force is removed, line $Y$.

As soon as the magnetizing force is released from a magnetized *ferromagnetic* substance, it tends to return at least part way back to its original unmagnetized state, but it will always retain some magnetism. This remaining magnetism is *residual magnetism*. Paramagnetic and diamagnetic materials, on the other hand, always become completely nonmagnetic when an external magnetizing force is removed from them.

**3.8 The Hysteresis Loop.** When a magnetizing force $H$ is applied to a piece of completely demagnetized ferromagnetic material, the flux density $B$ rises as shown by the dotted curve $X$ (Fig. 3.7). If the magnetizing force $H$ is removed from the ferromagnetic material, the flux density decreases but drops back only part way to zero, as shown by the curve $Y$. The opposition of the domains to roll back to the unmagnetized state is known as *hysteresis* (pronounced hiss-ter-ee-sis). The magnetism left in the metal is residual magnetism. For soft iron it will be small, while for steels and iron alloys it will be considerably greater. With the latter materials the $B$ value will not drop as far toward zero.

If a magnetizing force in the opposite direction is now applied to the ferromagnetic material, a certain value of this $-H$ will be necessary to counteract the residual magnetism and bring the $Z$ portion of the curve down to point $C$. This point represents zero flux density, or complete demagnetization.

The opposite-direction magnetizing force, or $-H$, required to demagnetize the material completely is known as the *coercive force* (ko-urs-iv) and is indicated by the length of the line, $O$ to $C$.

In a practical case, where an iron core has a coil of wire wrapped around it, if an alternating current is made to flow through the coil, a curve called a *hysteresis loop* may be drawn to indicate the flux-density variations under changing magnetizing forces, as shown in Fig. 3.8. The dotted line shows the magnetization when the unmagnetized iron was first subjected to the force. The remainder of the loop indicates the flux density $B$ that results when the magnetizing force $H$ is alternately reversed.

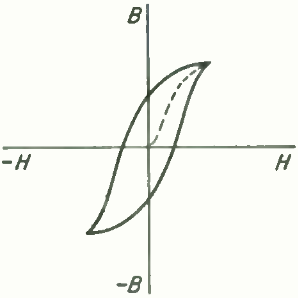


Fig. 3.8. Complete hysteresis loop produced by a cycle of magnetization.

As current through the coil increases in one direction, the $H$ increases, producing an increase in $B$. As the current decreases, the $H$ decreases, resulting in a lessening of $B$. As the current reverses, the $H$ increases in the opposite direction, the domains are rolled over, and the $B$ follows in the opposite direction.

With a full cycle of a-c a hysteresis loop is developed enclosing a given area. A soft iron will be represented by a slim loop (Fig. 3.9*a*). Steel results in a broader loop (Fig. 3.9*b*). Special iron alloys, such as alnico, have a loop approaching a rectangle in shape (Fig. 3.9*c*).

It requires an expenditure of a certain amount of energy to reverse the magnetism, or realign the domains, in a piece of ferromagnetic material. The energy lost due to hysteresis appears as heat in the magnetic material. For this reason, when transformers using a-c in them are made with iron cores, it is necessary to select metals having narrow hysteresis loops and with little *hysteretic* loss. Even so, the core of a transformer always heats a little because of hysteresis loss.

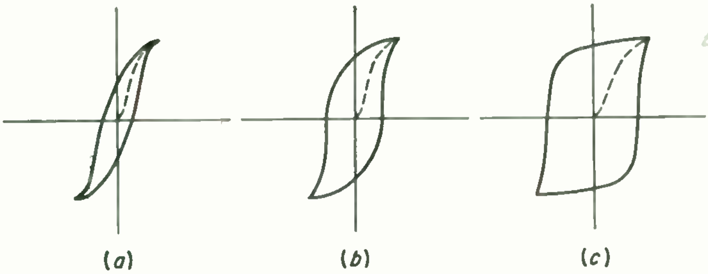


Fig. 3.9. Hysteresis loop for (*a*) soft iron, (*b*) steel, (*c*) alnico-type materials.

**3.9 Permanent and Temporary Magnets.** A ferromagnetic substance that holds magnetic-domain alignment well (has a high value of retentivity) and has a broad hysteresis loop is used to make *permanent* magnets. One of the strongest of the permanent magnets is made of a combination of iron, aluminum, nickel, and cobalt, called *alnico*. It is used in horseshoe magnets, electrical meters, headphones, loudspeakers, radar transmitting tubes, and in many other applications. Other magnetically hard, or permanent-magnet, materials are cobalt steel, nickel-aluminum steels, and special steels.

Ferromagnetic substances that lose magnetism easily (have a low value of retentivity) are used to make *temporary* magnets. They find use in transformers, chokes, relays, and circuit breakers. Pure iron and permalloys (*perm* derived from permeable, *not* from permanent) are examples of magnetically soft, or temporary-magnet, materials. Finely powdered iron dust, held together with a nonconductive binder, is used for cores in many radio applications.

**3.10 Magnetizing and Demagnetizing.** There are two simple methods of magnetizing a ferromagnetic material. One is to wrap a coil of wire around the material and force a direct current through the coil. If the ferromagnetic material has a high value of retentivity, it will become a permanent magnet. If the material being magnetized is heated and allowed to cool while subjected to the magnetizing force, a greater number of domains will be swung into alignment and a greater permanent flux density will result. Hammering or jarring the material while under the magnetizing force also tends to increase the number of domains that will be affected.

A less effective method of magnetizing is to stroke a high-retentivity material with a permanent magnet. This will align some of the domains of the material and produce a relatively weak permanent magnet.

If a permanent magnet is hammered, many of its domains will be jarred *out* of alignment and the value of flux density will be lessened. If heated, it will lose its magnetism because of increased molecular movement upsetting the domain structure. Strong opposing magnetic fields brought near a permanent magnet may also decrease its magnetism. It is important that equipment containing permanent magnets be treated with care. They must be protected from physical shocks, excessive temperatures, and stray magnetic fields.

When tools or objects such as screwdrivers or watches become permanently magnetized, it is possible to demagnetize them by slowly moving them into and out of the core area of a many-turn coil in which a relatively strong a-c is flowing. The a-c produces a continually alternating magnetizing force. As the object is placed into the core area it is alternately magnetized in one direction and then the other. As it is pulled farther away, the alternating magnetizing forces become weaker. When it is finally out of the field completely, the residual magnetism will usually be so low as to be of no consequence.

**3.11 The Magnetic Circuit.** The magnetomotive force, the reluctance of the magnetic material used, and the flux developed are often likened to the electric circuit, where electromotive force applied across resistance produces current. The similarities are:

$E$ = electromotive force similar to $F$ = magnetomotive force
$R$ = resistance similar to $\mathcal{R}$ = reluctance
$I$ = current similar to $\phi$ = flux

In the electric circuit the three letters can express the concept that the current in a circuit is directly proportional to the emf and inversely proportional to the resistance, by the Ohm's-law formula

$$I = \frac{E}{R}$$

where $I$ is the current in amperes; $E$ is the emf in volts; and $R$ is the resistance in ohms.

In the magnetic circuit the idea that the total flux is directly proportional to the mmf and inversely proportional to the reluctance of the material used can be expressed by the formula

$$\phi = \frac{F}{\mathcal{R}}$$

ampere turns
flux in lines
reluc -

where $\phi$ is the flux in lines; $F$ is the mmf in ampere-turns; and $\mathcal{R}$ is the reluctance, or reciprocal, of the permeability.

This is sometimes referred to as *Ohm's law for magnetic circuits.*

Since the permeability curve of all magnetic materials is curved, or *nonlinear* (non-lin-ee-ur, meaning "not like a straight line"), the reluctance value of magnetic materials will also be nonlinear under varying values of $H$. Unless permeability curves for the metal being investigated are available, accurate magnetic-circuit computations are not possible. Magnetic-circuit computations will not be dealt with in this book.

**3.12 English versus Cgs Units.** The explanation of magnetism has been made using the English units of measurement in the belief that you will be able to follow the explanations better if they are given in such familiar words as "inches," "square inches," and "ampere-turns."

In 1930, in an attempt to clear up the many differences of terminology then in use for magnetism, the International Electrotechnical Commission adopted *cgs* (centimeter, gram, second) units of measurement (Table 3.1).

Table 3.1

| Symbol | Term | Cgs unit name | English equivalent |
|---|---|---|---|
| $F$ | Magnetomotive force | Gilbert | 1.26 amp-turns |
| $H$ | Magnetizing force | Oersted | 0.495 amp-turn/in. |
| $\phi$ | Magnetic flux | Maxwell | Lines |
| $B$ | Magnetic-flux density | Gauss | 0.155 line/in.$^2$ |

While both the English and the cgs systems are used in magnetic work, the cgs may be considered more desirable for the engineer. As a result, the answer to the question, "What is the unit of magnetomotive force?" may be "gilbert" instead of "ampere-turn." The same is true for the oersted (ur-sted) as the magnetizing force, instead of ampere-turns per inch, maxwells for magnetic flux, and gauss (gows) for flux density.

The number of gilberts produced in a circuit can be found by multiplying the ampere-turns by 1.26. The oersted is the magnetizing force in gilberts per *centimeter*. The gauss is the flux density in maxwells per *square centimeter*.

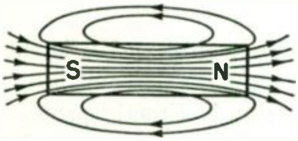


Fig. 3.10. Magnetic poles are determined by direction of lines of force.

**3.13 Permanent-magnet Fields.** When a piece of magnetically hard material is subjected to a strong magnetizing force, its domains are aligned in the same direction. When the magnetizing force is removed, many of the domains remain in the aligned position, and a permanent magnet results.

As previously stated, the north pole is any place where the direction of the magnetic lines of force is outward from the magnet. The south pole is any place where the direction of the lines is inward. This is illustrated in Fig. 3.10.

It has been explained that the lines of force surrounding current-carrying wires opposed each other if the lines had the same direction and attracted each other if of opposite direction. The same is true of the fields of permanent magnets. When similar poles are held near each other, lines of similar direction are opposing, tending to push the magnets apart physically. Unlike, or dissimilar, poles held near each other produce a physically attracting effect because of lines of force from both magnets which join as long enveloping loops, as illustrated in Fig. 3.11.

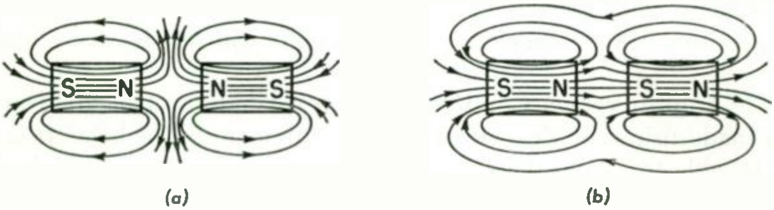


Fig. 3-11. Magnetic fields with (*a*) like lines repelling and (*b*) unlike lines attracting and joining.

**3.14 Magnetic-field Distortion.** Under normal circumstances a permanent magnet made into bar shape and suspended in the air will have a field surrounding it somewhat similar to that shown in Fig. 3.10.

When a piece of highly permeable material such as pure iron and a piece of low-permeable material such as copper are placed in the field, as illustrated in Fig. 3.12, the field pattern is distorted.

The copper, having practically the same permeability as the air, has almost no effect on the magnetic lines of force. The iron, being thousands of times more permeable than air, is a highly acceptable medium in which the lines of force may exist, and most of the lines on that side, and some of the lines from the other side of the magnet, detour into the iron. This produces a distorted field pattern and results in a highly concentrated field between the magnet and the piece of iron. This ability to produce a concentrated field by using iron to close the magnetic gap between north and south poles of magnets is used in many instances in radio and electricity.

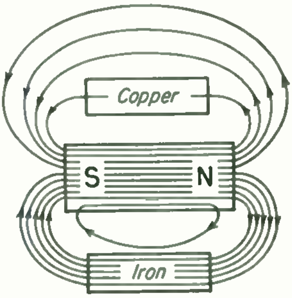


Fig. 3.12. Distortion of bar magnet field due to iron, and lack of distortion with low-permeability material.

If a magnet is completely encased in a magnetically soft iron box, all its lines of force remain in the walls of the box and there is no external field. This is known as magnetic shielding. Shielding may be used in the opposite manner. An object completely surrounded by an iron shield will have no external magnetic fields affecting it, since all the lines of force will remain in the highly permeable shield.

**3.15 The Magnetism of the Earth.** When the world was formed, enough of the ferromagnetic materials making up the earth had domains aligned in such a way that the earth appears to be a huge permanent magnet. The direction taken by the lines of force surrounding the surface of the earth is inward at a point near what is commonly known to be the north pole of the world and outward near the earth's south pole. This results in a rather confusing set of facts. The *geographical north pole* of the earth is actually near its *south magnetic pole*, and the *geographical south pole* is near the *north magnetic pole*, as shown in Fig. 3.13.

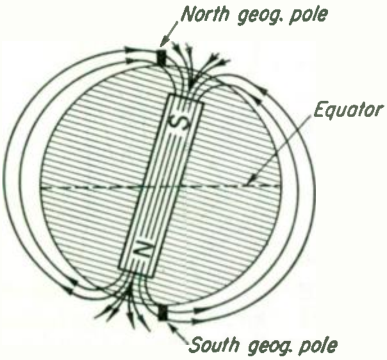


Fig. 3-13. Permanent-magnet field of the earth.

The familiar magnetic navigational compass consists of a small permanent magnet balanced on a pivot point. The magnetic field of the compass needle lines itself up in the earth's lines of force. As a result, the *magnetic north* end of the compass needle is pulled toward the earth's *magnetic south* pole, since unlike poles attract each other. This means that when the compass needle is pointing toward the geographical north, its north end is actually pointing toward a magnetic south pole. Navigators disregard the earth's true magnetic polarity and consider only the compass needle. To them, anything toward which the north end of the compass points is said to be "north" of the compass, even though it must have a south magnetic polarity.

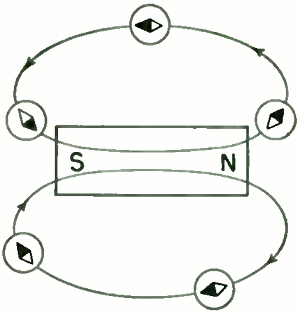


Fig. 3-14. Compasses indicate direction of magnetic field surrounding a bar magnet.

**3.16 Using a Magnetic Compass in Electricity.** When a magnetic field exists in an area and a freely suspended permanent magnet is moved into this field, the lines of force of the permanent magnet will try to line up in the same direction taken by those of the field. The most concentrated group of lines of force of the magnet, its internal field, lines up with the external field.

A small magnetic pocket compass moved to different points in a field produced by a powerful permanent magnet will indicate the direction of the magnet's field, as shown in Fig. 3.14. In the same manner, the direction of the lines of force surrounding a coil carrying a direct current can be checked. Note the indication given by the compass needle when *inside* the coil: the north end of the compass will point to the north end of the coil. This is only true inside the coil. Outside, the north end of the compass points in the direction of the lines of force which run toward the south end of the coil. This is illustrated in Fig. 3.15.

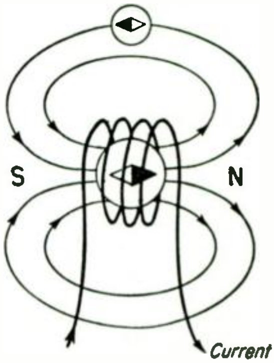


Fig. 3.15. Compass indications inside and outside a current-carrying coil.

If the current direction in the coil is reversed, the compass will also reverse. If an a-c is flowing in the coil, the compass will not be able to follow rapid field reversals and will give no indication. If the a-c flow is strong enough, the compass may be demagnetized and become useless.

The direction of current in a wire can be determined with a compass. Current flowing along a wire sets up lines of force around it. If a compass is brought near the wire, the needle will swing at right angles to the current and in the direction of the lines of force surrounding the wire. The north pole of the compass indicates the direction of the lines of force around the wire, as illustrated in Fig. 3.16. By applying the left-hand current rule, the direction of current can be determined.

If the current direction is reversed, the direction of the lines of force

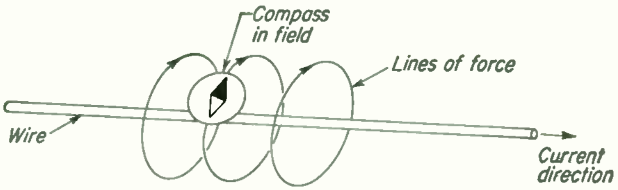


FIG. 3.16. Compass indicating the direction of the magnetic field around a current-carrying wire.

will reverse and the compass needle will swing around 180°. As in a coil, the compass will not indicate if the current is alternating. If the a-c is strong enough, it may demagnetize the compass.

**3.17 Electrons Moving in a Magnetic Field.** Electrons will travel in a straight line in a magnetic field provided they are moving in a direction parallel to the lines of force.

When electrons are propelled *across* lines of force, they will move in a curved path and at right angles to the lines of force. Figure 3.17 illustrates the path that will be taken by electrons moving into the magnetic field shown. The crosses represent the rear view of arrows that indicate the direction of lines of force pointing into the page.

The direction taken by the electrons as they curve through a magnetic field can be determined by using the *right-hand motor rule*, as illustrated. This states, "With the thumb, first, and second fingers of the right hand held at right angles to each other, the first finger pointing in the direction of the magnetic field, the second finger in the direction of the electron movement, the thumb will indicate the deflection of the electron." Check the electron path taken in the illustration by this rule.

If a *wire* is carrying the electrons through the magnetic field, the upward pressure on the electrons tends to move the wire in an upward direction.

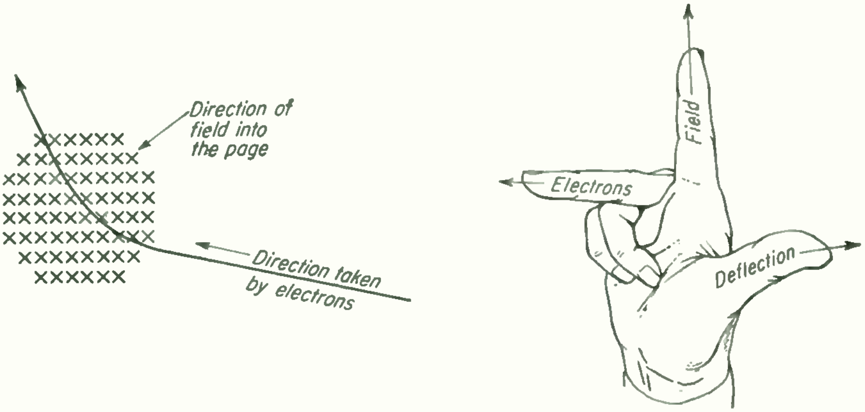


FIG. 3.17. Right-hand motor rule and direction taken by electrons moving through a magnetic field.

This is the principle by which electric motors operate and is discussed in the chapter on Motors and Generators.

Free electrons moving through magnetic fields are to be found in television picture tubes and other vacuum tubes.

**3.18 Generating an Emf by Magnetic Means.** When a wire is moved *parallel* to lines of force, no effect is produced on the free electrons in the wire.

However, when a conductor is moved upward through the magnetic field shown in Fig. 3.18, an electron flow is induced toward the right in the conductor. This current direction may be determined by using the *left-hand generator rule*. This three-finger rule is somewhat similar to the right-hand motor rule. It may be stated, "With the thumb, first and second fingers of the *left* hand held at right angles to each other, the first finger pointing in the direction of the magnetic field, the thumb in the direction of the conductor's motion, then the second finger indicates the direction of the induced emf, or current flow."

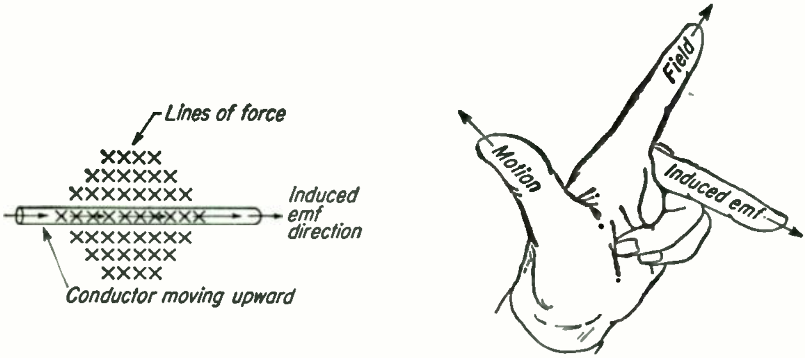


Fig. 3.18. Left-hand generator rule and direction of induced emf when a conductor moves through a magnetic field.

An explanation of the induction of a current in a conductor may be given as follows (Fig. 3.19): When a wire crosses a magnetic line of force (*a*), the line is stretched around the wire (*b*) and rejoins itself behind the wire (*c*), and the little loop developed around the wire collapses inward (*d*). The free electrons in the wire move at right angles to the magnetic loop collapsing inward (*e*) and are forced along the wire. The induced current in the wire due to the collapsing loop is outward from the page in the illustration. Check this with the left-hand generator rule. (HINT The collapsing-field motion is inward, which is the same as an outward motion of the conductor!)

While the explanation is given in terms of an induced current it is usually considered to be an emf that is induced in a conductor moving across a magnetic field. Both are correct, since producing a difference o potential between the two ends of the conductor requires some of the free electrons in the wire to be moved to one end and some removed from the other end. This is usually considered as a charging current. If a load is connected across the ends of the conductor, many more electrons will be forced into movement. In this latter case the heavy current will produce a magnetic field around the conductor in a direction that will oppose the original magnetic field. Physical or mechanical energy will now be required to move the conductor through the field. With no load, almost no energy is required to move the conductor. This is the basic theory of an electric generator, explained in the chapter on Motors and Generators.

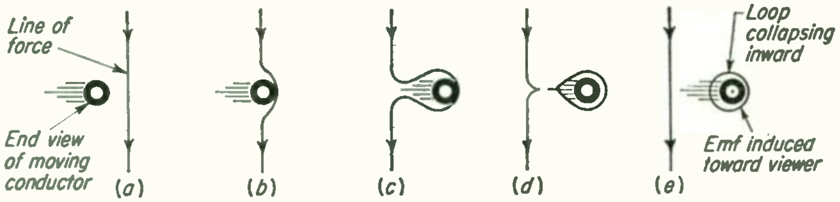


Fig. 3.19. Induction of an emf into a wire cutting through a line of force.

The factors that determine the amplitude, or strength, of the induced emf are:

1. Strength of the magnetic field (number of lines per square inch)
2. Speed of the conductor motion across the lines of force
3. Number of conductors connected in series (as in a generator)

These factors can be simply expressed in the rule, "The greater the number of lines cut per second, the higher the voltage induced." When magnetic lines are cut at a rate of 100 million per second, an emf of one volt is produced.

**3.19 Magnetostriction.** In a few applications in communications equipment the property of ferromagnetic materials to expand or contract when they are subjected to a magnetizing force is used. This is *magnetostriction.*

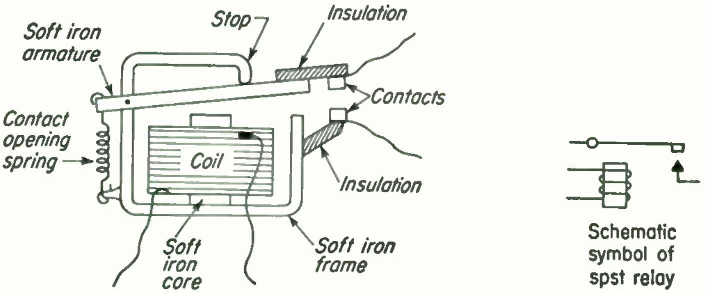
Nickel constricts when under a magnetizing force, while iron expands. A small part of the magnetic energy stored in such metals is usable as mechanical energy in this way.

The maximum contraction or expansion occurs at magnetic saturation. The direction of the magnetizing force has no effect on the direction of strain. When a piece of nickel is wrapped with a coil of wire, it will contract regardless of the direction of the current in the coil.

When the magnetizing force is removed, the magnetostrictive material springs back to its normal shape or size. The mechanical energy is converted back into magnetic energy and can be converted further to electric energy. If the current used as the magnetizing force is continuously pulsating or alternating, the material will continuously vibrate mechanically.

**3.20 Relays.** A relay is a relatively simple magnetic device, normally consisting of a coil, a core, and a movable *armature*, on which *make and break* contacts are fastened. Figure 3.20 illustrates one of the simpler relays used to close a circuit when the coil is energized. It is known as a single-pole-single-throw, or SPST, relay. The schematic symbol used in electrical diagrams is also shown.

The core, the U-shaped body of the relay, and the straight armature bar are all made of magnetically soft ferromagnetic materials having high permeability and little retentivity. One of the relay contacts is attached by an insulating strip to the armature, and the other to the relay body with an insulating material. In this way, the contacts are electrically separated from the operational parts of the relay. A spring holds the armature up when no current flows through the coil, opening the contacts.



Schematic symbol of spst relay

FIG. 3.20. Functional parts of a single-pole single-throw d-c relay.

When current flows in the coil, the core is magnetized and lines of force flow around the body of the relay. The gap between the core and the armature is filled with magnetic loops trying to contract. These contracting lines of force overcome the tension of the spring and pull the armature toward the core, closing the relay contacts.

When the current in the coil is stopped, the magnetic circuit loses its magnetism and the spring pulls the armature up, breaking the contact connection.

Relays are useful in closing and opening either high-voltage circuits or high-current circuits with relatively little voltage and current in the coil circuit.

In some cases it may be required to change the operating voltage of a relay coil.

*Example:* A 6-volt relay is to be used on 12 volts. The magnetizing force to attract the armature is equal to the ampere-turns of the coil. If the coil has 6 ohms resistance and 300 turns, the current will be equal to $I = E/R$, or $6/6$, or 1 amp. The ampere-turns required is 1 amp times 300 turns, or 300 amp-turns. A resistance may be added in series with the coil to limit the current to 1 amp when across 12 volts. This resistance must produce a 6-volt drop across it when 1 amp is flowing through it. The resistance must be $R = E/I$, or $6/1$, or 6 ohms. However, the heat developed in the resistance is a complete waste. It may be more desirable to purchase a 12-volt coil for the relay or to wind one. To wind one, the size of the wire in the 6-volt coil must be determined. Then a wire having twice the resistance per unit length and 70 per cent of the diameter must be used. This is obtained by using a wire having a gage three units higher. For example, No. 27 wire has twice the cross-section area of No. 30, and therefore half the resistance. Number 30 has a diameter of 10 mils, which is 70 per cent of the 14.2-mils diameter of No. 27 wire. When a coil is wound with the thinner wire to about the same size as the original coil, it will have four times the resistance and twice as many turns. With 12 volts, ½ amp will flow through the 600 turns. This represents 300 amp-turns, the required magnetizing force.

If a 12-volt relay coil is to be changed to operate on 6 volts, a wire 1.4 times the diameter of the original should be used.

To reduce high-resistance oxidation of relay contacts, they are usually made of silver or tungsten. The silver contacts may pit and require filing to smooth them from time to time.

More complicated relays are discussed later in the various types of equipment with which they are used.

When a voltage is applied across a single-layer coil, often called a *solenoid*, the current is proportional to the resistance of the wire in the turns of the coil. If a few turns of the same size wire are added, the number of turns is increased but the value of resistance is also increased proportionately, resulting in a proportionate decrease in current. Therefore the ampere-turns of the circuit and the strength of the magnet do not change materially, although they may decrease very slightly. However, when a coil is wound with several layers of wire, as in a relay coil, the length of the magnetic core is shorter and the total field is more condensed and is stronger. Increasing the layers in a multilayer coil increases the magnetic-field intensity tremendously.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** What material is frequently used for relay contacts? (3.20) silver + tungsten **[3]**

**2.** Which factors influence the direction of magnetic lines of force generated by an electromagnet? (3.2) **[3 & 6]**

**3.** What is meant by ampere-turns? (3.4, 3.12) **[3 & 6]**

**4.** Define the term permeability. (3.5) **[3 & 6]**

**5.** Define the term reluctance. (3.5) [illegible] **[3 & 6]**

**6.** Define the term residual magnetism. (3.7, 3.8) **[3 & 6]**

**7.** Define the term hysteresis. (3.8) **[3 & 6]**

**8.** How can the direction of flow of d-c electricity in a conductor be determined? (3.16) [illegible] **[3 & 6]**

**9.** How may a magnetic compass be affected when placed within a coil carrying an electric current? (3.16) will align [illegible] **[3 & 6]**

**10.** Which factors determine the amplitude of the emf induced in a conductor which is cutting magnetic lines of force? (3.18) 1 str. of field 2 rate of speed 3 # of conductors in series **[3 & 6]**

**11.** Neglecting temperature coefficient of resistance and using the same gage of wire and the same applied voltage in each case, what would be the effect upon the field strength of a single-layer solenoid of a small increase in the number of turns? (3.20) remains same due to increased resistance **[3 & 6]**

**12.** Name at least five pieces of radio equipment which make use of electromagnets. (3.1) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for General, Conditional, and Technician Class licenses should be able to answer the following question:

1. Magnetomotive force (mmf) may be measured in what two units? (3.12)

Gilberts + 1.26 ampere turns

## CHAPTER 4

# ALTERNATING CURRENT

**4.1 Methods of Producing Emf.** There are several methods by which an electromotive force can be produced. So far a unidirectional constant-amplitude emf, known as *direct current*, or d-c, has been the only type given particular attention. Some of the methods by which d-c can be produced are:

*Chemical.* By batteries.

*Thermal.* Heat applied to a thermocouple junction produces a small emf across the junction.

*Photoelectric.* Light energy striking certain materials produces a current from or in the material.

*Contact, or Friction.* Dissimilar materials rubbed together produce a static charge. (EXAMPLES: An automobile in motion. Walking across a thick wool rug. Stroking a cat with rubber.)

Alternating current has been mentioned from time to time. From this point on, a-c becomes more important. Some methods by which it can be produced are:

*Magnetic.* Mechanical motion of a wire through magnetic fields induces an alternating emf in the wire, as in generators or alternators.

*Magnetostrictive.* Mechanical vibration of ferromagnetic materials induces an alternating emf in a wire wrapped around the material.

*Piezoelectric.* Mechanical vibration of quartz or Rochelle salt produces an alternating emf between two plates on opposite sides of the crystal.

**4.2 A Basic Concept of Alternating Current.** A generator that develops an emf that alternately forces electrons through a circuit in one direction, stops them, and then forces them in the opposite direction is called an *alternator*. It produces alternating voltages, which in turn can produce alternating currents in a circuit.

When it comes to doing electrical work, such as rotating motors, lighting lamps, and so on, either d-c or a-c can be used. In some cases it may be easier to do it with one, in other cases with the other.

Perhaps the biggest advantage of a-c is the ease with which it can be stepped up or stepped down by a transformer, in itself a relatively simple piece of equipment. When electric power is transported over long distances there is much less power lost in heating the power lines themselves if the voltage is high, because with higher voltages less current is required to produce the same amount of power at the far end of the line. Power, or heat, loss in a line is computed by the power formula $P = I^2R$. Since power loss is proportional to the *current squared*, anything that will lessen the required current will greatly lessen the power lost in heat. Doubling the voltage in a system reduces the required current to one-half for the same power. Since power is proportional to the current squared, one-half squared equals one-quarter the power loss in the resistance of the wires. This is the reason why power companies transport electric energy over long distances at potentials of 110,000 volts or more.

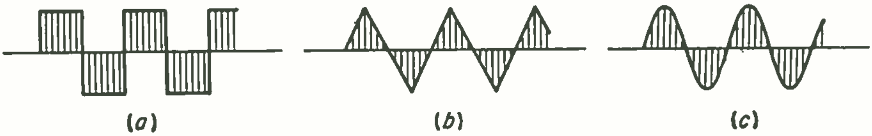


FIG. 4.1. Three possible a-c waveshapes. (*a*) Square wave. (*b*) Saw-tooth wave. (*c*) Sine wave.

Alternating current or voltage can be produced in many forms. Three different forms are illustrated in Fig. 4.1.

Figure 4.1*a* shows current flowing in one direction at a constant amplitude for a period of time, and then immediately reversing to the opposite *direction of flow* in the circuit for a period of time, and then again reversing to the first direction, and so on. This is known as a *square-wave* form of a-c.

Figure 4.1*b* shows the current starting to flow at a low value, rising to a peak value for an instant, then decreasing to zero, then starting to flow and increasing in the opposite direction. This is a *saw-tooth* form of a-c.

Figure 4.1*c* shows the current rising to a peak, as it did in the saw-tooth waveform, except that it approaches the peak more slowly. If the current increases as the *sine of the angle* (explained later), it is known as *sine-wave*, or *sinusoidal* (pronounced **sign-you-soy-dl**), a-c. Sine-wave a-c is considered to be the perfect waveform. It is the type normally used by power companies and generated by radio stations. Whenever a-c is mentioned it is considered to be sinusoidal unless specified to be otherwise.

**4.3 The A-C Cycle.** The electron flow in an a-c circuit is continually reversing. Each time it reverses it is said to be *alternating*. Two of these *alternations* result in a *cycle*. This is illustrated in Fig. 4.2, which shows two cycles of a-c.

The curved line represents the amount of current flow (or voltage) in a circuit. It indicates that the current begins to flow at the point of time marked 0°, increases until the 90° point is reached, and then decreases in strength to the 180° point. This completes one-half cycle, or one alternation. The current now reverses direction and increases in strength to the 270° point, and then decreases to zero current at the 360° point. It has completed one cycle, 360°, and the starting condition is again established. (A cycle may also be considered as starting at the 90° point and moving through to the next 90° point, since the starting condition is again reached. However, a cycle is normally considered to start at 0°.)

The horizontal line in Fig. 4.2 on which the degrees are marked is known as the *time line*, since it represents time progressing to the right.

A complete cycle is represented by 360°, a half cycle is represented by 180°, a quarter cycle by 90°. A point on the time line one-third of the way from 0 to 90° is represented as 30°. A point two-thirds of the time from the zero point to the maximum is said to be 60°. The maximum point is at either 90 or 270°.

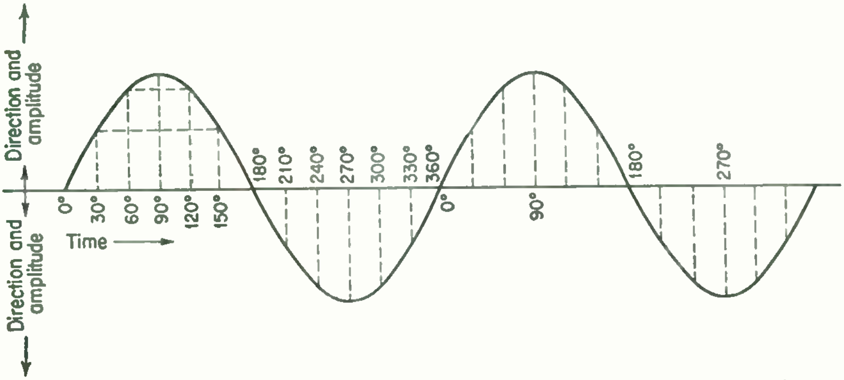


FIG. 4.2. Two cycles of sine-wave a-c, amplitudes shown every 30 electrical degrees.

A point 30° past 90° is 120°, and the amplitude of a current, or voltage, at 120° will equal the amplitude of the current, or voltage, at the 60° point. This can be seen in the illustration.

If the cycle is a true sine wave, the amplitude of the current at the 30° point will be exactly one-half of the maximum value. It will have the same value at the 150, 210, and 330° points. Mathematically, the *sine of 30°* is 0.5, or *one-half of the maximum* value, whatever the maximum happens to be. The sine values of angles in degrees or to tenths of a degree can be found in mathematics tables. At this time the sine of only four angles will be discussed, 0, 30, 60, and 90°.

The sine of 60° is 0.86. Therefore the amplitude of the cycle at 60° is *0.86 of the maximum* value. The amplitude of the current at the 120, 240, and 300° points will be the same as at 60°.

The sine of 0, 180, and 360° is zero. The sine of 90 and 270° is the maximum, or peak, value.

A circle may also be used to represent a complete cycle. In electrical work, the circle is considered as starting at the right-hand side and as rotating *counterclockwise*—up, over, down, and back to the start, as shown in Fig. 4.3.

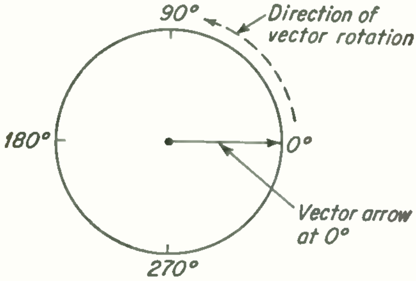


FIG. 4.3. Vector method of indicating an a-c cycle.

According to the circle, 90° is actually a quarter of a cycle from the start, 180° is half a cycle, and so on. This method of indicating the number of electrical degrees, or the *angle*, is quite graphic. A point 90° from the starting point of the circle is actually 90°, or a right angle from the starting point.

The arrow from the center of the circle to the zero point in the illustration above may be termed a *vector* arrow. A quarter cycle represents 90° rotation of the vector arrow. A half cycle represents 180° rotation of the vector arrow. The position of the vector arrow in relation to the zero direction indicates an angle from zero. This can be called an *angular vector* since it is indicating an angle.

An example of a vector arrow used as an *amplitude vector* is shown in the cycle of Fig. 4.4. In this case the length of the vector arrows varies as the amplitude of the current varies. These vectors do not indicate angles, but they do indicate the amplitude of the current, or voltage, at the "angle" in degrees along the time line at which they are drawn. Their direction indicates the relative direction of the current in the circuit.

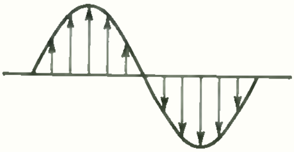


FIG. 4.4. Vectors indicating instantaneous amplitudes every 30° of one cycle.

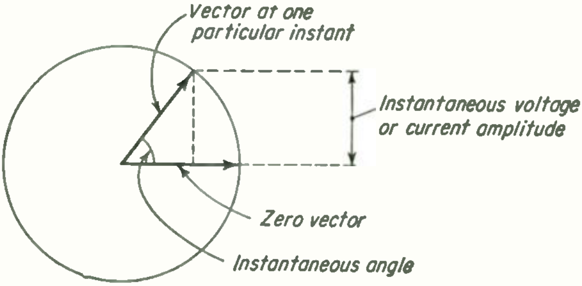


FIG. 4.5. Position of vector indicates instantaneous voltage or current amplitude at that particular instant.

They show that the current of the first half cycle is flowing in one direction in the circuit, and in the opposite direction during the second half cycle.

Vector arrows are handy implements to represent quantities, angles, or directions. The amplitude vectors are visually indicating the *instantaneous* values. If a vector arrow in a sine wave is drawn at the peak, the instantaneous value is the maximum value. If the vector is drawn at the 30° point on the time line, the instantaneous value is 0.5 of the maximum. The vector arrow at 60° will show an instantaneous value of 0.86 maximum. An instantaneous value indicates the value of a voltage, or current, at a particular instant.

Rotating vectors have been explained as indicating the angle of instantaneous values of current, or voltage, in a cycle. The distance between the point of the rotating vector arrow and the zero vector line indicates the instantaneous amplitude, as illustrated in Fig. 4.5.

**4.4 Peak and Effective A-C Values.** A 10-amp direct current and a 10-amp *peak* alternating current are both graphed to the same scale in Fig. 4.6. The d-c represents a constant 10-amp value. The a-c rises to a peak of 10 amp but is at this value for only an instant. Then it drops to zero, reverses, increases to 10 amp in the opposite direction, and then drops to zero again. Although it is equally effective in doing work on both half cycles, during most of the cycle the a-c has a value less than the constant 10-amp d-c and will be unable to produce as much heat or accomplish as much work as an equivalent peak d-c can.

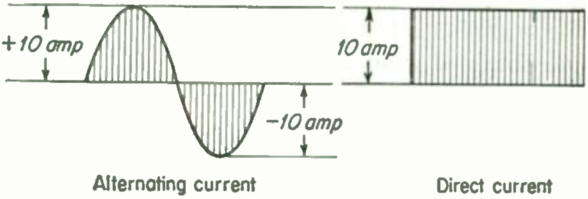


FIG. 4.6. Comparison of 10-amp peak a-c wave and 10-amp d-c.

Power being proportional to either $E^2$ or $I^2$ ($P = E^2/R$, or $= I^2R$), if all the instantaneous values of a complete cycle of sine-wave voltage, or current, are squared, and then the average, or mean, of all the squared values are found, the square root of this mean value will be 0.707 of the peak value. This *root-mean-square*, or rms, value represents how effective an a-c will be in comparison with its peak value. The *effective* value of the a-c cycle is equal to 0.707 of the peak. In the comparison of d-c and a-c, the 10-amp peak a-c will be only as effective at producing heat and work as 7.07 amp of d-c. It may be said that the effective value of an a-c is its *heating* value.

To determine the peak value of an a-c that is as effective as d-c, it is necessary to multiply whatever effective value is given by the reciprocal of 0.707 (1/0.707), which is 1.414. For an a-c to be as effective as 10 amp of d-c, it must be 10 × 1.414, or 14.14, amp at the peak.

Peak and effective values are not used with d-c, since they are the same quantities with a current that does not vary.

Peak and effective factors of 1.414 and 0.707 are applicable only when the current, or voltage, is a sine wave. With square-wave a-c the effective factor will be much higher than 0.707. With saw-tooth waveshapes the factor is less and usually approximates 0.5. The a-c produced by microphones responding to certain types of noises may have an effective value of only 0.3 or 0.2 of the peak value. However, the sine-wave factors are the most important to remember since a-c is usually considered to be sinusoidal.

In everyday work with a-c, it is the effective value that is used. When problems are given, it is always assumed that the effective value is to be employed, unless stated otherwise. When the power company states it is furnishing 120 volts a-c, it means an effective 120 volts, or 170 volts peak (120 × 1.414).

**4.5 The Average Value of A-C.** An a-c cycle has a peak and an effective value and also a less frequently used value called the *average*. It is the value obtained when 360 instantaneous values, each separated by one degree, are added and then the average of them all is found by dividing the sum by 360. This results in the average value, which is 0.636 of the peak value.

The average value tends to be confusing to the beginner. He confuses average with effective, probably because it seems that the average value should represent how much work the a-c cycle should do. As pointed out previously, however, it is the effective, or rms, value that does this.

To summarize:

A-c peak value = 1.414 times the effective value
A-c effective value = 0.707 times the peak value
A-c average value = 0.636 times the peak value

From these values it is possible to compute the multiplying factor to change from average to peak, 1.57; the factor to change from effective to average, 0.9; the factor to change from average to effective, 1.11.

At this point it might be well to advise the beginner to disregard the average value temporarily. Later, in the study of meters and power supplies, it is used and discussed.

**4.6 Frequency.** The number of times an alternating current goes through its complete cycle per second is known as its *frequency*.

The basic unit of measurement of frequency is *cycles per second*. It is customary to omit the "per second" in normal usage.

To simplify terminology, *kilocycle*, meaning 1,000 cycles (abbreviated *kc*), and *megacycle*, meaning one million cycles (abbreviated *Mc*), may be used. Thus, a frequency of 3,500,000 cycles can be expressed as 3,500 kilocycles (3,500 kc), or 3.5 megacycles (3.5 Mc).

Frequency is also used when speaking of various waveforms other than electric. Sound waves, which are disturbances of the air, use this term.

For example, when middle C is played on a musical instrument, an air disturbance with a frequency of 256 cycles per second is set up. The lowest tone that can be heard by humans is about 20 cycles. The highest audible, or *audio*, tones are usually between 15 and 20 kc. A device that can change sound waves to equivalent frequency a-c is the microphone.

Table 4.1

| *Terms used* | *Frequency range* |
|---|---|
| Power frequencies | 30 to 800 cycles |
| Audio frequencies (AF) | 20 to 20,000 cycles |
| Video frequencies | 15 to over 4,500,000 cycles |
| Supersonic or ultrasonic frequencies | 25 kc to over 1,000 kc |
| Very low radio frequencies (VLF) | 10 kc to 30 kc |
| Low radio frequencies (LF) | 30 kc to 300 kc |
| Medium radio frequencies (MF) | 300 kc to 3,000 kc |
| High radio frequencies (HF) | 3 Mc to 30 Mc |
| Very high radio frequencies (VHF) | 30 Mc to 300 Mc |
| Ultrahigh radio frequencies (UHF) | 300 Mc to 3,000 Mc |
| Superhigh radio frequencies (SHF) | 3,000 Mc to 30,000 Mc |
| Extremely high radio frequencies (EHF) | 30,000 Mc to 300,000 Mc |

The list of frequencies in Table 4.1 indicates the terminology that may be used for different a-c frequencies. Note the overlapping of the frequencies from 10,000 to 1 million cycles. The letters in parentheses are abbreviations commonly used.

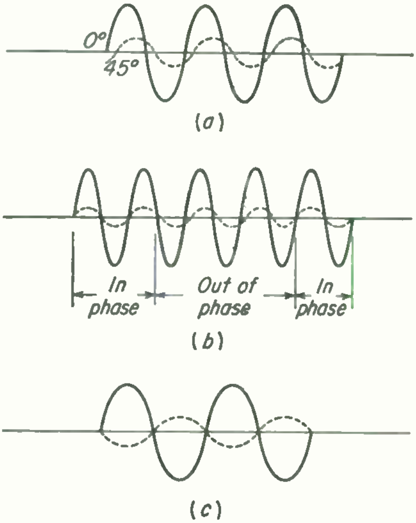


FIG. 4.7. Three examples of phase displacement between two waves. (*a*) Solid line leads dotted line by 45°. (*b*) Dotted line falls out of and back in phase. (*c*) Two waves 180° out of phase.

At power frequencies, materials such as fiber, cambric, cotton, some types of glass, black rubber, and impure bakelite are satisfactory insulators. At radio frequencies, mica, low-loss hard rubber, special porcelains, Isolantite, Mycalex, polystyrene, steatite, plastics, and special glasses have lower losses and are to be preferred.

**4.7 Phase.** There are three ways in which alternating currents, emfs, or waves can differ. These are (1) amplitude, (2) frequency, and (3) phase.

The *amplitude* is the relative height of the a-c wave.

The *frequency* is the number of cycles per second.

The *phase* is the number of electrical degrees one wave leads or lags another. Figure 4.7*a* illustrates two a-c waves graphed on the same time line. The solid-line wave starts upward before the dotted-line wave and is therefore "leading" the dotted line. They are out of phase, or out of step, by approximately 45°. If they were in phase they would go to maximums at the same instant and to zero at the same instant.

The two waves shown in Fig. 4.7*b* start out in phase, drop out of phase, and then return in phase again. To change phase this way, one or both of the waves must change frequency slightly. These waveforms may represent two voltages, two currents, or a voltage and a current. The two waves shown in Fig. 4.7*c* are 180° out of phase.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

1. What are the frequency ranges included in the following frequency subdivisions: MF (medium frequency), HF (high frequency), VHF (very high frequency), UHF (ultrahigh frequency), SHF (superhigh frequency), and EHF (extremely high frequency)? (4.6) **[3]**

2. What is the relationship between the effective value of an RF current and the heating value of the current? (4.4) **[3 & 6]**

3. What is the effective value of an a-c sine wave in relation to its peak value? (4.4) **[3 & 6]**

RF 1 isolantite
2 polystyrene
3 plastic
4 steatite

4. Name four materials which are good insulators at radio frequencies. Name four materials which are not good insulators at radio frequencies, but which are satisfactory for use at commercial power frequencies. (4.6) **[3 & 6]**

5. What is the meaning of phase difference? (4.7) **[3 & 6]**

Pwr 1 fiber
2 blk rubber
3 cotton
4 cambric

6. Indicate by a drawing a sine wave of voltage displaced 180° from a sine wave of current. (4.7) **[3 & 6]**

7. What is the ratio of peak to average values of a sine wave? (4.5) **[6]**

.707 — 1.414

## AMATEUR LICENSE INFORMATION

It is recommended that applicants for Novice Class licenses be able to answer questions prefaced by a star. Applicants for General, Conditional, and Technician Class Licenses should be able to answer all questions.

★1. What is the relationship between a cycle and a kilocycle? Between a cycle and a megacycle? (4.6)

★2. What is the recognized abbreviation for kilocycles? For megacycles? (4.6)

3. What is meant by power frequency, audio frequency, and radio frequency? (4.6)

4. In what three ways may a-c waves differ? (4.7)

5. How much greater is the peak value of a sine-wave a-c than the effective value read on an a-c meter? (4.4)

6. What is the unit of measurement of frequency? (4.6)

## CHAPTER 5

# INDUCTANCE AND TRANSFORMERS

**5.1 Inductance.** Coils of wire have been mentioned in the chapter on Magnetism, when the electromagnetic effect produced by current flowing through them was considered. An equally and probably more important aspect of the operation of a coil is its property to oppose any *change* in current through it. This property is called *inductance.* To explain it, the coil will first be straightened out and its functioning as a straight piece of wire will be discussed.

When a current of electrons starts to flow along any conductor, a magnetic field starts to expand from the center of the wire. These lines of force move outward, through the conducting material itself, and then continue into the air. As the lines of force sweep outward through the conductor, they induce an emf *in the conductor itself.* This induced voltage is always in a direction opposite to the direction of current flow. Because of its opposing direction it is called a *counter emf*, or a *back emf.* The direction of this self-induced counter emf can be verified by using the left-hand generator rule (Sec. 3.18).

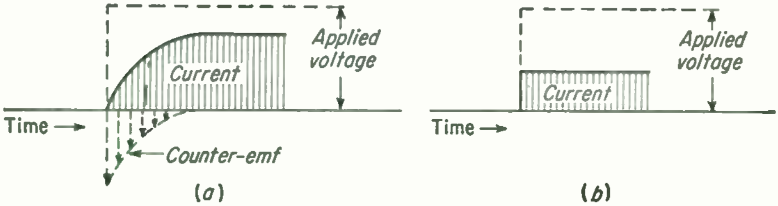


FIG. 5.1. Rise in current plotted against a time base (*a*) for an inductive circuit, (*b*) for a resistive circuit of negligible inductance.

The effect of this backward pressure built up in the conductor is to oppose the establishment of a maximum value of current. It must be understood that this is a temporary condition. When the current eventually reaches a steady value in the conductor, the lines of force will no longer be expanding or moving and there will no longer be any counter emf produced. At the instant when current begins to flow, the lines of force are expanding at the greatest rate and the greatest value of counter emf will be developed. At the starting instant the counter emf has a value just short of the applied, or source, voltage (Fig. 5.1*a*).

The current value is small at the start of current flow. However, as the lines of force move outward, the number of lines of force cutting the conductor per second becomes progressively smaller and the counter emf becomes progressively less. After a period of time the lines of force expand to their greatest extent, the counter emf ceases to be generated, and the only emf in the circuit is that of the source. Maximum current can now flow in the wire or circuit, since the inductance is no longer reacting against the source voltage.

If it were possible to produce a current by applying a voltage across a wire and *not* produce a counter emf, then Fig. 5.1*b* would represent the action of the current. It shows a current reaching the maximum value instantly—just as soon as the voltage is applied.

**5.2 Self-induction.** When the switch in a current-carrying circuit is suddenly opened, an action of considerable importance to some phases of radio and electricity takes place. At the instant the switch breaks the circuit, the current due to the applied voltage would be expected to cease abruptly. With no current to support it, the magnetic field surrounding the wire should collapse back into the conductor at a tremendously high rate, inducing a high-amplitude emf in the conductor. Originally, when the field built outward, a counter emf was generated. Now, with the field collapsing inward, a voltage in the opposite direction is produced. This might be termed a *counter counter emf*, but is usually known as a *self-induced emf*. This self-induced emf is in the direction of the applied source voltage. Therefore, as the applied voltage is disconnected, the voltage due to self-induction establishes current flow through the circuit in the same direction and aiding the source voltage. With the switch open it would be assumed that there is no path for the current, but the induced emf immediately becomes great enough to ionize the air at the opened switch contacts and a spark, or arc of current, appears between them. The arc lasts as long as energy stored in the magnetic field exists. This energy is dissipated as heat in the arc.

With circuits involving low current and short wires, the energy stored in the magnetic field will not be great and the spark may be insignificant. With long lines and heavy currents, the inductive arc, when the circuit is interrupted, becomes of considerable consequence. Inductive arcs several inches long may form between opened switch contacts. The heat developed by arcs of such magnitude tends to melt the switch contacts and is a source of difficulty in high-voltage, high-current circuits.

Note that regardless of any change of current amplitude or direction in a conductor, the induced emfs oppose the current change. With a steady, unvarying direct current, there is no change of current and no opposition developed. When a varying d-c is flowing, as the source voltage increases, the counter emf opposes the increase. As the source voltage decreases, the self-induced emf opposes the decrease. An alternating current is in a constant state of change and a continual opposing or reacting action results. From this behavior comes the definition: *Inductance is the property of any circuit which opposes any change in current.* Another definition: *Inductance is the property of a circuit by which energy is stored in the form of an electromagnetic field.*

The unit of measurement of inductance is the *henry*, defined as the amount of inductance required to produce an average counter emf of one volt when an average current *change* of one ampere per second is under way in the circuit. Inductance is represented by the symbol *L* in electrical problems, and henrys by h.

**5.3 Coiling an Inductor.** In the explanations so far, it has been indicated that a piece of wire has the ability of producing a counter emf and therefore has a value of inductance. Actually, a small length of wire will have an almost insignificant value of inductance by general electrical standards. One henry represents a relatively large inductance in most radio applications, where millihenrys and microhenrys are more likely to be used. A straight piece of wire would have to be thousands of yards long before it would have one henry of inductance. On the other hand, if a few hundred feet of wire are wound onto an iron or other high-permeability core, intense magnetic fields are produced and the inductance value of the circuit may be several henrys.

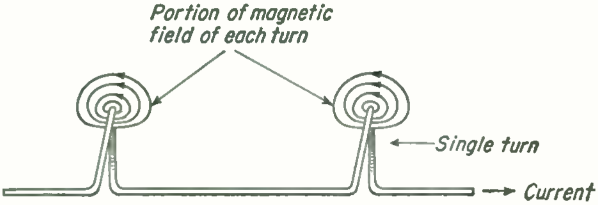


FIG. 5.2. Fields surrounding two separated turns.

Even without the iron core, a given length of wire will have much greater inductance if wound into coil form. Consider Fig. 5.2, showing two loops of wire separated by enough distance so that there is essentially no interaction between their two magnetic fields. Neglecting the inductance of the connecting wires, it may be said that these two loops, or *turns*, have twice the inductance of a single turn.

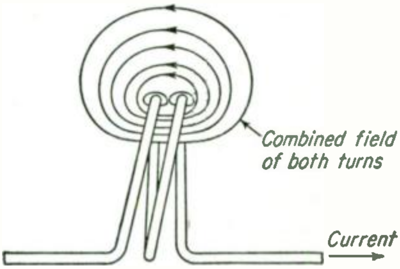


FIG. 5.3. Field surrounding two close-wound turns.

When the two loops are wound next to each other, as shown in Fig. 5.3, with the same current flowing, there are now twice the number of magnetic lines of force cutting each turn. With two turns, *four* times the counter emf is developed. With three turns, three times the number of lines of force cut three turns (3 times 3), so *nine* times the counter emf is developed. The inductance of a coil varies as the number of turns *squared*, or as $N^2$, where $N$ stands for the number of turns. However, it can be seen that length of the coil is also going to enter into the exact computation of the inductance of a coil. If the turns are stretched out, the field intensity will be less and the inductance will be less. Furthermore, the larger the radius or diameter of the coil, the longer the wire used and the greater the inductance. In many radio applications, single-layer air-core coils with a length approximately equal to the diameter are used. A formula that will give the approximate inductance of such a coil in *microhenrys* (abbreviated $\mu$h) is

L microhenries

$$L = \frac{r^2N^2}{9r + 10l}$$

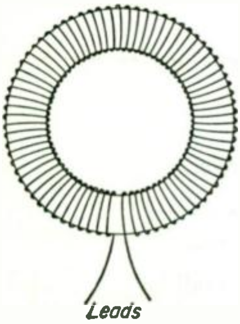


FIG. 5.4. Coil wound in toroid form.

where $L$ is inductance in microhenrys; $r$ is radius in inches; $N$ is number of turns; and $l$ is length of coil in inches.

For more accurate and detailed formulas to compute inductance of various shapes of coils with various permeability cores, refer to radio or electrical engineering handbooks.

The inductance of straight wires alone is encountered in antennas, in power lines, and in ultrahigh-frequency equipment. In most electronic and radio applications where inductance is required, space is limited, and wire is wound into either single-layer or multilayer coils, using air, powdered-iron compound, or laminated (many thin sheets) iron cores. The advantage of multilayer coil construction when high values of inductance are required becomes obvious when it is considered that while two closely wound turns produce four times the inductance of one, the addition of two more turns closely wound on top of the first two will provide almost 16 times the inductance.

In many radio applications air-core coils are constructed with iron-compound cylinders that can be slid into or out of the core space of the coil. This results in a controlled variation of inductance, maximum when the iron core is in the coil and minimum with it out.

A special type of coil used in many communications circuits is the *toroid*. It consists of a doughnut-shaped powdered-iron-compound core, either single-layer- or multilayer-wound, as shown in Fig. 5.4. Its advantages are high values of inductance with little wire, and therefore little resistance in the coil, and the fact that *all* the lines of force are in the core and none outside (provided there is no break in the core). As a result it requires no shielding to prevent its field from interfering with outside circuits and to protect it from effects of fields from outside sources. Two toroids can be mounted so close that they nearly touch and there will be almost no interaction between them.

**5.4 The Time Constant of an Inductance.** The time required for the current to rise to its maximum value in an inductive circuit after the voltage has been applied will depend on both the inductance and the resistance in the circuit. With a constant value of resistance in a circuit, the greater the inductance, the greater the counter emf produced and the longer the time required for the current to rise to maximum.

With a constant value of inductance in a circuit, the more resistance, the less current that can flow. The less current, the less possible counter emf to oppose the source emf and the less time required to reach a maximum current value.

It has been found that the time required for the current to rise to 63 per cent of the maximum value can be determined by

Time Constant

$$T = \frac{L}{R}$$

where $T$ is time in seconds; $L$ is inductance in henrys; and $R$ is resistance in ohms.

According to this formula, a 10-henry coil with 10 ohms resistance will allow current to rise to 63 per cent of maximum in one second. In the next second, the current will rise 63 per cent of the remaining amount toward maximum, and so on. (If a coil could be produced with zero ohms resistance, the current would *never* arrive at the maximum value.) A time equivalent to about five times the value computed by the time-constant formula results in a current within 1 per cent of the maximum that will ever be attained. A circuit with zero inductance and only resistance will reach the maximum current value instantly.

The time-constant formula also indicates the time required for current to decrease 63 per cent from maximum, or to drop to 37 per cent of the maximum value.

**5.5 The Energy in a Magnetic Field.** Current flowing in a wire or coil produces a magnetic field around itself. If the current suddenly stops, the magnetic field held out in space by the current will collapse back into the wire or coil. Unless the moving field has induced a voltage and current into some external load circuit, all the energy taken to build up the magnetic field will be returned to the circuit as electric energy as the field collapses.

The amount of energy in joules that is being stored in a magnetic field at any instant can be determined by the formula

$$E_n = \frac{LI^2}{2}$$

Joules

$E_n = \frac{1}{2} LI^2$

↑ FCC

where $E_n$ is energy in joules; $L$ is inductance in henrys; and $I$ is current in amperes.

**5.6 Choke Coils.** The ability of a coil to oppose any change of current is used to smooth out varying or pulsating types of current. In this application the inductor is known as a *choke coil*, since it chokes out variations of amplitude. For radio-frequency a-c or varying d-c an air-core coil is used, but for lower-frequency circuits greater inductance is required. As a result, iron-core choke coils are to be found in audio-frequency and power-frequency applications.

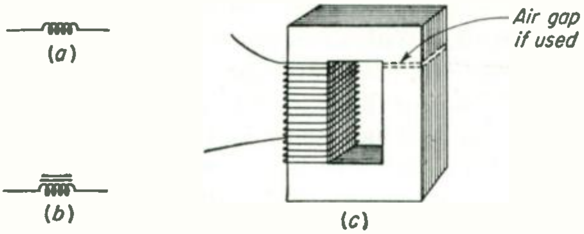


FIG. 5.5. (a) Symbol for air-core coil. (b) Symbol for iron-core coil. (c) An iron-core choke coil.

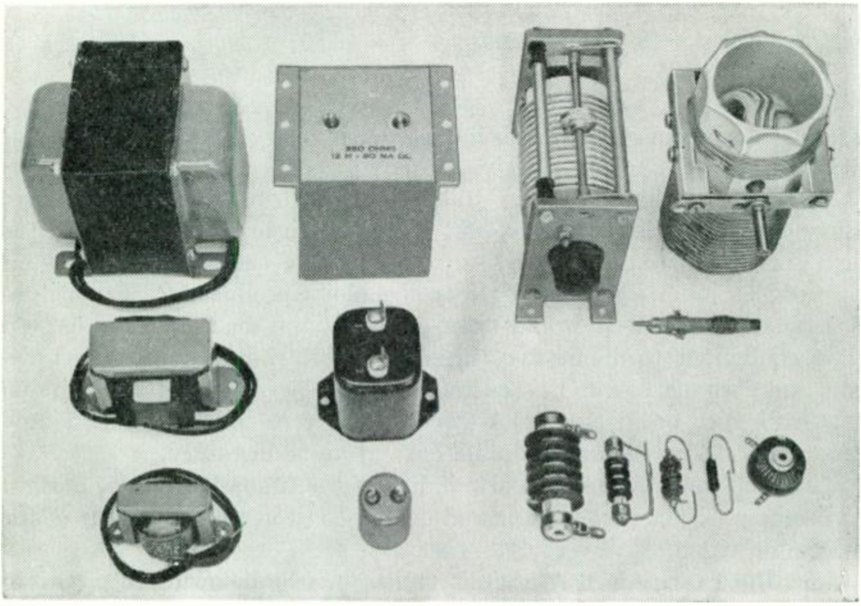


FIG. 5.6. Inductances. Left rows, iron-cored power supply and audio chokes. Upper right, variable inductances employing a movable connector, a rotating coil inside an outer coil (variometer), and a screwdriver-adjustable powdered-iron core. Lower right, air-cored RFC coils.

A choke coil will hold a nearly constant inductance value until the core material becomes saturated. When enough current is flowing through the coil to magnetically saturate the core, then variations of current above this value can produce no appreciable counter emfs and the coil no longer acts as a high value of inductance to these variations. To prevent the core from becoming magnetically saturated, a small air gap may be left in the iron core. The air gap introduces so much reluctance in the magnetic circuit that it becomes difficult to make the core carry the number of lines of force necessary to produce saturation. The gap also decreases the inductance of the coil.

Figure 5.5 shows the symbol for an air-core coil or choke, an iron-core coil or choke, and a simplified picturization of an iron-core choke.

**5.7 Mutual Inductance.** A single coil has a value of inductance, or self-inductance. As explained previously, a coil has one henry of inductance if an average current change of one ampere in one second produces an average counter emf of one volt in it.

If one coil is placed near a second, it will be found that alternating or varying currents in the first produce moving magnetic fields that will induce voltages in the second coil. The farther apart the two coils are, the fewer the number of lines of force that interlink the two coils and the lower the voltage induced in the second coil (100 million lines per second cutting one turn induce one volt).

When an average current change of one ampere per second in the first coil can produce moving fields that will induce an average of one volt in the second, the two coils are said to have a *mutual inductance* of one henry, regardless of the inductance values of the two coils themselves.

The mutual inductance can be increased by moving the two coils closer together or by increasing the number of turns of either coil.

In power *transformers* the two coils are so arranged that almost all the lines of force of the first coil cross the turns of the second coil and a high mutual inductance results.

When *all the lines of force from one coil* cut *all* the turns of a second coil, *unity coupling* exists, and the mutual inductance may be found by the formula

$$M = \sqrt{L_1 L_2}$$

unity Coeff of Coupling only

where $M$ is mutual inductance in henrys; $L_1$ is the inductance of one coil in henrys; and $L_2$ is the inductance of the second coil in henrys.

This formula assumes 100 per cent coupling between the two coils. If all the lines from the first coil do not cut all the turns of the second coil, the mutual inductance is determined by the formula

$$M = k\sqrt{L_1 L_2}$$

where $k$ is the coefficient or coupling.

*Example:* If a 2-henry coil has 84 per cent of its lines of force cutting a 4.5-henry coil, what mutual inductance exists? Substituting in the formula given above,

$$M = k\sqrt{L_1 L_2} = 84\%\sqrt{2(4.5)} = 0.84\sqrt{9} = 0.84(3) = 2.52 \text{ henrys}$$

**5.8 Coefficient of Coupling.** The degree, or closeness, of coupling can be expressed as a percentage. While the term *percentage of coupling* can be used, another term, *coefficient of coupling*, is to be preferred. One hundred per cent is equivalent to a coefficient of 1.0, or unity; 95 per cent is equivalent to a coefficient of coupling of 0.95; and so on.

The coefficient of coupling between two coils can be computed from the rearrangement of the mutual inductance formula

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

The answer obtained in this formula will always be a decimal, unless the coefficient were unity. By multiplying a coefficient by 100, the answer will be in percentage.

*Example:* The mutual inductance between two coils is 0.1 henry, and the coils have inductances of 0.2 and 0.8 henry, respectively. What is the coefficient of coupling?

Substituting in the formula,

$$k = \frac{M}{\sqrt{L_1 L_2}} = \frac{0.1}{\sqrt{0.2(0.8)}} = \frac{0.1}{\sqrt{0.16}} = \frac{0.1}{0.4} = 0.25, \text{ or } 25\%$$

Coils with relatively high coefficients of coupling may be said to be *tightly* coupled. With low values of coupling they are said to be *loosely* coupled. What is tight and what is loose vary in different applications. In power transformers the coefficient may exceed 0.98, while in some radio circuits coefficients as low as 0.01 are readily usable.

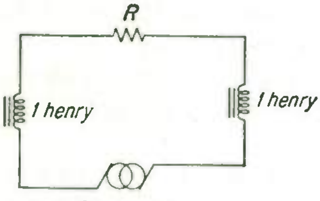


FIG. 5.7. Two uncoupled inductances in a series circuit.

**5.9 Inductances in Series.** Electric circuits often have two or more inductances in them. Whether the magnetic fields of the two coils interlink or not determines the effective amount of inductance presented to the circuit by the coils.

Figure 5.7 shows two 1-henry coils and a resistor in series across an a-c source. Since the two coils are apparently widely separated, no interlinkage of fields occurs and the total inductance in the circuit is simply 2 henrys (neglecting any slight inductance in the connecting wires). The formula for uncoupled inductances connected in series is

$$L_t = L_1 + L_2 + L_3 + \cdots$$

where $L_t$ is the total inductance in henrys; and $L_1$, $L_2$, etc., are other inductances in henrys.

(Note the similarity of this series-inductance formula to that of series resistors.)

Figure 5.8 shows two 1-henry coils and a resistor in series across an a-c generator, but the two coils are close enough so that the lines of force from one interlink the other coil. Now, the mutual inductance will affect the total inductance value. If the coils are wound in the same direction, the emf induced from one to the other will be *in phase*, or additive, and the total inductance value will be more than the simple addition of the two inductance values alone. The effective inductance of two in-phase series-connected inductances is determined by using the formula

$$L_t = L_1 + L_2 + 2M$$

where $M$ is mutual inductance in henrys; and other symbols as given above.

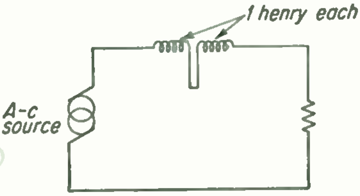


FIG. 5.8. Two series inductances placed to intercouple their fields.

If the two coils were unity-coupled and each had 1 henry of self-inductance, the total inductance value would be 4 henrys.

If two coils are wound in *opposite* directions and coupled, the induced emf in the coils will be in opposition, or *out of phase*, and will tend to cancel each other, resulting in less effective inductance. The formula in this case is

$$L_t = L_1 + L_2 - 2M$$

If the two coils were unity-coupled and each had 1 henry of self-inductance, the total inductance value would be zero henrys. The two coils would have completely canceled each other's inductance.

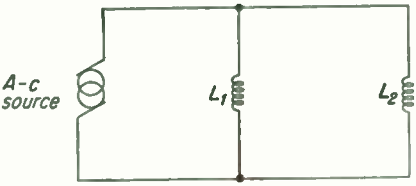


FIG. 5.9. Two parallel inductances.

**5.10 Inductances in Parallel.** In some cases in radio and electronics two or more inductors, or inductances, are connected in parallel, as shown in Fig. 5.9.

If the two inductances have 1 henry each, the resultant inductance (assuming no interaction of their fields) will be ½ henry. This inductance is computed using a formula similar to the parallel-resistance formula:

$$L_t = \frac{L_1L_2}{L_1 + L_2}$$

If three or more inductances are in parallel, a formula similar to the parallel-resistance formula may be used:

$$L_t = \frac{1}{1/L_1 + 1/L_2 + 1/L_3}$$

Since coils are rarely connected in parallel *and* intercoupled, the necessarily more complicated formulas required will not be presented.

**5.11 Shorting a Turn in a Coil.** There are several methods of reducing the inductance of a coil, for example, taking turns off of the coil, stretching the coil out until it has a greater length, and using a less permeable core. Another method is to short out one of the turns of the coil, as shown in Fig. 5.10.

FIG. 5.10. Coil with a shorted turn.

If one turn of a coil is shorted, there is one less turn in the coil and the coil has a little less inductance. If d-c is flowing through the coil, there will be relatively little change in the magnetic field around the coil. However, when a-c flows through the coil, the expanding and contracting fields from adjacent turns cut the shorted turn and induce an emf in it. This emf induces a relatively high-amplitude current in the shorted turn.

The emf induced in the shorted turn is a counter emf. It produces a current in the shorted turn in an opposite direction to that flowing in the remainder of the coil. This results in a counteracting field, partially canceling the field of the coil. The inductance of the coil is materially reduced, much more than would result from cutting off the turn.

In some radio applications where a variation of inductance is desired, a shorted turn in the form of a loop of wire or a brass disk may be brought near a coil, effectively reducing the inductance of the coil. The closer the loop is to the coil, the more it counteracts the inductance of the coil. A shorted turn will usually become warm, or hot, depending on how much current is induced in it.

**5.12 Inductive Reactance.** It has been explained previously that d-c flowing through an inductance produces no counter emf to oppose the current. With varying d-c, as the current tries to increase, the counter emf opposes the increase. As the current tries to decrease, the counter counter emf opposes the decrease. Alternating current is in a constant state of change, and the effect of the magnetic fields results in a continual induced voltage opposition to the current. This reacting ability of the inductance against the changing current is called *inductive reactance.*

Inductance is the property of a circuit to oppose any change in current and is measured in henrys. Inductive reactance is a measure of how much counter-emf opposition the circuit will produce under different conditions and is measured in *ohms.*

It may be considered that the inductance of a coil does not change. Whether it is used in a d-c circuit, or in a 60-cycle circuit, or in a 10,000-cycle circuit or whether it lies unused on a shelf, a 1-henry inductance has a value of 1 henry. Its *property* has not changed. When d-c is flowing through a 1-henry coil, it will not oppose the current flow in any way, unless there is ohmic resistance in the coil. In a low-frequency 60-cycle circuit, the magnetic field builds up and collapses relatively slowly and relatively little counter emf may be developed to oppose the current in the circuit. In a higher frequency circuit, the magnetic field moves more rapidly, produces more counter emf, and opposes the current more. The amount of opposition, or reactance, varies directly as the frequency of the current variation.

A 1-henry coil will produce a certain value of opposition to a 60-cycle a-c. A 2-henry coil has twice the counter-emf-producing capability and opposes the current change twice as much. Therefore reactance is also directly proportional to the inductance value.

When the inductance in henrys is multiplied by the frequency in cycles and this is multiplied by $2\pi$ (Greek letter pi), an inductive reactance value results that is similar to a resistance value in ohms. The inductive-reactance formula is

$$X_L = 2\pi FL$$

where $X_L$ is inductive reactance in ohms; $\pi$ is 3.14; $F$ is frequency in cycles per second; and $L$ is inductance in henrys.

The Greek letter $\omega$ (omega) is often used to indicate $2\pi F$. (This is known as the angular velocity of the cycle and indicates how fast the current is changing.) Thus, $X_L = \omega L$.

As an example of how much inductive reactance is presented by a circuit composed of a source of a-c and an inductance, consider the circuit shown in Fig. 5.11, where the source has a frequency of 3,000 cycles and the inductance is 2 henrys. Substituting in the inductive-reactance formula,

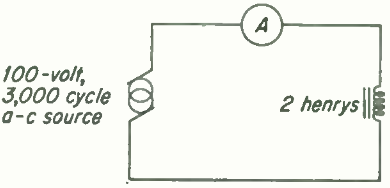


FIG. 5.11. Current determined by the value of inductive reactance in the circuit.

$$X_L = 2\pi FL = 2(3.14)3{,}000(2) = 6.28(6{,}000) = 37{,}680 \text{ ohms}$$

The 2-henry coil presents 37,680 ohms of opposition to a 3,000-cycle a-c and will limit the amplitude of the current in the circuit exactly as much as if a 37,680-ohm resistance were used instead. For this reason, reactance can be substituted for resistance in Ohm's-law formulas, but only if the circuits are purely reactive. Ohm's law for reactive circuits states, "The current in a reactive circuit is directly proportional to the voltage and inversely proportional to the reactance." In formula form,

$$I = \frac{E}{X} \qquad E = IX \qquad X = \frac{E}{I}$$

where $I$ is current in amperes; $E$ is emf in volts; and $X$ is reactance in ohms. (The general reactance symbol $X$ is used in these formulas, rather than $X_L$, because there is another reactance, known as *capacitive reactance*, with the symbol $X_C$, explained in the next chapter. These

Ohm's-law formulas apply equally well to either $X_L$ or $X_C$. When it is desired to specify inductive reactance only, the symbol $X_L$ should be used.)

If the a-c generator in Fig. 5.11 produces an effective emf of 100 volts, the current may be determined by Ohm's law:

$$I = \frac{E}{X} = \frac{100}{37{,}680} = 0.00265 \text{ amp, or } 2.65 \text{ ma}$$

In general practice, Ohm's law for reactive circuits may be used only when the reactance value is at least 10 times more than the resistance. If there is an appreciable proportion of resistance in the circuit, *Ohm's law for a-c circuits* (Sec. 7.2) must be used.

The inductive-reactance formula $X_L = 2\pi FL$ indicates that reactance is directly proportional to inductance. Therefore if two equal inductances are connected in series (with zero mutual inductance), the reactance presented by the two is twice as much as that of one alone.

### Practice Problems

**1.** What is the inductance of a coil in microhenrys having a diameter of 1.5 inche a length of 2 inches, and 50 turns? What is the inductance in millihenrys?

**2.** A 5-henry coil is in series with a 100-ohm resistance, a switch, and a battery. How long will it take for the current to reach 63 per cent of the full value after the switch is closed? How long will it take to reach approximately full current?

**3.** How much energy in wattseconds is contained in the field of a 7-henry choke coil when 500 ma is flowing through it?

**4.** What is the mutual inductance of two unity-coupled coils of 4 and 9 henrys?

**5.** What is the mutual inductance of a 4-henry and a 5-henry coil when they have a coefficient of coupling of 0.85?

**6.** What is the total inductance of a 3-henry and a 4-henry coil connected in series and 40 per cent coupled with fields aiding?

**7.** What is the total inductance of a 5-henry and an 8-henry coil connected in series if the coefficient of coupling is 0.75 and the fields are opposing?

**8.** What is the reactance of a 10-henry choke coil to 120 cycles?

**9.** What is the reactance of a 5-mh choke coil to 1,000 kc?

**10.** What is the reactance of a 600-$\mu$h coil to 4 Mc?

**11.** What inductance is required to present 500 ohms of reactance to a 10-kc a-c?

**12.** At what frequency does a 0.04-henry coil have a reactance of 3,000 ohms?

**13.** How much current flows through a 2-henry choke coil when it is connected across a 120-volt 60-cycle power line?

**14.** An RF choke coil develops a 200-volt drop across it when a 5-ma 2-Mc a-c flows through it. What reactance does it present to this frequency?

**15.** How much voltage drop will occur across an audio choke coil having 5 henrys when 150 ma of 40-cycle a-c flows through it?

**5.13 Phase Relationships with Inductance.** When a coil is connected across an a-c generator, as shown in Fig. 5.12, the current in the coil will not rise to a peak at the instant that the voltage attains a peak value. According to theory, the current in the coil will lag the source voltage by 90°, provided there is no resistance in the circuit.

When an inductive circuit having negligible resistance is first turned on, the current and voltage start out in phase as a varying d-c. The starting operation is quite complex and will not be dealt with here. However, after a few voltage cycles the circuit current begins to alternate, and then settles down into what is known as a *steady-state* a-c and continues to operate in this manner until something in the circuit is changed. All explanations here will be for steady-state conditions.

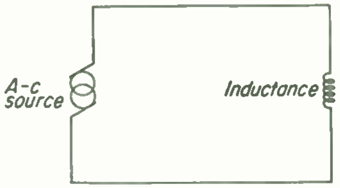


FIG. 5.12. Purely inductive circuit.

Figure 5.13 represents one cycle of steady-state a-c flowing through a circuit made up of an inductance with no resistance in it. The particular *current* cycle under consideration is from a maximum positive current value to a maximum negative value and back to a maximum positive value again.

As the current increases through an inductor, the magnetic field increases, exactly in step. At the instant the current reaches its maximum positive value, its *rate of change* is zero. This means maximum field strength but zero magnetic-field *movement*, and therefore zero induced or counter emf due to moving magnetic fields. The induced emf is indicated by the dotted curve. Thus, maximum current and zero induced emf occur at the same instant.

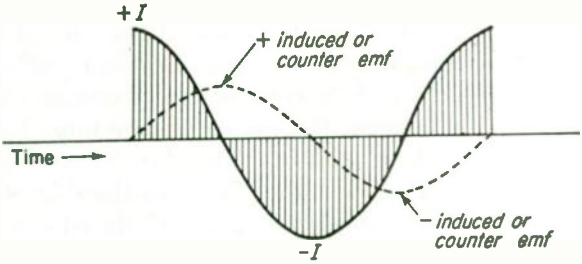


FIG. 5.13. Phase relationships of the current in a coil and the induced counter emf.

As the current diminishes toward zero, the magnetic field collapses inward toward the center of the coil. As the current nears the zero point its *rate of change* is very rapid, producing maximum induced positive voltage at the zero-current instant.

The current then starts to increase in the negative direction, producing an opposite-polarity magnetic field expanding as the current increases. This *reversed-polarity expanding field* produces a voltage of the same polarity as the *original contracting field* did. This is a significant point. Reversing the field polarity and also reversing the *contracting motion* to an *expanding motion* is a double reversal. A double reversal produces the same, or original-direction, induced emf. (This is similar to a person walking north. If he reverses direction twice, he is still going north.) Therefore, as the current reverses, the induced emf is still in the same direction (positive) and continues to be developed as long as the current is changing. As the current approaches the maximum value in the negative direction, its rate of change decreases to zero at the maximum current point. At this instant there is zero induced voltage in the coil again.

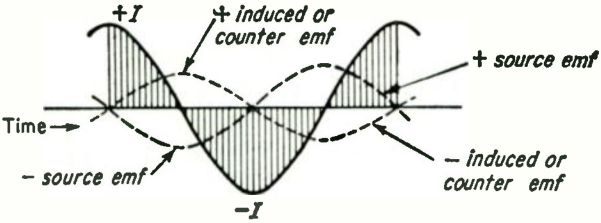


Fig. 5.14. Phase relationships between current in a coil, induced or counter emf, and source emf.

As the current begins to drop from maximum negative toward zero, its rate of change begins to increase, developing an induced emf again, but this time in the negative direction. As the current reaches the zero value, the induced voltage again is at a maximum, but at a maximum negative value.

As the current swings up from zero to maximum in the positive direction, the induced voltage drops from maximum negative to zero once more. This completes one full cycle of current and induced voltage.

By reference to the figures it can be seen that the current and induced voltage in the coil are constantly a quarter of a cycle, or 90° out of phase.

Since the induced voltage is a counter emf (counter to the source voltage) the source voltage must be 180° out of phase with it. The three curves shown in Fig. 5.14 show the phase relationship of the source, or applied, voltage, the induced voltage, and the current in a purely inductive circuit. The current is 90° lagging behind the source voltage. In an inductance, then, the current always lags the applied voltage by 90°.

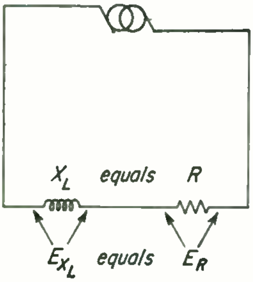


Fig. 5.15. When $X_L$ and $R$ are equal, the voltage drop across the reactance will equal the voltage drop across the resistor.

**5.14 Phase with Both Inductance and Resistance.** When inductance and resistance are in series in a circuit, the number of degrees the source voltage and the circuit current will be out of phase depends upon the relative resistance and reactance values. A circuit is shown in Fig. 5.15, with the resistance and the reactance values equal.

The current in all parts of this circuit is in exactly the same phase, since it is a series circuit.

When the current through the resistance is at a maximum value, the voltage drop across it is at a maximum, since the voltage and current across and through a pure resistance are always exactly in phase.

The current in the coil *leads* the induced or counter emf by 90°. The applied *voltage* across the coil is 180° out of phase with the induced emf, and therefore leads the current by 90°.

The source sees only one current in the circuit, but sees the result of two voltage drops, one across the resistor and in phase with the current, the other across the coil and leading the current by 90°. Since the resistance and reactance are equal, the source sees two voltage drops of equal magnitude but 90° out of phase. As a result the source sees a resultant voltage drop equal to itself but 45° out of phase and leading the circuit current (Fig. 5.16).

If there is more resistance than reactance, the phase will be closer to zero degrees. If there is more reactance, the phase will be closer to 90°. This is discussed in Sec. 7.3.

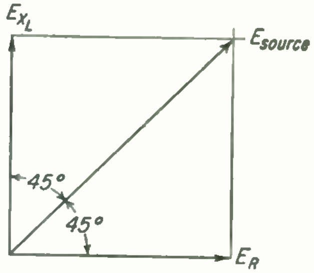


FIG. 5.16. Vector representation of the source voltage, voltage across the reactance, and voltage across the resistor.

**5.15 Transformers.** One of the most common components, or parts, used in electricity, electronics, and radio is the transformer. The word itself indicates that it is used to transform, or change, something. In practice a transformer may be used to step up or step down a-c voltages, or to produce a high alternating current of low voltage from a low-current high-voltage source, or to change the impedance of a circuit to some other impedance, the better to transfer energy from one circuit to another.

In its simplest form, a transformer consists of a *primary* wire and a *secondary* wire laid side by side, as shown in Fig. 5.17. The only parts of the primary and secondary circuits to be considered at this time are the portions lying parallel to each other. When the source is producing an alternating voltage, an alternating current will be developed in the primary wire, as indicated by the arrows, producing expanding and contracting magnetic fields around the primary wire. These fields induce a counter emf in the primary, which attempts to counteract the source voltage, and therefore act to limit the primary current value. (In practical transformers the primary coil has a sufficient number of turns and therefore enough inductance and inductive reactance to produce a counter emf almost equal to the source voltage. The simplified transformer would not produce sufficient counter emf at low frequencies to be practical.)

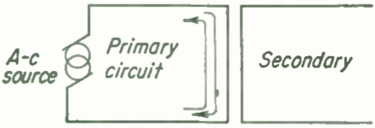


FIG. 5.17. Basic transformer, with a-c flowing in the primary.

In addition to the counter emf induced into the primary circuit by self-induction, the expanding and contracting fields from the primary cross the secondary wire and induce an a-c emf in this wire. According to the left-hand generator rule (Sec. 3.18), if the current flow in the primary is downward, the induced emf in the secondary will be upward, 180° out of step, or *out of phase* with the primary emf, as shown in Fig. 5.18.

There is no load shown across the secondary circuit. If the secondary has no load, no current flows in it, although a voltage is developed across it. If the secondary has a voltage induced in it but no current, there is no power developed in the secondary and the current in the primary will be the same as though there were no secondary.

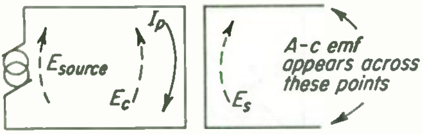


FIG. 5.18. Basic transformer, with no load across secondary.

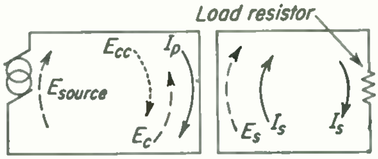


FIG. 5.19. Currents and voltages in a transformer when a resistor is connected across the secondary.

When a load resistor is connected across the secondary of a transformer, as shown in Fig. 5.19, several things occur. Step by step these are:

1. The source emf, $E_{source}$, produces primary current, $I_p$.
2. Primary current produces counter emf, $E_c$, in the primary.
3. Primary current also produces an induced secondary emf, $E_s$.
4. $E_s$ produces current $I_s$, through secondary and load.
5. $I_s$ produces a magnetic field expanding outward from the secondary.
6. Expanding fields from the secondary induce a "counter counter emf," $E_{cc}$, in the primary (opposite to the original counter emf in the primary and in the same direction as the source voltage).
7. $E_{cc}$ partially cancels counter emf of primary.
8. Cancellation of primary counter emf allows the source emf to send more current through the primary.

Therefore, when a load is connected across the secondary, the primary current increases. This results in more electric power fed to the primary to be converted to magnetic energy, which is transferred in turn to the secondary and reconverted to electric energy in the load in the secondary.

**5.16 Construction of Transformers.** Transformers used in radio and electricity are constructed with a primary coil and one or more secondary coils. The second secondary may be termed the *tertiary* (pronounced tur-she-airy, meaning "third") winding, and the third secondary may be termed the *quaternary* (meaning "fourth") winding. It is more usual to designate the windings by their function, however. Thus, a radio power transformer may be said to have a *primary*, a *high-voltage secondary*, a *5-volt filament winding*, and a *6.3-volt filament winding*.

Figure 5.20 illustrates two of many possible methods of constructing a power-frequency transformer and the symbol for an iron-core transformer. The secondary coil wound over the primary coil is probably the more frequently used method.

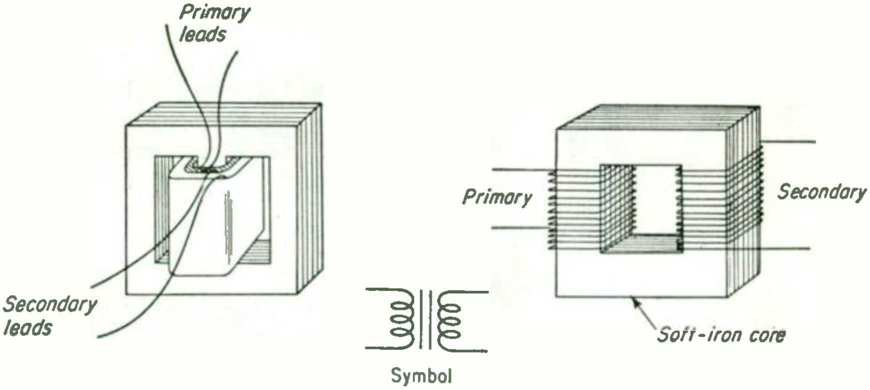


Fig. 5.20. Iron-core transformers and symbol.

In power transformers, there are several hundred turns in the primary and an equivalent number of turns on the secondary if it is desired to produce a secondary voltage equal to the voltage applied across the primary. If a greater secondary voltage is desired, more turns will be wound on the secondary than on the primary.

Transformers for higher frequencies use less iron in their cores. If the frequency is in the RF range, either air cores or small powdered-iron-compound cores are used. Figure 5.21 illustrates a possible RF transformer and its symbol used in schematic diagrams. The core is some type of nonconducting material having the same permeability as air. Such a transformer is classed as an *air-core* transformer.

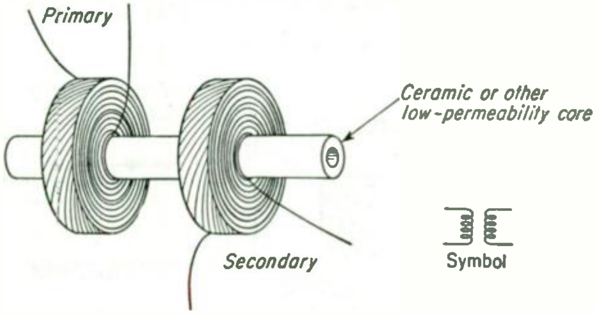


Fig. 5.21. An air-core transformer and symbol.

**5.17 Eddy Currents.** To produce a transformer of high efficiency and with a minimum number of turns, the primary and secondary are wound on a core of iron or other high-permeability material. As a result, when a transformer is in operation, intense moving magnetic fields are produced in the core. These fields induce circulating currents in the core material because iron is a fairly good electric conductor. Such little whirlpoollike currents are known as *eddy currents* and produce considerable $I^2R$ power loss in the form of heat in the core. Figure 5.23 indicates the path of eddy currents in a solid core wound with a single turn of wire in which the current is increasing. The direction of the eddy-current flow can be determined by using the left-hand generator rule.

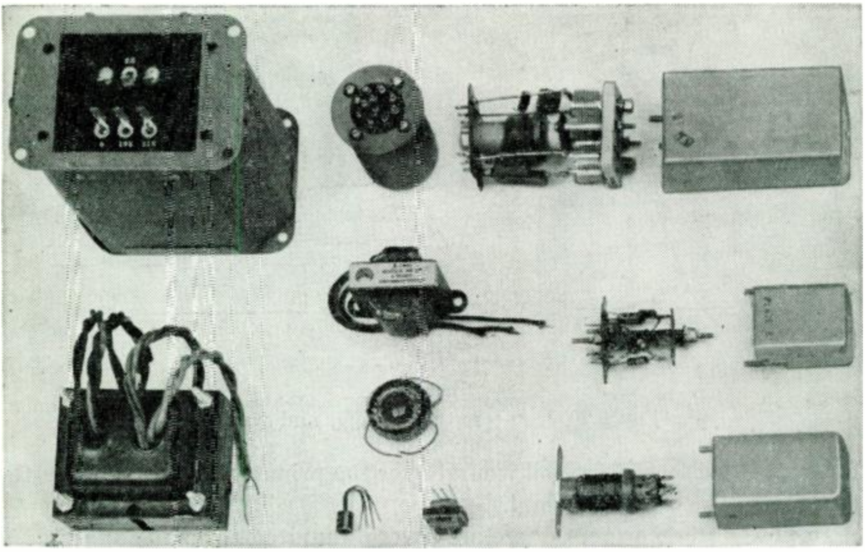


FIG. 5.22. Transformers. Left column, iron-cored power frequency. Center column, AF interstage, output, toroidal, transistor interstage, and transistor power output. Right column, RF transformers, air- or powdered-iron-cored, removed from their shield cans.

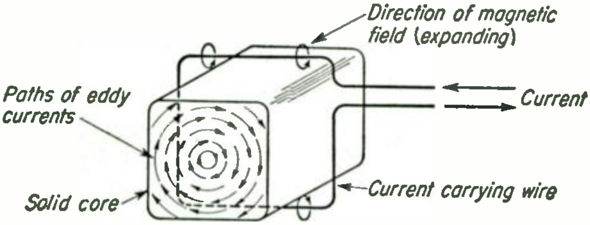


FIG. 5.23. High-amplitude eddy current in solid core.

Eddy currents are decreased in strength by using many thin sheets rather than a solid block of iron. Each separate sheet must be coated with an insulating scale or varnish. When the core is made of such sheets, the length of any one eddy-current path is limited to the thickness of the sheet, as shown in Fig. 5.24. Limiting the length of the path also limits the amplitude of the eddy currents and holds the $I^2R$ heat loss to a minimum.

Slicing the core into thin sheets is known as *laminating* the core. The thinner the laminations, the less the eddy-current loss. The cores of the two transformers in Fig. 5.20 are shown as being laminated.

As frequency is increased, flux movement increases and eddy-current losses increase. It has been found advantageous to use a powdered-iron core for higher-frequency applications. A difficulty in constructing such iron cores is the requirement that each magnetic particle be insulated from adjoining particles to prevent eddy currents from developing should the particles touch or make electrical contact with each other.

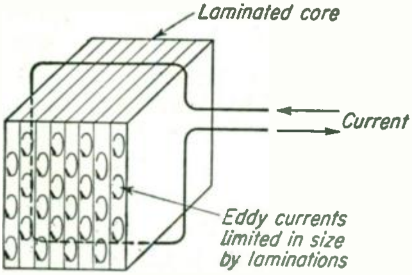


FIG. 5.24. Eddy currents reduced in amplitude by laminations.

**5.18 Hysteresis.** When a substance such as iron is in an unmagnetized state, its domains are not arranged in any particular manner. When a magnetizing force is applied to the domains, they rotate into a position in line with the magnetizing force. If the magnetizing force is reversed, the domains must rotate into an opposite position. In rotating from one alignment to the opposite, the domains must overcome a certain amount of frictional, or resisting, effect in the substance. In some materials the resisting effect is very small, while in others it is appreciable. The energy converted into heat overcoming the resisting effect is known as the *hysteretic loss*, or more commonly as *hysteresis*.

Hysteresis occurs in iron cores of transformers. When an alternating current is producing the magnetic force, the magnetism will be reversing in polarity and hysteresis is present. As the frequency is increased, the alternating magnetizing force will no longer be able to magnetize the material completely in either direction. Before the substance becomes fully magnetized in one direction, the opposite magnetizing force will begin to be applied and start to reverse the rotation of the domains. The higher the frequency, the less fully the material will become magnetized.

Transformers operated on low-frequency a-c may not have much hysteresis, but the same cores used with a higher frequency will have greater hysteresis and may also be less efficient because of their inability to magnetize fully in both directions.

**5.19 Copper Loss.** Transformers are not only subject to eddy-current and hysteresis losses in the core, but also to a *copper loss*. This occurs in the copper wire of the primary and secondary. The current flowing through whatever resistance exists in these windings produces heat. The heat in either winding, measured in watts, can be found by the power formula $P = I^2R$. For this reason the copper loss is also known as the $I^2R$ *loss.* The heavier the load on the transformer (the more current that is made to flow through the primary and secondary), the greater the copper loss.

With one layer of wire wound over another in a transformer, there is a tendency for the heat to remain in the wires more than if the wires were separated and air-cooled. Increased temperature results in increased resistance of a copper wire. As a result it becomes necessary to use heavier wire to reduce resistance and heat loss in transformers than would be required for an equivalent current value if the wire were exposed to the air during operation.

**5.20 External-induction Loss.** Another loss in a transformer is due to external induction. Lines of force expanding outward from the transformer core may induce voltages, and therefore currents, into outside circuits. These currents flowing through any resistance in any outside circuit can produce a heating of the external resistance. The power lost in heating these outside circuits represents a power loss to the transformer, since this power is not delivered to the transformer secondary circuit. Actually, in a well-designed transformer, the amount of power lost in this fashion is usually very small. However, the voltages induced into nearby wires of certain types of amplifying circuits can produce undesirable voltages in these circuits, even though the power loss to the transformer is negligible.

**5.21 Leakage Flux.** Any lines of force from the primary of a transformer that do not cut secondary turns, and therefore are not inducing an emf into the secondary, are considered leakage flux, or leakage lines of force.

**5.22 The Voltage Ratio of Transformers.** One of the main uses of transformers is to step up a low-voltage a-c to a higher voltage. This can be accomplished by having more turns on the secondary than on the primary, as illustrated in the simple transformer in Fig. 5.25.

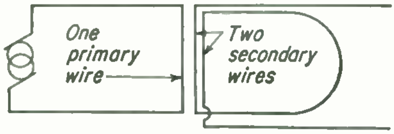


FIG. 5.25. Basic transformer with a 1:2 step-up ratio.

This transformer has a single wire for the primary and two wires *in series* in the secondary. Each of the secondary wires will pick up the same value of voltage since both are being cut by the same number of lines of force from the primary. In transformer operation it is found that if there is a 1-volt drop across each primary wire of a transformer, each wire of the secondary will pick up 1 volt. The two 1-volt induced emfs in the secondary are in series, resulting in an output of 2 secondary volts.

As long as the coefficient of coupling is high in a transformer, the no-load voltage ratio will be equal to the turns ratio. If the primary is wound with 500 turns and the secondary with 1,000 turns, the secondary voltage will be twice any voltage applied across the primary. The fact that the voltage ratio is equal to the turns ratio can be expressed in formula form as

$$\frac{T_p}{T_s} = \frac{E_p}{E_s}$$

where $T_p$ is the number of primary turns; $T_s$ is the number of secondary turns; $E_p$ is the primary voltage; $E_s$ is the secondary voltage.

The voltage ratio also works in reverse. If the primary has 200 turns, the secondary has 40 turns, and 100 volts is connected across the primary, the secondary voltage can be determined by the formula

$$\frac{T_p}{T_s} = \frac{E_p}{E_s}$$

$$E_s = \frac{E_pT_s}{T_p} = \frac{100(40)}{200} = \frac{4{,}000}{200} = 20 \text{ volts}$$

**5.23 The Power Ratio of Transformers.** There is no step-up of power in a transformer. It is possible to step voltage either up or down, but the basic ratio of *power* into the primary to *power* out of the secondary is 1:1. Actually, there is always some loss in a transformer, so that less power will always be drawn from the secondary than goes into the primary.

Power transformers are constructed to handle a certain number of watts, or *volt-amperes.* This usually means that a 100-volt 500-watt transformer, for example, will have a primary wound with wire that will carry only enough current to produce 500 watts in the primary. By the power formula $P = EI$, or $I = P/E$, it can be computed that 5 amp is the maximum the primary wire will be required to carry, regardless of whether the transformer is going to step up the secondary voltage or step it down. The primary will be wound with the thinnest wire that will stand that current without excessive heating. If more than 500 watts is drawn by the secondary load, the primary will be called on to carry more than 5 amp and will become overly hot and may burn the insulation on the wires or melt the wire itself.

The secondary will also be wound with a wire that will approach its safe heating limit when 500 watts is being drawn from the secondary.

If the transformer has a step-up ratio of 1:5, the secondary voltage will be 5 times 100 volts, or 500 volts. Inasmuch as the limiting factor is the 500 watts into the primary, the secondary can only be called upon to deliver 1 amp at 500 volts or the power delivered by the secondary will be more than 500 watts. If the primary has to draw more than 500 watts to satisfy the demands of the secondary, the transformer may burn out. If overloaded, either the primary or the secondary may fail.

To protect transformers from overloads, fuses or overload relays are connected in the primary circuit. A 5-amp fuse in series with the primary of the transformer mentioned above would burn out if more than the maximum safe current of 1 amp were drawn by the transformer secondary.

**5.24 The Current Ratio of Transformers.** A *step-up* transformer may produce more voltage across the secondary than is applied across the primary, but the secondary current will have to be proportionately less than the primary current.

This was indicated by the 500-watt 1:5-ratio step-up transformer previously mentioned. With 100 volts across the primary, the secondary produced 500 volts. With a load that draws 1 amp (a 500-ohm resistor, for example) connected across the secondary, the primary will be called upon to draw 5 amp of current from the source. This represents a primary to secondary step-down of current from 5 amp to 1. A voltage step-up transformer may be considered as a current step-down transformer; or conversely, a voltage step-down transformer may be considered as a current step-up transformer. At least, the secondary current will be inversely proportional to the turns ratio. This can be expressed in formula form by

$$\frac{T_p}{T_s} = \frac{I_s}{I_p}$$

where $T_p$ is the number of primary turns; $T_s$ is the number of secondary turns; $I_p$ is the primary current; and $I_s$ is the secondary current.

**5.25 Transformer Efficiency.** It will always be found that more power is fed to the primary of a transformer than is delivered by the secondary. The difference in power between the input and the output is the sum of all the power losses in the transformer.

The ratio of the output power to the input power is the efficiency of the transformer, and the factors that determine it are the copper loss, eddy-current loss, hysteretic loss, and external-induction loss. The output-to-input ratio always results in a decimal number less than 1.0. In practice, efficiency is given in percentage rather than in the decimal equivalent. It is only necessary to multiply the decimal by 100 to determine the percentage. The formula for percentage of efficiency for a transformer is

$$\%\ \text{efficiency} = \frac{P_s}{P_p} \times 100$$

where $P_s$ is the power in the secondary; and $P_p$ is the power in the primary.

If the over-all efficiency of a transformer is known, the primary power times the percentage of efficiency is the secondary power, $\%(P_p) = P_s$.

*Example:* If a power transformer has a primary voltage of 4,400 volts, a secondary voltage of 220 volts, and an efficiency of 98 per cent when delivering 23 amp of secondary current, what is the value of primary current? In this case, 23 amp at 220 volts, or 5,060 watts, represents 98 per cent of the power being fed into the primary. By substituting in the formula,

$$\% (P_p) = P_s$$
$$P_p = \frac{P_s}{\%} = \frac{5{,}060}{0.98} = 5{,}163 \text{ watts}$$

Using the power formula $P = EI$ and substituting in this formula,

$$P = EI$$
$$I = \frac{P}{E} = \frac{5{,}163}{4{,}400} = 1.17 \text{ amp}$$

It will be found that power transformers are always warm to the touch when operating. This heat is due to internal losses. In some cases it becomes necessary to air-cool transformers to keep them from overheating and damaging the insulation on the wires of the windings. Some transformers are built into oil-filled cases. The oil helps to insulate the internal wiring, preventing moisture from forming on the insulation, which might result in breakdown of the insulation, and also carries heat from the windings to the outer case to be dissipated into the air.

**5.26 Autotransformers.** An *autotransformer*, or *autoformer*, consists of a single winding with one or more taps on it, as shown in Fig. 5.26.

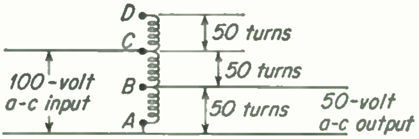


FIG. 5.26. Autotransformer used as a 2:1 step-down transformer.

If a 100-volt source of a-c is connected between points *A* and *C* and there are 100 turns between these points, there will be an emf of 1 volt induced in each of these turns, as well as in each of the turns from *C* to *D*. If a load is connected across points *A* and *B*, as shown, it will be across 50 volts. If connected across *A* and *C*, it will be across 100 volts. If connected across *A* and *D*, it will be across 150 volts. Thus an autotransformer can be used as a step-down or step-up device, depending upon how it is connected.

If the load is connected between *A* and a tap that can be adjusted to any turn between *A* and *D*, any desired voltage up to 150 in 1-volt steps can be developed across the load. Such autotransformers are made and sold under trade names such as Powerstat, Variac, etc.

A disadvantage in using an autotransformer is the common connection between the primary and secondary circuits, because it is often desirable to have the primary and secondary circuits isolated from each other electrically.

If isolation is not a factor, in some cases a transformer can be connected as an autotransformer and more or less output voltage can be obtained than the turns ratio of the transformer would normally give.

**5.27 Practical Transformer Considerations.** In radio and electronics, there are several types of transformers in use. Three common types are power transformers, AF transformers, and RF transformers.

A power transformer in general radio use is normally made to operate across a 110- to 440-volt a-c line. It is a heavy iron-encased piece of equipment. The resistance in the primary winding ranges from a fraction of an ohm to possibly 5 ohms. The inductive reactance of the primary winding acts to limit the primary current to a low value when connected across an a-c power line. If such a transformer is connected across a similar-voltage d-c line, the low resistance will allow excessively high current to flow in the primary and the primary will heat excessively and burn out or the line fuses will blow out. Care must be taken not to connect the primary of a power transformer across a d-c power line.

Power transformers are made to operate on one particular frequency, usually 60 cycles. In most cases, such transformers will operate fairly satisfactorily across any frequency between 50 and 70 cycles. However, if the frequency is much too high, the inductive reactance of the primary will prevent the primary from drawing sufficient power. There will be more iron in the core than is necessary, and hysteresis and eddy-current losses will be excessive. If the frequency is too low, the primary will not have sufficient reactance and too much primary current will flow, producing considerable copper loss, and the transformer may start to smoke. There will not be enough iron in the core, and the transformer will not be capable of its rated power output.

If a turn in either the primary or secondary of a power transformer shorts out for some reason, a high current will be induced in the turn, producing excessive heat in the transformer, due not only to the shorted turn heating but also to the cancellation of the inductance of the primary by the magnetic field set up by the shorted turn. Cancellation of the inductance materially decreases the inductive reactance of the primary, and excessive primary current flows.

Audio transformers are also iron-cored, usually smaller than power transformers, and are connected in series with a relatively high-resistance vacuum tube across a source of d-c. The resistance of the vacuum tube limits the primary current to a safe d-c value and prevents the primary from burning out.

Radio-frequency transformers are normally air-core transformers and are made to operate across RF a-c directly, or in series with a vacuum tube across a source of d-c.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

1. State the mathematical formula for the energy stored in the magnetic field surrounding an inductance carrying an electric current. (5.5) [3]
2. What is meant by the term unity coupling? (5.8) [3]
3. What is the reactance of a 5-mh coil at a frequency of 1,000 kc? (5.12) [3]
4. Why are laminated iron cores used in audio and power transformers? (5.17) [3]
5. If a power transformer having a voltage step-up ratio of 1:5 is placed under load, what will be the approximate ratio of primary to secondary current? (5.24) [3]
6. What would be the effect if direct current were applied to the primary of an a-c transformer? (5.27) [3]
7. What would be the effects of connecting 110 volts at 25 cycles to the primary of a transformer rated at 110 volts and 60 cycles? (5.27) [3]
8. Define the term inductance. (5.1, 5.2) [3 & 6]
9. What is the unit of inductance? (5.2) [3 & 6]
10. What is the effect of adding an iron- to an air-core inductance? (5.3) [3 & 6]
11. What is the relationship between the number of turns and the inductance of a coil? (5.3) [3 & 6]
12. What will be the effect of a shorted turn in an inductance? (5.11) [3 & 6]
13. Why may a transformer not be used with d-c? (5.27) [3 & 6]
14. If the mutual inductance between two coils is 0.1 henry and the coils have inductances of 0.2 and 0.8 henry, respectively, what is the coefficient of coupling? (5.8) [4]
15. What is the total reactance of two inductances connected in series with zero mutual inductance? (5.12) [4]
16. When two coils of equal inductance are connected in series with unity coefficient of coupling and their fields are in phase, what is the total inductance of the two coils? (5.9) [4]
17. What factors determine the core losses in a transformer? (5.17, 5.18) [4]
18. What circuit constants determine the copper losses of a transformer? (5.19) [4]
19. If a power transformer has a primary voltage of 4,400 volts and a secondary voltage of 220 volts and the transformer has an efficiency of 98 per cent when delivering 23 amp of secondary current, what is the value of primary current? (5.25) [4]
20. What is the total inductance of two coils connected in series but without any mutual coupling? (5.9) [6]
21. What is the total inductance of two coils connected in parallel but without any mutual coupling? (5.10) [6]
22. What is the reactance of a 2-henry choke coil at a frequency of 3,000 cycles? (5.12) [6]
23. A series inductance, acting alone in an a-c circuit, has what properties? (5.12, 5.13) [6]
24. Define the following terms: Eddy currents. (5.17) Hysteresis. (5.18) [6]
25. What is the secondary voltage of a transformer which has a primary voltage of 100, primary turns 200, and secondary turns 40? (5.22) [6]
26. What factors determine the no-load voltage ratio of a power transformer? (5.22) [6]
27. What factors determine the ratios of primary and secondary currents in a power transformer? (5.24) [6]
28. What factors determine the efficiency of a power transformer? (5.25) [6]
29. If part of the secondary winding of the power-supply transformer of a transmitter were accidentally shorted, what would be the immediate effect? (5.27) [6]

**30.** What would happen if a transformer designed for operation on a 60-cycle voltage were connected to a 120-cycle source of the same voltage? (5.27) **[6]**

**31.** What would happen if a transformer designed for operation on 500 cycles were connected to a 60-cycle source of the same voltage? (5.27) **[6]**

**32.** A radio receiver has a power transformer and rectifier designed to supply plate voltage to the vacuum tubes at 250 volts when operating from a 110-volt 60-cycle supply. What will be the effect if this transformer primary is connected to a 110-volt d-c source? (5.27) **[6]**

## AMATEUR LICENSE INFORMATION

It is recommended that applicants for Novice Class license examinations be able to answer questions prefaced by a star. Applicants for General, Conditional, and Technician Class licenses should be able to answer all questions.

★**1.** What is an RF choke coil? (5.6)

★**2.** What is an AF choke coil? (5.6)

**3.** What is inductance? (5.1, 5.2)

**4.** What is the unit of measurement of inductance? (5.2)

**5.** What formula can be used to compute inductances in series with zero mutual inductance? (5.9)

**6.** What formula can be used to compute inductances in parallel with zero mutual inductance? (5.10)

**7.** What factors determine the ratios of primary and secondary voltages in a power transformer? (5.22)

**8.** Why may an a-c power transformer not be used with d-c? (5.27)

**9.** What is the formula used to compute inductive reactance? (5.12)

## CHAPTER 6

# CAPACITANCE

**6.1 The Capacitor.** One of the most used parts in radio and electronics is the *capacitor* (also called a *condenser*). A capacitor has the ability to hold a charge of electrons. The number of electrons it can store under a given electric pressure is a measure of its *capacitance* (sometimes called *capacity*).

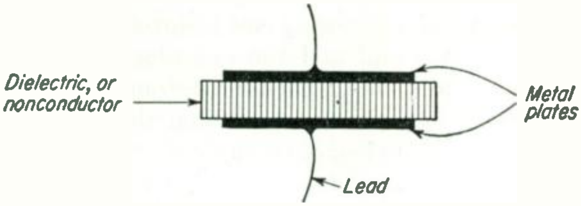


FIG. 6.1. Basic capacitor, two metal plates separated by a nonconducting dielectric.

In the past the word "condenser" was used almost entirely when speaking of capacitors. Today, both words, capacitor and condenser, are used. It is possible that the term "condenser" will die out in the near future. For this reason the word "capacitor" will be used throughout this book.

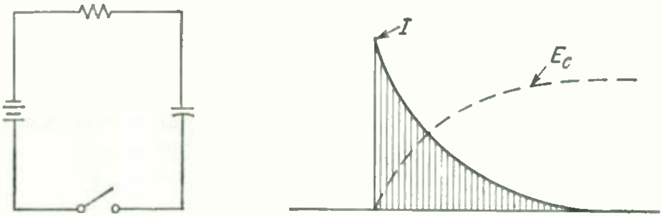


FIG. 6.2. RC circuit, with graphs of current flowing into the capacitor and voltage building up across it when the switch is closed.

Two separate metallic plates with a nonconducting substance sandwiched in between them, as illustrated in Figure 6.1, form a simple capacitor.

It is important to understand the current and voltage changes that take place in a circuit in which a capacitor is connected. Figure 6.2

shows a simple circuit with a battery, switch, resistor, and capacitor in series and a graph of the current and voltage changes that will take place when the switch is closed.

With the switch open, the capacitor will be assumed to have zero charge; that is, both plates have the normal number of electrons and protons in the molecules of the metal.

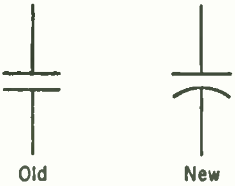


Fig. 6.3. Symbols used to denote fixed capacitors.

At the instant the switch is closed, the electric pressure of the battery begins to force electrons into the top plate from the negative terminal of the battery and pull others out of the bottom plate toward the positive end of the battery. As the electron difference is developed between the two plates, electrostatic lines of force appear in the region between the plates.

At the instant the switch is closed, there is no opposing emf in the capacitor and the amplitude of the current is determined only by the resistance in the circuit. As time progresses, more electrons flow into the capacitor and a greater opposing emf is developed in it. The difference between the source emf and the opposing emf becomes smaller. The opposing emf across the capacitor continually increases, and the circuit current continually decreases. When the opposing emf equals the source emf, there will no longer be any current in the circuit, and the voltage across the capacitor will be at a maximum and equal to the source voltage, as shown by the $E$ and $I$ curves in the graph.

A capacitor that will store a difference of one coulomb ($6.28 \times 10^{18}$ electrons) when an emf of one volt is applied across it has the capacitance value of one *farad*. Two volts across this same capacitor would store two coulombs. In radio and electronics one farad is more capacitance than is ever used. Practical capacitance values are measured in microfarads (millionths of a farad) or in micromicrofarads. Microfarads are abbreviated $\mu$f, although uf, mf, $\mu$fd, ufd, and mfd may also be used at times. It is important to be able to convert from $\mu$f to $\mu\mu$f. For instance,

$$1\ \mu\text{f} = 1{,}000{,}000\ \mu\mu\text{f} \qquad 250\ \mu\mu\text{f} = 0.00025\ \mu\text{f}$$
$$0.005\ \mu\text{f} = 5{,}000\ \mu\mu\text{f} \qquad \mu\text{f} \times 10^{6} = \mu\mu\text{f}$$
$$0.00004\ \mu\text{f} = 40\ \mu\mu\text{f} \qquad \mu\mu\text{f} \times 10^{-6} = \mu\text{f}$$

The time that is required for a capacitor to attain a charge is proportional to the capacitance and to the resistance in the circuit. The *time constant* of a resistance-capacitance circuit is

$$T = RC$$

where $T$ is the time in seconds; $R$ is the resistance in ohms; and $C$ is the capacitance in farads.

The time in the formula is that required to attain 63 per cent of the voltage value of the source. It is also the time required for a charged capacitor to discharge 63 per cent when connected across the value of resistance used in the formula. (Note the similarity to the time constant of a resistance-inductance circuit.) The time required to bring the charge to about 99 per cent of the source voltage is approximately five times the time computed by using the time-constant formula.

If there is no resistance in the circuit, the time required is zero and a capacitor will charge or discharge immediately.

A 4-$\mu$f capacitor and a 1-megohm resistor have a time constant of $0.000004 \times 1{,}000{,}000$, or 4 seconds.

In the previous chapter, inductance was defined as "the property of a circuit to oppose any *change in current.*" Capacitance may be defined as "the property of a circuit to oppose any *change in voltage.*" In the d-c circuit discussed, it has been explained that capacitance develops an opposition emf to the change of voltage from a zero value to any given value. When a resistor is connected across a charged capacitor that has been disconnected from the charging source, the opposing emf that had been developed in the capacitor during the charging period discharges, driving current through the resistor. In a varying d-c or a-c circuit, in which the emf is continually varying in amplitude, capacitance will continually oppose the changing source emf.

**6.2 Factors Determining Capacitance.** The factors that determine capacitance are the area of the plates exposed to each other, the spacing between the plates, and the composition of the nonconducting material between the plates.

Two plates, each one inch square (1 in.$^2$), when separated by 1/1,000 in. of air, produce a capacitance of 225 $\mu\mu$f. If each plate area is increased to 2 in.$^2$ and the spacing remains 0.001 in., the capacitance becomes twice as much, or 450 $\mu\mu$f. Therefore capacitance is directly proportional to the plate areas exposed to each other.

If the spacing of the two 1-in.$^2$ plates is increased to 0.002 in. the path of the electrostatic lines of force between the negative plate and the positive plate is twice as great, resulting in only half as intense an electrostatic field and only half as much capacitance. Therefore capacitance is inversely proportional to the spacing between plates.

The nonconducting material between the plates, called the *dielectric* material, determines the concentration of electrostatic lines of force. If the dielectric is air, a certain number of lines of force will be set up. Other materials offer less opposition to the formation of electrostatic lines of force in them. For example, if a certain type of paper is used instead of air, the number of electrostatic lines of force between the plates may be twice as great. Such a capacitor will have twice as much capacitance and will have two times as many electrons flowing into and out of it with the same applied source emf. The paper is said to have a *dielectric constant*, or *specific inductive capacity*, of two times that of air. Therefore capacitance of a capacitor is directly proportional to the dielectric constant.

A formula to determine the capacitance of a two-plate capacitor including these three factors is

diel const

$$C_{\mu\mu f} = \frac{0.225KA}{S}$$

area inches

space in inches

where $C$ is in $\mu\mu$f; $K$ is the dielectric constant; $A$ is the area of *one* plate in square inches; and $S$ is the spacing between plates in inches.

This formula is for a two-plate capacitor. If additional capacitance is desired, it is possible to stack more plates on top of one another, separating each with a strip of dielectric material. A three-plate capacitor will have twice the plate area exposed, as shown in Fig. 6.4, and have twice the capacitance. A four-plate capacitor has three times the plate area exposed and three times the capacitance. The formula for multiplate capacitors is

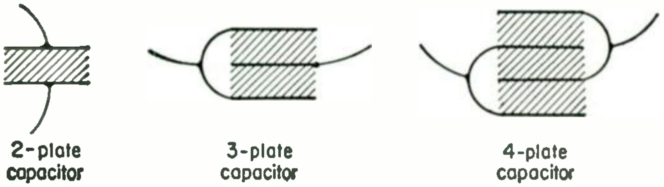


FIG. 6.4. A three-plate capacitor has twice the capacitance of a two-plate. A four-plate capacitor has three times that of the two-plate.

not to be

$$C_{\mu\mu f} = \frac{0.225KA(N-1)}{S}$$

where $(N - 1)$ is the number of plates minus 1 used in the capacitor.

The approximate dielectric constant, or specific inductive capacity of some common materials used as the dielectric of capacitors, is given in Table 6.1.

The dielectric constant of *solid* dielectric materials will decrease with an increase in frequency. The molecules of the dielectric apparently do not have sufficient time to conform to the rapidly changing electrostatic lines of force that they must support. If the lines of force cannot be fully developed in the molecules of the dielectric, the dielectric constant is less and the capacitance of the capacitors will be less. Thus, a 0.1-$\mu$f paper capacitor may have this value of capacitance at 1 Mc but will have considerably less at 100 Mc.

**6.3 Dielectric Losses.** Almost all the energy stored in the electrostatic field of a capacitor is converted into electromagnetic, or heat, energy when it is discharged. However, there are two losses that occur in the dielectric itself.

Electrons on the negative plate of a charged capacitor may find a high-resistance path to the positive plate either through the dielectric or over the surface of the capacitor. The more leakage electrons, the fewer electrostatic lines of force and the smaller the value of energy that can be converted to use from the electrostatic field. Therefore leakage current is a loss to a capacitor. Leakage current flowing through any high-resistance path produces heat ($P = I^2R$).

Table 6.1

| *Material* | *Dielectric constant* |
|---|---|
| Glass | 4–7 |
| Porcelain | 6–7 |
| Quartz | 4 |
| Rubber | 2–3 |
| Mica | 5–7 |
| Paper | 2–3 |
| Air | 1 |
| Vacuum | 1 |
| Ceramics | 5–4,000 |
| Water | 80 |

Another dielectric loss is due to hysteresis and is also indicated by heat in the capacitor. It can be considered to be caused by the friction of the molecules of the dielectric material as they are changed from one strained position to the opposite by reversing electrostatic lines of force between the plates. Hysteresis is normally only significant when an alternating current produces rapid charging and discharging of the capacitor. Hysteresis increases as the frequency of the a-c increases. For this reason, many capacitors operate satisfactorily at lower frequencies but fail at higher.

Vacuum, air, and mica capacitors have little leakage or hysteresis. Paper may have considerable leakage and hysteresis, particularly if the dielectric has moisture in it.

An interesting and significant phenomenon is produced in some solid-material dielectric capacitors. Such a capacitor can be charged by a d-c voltage, disconnected from the charging source, and remain charged. A wire connected across the capacitor terminals will discharge the capacitor, usually with an audible and visible electric spark. If the wire is disconnected for a short time and then connected across the *discharged* capacitor again, another spark is produced, indicating that the dielectric had not released all the stored energy on the first discharge. During the charged period dielectric molecules some distance from the capacitor plates capture some electrons. These take time to work back to the plates through the high resistance of the dielectric after the capacitor is discharged. This *dielectric absorption* may not be too significant when the capacitor operates in a d-c circuit, but in high-frequency a-c or varying d-c circuits it decreases the effectiveness of the capacitor.

**6.4 Working Voltage and Dielectric Strength.** One rating of capacitors is the *working voltage.* This is the maximum voltage at which the capacitor will operate without leaking excessively or arcing through. Sufficient leakage through the dielectric over a period of time can produce a carbonized path across the dielectric, and the capacitor will act as a conductor. In such a case it is said to be *burned out,* or *shorted.*

A burned-out capacitor should not be confused with an *open* one. An open capacitor has lost its storage ability, either because of the breaking off of a wire lead internally, or, in the case of an electrolytic capacitor, because the electrolyte has dried out.

The working voltage is usually rated as a d-c value. A capacitor may be rated to work at 600 volts on d-c circuits, but when used in power-frequency a-c circuits its effective a-c working voltage will be about one-half the d-c rating. As the frequency of the a-c is increased, the working voltage of the capacitor decreases, particularly when the frequency rises above a few megacycles. Heating the dielectric will decrease the breakdown voltage point.

The dielectric strength, or number of volts that the dielectric will stand per 0.001 in. of dielectric thickness, varies considerably with different materials. Air has a dielectric strength of about 80 volts; bakelite about 500 volts; glass 200 to 300 volts; mica about 2,000 volts; untreated paper a few hundred volts; waxed or oiled paper 1,000 to 2,000 volts.

**6.5 Energy Stored in a Capacitor.** When a capacitor is charged and then disconnected from the charging source, it has a difference of electrons between the two plates, and the dielectric molecules are under the stress of electrostatic lines of force. If the charged capacitor is connected across a light globe, for example, the excess electrons on the negative plate will flow through the globe to the positive plate until the electron inequality between the plates is balanced. When the two plates have an equal number of electrons, the capacitor will no longer have any charge and no current will flow.

While moving through the light globe, the electrons liberate the energy of their motion in the form of heat. In this case the light globe may flash for an instant and then go out. The amount of energy stored by the electrostatic field in the dielectric of a capacitor can be computed, using wattseconds or joules as the unit of measurement, by the formula

[illegible] volts

$$E_n = \frac{CE^2}{2}$$

Joules

where $E_n$ is energy in joules or wattseconds; $C$ is in farads; and $E$ is in volts.

**6.6 Quantity of Charge in a Capacitor.** The *charge* of a capacitor may be considered as the difference in number of electrons on the two plates. Since this difference involves a quantity of electrons, the unit of quantity of charge is the coulomb. In formula form, the quantity of charge in a capacitor is

$$\text{coulombs}\rightarrow Q = \underset{\uparrow\ \text{farads}}{C}E \leftarrow \text{volts}$$

where $Q$ is in coulombs; $C$ is in farads; and $E$ is in volts.

*Example:* If a 1-μf capacitor is across 10 volts d-c, the electron difference between the positive and the negative plates will be

$Q = CE = 0.000001(10) = 0.00001$ coulomb, or $= 10^{-5}$ coulomb
$10^{-5}$ coulomb $= 6.28 \times 10^{18}\ (10^{-5})$
$Q = 6.28 \times 10^{13}$ electrons

It can be reasoned that if a 0.1-μf capacitor is charged by a 125-volt source, an electron difference will be developed of $Q = CE$, or 0.0000001(125), or 0.0000125 coulomb between the plates. If the charged capacitor is disconnected from the source, it still retains the electron difference on its plates (assuming no leakage). If another *similar* uncharged capacitor is connected across the charged capacitor, electrons flow from the charged to the uncharged capacitor. Since both are of equal capacitance, each will have half of the electron difference, or 0.00000625 coulomb. A capacitor losing half its electron charge will have only half the voltage across it. Each of the two parallel capacitors now have 62.5 volts across them. Nothing has actually been lost, however. If the two capacitors are disconnected and reconnected in series, the total voltage drop across the two capacitors is 125 volts and the same number of electrons are still in storage in the capacitors.

**6.7 Electrolytic Capacitors.** Basically, most capacitors are constructed by placing a conducting plate, a sheet of dielectric, another conducting plate, a sheet of dielectric, etc., one on top of the other until the desired capacitance is obtained.

A chemical type of capacitor has been developed that has the advantage of small physical size with relatively large capacitance. It is called an *electrolytic* capacitor. It consists of a coated aluminum positive plate immersed in a solution called an *electrolyte*. (An electrolyte is an ionized solution that will carry electric current when subjected to electric pressure.) The aluminum sheet is the positive plate, and the electrolyte is the negative "plate," if a liquid can be called a plate. To make an electrical connection to the liquid, another sheet of metal, usually aluminum foil, is placed in the solution. The aluminum positive plate and the solution are subjected to an electric potential to *form* an oxidized film on the positive plate. This oxide film is the dielectric that separates the aluminum plate from the electrolyte plate.

The thickness of the formed film on the positive plate determines the breakdown voltage. Electrolytic capacitors range from 6-volt working voltages to about 700 volts, depending on the oxide-film thickness. A capacitor formed to operate on 450 volts, but used on 150 volts, will ultimately re-form to the 150-volt value. The re-formed dielectric is thinner, and the capacitance of the capacitor increases. In general, it is a good policy for electrolytic capacitors to be operated at voltages close to their rated values.

The wet-type electrolytic capacitor has been supplanted by a *dry* type. Actually, a dry type uses paper or gauze moistened with electrolyte as one plate and a formed aluminum plate as the positive plate. A second unformed piece of aluminum foil is laid against the moist gauze to make the necessary negative electrical terminal. In practice, the formed aluminum-foil plate, the gauze, and the second aluminum foil are rolled into a small cylinder and then sealed to make the capacitor airtight. This prevents the electrolyte from drying out.

The range of capacitances for electrolytic capacitors usually available is from about 4 $\mu$f to over 5,000 $\mu$f.

Although physically small and relatively inexpensive, electrolytic capacitors have some disadvantages. They dry out over a period of time and lose their capacitance value. They have a small leakage current when in operation that tends to raise the *power factor* of the capacitor. Using them on voltages above the rated voltage increases the leakage current and produces increased heat, tending to dry them out or destroy the dielectric film, or to generate steam internally, causing them to explode. They have relatively low voltage ratings when compared with some mica or paper capacitors. They are *polarized* and must be connected with the positively formed plate to the positive terminal of the circuit in which they are used. (They are marked + at one terminal and − at the other terminal.) This limits them to use in d-c or varying d-c circuits only. They must not be used across an alternating voltage. To prevent the electrolyte from drying, they should not be allowed to become warm.

For electric motors, a special type of electrolytic capacitor is manufactured that can be used with a-c, but the electrolytic capacitor used in radio and the usual electronic circuits is the polarized type.

**6.8 Variable Capacitors.** There are two types of capacitors that allow their capacitance to be varied, *adjustable* and *variable.*

Adjustable capacitors are usually constructed of two or more flat plates separated by sheets of mica. The plates are so arranged that they normally hold themselves apart slightly. A machine screw is used to press the plates together, thereby increasing the capacitance. Adjustable capacitors may be known as padders or trimmers. They are commonly available in capacitances from a few $\mu\mu$f to 1,000 or more $\mu\mu$f, at a working voltage of 300 to 600 volts.

Variable capacitors have a set of *stator*, or stationary, plates and a set of *rotor*, or rotatable, plates. When the shaft is rotated, the rotor plates mesh into the stator plates (without touching them), varying the exposed plate areas and thereby the capacitance of the capacitor (Fig. 6.5). The dielectric of these capacitors is usually air, although there are some special vacuum dielectric variables used in radio transmitters.

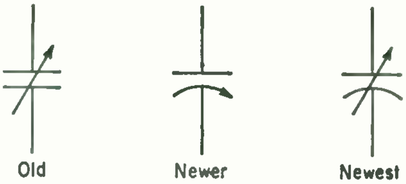


FIG. 6.5. Symbols used to denote variable capacitors.

Variable capacitors are made in many sizes and shapes. Their capacitance values range from a few $\mu\mu$f to 1,000 or more $\mu\mu$f. Receiver-type variable capacitors have very small spacing between plates. Transmitting capacitors may have ¼ inch to 1 inch or more spacing, depending on the voltages encountered in the output of the stages in which they are used.

**6.9 Modern Capacitors.** There are many types of capacitors in general use in radio and electronics today. Some are listed below with a brief statement as to relative dielectric leakage, whether obtainable in a fixed or variable type, approximate working-voltage ranges available, approximate capacitance values available, and frequencies with which they may be used.

1. *Vacuum Dielectric.* Practically no leakage. Made in both fixed and variable types. Used in 5,000- to 50,000-volt service. Capacitances of 5 to 250-$\mu\mu$f. Relatively efficient to well over 1,000 Mc. Mostly used in transmitters.

2. *Air Dielectric.* Very little leakage except through insulators holding plates. Made in fixed, adjustable, and variable types. Used in low- and high-voltage applications, both receivers and transmitters. Wide variety and capacitance range for both fixed and variable. Rarely much more than 400-$\mu\mu$f capacitance. May be used up to more than 300 Mc. Variable air capacitors are the usual tuning element in receivers and transmitters.

3. *Mica Dielectric.* Very little leakage except through material which encases the plates and dielectric. Made in both fixed and adjustable types. Working voltage ranges from 350 to several thousand volts, depending on thickness of dielectric used. Capacitances from 1.5 $\mu\mu$f to 0.1 $\mu$f. Used in RF circuits up to more than 300 Mc, although efficiency drops off over 10 Mc. Fixed types are used as RF bypass capacitors, etc. The adjustable types are used as padders or trimmers. *Silver mica* capacitors are within 5 per cent of their rated capacitance

values and tend to hold constant capacitance even under adverse operating conditions.

4. *Ceramic Dielectric.* Low leakage. Fixed and adjustable types. Capacitances from 1.5 μμf to 0.01 μf for fixed types. Up to 100 μμf for adjustable types. Approximately 500 volts working voltage. Useful up to more than 300 Mc with good efficiency. Replacing mica capacitors in many circuits.

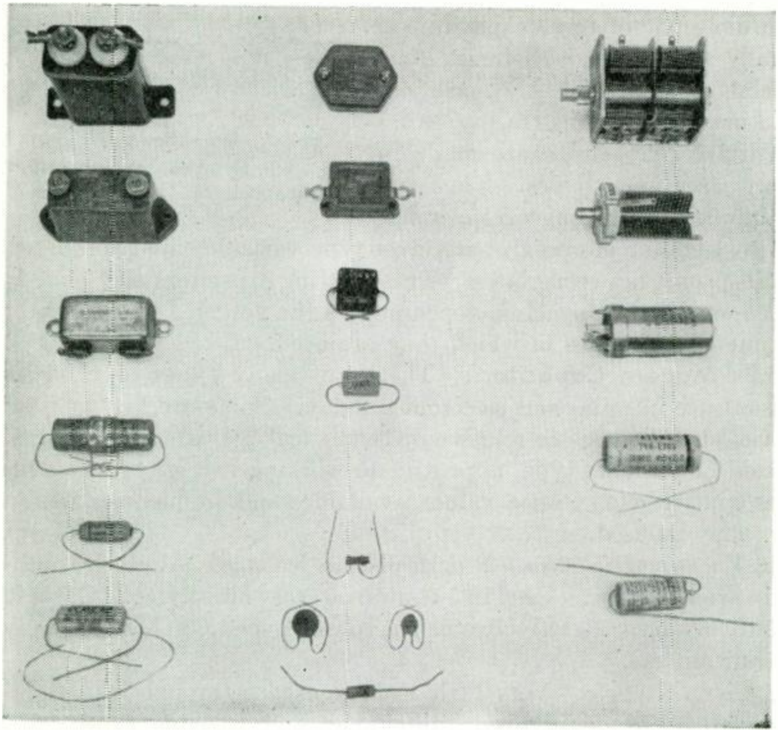


FIG. 6.6. Capacitors. Left column, fixed paper-dielectric capacitor. Top center, fixed mica capacitor. Bottom center, ceramic capacitors. Top right, variable air capacitors. Bottom right, electrolytic capacitors.

5. *Paper Dielectric.* Wax-impregnated paper used. Relatively low leakage when new. When moisture seeps in, the leakage becomes very high and the dielectric carbonizes at low voltages. Fixed types only. Ranges in capacitance from 10 μμf to 10 μf. Working voltages from 150 to several thousand volts, depending on thickness of paper. Efficient up to 1 or 2 Mc. Above this frequency they rapidly become less effective, because of dielectric fatigue and hysteresis.

6. *Oil-filled.* These are a type of paper capacitor. The paper is impregnated with oil, keeping moisture out of the paper and increasing working voltage and dielectric constant. Used in capacitors for 600

volts to several thousand volts working rating. Not used in high-frequency circuits. Capacitances range from 1 to 10 μf.

7. *Electrolytic.* Considerable leakage, particularly if used on voltages over the rated value. Fixed types only. Ranges in capacitance from a few to several thousand μf. Working voltages from 6 volts up to about 700 volts. Normally polarized and require positive terminal be connected to positive terminal of the circuit. Dry out and lose capacitance. Limited life expectancy. Useful only in d-c circuits or in circuits where the d-c component exceeds the a-c component.

**6.10 Power Factor in Capacitors.** Capacitors are often tested to find their *power factor.* With little or no leakage or losses, a capacitor has a low power factor. This is actually a percentage rating of the losses in a capacitor. With no losses, the power factor is zero. As leakage develops through the capacitor the power factor increases. A power factor of 1 means all leakage and no capacitive effect at all. Most capacitors when tested for power factor will indicate very close to zero. Electrolytic capacitors may read small power-factor values and still be usable. If their power factor increases above 0.1 or 0.2, it is assumed that they should be replaced.

**6.11 Inductance in Capacitors.** There is a small value of inductance in all capacitors arising from the counter emf developed in the leads of the capacitor and the current traveling along the plates. In most low-frequency applications this inductance can be ignored. However, at frequencies over about 10 Mc the inductance of long leads may become important. Leads should be kept as short as possible in order not to interfere with the operation of high-frequency circuits.

Just as there is inductance in capacitor leads, there is *distributed capacitance* in coils. There is a small value of capacitance between adjacent turns of a coil and from one end of the coil to the other. For this reason it is impossible to produce pure inductance or pure capacitance.

**6.12 Changing Varying D-C to A-C.** When a capacitor is connected in a series circuit consisting of a source of voltage, an ammeter, a switch, and the capacitor, as shown in Fig. 6.7, current will flow in the circuit under certain conditions.

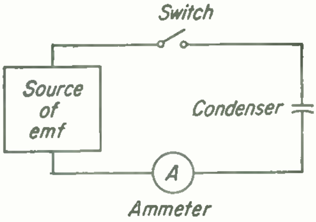


Fig. 6.7. A capacitor, an ammeter, and a switch in series across a source of emf.

If the source of emf is a battery or other d-c source, when the switch is closed, electrons will flow in the circuit until the capacitor is charged to the source voltage. The ammeter will respond with a momentary indication and then will drop back to zero and remain there. From then on, no current will flow in the circuit. It may be said that a series capacitor blocks d-c in a circuit.

If the source of emf produces a-c, the emf from the source will constantly be changing, the capacitor will constantly be charging and discharging, and an alternating current will flow through the meter. A capacitor may be used to complete a circuit if the source is producing an alternating emf. It may be considered as a conductor for a-c, although electrons do not pass across the dielectric.

If the source produces a varying d-c emf, the periodic increase and decrease of emf result in a continual charging and partial discharging of the capacitor. Since the charging and discharging current flows back and forth through the meter, the ammeter will have an *alternating* current flowing through it. A capacitor in series with a circuit having a varying d-c source produces a current that is alternating. The capacitor is said to block the d-c but pass the *a-c component.* Figure 6.8 shows a varying d-c and the a-c component of the variation. This is an important point. Most vacuum-tube circuits have a varying d-c flowing in them. When a load is coupled to the circuit by a capacitor, only the variation, the a-c component, is transferred to the load. Alternating current flows in the load, not varying d-c.

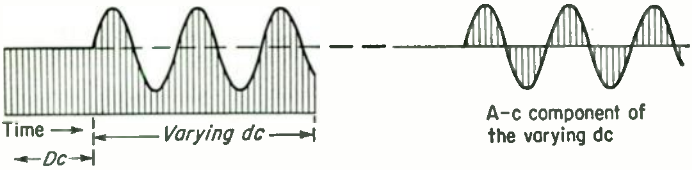


FIG. 6.8. Varying d-c emf and the resultant a-c component produced when a capacitor is in series with the circuit.

**6.13 Capacitive Reactance.** How effective a capacitor may be in allowing a-c to flow depends upon its capacitance and the frequency used. The greater the capacitance, the more electrons required to charge it to the source-voltage value. The smaller the capacitor, the fewer electrons required to bring it to full charge. It is possible to control the current flow in an a-c circuit by changing the capacitance, somewhat as current can be controlled by varying the resistance in a circuit.

The higher the frequency of the a-c in the circuit, assuming the same peak voltage, the greater the number of electrons that must flow into and out of the capacitor *per second* to bring it to full charge. The more electrons per second, the greater the number of amperes that flow in the circuit.

The actual *a-c resistance* effect of a capacitor is known as its *capacitive reactance,* is measured in ohms, and can be determined by combining the value of capacitance and the frequency in the formula

$$X_C = \frac{1}{2\pi FC}$$

where $X_C$ is the reactance in ohms; $F$ is the frequency in cycles; $C$ is the capacitance in farads; and $\pi$ is 3.14.

*Example:* The reactance value of a capacitor of 0.005 μf to a frequency of 1,000 kc may be found by substituting these values in the capacitive-reactance formula:

$$X_C = \frac{1}{2\pi FC} = \frac{1}{6.28(1{,}000{,}000)0.000000005} = \frac{1}{6.28(0.005)} = \frac{1}{0.0314} = 31.8 \text{ ohms}$$

The reactance of a capacitor is inversely proportional to the frequency. If the reactance is 31.8 ohms at 1,000 kc, it will be one-half as much, or 15.9 ohms at 2,000 kc, and one-tenth as much at 10,000 kc. This inverse proportion can be expressed by

$$\frac{F_1}{F_2} = \frac{X_{C_2}}{X_{C_1}}$$

where $F_1$ is one frequency; $F_2$ is another frequency; $X_{C_1}$ is the capacitive reactance at frequency $F_1$; and $X_{C_2}$ is the capacitive reactance at frequency $F_2$.

This formula can be used to solve problems such as the following:

What is the reactance of a capacitor at the frequency of 1,200 kc if its reactance is 300 ohms at 680 kc? By substituting the given values in the formula, the answer is found by

$$\begin{aligned} \frac{F_1}{F_2} &= \frac{X_{C_2}}{X_{C_1}} \\ \frac{1{,}200 \text{ kc}}{680 \text{ kc}} &= \frac{300}{X_{C_1}} \\ 1{,}200X_{C_1} &= 300(680) \\ X_{C_1} &= \frac{204{,}000}{1{,}200} = 170 \text{ ohms} \end{aligned}$$

The same answer will be obtained if the 300 ohms reactance and 680 kc are used in the capacitive-reactance formula, rearranged to solve for the capacitance. The unknown reactance is then determined by using this capacitance and the 1,200-kc frequency.

With the capacitive-reactance value known, it is possible to use the *Ohm's law for reactive circuits*, as explained in Sec. 5.12. Reactance is substituted in place of resistance in the d-c Ohm's law. The three derivations of the formula are

$$I = \frac{E}{X_C} \qquad E = IX_C \qquad X_C = \frac{E}{I}$$

**6.14 Capacitors in Parallel.** It is often necessary to connect two or more capacitors in parallel to obtain more capacitance. Figure 6.9*a* shows two 1-μf capacitors connected in parallel. Plates *A* and *B* in the first capacitor have a certain area and are separated by a dielectric, resulting in 1 μf of capacitance. The other capacitor has similar plate areas, similar dielectric, and therefore the same capacitance. If plates $A$ and $B$ and plates $C$ and $D$ are connected together electrically, as shown in Fig. 6.9*b*, the result will be equivalent to a capacitor with twice the plate area and the same dielectric and, as a result, twice the capacitance.

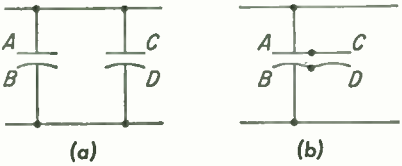


FIG. 6.9. Two similar parallel capacitors have twice the capacitance of one alone.

Whether the capacitors are connected as in diagram *a* or as in diagram *b*, the total capacitance is equal to the sum of the two capacitance values.

The formula for computing the capacitance of two or more capacitors in parallel is simply

$$C_t = C_1 + C_2 + C_3 + \cdots$$

where $C_t$ is the total capacitance; $C_1$ is one capacitor; $C_2$ is a second capacitor; and $C_3$ is a third capacitor.

*Example:* Capacitors of 1, 3, and 5 $\mu$f are connected in parallel:

$$C_t = C_1 + C_2 + C_3 = 1 + 3 + 5 = 9\ \mu\text{f}$$

Care must be exercised when connecting two or more capacitors in parallel. The highest voltage a group of parallel capacitors will stand will be determined by the lowest working-voltage rated capacitor. If two capacitors have a working-voltage rating of 500 volts each and a third has a rating of 400 volts, no more than 400 volts should be used across the circuit when the three are in parallel.

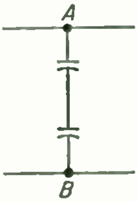


FIG. 6.10. Series capacitors increase dielectric thickness across line and result in less total capacitance.

**6.15 Capacitors in Series.** There are many cases in radio and electronics where two or more capacitors are connected in series, as shown in Fig. 6.10. When two 1-$\mu$f capacitors are connected in series, the total capacitance is 0.5 $\mu$f. The circuit is acting as one capacitor with the top plate connected to point $A$ and the bottom plate connected to point $B$. Between these two points there is twice the dielectric spacing of one capacitor. Any time the spacing between plates is increased, the capacitance decreases, according to the formula for computing capacitance (Sec. 6.2).

The capacitance of two or more *similar* capacitors in series is equal to the capacitance of one of them divided by the total number. Thus, four 10-$\mu$f capacitors in series present a total capacitance of 10/4, or 2.5 $\mu$f. Two equal capacitances in series total half the capacitance of one. Since capacitive reactance is inversely proportional to capacitance, according to the formula $X_C = 1/2\pi FC$, the reactance of two equal series capacitors will be twice the reactance of one.

Two formulas for computing unequal-capacitance capacitors in series are given below. The first is for two series capacitors, and the second can be used for any number of capacitors in series. Note the similarity of these formulas to the parallel-resistance formulas (Sec. 2.15).

$$C_t = \frac{C_1 C_2}{C_1 + C_2} \qquad \text{or} \qquad C_t = \frac{1}{1/C_1 + 1/C_2 + 1/C_3}$$

*Example:* The total capacitance of three capacitors in series, having 5, 3, and 7 μf, respectively, is

$$C_t = \frac{1}{\frac{1}{5} + \frac{1}{3} + \frac{1}{7}} = \frac{1}{\frac{21}{105} + \frac{35}{105} + \frac{15}{105}} = \frac{1}{\frac{71}{105}} = \frac{105}{71} = 1.48\ \mu\text{f}$$

Since two similar capacitors in series present twice the dielectric spacing across the circuit, the working voltage of two such capacitors in series will be doubled. If each has a rating of 500 volts, the two in series will stand 1,000 volts.

When capacitors in series are connected across a difference of potential, the sum of the voltage drops across each of them will always equal the source voltage. Furthermore, the value of the voltage drop across a particular capacitor in a series group will be *inversely proportional* to the ratio of its *capacitance* to the total, or *directly proportional* to its *reactance*. For example, a 1-μf and a 2-μf capacitor are in series across a 300-volt source. There will be 200 volts across the 1-μf capacitor and 100 volts across the 2-μf. This will be true whether the capacitors are across a-c or d-c, if leakage is not present in the d-c case.

It is sometimes desirable to equalize the d-c voltage across two capacitors of somewhat unequal value when connected in series. This can be done by connecting resistors of equal value across them, as shown in Fig. 6.11.

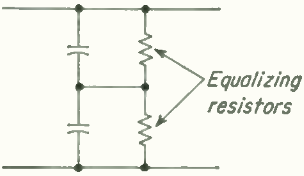


FIG. 6.11. Equalizing resistors across capacitors connected in series.

In an emergency, or when a surplus of low-voltage capacitors is on hand, it is possible to connect several in series and use them across a high-voltage circuit. For example, if it is desired to have 1.5 μf of capacitance across a 1,600-volt circuit, and a number of capacitors rated at 400 volts and 2 μf each are available, four 2-μf 400-volt capacitors in series produce a capacitance of 0.5 μf capable of standing 1,600 volts. Three parallel groups of four capacitors (a total of 12 capacitors) will give the desired 1.5-μf capacitance suitable for the 1,600-volt circuit. The use of equalizing resistors across each capacitor would be desirable.

**6.16 Phase Relationships with Capacitance.** In the preceding chapter it was explained that alternating current and voltage will be out of phase in a circuit in which inductance is present. In an inductive circuit the current may lag the voltage by as much as 90°. In an a-c circuit containing series capacitance, the current and voltage may also be out of phase by as much as 90° but the *voltage will lag the current.*

The voltage and current relationship of a capacitive circuit can be explained briefly by referring to Fig. 6.12, showing a capacitor across a source of a-c emf, a graph of the emf shown by the dotted line, and the current represented by the solid line. The voltage varies and alternates from maximum in one direction, point 1 on the graph, to maximum in the opposite direction, point 4, and back to the original value, point 5.

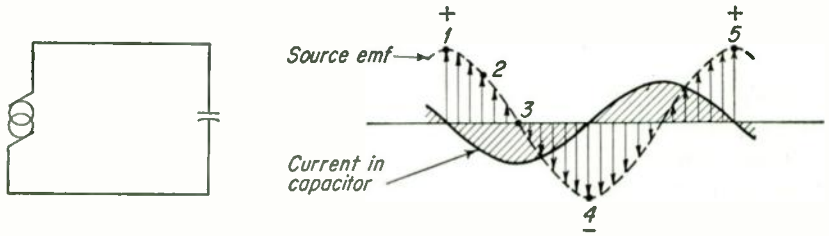


FIG. 6.12. Voltage and current phase relationships in a purely capacitive circuit.

As the source emf increases toward a maximum, more and more electrons are forced into the capacitor. At the instant of maximum pressure, point 1, the capacitor is charged; there will be no electrons *moving* into the capacitor or in motion at any place in the circuit. The condition that exists is maximum pressure but no current (Figs. 6.12 and 6.13*a*).

The emf is at a maximum value for only an instant, and then begins to fall off. As the electric pressure becomes less, all the electrons that had been forced into the capacitor as it was charged comprise an opposing emf greater than the decreasing source emf, and current begins to move out of the negative plate of the capacitor in a direction *opposite* to the source pressure. This is shown in Fig. 6.13*b*, and by point 2 in Fig. 6.12.

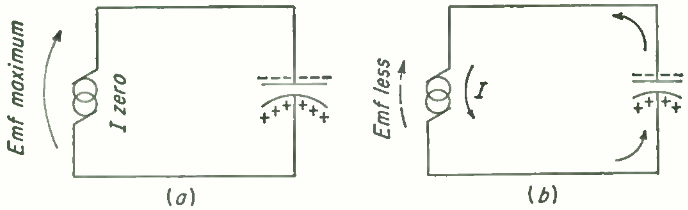


FIG. 6.13. (*a*) As the voltage reaches maximum, the current ceases to move. (*b*) As the emf decreases, current flows out of the capacitor.

The source emf continues to decrease, and the current flows out of the capacitor in a direction opposite to the emf, until the emf reaches zero and reverses. Then the current will be moving in the same direction as the source voltage. At the instant the voltage reaches zero, the number of electrons moving from one plate to the other attains a maximum value, as indicated at point 3 on the graph. From now on, as the emf increases toward maximum (in the negative direction on the graph) the capacitor is charging. When the source emf reaches maximum the capacitor reaches maximum charge and the number of electrons moving into it will be zero. The condition that exists is again maximum source voltage and no current flow in the circuit (Fig. 6.12, point 4).

It should be noted that at point 3 on the graph, the current is at a maximum in the negative direction. The voltage does not reach maximum in the negative direction until 90° later. Therefore the current leads the voltage in a purely capacitive circuit by 90°.

However, the applied voltage and the current will be 90° out of phase only when there is no resistance in the circuit. With any series resistance in the circuit the difference in phase will be less than 90°. The phase difference decreases as the proportion of resistance to capacitive reactance increases. When the circuit has a small value of capacitive reactance and proportionately large resistance, the circuit is predominantly resistive and the phase approaches 0°.

**6.17 Considerations When Selecting Capacitors.** When replacing or purchasing capacitors, you should consider several factors, as follows:

1. *Working Voltage.* If the circuit in which the capacitor is to be used is a 350-volt circuit, purchase a capacitor with a working-voltage rating at least 10 to 20 per cent higher than 350 volts.

2. *Capacitance.* Replace with a capacitor having as nearly the same capacitance as possible.

3. *Type of Dielectric.* For RF a-c, mica, air, vacuum, or ceramic dielectric capacitors are suitable. For AF a-c, mica, ceramic, or paper dielectric capacitors are suitable. For d-c filter circuits, paper or electrolytic capacitors are suitable.

4. *Physical Size.* Ceramics are usually smaller than mica and paper equivalents. Electrolytics are much smaller than paper.

5. *Cost.* Probable cost, per microfarad, in ascending order: electrolytic, ceramic, paper, mica, air, vacuum.

6. *Variable, Adjustable, or Fixed.* As required by the circuit.

7. *Temperature.* Capacitors in confined areas may become overheated and burn out. In particular, it is not advisable to overheat paper or electrolytic capacitors. Electrolytics dry out near hot tubes, rectifiers, or resistors.

8. *Temperature Coefficient.* Some capacitors have a positive temperature coefficient (increase capacitance with increase of heat); others have a negative temperature coefficient (decrease capacitance with an increase of heat); and others have a zero temperature coefficient (no change of capacitance with an increase of heat). This is only important when exact capacitance values are required, as in oscillator circuits.

**6.18 Capacitance Color Code.** Fixed capacitors may be marked with their capacitance and working voltage. The markings will be either in printed numbers or in colors, using the same number-color code used with resistors (refer to Sec. 1.13).

The simplest of the generally used codes is the three-dot EIA code, used with capacitors with a rating of 500 working volts and a tolerance of 20 per cent, plus or minus the coded value. An example of such a 580-$\mu\mu$f capacitor is shown in Fig. 6.14.

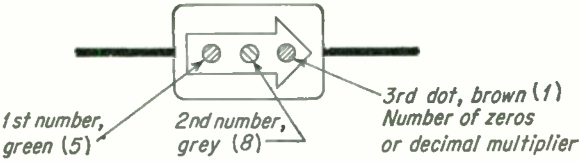


FIG. 6.14. A three-dot EIA 580-$\mu\mu$f mica capacitor.

The six-dot EIA code includes a marking of the voltage rating and the tolerance as well as three numbers and a multiplier. The tolerance in per cent is indicated by the numbers assigned to the colors given in Table 1.2 (Sec. 1.13); absence of color represents a tolerance of 20 per cent. The voltage rating is 100 times the color-code number. Thus, yellow equals 400 volts. An example of a 7,500-$\mu\mu$f 500-volt 10 per cent–tolerance capacitor is shown in Fig. 6.15.

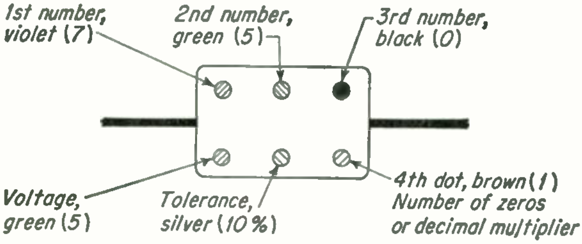


FIG. 6.15. A six-dot EIA 7,500-$\mu\mu$f 500-volt 10 per cent–tolerance capacitor.

The Joint Army-Navy (JAN) code also uses six dots, but only five are usually of general significance. If paper capacitors, the first dot is silver; if mica, it is black. An example of a 4,700-$\mu\mu$f mica 5 per cent–tolerance capacitor is shown in Fig. 6.16.

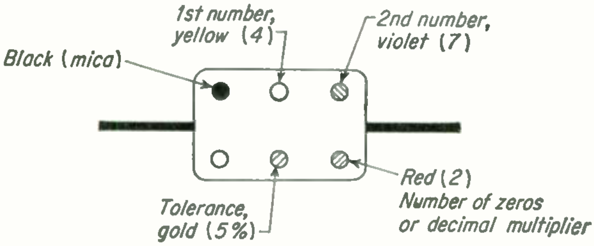


FIG. 6.16. A six-dot JAN 4,700-$\mu\mu$f mica 5 per cent–tolerance capacitor.

Some ceramic capacitors are cylindrical and marked with a series of dots. An example of a 3,800-$\mu\mu$f 10 per cent–tolerance capacitor is shown in Fig. 6.17.

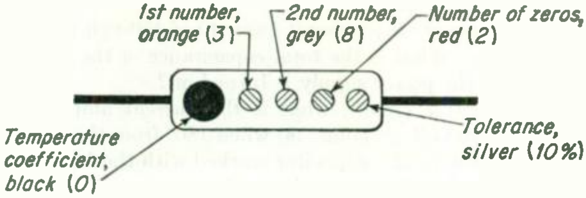


FIG. 6.17. A 3,800-$\mu\mu$f 10 per cent–tolerance zero-temperature-coefficient ceramic capacitor.

The *temperature coefficient* is the degree by which the capacitor will change its capacitance with a change in temperature. If it does not change its capacitance at all, it has a zero coefficient. If it increases capacitance with increased temperature, it has a positive coefficient. If the coefficient is $-150$, the capacitance will decrease 150 parts per million per degree centigrade increase in temperature. Some color-coded temperature coefficients are given in Table 6.2.

Table 6.2

| | |
|---|---|
| Black | 0 |
| Orange | −150 |
| Violet | −750 |
| Gray | 30 |
| White | 500 |

## Practice Problems

**1.** A 0.1-$\mu$f capacitor and an 8-meg resistor are connected across a 500-volt d-c source. How long does it take for the capacitor to attain a charge (*a*) equivalent to 63 per cent of the source voltage, (*b*) essentially equivalent to the source voltage?

**2.** A fixed air dielectric capacitor is made up of seven plates laid one on top of the other, each having 3.5 in.$^2$ of surface area and each separated from adjacent plates by 0.002 in. Alternate plates are connected together. What capacitance does the capacitor have (*a*) in microfarads, (*b*) in micromicrofarads?

**3.** A 4-$\mu$f capacitor is connected across a 600-volt d-c power supply and then disconnected. (*a*) How much electrical energy will a person receive if he holds his fingers on the two terminals of the charged capacitor? (*b*) How many electrons would pass through his flesh before the capacitor became completely discharged? (*c*) Do you think that this would be enough to kill him?

**4.** If the charged capacitor in problem 3 is disconnected from the power supply and is then connected across an uncharged 4-$\mu$f capacitor, what voltage drop will appear across the two capacitors in parallel?

**5.** What is the capacitive reactance of a capacitor having 0.2 $\mu$f in a 15.9-kc circuit?

**6.** What is the reactance of a 0.01-$\mu$f capacitor to 3 kc a-c?

**7.** What is the capacitive reactance of a capacitor having 400 $\mu\mu$f in a 3.8-Mc circuit?

**8.** If a capacitor has 1,500 ohms reactance to a frequency of 8 Mc, what reactance will it have to a frequency of 400 kc?

9. When a 3-μf capacitor is connected across an 800-cycle signal generator producing an a-c of 60 volts rms, how much current flows in the circuit?

10. How much voltage will be developed across the capacitor when a capacitor and resistor are in series across a 100-volt a-c power line, if the capacitive reactance is 300 ohms and the current 200 ma?

11. A 400-volt power-supply filter circuit has a 40-μf 450-volt and an 80-μf 150-volt capacitor in parallel. (*a*) What is the total capacitance of the two capacitors? (*b*) What will happen when the power supply is turned on?

12. In a purely capacitive circuit, what is the current amplitude (*a*) when the current is 270° from a zero voltage point, (*b*) when 180° from the zero point?

13. What is the capacitance of a capacitor marked with the following dot sequence: (*a*) Red, green, yellow? (*b*) Blue, gray, brown?

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

1. How many micromicrofarads are there in one microfarad? (6.1) **[3]**

2. What precaution should be observed when connecting electrolytic capacitors in a circuit? (6.7) **[3]**

3. What is the reactance value of a capacitor of 0.005 μf at a frequency of 1,000 kc? (6.12) **[3]**

4. If capacitors of 1, 3, and 5 μf are connected in parallel, what is the total capacitance? (6.14) **[3]**

5. What is the unit of capacitance? (6.1) **[3]**

6. If the specific inductive capacity of a capacitor dielectric material between the capacitor plates were changed from 1 to 2, what would be the resultant change in capacitance? (6.2) **[3 & 6]**

7. What effect does a change in the dielectric constant of a capacitor dielectric material have upon the capacitance? (6.2) **[3 & 6]**

8. Explain the effect of adding plates upon the capacitance. (6.2) **[3 & 6]**

9. The charge in a capacitor is stored in what portion? (6.5) **[3 & 6]**

10. State the formula for determining the quantity of charge of a capacitor. (6.6) The energy stored in a capacitor. (6.5) **[3 & 6]**

11. Given two identical mica capacitors of 0.1 μf capacitance each. One of these is charged to a potential of 125 volts and disconnected from the charging circuit. The charged capacitor is then connected in parallel with the uncharged capacitor. What voltage will appear across the two capacitors connected in parallel? (6.6) **[3 & 6]**

12. What factors determine the charge stored in a capacitor? (6.6) **[3 & 6]**

13. The voltage drop across an individual capacitor of a group of capacitors connected in series across a potential is proportional to what factors? (6.15) **[3 & 6]**

14. If capacitors of 5, 3, and 7 μf are connected in series, what is the total capacitance? (6.15) **[3 & 6]**

15. What is the formula used to determine the total capacitance of three or more capacitors connected in series? (6.15) **[3 & 6]**

16. Having available a number of capacitors rated at 400 volts and 2 μf each, how many of these capacitors would be necessary to obtain a combination rated at 1,600 volts and 1.5 μf? (6.15) **[3 & 6]**

17. What is the reactance of a capacitor at the frequency of 1,200 kc if its reactance is 300 ohms at 680 kc? (6.13) **[4]**

18. What is meant by the time constant of an RC circuit? (6.1) **[4 & 6]**

19. What factors determine the breakdown voltage rating of a capacitor? (6.4) **[6]**

20. What is the meaning of electrolyte? (6.7) **[6]**

**21.** Explain the principle of operation of an electrolytic capacitor. What precaution should be observed when connecting electrolytic capacitors in series? (6.7) **[6]**

**22.** What is a desirable feature of an electrolytic capacitor as compared with other types? (6.7) **[6]**

**23.** What is the total reactance when two capacitances of equal value are connected in series? (6.15) **[6]**

**24.** What is the reactance of a 0.01-$\mu$f capacitor at a frequency of 3,000 cycles? (6.18) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**1.** What is the primary function of a capacitor? (6.1)

**2.** What is meant by the time constant of a resistance-capacitance circuit? (6.1)

**3.** What is the time constant of a 4-$\mu$f capacitor and a 1-meg resistor? (6.1)

**4.** What is the formula for computing the reactance of a capacitor? (6.13)

**5.** What is the formula for determining the total capacitance of two or more capacitors in series? (6.15) In parallel? (6.14)

**6.** What is the unit of measurement of capacitance? (6.1)

# CHAPTER 7

# ALTERNATING-CURRENT CIRCUITS

**7.1 Effects of Inductance, Capacitance, and Resistance.** Radio is a study of alternating currents of various frequencies, operating in many different types of circuits.

In previous chapters it was pointed out that inductance alone in a circuit has the property by which it (*a*) opposes any change in current, (*b*) produces an electromagnetic field around itself, (*c*) tends to limit a-c flow in the circuit, (*d*) passes d-c without attenuation, and (*e*) produces a phase difference of 90°, with the current lagging the voltage of the circuit.

Capacitance alone in a circuit has the property by which it (*a*) opposes any change in voltage, (*b*) produces an electrostatic field between its plates, (*c*) tends to limit a-c flow in the circuit, (*d*) blocks d-c flow, and (*e*) produces a phase difference of 90°, with the voltage lagging the current of the circuit.

Resistance alone in a circuit limits the current that can flow at a given voltage, but produces no phase difference between the current and voltage of the resistance.

**7.2 Inductance and Resistance in Series.** When an inductance and resistance in series are connected across a source of alternating emf, as indicated in Fig. 7.1, an alternating current flows in the circuit. It has been explained that either resistance alone or inductance alone in a circuit will limit the current that flows.

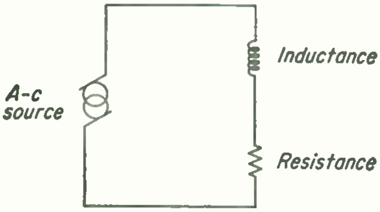


Fig. 7.1. Inductance and resistance in series across an a-c source.

With resistance alone in the circuit, the current and voltage will be in phase, all the power in the circuit will be converted to heat, and the formula used to compute $E$, $I$, and $R$ will be the Ohm's-law formula $I = E/R$.

With inductance alone in the circuit, the current and voltage will be 90° out of phase, all the power in the circuit will be expended in producing a magnetic field around the coil during one-half of the a-c cycle, and then all the power will be returned to the circuit again during the other half of the cycle. No power is actually "lost" in heat. The formula used to compute $E$, $I$, and $R$ in reactive circuits is $I = E/X$.

With both resistance and inductance in a series a-c circuit, it is often necessary to compute current, voltages, impedance, phase angle, volt-amperes (apparent power), true power, and power factor.

If the inductance value and the a-c frequency are known, the inductive reactance of the coil in ohms can be determined by the formula $X_L = 2\pi FL$, where $F$ is in cycles, and $L$ is the inductance in henrys.

Since the load in Fig. 7.1 is not purely resistive, the total opposition will not be the resistance value alone. The opposition of the load is not purely reactive either and will not be the reactance value alone. Instead, a value that is a resultant of the resistance and reactance will have to be determined. This value will be called the *impedance* of the circuit. The symbol assigned to it in a-c problems is $Z$, and it is measured in ohms.

While reactance acts as an opposition, and in some ways may be considered similar to resistance, it must be considered to be setting up its opposition at right angles to the opposition of resistance rather than opposing in the same direction. This can be shown by a vector diagram such as Fig. 7.2*a*. The vector diagram indicates, by the relative lengths of the vector arrows, a circuit in which the resistance value in ohms is less than the reactance value in ohms. The actual a-c opposition will be something more than either the $X_L$ or the $R$ values alone, but how much?

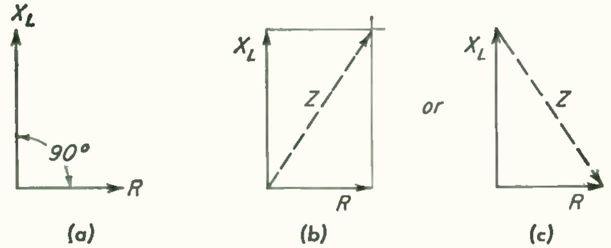


FIG. 7.2. Reactance and resistance vectors plotted at right angles. The third side of the right triangle represents the impedance.

To determine the actual value of opposition, or impedance, lines may be drawn parallel to the resistance vector and to the reactance vector, forming a parallelogram as shown in Fig. 7.2*b*. The length of the dotted vector $Z$ from the point of origin of the vector arrows diagonally across the parallelogram indicates the impedance of the circuit.

The triangle made by the $R$ side, the $Z$ side, and the side equivalent in length to the $X_L$ vector is a right triangle, since one of its angles is 90°.

It is possible to determine the numerical value of the $Z$ side of the right triangle, if the $R$ and $X_L$ sides are known, by using the Pythagorean theorem, which states: *The square of the hypotenuse of a right triangle is equal to the sum of the squares of the other two sides.* (The hypotenuse is the side opposite the right angle, the $Z$ side in this case.)

The Pythagorean theorem can be stated in formula form:

$$Z^2 = R^2 + X_L^2$$

Taking the square root of both sides of the equation, the formula becomes

$$\sqrt{Z^2} = \sqrt{R^2 + X_L^2}$$
$$Z = \sqrt{R^2 + X_L^2}$$

This formula can be used in a problem such as the following:

The resistance in a circuit is 3 ohms, and the inductive reactance is 7 ohms. What is the impedance? Figure 7.3 illustrates the circuit.

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{3^2 + 7^2} = \sqrt{9 + 49} = \sqrt{58} = 7.61 \text{ ohms}$$

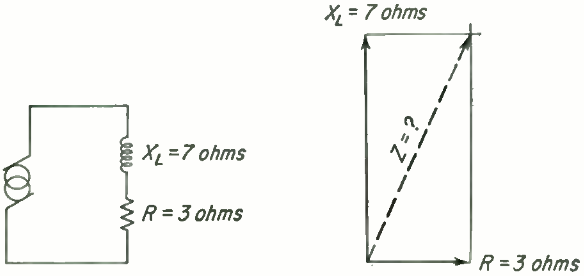


FIG. 7.3. Schematic and vector diagrams of the problem: What is the impedance value if $R$ is 3 ohms and $X_L$ is 7 ohms?

With the impedance value it is possible to solve problems involving Ohm's law in a-c circuits by substituting the $Z$ value for the $R$ in the d-c Ohm's-law formulas. The formulas in Table 7.1 are for use in d-c circuits (negligible reactance), in reactive circuits (negligible resistance), and in a-c circuits ($R$ and $X$ involved).

**Table 7.1 Ohm's-law Formulas**

| For d-c circuits | For purely reactive circuits | For a-c circuits |
|---|---|---|
| $I = \frac{E}{R}$ | $I = \frac{E}{X}$ | $I = \frac{E}{Z}$ |
| $E = IR$ | $E = IX$ | $E = IZ$ |
| $R = \frac{E}{I}$ | $X = \frac{E}{I}$ | $Z = \frac{E}{I}$ |

In the example problem used above, the impedance was computed to be 7.61 ohms. If a current of 10 amp is flowing through the circuit, the voltage of the source must be

$$E = IZ = 10(7.61) = 76.1 \text{ volts}$$

In problems such as, "What is the impedance of a solenoid-type coil if its resistance is 5 ohms and 0.3 amp flows through the winding when 110 volts at 60 cycles is applied to the solenoid?" both current and voltage are given. Using Ohm's law for a-c circuits, $Z = E/I$, or 110/0.3, or 367 ohms. Neither the 5 ohms resistance nor the frequency of 60 cycles is needed to solve for the impedance.

**7.3 The Phase Angle.** The current in an inductance lags the voltage across it by 90°. As long as the inductance itself has zero or negligible resistance, the *phase angle* of the voltage and current of the coil will be 90°.

The current through a resistance will always be in phase with the voltage across it and have a phase angle of 0°.

When there is both resistance and reactance present in the circuit, the phase angle of the circuit as a whole will be neither 90 nor 0° but some intermediate value. This will be the phase angle that is seen by the source as it looks into the whole circuit connected across it. The number of degrees will be equal to the angle formed between the $Z$ and the $R$ sides of the $Z$, $R$, and $X$ triangle of the circuit. This phase angle is usually indicated by the Greek letter $\theta$ (theta). Figure 7.4 illustrates a circuit having 10 ohms inductive reactance and 20 ohms resistance. The impedance value is determined as illustrated previously:

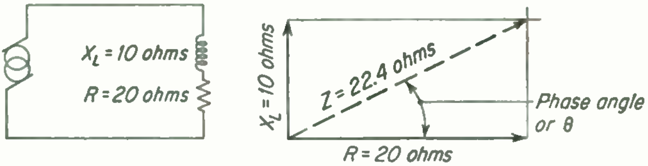


FIG. 7.4. The phase angle is formed by the resistance and impedance sides of the vector triangle.

$$Z = \sqrt{R^2 + X^2} = \sqrt{(20)^2 + (10)^2} = 22.4 \text{ ohms}$$

One method of determining the number of degrees of the phase angle is to draw the vector diagram of the resistance and reactance of the circuit in question and with a protractor measure the angle between the $R$ and $Z$ sides.

Another method of determining the phase angle is to compute the numerical value of the ratio of the two sides, $R$ and $Z$. This *ratio* of $R$ to $Z$, or $R/Z$, has been given the name *cosine*. In the problem above, the cosine of $R/Z$ is equal to 20/22.4, or 0.8928.

In trigonometric tables (Appendix A), it is possible to look up the angle associated with the cosine value of 0.8928. By searching through the cosine, or *cos*, values given in the tables, a number approximately equal to 0.8928 will be found. In this particular problem, a cosine value of 0.8910 is found to equal 27°. By more careful searching it will be found that 0.8926 is equal to 26.8°. This is close enough for general use. The angle by which the current lags the voltage in this particular inductive circuit is 26.8°. The circuit has a phase angle of 26.8°.

Although the phase angle is usually found by using the cosine ratio $R/Z$, it can also be found by using the ratio of sides $X/Z$, which is known as the *sine*, or *sin*, value. The angle associated with the sine value will be the same phase angle. The ratio of sides $X/R$ is known as the *tangent*, abbreviated *tan*, and may also be used to determine the phase angle.

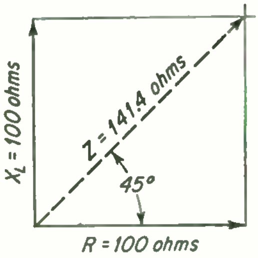


FIG. 7.5. Vector diagram of a circuit having equal resistance and inductive reactance.

In a circuit having equal values of inductive reactance and resistance, the vector arrows are equal in length, the impedance will be 1.414 times the resistance (or reactance) value, and the phase angle will be half of 90°, or 45°, as shown in Fig. 7.5.

**7.4 Vector Addition.** The circuit having 10 ohms inductive reactance, 20 ohms resistance, and 22.4 ohms impedance, but with an ammeter added indicating 10 amp of current, is shown in Fig. 7.6.

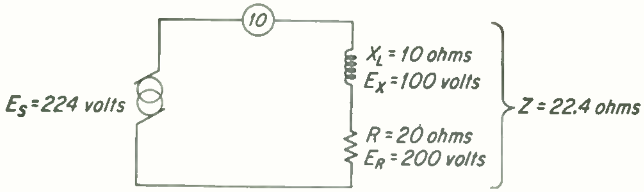


FIG. 7.6. A 224-volt source will develop a reactive 100 volts and a resistive 200 volts across this series circuit.

If 10 amp flows through a reactance of 10 ohms, the voltage drop across the reactance will be

$$E_{X_L} = IX_L = 10(10) = 100 \text{ volts}$$

If 10 amp flows through a resistance of 20 ohms, the voltage drop across the resistance will be

$$E_r = IR = 10(20) = 200 \text{ volts}$$

The sum of the two voltage drops, the reactive 100 volts and the resistive 200 volts, would appear to equal 300 volts. However, the voltage across the reactance will lead the current through it by 90°. The voltage across the resistance is in phase with the current through it. These two voltages, being 90° out of phase, must be added *vectorially*, as shown in Fig. 7.7. This will be recognized as being similar to the determination of the impedance of the circuit when reactance and resistance values in ohms were used. In this case, reactive and resistive *voltages* are plotted 90° out of phase, and the resultant is the source voltage value.

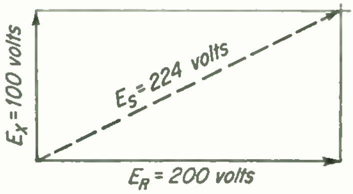


FIG. 7.7. Vector representation of the source voltage and the distribution of reactive and resistive voltages.

Using the Pythagorean theorem again, the formula for determining the resultant voltage becomes

$$E_s^2 = E_R^2 + E_X^2$$
$$E_s = \sqrt{E_R^2 + E_X^2}$$

where $E_s$ is the source voltage; $E_R$ is the resistive voltage; and $E_X$ is the reactive voltage.

Substituting the values in the problem above,

$$E_s = \sqrt{(200)^2 + (100)^2} = \sqrt{40{,}000 + 10{,}000} = 224 \text{ volts}$$

Here is a case where 200 and 100 volts equals 224 volts, but only if they are added *vectorially*, at right angles.

The total voltage may also be determined by using the Ohm's-law formula $E = IZ = 10 \times 22.4 = 224$ volts. An important point here is the understanding that the source voltage represents a resultant of the reactive and resistive voltage drops across the circuit.

In an a-c circuit involving inductance, capacitance, and resistance in series, the sum of all the voltage drops in the circuit will add up to more than the source voltage unless they are added vectorially.

**7.5 Apparent and True Power.** In the simpler series-type circuits such as the one described so far, the only part of the circuit actually losing power is the resistor. The resistor loses power in the form of heat whenever current flows through it. The current flowing through the coil produces energy that is stored in the magnetic field around the coil. When the current alternates, the magnetic field collapses and returns all its energy to the circuit. Therefore there is no loss of power in the inductance itself. This is considering the inductance to have negligible resistance in its turns and no coupling to any other external circuit.

The series circuit used before, but with a voltmeter included, is shown in Fig. 7.8. All known values are indicated. The *apparent power* can be determined by using the visually apparent values shown by the voltmeter (224 volts) and by the ammeter (10 amp). Since power can be determined by the formula $P = EI$, the *apparent* power of the circuit is 224(10), or 2,240 watts.

The power lost in *heat* is usually computed by the formula $P = I^2R$, in this case $10^2(20)$, or 100(20), or 2,000 watts. This is called the *true power* of the circuit.

The true power of this simple circuit can also be determined by using either of the formulas $P = E^2/R$ or $P = EI$, if the voltage across the *resistor* is used in the equation. However, experience has shown that the use of the formula $P = I^2R$ to solve for true power results in fewer difficulties for a beginner, and it should be used if possible.

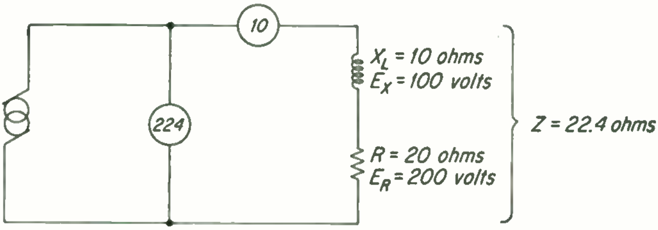


FIG. 7.8. The apparent power is the value obtained when the source voltage is multiplied by the current read on the meters.

The use of the term *volt-amperes* (abbreviated volt-amp, or VA) is preferred by many to the term apparent power. In a purely reactive circuit, there may be volts forcing amperes to flow, but if all the energy stored in the field of the reactance is returned to the circuit, there is only an apparent power but no actual loss of power.

**7.6 Power Factor.** When the true and apparent powers are expressed as a ratio, with the true power above and the apparent power below, a decimal number between zero and 1.0 results. The ratio of true to apparent power in a circuit is known as the *power factor* of the circuit. This can be expressed as

$$\text{pf} = \frac{\text{true power}}{\text{apparent power}} = \frac{I^2R}{\text{VA}}$$

where $I^2R$ is the true power; VA is the volt-amperes as determined by a voltmeter and ammeter; and pf is the power factor.

In the circuit used as the example so far, this ratio is

$$\text{pf} = \frac{2{,}000 \text{ watts}}{2{,}240 \text{ watts}} = 0.8928$$

Note the reappearance of the number 0.8928. This will be recognized as the cosine value determined by dividing the resistance by the impedance. Besides representing the cosine of 26.8°, this decimal figure 0.8928 is the power factor of the circuit. Since either the ratio of true to apparent power or the ratio of resistance to impedance produces the same decimal figure, either ratio can be used to determine the power factor of a *series* circuit. Thus, three methods of determining power factor are

$$\text{pf} = \frac{I^2R}{\text{VA}} = \frac{R}{Z} = \cos\theta$$

By algebraic rearrangement, the true power can be computed by multiplying the apparent power by the power factor:

$$P = \text{VA}(\cos \theta)$$

The power factor is in reality a comparison of the amount of power a circuit is apparently using and what it is actually using. It is often expressed as a percentage. Thus, a power factor of 0.8928 can be said to be a power factor of 89.28 per cent.

Power factor is important when wiring a circuit. Consider an electric circuit having a power factor of 0.5, a source voltage of 100 volts, and an impedance of 20 ohms. According to Ohm's law the current in the circuit is $I = E/Z$, or $^{100}/_{20}$, or 5 amp. An ammeter in the circuit will read 5 amp. Apparent power is the product of source voltage and current through the source, in this case 100(5), or 500 watts. Since true power is apparent power times power factor (volt-amp times cos $\theta$), the load in the circuit must be receiving 100(5)(0.5), or 250 watts. The wires of the circuit must carry the current of 5 amp that is shown by the ammeter instead of only 2.5 amp normally required when 100 volts produces 250 watts of power in a device.

Why is 5 amp flowing when only 2.5 amp should produce the power? The answer lies in the fields developed around the reactance of the circuit. Energy is required to build up the field of a reactance, but this energy is returned to the circuit when the field collapses. The energy is carried in the form of current from the source and is returned as current to the source. At the *same time* the load is constantly demanding energy, and therefore current.

It must be understood that apparent power does not mean *fictitious* power. It has its effect in electric circuits. The engineers must build circuits in which the true power approaches the apparent power (high power factor), thereby enabling the use of smaller connecting wires, lessening the cost of installation, and improving the operation of electrical equipment.

If the reactance causing a low power factor in a circuit is due to inductive reactance, it is possible to raise the power factor by adding some capacitive reactance to the circuit to balance out the inductive reactance, leaving the circuit more nearly resistive and with a higher power factor.

The power factor of a circuit may be referred to as being either *leading* or *lagging*. A lagging power factor indicates the *current is lagging* the voltage in the circuit (inductive circuit). A leading power factor means the *current is leading* the voltage (capacitive circuit).

An example of a problem involving a power factor is the following:

If a 220-volt 60-cycle line delivers 100 watts at 80 per cent power factor to a load, what is the phase angle between the line current and line voltage, and how much current flows in the line?

First, the cosine of the phase angle is the power factor. This is indicated by

$$\cos\theta = \text{pf} = 80\% = 0.80$$

From a table of trigonometric functions, 0.80 is found to be the cosine of 36.9°, which is the phase angle between the current and voltage. (It is impossible to tell whether the current is leading or lagging the voltage in this circuit from the information given.)

Second, in practice, when power is mentioned, *true power is understood.* Therefore the 100 watts in the problem must be assumed to be true power. Since true power equals volt-amperes times power factor, or

$$P = \text{VA(pf)} = \text{VA}(\cos\theta)$$

then

$$\text{VA} = \frac{P}{pf} = \frac{100}{0.80} = 125$$

The volt-amperes value represents the product of what would be read by a voltmeter across the load and an ammeter in series with the load. Rearranging the apparent-power formula $P = \text{VA}$ to read $A = P/V$, the current is

$$A = \frac{P}{V} = \frac{125}{220} = 0.568 \text{ amp}$$

**Practice Problems**

1. A circuit consists of an inductance having a reactance value of 300 ohms and a resistance of 100 ohms in series. It is connected across a 50-volt a-c source. What is the (*a*) impedance of the circuit, (*b*) apparent-power value, (*c*) true-power value, (*d*) power factor, (*e*) phase angle, (*f*) power lost in heat, (*g*) current in the inductance, (*h*) current in the resistance, (*i*) current in the source?

2. A series inductance and resistance circuit is known to have an impedance of 141 ohms to 500-cycle a-c. An ohmmeter shows the total resistance to be 100 ohms. The circuit is connected across a 120-volt source. What is the (*a*) reactance of the circuit, (*b*) apparent power, (*c*) true power, (*d*) power factor, (*e*) phase angle, (*f*) voltage across the inductance, (*g*) voltage across the resistance?

**7.7 Capacitance and Resistance in Series.** A circuit composed of an a-c source, a capacitor (condenser), and a resistance in series is shown in Fig. 7.9.

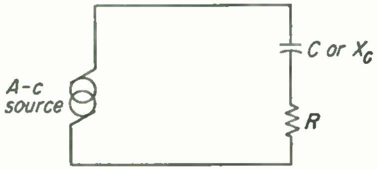


FIG. 7.9. Capacitor and resistor in series across an a-c source.

If the capacitance value and the a-c frequency are known, the capacitive reactance of the capacitor in ohms can be computed by using the formula

$$X_C = \frac{1}{2\pi FC}$$

where $F$ is frequency in cycles; and $C$ is capacitance in farads.

The capacitive-reactance value in ohms can be used in conjunction with the resistance for a-c-circuit computations very much the same as inductive reactance and resistance were used.

As with a coil and resistor in series, the capacitive-reactance vector value may be plotted at right angles to the resistance vector, as shown in Fig. 7.10. Note, however, that the $X_L$ vector was shown pointing upward, but the $X_C$ vector is shown pointing downward, a 180° difference in direction, indicating that $X_L$ and $X_C$ vectors would tend to cancel each other.

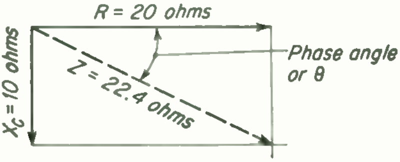


FIG. 7.10. Vector representation of resistance, capacitive reactance, and the resultant impedance.

The vector sum of the capacitive reactance and resistance is the impedance value and is determined by using the same formula:

$$Z = \sqrt{R^2 + X_c^2}$$

With the impedance value in ohms, either the voltage or the current can be computed by using Ohm's-law formulas for a-c circuits:

$$I = \frac{E}{Z} \qquad E = IZ$$

In a series circuit the current is the same in all parts of the circuit at any instant. In a purely capacitive circuit the voltage lags the current by 90°. In a resistive circuit the voltage and current are in phase. In a circuit made up of both $X_C$ and $R$, the phase angle between $E$ and $I$ will be something between 0 and 90°. The phase angle, as in the inductive circuit described previously, may be solved for graphically or by determining the angle represented by the ratio of $R/Z$. The ratio of the resistive voltage drop to the source voltage ($E_R/E_s$) will be proportional to the ratio of resistance to impedance and may also be used to determine phase angle.

A capacitive circuit has a *leading power factor*, found by:

1. Dividing $R$ by $Z$ (pf $= R/Z$)
2. Dividing true power by the apparent power (pf $= I^2R/\text{VA}$)
3. Finding the cosine value of the angle between the current and voltage of the circuit (pf $= \cos\theta$)

Since the ratio of the voltage drop across the resistance to the voltage drop across the source is proportional to the ratio of resistance to impedance, it might also be used to determine power factor in a series circuit:

$$\text{pf} = \frac{E_R}{E_s}$$

The computations of impedance, phase angle, and power factor are performed the same way, regardless of whether the circuit has a coil and resistor in series or a capacitor and resistor in series.

Whereas capacitance can be added to correct for a lagging low power factor, a leading low power factor in a capacitively reactive circuit can be corrected (raised) by adding inductance to the circuit.

**7.8 Inductance, Capacitance, and Resistance in Series.** A circuit containing a coil, capacitor, and resistance all in series across a source of a-c is shown in Fig. 7.11. If the inductance and the capacitance values and the frequency are known, the reactances can be found by applying the usual reactance formulas:

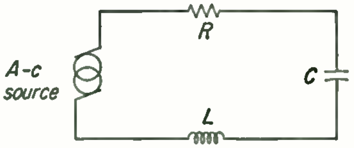


FIG. 7.11. Resistance, capacitance, and inductance in series across an a-c source.

$$X_L = 2\pi FL \qquad X_C = \frac{1}{2\pi FC}$$

With the reactance and resistance values known, the impedance of the circuit can be determined as with the simpler series circuits described before, using the same basic impedance formula:

$$Z = \sqrt{R^2 + X^2}$$

However, when drawing a vector diagram of resistance, inductive reactance, and capacitive reactance in series, the two reactances are plotted in opposite directions and 90° from the resistance. Figure 7.12 illustrates a large value of inductive reactance and a smaller value of capacitive reactance.

Examination of the vector diagram shows that $X_C$ and $X_L$ are each 90° from $R$, but in such directions that they tend to cancel each other. If there is more $X_L$ than $X_C$, as shown, the resultant, or net reactance, will be $X_L$. The net reactance is obtained by subtracting the smaller value from the larger. The complete impedance formula for a series a-c circuit is

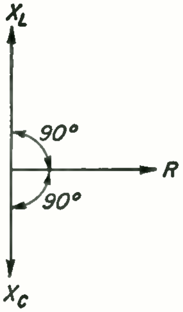


FIG. 7.12. Vectors of inductive and capacitive reactance are plotted 180° out of phase and 90° from the resistance vector.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

In cases where $X_C$ is greater than $X_L$, the formula is

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

*Example:* What is the impedance of a series circuit consisting of a resistance of 4 ohms, an inductive reactance of 4 ohms, and a capacitive reactance of 1 ohm? The circuit and vector diagrams are shown in Fig. 7.13.

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{4^2 + (4 - 1)^2} = \sqrt{16 + 9} = \sqrt{25} = 5 \text{ ohms}$$

If the generator in the problem above produced 50 volts, the current, according to Ohm's law, is

$$I = \frac{E}{Z} = \frac{50}{5} = 10 \text{ amp}$$

Conversely, if the circuit current is known to be 10 amp, the voltage of the source, according to Ohm's law, is

$$E = IZ = 10(5) = 50 \text{ volts}$$

The current through each part of the circuit is 10 amp. This fact bears repeating: In a *series* circuit the current is the same in all parts of the circuit. At any instant when the current reaches its peak value in the resistance, the current is also at a peak value in the inductance and in the capacitance. The *voltage* across the reactances may be out of phase with the current, but the current in all parts of the circuit, including the source, is in phase.

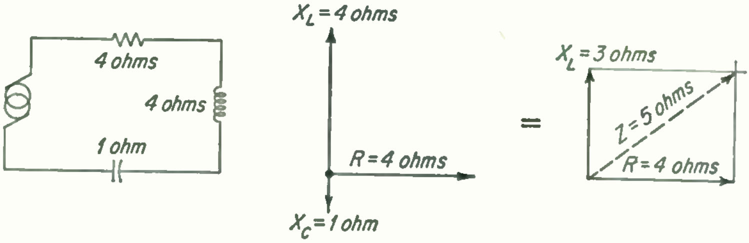


FIG. 7.13. Schematic and vector diagrams of 4 ohms resistance, 4 ohms inductive reactance, and 1 ohm capacitive reactance in series.

The voltage drop across each part of the circuit above, with a current of 10 amp, will be

$$\begin{aligned} E_R &= IR &&= 10(4) = 40 \text{ volts} \\ E_{X_C} &= IX_C &&= 10(1) = 10 \text{ volts} \\ E_{X_L} &= IX_L &&= 10(4) = 40 \text{ volts} \end{aligned}$$

The power factor of the problem above is probably most simply determined, as explained previously, by using the ratio of $R$ to $Z$, or 4/5, which equals 0.80.

If a series circuit has capacitance and inductance but zero resistance, the impedance formula eliminates the $R$ value and becomes

$$Z = \sqrt{(X_L - X_C)^2} = X_L - X_C$$

With no resistance, the phase angle will be 90°. The power factor will be $R/Z$, or $0/Z$, which is equal to zero. With a power factor of zero there must be no loss of power in the circuit. The circuit is completely reactive and behaves as either a purely capacitive or purely inductive circuit, depending on which reactance is greater.

In the special case where $X_L$ equals $X_C$, a condition known as *resonance* occurs. When the impedance formula for a series circuit with zero resistance is applied to a series-resonant circuit, the impedance is

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{0^2 + 0^2} = 0 \text{ ohms}$$

**7.9 Accuracy of Computations.** In problems where the resistance value in a series circuit is *more than 10 times* the net reactance value, for most practical purposes the reactance can be disregarded. Consider the following example:

A series circuit has a resistance of 100 ohms and a reactance of 10 ohms. The impedance is

$$Z = \sqrt{R^2 + X^2} = \sqrt{(100)^2 + 10^2} = \sqrt{10{,}000} = 100.5 \text{ ohms}$$

The 100.5-ohm impedance is within 0.5 per cent of the resistance value of 100 ohms. Most meters used for voltage, current, and resistance measurements are only guaranteed to be accurate within 2 per cent of full scale. This is one reason why mathematical accuracy to the third significant figure is all that is required in general work. For more accurate work, expensive laboratory instruments must be used and accuracy to the fourth or more significant figures becomes practical.

Since the above circuit as a whole acts almost as a pure resistance, the source current and voltage will be nearly in phase and the power factor will approach unity (1).

If the values were reversed, that is, the reactance were more than 10 times the resistance, for most purposes the circuit might be considered to be completely reactive. Simplifications or generalities of this type should be applied with caution, however.

The knowledge that any series circuit has a resistance value much larger than its total reactance value should indicate, even before a problem is worked, what the approximate impedance, phase angle, and power factor should be. If computed answers do not correspond to generalized theory, there is a good possibility that errors were made in the mathematical solving of the problem.

**7.10 Proving Problems.** Occasionally it is possible to work a problem in which members of the equation are squared and an obviously incorrect answer results. This can be demonstrated by the following problem:

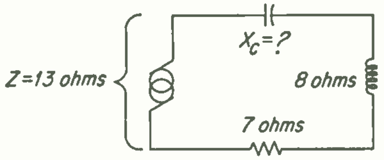


FIG. 7.14

A series circuit contains 7 ohms resistance, 8 ohms inductive reactance, and 13 ohms impedance. What is the capacitive-reactance value? Figure 7.14 shows the diagram of the circuit. Working with the series-circuit formula:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$
$$Z^2 = R^2 + (X_L - X_C)^2$$
$$Z^2 - R^2 = (X_L - X_C)^2$$
$$\sqrt{Z^2 - R^2} = X_L - X_C$$
$$X_C + \sqrt{Z^2 - R^2} = X_L$$
$$X_C = X_L - \sqrt{Z^2 - R^2} = 8 - \sqrt{(13)^2 - 7^2} = 8 - \sqrt{120} = 8 - 10.95 = -2.95 \text{ ohms}$$

When the answer, $-2.95$ ohms, is substituted in the original formula to prove the answer, the impedance works out to be 8.7 ohms instead of the specified 13 ohms. Something is wrong.

Checking back over the original formula, it is found that there are two ways of writing it:

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \qquad \text{or} \qquad Z = \sqrt{R^2 + (X_C - X_L)^2}$$

Apparently the wrong formula was used. By the second formula the problem is solved as

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$
$$X_C = X_L + \sqrt{Z^2 - R^2} = 8 + \sqrt{(13)^2 - 7^2} = 8 + 10.95 = 18.95 \text{ ohms}$$

When the value 18.95 is substituted in the original formula in place of $X_C$, the impedance value proves as 13 ohms.

A vector diagram of the problem would have shown that an $X_C$ greater than the inductive value would be required to produce the 13 ohms impedance and that the formula with a greater $X_C$ would be indicated as the one to use. It is always well to draw a vector representation of an a-c circuit before working it.

### Practice Problems

1. A series circuit has an inductive reactance of 14 ohms, a resistance of 6 ohms, and a capacitive reactance of 6 ohms. What is the (*a*) impedance of the circuit, (*b*) power factor, (*c*) phase angle?

2. An alternating current of 5 amp flows in a series circuit composed of 12 ohms resistance, 15 ohms inductive reactance, and 40 ohms capacitive reactance. What is the (*a*) impedance of the circuit, (*b*) voltage across the circuit, (*c*) power factor, (*d*) phase angle, (*e*) voltage across the coil, (*f*) voltage across the capacitor?

3. A lamp, rated at 100 watts and 115 volts, is connected in series with an inductive reactance of 355 ohms and a capacitive reactance of 130 ohms across a voltage of 220 volts. What is the (*a*) resistance of the lamp, (*b*) impedance of the circuit, (*c*) current of the circuit, (*d*) current through the lamp, (*e*) power factor of the circuit, (*f*) phase angle of the circuit?

4. A potential of 110 volts is applied to a series circuit containing an inductive reactance of 25 ohms, a capacitive reactance of 10 ohms, and a resistance of 15 ohms. What is the (*a*) impedance of the circuit, (*b*) power factor, (*c*) phase angle, (*d*) current in the circuit?

**7.11 The *j* Operator.** The letter *j* is used extensively in electrical engineering as a means of notation, or as a means of labeling the quantity in front of which it is placed. It is known as the *j operator*.

The *j* operator in front of a number indicates that the quantity is 90° (no more and no less) out of phase with something else. It can be considered as a 90° rotation of a vector arrow.

A positive *j* indicates a normal, *counterclockwise* rotation of the vector by 90°. It is possible to express "the 3.7-amp current in this particular capacitive circuit is leading the voltage by 90°" by merely writing *j*3.7 amp. The notation *j*2 volts indicates that the voltage vector is leading the current vector by 90°, which is only true in an inductive circuit, and that the value of the voltage is 2 volts.

A negative $j$ ($-j$) indicates a *clockwise* rotation of the vector by 90°. The sentence "the 4.2-amp current in this inductive circuit is lagging the voltage by 90°" may be expressed by $-j4.2$ amp. The notation $-j83$ volts indicates a capacitively reactive voltage of 83 volts, with the voltage lagging the current by 90°.

The $j$ indicates 90°, and the negative or positive sign prefixing it indicates the direction of vector rotation.

When drawing vectors to represent reactance values, it is standard practice to show the inductive-reactance values 90° ahead of the zero value, or upward. The capacitive-reactance value is shown 90° behind the zero value, or downward. Therefore a $j$ operator before a reactance value such as $j276$ ohms indicates an inductive reactance of 276 ohms, while $-j75$ ohms indicates a capacitive reactance of 75 ohms.

A $j$ operator is not used before an impedance value because impedance assumes some resistance and therefore less than a 90° phase angle.

Information on the $j$ operator is included here more as general information for the student who will find it in other reference reading than as a requirement for basic electrical or radio understanding.

**7.12 Parallel A-C Circuits.** Methods of solving series a-c circuits and for solving parallel circuits are somewhat different. Considerable confusion may result from a carry-over of procedure between the two types. To try to prevent this, and at the same time to introduce two new electrical terms, an entirely different method will be employed to compute the impedance of parallel circuits. Basically, this method is similar to the method of computing resistors in parallel, discussed in the chapter on Direct-current Circuits. Resistors in parallel can be computed by converting the resistance values into their equivalent reciprocal values, their *conductances*, and then by adding the conductances. The symbol used to denote conductance is $G$. The reciprocal of the total conductance is the resistance.

$$G_t = \frac{1}{R} + \frac{1}{R} + \frac{1}{R} \qquad \text{or} \qquad R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

This last formula is used to solve for the total resistance of any number of parallel resistors. It is valid for a-c circuits as well as d-c circuits as long as there is *only resistance* in the circuit. If any reactance is present in any branch of the circuit, the formula will not hold true. However, a variation of this formula can be used.

In order to solve for the impedance, power factor, phase angle, and so on, in circuits having resistance and reactance in parallel, two new terms used in electrical circuitry may become necessary. The first is *sus-*

*ceptance*, the reciprocal of reactance, or $1/X$. It is represented by the symbol $B$ and is measured in mhos, as is conductance.

The second new term is *admittance*, the reciprocal of impedance, or $1/Z$. It is represented by the symbol $Y$ and is also measured in mhos.

In summary, in circuits having resistance and reactance in parallel,

$$G = \frac{1}{R} \qquad B = \frac{1}{X} \qquad Y = \frac{1}{Z}$$

Conductance susceptance ad

**7.13 Inductance and Resistance in Parallel.** To solve for the total impedance of a resistance and reactance in *parallel*, it is important to understand that the *series* impedance formula $Z = \sqrt{R^2 + X^2}$ *cannot* be applied. However, the same type of formula substituting the reciprocal values can be used. The reciprocal of $Z$ is $Y$, the reciprocal of $R$ is $G$, and the reciprocal of $X$ is $B$. Therefore the formula to solve for the *admittance* of a parallel resistance and reactance is

$$Y = \sqrt{G^2 + B^2}$$

The impedance, being the reciprocal of the admittance $Y$, can now be found by dividing the $Y$ value into 1. The circuit shown in Fig. 7.15 is solved:

$$Y = \sqrt{G^2 + B^2} = \sqrt{(0.1)^2 + (0.1)^2} = \sqrt{0.01 + 0.01} = \sqrt{0.02} = 0.1414 \text{ mho}$$

Since $1/Y = Z$, then

$$Z = \frac{1}{0.1414} = 7.07 \text{ ohms}$$

This formula is actually solving a right triangle having $G$, $B$, and $Y$ sides, similar to the right triangle used in series circuits having $R$, $X$, and $Z$ sides. A comparison of the two triangles is shown in Fig. 7.16.

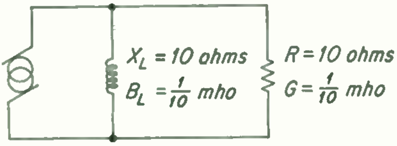


FIG. 7.15. Circuit having inductance and resistance in parallel across an a-c source.

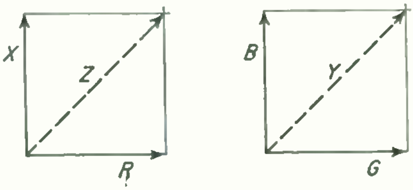


FIG. 7.16. Series-circuit $X$, $R$, and $Z$ vectors compared with parallel-circuit $B$, $G$, and $Y$ vectors.

In *series* circuits the phase angle is the angle between the $R$ and $Z$ sides. In *parallel* circuits the phase angle is similarly the angle between the $G$ and $Y$ sides. If $G$ and $Y$ are known, the phase angle of the whole circuit is equal to the cosine $G/Y$. In the circuit of Fig. 7.15, $G/Y$ is equal to 0.100/0.1414, or 0.707. From a table of trigonometric functions, this angle, the phase angle, is found to be 45°. In this particular case, the angle should be recognized as being 45°, because both the $B$ and $G$ vectors are of equal length.

With the impedance of the circuit known, Ohm's law can be applied to the circuit to solve for either current or voltage. If the source voltage in Fig. 7.15 is 20 volts, the total current in the circuit is

$$I = \frac{E}{Z} = \frac{20}{7.07} = 2.83 \text{ amp}$$

Solving each individual branch separately, the currents are

$$I = \frac{E}{R} = \frac{20}{10} = 2 \text{ amp}$$

$$I = \frac{E}{X} = \frac{20}{10} = 2 \text{ amp}$$

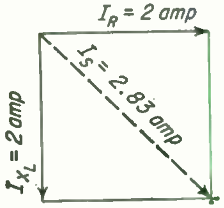


FIG. 7.17. In parallel circuits the *currents* of the branches can be vectored.

As with the vector diagram of $B$ and $G$ in a parallel circuit, it is found that a vector diagram of the branch *currents* will also plot in such a way that the phase angle, and therefore the power factor, can be determined from it. Figure 7.17 shows the current vector diagram of the circuit described above, using the resistive current and the inductive-reactance current, which together produces a resultant that represents the source current of 2.83 amp.

In parallel resistance and reactance circuits, where resistance and reactance are not present in the *same* branch, the circuit may also be solved without the use of susceptance, conductance, and admittance by assuming a convenient source voltage and solving for the separate branch circuits. By using the current vector triangle of $I_R$, $I_X$, and $I_s$, the cosine $I_R/I_s$ will be the power factor and the angle to which it is equivalent will be the phase angle. Increasing or decreasing the assumed source voltage will have no effect on the *ratio* of the currents, and therefore will give the same phase angle and power factor.

*Example:* What is the impedance of a circuit having an inductance with a reactance of 50 ohms in parallel with a resistance of 25 ohms? Assuming a 100-volt source, Fig. 7.18 illustrates the schematic and vector diagrams.

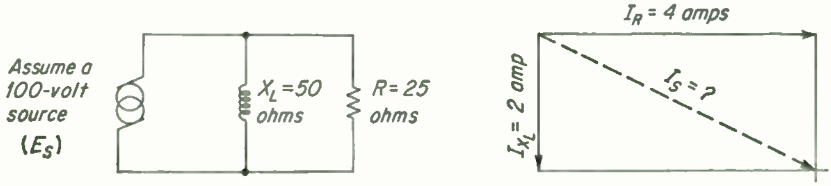


FIG. 7.18. A convenient source voltage can be assumed when computing the impedance of a parallel circuit.

$$I_r = \frac{E_s}{R} = \frac{100}{25} = 4 \text{ amp}$$

$$I_{XL} = \frac{E_s}{X_L} = \frac{100}{50} = 2 \text{ amp}$$

$$I_s = \sqrt{I_r^2 + I_{XL}^2} = \sqrt{4^2 + 2^2} = \sqrt{16 + 4} = \sqrt{20} = 4.48 \text{ amp}$$

$$Z = \frac{E_s}{I_s} = \frac{100}{4.48} = 22.2 \text{ ohms}$$

**7.14 Capacitance and Resistance in Parallel.** Capacitance and resistance in parallel are computed the same as inductance and resistance, except that the susceptance or reactive current vectors are drawn in opposite directions.

### Practice Problems

1. A coil with a reactance value of 25 ohms is connected across a 50-volt source. A resistance of 40 ohms is also connected across the same source of emf. What is (*a*) the admittance of the circuit, (*b*) the impedance of the circuit, (*c*) current in the coil, (*d*) current in the resistor, (*e*) power being dissipated?

2. A 120-volt power source delivers 200 watts at 90 per cent power factor to a parallel resistance and inductance. What is the (*a*) phase angle, (*b*) current in the line, (*c*) impedance of the load, (*d*) apparent power of the load?

3. A 1-$\mu$f capacitor is connected across a 530-ohm electric light operating on a 110-volt 60-cycle line. What is the (*a*) impedance offered to the source, (*b*) power factor of the circuit, (*c*) phase angle, (*d*) current drawn by the light, (*e*) current in the wires of the line?

**7.15 Capacitance, Inductance, and Resistance in Parallel.** When capacitance, inductance, and resistance are all in parallel, the same voltage is across all branches. The current in the inductance branch will lag the source voltage by 90°, and the current in the capacitance branch will lead the source voltage by 90°. Therefore the two reactive currents will tend to cancel each other as far as the source is concerned. If these reactive currents happen to be equal, the only current that the source must supply is that of the resistive branch. This special condition, where $X_L = X_C$, is known as *parallel resonance* and is discussed in the next chapter.

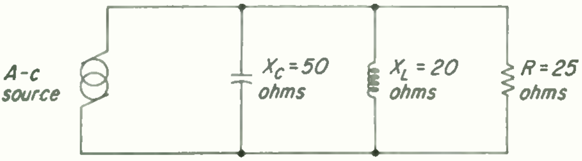


FIG. 7.19. Resistance, capacitive, and inductive reactance in parallel across an a-c source.

When the inductive reactance and the capacitive reactance are not equal in a parallel circuit, as shown in Fig. 7.19, the circuit can be worked by either the admittance method or by the current vector method.

By the admittance method, the reactances are converted to their susceptance values and the resistance to its conductance. For the example circuit these are:

re clance $X_C = 50$ ohms $\quad B_C = 1/50 = 0.02$ mho subseptance
$X_L = 20$ ohms $\quad B_L = 1/20 = 0.05$ mho
resistance $R = 25$ ohms $\quad G = 1/25 = 0.04$ mho conductance

Since inductive and capacitive reactances are plotted 180° out of phase, the inductive and capacitive susceptances are also plotted in opposite directions. As a result, the net susceptance of the circuit will be the difference between the inductive and capacitive susceptances. In this case, the net susceptance is

$$B = 0.05 - 0.02 = 0.03 \text{ mho}$$

[If the reciprocal of the difference of the *reactances* (50 − 20 = 30) had been used, the net value would have worked out to be 0.0333 mho, which is incorrect.]

The net susceptance is 0.03 mho, and the conductance is 0.04 mho. Substituting these values in the admittance formula,

$$Y = \sqrt{G^2 + B^2} = \sqrt{(0.04)^2 + (0.03)^2} = \sqrt{0.0016 + 0.0009}$$
$$= \sqrt{0.0025} = 0.05 \text{ mho}$$

Since $Z = 1/Y$, then

$$Z = \frac{1}{0.05} = 20 \text{ ohms}$$

Using the impedance value and assuming a source emf of 100 volts, the current of the whole circuit can be found by using Ohm's law:

$$I = \frac{E}{Z} = \frac{100}{20} = 5 \text{ amp}$$

Both the power and power factor of the whole parallel circuit are determined almost the same as in series circuits. The true power is the power dissipated in the resistance and is usually found by the formula $P = I^2R$, where $I$ is the current flowing through the resistance ($I_R = E/R = 100/25 = 4$ amp). For the circuit in Fig. 7.19, $P = I^2R$, or $4^2(25)$, or 400 watts. True power may also be found by multiplying the apparent power by the power factor.

The apparent power of the whole circuit can be found by multiplying the source voltage by the source current. For the circuit above, $P_a = VA$, or 100(5), or 500 watts.

The power factor in *series* circuits is equal to $R/Z$. In *parallel* circuits the power factor is equal to $G/Y$. In the circuit above, pf $= G/Y$, or 0.04/0.05, or 0.8000.

In *series* circuits the power factor is also the ratio of the resistive *voltage* to the source voltage. In *parallel* circuits the power factor is the ratio of resistive *current* to the source current, or pf $= I_R/I_s$. In the example circuit, pf $= 4/5$, or 0.8000.

In either series or parallel circuits the power factor will be the ratio of the true power to the apparent power, or pf = $P/VA$. In the example circuit, pf = $P/VA$, or 400/500, or 0.8000.

The phase angle of the circuit is the angle represented by the cosine value of the power factor, as determined by any of the above methods. In the example circuit it is found to be 36.9° by referring to a table of trigonometric functions.

In a parallel circuit, when the net reactance value is more than 10 times the resistance, for most practical purposes the reactance can be disregarded as it will have little effect on the value of current flowing, on the impedance of the circuit, on the phase angle, or on the power factor. For example:

A parallel circuit is made up of five branches, three of the branches being pure resistances of 7, 11, and 14 ohms, respectively. The fourth branch has an inductive-reactance value of 500 ohms. The fifth branch has a capacitive reactance of 900 ohms. What is the total impedance of this network, and which branch will dissipate the greatest amount of heat?

By observation it can be seen that the net reactance will be the difference between 900 and 500 ohms, or 400 ohms reactance. This is in parallel with a net resistance value of 3.27 ohms (the three parallel resistors). Since the net reactance value is more than 100 times the net resistance value, the impedance of the circuit can be assumed to be the resistive value of 3.27 ohms. The branch which will dissipate the greatest amount of heat is the one having the lowest resistance value, which is the 7-ohm branch.

The following is an example of the use of the current-vector method of solving a parallel a-c circuit problem:

An alternating voltage of 115 volts is connected across a parallel circuit made up of a resistance of 30 ohms, an inductive reactance of 17 ohms, and a capacitive reactance of 19 ohms. What is the total circuit drain from the source? A diagram of this circuit is shown in Fig. 7.20. The current values through the three branches are

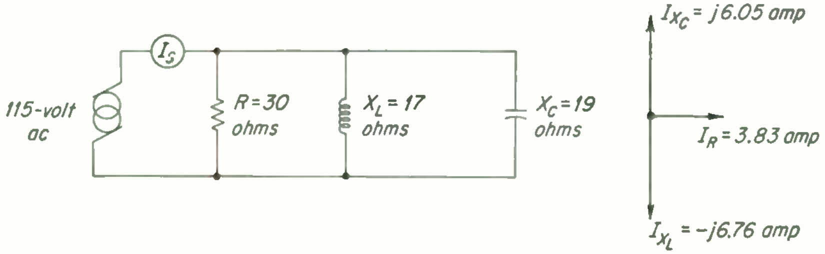


FIG. 7.20. The source current can be determined by current vectors of the three branches.

$$I_R = \frac{E}{R} = \frac{115}{30} = 3.83 \text{ amp}$$

$$I_{XL} = \frac{E}{X_L} = \frac{115}{17} = -j6.76 \text{ amp}$$

$$I_{XC} = \frac{E}{X_C} = \frac{115}{19} = j6.05 \text{ amp}$$

The net current between the $-j6.76$ and the $j6.05$ amp is $-j0.71$ amp.

The resistive current is 3.83 amp, and the net inductively reactive current is 0.71 amp. The vector diagram of the circuit is shown in Fig. 7.21. The source current $I_s$ is the current that flows through the parallel circuit.

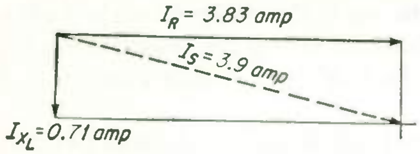


FIG. 7.21. Resultant vector diagram when the reactive-current values are subtracted from each other.

Using the Pythagorean theorem to solve for the hypotenuse of the right triangle composed of sides $I_r$, $I_{XL}$, and $I_s$:

$$I_s = \sqrt{I_r^2 + I_x^2} = \sqrt{(3.83)^2 + (0.7)^2}$$
$$= \sqrt{14.7 + 0.504} = \sqrt{15.2} = 3.9 \text{ amp}$$

The impedance can be found by using Ohm's law: $Z = E/I$, or 115/3.9, or 29.5 ohms.

The power factor is the ratio of the $I_r$ to the $I_s$, or pf $= I_r/I_s$, or 3.83/3.9, or 0.9821. From a table of trigonometric functions the phase angle is found to be 10.8°.

The true power is $P = I^2R$, or $(3.83)^2(30)$, or 440 watts.

The apparent power, or volt-amperes, is VA = 115(3.9), or 448.5 watts.

### Practice Problems

1. A coil with a reactance of 300 ohms, a capacitor with a reactance of 100 ohms, and a 400-ohm resistor are all connected across a 120-volt a-c source. What is (*a*) the impedance of the circuit, (*b*) the power factor? (*c*) Is the power factor lagging or leading? What is (*d*) the total current value, (*e*) the phase angle?

2. A 100-volt a-c generator is connected across a circuit consisting of a coil with 70 ohms reactance, a capacitor with 90 ohms reactance, a 600-ohm resistor, and a second resistor of 400 ohms, all in parallel. (*a*) Which branch dissipates the most power? What is (*b*) the total impedance of the network, (*c*) the apparent power, (*d*) the true power, (*e*) the power factor, (*f*) the phase angle?

**7.16 Complex Parallel-Series Circuit.** The admittance formula $Y = \sqrt{G^2 + B^2}$ can also be applied to a more complex parallel-series-type a-c circuit, such as shown in Fig. 7.22.

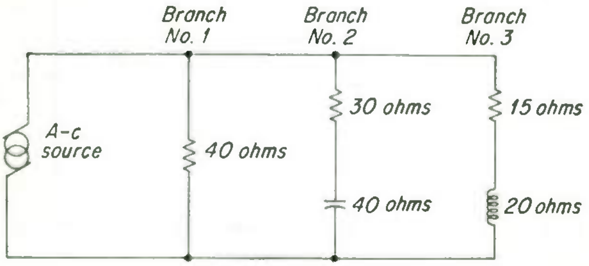


FIG. 7.22. A more complex parallel-series circuit that can be computed by the admittance method.

In branch 1, composed of pure resistance, the conductance value is simply the reciprocal of the resistance, or

$$G = \frac{1}{R}$$

In the two other branches there is both resistance and reactance in series. When a circuit has both resistance and reactance in series, the conductance is found by a formula that takes both into consideration. This formula is

Conductance

$$G = \frac{R}{Z^2}$$

Similarly, to compute the susceptance of a branch that has both resistance and reactance in series, the susceptance is found by the formula

ceptance

$$B = \frac{X}{Z^2}$$

The admittance of the whole circuit can be found by using the formula

adm

$$Y = \sqrt{G_T^2 + B_T^2}$$

In this formula, the total $G$ value is the sum of all the branch conductances. (In any purely reactive branch the $G$ will be zero.) The total $B$ value is the difference between the inductive and the capacitive susceptance branches. (In any purely resistive branch the $B$ will be zero.) In expanded form the admittance formula may be written

$$Y = \sqrt{(G_1 + G_2 + G_3)^2 + (B_1 + B_2 - B_3)^2}$$

The impedance of the circuit in Fig. 7.22 is determined by this formula:
*Branch* 1:

$$G_1 = \frac{1}{R} = \frac{1}{40} = 0.025 \text{ mho}$$

$$B_1 = 0 \text{ mho}$$

*Branch* 2:

$$Z_2 = \sqrt{R^2 + X^2} = \sqrt{(30)^2 + (40)^2} = \sqrt{900 + 1{,}600} = 50 \text{ ohms}$$

$$G_2 = \frac{R}{Z^2} = \frac{30}{(50)^2} = \frac{30}{2{,}500} = 0.012 \text{ mho}$$

$$B_2 = \frac{X}{Z^2} = \frac{40}{(50)^2} = \frac{40}{2{,}500} = 0.016 \text{ mho}$$

*Branch* 3:

$$Z_3 = \sqrt{R^2 + X^2} = \sqrt{15^2 + 20^2} = \sqrt{625} = 25 \text{ ohms}$$

$$G_3 = \frac{R}{Z^2} = \frac{15}{(25)^2} = \frac{15}{625} = 0.024 \text{ mho}$$

$$B_3 = \frac{X}{Z^2} = \frac{20}{(25)^2} = \frac{20}{625} = 0.032 \text{ mho}$$

The sum of all $G$'s ($G_t$):

$$G_T = G_1 + G_2 + G_3 = 0.025 + 0.012 + 0.024 = 0.061 \text{ mho}$$

The sum of all $B$'s ($B_T$):

$$B_T = B_1 + (B_2 - B_3) = 0 + (0.016 - 0.032) = 0.016 \text{ mho}$$
$$Y = \sqrt{G_T^2 + B_T^2} = \sqrt{(0.061)^2 + (0.016)^2} = \sqrt{0.003721 + 0.000256}$$
$$= \sqrt{0.003977} = 0.0631 \text{ mho}$$
$$Z = \frac{1}{Y} = \frac{1}{0.0631} = 15.8 \text{ ohms}$$

The power factor can be found by using the formula pf = $P/\text{VA}$, using any convenient source voltage. The true power is the sum of all three $I^2R$ power values in the circuit. The apparent power is the power indicated by the product of the voltage across the circuit and the current from the source. The power factor is the cosine of the phase angle and may be found in a table of trigonometric functions.

There are other methods of solving for the impedance of this type of complex circuit. However, the current-vector method becomes involved in a sine and cosine formula and requires a table of trigonometric functions to determine the impedance. The admittance method can be used without reference to any tables, which may be an advantage in some cases.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

1. What are the properties of a series capacitor, acting alone in an a-c circuit? (7.1) **[3]**

2. In a circuit consisting of an inductance having a reactance value of 100 ohms and a resistance of 100 ohms, what will be the phase angle of the current with reference to the voltage? (7.3) **[3]**

3. What factors must be known in order to determine the power factor of an a-c circuit? (7.6) **[3]**

4. Given a series circuit consisting of a resistance of 4 ohms, an inductive reactance of 4 ohms, and a capacitive reactance of 1 ohm, the applied circuit alternating emf is 50 volts. What is the voltage drop across the inductance? (7.8) **[3]**

5. What unit is used in expressing the a-c impedance of a circuit? (7.2) **[3 & 6]**

6. State Ohm's law for a-c circuits. (7.2) **[3 & 6]**

7. What is the impedance of a solenoid if its resistance is 5 ohms and 0.3 amp flows through the winding when 110 volts at 60 cycles is applied to the solenoid? (7.2) **[3 & 6]**

8. What is the meaning of power factor? (7.6) **[3 & 6]**

9. What does the term power factor mean in reference to electric power circuits? (7.6) **[4]**

10. A series circuit contains resistance, inductive reactance, and capacitive reactance. The resistance is 7 ohms, the inductive reactance is 8 ohms, and the capacitive reactance is unknown. What value must this capacitor have in order that the total circuit impedance be 13 ohms? (7.10) **[4]**

11. If an alternating current of 5 amp flows in a series circuit composed of 12 ohms resistance, 15 ohms inductive reactance, and 40 ohms capacitive reactance, what is the voltage across the circuit? (7.10) **[4]**

12. If a lamp rated at 100 watts and 115 volts is connected in series with an induc-

tive reactance of 355 ohms and a capacitive reactance of 130 ohms across a voltage of 220 volts, what is the current value through the lamp? (7.10) **[4]**

**13.** A potential of 110 volts is applied to a series circuit containing an inductive reactance of 25 ohms, a capacitive reactance of 10 ohms, and a resistance of 15 ohms. What is the phase relationship between the applied voltage and the current in this circuit? (7.10) **[4]**

**14.** A parallel circuit is made up of five branches, three of the branches being pure resistances of 7, 11, and 14 ohms, respectively. The fourth branch has an inductive-reactance value of 500 ohms. The fifth branch has a capacitive reactance of 900 ohms. What is the total impedance of this network? If a voltage is impressed across this parallel network, which branch will dissipate the greatest amount of heat? (7.15) **[4]**

**15.** If an alternating voltage of 115 volts is connected across a parallel circuit made up of a resistance of 30 ohms, an inductive reactance of 17 ohms, and a capacitive reactance of 19 ohms, what is the circuit-current drain from the source? (7.15) **[4]**

**16.** What is the total impedance of a series a-c circuit having a resistance of 3 ohms, an inductive reactance of 7 ohms, and zero capacitive reactance? (7.2) **[6]**

**17.** If a 220-volt 60-cycle single-phase line delivers 100 watts at 80 per cent power factor to a load, what is the phase angle between the line current and the line voltage? How much current flows in the line? (7.6) **[6]**

**18.** What is the meaning of the term leading power factor? (7.6) **[6]**

**19.** How can low power factor in an electric power circuit be corrected? (7.6) **[6]**

**20.** What is the total impedance of a series a-c circuit having an inductive reactance of 14 ohms, a resistance of 6 ohms, and a capacitive reactance of 6 ohms? (7.10) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**1.** What is the name given to the a-c resistance of an electric circuit, and in what unit is it measured? (7.2)

**2.** What are the properties of inductance alone in an a-c circuit? (7.1)

**3.** What are the properties of capacitance alone in an a-c circuit? (7.1)

**4.** What are the properties of resistance alone in an a-c circuit? (7.1)

# CHAPTER 8

# RESONANCE AND FILTERS

**8.1 Resonance.** Resonant circuits are the basis of all transmitter, receiver, and antenna operation. Without resonant circuits there would be no radio communication.

A brief mention was made of series resonance and parallel resonance in the chapter Alternating-current Circuits. In both cases it was explained that when the inductive reactance ($X_L$) of a coil equals the capacitive reactance ($X_C$) of a capacitor (condenser), whether the coil and capacitor are connected in series or in parallel, a condition known as resonance occurs. Figure 8.1 illustrates a series resonant and a parallel-resonant circuit.

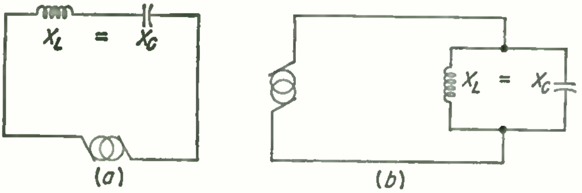


FIG. 8.1. (*a*) Series-resonant circuit across a source of a-c. (*b*) Parallel-resonant circuit.

Since resonance is the condition when $X_L$ equals $X_C$, the formula for resonance is

$$X_L = X_C \qquad \text{or} \qquad 2\pi FL = \frac{1}{2\pi FC}$$

where $X_L$ is inductive reactance in ohms; $X_C$ is capacitive reactance in ohms; $F$ is frequency in cycles (per second); $L$ is inductance in henrys; and $C$ is capacitance in farads.

Examination of the formula shows that while the inductive reactance is directly proportional to frequency, the capacitive reactance is inversely proportional to frequency. With any given coil and capacitor, as the frequency increases, the reactance of the coil increases, but the reactance of the capacitor decreases. At some frequency, the two reactances will be equal in value. At that one frequency the condition of resonance occurs. At all other frequencies the circuit shown in Fig. 8.1*a* is merely a series a-c circuit, and that in Fig. 8.1*b* is merely a parallel a-c circuit.

To determine the frequency at which a coil and capacitor will resonate, it is necessary only to rearrange the resonance formula above and solve for $F$:

$$\begin{aligned} 2\pi FL &= \frac{1}{2\pi FC} \\ 2\pi FL(2\pi FC) &= 1 \\ 4\pi^2F^2LC &= 1 \\ F^2 &= \frac{1}{4\pi^2LC} \\ F &= \frac{1}{2\pi\sqrt{LC}} \end{aligned}$$

By dividing the $2\pi$ portion into the 1, the frequency formula can be simplified to

$$F = \frac{0.159}{\sqrt{LC}} \qquad \text{or} \qquad F = \frac{0.159}{\sqrt{L}\sqrt{C}}$$

These formulas are important when it is desired to know the resonant frequency of a circuit.

*Example:* The inductance is 150 $\mu$h and the capacitance is 160$\mu\mu$f.

$L = 0.000150$ henry, or $15 \times 10^{-5}$ henry
$C = 0.000000000160$ farad, or $16 \times 10^{-11}$ farad

$$F = \frac{0.159}{\sqrt{LC}} = \frac{0.159}{\sqrt{15 \times 10^{-5} \times 16 \times 10^{-11}}} = \frac{0.159}{\sqrt{240 \times 10^{-16}}} = \frac{0.159}{15.5 \times 10^{-8}}$$

$$= \frac{0.159 \times 10^8}{15.5} = 0.01026 \times 10^8 = 1{,}026{,}000 \text{ cycles, or } 1{,}026 \text{ kc, or } 1.026 \text{ Mc}$$

According to the formula, the frequency of resonance is inversely proportional to the *square root* of either $L$ or $C$. To demonstrate, if the factor 0.159 is simplified to 1 and a value of 2 is assigned to both $L$ and $C$, the frequency is

$$F = \frac{1}{\sqrt{2 \times 2}} = \frac{1}{\sqrt{4}} = \frac{1}{2}$$

If the inductance is increased 4 times, the frequency is then

$$F = \frac{1}{\sqrt{8 \times 2}} = \frac{1}{\sqrt{16}} = \frac{1}{4}$$

Increasing the inductance 4 times results in a lowering of the frequency to half the original. Similarly, increasing the capacitance 4 times will also result in a frequency one-half the original.

Any time the *LC product* is increased 4 times, by quadrupling the inductance, by quadrupling the capacitance, by doubling both $L$ and $C$, or by any other means, the frequency will be half of the original.

Any time the $LC$ product is decreased to ¼ by any means, the frequency will be doubled.

As long as the $LC$ product remains the same, the frequency will remain the same. For example, in a 1,000-kc circuit, if the inductance is halved and the capacitance is doubled, the $LC$ product has not changed and the frequency remains 1,000 kc.

It is possible to further rearrange the resonance formula to solve for the inductance needed to resonate with a given capacitance or the capacitance needed to resonate with a given inductance to form a resonant circuit at a desired frequency:

$$2\pi FL = \frac{1}{2\pi FC}$$

$$4\pi^2F^2LC = 1$$

$$C = \frac{1}{4\pi^2F^2L}$$

$$L = \frac{1}{4\pi^2F^2C}$$

The capacitance formula may be used, for example, to determine the capacitance that must be shunted across a coil having an inductance of 56 μh in order that the circuit resonate at 5,000 kc:

$$C = \frac{1}{4\pi^2F^2L} = \frac{1}{4(9.86)(5 \times 10^6)^2(56 \times 10^{-6})} = \frac{1}{39.4(25 \times 10^6)56} = \frac{1 \times 10^{-6}}{39.4(25)56}$$

$$= \frac{0.000001}{55{,}160} = 0.000000000018 \text{ farad, or } 0.000018\ \mu\text{f, or } 18\ \mu\mu\text{f}$$

Note that $4\pi^2$ is 4 times $(\pi^2)$, not $(4\pi)^2$. It might be well to memorize $4\pi^2$ as 39.4 for working problems of this type.

While a given coil and capacitor will resonate at essentially the same frequency regardless of whether they are connected in series or in parallel, a series-resonant circuit behaves in many ways opposite to a parallel-resonant circuit.

**8.2 Series Resonance.** The series a-c circuit shown in Fig. 8.2 can be classed as series-resonant because the inductive reactance equals the capacitive reactance at the frequency of the source.

In any series circuit, whether resonant or not, the same value of current flows in all parts of the circuit at any one instant. If at a particular instant there is one ampere flowing through the resistor in Fig. 8.2, there is also one ampere flowing through the coil and the capacitor at the same instant. However, the voltage across the capacitor is 90° behind the circuit current, while the voltage across the coil is 90° ahead of the current. The current through and the voltage across the resistance are in phase.

Figure 8.3 is a graph of the voltages and current in a series circuit using vector arrows.

The $E_{XL}$ and the $E_{XC}$ are 180° out of phase. At resonance, when the reactance values are equal, the reactive voltages, being exactly equal and opposite, cancel each other completely as far as the source is concerned. Therefore between points $A$ and $B$ in Fig. 8.2 there is zero volts, although there is a voltage drop across the $X_C$ equal to that across the $X_L$.

If the source sees the coil and capacitor together as having a zero-voltage drop across them, it sees them as a perfect conductor, or as zero impedance. If the reactances are not exactly equal (a nonresonant condition), the voltages do not exactly cancel, and the source sees the two reactances as having a resultant voltage drop across them, and therefore as having some value of reactance or impedance.

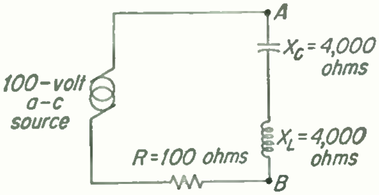


FIG. 8.2. The voltage drop between points $A$ and $B$ is zero. The source voltage appears across the resistor.

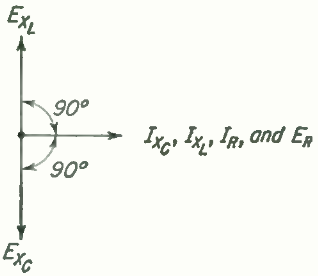


FIG. 8.3. Vector diagram of the phase and amplitude of the currents and voltages in a series-resonant circuit.

Theoretically, if a series $LC$ circuit has no resistance and is connected across a source of a-c to which it is resonant, it presents zero reactance, zero resistance, and zero impedance.

The current-limiting factor in a series-resonant circuit is the resistance. In Fig. 8.2, with a source voltage of 100 volts, a resistance of 100 ohms, and 4,000-ohm reactances, the reactances cancel, leaving the source looking at the 100-ohm resistance. The current *flow* in the circuit is $I = E/R = {}^{100}\!/_{100} = 1$ amp. Thus, a resonant circuit is considered to be purely resistive. The impedance value of a series-resonant circuit is the value of series resistance in the circuit.

Capacitors are usually considered to have negligible series resistance in them. However, coils may have considerable resistance in the wire with which they are wound. This resistance in the coil itself is usually treated as an external resistor. In the circuit of Fig. 8.2, if the coil having 4,000 ohms of reactance also has 100 ohms of resistance in its wire, the diagram as drawn is a proper method of indicating the circuit factors.

In a common radio circuit the condition of *series* resonance occurs (Fig. 8.4), but is not apparent. In this circuit a transformer primary is connected across a source of a-c, and the secondary coil has a capacitor across it, with a reactance value equal to the reactance of the secondary coil. These reactances form a resonant circuit. At first glance it appears that the capacitor shunted across the coil forms a parallel-resonant circuit. However, the primary is inducing an a-c emf into each turn of the secondary coil. An emf is not being applied across the ends of the coil. Theoretically, the secondary may be considered to have been opened up and a source of a-c to have been inserted in series with the turns, as illustrated in Fig. 8.5. Since the induced emf is apparently in series with the coil, the circuit is classed as a series-resonant circuit. The load on the secondary is in parallel with the capacitor and coil, however. Any emf developed across the circuit produces current in the load.

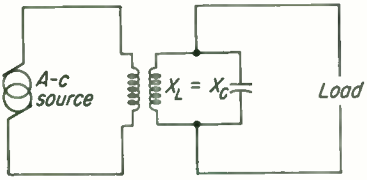


FIG. 8.4. The secondary is a series-resonant circuit.

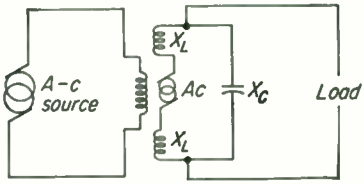


FIG. 8.5. Effectively, emf is induced in series with the inductance.

Should the primary coil be brought to resonance by connecting the proper value capacitor across it, the primary will be a parallel-resonant circuit, since the a-c voltage is being impressed across it and not induced into its turns.

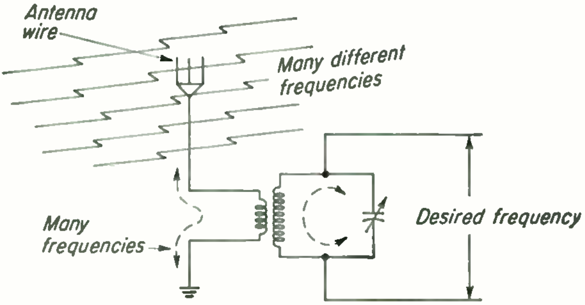


FIG. 8.6. A tuned circuit accepts signals at its resonant frequency but rejects all other frequencies.

Tuned transformers such as these are used extensively in radio receivers and transmitters to select a desired frequency when many frequencies are available. Figure 8.6 shows an antenna connected to the primary of a transformer. The antenna circuit is completed by connecting the lower end of the primary to ground. Radio signals in the air pass across the antenna wire, inducing radio-frequency a-c voltages in the antenna-ground circuit. There are actually thousands of a-c signals of different frequencies being induced into the antenna simultaneously all the time. The problem is to pick out only the desired frequency.

A secondary coil can be loosely coupled to the primary, and a *variable* capacitor connected across its terminals. By varying the capacitance, it is possible to "tune" the series-resonant secondary circuit over a band of frequencies. At any frequency where the $X_L$ of the coil equals the $X_C$ of the capacitor, the secondary will appear as a low-impedance circuit to this frequency, and as a result this one frequency will produce a significant current in the secondary. With a high-amplitude current flowing, a relatively high-amplitude voltage of the resonant frequency will be developed across the reactances.

To any frequency other than the resonant frequency, the series-resonant circuit will have greater impedance and will oppose the flow of a-c at that frequency, resulting in smaller currents and less reactive voltages for frequencies off resonance.

It has been pointed out that the impedance of a series circuit at resonance is equal to the resistance value of the circuit, but what impedance will a resonant circuit have to frequencies other than its resonant frequency?

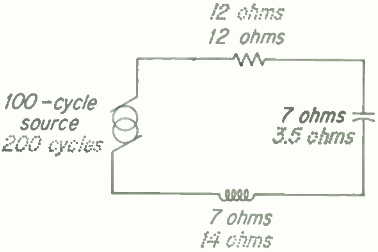


FIG. 8.7. Doubling the frequency doubles the inductive and halves the capacitive reactance. The circuit is not resonant to the new frequency.

The circuit shown in Fig. 8.7 illustrates a series-resonant circuit with 12 ohms resistance, 7 ohms capacitive reactance, and 7 ohms inductive reactance across a 100-cycle source. The impedance of the circuit is equal to the value of the resistance alone, or 12 ohms. If the frequency is increased to twice the original, or 200 cycles, what is the impedance of the circuit?

Since inductive reactance is directly proportional to frequency, when the frequency is doubled, the inductive reactance will be 2 times its original 7-ohm value, or 14 ohms. When the frequency is doubled, the capacitive reactance, being inversely proportional to frequency, becomes one-half its original value, or 3.5 ohms. The resistance value remains the same for all frequencies. The impedance is now

$$Z = \sqrt{R^2 + (X_C - X_L)^2} = \sqrt{12^2 + (14 - 3.5)^2} = \sqrt{144 + 110.25} = \sqrt{254.25}$$
$$= 15.9 \text{ ohm}$$

**8.3 Parallel Resonance.** A coil and capacitor connected as shown in Fig. 8.8 form a parallel a-c circuit. If the two reactances $X_C$ and $X_L$ have the same reactance to the frequency of the a-c, the circuit is known as a parallel-resonant circuit. It may also be referred to as an *anti-resonant* circuit.

If the capacitor is temporarily disconnected leaving the 100-ohm reactance coil across the 100-volt source, according to Ohm's law for a-c circuits the current in the coil will be

$$I = \frac{E}{Z} \qquad \text{or} \qquad I = \frac{E}{X} = \frac{100}{100} = 1 \text{ amp}$$

If the 100-ohm reactance capacitor is reconnected across the coil, 1 amp will flow in the capacitor also. Placing the capacitor across the coil in this circuit does not change the current in the coil, even though a resonant circuit is formed (provided there is no series resistance in the source line).

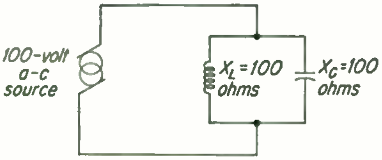


FIG. 8.8. Parallel, or antiresonant, circuit.

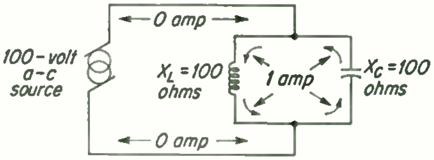


FIG. 8.9. With no resistance in a parallel-resonant circuit, current oscillates in it, but the source current is zero.

In a parallel-resonant circuit the same voltage is across both the coil and the capacitor. However, in the inductive branch the current lags the source voltage by 90°, and in the capacitive branch the current leads the source voltage by 90°. Since the two currents are 180° out of phase, at the instant that current is flowing down through the coil an equal current must be flowing up into the capacitor, as illustrated in Fig. 8.9.

As far as the source is concerned, 1 amp is flowing down through the coil and 1 amp is flowing up through the capacitor at the same time. Since it is impossible for current to flow in two directions at once in either of the source lines, there must be zero current from the source but 1 amp flowing from one reactance to the other. The electrons that make up the current in the reactances move from the top plate of the capacitor down through the coil and over to the lower capacitor plate. When the source voltage alternates, the electrons retrace their path back up through the coil to the top plate of the capacitor. This circulating current of 1 amp flows between the reactances, but *no current* flows into and out of the source!

Because the source is supplying no current, it should be possible to disconnect the source and the electron current should continue to *oscillate* back and forth between capacitor and coil indefinitely. With no resistance or losses in the circuit, this would be true. This ability of a resonant circuit to sustain electron oscillation is known as *flywheel effect*, because of its similarity to the action of a mechanical *flywheel*, which, once started, tends to keep going until stopped by friction or by other losses.

Since the source voltage is across the resonant circuit and no current flows in the source, the parallel-resonant circuit impedance must be

$$Z = \frac{E_s}{I_s} = \frac{E_s}{0} = \infty \text{ (infinite) ohms}$$

Both infinite ohms impedance and ceaseless oscillations are impossible. The circuits shown have neglected resistance as well as inductive losses to external circuits. There is no coil or capacitor that does not have some series-resistance value. Figure 8.10 shows the circuit redrawn in a more practical form, including resistances in each branch. With the same source voltage, less current will flow in the branches because of increased impedance. The impedance of each *branch* can be computed as $Z = \sqrt{R^2 + X^2}$.

Current flowing through the resistances heats them. The heat represents a power loss. If the source is disconnected, the energy of the electrons will almost immediately be dissipated in heating the resistors and the electrons will cease to oscillate. With a power loss in the circuit, the source must feed power into the circuit to make up for the loss. To feed the power into the circuit, current will have to be fed to it. Therefore enough source current must flow in all parallel-resonant circuits to make up for the losses in the circuit.

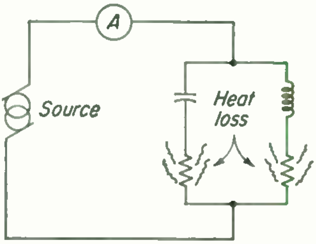


FIG. 8.10. Losses in the tuned circuit demand current from the source.

With pure reactances and zero resistance in the circuit, the source current is zero. When resistors are added in series with either branch, the source current *increases*.

As a generalization, for resonant circuits with little resistance:

| *Series resonance* | *Parallel resonance* |
|---|---|
| The impedance across the circuit is low or zero (equals the resistance). | The impedance across the circuit is high or infinite. |
| The voltage drop across the circuit is low or zero. | The voltage drop across the circuit is equal to the source voltage or less. |
| The current flow from the source is high or infinite. | The current from the source is low. |
| The voltage drop across either reactance is equal to $E = IX$ and may be greater than the source voltage. | The current through each reactance is equal to $I = E/X$ and will be greater than the source current. |
| The circuit acts as a purely resistive (zero reactance) load to the source, and therefore has a power factor of 1. | The circuit acts as a purely resistive load to the source and therefore has a power factor of 1. |
| The phase of the current and voltage, as seen by the source, is 0°, or in phase. | The phase of the source current and voltage is 0°, or in phase. |
| | The phase of the current and voltage of each reactance is 90°. |
| | Adding resistance to either branch *lowers* the impedance of the whole circuit. |

The impedance of a parallel-resonant circuit can be determined in several ways:

1. If the source voltage and current are known, the impedance can be found by using Ohm's law:

$$Z = \frac{E_s}{I_s}$$

2. The product of the *series* impedance of both legs of the circuit, $Z_C = \sqrt{R^2 + X_C^2}$, *times* $Z_L = \sqrt{R^2 + X_L^2}$), divided by the total *series* impedance of the coil, capacitor, and any resistance in the two branches, $Z = \sqrt{R^2 + (X_L - X_C)^2}$, will give the parallel impedance of the circuit. The formula is

$$Z_p = \frac{Z_C Z_L}{Z_s}$$

where $Z_p$ is the impedance of the parallel circuit; $Z_C$ is the impedance of the capacitive leg; $Z_L$ is the impedance of the inductive leg; and $Z_s$ is the series impedance of the two legs.

Since the impedance of a series-resonant circuit equals the resistance in the circuit, the formula may also be given as

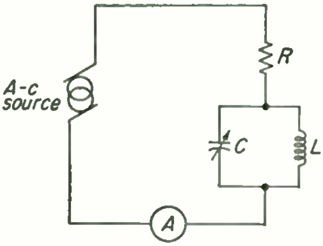


FIG. 8.11. At resonance the voltage drop across the tuned circuit is a maximum; across the resistance a minimum.

$$Z_p = \frac{Z_C Z_L}{R}$$

where $R$ is the total resistance in the two legs.

3. When the reactance value is more than 10 times the resistance of the inductive branch, a simple formula that will give an approximate impedance value is

$$Z = \frac{X_L^2}{R}$$

4. The circuit may be treated as a parallel a-c circuit and the admittance computed by the parallel-circuit formula: $Y = \sqrt{G^2 + B^2}$. The reciprocal of the admittance is the impedance.

5. The circuit may be treated as a parallel a-c circuit by assuming a convenient source voltage and using the vectorial sum of the branch currents, $I_s = \sqrt{(I_{ZL} \cos \theta + I_{ZC} \cos \theta)^2 + (\pm I_{ZL} \sin \theta \pm I_{ZC} \sin \theta)^2}$ to solve for the impedance by Ohm's law: $Z = E_s/I_s$.

A circuit involving parallel resonance that is very common in radio is shown in basic form in Fig. 8.11. A source of 100 volts feeds a parallel circuit through a series resistance. Either the capacitor or the coil may be variable to adjust the parallel circuit to resonate at the frequency of the source. In the diagram the capacitor is shown as being variable. The ammeter indicates the source current.

When the capacitor is varied, there should be some value of capacitance at which its reactance to the source frequency is equal to the inductive reactance offered to that frequency by the coil. At this resonant condition, the source current should drop to nearly zero (assuming negligible resistance in the coil and capacitor). With little current through the resistor *R*, there will be little voltage drop across it and almost the full source voltage will appear across the parallel circuit. The current circulating between the coil and capacitor will be at a maximum.

When the capacitance is varied to any other value, the circuit will no longer be resonant. It will no longer present as high an impedance to the a-c, and current will flow in the source lines. Current flowing through the resistor *R* will produce a voltage drop across it. If there is a 10-volt drop across the resistor, the voltage across the resonant circuit will be only 90 volts. The further the circuit is tuned from resonance, the greater the source current and therefore the less the voltage across the parallel circuit. The less voltage appearing across the parallel circuit, the less current will circulate in it. Maximum voltage across a parallel circuit, when resistance is in *series* with it, will always occur at resonance. Maximum circulating current in the LC circuit will also occur at resonance. This explains why resonance of the plate tuning circuit of an RF amplifier stage in a transmitter is indicated by *minimum* plate current.

## Practice Problems

**1.** A 2-henry coil and a 0.001-$\mu$f capacitor are connected in series. At what frequency will they resonate? If connected in parallel, at what frequency will they resonate?

**2.** A series-resonant circuit consists of a resistance of 6.5 ohms and equal inductive and capacitive reactances of 175 ohms. The applied or source voltage is 260 volts. What is the (*a*) impedance of the circuit, (*b*) current of the circuit, (*c*) voltage drop across the inductance, (*d*) voltage drop across the capacitance?

**3.** A parallel-resonant circuit made up of two 380-ohm reactances and having zero resistance in it is in series with a 24-ohm resistor across a 120-volt a-c line. What is the (*a*) voltage drop across the resistor, (*b*) voltage drop across the parallel circuit, (*c*) current value in the parallel circuit, (*d*) value of reactance across the capacitor?

**4.** In a given a-c series circuit, the resistance, inductive reactance, and capacitive reactance are of equal magnitude of 11 ohms and the frequency is reduced to 0.411 of its value at resonance. At the new frequency, what is the (*a*) inductive reactance, (*b*) capacitive reactance, (*c*) impedance?

**5.** What is the resonant frequency of a tuned circuit consisting of a capacitor of 500 $\mu\mu$f, a tuning coil of 150 $\mu$h, and a resistance of 10 ohms?

**6.** What value of capacitance is required to tune a 40-$\mu$h coil to a frequency of 8 Mc?

**7.** What value of inductance is required to tune a circuit having 0.0005 $\mu$f to 450 kc?

**8.** A variable capacitor has a minimum capacitance of 20 $\mu\mu$f and a maximum capacitance of 300 $\mu\mu$f. If connected across a 100-$\mu$h coil, what is the highest frequency to which it can be made resonant, and what is the lowest frequency?

**9.** A parallel-resonant circuit having a coil with 800 ohms reactance is connected across a 36-volt a-c. If there is no resistance in the circuit, what is the current (*a*) in the LC circuit, (*b*) in the source?

**8.4 The $Q$ of a Circuit.** A term often applied to a-c circuits involving inductance and capacitance is $Q$. The symbol $Q$ can be considered to mean *quality*, in a sense.

A coil of high $Q$ means one that has little resistance or other losses in it. As far as *coil quality* is concerned, it has mostly inductance and only a little resistance. Without the resistance the coil would be a perfect inductance. With zero resistance the $Q$ of a coil would be infinite. It is impossible to have a coil without resistance or losses, and therefore the $Q$ of a coil will always be some finite value.

The $Q$ of a coil is considered as the ratio of its reactance value in ohms to its resistance value in ohms. For example, a coil has a reactance of 100 ohms to a certain frequency and a resistance of 1 ohm.

$$Q = \frac{X_L}{R} = \frac{100}{1} = 100$$

where $X_L$ is inductive reactance in ohms; and $R$ is resistance in ohms.

There is no unit of measurement assigned to $Q$. In the example above, it is merely stated: The coil has a $Q$ of 100.

If a coil with 100 ohms reactance has 20 ohms resistance, the $Q$ value is 5. A low $Q$ value may indicate a relatively high resistance in the coil itself, or a loss to the coil due to energy inductively coupled out of it, or the coil has little reactance at the frequency being used. Because inductive reactance is directly proportional to frequency, a given coil will have greater $Q$ when used in circuits of higher frequencies, provided losses do not increase at a greater rate than the reactance value increases.

Capacitors also have a value of $Q$. As with a coil, the $Q$ is the ratio of the capacitive reactance to the resistance in series with the capacitor. This resistance may be in the leads, or may be the result of losses in the capacitor. In formula form:

$$Q = \frac{X_C}{R}$$

Because the losses in most capacitors are small, and because coils usually have a relatively greater resistance, the $Q$ of a resonant circuit is usually considered to be equal to the $Q$ value of the coil, whether the coil and capacitor are in series or in parallel.

When resistance is in *series* with a reactance, the $Q$ is inversely proportional to the resistance; that is, an increase in resistance produces a lowering of $Q$.

However, when a resistor is connected *across* a coil or capacitor, the $Q$ of the circuit will vary directly with the value of the resistance. The $Q$ will be relatively high when a high resistance is across the circuit and low when a low resistance is across it. The $Q$ will be maximum with infinite resistance across the circuit.

A resistor is often connected across a resonant LC circuit to lower its

$Q$, producing a broader tuning response of the circuit. It will no longer be as sensitive to frequencies at or very close to the resonant frequency. A diagram of a parallel-resonant circuit with a loading resistor $R$ shunted across it to lower the $Q$ is shown in Fig. 8.12.

The lower the value of the parallel resistance, the greater the proportion of resistive current flowing in the circuit. With a low resistance, the source sees the whole LCR circuit more as a resistance than as a resonant circuit. If there is any resistance in the source line, the voltage drop across the tuned circuit will be small and little current will flow in the LC circuit.

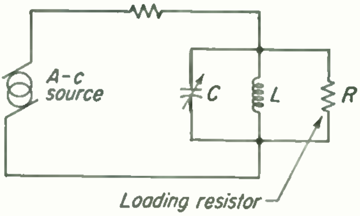


FIG. 8.12. A loading resistor across a tuned circuit to broaden the circuit's frequency response.

The dielectric of a capacitor normally has extremely high resistance, in the hundreds or thousands of megohms. However, if the dielectric leaks even a little, the conductance of the dielectric increases. This is equivalent to having a resistance between the plates of the capacitor. This parallel-resistance effect lowers the $Q$ of the capacitor and the $Q$ of any resonant circuit in which it is used.

How a coil is constructed helps to determine its $Q$. Some of the methods of attaining a high $Q$ are:

1. Spacing the wires of the coil by a distance approximately equal to the diameter of the wire used.
2. Using a coil with a length slightly greater than its diameter, if a single-layer coil.
3. Using low-loss core materials to decrease eddy current and hysteresis losses.
4. Covering the wire with an insulating material that has low dielectric hysteresis loss. (This increases the $Q$ of the capacitance that exists between adjacent turns in a coil, known as the *distributed capacitance*.)
5. Using larger wire or wire of better conducting material to reduce skin effect (defined below).

At higher frequencies the electrons flowing in a coil or wire tend to flow only on or near the surface of the wire. Thus, only a small proportion of the wire is actually carrying current. The effective lessening of the usable cross-section area results in an effectively higher resistance of the wire at high frequencies and a lower $Q$. This increased resistance effect is known as *skin effect*. Skin effect can be decreased by (*a*) using larger wire, (*b*) silver-plating the wire, since silver is the best conducting material, (*c*) making the coil with fewer turns but increasing the permeability of the core by using materials such as powdered iron which have little core loss, (*d*) using Litz wire, a multistranded, insulated wire, to give more surface, particularly at frequencies below about 500 kc.

The $Q$ of resonant circuits used in communications may be about 5 to 15 in radio transmitters, 25 to 200 in RF tuned circuits in receivers, or several hundred in specially designed high-$Q$ *filter* circuits. By using *regeneration* in vacuum-tube or transistor circuits, it is possible to obtain a resonant circuit with a $Q$ well over 10,000.

**8.5 Decibels.** One of the important mathematical tools of communications is the *decibel* (abbreviated db). This is a measurement of the ratio of one power to another, one voltage to another, or one current to another. An audio amplifier can increase the power of an AF alternating current or increase an AF a-c voltage. If it can increase a 5-watt input to a 50-watt output, it has increased the signal 10 db. The same amplifier will also increase a 0.5-watt input to a 5-watt output, still a gain of 10 db. If the volume control is turned up, the 0.5-watt input signal may be amplified to a 50-watt output. The hundredfold increase is a gain of 20 db. This will be recognized as a logarithmic increase by those familiar with logarithms. For those not familiar with them, a brief explanation is given here.

In the equation $10^2 = 100$, the 2 is the *exponent*, the 10 may be called the *base*, and 100 the *number*. The exponent 2 can also be called the *logarithm* of the number 100 to the base 10. Logarithmically, this is stated: $\log_{10} 100 = 2$ and is read: "The logarithm to the base 10 of the number 100 is 2." Since the system of logarithms in general use always employs a base of 10, it is customary to express an equation as merely $\log 100 = 2$ and say, "The log of 100 is 2."

The equation $10^3 = 1{,}000$, may be expressed: $\log 1{,}000 = 3$. The logarithm of any number between 100 and 1,000 will have to be between 2 and 3, or 2 plus some decimal fraction. For example, log 500 happens to be 2.6990. A logarithm such as 2.6990 is composed of two parts. The whole number is called the *characteristic*, and the decimal fraction part is called the *mantissa*.

The characteristic is determined by finding between which $\log_{10}$ the *number* falls, as shown in Table 8.1.

Table 8.1

| *For numbers between:* | | | *The characteristic is:* |
|---|---|---|---|
| 0.001 | and | 0.009999 | −3 |
| 0.01 | and | 0.09999 | −2 |
| 0.1 | and | 0.9999 | −1 |
| 1 | and | 9.999 | 0 |
| 10 | and | 99.99 | 1 |
| 100 | and | 999.9 | 2 |
| 1,000 | and | 9,999 | 3 |

Note that the characteristic is one less than the number of whole digits in the number. The number 435 has a characteristic of 2; 86 has a characteristic of 1; 0.05 has a characteristic of −2; and so on.

The mantissa value, or decimal-fraction part of the logarithm, is found in a table of common logarithms, as in the Appendix.

*Example:* log 8,450 = ? The characteristic is one less than the four digits in the number, or 3 in this case. Therefore log 8,450 = 3 + ? The mantissa is found in the tables in the 84 line under the 5 column and is 9,269. Thus, log 8,450 = 3.9269.

Check the following logarithms for characteristic and mantissa:

$$\log 23 = 1.3617 \qquad \log 15{,}500 = 4.1903 \qquad \log 629 = 2.7987$$

Although log 0.28 = −1.4472, the negative characteristic is not usually used. Instead, a value equal to it is employed. Thus,

$$\log 0.28 = 9.4472 - 10.$$

Similarly, log 0.00862 = 7.9355 − 10. In this way the negative characteristic does not complicate computations.

The number of decibels change between two *voltages* (or two currents) can be computed by the formula

$$\text{db} = 20 \log_{10} \frac{E_1}{E_2}$$

If the *voltage* input to an amplifier is 6 volts and the output is 30 volts, the ratio of the second to the first is 5:1. In decibels it is

$$\text{db} = 20 \log {}^{30}\!/_{6} = 20 \log 5 = 20(0.6990) = 13.98 \text{ db}$$

While this may also be computed as 20 log $^6\!/_{30}$, it is usually simpler to work with whole numbers rather than fractions. As a result, the larger number of the two in question is placed above the fraction bar.

The formula assumes that the input impedance equals the output impedance.

The number of decibels change between two *power* values can be computed by the formula

$$\text{db} = 10 \log_{10} \frac{P_1}{P_2}$$

How many decibels gain does an amplifier have if it produces 40 watts output with an input of 0.016 watt? By the formula,

$$\text{db} = 10 \log \frac{40}{0.016} = 10 \log 2{,}500 = 10(3.3979) = 33.9 \text{ db}$$

The same formula can be used for the following problem:

How much output power will be produced by an amplifier capable of 25 db gain if fed an input of 0.001 watt? From the formula,

$$\text{db} = 10 \log \frac{P}{0.001}$$

$$25 = 10 \log \frac{P}{0.001}$$

$$2.5 = \log \frac{P}{0.001}$$

This states: The log of the number $P/0.001$ is 2.5, or

$$\log \frac{P}{0.001} = 2.5000$$

The 5000 is the mantissa. Searching through the mantissas in the tables, 5000 is found in the 31-6 line and column. The 2 is the characteristic and indicates three whole numbers in the logarithm. Therefore

$$\frac{P}{0.001} = 316.0$$
$$P = 316(0.001) = 0.316 \text{ watt}$$

For exact decibel computations the logarithmic formulas should be used. However, a fairly accurate calculation is possible by applying one or more of the following ratios, particularly when logarithmic tables are not available:

1 db = a *power* gain of 1.26 (26%)
3 db = a *power* gain of 2
6 db = a *power* gain of 4
10 db = a *power* gain of 10
20 db = a *power* gain of 100

While the power ratios above are stated as gains, they might also be stated as losses. The voltage or current ratios will be the square root of these power gains. Thus 3 db equals a power gain of 2, or a voltage or current gain of $\sqrt{2}$, or 1.414.

The 1-, 3-, and 10-db ratios can be used in the problem above involving the amplifier with 0.001 watt input and 25 db gain:

Since 10 times the power equals 10 db, the 0.001-watt input increased by 10 db represents 0.01 watt. A second 10-db increase (total of 20 db) represents 0.1 watt. The remaining 5 db can be computed: 3 db of this represents twice the power of 20 db, or 0.2 watt. One decibel more (total 24 db) represents 0.2 + 26 per cent of 0.2, or 0.2 + 0.052, or 0.252 watt. One decibel more (total of 25 db) represents 0.252 + 26 per cent (0.252), or 0.252 + 0.065, or 0.317 watt. Compare this with the 0.316 watt obtained by logarithmic computation.

A simpler, although less accurate, approximation of the last 5 db would be to say it was slightly less than 6 db, or a little less than 0.4 watt.

Inasmuch as the decibel is used as a unit of measurement in systems in which power decreases to a threshold value before it reaches an absolute zero, it is necessary to make an arbitrary selection of some power and assign it as the *zero* level. Power values more than the zero level are considered as +db; those less than the zero level are −db.

In the past there have been several reference points established as zero levels. Today, 0.001 watt (1 milliwatt) is being accepted more and more as the standard, although 0.006 watt is also used. The term *dbm* is often used to signify db with a reference zero value of one milliwatt (abbreviated mw). In audio work the volume unit (abbreviated VU) is used. It is also a decibel unit using 0.001 watt as the reference level.

The decibel is discussed further in Sec. 16.3.

### Practice Problems

1. Using a base of 10, what is the logarithm of (*a*) 420, (*b*) 27, (*c*) 42,600, (*d*) 0.135, (*e*) 0.00423?
2. A vacuum-tube circuit is fed a 2-mv signal and has a 0.025-volt output. How many decibels gain does it have?
3. A transistor circuit is capable of 20 db gain. If the input a-c signal is 0.0045 amp, what is the output current?
4. An amplifier has 53 db gain and 10 watts output. What input signal power does it require?
5. A 2-watt signal is fed to a resistor network. The network loses a portion of any power fed to it. How many decibels must it lose to have an output of zero VU?
6. A microphone is rated at −65 dbm. How many decibels gain must an amplifier have to bring its output up to (*a*) 0.001 watts, (*b*) 10 watts, (*c*) 18 watts?

**8.6 Bandwidth.** In radio circuits there are many cases where it is desired to limit the passage of a-c to one particular frequency, or more practically, to a small band of frequencies. It has been stated previously that a series-resonant circuit in series with an a-c line will pass current of the frequency of resonance very well but will attenuate (decrease or reduce) current of frequencies either higher or lower. The further from the resonant frequency, the greater the attenuation. A graph, or curve, of the response of such a circuit is shown in Fig. 8.13. If this curve represents the response curve of a radio receiver, when the receiver is tuned from station to station this curve can be thought of as moving either up or down in frequency.

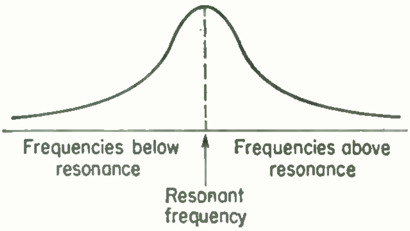


Fig. 8.13. Maximum current flows in a series circuit at resonance; less at other frequencies.

The question arises: "How wide a band of frequencies is being passed by this series-resonant circuit?" By examination of the curve it can be seen that the band of frequencies being passed at absolute maximum may be rather small. A much wider band of frequencies is being passed between half-amplitude points. According to the curve, a very wide band of frequencies is being passed between low-amplitude points. Just where should the bandwidth be measured?

One standard method of measuring bandwidth is to measure the width of either the *voltage* or *current* response curve between points 0.707 of maximum. Figure 8.14 illustrates the curve of a circuit resonant at 1,000 kc. The two points on the curve that are 0.707 of maximum are shown at about 985 and 1,015 kc. At this amplitude the bandwidth is the difference between 985 and 1,015, or 30 kc. If the circuit were tuned to resonate at 1,040 kc, its bandwidth would remain essentially the same, 30 kc. Only the resonant frequency would shift.

Power is proportional to either the voltage squared or the current squared. Since $(0.707)^2$ is equal to 0.5, dropping to the 0.707 point on a voltage or current curve is equivalent to dropping to the half-power point. This is approximately equal to dropping 3 db.

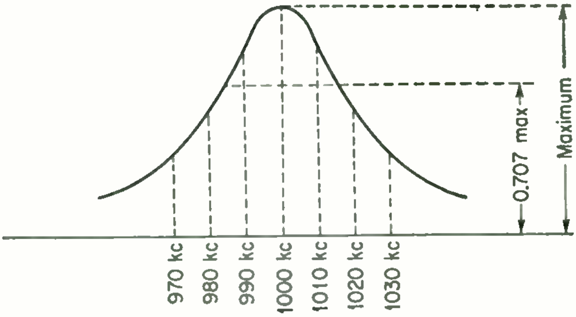


FIG. 8.14. Curve of a circuit with a bandwidth of 30 kc.

One method used to express bandwidth, particularly when using multiple-tuned circuits, is to state the bandwidth for a certain decibel loss. For example, a broad tuning receiver may be said to be 25 kc wide 20 db down. This means that signals 12½ kc higher or lower than the resonant frequency will have only one-tenth as much voltage (−20 db) or current as signals at the resonant frequency. Another receiver may be 6 kc wide 20 db down its response curve. The first receiver has a bandwidth of more than four times the second receiver. For certain types of reception this is an advantage; for others it is not.

**8.7 Bandwidth of Transformers.** An important circuit in radio is the tuned transformer, in which both primary and secondary are tuned to the same frequency. The bandwidth of a tuned transformer will vary with the degree of coupling as well as with the $Q$ of both primary and secondary circuits. Determination of the bandwidth of such circuits is rather complex if investigated for all possibilities. Only a few fundamental ideas will be presented.

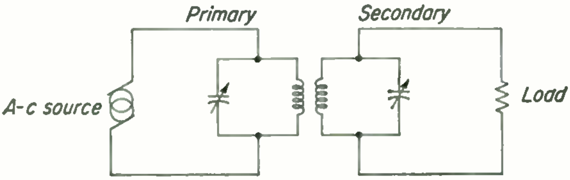


FIG. 8.15. Double-tuned transformer.

In Fig. 8.15 if all the lines of force from the primary cut all the secondary turns, the condition of unity coupling exists and the coefficient of coupling $k$ equals 1, as explained in Sec. 5.8. In such a condition the transformer will pass practically all frequencies equally well and for all intents represents the extremity of broadness. Tuning the circuits would have very little effect on the frequency response.

In a more practical form, if the coefficient of coupling is equal to, possibly, 0.001, with each circuit tuned to the same frequency, and assuming an equal $Q$ for both primary and secondary circuits, the frequency response of the circuit will follow the *universal resonance curve.* This is the relative frequency response curve of series-resonant circuits (when the $Q$ is over 5), or of parallel-resonant circuits, or of two tuned and coupled circuits. The shape of this curve is shown in Fig. 8.16.

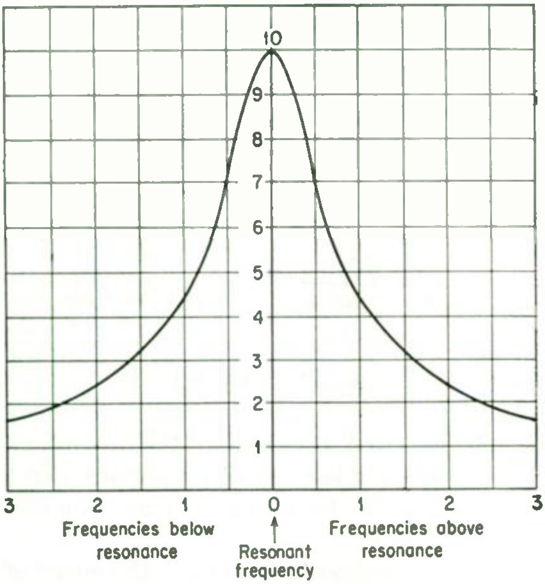


FIG. 8.16. Universal resonance curve. Curve of current flowing in series- or parallel-tuned circuits, or impedance across a parallel circuit.

The universal resonance curve illustrates, for example, the current amplitudes in a certain series-resonant circuit if a variable frequency is applied to the circuit. When the applied a-c is 2 kc below the frequency of resonance (2 on graph), the particular circuit will pass only about one-fourth the current that it will when the frequency is changed to resonance. If the frequency is raised 2 kc above resonance, the current flow in the circuit will drop to about one-fourth the resonant-frequency value.

If the $Q$ of the circuit is raised, the peak-amplitude current can be developed with less source voltage and the response at the ¼-current point will be less than 2 kc from resonance. If the $Q$ is doubled, the ¼-current frequency will be 1 kc above and below resonance for this particular circuit, and the bandwidth is halved. The curve for the high-

$Q$ circuit will look the same if the values of the upper- and lower-frequency markings are doubled; that is, if the 1 is shown as 2 on the graph, etc.

This same curve also indicates the relative rise in impedance for a parallel-resonant circuit when the circuit is subjected to a variable frequency. At resonance the peak impedance is reached. In the example curve given, the impedance will drop to $\frac{1}{4}$ for 2 kc from resonance.

The double-tuned transformer, with both primary and secondary tuned to the same frequency, has two resonant circuits, each one attempting to select the resonant frequency and reject all other frequencies. The curve for such a circuit, with a low coefficient of coupling, will be the product of the two curves separately; that is, at what would have been the $\frac{1}{4}$-amplitude point for one circuit alone, the response will be $\frac{1}{4}$ times $\frac{1}{4}$, or $\frac{1}{16}$, the response with both circuits. The two tuned circuits, when loosely coupled, produce a bandwidth approximately one-fourth that of either coil alone, assuming the same $Q$ for each.

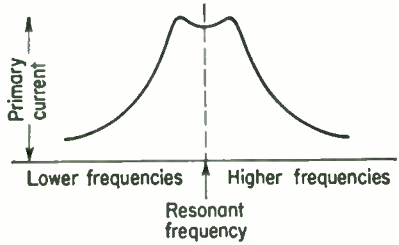


FIG. 8.17. As coupling increases, primary current curve dips.

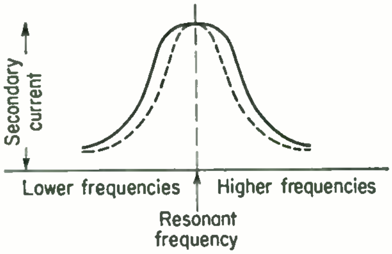


FIG. 8.18. As coupling increases, secondary current curve flattens and broadens.

As the coupling is increased, the curve of the *primary current* begins to dip at the resonant frequency because of a resistance effect being coupled into it from the secondary. Its curve appears somewhat as shown in Fig. 8.17.

As soon as the primary-current dip occurs, the curve of the *secondary current* no longer continues to rise with increased coupling as sharply as when the primary had no dip and the curve of the secondary current begins to flatten at the top (Fig. 8.18).

As the coupling between primary and secondary is increased, the top of the secondary-current curve flattens more and more, until a point is reached where an increase in coupling no longer raises the secondary-current peak amplitude. This value of coupling is known as *critical coupling*. The coefficient of coupling $k$ may perhaps be in the region of 0.01. The bandwidth at critical coupling is wider than when the two circuits were loosely coupled, but the amplitude is maximum. If the two coils have high $Q$ values, the bandwidth may still be relatively narrow. In many cases in radio, a flattened-peak response is desired. Therefore the two circuits will be coupled to the critical value or slightly over. For maximum sharpness, they are coupled to less than the critical point.

When coupling is increased past the critical point, the peak current in the secondary at resonance drops and two peaks appear, one on either side. The two circuits are now said to be *overcoupled*, and a secondary current curve may result somewhat as shown in Fig. 8.19.

The peaks of the two "shoulders" remain substantially at the same amplitude as at critical coupling, but the bandwidth of the curve is considerably broader. This double-humped response is sometimes called *split tuning* and is the result of overcoupling.

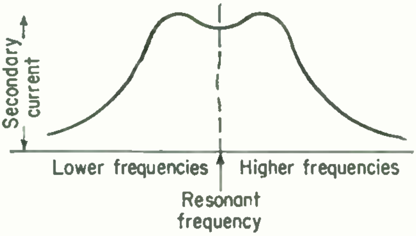


FIG. 8.19. Tight coupling develops shoulders on the secondary current curve, and the response broadens materially.

**8.8 Filters.** Many circuits in radio and electronics use *filters*. A filter may be considered to be a combination of capacitors, coils, and perhaps resistance that will allow certain desired frequencies to pass through or be impeded.

The transformer with a tuned primary and tuned secondary forms a type of *bandpass*-filter circuit, since it passes the frequency to which it is tuned and a few adjacent frequencies but attenuates both higher and lower frequencies.

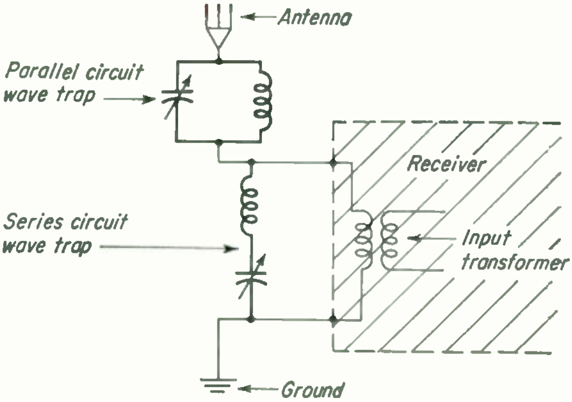


FIG. 8.20. Parallel- and series-tuned wavetraps in the antenna-ground circuit of a receiver.

A *band-stop* filter is used to attenuate one frequency or a small band of frequencies and pass all others. The so-called "wavetrap" is an elementary form of a band-stop filter. It can be used in the antenna or other circuits of a receiver to prevent undesired signals from interfering with a desired signal. Figure 8.20 shows two wavetraps, one a parallel-resonant circuit in series with the antenna and the other a series-resonant circuit across the antenna-to-ground connections of a receiver. The parallel-resonant circuit offers very high impedance to the frequency to which it is tuned and relatively low impedance to all other frequencies. This high impedance reduces current in the antenna circuit at the frequency of resonance and therefore prevents current at this frequency from flowing in the receiver input winding. This frequency is not received.

The series-resonant circuit offers *low* impedance to any signals at its resonant frequency, effectively short-circuiting the antenna-to-ground circuit of the receiver at this frequency, preventing this frequency from being received.

Usually only a single wavetrap is used, but for greater attenuation of an interfering signal, both may be used.

Besides the bandpass and the band-stop filters, two other frequently used filters are the *low-pass* and the *high-pass* types.

An example of a low-pass filter using a single coil in series with a line between a source and load, with a capacitor across the line, is shown in Fig. 8.21. The inductive reactance of the coil will oppose higher frequencies more than it will oppose low frequencies. The capacitive reactance of the capacitor presents a better path *across* the line for higher frequencies than does the load. In this way, both reactances are acting to attenuate the high frequencies but to allow the low frequencies to pass to the load.

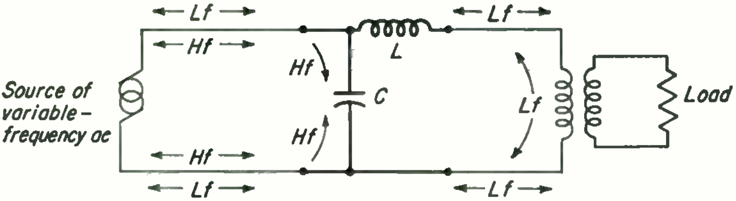


FIG. 8.21. Single-section constant-*k* low-pass filter between a source and load.

This low-pass filter is one of the simplest of the group known as *constant-k* filters. They derive their name from the fact that the product of the $X_L$ times the $X_C$ is constant at all frequencies. For example, at a certain frequency the inductive reactance may be 400 ohms and the capacitive reactance may be 100 ohms. The product of the two is 40,000. At twice the frequency the $X_L$ will be twice as much, or 800 ohms, and the $X_C$ will be half as much, or 50 ohms. The product of the two is still 40,000. In this case the 40,000 is the constant $k$.

A coil in series with a line will not oppose d-c, but will progressively decrease the a-c flowing through it as the frequency is increased. However, a constant-*k* filter will pass all frequencies up to what is known as the *cutoff frequency*, and then begin to attenuate all frequencies above this (Fig. 8.22). The cutoff frequency for a constant-*k* low-pass filter may be determined by using the formula

$$F_0 = \frac{1}{\pi\sqrt{LC}}$$

where $F_0$ is the cutoff frequency in cycles; $L$ is the inductance in henrys; and $C$ is the capacitance in farads.

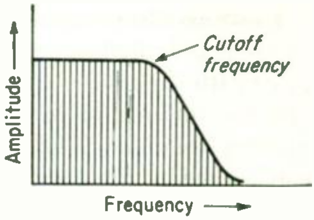


Fig. 8.22. Frequency response of a low-pass filter.

The attenuation with high-$Q$ reactances will be fairly sharp, but when even sharper cutoff characteristics are required, more complicated filters, made up of two or more constant-*k* sections, must be used.

A simple constant-*k* ***high-pass*** filter is shown in Fig. 8.23. The capacitor in series with the line passes the high frequencies to the load, while the coil across the line forms a better path than does the load for low frequencies, preventing low frequencies from appearing in the load. The result is the passage of the high frequencies only (Fig. 8.24). The cutoff frequency of the constant-*k* high-pass filter is determined by

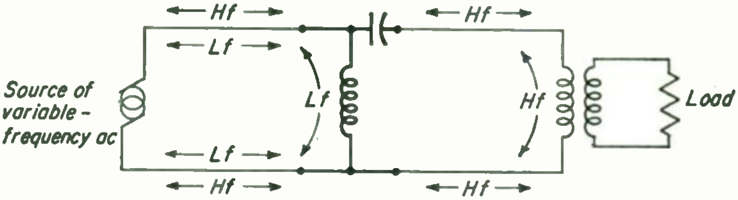


Fig. 8.23. Single-section constant-*k* high-pass filter circuit.

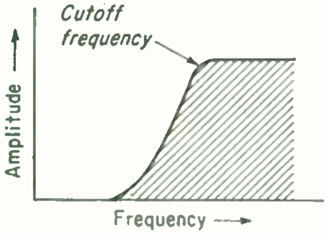


Fig. 8.24. Frequency response of a high-pass filter.

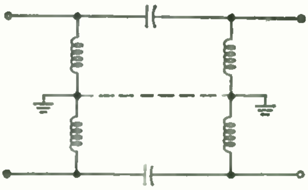


Fig. 8.25. A balanced constant-*k* high-pass filter circuit.

$$F_0 = \frac{1}{4\pi\sqrt{LC}}$$

The constant-*k* filters shown so far have been the *unbalanced* type. A *balanced* constant-*k*, high-pass filter is shown in Fig. 8.25. It is said to be balanced because the filter elements are similar on both sides of the line and because the center of the reactance across the line is usually connected to ground, as shown.

*Low-pass* filters are used in power supplies of receivers and transmitters where it is desired to pass d-c but prevent current variations. A low-pass filter with the proper cutoff frequency can be used between a transmitter and its antenna to prevent frequencies higher than the desired transmitting frequency (harmonics) from appearing in the antenna. This can reduce interference to nearby receivers or television sets.

*High-pass* filters with the proper cutoff frequency can be used between a TV receiver and its antenna to prevent nearby lower-frequency signals from interfering with TV reception. Such a filter passes the higher-frequency TV signals but attenuates any lower frequencies fed to it.

The simpler filter theory assumes that the source impedance and the load impedance are equal and that the filter is inserted between these two equal impedances. When the source and load impedance are different, filter circuits may have considerably different characteristics.

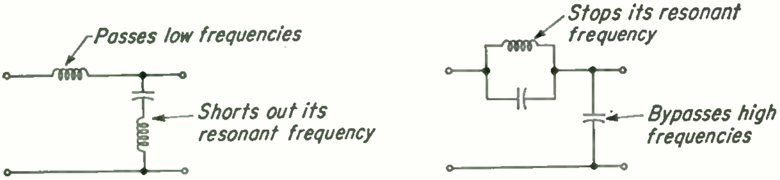


FIG. 8.26. Single-section *m*-derived low-pass filter circuits.

For sharper cutoff than is possible with constant-*k* filters, an *m-derived* filter may be used. This filter can be recognized by its series- or parallel-type resonant circuit in series with or across the line. A series-resonant wavetrap circuit across the line, or a parallel-resonant wavetrap circuit in series with the line, produces essentially infinite attenuation of the frequency to which it is tuned, and therefore zero transmission of that frequency along the line. Figure 8.26 shows two simple *m*-derived, low-pass filters.

The *m* may be considered to be a ratio of the cutoff frequency to the frequency of infinite attenuation (zero output) in a low-pass filter and will be something between 1 and 0. An *m*-derived, low-pass filter with an *m* value of 1 has the same attenuation or transmission curve as a constant-*k* filter and has no point of infinite attenuation. In such a case, the tuned circuit involved has either negligible capacitance or inductance. As the *m* value decreases, a point of infinite attenuation develops. As the *m* value decreases further, the point of infinite attenuation begins to approach the cutoff frequency, producing an increasingly steep attenuation, as shown on the transmission curve in Fig. 8.27. However, the lower the *m* value, the less the attenuation at frequencies beyond the point of infinite attenuation. With an *m* value of zero, the untuned filter component is negligible and the circuit operates as a wavetrap, with little attenuation of any frequencies except those at or near the resonant frequency of the tuned components. In practice it has been found that an $m$ value of about 0.6 is a good compromise between steep cutoff, and transmission past the point of infinite attenuation.

Figure 8.28 illustrates two $m$-derived, high-pass filters. The various types of filter circuits are often named according to a letter that the filter components form. Figure 8.29 illustrates three types of low-pass filters, a T, an L, and a pi (from the Greek letter $\pi$).

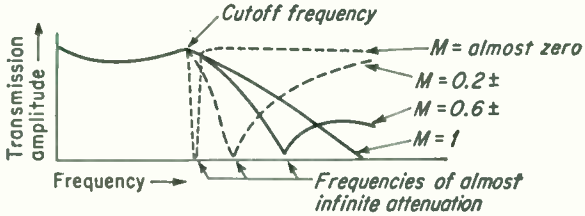


Fig. 8.27. Frequency responses of an $m$-derived low-pass filter with different values of $m$.

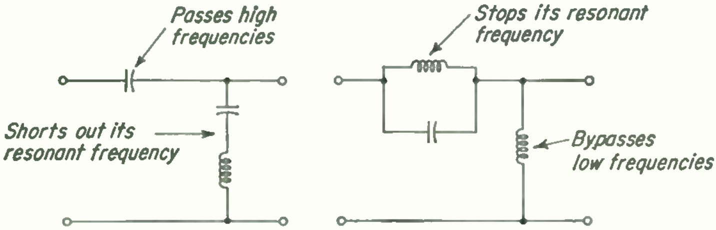
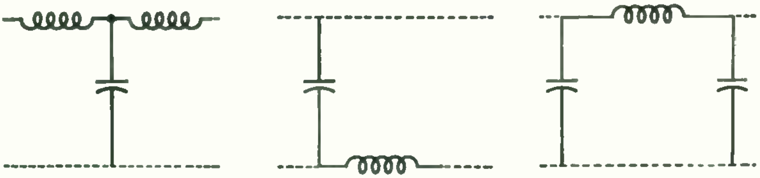


Fig. 8.28. Single-section $m$-derived high-pass filter circuits.



T type

L type

π type

Fig. 8.29. Three filter-circuit configurations.

To determine filter-component values, refer to radio or electrical engineering handbooks or communications texts of more advanced level.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

1. State the formula for determining the resonant frequency of a circuit when the inductance and capacitance are known. (8.1) [3]

2. What is the value of total reactance in a series-resonant circuit at the resonant frequency? (8.2) [3]

**3.** What is the value of reactance across the terminals of the capacitor of a parallel-resonant circuit at the resonant frequency and assuming zero resistance in both legs of the circuit? (8.3) **[3]**

**4.** Under what conditions will the voltage drop across a parallel tuned circuit be a maximum? (8.3) **[3]**

**5.** Given a series-resonant circuit consisting of a resistance of 6.5 ohms and equal inductive and capacitive reactances of 175 ohms. What is the voltage drop across the inductance when the applied circuit potential is 250 volts? (8.3) **[3]**

**6.** What is the meaning of skin effect in conductors of RF energy? (8.4) **[3]**

**7.** What is the purpose of a wavetrap in a radio receiver? (8.8) **[3]**

**8.** Define the term decibel (8.5) **[3 & 6]**

**9.** In a parallel circuit composed of an inductance of 150 $\mu$h and a capacitance of 160 $\mu\mu$f, what is the resonant frequency? (8.1) **[4]**

**10.** What value of capacitance must be shunted across a coil having an inductance of 56$\mu$h in order that the circuit resonate at 5,000 kc? (8.1) **[4]**

**11.** If in a given a-c series circuit, the resistance, inductive reactance, and capacitive reactance are of equal magnitude of 11 ohms and the frequency is reduced to 0.411 of its value at resonance, what is the resultant impedance of the circuit at the new frequency? (8.2, 8.3) **[4]**

**12.** If an a-c series circuit has a resistance of 12 ohms, an inductive reactance of 7 ohms, and capacitive reactance of 7 ohms at the resonant frequency, what will be the total impedance at twice the resonant frequency? (8.2) **[4]**

**13.** What is meant by the *Q* of an RF inductance coil? (8.4) **[4]**

**14.** What effect does a loading resistance have on a tuned RF circuit? (8.4) **[4]**

**15.** What is the formula for determining the decibel loss or gain in a circuit? (8.5) **[4]**

**16.** What is a low-pass filter? A high-pass filter? (8.8) **[4]**

**17.** Draw a diagram of a simple low-pass filter. (8.8) **[4]**

**18.** State the formula for determining the resonant frequency of a circuit when the inductance and capacitance are known. (8.1) **[6]**

**19.** What changes in circuit constants will double the resonant frequency of a resonant circuit? (8.1) **[6]**

**20.** If a parallel circuit, resonant at 1,000 kc, has its values of inductance halved and capacitance doubled, what will be the resultant resonant frequency? (8.1) **[6]**

**21.** What is the total reactance of a series a-c circuit containing no resistance and equal values of inductive and capacitive reactance? (8.2) **[6]**

**22.** What is the total impedance of a capacitor and inductor having equal values of reactance when connected in parallel? (8.3) **[6]**

**23.** Assume an inductance of 5 henrys in parallel with a capacitance of 1$\mu$f. If there is no resistance in either leg of this circuit, what is the equivalent impedance of the parallel network at resonance? (8.3) **[6]**

**24.** What is the resonant frequency of a tuned circuit consisting of a capacitor of 500 $\mu\mu$f, a tuning coil of 150 $\mu$h, and a resistance of 10 ohms? (8.3) **[6]**

**25.** How may the *Q* of a parallel-resonant circuit be increased? (8.4) **[6]**

**26.** Draw a simple schematic diagram of a wavetrap in an antenna circuit for attenuating an interfering signal. (8.8) **[6]**

**27.** What are some uses of a low-pass-filter network? (8.8) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

★**1.** What is meant by resonance? (8.1)

★**2.** What is meant by attenuation? (8.6)

**3.** What is the formula for resonance? (8.1)

**4.** What is the relative impedance of a series-tuned circuit at resonance? (8.2) Of a parallel-tuned circuit? (8.3)

**5.** What relative current flows in the source when a parallel-resonant circuit is connected across it? (8.3)

**6.** If inductance is kept constant, what must be done to the capacitance of a tuned circuit to double the resonant frequency? (8.1)

**7.** What must be done to the $LC$ product to halve the resonant frequency? (8.1)

**8.** What is meant by the $Q$ of a circuit? (8.4)

**9.** What is the name of the phenomenon that results in little or no current flowing in the center of wires carrying high-frequency currents? (8.4)

**10.** Draw a simple schematic diagram of a wavetrap in an antenna circuit to attenuate an interfering signal. (8.8)

**11.** What is meant by a constant-$k$ filter? (8.8)

**12.** Name two applications of low-pass filters in amateur work. (8.8)

**13.** Name an application of a high-pass filter in amateur work. (8.8)

**14.** Draw a schematic diagram of a balanced-type high-pass-filter circuit. (8.8)

**15.** Draw a schematic diagram of an unbalanced-type low-pass-filter circuit. (8.8)

# CHAPTER 9

# VACUUM TUBES

**9.1 Vacuum Tubes.** Since about 1920 the vacuum tube has been the basis of operation for all up-to-date radio equipment. Prior to 1920, coherers, crystal detectors, and spark and arc transmitters had their day, but by 1927 the vacuum tube had made these obsolete. Today the highly efficient transistor appears destined to take over many of the jobs presently handled by vacuum tubes. However, the vacuum tube is still probably the most important electronic and radio part.

This treatment of vacuum-tube theory is of the physical and electrical operation of the tubes themselves rather than in the many circuits in which the tubes find use. Uses of vacuum tubes are dealt with in subsequent chapters.

**9.2 Cathodes.** A *cathode*, in the study of vacuum tubes, is something capable of emitting electrons. For example, a piece of wire carrying an electric current becomes warm. If sufficient current flows, the wire becomes white-hot. At this temperature the electrons whirling around the atoms of the wire move so rapidly that some of the less tightly bound fly outward, away from the atoms of the wire into the surrounding space. This produces a cloud of free electrons around the wire as long as it is white-hot. The wire has become a cathode.

A common example of a cathode is an incandescent light globe. The filament wire when heated by current flowing through it emits a radiation called light, another radiation called heat, and also the unseen cloud of electrons sprayed outward from the filament. When the filament-wire atoms lose electrons they are left with a positive charge. The electrons sprayed outward are attracted back toward the positively charged atoms. This results in a constant out and back movement of electrons in the area directly surrounding the wire. These loose, negatively charged electrons are the *space charge*. When the wire loses its heat, the space-charge electrons return to the wire.

The space charge in a light globe has no practical use, but in radio tubes it is highly important. The central element in a radio tube is a filament acting as a cathode. To allow space-charge electrons to travel unimpeded through the tube, all the air inside the tube is pumped out.

In this evacuated space, with no air molecules to get in the way, the space-charge electrons can move freely to any other element in the tube.

All old-time tubes had filaments that produced the electron emission when they were heated, and most high-power transmitting tubes still use filament-type cathodes, but most receiving tubes now use heater cathodes. A heater cathode consists of a metal cylinder coated with special oxides that liberate great quantities of electrons when heated to a relatively low temperature. Down the center of the cylindrical, coated cathode runs an insulated heater wire (Fig. 9.1*b*). When current flows through the heater wire, the cylinder surrounding it heats and the external oxide coating on the outside of the cylinder emits electrons.

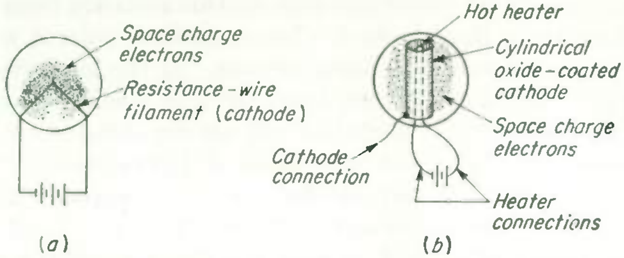


FIG. 9.1. Electron emission from cathodes. (*a*) Directly heated cathode. (*b*) Indirectly heated cathode.

The filament-wire type of cathode heats and cools rather rapidly. As a result, when a 60-cycle a-c is used to heat the filament, the temperature of the wire varies during each alternation, resulting in a periodic variation in the number of emitted electrons 120 times per second. Because a constant emission is usually required in vacuum tubes, this electron variation is undesirable. Since it takes 10 to 15 sec for the cathode surface of a heater cathode to heat to the point of liberating electrons, the small, rapid changes in temperature of the insulated heater wire, due to the alternating current flowing through it, have no effect on the surface temperature of the cathode sleeve, and a constant number of electrons is emitted from the cathode surface.

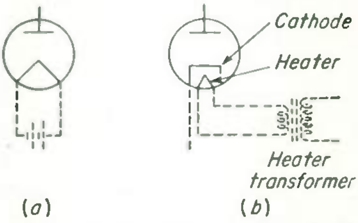


FIG. 9.2. Symbols used to indicate (*a*) directly and (*b*) indirectly heated cathodes.

Most receivers take 10 to 15 sec to start working after being turned on because the cathode must reach an operating temperature. Portable or battery-operated receivers may use filament-type tubes and operate the instant the switch is turned on.

The symbols used to designate a filament-type tube and a heater-cathode-type tube are shown in Fig. 9.2.

The filament type, also known as a *directly heated* cathode tube, is shown with a battery connected in the filament circuit. The second element in the tube is a plate, or anode.

The heater-cathode type, also known as an *indirectly* heated cathode tube, shows the heater circuit connected to an a-c source, a transformer. The cathode cylinder is indicated by the caplike symbol over the heater.

An electrical insulation between the heater wires and the inner surface of the metallic cathode sleeve prevents electron emission from the heater from reaching the cathode. Such a heater-cathode current would interfere with proper operation of many circuits. If the insulation between the heater and cathode does break down, the tube is said to have a heater-cathode leak. The heater insulation will usually stand about 100 volts, although some tubes are made to withstand 450 or more volts without breaking down. It is important that an excessive potential never be developed between the heater and cathode.

Alternating current is used to heat the filaments whenever possible because of its more general availability. Direct current is usually obtained from batteries, which wear out, are costly, and must be replaced frequently. Power from small "penlight" cells, or B batteries, can cost more than $45 per kilowatthour, as compared with about 3 to 5 cents per kilowatthour for a-c power from public utilities.

**9.3 Filaments.** Filaments in directly heated vacuum tubes are usually one of the three types listed below:

1. *Nickel Wires with Oxide Coating.* The nickel wire is heated, causing the oxide coating on the wire to emit electrons. It is only necessary to heat the wire to a dull red or orange-red color (800° centigrade) for normal operation. Such filaments are used in both receiving and transmitting tubes. The oxide coating often flakes off in old tubes and can be seen as loose white particles when the tube is turned upside down. When the oxide coating is lost to the filament, emission becomes very low, and the tube is normally unusable.

2. *Tungsten Wires.* The tungsten wire requires a relatively high operating temperature, about 2300°C, at which temperature it is incandescent, being yellow or white-hot. Even at that temperature its emission is relatively small. Tungsten filament tubes require considerable power to heat them. The filaments are relatively rugged, however, and are found in transmitting tubes where very high plate voltages (in the thousands of volts) are used.

3. *Thoriated-tungsten Wires.* Thorium is an excellent electron emitter, but wires made of this material alone are not strong enough for practical use. By mixing a little thorium with the more rugged tungsten a thoriated-tungsten wire will emit large numbers of electrons at lower temperatures than are required for pure tungsten. These filaments operate at about 1600°C and burn at a bright orange heat. Their

filament power consumption for a given emission value is much lower than pure tungsten. Such filaments are used in transmitting tubes.

In some cases, thoriated-tungsten filaments may be rejuvenated when the outer thoriated layer loses too many thorium molecules. This is accomplished by first removing the plate voltage from the tube, and then *flashing* the filament by applying a filament voltage two to three times the normal value for a few seconds. If this does not burn out the filament, the voltage is brought down to about 1½ times normal, and the filament is operated at this value for 10 to 20 min. This boils thorium atoms out to the surface of the tungsten wire, and the filament will emit electrons almost as well as when new.

Generally speaking, when plate voltages up to approximately 500 volts are used in a tube, the filament or cathode will be oxide-coated. With plate voltages from about 500 to 6,000 volts the filaments will usually be thoriated tungsten. Above 6,000 volts pure tungsten is usually considered more satisfactory.

When a filament wire is heated it emits electrons, but the heat and the electron movement also carry off a few molecules of the wire. The higher the temperature, the more molecules lost to the filament. These molecules fly out into the tube and deposit themselves on the inside of the glass envelope or on the other elements of the tube. Eventually one point in the filament wire becomes so thin that it melts apart. The tube is burned out. Old tubes often have a dark deposit of filament molecules at the top of the glass envelope. New tubes will not normally have this deposit.

**9.4 Correct Filament Voltage.** It is necessary to use the correct voltage across the filament or heater of a tube to obtain optimum tube life. If a tube is rated at 6.3 volts, it will have a certain life expectancy. If operated at 7 volts, it will have a greater filament emission because of increased filament current, but the temperature of the filament wire will be so high that molecules of the filament will be more rapidly boiled off, greatly shortening the life of the tube.

On the other hand, lower filament voltage will produce less emission but will increase the life expectancy of the tube considerably. The tube manufacturer must balance filament emission against life expectancy when producing tubes.

**9.5 The Anode, or Plate.** Vacuum tubes are just what their name indicates. The space inside the outer glass or metal shell, or *envelope*, has been pumped out until there is no air or gas left inside. This vacuum is made as *hard* as possible by the manufacturer.

When a piece of metal called either a *plate* or *anode* is placed inside the evacuated space, it will pick up a few of the electrons given off by the filament or heater cathode. If the plate is connected to the cathode through a meter, as shown in Fig. 9.3, the meter will register a small current. When the cathode loses its heat, the current in the *plate circuit* will stop.

If the plate is made even the slightest bit negative in respect to the cathode, this negative charge on the plate will repel electrons from the cathode and the space charge, and no current will flow in the plate circuit. In Fig. 9.4, the plate has been made slightly negative by adding a battery in series with the plate circuit, with the negative end of the battery connected to the plate, the positive end to the cathode.

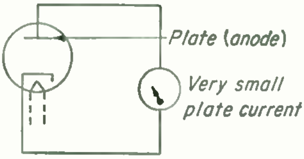


FIG. 9.3. The plate collects some emitted electrons, and a small plate-circuit current flows.

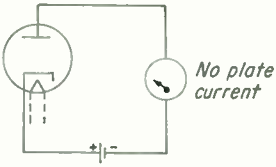


FIG. 9.4. No current flows if the plate is negatively charged in respect to the cathode.

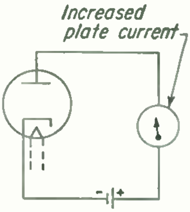


FIG. 9.5. Increasing the positive charge on the plate increases the plate current.

If the battery is placed in the circuit with opposite polarity connections (Fig. 9.5), the plate-circuit meter will show an increase in plate current. The higher the positive potential on the plate, in respect to the cathode, the greater the plate current. This is one of the important points in vacuum-tube theory. The plate current in the simpler types of vacuum tubes is essentially directly proportional to the *positive* voltage applied to the plate. This is shown in a graph (Fig. 9.6), called an $E_pI_p$ curve. It can be read as follows: At zero volts on the plate, the current is less than 2 ma. At 10 volts on the plate the current is 17 ma. At 20 volts, the plate current is 31 ma. At 30 volts the $I_p$ is 50 ma. With an $E_p$ of 40, the $I_p$ is 71 ma, etc. This is a simplified example. It will be found that the line will actually curve upward continually until it approaches the *saturation point*, when it will begin to flatten off. The plate is *saturated* when it is accepting all the electrons given off by the cathode.

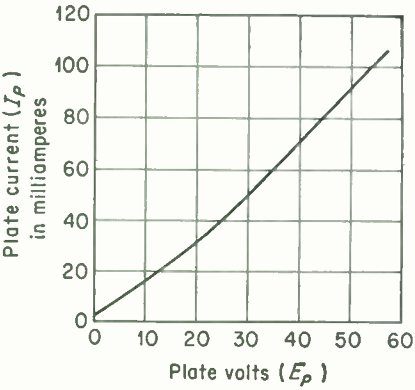


FIG. 9.6. Plate-voltage–plate-current ($E_pI_p$) curve.

**9.6 The Plate Load.** In all working circuits involving vacuum tubes there will be found a *load* connected somewhere in the plate circuit. The load may be a resistor, across which a varying d-c voltage will be produced when the current through it varies. The load may be an inductance, called a *choke coil*, across which an alternating voltage will be developed when the current through it is varied. The load may be the primary of a transformer, in the secondary of which an a-c voltage will be induced when the primary current varies. The load may be a meter, a relay, a loudspeaker, or a pair of earphones. It is always in or across the load that the result of the operation of the tube is made apparent.

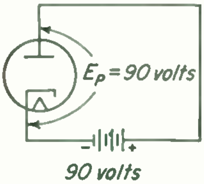


FIG. 9.7. With no resistance in the circuit, the plate voltage equals the supply voltage.

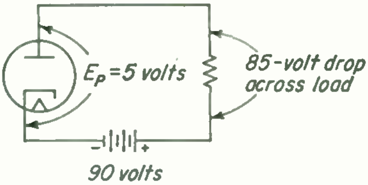


FIG. 9.8. The plate voltage is the difference between the supply and the voltage drop across the resistance.

In Fig. 9.5 the plate-circuit load is a meter. In Fig. 9.7 there is no load, as this circuit is merely used to explain a point and is not used in practice. In Fig. 9.8 the load is a resistor.

**9.7 Plate Voltage.** The difference in potential between the plate and the *cathode* of a vacuum tube is the *plate voltage*. Figure 9.7 shows a diode tube with a 90-volt battery in the plate-cathode circuit. In this case the plate voltage is 90 volts.

In Fig. 9.8, in addition to the 90-volt battery, the plate circuit contains a load resistance. The current through the resistance produces a voltage drop across it. If the voltage drop across the load is 85 volts, the plate voltage must be 5 volts. In this case there is a power-supply voltage of 90 volts, a load voltage of 85 volts, and a plate voltage of 5 volts.

The information above refers to a heater-cathode-type tube. But what is the actual plate voltage when a filament-type tube is used? Figure 9.9 shows such a circuit.

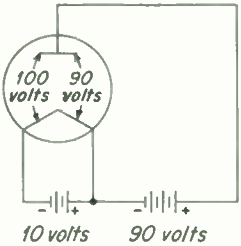


FIG. 9.9. The plate voltage is the supply voltage plus half the filament voltage.

In this circuit there is a 90-volt difference of potential between one side of the filament and the plate and 100 volts between the other side of the filament and the plate (10 volts across the resistance of the filament wire itself). What is the plate voltage? In this case the plate voltage will be the average of 90 and 100, or 95 volts.

If the filament battery has its polarity reversed, as in Fig. 9.10, there will be 90 volts between one side of the filament and the plate and 80 volts from the other. The average plate voltage is now 85 volts.

If a 10-volt peak a-c is used to heat the filament (Fig. 9.11), the average plate voltage will vary from 95 to 85 volts at the frequency of the a-c. This will cause the plate current to vary at this same frequency.

Usually a *constant* plate-circuit supply voltage is desired in vacuum-tube circuits. With d-c for both filament and plate supply there is no reason for the plate voltage to vary. To prevent plate-voltage variations and still use the more readily available a-c to heat the filament, the filament circuit can be center-tapped. The plate-circuit power supply is then connected to the center tap instead of to one side of the filament (Fig. 9.12).

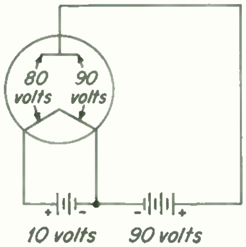


FIG. 9.10. The plate voltage is the supply voltage minus half the filament voltage.

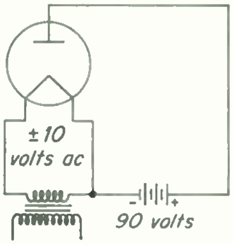


FIG. 9.11. An a-c filament source results in a varying plate voltage.

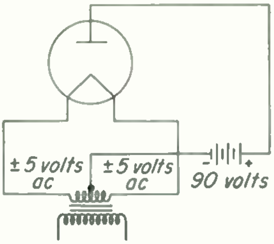


FIG. 9.12. Center-tapping the a-c filament source results in a constant plate voltage.

If the output of the transformer is 10 volts, at the instant of maximum voltage there will be 5 volts between the center tap and either filament terminal. One terminal will be 5 volts positive, the other 5 volts negative. The voltage difference between one side of the filament and the plate will be 85 volts and between the other side and the plate 95 volts, an average of 90 volts. Regardless of what the instantaneous a-c filament voltage happens to be, or its polarity, the average will now be 90 volts between filament and plate and the plate current will not be varied by the a-c filament supply. Center-tapping the filament supply is a requirement for practically all tubes using directly heated filaments with a-c.

Since the filament is heating and cooling slightly every alternation, there may be a slight variation of electron emission when the current drops to zero and then rises to maximum. With 60-cycle a-c, the slight plate-current variation will have a frequency of 120 cycles.

An alternate method of center-tapping the filament circuit is shown in Fig. 9.13. In this case, the filament circuit has a center-tapped 10- to 50-ohm resistor connected across it. The negative return from the plate supply is connected to this point, producing the same reduction of plate-voltage variation that was produced by center-tapping the transformer. There will be a slight voltage drop across the resistance which will subtract from the plate voltage.

When vacuum tubes are used in audio- or radio-frequency circuits it becomes necessary to connect *bypass* capacitors from the center tap on the resistor or on the transformer to each side of the filament.

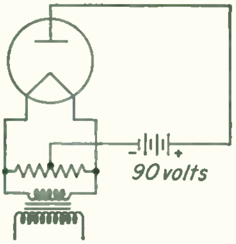


FIG. 9.13. Another method of center-tapping an a-c filament source.

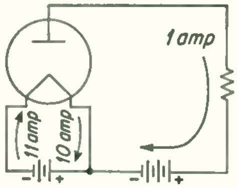


FIG. 9.14. A d-c-operated filament has more emission from one end of the filament wire than from the other.

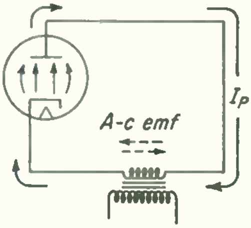


FIG. 9.15. An alternating emf in the plate circuit of a diode produces a pulsating d-c.

**9.8 Reversing Filament Polarity.** The diagram in Fig. 9.14 shows a directly heated diode tube with d-c as the heating current. Where does the plate current flow?

The electrons drawn to the plate by its positive polarity flow through the load, the plate battery, and to the filament. For convenience, the plate current will be assigned a 1-amp value and the filament current a 10-amp value. The 10 amp flows from the negative end of the filament battery through the filament wire to the positive end of the filament battery, through the battery to the negative terminal, and so on.

The plate current cannot buck the filament current, so it must send its 1 amp through the filament battery and to the negative end of the filament. This means that 11 amp is flowing through the negative end of the filament, but only 10 amp is flowing through the positive end. The other ampere is given off as an electron emission by the filament. Since the negative end of the filament is carrying more current, it is heated more and tends to wear out first. This is one reason why high-power transmitting tubes, when heated by d-c, either have their filament connections reversed periodically or reverse the filament-battery polarity to prolong their lives. If a-c is used to heat the filament, the polarity is constantly reversing and this problem does not exist.

**9.9 Diode Tubes and Rectification.** Tubes with two elements or electrodes in them are called *diodes* (*di* means "two"). A diode tube has a cathode that emits electrons and an anode, or plate, that collects electrons when it is positive. A diode may be said to have a filament and plate or a heater cathode and plate.

Diodes act as one-way conductors (Fig. 9.15). If the plate is made positive with respect to the cathode, it attracts space-charge electrons and current flows in the plate circuit. If the source of plate voltage in the plate circuit is a transformer, the plate voltage is alternating. At one instant the right-hand end of the transformer secondary winding may be positive and the left-hand end negative. On the next half cycle the right-hand end will be negative and the left-hand end positive.

When the right-hand end is positive, the plate connected to it is made positive and electrons are attracted from cathode to plate, through the transformer secondary and back to the cathode. This completes the electric plate circuit. When the right-hand end of the transformer is negative, the plate is charged negatively, and, as explained before, repels the space-charge electrons and refuses to allow electrons to move across the tube. (The plate, being *cold*, cannot emit electrons.) Therefore, there will be no plate current flowing during the *negative* half cycle of the alternating voltage.

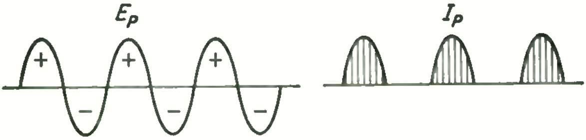


FIG. 9.16. A diode allows only half of the a-c cycle to produce current in the plate circuit.

In this way the diode tube acts as a one-way gate. It is said to be *rectifying* the a-c; that is, it allows only one half cycle of the emf to produce current in the circuit. The current in the plate circuit under this condition is pulsating (Fig. 9.16). This one-way-gate effect is the main use of the diode-type tube in radio and electronics. A diode tube is often referred to as a *rectifier* tube, although other types of tubes can produce rectification also.

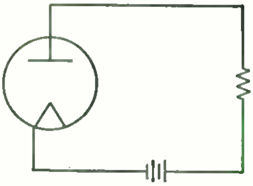


FIG. 9.17. Diagram of a filament-type diode. The filament supply is omitted to simplify the diagram.

In diagrams showing either filament or heater-cathode tubes, the heater circuits may not always be completed. Figure 9.15 is an example of this abbreviated diagraming of a heater-cathode diode. Figure 9.17 shows an abbreviated diagram of a filament tube. It is assumed that you understand that the heater or filament is connected to some source of power—either battery or transformer.

**9.10 The Vacuum in a Vacuum Tube.** Any molecules of air or gas of any kind left inside a vacuum tube after it has been evacuated will interfere with the required free movement of electrons from the cathode to the anode or to any other elements in the tube. The manufacturer pumps out all the gas it is possible to pull out by mechanical pumping and then seals the outer glass or metal envelope of the tube. Inside are all the elements of the tube plus a small piece of chemically active metal, such as magnesium, called a *getter*. By induction, the elements and the active metal getter are heated. The getter explodes or burns and combines chemically with any molecules of gas that are still in the vacuum depositing part of itself in combination with the gas molecules on the inside of the envelope. From the outside this deposit appears as a silvered-mirror surface.

A high degree of vacuum is known as a *hard* vacuum. A vacuum tube which is gassy for any reason is known as a *soft* tube. Tubes become soft because of leaks through the glass or metal envelope at sealed edges or because of unintentional overheating of the elements, which may liberate some of the gas molecules that are normally present in solids. For the latter reason, during the manufacture of a tube, the metal elements are heated in an attempt to drive out as many of the gas molecules as possible.

Soft vacuum tubes usually show a faint purple or blue haze between elements. The intensity of this glow varies directly with the plate current flowing through the tube. Some tubes, when operated at high voltages, produce a blue glow where electrons strike the inner surface of the glass envelope. This does not indicate the presence of gas but is the conversion of electric energy into light energy as the electrons strike some of the getter or glass molecules on the inner surface of the glass envelope.

Gas-filled tubes, discussed next, are also known as soft tubes, although the meaning of the word soft does not here indicate faulty operational characteristics as it does when applied to vacuum tubes.

**9.11 Gaseous Diodes.** If a diode tube is evacuated and then some liquid mercury or an inert gas is inserted, a gaseous diode is produced.

In gaseous diodes, the filament is heated and electrons are emitted as in vacuum tubes but the electrons do not go directly to the plate. Instead, they start toward the plate but soon strike a gas molecule. In the case of mercury vapor, if the difference of potential between cathode and plate is 15 volts or more, the speed of the electron is sufficient to dislodge two or more electrons from the gas molecule. This splits the gas molecule into a positive ion (the gas molecule minus one or more electrons) and one or more free electrons. The relatively heavy positive ions start to move toward the filament, and the free electrons move toward the positive plate. The positive ions move only a short distance before an electron from the cathode fills in each "hole" produced by a freed electron, bringing the electric charge of the molecule back to its normal neutral charge. It is no longer attracted to either a positive or a negative charged area, until ionized again by another electron from the cathode.

The free electrons either travel directly to the plate or ionize another molecule as they move toward the positive potential. This electron movement from ion to ion is continued, resulting in a currrent of electrons from filament to plate.

An advantage of gaseous diodes is in their efficiency. Electrons travel only a short distance and therefore do not strike the plate with great force. Little heat dissipation or loss is produced at the plate. Such tubes require little ventilation. They carry relatively high currents and have a relatively constant voltage drop across them. Mercury-vapor tubes are examples of this type of a gaseous diode, discussed in the chapter on Power Supplies.

One gaseous diode using argon gas has a coiled filament wire and a carbon plate. It is known as a Tungar bulb and is used in battery-charging circuits.

Gaseous diodes glow blue with mercury vapor and purple or pinkish with other gases.

**9.12 Cold-cathode Tubes.** Tubes filled with the proper gas under the correct pressure will ionize and pass an electronic current if the voltage across them is greater than the ionization potential of the gas used. If the area of one of the electrodes in the tube is greater than the area of the other electrode, more current will flow from the large- to the small-area element than in the opposite direction. The large-area element becomes the cathode and the small-area element the anode, or plate, as indicated in Fig. 9.18. There is no heated filament or cathode.

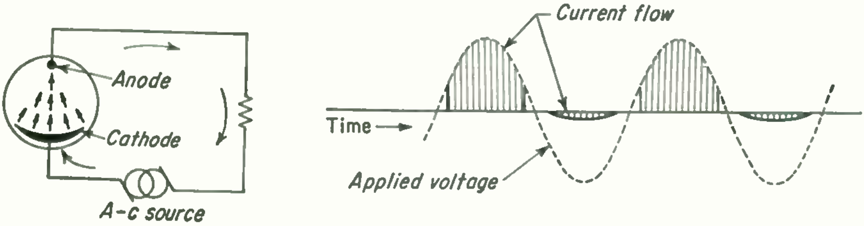


FIG. 9.18. More current flows from a large-area electrode than from a small one in a cold-cathode gas-filled tube.

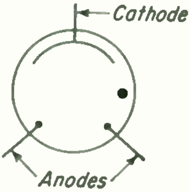


FIG. 9.19. Symbol for a two-anode gas-filled rectifier tube.

There is a small current flow in the opposite direction, but for most purposes, when an a-c emf is applied across the tube, as shown, the current through the load resistor is substantially pulsating d-c. The current does not start to flow until the applied voltage reaches the ionization potential and stops flowing when the applied voltage drops to the extinguishing potential of the gas used.

These tubes can be used in power supplies when it is desired to change an a-c to pulsating d-c. In practical circuits a double-diode tube, called a *full-wave rectifier*, is used (Fig. 9.19). Rectification is explained in the chapter on Power Supplies.

**9.13 Gaseous Triodes, or Thyratrons.** The ionizing voltages for certain gaseous tubes is relatively constant if the gas pressure is maintained constant. For example, if a tube ionizes at 15 volts, the voltage across it can be brought up from zero to 15 volts. At this potential the tube ionizes and current flows. At 15 volts the tube is an excellent conductor. If the voltage is now decreased a few volts, the gas will de-ionize and no current will flow. This feature offers electronic possibilities for controlling currents in many types of circuits.

If a third element is inserted between the cathode and the plate, so that an electrostatic charge on it will affect the ionization of the gas between the cathode and plate, it is possible to control the ionization voltage of the tube. If the third element, called a *grid*, is made negative in respect to the cathode, the negative electrostatic field produced in the region between the cathode and plate will counteract the positive charge of the plate, resulting in lower electron velocities and less tendency to ionize the gas. It will now be necessary to increase the positive potential on the plate to produce ionization. The value of the negative charge on the grid determines the ionization potential required on the plate. The tube will not de-ionize until the plate potential drops below the normal extinction voltage of the gas used.

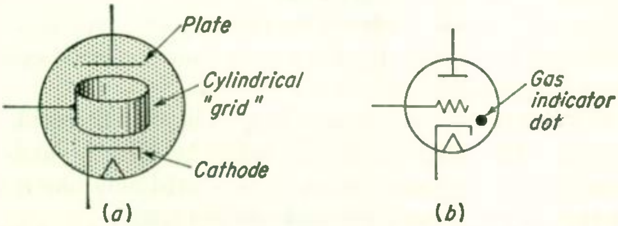


FIG. 9.20. (*a*) A cylindrical grid thyratron tube. (*b*) Symbol of the same tube. Dot indicates gas in envelope.

Figure 9.20 shows a simplified illustration and symbol of a three-element, gaseous *triode* tube, known as a *thyratron*. There are also four-element gaseous control tubes. The dot in the symbol of a tube indicates gas. Without the dot the tube would be assumed to be a vacuum tube.

**9.14 Triode Tubes.** Vacuum-type diodes, or two-element tubes, act as one-way conductors (or as one-way resistors). If the resistance of a diode is measured, it will be found to be very low. With only a very few volts across it, enough current may flow through a diode to damage it. As a result, practical circuits involving diodes always have some resistance as the load in the circuit. An example was shown in Fig. 9.8. In this circuit an increase in B-battery voltage produces an essentially proportional increase in plate current in the circuit.

When a vacuum tube with a cathode and a plate has a wire meshwork built into it between cathode and plate, the wire meshwork is called a *grid*. The tube can be diagramed as shown in Fig. 9.21. Such a three-element tube is called a *triode*. All the electrons flowing from the cathode to the plate must pass through the spaces between the wires of the grid. If the grid has no electric charge, it will allow the electrons to pass almost as though it were not there. However, if the grid is made a little negative (in respect to the cathode), it tends to repel the negative-space-charge electrons being attracted toward the plate, thereby decreasing the cathode-to-plate current somewhat. A strong negative charge on the grid can stop the plate-current flow entirely. A varying negative charge on the grid will produce a varying plate current. Thus, *voltage variations* in the grid circuit produce *current variations* in the plate circuit.

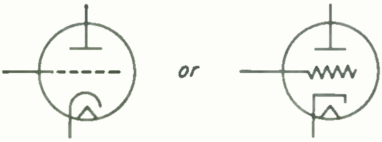


FIG. 9.21. Symbols used for triode tubes in schematic diagrams.

Since an increase in negative charge results in less plate current, making the grid negative increases the plate-circuit resistance. The tube may be considered to be acting as a variable resistance, with the voltage applied between the grid and cathode being the controlling factor. The more negative the grid, the higher the resistance between cathode and plate. The more positive the grid, the lower the resistance of the tube. However, the grid is not made to be driven very positive. In actual operation the grid is usually made to vary more or less negatively, but may never be driven positive.

Because of the plate-current-controlling ability of the grid, it is called the *control grid*. The British call such tubes "valves," which is actually a more descriptive term than "tube." The grid acts like a valve, controlling the flow of electrons from cathode to plate.

The resistance between cathode and plate can be computed using Ohm's law:

Plate Resistance

$$R_p = \frac{E_p}{I_p}$$

where $R$ is the d-c resistance of the tube in ohms; $I_p$ is the plate current in amperes; and $E_p$ is the plate voltage.

This resistance value is known as the *d-c resistance* of the vacuum tube and is useful in some special circuits. There is another value which is *more* important, the *a-c resistance*, or the *plate impedance*, of the tube, to be discussed later.

**9.15 The Amplification Factor.** How effective a controlling device the grid is can be illustrated by an example. Consider the circuit in Fig. 9.22. With this particular tube, if the voltage on the grid is $-5$ volts and the plate voltage is 100, the plate current indicated by the meter is 0.01 amp, or 10 ma.

Since plate current is essentially directly proportional to plate voltage in this type of tube, the plate current will rise to 20 ma if the plate voltage is raised to 200 volts. It takes 100 volts on the plate to increase the plate current 10 ma.

Going back to the −5 volts on the grid, 100 volts on the plate, and the resultant plate current of 10 ma: If the grid voltage is reduced from −5 to zero, the plate current will increase. In this particular tube it increases to 20 ma with this 5-volt change in grid voltage. This is a 10-ma increase, just the same as that produced by increasing the plate voltage 100 volts. Since a *5-volt change* in the grid circuit can control the plate current just as much as a *100-volt change* of plate voltage can, grid voltage is 20 times more effective in controlling plate current than the plate-circuit voltage is. This number is known as the amplification factor, or $\mu$ (Greek letter mu) of the tube. Small voltage changes in the grid circuit can produce the equivalent of much larger plate-voltage changes.

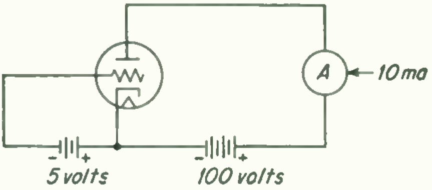


FIG. 9.22. Circuit to illustrate controlling effect of grid voltage on plate current.

While this tube has a $\mu$ of 20, the *voltage* variation, or output, across the plate-circuit load will not be 20 times the signal voltage applied to the grid of the tube. However, actual voltage amplifications equal to one-half to two-thirds of the $\mu$ value are quite common. In the case of a tube with a $\mu$ of 20, it is feasible to produce a 10- to 14-times amplification of signals fed into the grid-cathode circuit.

**9.16 How the Triode Amplifies.** The circuits described so far are not practical amplifiers, but the circuit shown in Fig. 9.23 will actually amplify an input signal. *Signals* that are amplified in an amplifier stage are either a-c or varying d-c voltages. In this case, an a-c voltage induced into the secondary of the transformer and applied between grid and cathode is used as the signal to be amplified.

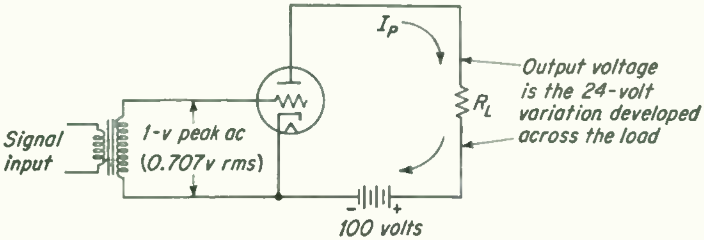


FIG. 9.23. Circuit capable of producing an output-voltage variation 12 times the input-voltage variation.

With no signal applied to the grid and with 100 volts of plate battery, the d-c voltage drop across the load resistor $R_L$ might be 75 volts. As the input signal reaches a peak of 1 volt negative, the current in the plate circuit will decrease. The voltage drop across the plate load resistor might possibly drop in value by 12 volts. There will now be 63 volts across $R_L$. As the grid voltage swings to 1 volt positive, the plate current will increase, until there is a voltage drop of perhaps 87 volts across the load resistor. As the grid voltage varies from $-1$ volt to $+1$ volt (a 2-volt peak-to-peak variation), the voltage across the load resistance varies between 87 and 63, or 24 volts. The ratio of 2:24 volts indicates that across the plate load resistor a voltage variation will appear that will be 12 times the voltage variation applied between grid and cathode. The actual amplification of the tube and its circuits in this case is 12, although the tube itself may have an amplification factor of 20.

If the resistance value of the plate load is increased, the actual amplification will become greater. Theoretically, if the plate-load resistance is infinite, the gain of the stage, the actual amplification, will equal the amplification factor of the tube. However, resistance values much over 1,000,000 ohms will decrease the plate current so much that the tube may not operate satisfactorily or may drop the plate voltage so much that impractically high supply voltages would be required. Practical plate-load resistance values will range from about 5,000 to about 500,000 ohms.

In many cases, an a-c signal output is desired from an amplifier stage. The signal output in the circuit described is a varying d-c. As the varying plate d-c is fed through a transformer primary, the signal will be converted to a-c in the secondary. Also, by the use of a capacitor and another resistor, an a-c output voltage can be produced from the varying d-c in the plate circuit, discussed in the chapter on Audio-frequency Amplifiers.

While this amplifier stage is capable of amplifying a signal voltage, it is still not a common type of circuit. A *bias* voltage is usually added to the grid circuit.

**9.17 Bias Voltage.** In the amplifier circuit previously discussed, the grid was first driven negative and then positive. In many practical circuits, to prevent distortion of the signal, it is desirable that the grid never be allowed to become positive and thus draw grid current ($I_g$) from the cathode. This is accomplished by adding a *C battery*, or other voltage supply, in series with the grid-cathode circuit. The battery has its negative terminal connected to the grid through the grid-circuit transformer and its positive terminal to the cathode (Fig. 9.24). This negative d-c voltage added in series with the grid circuit is known as a *bias* voltage.

If a negative 10-volt bias is enough to cut off the plate current entirely with a given plate voltage, then a possible voltage for the C battery would be about half of this, or 5 volts.

With a 5-volt bias applied to the grid by the battery, it is possible to accommodate a peak a-c emf of nearly 5 volts from the secondary of the grid-circuit transformer and neither cut off the plate current at any time nor drive the grid into the positive region.

Notice that the plate supply is not applying any negative voltage to the grid circuit. This supply is connected between cathode and plate and is not in, or affecting, the grid circuit at all. On the other hand, the C battery is between cathode and grid and is not applying any voltage to the plate circuit. If the B battery has 100 volts and the C battery shown has 5 volts, there may be a 105-volt difference in potential between *plate* and *grid*, but this voltage is rarely considered in theory or application and may be ignored.

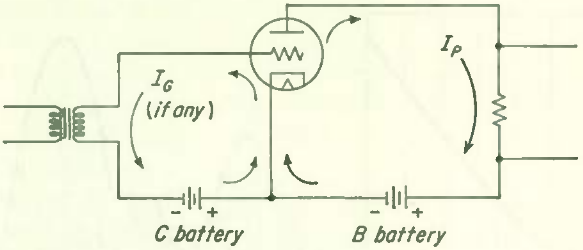


Fig. 9.24. Bias battery in grid circuit and direction of current flow in the grid and plate circuits.

In the basic amplifier, the grid circuit and the plate circuit are two separate circuits that happen to have a common cathode connection. The grid circuit consists of the cathode, C battery, grid-circuit signal-input device (the transformer secondary in the diagram), and the grid. The plate circuit consists of the cathode, plate, load (resistor), and B battery. The two circuits work independently of each other, although a change in the *grid*-circuit *voltage* will change the *plate*-circuit *current*.

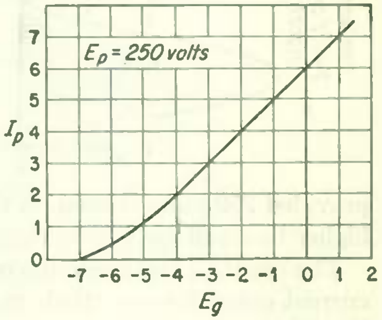


Fig. 9.25. Curve of plate current for various grid-voltage values ($E_gI_p$), with a constant plate voltage.

**9.18 Grid-voltage Plate-current Curves.** How much will a variation of the grid voltage affect the plate current in a particular triode tube? To determine this, a grid-voltage versus plate-current ($E_gI_p$) curve (Fig. 9.25) may be used. If this curve is plotted with no load resistance in the plate circuit, it is called a *static* characteristic curve. If a load is used, an increase in plate current increases the voltage drop across the load and thereby lowers the actual plate voltage. A graph of such a working condition produces a *dynamic* characteristic curve. When graphed to the same scale, the dynamic will not rise as steeply as the static curve, although the relative curve shape will be approximately the same.

This particular graph is read as follows: The plate voltage is constant at 250 volts. With zero volts on the grid (no bias), the plate current is 6 ma. With $-2$ volts on the grid the plate current is 4 ma. At $-5$ volts the plate current is 1 ma, and at $-6$ volts the plate current is 0.5 ma. This tube is completely cut off by applying a $-7$-volt bias to its grid,

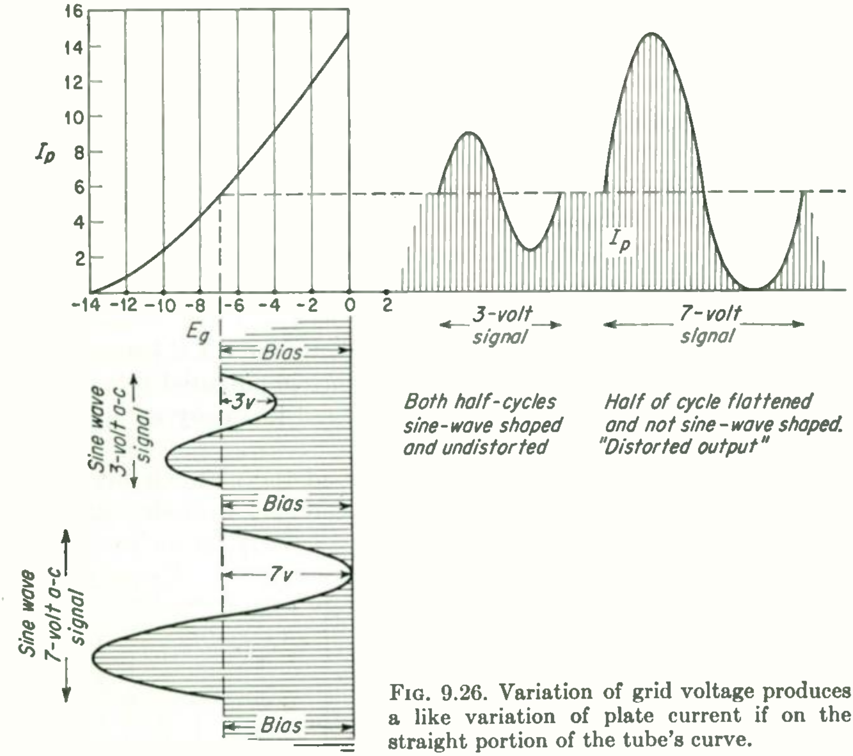


FIG. 9.26. Variation of grid voltage produces a like variation of plate current if on the straight portion of the tube's curve.

provided 250 volts is used on the plate. With a higher plate voltage, a higher bias voltage will be required to attain plate-current cutoff.

The negative voltage value required to produce almost complete plate-current cutoff for any triode may be found by dividing the plate voltage by the $\mu$ of the tube:

$$E_{co} = \frac{E_p}{\mu}$$

where $E_{co}$ is the cutoff bias voltage; $E_p$ is the plate voltage; and $\mu$ is the amplification factor of the tube.

The plate-current cutoff bias is the value that would be required to bring the curve to zero if it had no bend at the lower end. This would be $-6.5$ volts, approximately, in the graph shown, Fig. 9.25

Rearranging the formula above, the $\mu$ of the tube used as the illustration is

$$\mu = \frac{E_p}{E_{co}} = \frac{250}{6.5} = 38.5$$

It is not normally considered advisable to operate a tube in the bent portion of the curve, near the cutoff region. Such operation may cause distortion of the signal being amplified. In Fig. 9.26 a curve is shown with two input signals of different amplitudes. The first results in a plate-current variation having the same *waveshape* as the input signal because all the operation is under the straight portion of the curve. The negative half of the second, higher-amplitude input signal operates in the bent region of the curve. Part of the voltage operating in the bent area produces a flattening of the plate-current waveshape. This part of the signal is being distorted. The voltage drop across the plate load resistor with the higher-amplitude signal will not have the same waveshape as the voltage applied to the grid. The tube is said to be distorting the signal.

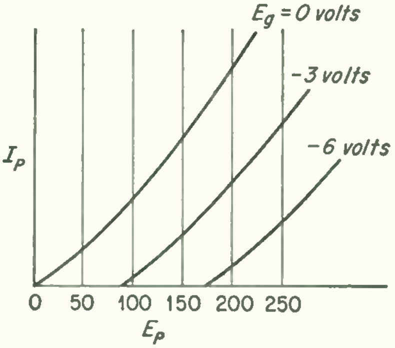


FIG. 9.27. Plate-voltage–plate-current ($E_pI_p$) curves for different values of grid bias.

Another type of graph is the $E_pI_p$ family of curves. This plots plate current against different plate voltages, with the grid bias held constant for each separate curve. This family illustrates how the bias required to produce plate-current cutoff varies with the plate voltage (Fig. 9.27).

**9.19 Factors Determining $\mu$.** It has been indicated that different triodes will have different amplification factors. The physical factors that control the $\mu$ are the relative spacing of the cathode, grid, and plate and the fineness or coarseness of the meshwork making up the grid.

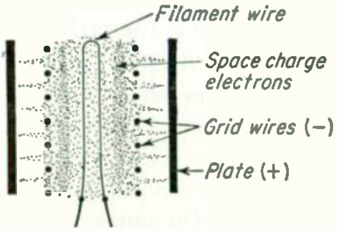


FIG. 9.28. Simplified cross section of a triode tube, illustrating element placement.

A simplified cross-section view of a triode is shown in Fig. 9.28. When the filament is heated, the space charge forms around it. Since the grid is biased to some negative value it repels the electrons and holds them close to the filament. The positive charge of the plate "reaches in" through the negative field set up by the grid wires and pulls electrons out to the plate. If the grid is too highly negative, the plate potential may not be strong enough to pull electrons through the spaces between the grid wires. It may be necessary to use a higher positive potential on the plate to attract electrons through a highly negative grid area.

If the manufacturer constructs the tube with the grid wires close to the *plate*, the plate will be able to pull more electrons through the grid wires, since its positive field easily cancels the relatively weak negative field of the nearby grid. In this condition a much higher negative grid bias is required to produce plate-current cutoff.

The greater the bias value required to produce plate-current cutoff, the greater the signal voltage required on the grid to control the plate current. Conversely, if the grid is moved closer to the filament, it takes relatively little signal voltage on the grid to vary the plate current of the tube. This produces a higher-$\mu$ tube.

Another factor in determining the $\mu$ of the tube is how closely the grid wires are meshed. The *closer the wires*, the more effective they are in preventing the positive pull of the plate from reaching the space-charge electrons, the less negative grid voltage required to produce plate-current cutoff, and the higher the $\mu$ of the tube.

**9.20 Plate Impedance.** The plate impedance, or a-c plate resistance, is a measurement of how the plate circuit (B battery, cathode, and plate) appears to the load. The tube and the B battery appear to the load as an a-c, a varying d-c, or a pulsating d-c source having a certain internal-impedance value. This internal-impedance value can be determined by using the formulas

$$Z_p \quad \text{or} \quad r_p = \frac{\Delta e_p}{\Delta i_p} \quad \text{or} \quad \frac{\partial e_p}{\partial i_p} \quad \text{or} \quad \frac{de_p}{di_p}$$

The Greek letters $\Delta$ and $\partial$ (pronounced DELTA) indicate a "small change in." The formula is read: "The plate impedance is the ratio of a small change in plate voltage to a small change in plate current." Plate impedance might be more simply expressed as the ratio $de_p/di_p$ of the tube. Note that this is a dynamic measurement—one made under actual operating conditions. Note also that it requires *small* changes in plate current and voltage. A tube is not a linear device, and therefore its characteristic curve is bent somewhat all along the curve. The smaller the changes used, the less bend is included in the computations and the more accurate is the answer given by the formula. (Note that this is a form of Ohm's law, where $R = E/I$.)

The plate impedance of a tube will vary somewhat, but is rather constant over the normal operating conditions. On the other hand, the d-c plate resistance varies widely with varying grid-bias values.

As in any electric circuit, to obtain maximum power output from a vacuum tube, the load impedance must equal the source, in this case the plate impedance of the tube.

**9.21 Mutual Conductance.** One of the factors by which a tube can be judged is its *mutual conductance*, also known as its *transconductance*.

In a given tube, if the grid voltage varies by some amount, the plate current will vary by a certain amount. Tubes having the ability of producing a relatively wide plate-current variation with a given grid-voltage variation have a high value of mutual conductance. (Note the difference between this and amplification factor.)

Mutual conductance can be found by the formula

$$g_m = \frac{di_p}{de_g}$$

where $g_m$ is mutual conductance in mhos; $di_p$ is change of plate current in amperes; and $de_g$ is change of grid voltage in volts.

This can be remembered by comparing it to the d-c circuit formulas $R = E/I$ and $G = I/E$.

*Example:* A tube changes its plate current 5 ma with a grid-voltage variation of 1 volt. What is the mutual conductance of the tube?

$$g_m = \frac{di_p}{de_g} = \frac{0.005}{1} = 0.005 \text{ mho, or } 5{,}000\ \mu\text{mho}$$

Another formula by which mutual conductance is computed is

$$\boxed{g_m = \frac{\mu}{r_p}}$$

where $\mu$ is the amplification factor of the tube; and $r_p$ is the a-c plate impedance.

If it is desired to use a tube to produce a high value of amplification of an input *voltage*, a tube with a high $\mu$ should be used. If it is desired to produce a large current variation in the load, as in a transformer, a tube with a high mutual conductance should be used. Transconductance values in modern tubes range from about 300 to more than 12,000 $\mu$mhos.

**9.22 Power Output.** Up to this point the consideration of amplifiers has centered on their ability to produce a *voltage* variation across the plate-circuit load impedance. Another consideration of vacuum tubes is the amount of *power* output obtainable from them.

A transformer-coupled amplifier circuit is shown in Fig. 9.29. With no input signal to the grid, there is plate current in the primary of the plate circuit transformer, but since there is no variation of this current, there is no voltage induced into the secondary and no power being delivered to the load resistor.

When a signal voltage is fed into the grid circuit, the plate current varies, inducing an a-c emf into the secondary of the output transformer. This produces current in the resistance load. The amplifier is now producing power output. Within limits, an increase in signal voltage increases the power output. Since power varies directly as the voltage squared ($P = E^2/R$), doubling the signal input will quadruple the output power.

The output transformer and resistor represent a load having a certain value of impedance. This load is connected across the source (amplifier tube and power supply). If the load impedance is equal to the a-c plate impedance, the maximum output power will be produced in the load.

Computation of the power output of this circuit can be made by measuring the voltage developed across the *load* resistance and the current flowing through it. According to the power formula $P = EI$, the product of these two values will be the power developed in the load. Since there is always a slight power loss in a transformer the tube will be delivering slightly more power than is computed. If the *resistance* value of the load is known, the power formulas $P = I^2R$ or $P = E^2/R$ may be used.

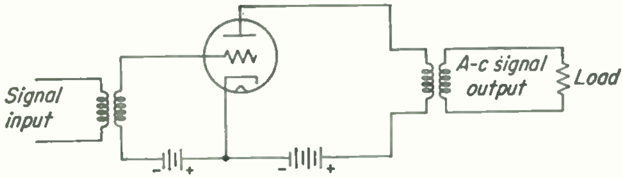


FIG. 9.29. Power is produced in the load resistor when an input signal is fed to the grid circuit.

A fairly accurate determination of the output power of a triode vacuum tube is given by the formula

$$P_o = \frac{\mu^2 E_g{}^2 Z_L}{(Z_L + Z_p)^2}$$

Triode

where $P_o$ is the output power in watts; $\mu$ is the amplification factor; $E_g$ is the rms signal voltage on the grid; $Z_L$ is the load impedance; and $Z_p$ is the plate impedance of the tube.

When *maximum* power output is required the load impedance must match the tube impedance. For *maximum* power output the formula above can be rearranged to read

$$P_{o,\max} = \frac{\mu^2 E_g{}^2}{4Z_p} \quad \text{or} \quad \frac{\mu^2 e_g{}^2}{8Z_p}$$

Max Pwr out

where $e_g$ is the *peak* a-c signal-voltage value.

*Undistorted* output is obtained when $Z_L$ equals two or three times the $Z_p$, depending on the requirements. A formula for undistorted output, where $Z_L = 2.5Z_p$ is

$$P_{o,\text{und}} = \frac{\mu^2 E_g{}^2}{5Z_p}$$

Undistorted P O

**9.23 Plate Dissipation and Saturation.** Electrons strike the plate surface of a tube when it is in operation. The energy of the electrons striking the plate is converted to heat. The plate of a tube is made to withstand only so many watts of plate heating. If the plate current is increased beyond the value that produces the maximum rated plate-dissipation value, the tube may be damaged. Excessive heat may liberate gas molecules from the plate, producing a soft, or gaseous, tube, or even melt the plate.

As the plate voltage is increased in a tube, the plate current increases. Eventually a voltage is reached where all the electrons in the space charge are going to the plate. The tube has reached the point of plate saturation. Any further increase in plate voltage will not increase the plate current. If a steadily increasing plate voltage is applied to the plate of a tube, the maximum safe plate dissipation will be exceeded before plate saturation occurs. However, if the plate current is made to come in pulses, by applying alternate negative and positive potentials to the grid, it is possible to allow the plate-current pulses (if of short enough duration) to reach saturation at the pulse peaks and still have the plate operating below maximum plate dissipation, since the plate can be cooling off in between the heavy pulses of plate current. In this case the *average* plate dissipation would not exceed the maximum rated dissipation value of the tube.

**9.24 Classes of Amplifiers.** There are many ways of operating amplifier tubes. Basically, these are broken down into different *classes.*

*Class A* uses a bias value equal to a little more than one-half the bias required to produce plate-current cutoff.

*Class B* indicates the bias is almost to the value of plate-current cutoff with no signal being applied to the grid. Between class A and class B are two intermediate classes known as class $AB_1$ and $AB_2$. Each of these classes will be discussed at greater length in the chapter on Audio-frequency Amplifiers.

*Class C* indicates the bias is greater than the plate-current cutoff value, and with no signal there is no plate current. This class will be discussed in the chapter on Radio-frequency Amplifiers.

How plate dissipation affects the output from the same tube in the three basic classes mentioned above can be indicated in the simple amplifier stage shown in Fig. 9.30.

The tube used will be assumed to have a 1-watt plate-dissipation rating. The plate, bias, and signal voltages can be increased until the plate current produces 1 watt of heat at the plate. At the same time there will be an a-c output power developed in the plate-circuit load because of the signal being applied to the grid circuit.

*Class A*. A tube biased to a little more than half the cutoff value and operating with plate current flowing all the time will have an output of about $\frac{1}{3}$ watt when the plate is dissipating 1 watt in heat. The total power applied to the plate circuit of the tube by the B battery is $1\frac{1}{3}$ watts, of which $\frac{1}{3}$ watt is usable a-c power output. The remainder is only heating the plate. One-third of a watt is 25 per cent of $1\frac{1}{3}$ watts. The class A stage will only be about 25 per cent efficient.

*Class B.* When biased almost to cutoff, the *same tube* will be able to stand a higher plate voltage and the grid circuit may be fed a greater-amplitude signal voltage. Under this condition the plate current comes in pulses and flows during only about one-half of each cycle of the signal. It will be found that a total of more than 2 watts can be fed into the plate circuit before the plate dissipates 1 watt. As a result, the power output will be more than 1 watt at maximum plate dissipation. The tube is more than 50 per cent efficient when operated in class B.

*Class C.* When biased beyond cutoff, the same tube will be able to stand even higher plate voltage and plate current flows for only about one-third of the input-signal cycle. The grid may be fed a still greater signal voltage. Now a total of nearly 4 watts can be fed to the plate circuit before the plate dissipates 1 watt in heat. Almost 3 watts is available as useful a-c output, and 1 watt is used up in heat. The stage is operating at about 75 per cent efficiency.

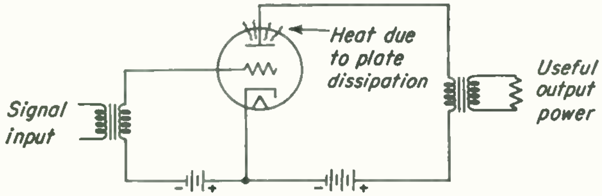


FIG. 9.30. The plate always dissipates some power in the form of heat.

It would seem that class C is the best way in which to operate a vacuum tube as an amplifier. In some cases it is, but such operation produces considerable distortion and cannot be used for AF amplification at all, although it can be used for certain types of RF amplifiers. Class B is also limited to certain types of AF or RF amplification. Only class A can be used in all types of amplification, although its low efficiency makes it undesirable in many applications.

When the power output of the power supply ($P = EI$) is known and the useful power output of the amplifier stage is also known, the plate-circuit efficiency is found by dividing the smaller value by the larger and multiplying by 100. The formula

$$\%\ \text{efficiency} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100$$

where $P_{\text{out}}$ is the a-c output power; and $P_{\text{in}}$ is the d-c plate-circuit power as read by an ammeter and voltmeter in the plate circuit.

*Example:* What is the efficiency if the d-c input power to a tube is 200 watts and the output is 140 watts?

$$\%\ \text{efficiency} = \frac{P_o}{P_i} \times 100 = \frac{140}{200} \times 100 = 0.7 \times 100 = 70\%$$

**9.25 Secondary Emission.** The *primary* emission in a vacuum tube is the electron emission from the cathode.

When the plate in a vacuum tube is charged highly positive, it may increase the velocity of electrons traveling toward it to such an extent that when they strike, each electron may dislodge one or more electrons from the plate. These electrons moving *from* the plate out into the vacuum form a *secondary emission.*

The effect of secondary emission may be great enough to produce a small negative space charge (cloud of electrons) near the plate, interfering with the normal flow of electrons to the plate.

If there is another element in the vacuum tube that has a positive charge on it, some of the secondary-emission electrons may move to that element instead of to the plate. This is usually undesirable, since only electrons that flow through the plate-circuit *load* can produce a usable output.

Since the grid of a triode tube is normally charged negatively, it does not attract any secondary electrons. For this reason secondary electrons in triodes are eventually returned to the plate, where they will travel through the load back to the positive potential of the B battery, or power supply, which is the desired path for them. However, if the grid is allowed to become positive, secondary electrons can flow to the grid and be lost to the plate circuit.

**9.26 Tetrode Tubes.** To obtain a high-amplification factor in a triode, the plate must be backed away from the cathode or a fine-grid meshwork must be used. Both of these methods tend to decrease the plate current, necessitating relatively high plate voltage to produce sufficient plate current to operate a high-$\mu$ tube. Another disadvantage in triodes is the relatively high interelectrode capacitance that exists between the plate and the grid because of their proximity to each other. This capacitance interferes with the ability of the tube to amplify properly under certain circumstances.

To overcome some of the difficulties that arise when the $\mu$ of a triode tube is increased and, possibly most important, to reduce the grid-plate capacitance, the *tetrode,* or four-element tube, was developed. In the tetrode, the grid is kept close to the cathode and the plate is moved outward from the cathode, increasing the $\mu$. Then, between grid and plate, a second grid is placed. It is called the *screen grid* (Fig. 9.31).

The screen grid is connected to a static, or unvarying, positive d-c potential of 100 volts or more. The positive field of the screen grid draws the space-charge electrons outward, away from the cathode. This puts the space-charge electrons in such a position that the plate potential can attract them. Thus, relatively high plate current and high $\mu$ are possible. At the same time the screen grid is *dynamically* (a-c) connected to the cathode with a *bypass* capacitor, as shown in heavy lines in the diagram in Fig. 9.32. The tetrode-circuit diagram is the same as the triode except for the addition of the screen grid and the bypass capacitor.

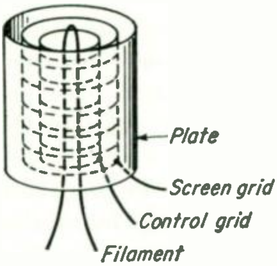


Fig. 9.31. Illustration of the placement of the elements in a tetrode tube.

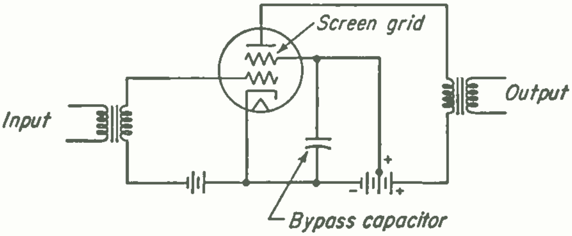


Fig. 9.32. Connections for the screen grid in a tetrode tube.

Since the control grid and plate are much farther apart, the interelectrode capacitance between them is greatly reduced. More important, the bypass capacitor on the screen grid effectively decreases the possible interaction between plate and grid. So, with a higher $\mu$ and less interaction between plate and grid due to capacitance, the tetrode tube affords more stable operation and much higher gain, or amplification. Amplifications up to several hundred times are possible with such a tube.

Triode tubes are rated by their $\mu$ values, but since the voltage applied to the screen grid can control the amplification of the tube, tetrodes are never rated by this factor.

There is one serious disadvantage in the operation of the original tetrode tubes. The positive screen grid has the effect of accelerating the electrons on their way to the plate. As a result, the secondary-emission current from the plate becomes rather high. In fact, if the plate voltage falls below that of the screen grid, the secondary-emission current from the plate may exceed the electron current to the plate. In this case the plate is essentially acting as a cathode. The secondary-emission electrons will travel to the screen grid, since it has a greater attractive force than does the plate. This sets up a backward current through the tube from plate to screen grid, interfering with the amplifying operation. Modern tetrode tubes, known as *beam-power tetrodes*, are constructed in such a way that the secondary-emission current to the screen grid is prevented from forming.

Tetrodes have extremely high plate-impedance values, ranging from

50,000 to 100,000 ohms. This presents difficulties in load-impedance matching when it is desired to use a transformer as the load in a tetrode-plate circuit.

As long as the plate voltage is greater than the screen voltage, the plate current in a tetrode is nearly independent of the plate voltage. Doubling the plate voltage will raise the plate current very little, whereas in a triode, doubling the plate voltage will approximately double the plate current. However, grid voltage variations, either control grid or screen grid, will control the plate current. The control grid is about 50 times as effective as the screen grid in controlling plate current, however.

**9.27 Beam-power Tetrodes.** One of the later developments in tetrode tubes is the beam-power tetrode. As its name indicates, this tube is not used as a voltage amplifier, but as a power amplifier.

The disadvantage of the secondary-emission electrons returning to the screen grid in the original tetrodes is overcome in two ways. First, the screen and control grids are so placed in the tube that the screen-grid wires are in the electron shadow of the control grid. Most of the electrons leaving the space charge are made to deviate outward from the control grid because of its negative charge and do not converge again until they have passed the screen grid. This tends to form a series of strong streams of electrons flowing to the plate, as shown in Fig. 9.33. Secondly, the tube has two deflector plates held at cathode potential, which further tends to restrict the travel of the electrons into a direct line, or beam, toward the plate.

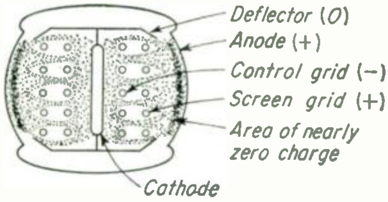


Fig. 9.33. Placement of elements in a beam-power tetrode, and paths taken by space-charge electrons when current is flowing across the tube.

The effect of the beaming of electrons is twofold. It results in a large number of electrons hitting the plate (a high-amplitude plate current), and it produces some secondary emission. However, the secondary-emission electrons are swept backward toward the plate again, because of the large number of advancing electrons. The net result is an area just in front of the highly positive plate, where there is virtually no charge. This area of zero charge tends to reduce the speed of the electrons flowing to the plate, reducing secondary emission.

One of the main advantages of the beam-power tetrode in AF amplification is its low value of third-harmonic distortion, resulting from the relatively constant area of zero potential in front of the plate.

The shading of the screen grid is not complete. There is some screen-grid current, but it is usually less than one-tenth of the plate-current value. When the *control grid* is at a less negative value, the screen grid is no longer shadowed as well as it was with a more highly negative control grid, and the screen-grid current increases. If the positive potential is disconnected from the plate, the electrons that would have gone to the plate now go to the screen and may melt the thin screen-grid wires. Beam-power tubes must never be operated without plate potential applied, unless a high negative control-grid bias is used.

Some beam-power tubes are made for audio circuits where the grid-plate capacitance does not materially affect operation. Such tubes may have rather poor grid-plate shielding. Other beam-power tubes, made for operation in RF circuits, are specially designed to reduce interelectrode capacitance and may require little or no *neutralization* to prevent instability of operation at normal radio frequencies.

Beam-power tetrodes have a plate current even more independent of the plate voltage than the original tetrodes had.

It is possible to connect the control and screen grids together and use the tetrode as a high-$\mu$ triode. Connecting screen grid and plate together forms a low-$\mu$ triode.

**9.28 Pentode Tubes.** The difficulty of secondary-emission electrons flowing from plate to screen grid in the original tetrodes makes them not too desirable. The addition of a third grid, called a suppressor grid, located between the screen grid and the plate, decreases the velocity of the electrons approaching the plate, provided this third grid has a zero or a negative charge. The lower the velocity of the electrons striking the plate, the less secondary emission is produced. Any secondary emission occurring does not have enough energy to move back across the zero-charged field around the suppressor grid. In this way any secondary-emission current from plate to screen grid is stopped. This five-element tube is known as a *pentode*. An illustration of the placement of the elements in a pentode is shown in Fig. 9.34.

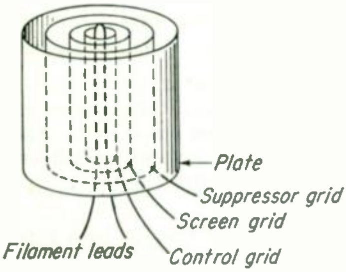


FIG. 9.34. Placement of the elements in a pentode tube.

The only difference between diagraming a pentode amplifier and diagraming a tetrode amplifier is the inclusion of the suppressor grid. The suppressor is almost always connected directly to the cathode. In fact, in some pentode tubes, the suppressor grid is connected to the cathode internally by the manufacturer. A diagram of a pentode tube in an amplifier circuit is shown in Fig. 9.35.

Besides having higher gain than tetrodes, the pentode tube has better shielding between plate and grid because of the additional grid which is always dynamically connected to cathode or ground. As with the tetrode, the pentode may require no neutralization when used in normal RF circuits.

In modern applications the original tetrode is no longer used. The beam-power tetrode is used in both AF and RF power amplifiers. Pentodes are used in low-power applications where voltage amplification is desired, as in receivers, although a few high-power transmitting pentodes are also used.

The pentode has even higher values of plate impedance than does the tetrode. Pentode plate impedances vary from about 100,000 to over 1 million ohms. Such high impedance makes load matching difficult, particularly when a nonresonant transformer is the plate load.

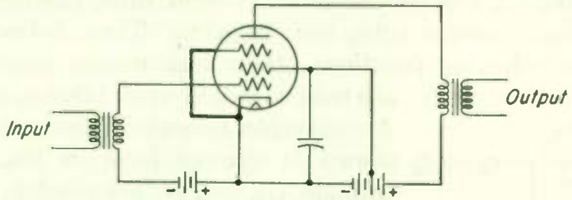


Fig. 9.35. Normal connection for the suppressor grid in a pentode tube.

In some receiver circuits a tube is required that does not drop sharply to cutoff as do all the amplifier tubes discussed so far. This requirement is met by spacing the control-grid wires of a pentode close together at the top and bottom and far apart at the center, as shown in Fig. 9.36. With no bias, electrons move freely to the plate between all grid wires. With a little negative bias, the closely spaced wires cut off the plate current. However, the more widely spaced wires continue to allow the electrons to flow between them. A relatively high negative charge is needed to cut off the plate current in such *remote-cutoff*, *variable-μ*, or *supercontrol* tubes.

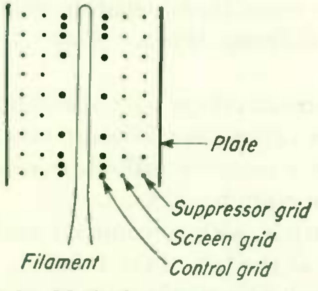


Fig. 9.36. Method of spacing the control-grid wires in a remote-cutoff pentode tube.

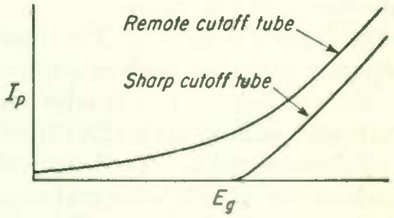


Fig. 9.37. Comparison of sharp-cutoff and remote-cutoff pentode $E_gI_p$ curves.

The grid-voltage plate-current curves for the usual type of *sharp-cutoff* amplifier tube and for a remote-cutoff tube are indicated in Fig. 9.37. The use of the remote-cutoff pentode is described in the chapter on AM Receivers.

**9.29 Shielding Tubes.** In the earlier days of radio the tubes were rather large and in some circuits one tube interacted with others because of the capacitance between them. It became necessary to construct metal shields around each tube to prevent this interaction. Later, the metal tube was developed and the metal envelope was used as the shield. More recently miniature tubes are being made so small that they may not interact in many circuits. If they do, small aluminum shields are placed around them and grounded as in earlier days.

**9.30 Tubes with More than Three Grids.** The pentode has the greatest number of grids used in normal amplifying tubes. However, there are tubes having a greater number of grids. A hexode, or six-element tube, has four grids. A heptode, or seven-element tube, has five grids. An octode, or eight-element tube, has six grids. These tubes are used in special circuits having functions other than merely amplification, or are used as two or more tubes in one envelope. An example of one is the pentagrid tube, shown in symbol form in Fig. 9.38. The cathode, $G_1$, and $G_2$ are used in conjunction with one signal frequency. The cathode and $G_4$ are used in conjunction with a second signal frequency. The current flowing from cathode to plate will have components of both frequencies in it, producing a third, or *difference*-frequency, and a fourth, or *sum*-frequency, component in the plate-circuit current.

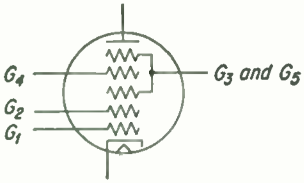


FIG. 9.38. Symbol of a pentagrid converter tube, showing the five grids.

**9.31 Multiunit Tubes.** To conserve space and the number of parts used in modern radio equipment, it is often possible to use multiunit tubes. Such tubes are actually two or even three separate tubes all within one envelope. There are many different types. Some of these are shown in Fig. 9.39.

*Twin, or Duodiodes.* Two diodes in one envelope with a common or separate cathodes, such as a type 6AL5, a seven-pin miniature tube.

*Twin Triodes.* Two triodes with either a common cathode or separate cathodes, such as type 12AT7, using a nine-pin noval base.

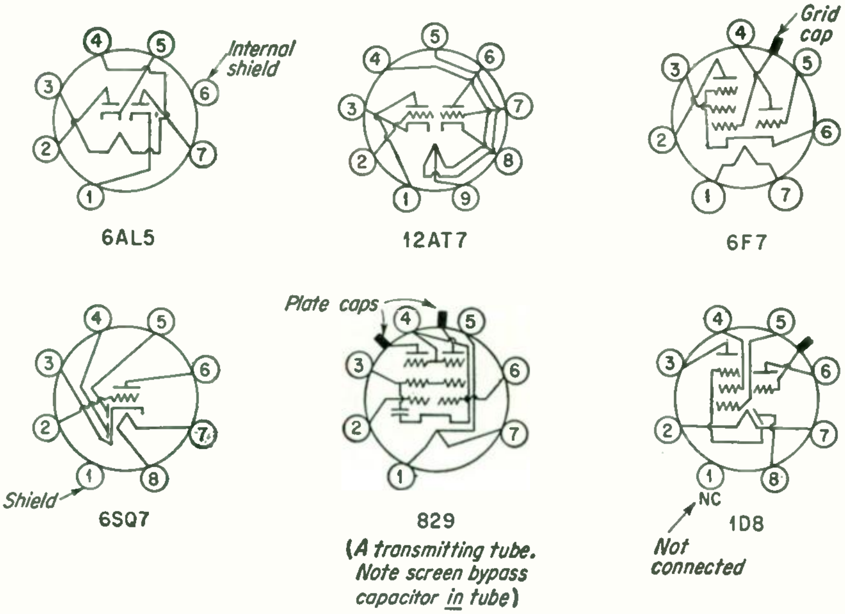
*Triode-Pentodes.* A triode and a pentode with a common cathode, such as a type 6F7, with grid connection at the top of the tube.

*Duplex-diode–Triodes.* Two diodes and one triode with a common cathode, such as a type 6SQ7, using an octal base.

*Twin Tetrodes.* Beam-power tetrodes with common cathodes and screen grids, such as a type 829, with plate leads coming out the top.

*Diode-Triode–Power Pentode.* A diode, triode, and power pentode using a common filament, such as a type 1D8, battery-portable tube.

**9.32 Symbols Used.** Symbols or abbreviations are used throughout electricity and radio. $E$ stands for voltage, $I$ for current, $R$ for resistance, and so on. The capital letters usually indicate the d-c value, the average d-c, or the effective a-c value. The small letters indicate either an



6AL5 12AT7 6F7

6SQ7 829 (*A transmitting tube. Note screen bypass capacitor in tube*) 1D8

FIG. 9.39. Pin connections for several types of tubes. Bottom view of sockets and pins.

instantaneous value of an a-c or the peak value. In summary, vacuum-tube circuitry symbols follow this same method:

$E_f$ = d-c or effective a-c filament voltage
$E_c$ = d-c bias voltage (as from a C battery)
$E_g$ = effective grid signal voltage
$e_g$ = instantaneous or peak grid signal voltage
$E_p$ = d-c or average d-c plate voltage
$e_p$ = instantaneous plate-to-cathode voltage during signal cycle
$E_b$ = plate-circuit battery or power-supply d-c voltage
$E_{sg}$ = d-c screen-grid voltage
$E_{sp}$ = d-c suppressor-grid voltage

The same general method is used to indicate currents as shown below:

$I_g$ = average grid current as read by a meter
$I_p$ = average plate current as read by a meter
$i_p$ = instantaneous plate current during the signal cycle

**9.33 Transmitting and Receiving Tubes.** Diode, triode, tetrode, and pentode tubes are all used in both transmitters and receivers. The difference between a transmitting and a receiving tube is generally in its physical size and ruggedness of construction of the elements.

Receiving tubes are small in size and usually have all the element connections attached to the metal pins at the base of the tube. In the past, to reduce grid-plate interelectrode capacitance, the *control-grid* connection was sometimes brought out of the top of a receiving tube.

Transmitting tubes are larger than receiving tubes and have heavier filaments for greater electron emission and larger plates to accommodate heavier plate current and to dissipate greater power in heat. They are correspondingly larger in all other elements. The *plate* connection of larger transmitting tubes is usually brought out the top of the tube to provide not only lower grid-plate capacitance but also to provide the best voltage insulation between the plate and other elements, since voltages applied to the plate of such tubes may be 500 to 10,000 volts or more.

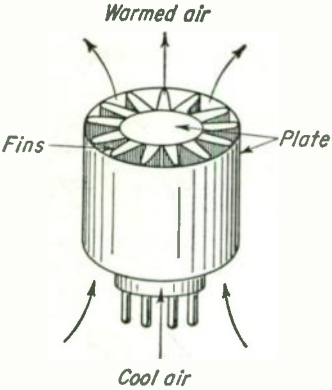


FIG. 9.40. Forced air flowing over the fins of an air-cooled tube carries away heat developed on the plate.

In some transmitting tubes the plate forms part of the outside envelope of the tube. When this is the case, fins may be attached to the outer surface of the plate (Fig. 9.40), and a forced draft of air passed over the fins rapidly dissipates heat developed on the plate. Such tubes are said to be *air-cooled*. Heat on the plate of the usual smaller vacuum tubes must be *radiated* from the plate, resulting in much less rapid dissipation of the heat.

**9.34 Water-cooled Tubes.** In high-powered transmitting tubes, considerable heat is produced at the plate by the heavy plate current. To carry this heat away from the plate, the plate of the tube can be made the outer shell, as shown in Fig. 9.41. The plate connection is made to the metal socket or jacket. The grid and filament leads come out through the glass part of the envelope. A stream of pure water is continually passed over the outer surface of the plate, keeping it cool.

The simplified illustration does not show the supports that are necessary to hold the tube elements in place, but affords an idea of how the elements are situated inside the tube. A possible plumbing system to accompany a water-cooled tube installation is shown in Fig. 9.42.

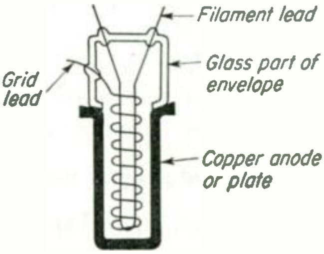


FIG. 9.41. Cross section of a water-cooled triode.

The water-cooled tube is set into a hollow metal jacket or socket. It is clamped in such a way that the joint between tube and socket is watertight but also makes a good electrical connection.

A pump circulates water through the system. The water passing over the plate of the tube is warmed and led off to the radiator, where it is cooled and then pumped back through the system again.

If the water leaving the tube is too hot because of excessive plate current, an overheat circuit breaker may be activated and the transmitter turned off automatically. This is a safety device to protect tube and transmitter in case of some malfunctioning of circuits.

If the pump is unable to supply sufficient water to the plate, the tube may become too hot. In such a case an underpressure circuit breaker can automatically turn off the transmitter until the proper water pressure is restored.

All water lines are made of rubber, plastic, porcelain, or other insulating materials. The water used must be pure in order that no current will be passed through it from the grounded pump to the highly positive plate. Any small leakage current that does flow through the water will be indicated by the meter shown between pump and ground. If the water becomes impure, it will pass more current. The greater the meter reading, the more impure the water must be. In some areas the water supplied by the local water company is pure enough for use directly into the system. In other areas distilled water must be used.

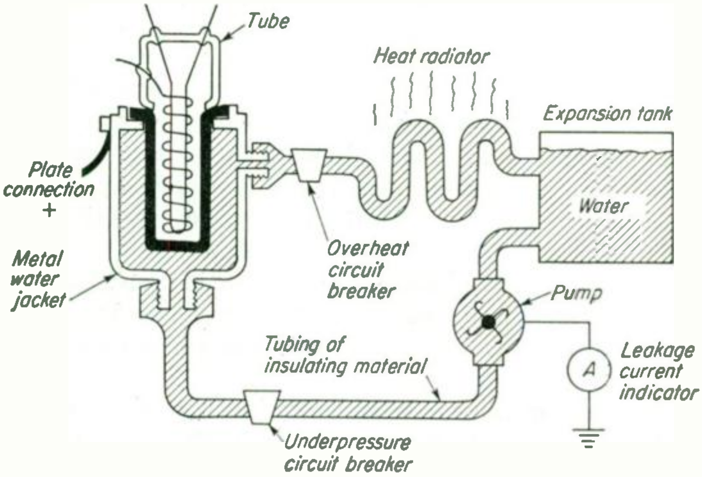


FIG. 9.42. Essential components of a water-cooling system for the tube in Fig. 9.41.

**9.35 Causes of Improper Plate Current.** When vacuum-tube circuits are operating improperly, the plate current of the tubes may be found to be either excessive or insufficient. A few causes of these difficulties are listed below.

*Excessive plate current* may be indicated by excessive heating of resistors and parts in the plate circuit or by reddening of the plate of glass envelope tubes and may be caused by excessive screen voltage; excessive plate voltage; insufficient negative, zero, or positive grid bias; positively charged suppressor grid; or a gaseous tube.

*Insufficient plate current* may be indicated by poor response or no response of the circuits. It may be caused by insufficient plate voltage; insufficient screen-grid voltage; excessive negative grid bias; disconnected control or screen grids; low emission from the cathode due to aging or to insufficient filament current; or a gaseous tube.

A more detailed listing of common circuit problems is included in other chapters.

**9.36 Causes of Tube Failure.** There are several reasons why vacuum tubes become inoperative. The list below includes some of the more common.

*Filament Failure.* Filament wires gradually lose molecules, weaken at one point, and burn out. Excessive jarring may rupture the filament. Too much filament current may burn out the wire. Filaments lose their ability to give off sufficient electrons.

*Tube Becomes Gassy.* Envelope leaks, and air is drawn into the tube. Internal elements give off gas when overheated by excessive current.

*Shorted Elements.* Wires from elements to the base pins sometimes touch each other. Heated elements in the envelope may sag and touch, welding themselves together. Heater-to-cathode insulation may break down.

*Loose Elements.* When elements are not welded properly, they vibrate and cause short circuits in the tubes or severe noises in the circuits in which the tubes are used. Jarring or heating may loosen internal-element welds.

**9.37 Battery Operation.** When batteries are used to power portable equipment using vacuum tubes, there are often three separate batteries.

The battery used to produce the filament-heating current is called the A battery. It must produce relatively high current at a low voltage. Voltages used are normally between 1.5 and 12 volts.

The battery used to produce the plate current is called the B battery. It must have a relatively high voltage, but in most cases only a low-current drain is required. The screen grid is also connected to the B battery, usually to a lower-voltage tap. B batteries range from 22½ to 135 volts.

The battery used to bias the control grids is called the C battery. Since there is no grid current in low-power equipment, the C battery is made for almost zero current flow but long life. It will range from 1.5 to 22.5 volts, depending upon the requirements of the tubes for which it supplies bias.

**9.38 High-frequency Tubes.** Ordinary diode, triode, tetrode, and pentode tubes will operate with frequencies up to well over 20 million cycles (20 Mc). Many of the newer miniature and subminiature tubes will operate satisfactorily as high as 100 to 400 Mc. However, when higher frequencies are to be used, special design is required in the manufacture of tubes.

In the superhigh-frequency range (SHF), 3,000 to 30,000 Mc, magnetrons and klystrons are usually used. These do not operate on the same principles as the tubes discussed in this chapter. (See chapter on Radar.)

In the ultrahigh-frequency range (UHF), 300 to 3,000 Mc, magnetrons and klystrons are often used, but specially constructed triodes such as the *lighthouse* tubes may also be employed. The type of construction of a lighthouse tube is indicated in Fig. 9.43.

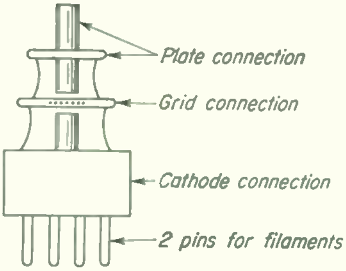


FIG. 9.43. Construction of a lighthouse high-frequency triode.

The lighthouse tube will operate at ultrahigh frequencies because its leads are very short and therefore have a small value of inductance. The spacing between cathode and plate is very small, allowing *transit time*,

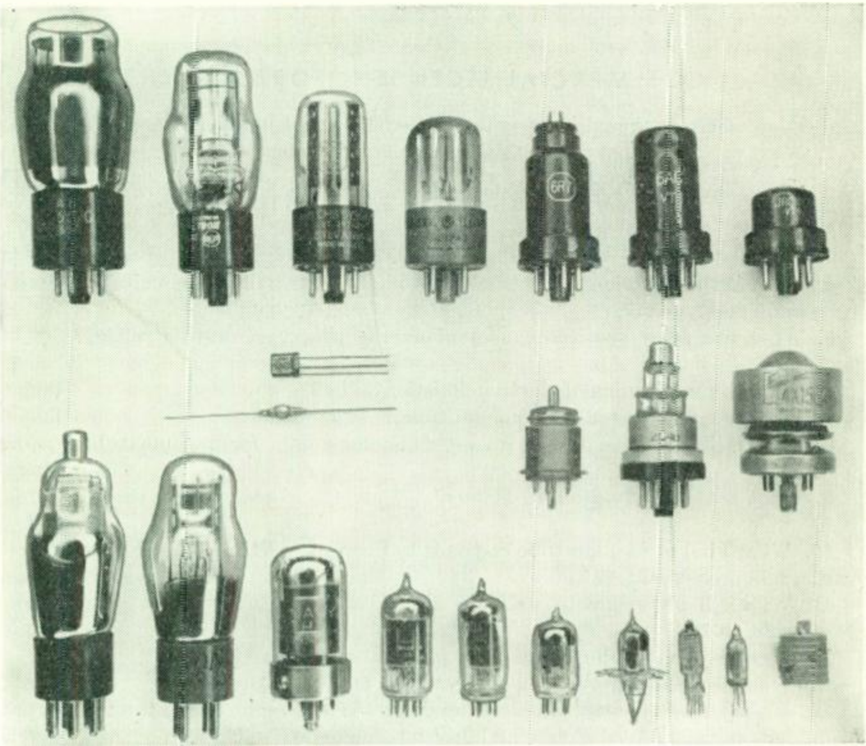


FIG. 9.44. Electron tubes. Top row, octal-base (eight-pin) glass and metal tubes. Center left, transistor and junction diode. Center right, two lighthouse tubes and an air-cooled transmitting beam-power tetrode. Bottom row, seven-pin, four-pin, loctal (eight-pin lock-in), noval (nine-pin), two miniatures (seven-pin), acorn, subminiature, and ceramic types of tubes.

the time taken by electrons in moving from the cathode to the plate, to be cut to a minimum.

The requirements for all tubes operating at higher frequencies is to have minimum inductance in the leads to the elements, short transit time, and as little interelectrode capacitance as possible.

One of the first successful high-frequency tubes was the *acorn* tube, so named because of its resemblance to an acorn. The elements are made very small. The leads are brought out directly through the glass envelope to shorten them as much as possible and to reduce interelectrode capacitance. The acorn tube shown in Fig. 9.44 will operate up to several hundred megacycles.

**9.39 Visual-indicating Tubes.** There are some types of tubes that give visual indications. One is the *tuning-eye* tube, or electron-ray tube, used in receivers and discussed in the chapter on AM Receivers. Another is the cathode-ray tube, used in oscilloscopes, television receivers, radar, loran, and in measuring devices. The basic operation of the cathode-ray tube is discussed in the chapter on Measuring Devices, and its other applications in other chapters.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** What are the primary advantages of a mercury-vapor rectifier as compared with the thermionic high-vacuum rectifier? (9.11) **[3]**

**2.** What are the primary characteristics of a gas-filled rectifier tube? (9.11) **[3]**

**3.** Describe the construction and characteristics of: (*a*) A thyratron tube. (9.11) (*b*) A battery-charging rectifier tube. (9.11). (*c*) A beam-power tube. (9.27) **[3]**

**4.** What is the direction of electronic flow in the plate and grid circuits of vacuum-tube amplifiers? (9.17) **[3]**

**5.** What are some possible causes of overheating vacuum-tube plates? (9.34, 9.35) **[3]**

**6.** What is the meaning of electron emission? (9.2) **[3 & 6]**

**7.** What is space charge in a vacuum tube? (9.2) **[3 & 6]**

**8.** Why is it desirable to use an a-c filament supply for vacuum tubes? (9.2, 9.8) **[3 & 6]**

**9.** What is the composition of filaments, heaters, and cathodes in vacuum tubes? (9.3) **[3 & 6]**

**10.** What kind of vacuum tube responds to filament reactivation and how is reactivation accomplished? (9.3) **[3 & 6]**

**11.** Why is it important to maintain transmitting-tube filaments at recommended voltages? (9.4) **[3 & 6]**

**12.** What is the meaning of the term plate saturation? (9.5) **[3 & 6]**

**13.** What is meant by the load on a vacuum tube? (9.6) **[3 & 6]**

**14.** When an a-c filament supply is used, why is a filament center-tap usually provided for the vacuum-tube plate and grid return circuits? (9.7) **[3 & 6]**

**15.** What is the purpose of a center-tap connection on a filament transformer? (9.7) **[3 & 6]**

**16.** Why is it advisable to reverse periodically the polarity of the filament potential of high-power vacuum tubes when a d-c filament supply is used? (9.8) **[3 & 6]**

**17.** What are the visible indications of a soft tube? (9.10) **[3 & 6]**

**18.** What is the getter in a vacuum tube? (9.10) **[3 & 6]**

**19.** What is meant by a soft vacuum tube? (9.10) **[3 & 6]**

**20.** Describe the electrical characteristics of: (*a*) A triode. (9.14) (*b*) A tetrode. (9.26, 9.27) (*c*) A pentode. (9.28) **[3 & 6]**

**21.** Describe the physical structure of a triode vacuum tube. (9.14, 9.19) **[3 & 6]**

**22.** What is the meaning of: (*a*) Amplification factor? (9.15) (*b*) Mutual conductance? (9.21) **[3 & 6]**

**23.** Explain the operation of a triode as an amplifier. (9.16, 9.17) **[3 & 6]**

**24.** What is the purpose of a bias voltage on the grid of an AF amplifier tube? (9.17) **[3 & 6]**

**25.** Draw a graph indicating how the plate current in a vacuum tube varies with plate voltage, grid bias remaining constant. (9.18) **[3 & 6]**

**26.** What is the meaning of the term maximum plate dissipation? (9.23) **[3 & 6]**

**27.** Describe the physical structure of a tetrode vacuum tube. (9.26) **[3 & 6]**

**28.** What is the primary purpose of a suppressor grid in a multielement vacuum tube? (9.28) **[3 & 6]**

**29.** What factors may cause low plate current in an amplifier? (9.35) **[3 & 6]**

**30.** What is the meaning of secondary emission? (9.25) **[3, 4, & 6]**

**31.** What is the primary purpose of a screen grid in a tube? (9.26) **[3, 4, & 6]**

**32.** Under what circumstances will the gain per stage be equal to the voltage amplification factor of the vacuum tube employed? (9.16) **[4]**

**33.** Why should the cathode of an indirectly heated type of vacuum tube be maintained at nearly the same potential as the heater circuit? (9.2) **[6]**

**34.** Is a tungsten filament operated at higher or lower temperatures than a thoriated filament? Why? (9.3) **[6]**

**35.** What is indicated when a blue glow is noticed within a vacuum-tube envelope? (9.10, 9.11) **[6]**

**36.** What are some of the indications of a defective vacuum tube? (9.10, 9.35) **[6]**

**37.** Describe the construction and the operation of rectifier tubes that are used for charging batteries. (9.11) **[6]**

**38.** Explain the principle of operation of the cold-cathode gaseous rectifying diodes. (9.13) **[6]**

**39.** What is the primary purpose of the control grid of a triode? (9.14) **[6]**

**40.** Draw a diagram of a resistance load connected in the plate circuit of a vacuum tube and indicate the direction of electronic flow in this load. (9.16) **[6]**

**41.** Define plate resistance in reference to vacuum tubes. (9.20) **[6]**

**42.** Describe the construction of a beam-power vacuum tube. In what types of circuit do these tubes find application? (9.27) **[6]**

**43.** What is an A battery? A B battery? A C battery? (9.37) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

★**1.** Name the elements in a triode tube. (9.14)

**2.** Why should directly heated filaments be center-tapped when operated from an a-c supply? (9.7)

**3.** What is meant by the term maximum plate dissipation? (9.23)

**4.** How is the plate-circuit efficiency of a tube determined? (9.24)

**5.** Name the elements of a tetrode tube. (9.26)

**6.** What is the purpose of a screen grid in a vacuum tube? (9.26)

**7.** Name the elements of a pentode tube. (9.28)

**8.** What are hexodes, heptodes, and octodes? (9.30)

# CHAPTER 10

# POWER SUPPLIES

**10.1 Types of Power Supplies.** There are many types of power supplies. A battery converts chemical energy into electric energy that may be used to operate receivers or transmitters. A motor generator consisting of a diesel or gasoline engine driving a generator produces electric power, or energy. These can be termed primary power supplies, since they produce electricity from other forms of energy.

Electronic power supplies used in radio consist of tubes, transformers, and other equipment with which electric energy in one form, usually alternating current, is converted to electric energy in another form, usually direct current.

Electronic supplies are usually lighter, less expensive, easier to maintain, cleaner, and less noisy than motor-generator supplies. However, motor-generator sets can produce low-voltage d-c at high current values with nearly ripple-free, well-regulated output. It is simple to control the output voltage of a generator over a wide range.

**10.2 Types of Rectifiers.** Rectification, or the changing of an a-c into a pulsating or varying d-c, can be accomplished by using (1) high-vacuum diode tubes, (2) mercury-vapor diode tubes, (3) cold-cathode diode tubes, or (4) copper-oxide, selenium, germanium, or other junction rectifiers.

**10.3 A Basic Rectifier Circuit.** A frequently used type of radio power supply utilizes 60-cycle a-c, converting or *rectifying* it to pulsating d-c, then smoothing, or *filtering*, the pulsations until an essentially smooth, unvarying d-c results. This can then be used as the plate-circuit voltage in vacuum-tube amplifier circuits.

The simplest rectifier circuit is the *half-wave* (Fig. 10.1). The a-c input produces an alternating emf in the secondary of the transformer, which attempts to force current through the secondary circuit, first in one direction and then in the opposite, alternately. If the rectifier is not in the circuit, an a-c will flow through the load resistance, but the characteristic of a rectifier is such that it will allow current to pass through it in one direction only. Although the transformer-secondary voltage may be alternating, the current can flow in the resistor only during one-half of each cycle. This produces a pulsating d-c in the circuit, as shown in

Fig. 10.2. The voltage drop across points *A* and *B* is also pulsating.

The half-wave may be the simplest rectifier circuit, but it has some serious disadvantages when used in power supplies. Only one-half of each a-c cycle can be put to use. The other half, when a negative potential is being applied to the plate of the tube, is represented as an emf in the transformer secondary but is powerless to cause current flow backward through the rectifier.

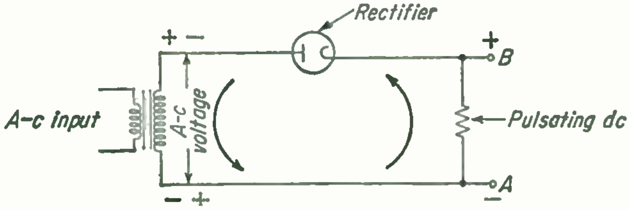


Fig. 10.1. Half-wave rectifier circuit.

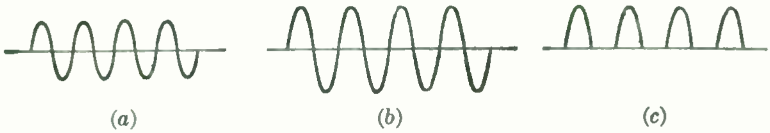


Fig. 10.2. The input a-c emf (*a*) is stepped up by a transformer (*b*) and rectified (*c*).

The *average* current of the half-wave pulses is equal to only 0.318 of the peak-current-amplitude value.

**10.4 Full-wave Rectification.** Two circuits that can be used in rectifier power supplies to utilize both halves of the a-c cycle are the *bridge* and the *full-wave center-tapped* rectifier circuits.

Figure 10.3 indicates the current in a bridge circuit during two alternate half cycles of a-c. Note the polarity markings on the transformer secondaries. During the half cycle when the top of the transformer is positive, rectifiers *A* and *B* pass current through the load resistor from right to left. Electrons cannot start from the negative end of the transformer, pass through rectifier *A* and the load resistor, and then move back to the negative end of the transformer through rectifier *D*, because they are repelled by the negative charge at that end of the transformer. They

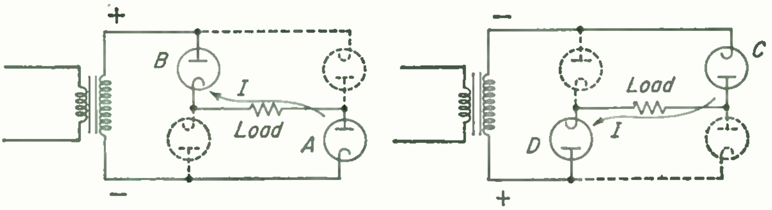


Fig. 10.3. Current flow through the load in a bridge-rectifier circuit during two half cycles.

are pulled toward the positive end of the transformer just as much as they are pushed from the negative end. During the half cycle when the bottom of the transformer is positive, rectifiers *C* and *D* pass current through the load resistor, again from right to left. On both half cycles the electrons find a path between the negative end of the transformer and the positive end in the same direction through the resistor.

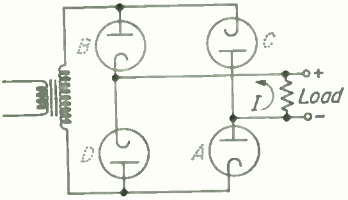


**Fig. 10.4.** Bridge-rectifier circuit in a practical form.

Figure 10.4 shows the bridge rectifier with the load at the right, as it is usually drawn in diagrams. Note that the bridge-rectifier system will need *three* separate filament sources. It is possible to parallel the filaments of tubes *B* and *D* and use one source for them, but tubes *A* and *C* must have separate filament sources of their own.


(a) (b)

**Fig. 10.5.** Comparison of (*a*) half-wave- and (*b*) full-wave rectified current pulses.

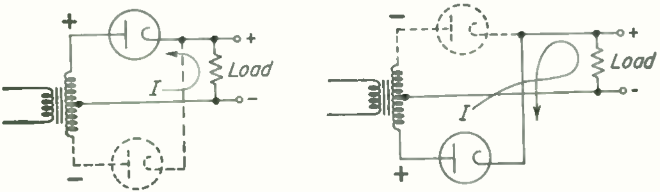


**Fig. 10.6.** Current flow through the load in a full-wave center-tap rectifier circuit during two alternations.

The current pulses from a half-wave rectifier circuit and from a full-wave rectifier are shown in Fig. 10.5. The average value of the pulses with full-wave rectification of a sine-wave cycle is equal to 0.636 of the peak value.

The other and more frequently used full-wave rectifier circuit is the center-tapped transformer type. The basic circuit is shown in Fig. 10.6.

During the half cycle when the top of the transformer is positive, current flows out of the center tap, *up* through the load resistor, and through the upper rectifier to the positive end of the transformer.

During the half cycle when the bottom of the transformer is positive, current flows out of the center tap, *up* through the load resistor, and through the lower rectifier to the positive end of the transformer. During both halves of the cycle current flows upward through the resistor. The two filaments can be connected in parallel and operated from one filament source.

Whereas the bridge circuit used the full output voltage of the transformer, the center-tap circuit never uses more than one-half of the total transformer voltage at one time. A 2,000-volt transformer produces only about 1,000 volts output with this circuit. In some cases this may be a disadvantage. In others, the three filament sources and the requirement of four tubes in a bridge circuit are also disadvantages.

If the plate and cathode connections of the two rectifier tubes are connected as shown in Fig. 10.7, the center tap on the transformer becomes the positive connection and the two plates are the negative potential of the power supply. The disadvantage of this type of circuit is the requirement of two filament-transformer windings, and it is rarely used.

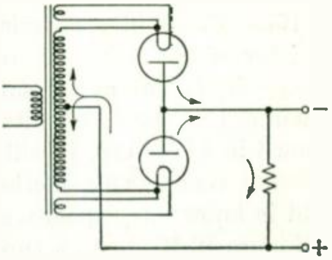


FIG. 10.7. Alternate form of a full-wave center-tap rectifier circuit.

Generally, using the same power transformer, a bridge-rectifier circuit will produce an output voltage twice that obtainable from a center-tapped full-wave circuit, but at only half the current. Thus, the power capabilities of either circuit are essentially equal.

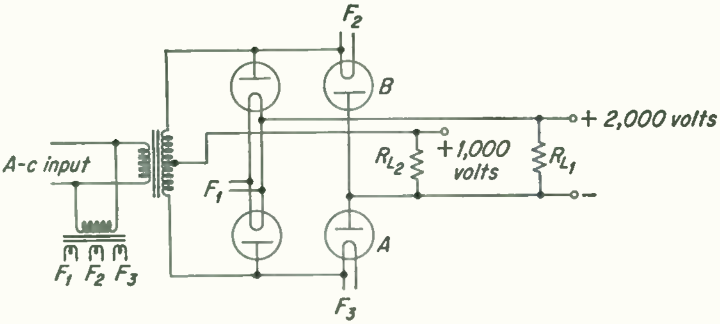


FIG. 10.8. Two output-voltage values from a single rectifier circuit.

**10.5 Two Voltages from One Transformer.** Using a center-tapped transformer, the bridge-rectifier circuit can be utilized to produce two separate full-wave-rectified voltages, one with half the voltage of the other. The circuit is shown in Fig. 10.8.

If the secondary voltage of the transformer is 2,000 volts, the output voltage across the load, $R_{L1}$, will be essentially 2,000 volts. By using the center tap on the secondary and the negative lead of the 2,000-volt circuit, a full wave rectified 1,000 volts will be obtained across the second load, $R_{L2}$. The 2,000-volt circuit is a normal bridge rectifier. The 1,000-volt circuit uses rectifiers *A* and *B* as a two-filament-source full-wave center-tapped rectification system, explained previously. With this circuit configuration the two voltages have a common negative lead.

Tubes *A* and *B* are being used in both power supplies and will therefore be carrying more current than the other two rectifiers. This fact will have to be considered in practical applications. Three separate filament windings are necessary.

**10.6 Capacitive Filtering.** The pulsating current through the load resistor of the half-wave rectifier, and therefore the voltage developed across it, is not at all smooth. Since the voltage required by most vacuum-tube plate circuits must have an unvarying characteristic, as shown in Fig. 10.9*b*, it will be necessary to smooth off the pulsations by *filtering* them. One method of filtering uses capacitors (condensers) and is known as capacitive filtering.

Figure 10.10 shows a capacitor connected across the output of a half-wave rectifier circuit. During one half of the a-c cycle, when the rectifier refuses to pass current, nothing happens in the circuit as far as current is concerned. On the other half cycle, the top of the transformer becomes positive and pulls electrons off of the top plate of the capacitor, through the rectifier, and drives electrons onto the lower plate of the capacitor. This charges the capacitor to the *peak* voltage of the a-c. For example, if the secondary voltage is 100 volts effective, the capacitor will be charged to a voltage equal to 1.414 times 100, or 141 volts d-c.

Fig. 10.9. (*a*) Pulsating d-c is smoothed to (*b*) pure d-c for use in electronic circuits.

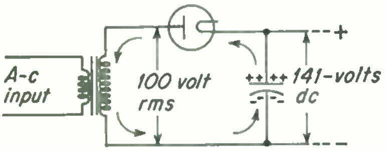


Fig. 10.10. Filter capacitor charges to the peak voltage value of the a-c.

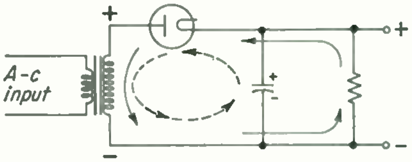


Fig. 10.11. During the rectifying half cycle, the load current comes from the transformer.

On the next half cycle, the current cannot push back through the rectifier, so the capacitor remains charged at 141 volts.

The next current-moving half cycle finds the potential again in position to push or pull electrons through the rectifier, but since the capacitor is already charged to the peak value, nothing happens in the circuit. The voltage across the filter capacitor is an unvarying d-c.

During the charging half cycle, the current in the transformer secondary has two components. One component charges the capacitor, the other flows through any *load* resistor, as indicated in Fig. 10.11. The current through the load may be considered as coming from the transformer.

During the noncharging half cycle, the transformer cannot push electrons backward through the rectifier, so that any current in the circuit during this time must come from the electrons that have been forced onto, or stored on, the plate of the capacitor. During this half cycle, the capacitor discharges through the resistor, as indicated in Fig. 10.12. Note that the current direction through the resistor is still upward. If the capacitor is large, it can hold sufficient electrons to keep current flowing through the resistor during all the noncharging half cycle. However, as it discharges, the potential difference across it decreases and it cannot maintain the same amplitude current through the resistor. Therefore the current through the resistor, as well as the voltage across it, drops off slowly during the noncharging half cycle. During the next charging half cycle, the capacitor is recharged to full voltage and the transformer drives the peak value of current through the resistor again.

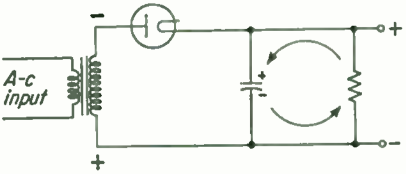


FIG. 10.12. During the nonrectifying half cycle the load current comes from the charged filter capacitor.

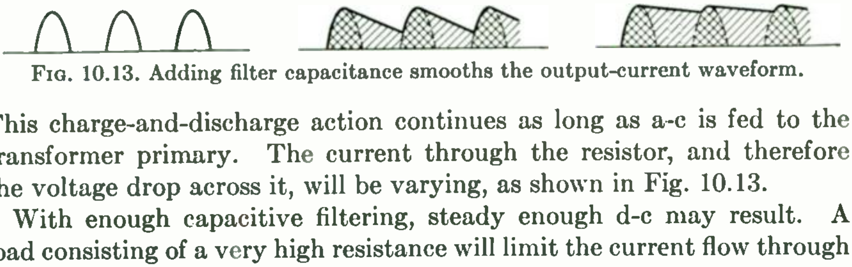


FIG. 10.13. Adding filter capacitance smooths the output-current waveform.

This charge-and-discharge action continues as long as a-c is fed to the transformer primary. The current through the resistor, and therefore the voltage drop across it, will be varying, as shown in Fig. 10.13.

With enough capacitive filtering, steady enough d-c may result. A load consisting of a very high resistance will limit the current flow through itself and therefore will discharge the capacitor very slowly. It is comparatively simple and inexpensive to filter such a light load. However, if a heavy load, with a *low value of effective resistance,* is connected across the output, the capacitor will be discharged rapidly through it, causing considerable variation of current between cycles. Additional capacitance will be required to counteract the rapid drop-off. In many cases it is not practical to keep adding capacitance. Instead, another type of filtering can be added, called *inductive filtering.*

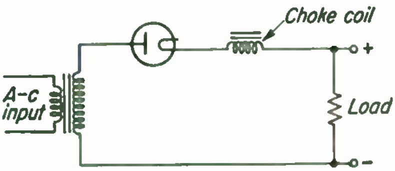


FIG. 10.14. Choke coil used to filter pulsating d-c.

**10.7 Inductive Filtering.** When an iron-core choke coil of several henrys of inductance is connected in series with a rectifier circuit, as shown in Fig. 10.14, a filtering, or smoothing, action results.

By definition, inductance has the property to oppose any *change* in current. Pulses of current through the choke coil build up a magnetic field around it, taking energy from the circuit to produce the field. As the pulse tries to decrease in amplitude, the magnetic field collapses and returns energy in the form of current to the circuit, thereby tending to hold the current constant. When pulsating d-c from a half-wave rectifier passes through the circuit in which a choke coil is placed, the increase in the pulse amplitude will be lessened, and the dropping off of the pulse will also be affected, as illustrated in Fig. 10.15.

**Fig. 10.15. Effect of inductive filtering alone on the output pulses of d-c.**

The action of the inductance is to prevent the pulses from attaining the amplitude that they would have had if the inductance had not been in the circuit. Also, there is a lengthening of the pulse duration. It is impractical to produce steady d-c by the use of inductance only. However, it is possible to use inductive and capacitive filtering together and produce substantially pure d-c with reasonably inexpensive parts.

**10.8 Capacitive-input Filtering.** While there are many variations of filter circuits, the one used more often than any other in power supplies is probably similar to the capacitive-input type shown in Fig. 10.16.

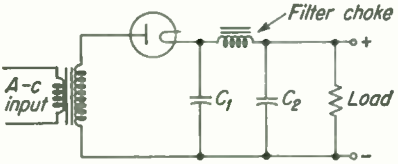


Fig. 10.16. Relatively common capacitive-input power-supply filter circuit.

This filter circuit can be recognized as a low-pass filter, previously discussed in the chapter on Alternating-current Circuits. Used to filter the output of a rectifier, it discriminates against any voltage and current variations but passes steady d-c (zero frequency) without attenuation.

Looking at the filter from the source of power, the transformer in this case, the first part of the filter seen is the capacitor, $C_1$. This is known as the *input capacitor* of the filter. It charges to the peak-voltage value of the transformer a-c and discharges somewhat during the noncharging half cycle. During the noncharging interval, the input-capacitor current flows through the load resistor and through the choke coil. The choke opposes any dropping off or change in this current, resulting in a fairly smooth d-c flow through the load. Added to this, the output capacitor, $C_2$, further tends to hold the voltage constant across the load. The net result is a smooth d-c suitable for most vacuum-tube circuits.

Practical values for a *half-wave*-rectifier power supply, similar to the one shown, might be $C_1 = 10$ to $20\ \mu f$, $C_2 = 20$ to $40\ \mu f$, choke coil $= 10$ to 30 henrys. On the other hand, with *full-wave* rectification circuits, the values of the filter components might be $C_1 = 5$ to $10\ \mu f$, $C_2 = 10$ to $20\ \mu f$, choke coil $= 5$ to 15 henrys. *Full-wave* rectification requires only about half as much filter as does *half-wave*. In most communications equipment, half-wave rectification is rarely used in the power supplies.

The values suggested above might be more than adequate with a relatively light load, or when used for a radio-frequency amplifier in a code transmitter. They may be insufficient for a very heavy load, or for use in a high-gain audio-frequency amplifier system. Note that the output capacitor is usually twice the input value. The input capacitor tends to determine the output voltage of the power supply, while the output capacitor acts as a storage tank of electrons. It is from the output capacitor that the load draws most of its current during the noncharging interval. In practical applications, with a medium load on the power supply, the output voltage of a capacitive-input filter system is roughly 85 per cent of the a-c peak voltage value.

Paper or oil-filled-paper dielectric capacitors are desirable for power-supply capacitors. For lower-voltage applications, electrolytics are suitable, provided they are not allowed to become warm because of proximity to parts that radiate heat.

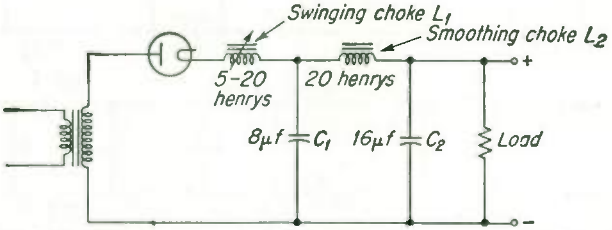


FIG. 10.17. Relatively common inductive-input power-supply filter circuit.

**10.9 Inductive-input Filtering.** The standard filter circuit discussed previously is known as a capacitive-input filter because the first part of the filter seen by the source is the capacitor. The diagram in Fig. 10.17 shows another form of filter circuit.

The first parts seen by the source when looking into this filter are a coil, $L_1$, and a capacitor, $C_1$, in series. To differentiate between this circuit and the capacitive-input filter, this one is known as an *inductive-input* filter. If the load is disconnected, the pulsating d-c from the rectifier will charge $C_1$ and $C_2$ to the peak value of the transformer after a few pulses. However, when a load is connected, current flows through $L_1$ and $L_2$. Since the current through $L_1$ will be pulsating and may be said to have an a-c component, a reactive voltage drop will occur across this choke coil ($E = IX_L$). $C_1$ can no longer charge to the peak value, but will usually fall to about 60 per cent of the peak. As a result, in practice, the voltage across $C_2$ may never be greater than this value, and may be somewhat less. Since the current through $L_2$ is essentially unvarying d-c, there is very little reactive voltage drop across it, although there will be a resistive voltage drop across it equal to the current times the ohmic resistance of the wire in the choke ($E = IR$). As discussed later, the inductive-input filter circuit may have better voltage regulation, but it will have less output voltage than a capacitive-input filter supply with normal load and the same power transformer. Technically, a choke-input filter may have a *small* value of input capacitance and still fall in the category of inductive input.

The input choke is usually a *swinging choke*, explained later. Any other chokes are *smoothing chokes.*

An inductive-input filter can be used with any type of rectifier, mercury-vapor, vacuum, or junction.

**10.10 Some Possible Filter Circuits.** In general, the more inductance and capacitance used in a filter circuit, the smoother the resulting d-c. Some of the many possible configurations of power-supply filters are shown in Fig. 10.18.

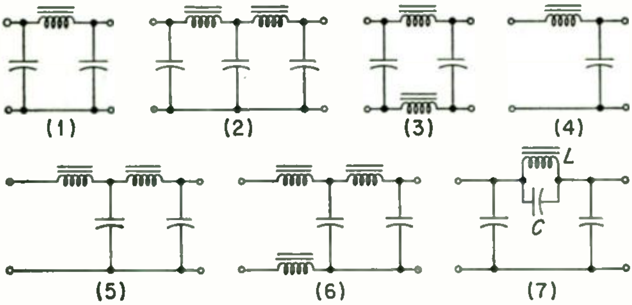


FIG. 10.18. Power-supply filter circuits.

The first filter (1) is a low-pass capacitive-input *π-section* filter. It is a single-section filter, whereas the second (2) is a two-section capacitive-input filter. The third (3) is another capacitive-input filter, adding a choke in the lower lead.

Filters 4, 5, and 6 are all choke-input types. It is usually considered undesirable to use an input choke in the grounded lead of a power supply, as in filter 6, because a ripple voltage of the source frequency can be developed across it, owing to primary-secondary capacitance in the power transformer.

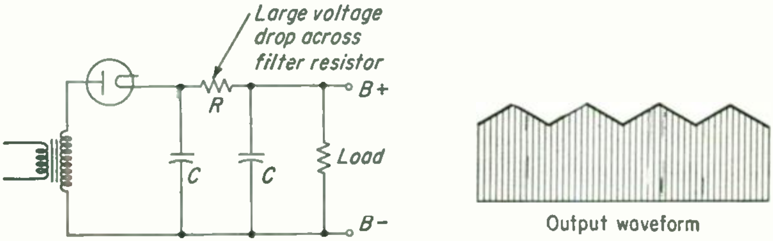
Filter 7 is a resonant filter. If $C$ and $L$ resonate at the pulsating d-c frequency (120 cycles for full-wave 60-cycle a-c), they form a parallel-resonant circuit and a high impedance to this frequency. This opposes variations at this frequency and results in better filtering.

Note that power-supply filters *always* have a capacitor across the output.

**10.11 RC Filters.** When the load is constant (as in equipment having all class A amplifiers) it is possible to produce better filtering than is possible with capacitors alone by using a resistor in place of the choke coil of the usual filter circuit. Figure 10.19 shows such a circuit. The resistor increases the time taken by the filter capacitor to charge and to discharge. This produces a less jagged waveform, and therefore a smoother d-c.

Two disadvantages of this type of filtering are the considerable voltage drop across the resistor used in the circuit (200 to 100,000 ohms depending on the load) and the variation of the average output voltage when the load demands varying values of current.

*RC* filters are found in communications equipment only in circuits where the current demand is very light. When the current demand is appreciable, relatively large capacitance values are required to produce adequate filtering.



Output waveform of *RC* filter

FIG. 10.19. Power supply with an RC filter.

**10.12 Filter Chokes.** There are several important factors to be considered regarding filter chokes used in power supplies. These are insulation, shielding, resistance, inductance, distributed capacitance, current-carrying ability, losses, and saturation.

Since the cores of most filter chokes are mounted on the metal chassis of the power supply, and at ground potential, and since the choke is not normally placed in the grounded leg of the filter, it is necessary that the windings be sufficiently insulated from the core to withstand the peak voltage developed in the circuit, and preferably for two or three times this value. Should the insulation break down and a spark jump from the turns to the core, the choke may be ruined, as well as the transformer and rectifier.

To prevent a-c being induced in turns of a choke by alternating magnetic fields, as might be produced by the fields of nearby power transformers, it may be necessary to shield completely the choke in a sheet-iron case. This will also prevent fluctuating fields of the choke from inducing an a-c emf in nearby wires in which such voltages would be detrimental (AF amplifier leads, for example).

If the windings of chokes are of small-diameter wire and many turns, the inductance may be great but the resistance of the coil may also be high. Since the load current flows through this resistance, there will be a d-c voltage drop across the choke equivalent to $E = IR$. Increasing the current increases the voltage drop across the choke. As the load draws more current from the power supply, the voltage drop across the choke increases and the output voltage of the supply decreases. In most cases the inability of the supply to hold a constant-voltage output will be detrimental to the operation of the circuit to which it is connected.

The greater the inductance in a choke, the more reactance it will have to varying currents, and therefore the greater "choking" action it will have. It becomes a problem of "how much inductance" against "how much resistance" can be tolerated.

Since capacitance acts as a passer of a-c or varying d-c, a choke with a high value of distributed capacitance across it will tend to choke down the variations by its inductance but pass them by its distributed capacitance. One tends to counteract the other. Properly constructed chokes have low distributed capacitance.

The amount of current that can be accommodated by a choke is primarily determined by the size of the wire used. The ventilation of the choke windings determines the current-carrying ability also. With poor ventilation a relatively small current may cause enough heat to produce deterioration of the insulation on the wires. With good ventilation the heat is dissipated rapidly and more current can be accommodated safely. Furthermore, heating the windings increases the resistance of the wires, which increases voltage-regulation difficulties.

If the current in the choke has a large variation of amplitude, eddy currents may develop in the core. This will result in a waste of energy by heating the core. As with transformers, the cores of chokes are laminated to prevent this loss. The steel used in the laminations has a low value of retentivity to decrease hysteresis losses.

If the laminations are not securely bolted together, they may vibrate when varying d-c flows through the windings. Except for an audible buzzing sound, the operation of the choke is not impaired.

Choke coils are capable of reacting against current variations only if their cores are not magnetically saturated. To prevent magnetic saturation at a relatively low current, the core must be constructed so that there is an interruption in the continuity of the magnetic-iron circuit. To increase the reluctance of the core, an air gap will be found in all cores of *smoothing*-type filter chokes. This gap will be only a small fraction of an inch across, usually with a piece of cardboard in it, but the gap prevents the core from becoming saturated unless an excessively high current flows through the windings. As a result, the choke adequately filters the varying d-c regardless of its average amplitude.

Whenever possible, as a safety precaution to prevent personnel from receiving an electric shock, the metal cases of chokes and transformers are connected to ground potential or to the metal chassis. This prevents the metal cases from picking up an electrostatic charge and reduces possibility of undesired interaction between the supply and other parts of the equipment.

Filter chokes range in value from 1 to 100 henrys, depending on the requirements of the circuits. In most cases they will be between 5 and 30 henrys.

**10.13 Swinging Chokes.** In filter circuits used with power supplies the input-filter choke is usually a *swinging* choke. A swinging choke has no air gap in its core. Because it has no air gap, the magnetic-iron core ~~will saturate at a medium current value.~~ With low current flowing through the choke it has high inductance and will filter effectively, but with high current it has less inductance and will saturate, presenting little opposition to the variations of any current flowing through it.

If the action of an operating choke is to decrease the variations of current through it, then a swinging choke with little current through it will decrease the pulse amplitude considerably. On the other hand, if the load is increased and greater current flows through the power supply, the swinging choke does not oppose the higher value of fluctuating current to any great extent. When the power supply is lightly loaded, its voltage will attain a certain value. Normally, when the load is increased, the voltage output of the power supply will decrease. But at such a time the swinging choke passes the increased current with less inductive opposition, thereby tending to keep the output voltage of the filter system at a more or less constant value. It tends to improve the *voltage regulation* of the power supply in which it is used.

Swinging chokes may have inductance values that swing from 5 henrys with a high current flowing through them to 20 henrys with low current.

**10.14 High-vacuum Rectifiers.** The high-vacuum diode was previously discussed in the chapter on Vacuum Tubes. These tubes are found in low-power-receiver power supplies as well as in high-voltage supplies in high-powered transmitters.

High-power, high-vacuum diode rectifiers are made in single units, with filament leads coming out at the base and the plate lead coming out at the top of the tube.

Low-power high-vacuum diodes are usually constructed as duo-diodes, with two plates and two filaments in one envelope. The filament and plate leads terminate at the base of the tube.

Some of the significant points regarding high-vacuum rectifiers are as follows:

1. They have variable voltage drop across them, relatively high when passing heavy currents and low when passing low-current values.
2. They dissipate considerable energy in heat, both from high filament temperatures and by radiation from the plate. Adequate ventilation must be provided, particularly in high-power applications.

3. They can be used with either inductive- or with capacitive-input filter circuits.

4. Low-power filament-type diodes can be operated as soon as the filament is turned on, with no warm-up period required. When the cathode is indirectly heated, there is a cathode warm-up period of about 10 sec before electrons are emitted from the cathode.

5. As with all *high-power* tubes having heavy, directly heated filaments, tube life of a diode rectifier is materially increased by slowly increasing the filament voltage and current when the tube is first turned on each day, to prevent fracturing the filament wires because of rapid heating and sudden expansion.

6. A light blue or purple haze between filament and plate of a high-vacuum rectifier indicates the presence of unwanted gas. In some cases the tube will operate for a long period of time with some gas in it. In other cases, when the gas leak is more rapid, the tube may require replacement in a few minutes. In any case, gassy tubes bear watching.

**10.15 Mercury-vapor Rectifiers.** Mercury-vapor diodes were mentioned in the chapter on Vacuum Tubes. There are a few duo-diode-type mercury-vapor diodes, but most are of the single-diode, high-voltage, high-current type. While the duo-diodes are sometimes found in receivers and audio amplifiers, mercury-vapor tubes are primarily for transmitters.

The ionization potential of a gaseous tube depends on several factors, such as type of gas used, pressure of the gas, size of electrodes, and whether a filament is one of the electrodes. As the pressure is reduced, the ionization voltage value increases until in a vacuum tube (practically no gas present) ionization does not occur under normal operating conditions. On the other hand, a gas with a certain medium gas pressure will ionize and pass current at relatively low voltages. If the gas is compressed further, the voltage to produce ionization will again *increase*.

Ionized mercury vapor affords a low-resistance path between cathode and plate and will support relatively high-current flow with little heating. Such a tube depends on ionization of the gas rather than on electron emission from a relatively hot filament to produce current flow. This results in greater current through the tube, less power required to heat the filament, less heating of the plate, and greater over-all efficiency of operation.

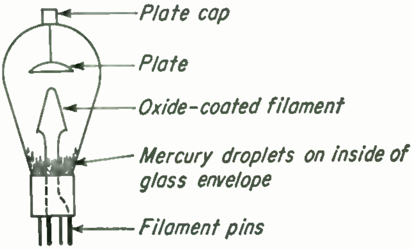


FIG. 10.20. Type 866A mercury-vapor rectifier tube.

Mercury-vapor rectifier tubes are usually constructed with a plate and an oxide-coated filament (Fig. 10.20). The glass envelope is evacuated except for some liquid mercury left inside the tube. The mercury settles in droplets at the bottom of the glass envelope. When the filament is turned on, the liquid mercury is vaporized by heat radiated from the hot filament and the gas pressure in the tube rises. This requires a little time. Electron emission from the filament partially ionizes the mercury vapor. When the tube is at its operating temperature, the gas pressure rises to a point where 15 volts between the hot filament and the plate will cause heavy ionization and allow a heavy current flow from filament to plate. Over a rather wide range of gas pressure this 15-volt ionization potential remains approximately the same. However, the potential required to produce a current *backward* through the tube, from plate to heated filament, is considerably higher because of the negative area produced by electron emission from the filament. By holding the gas pressure to a certain value, it is possible to have a tube with a 15-volt ionization emf one way and an *inverse* ionization voltage of several thousand volts in the other direction. This type of tube fills the requirement of a rectifier diode in a power supply.

If a mercury-vapor tube becomes overheated, its gas pressure may increase to the point where the inverse ionization voltage will fall below the peak voltage of the transformer to which the tube is connected and a *flash-back*, or *arc-back*, will occur in the tube.

If the mercury vapor is too cold, the *inverse-peak-voltage* rating of the tube may be high enough but the required forward ionization voltage will increase to greater than 15 volts. If this potential rises to about 22 volts, a phenomenon known as *double ionization* will occur. Double ionization means that two electrons are torn from molecules of the mercury. This results in the positive ions having twice the attraction toward the filament. High-speed ion bombardment of the filament will disintegrate the electron-emitting surface of the filament wire and ruin the tube. Excessive current through a mercury-vapor diode due to too heavy a load may also cause double ionization and deterioration of the filament.

A mercury-vapor tube must be warmed up for a period of 15 to 20 sec, depending on the surrounding air temperature, and must not be allowed to become overheated. If it becomes necessary to cool the tube, it is necessary to cool only the bottom, because it is there that the liquid mercury is deposited. Mercury-vapor tubes operate satisfactorily between about 20 and 70° centigrade.

Because the ionizing potential must be reached before the tube begins to pass current, there is always a 15-volt drop across any mercury-vapor tube in a power supply. This voltage value remains practically constant regardless of the load.

Mercury-vapor tubes must not work into a capacitive-input filter circuit. In such a circuit, when the alternating emf of the transformer increases from zero up to a value 15 volts more positive than the cathode of the tube, current suddenly starts flowing. This sudden, steep-sided wave of current represents the equivalent of a very-high-frequency pulse. The reactance of the capacitor is very low, practically a short circuit, for such a high-frequency current. As a result, during this instant a relatively high current flows in the transformer-tube-capacitor circuit, producing double ionization and deterioration of the filament. A mercury-vapor tube will operate only a few minutes to a few hours into a capacitive-input filter.

When a choke coil is added in series with the input-filter capacitor, as in inductive-input filtering, the choke opposes any sudden change in current and prevents any heavy instantaneous current flow, protecting the tube.

Even with the inclusion of the input choke, the tube still produces a slight current surge because of the distributed capacitance of the choke coil and transformer at the instant of ionization. This surge sets up a damped oscillatory wave, similar to a spark-transmitter emission in the transformer-tube-filter circuit. This low-intensity wideband signal can be picked up by nearby receivers as a disturbing *hash*, or buzzing sound, over most of the usable RF spectrum. It may also be heard in high-gain AF amplifiers. To stop this, 5- to 20-mh RF chokes may be connected in series with each plate lead of the rectifier tube and 0.001- to 0.005-$\mu$f mica RF filter capacitors added, as shown in Fig. 10.21.

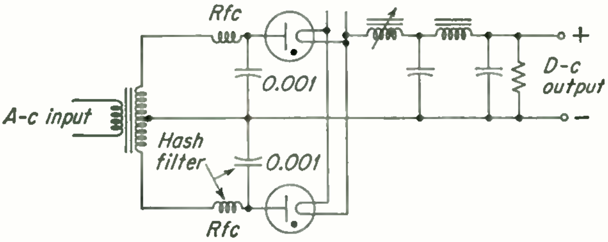


FIG. 10.21. Power supply with full-wave rectification, mercury-vapor tubes, inductive input, and hash filters.

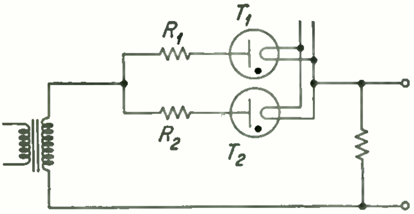


FIG. 10.22. Equalizing resistors required when two mercury-vapor tubes are in parallel.

Mercury-vapor tubes pass relatively high current for a given filament rating. For example, an 866A tube may pass a peak current of 2 amp or an average current of 0.5 amp. When more current must be passed, two or more tubes may be connected in parallel, as shown in Fig. 10.22.

The voltage drop across a mercury-vapor tube remains at approximately 15 volts regardless of the value of current passing through it. However, two parallel tubes of the same type may have slightly different ionization voltages. Suppose tube $T_1$, in Fig. 10.22, will ionize at 14.9 volts and tube $T_2$ at 15.1 volts. With these two tubes in parallel the voltage builds up across both tubes at the same time. Tube $T_1$ ionizes as soon as the emf across it reaches 14.9 volts, and no more than 14.9 volts will appear across $T_2$, and it will never pass current unless the two resistors $R_1$ and $R_2$ are in the circuit. With these resistors in the circuit, the voltage across $T_2$ will be the 14.9 volts across $T_1$ plus the voltage drop across $R_1$ when current flows through it. This will be more than the necessary 15.1 volts, and $T_2$ ionizes and passes half of the circuit current. These are called *equalizing resistors* and may have values ranging from 10 to 100 ohms.

When mercury-vapor tubes are *first placed* in a piece of equipment, droplets of mercury may be present on the filament and plate. To assure vaporization of these droplets, the filament of the tube must be run for about 15 min before plate voltage is applied. Thereafter, a 15- to 20-sec warm-up period is all that is necessary.

**10.16 Inverse Peak Voltage.** The inverse peak voltage that a mercury-vapor diode will stand depends upon the gas pressure in the tube. The higher the gas pressure, the lower the reverse voltage needed to produce an arc-back of current in a direction opposite to the desired current in the tube.

X

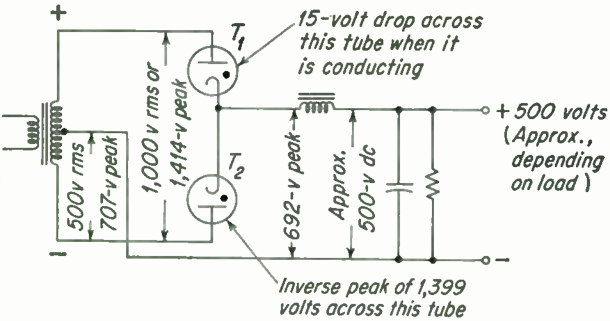
The only control an operator has on the gas pressure in a mercury-vapor tube is to keep the mercury at the desired temperature. If the mercury temperature increases, the gas pressure increases and the tube is more likely to arc back.

The inverse peak voltage being applied to a rectifier tube by the power transformer connected to it can be determined by multiplying the a-c rms (effective) voltage across the entire secondary of the transformer by 1.414, which gives the peak voltage.

Figure 10.23 shows a center-tapped full-wave rectifier system using mercury-vapor tubes. The a-c voltage across the secondary is 500 plus 500, or 1,000 volts effective; and 1,000 times 1.414 equals 1,414 peak volts being developed across the secondary. When the top of the transformer is positive, $T_1$ is conducting and there is a 15-volt drop across it. At that instant, $T_2$ has a negative potential on its plate. The potential difference between the plate and filament of tube $T_2$ is 1,414 volts less the 15 volts across $T_1$, or 1,399 volts. If the tubes had inverse-peak-voltage ratings of 1,200 volts, they would arc back. If they had inverse peak rating of more than 1,400 volts, they would operate without any arc-back. Note that it is the *peak* a-c voltage of the transformer, not the effective voltage rating, that must be less than the inverse peak rating of the tube.

The maximum allowable total secondary voltage of a transformer to be used in a center-tapped full-wave rectifier circuit is equal to 0.707 of the peak-inverse-voltage rating of the tubes used. For example, if the tubes are rated at 10,000 volts peak inverse voltage, the secondary should not produce a peak voltage of more than 10,000 volts (less the voltage drop across either tube when conducting). The effective value of 10,000 volts peak is 0.707 times 10,000, or 7,070 volts. However, if a center-tapped 7,000-volt transformer is used, the circuit will be operating too close to the rated values for safety. To assure more reliable operation, the voltage used should be limited to perhaps 90 per cent or less of the maximum computed voltage.

The inverse peak voltage across any mercury-vapor tube in a *bridge-rectifier* circuit is also equal to the peak a-c voltage minus the 15-volt drop across the other tube operating in series with it at the time. + DC



AC peak 707
DC out 692
1399 PIV

FIG. 10.23. Voltages appearing across various parts of a full-wave rectifier, inductive-input filter circuit.

The inverse peak voltage of a *half-wave rectifier* circuit with *capacitive-input* filtering would be practically twice the peak a-c voltage of the secondary. For example, if the plate is driven to a peak voltage of 1,400 volts by the transformer, the capacitor charges to nearly 1,400 volts. The capacitor holds this charge for a time. Since the plate is charged 1,400 volts negative when the a-c cycle reverses, there is nearly 1,400 volts positive on the cathode, and 1,400 volts negative on the plate, or a difference of about 2,800 volts across the tube. However, *mercury-vapor* tubes are always operated with inductive-input filtering. The input choke holds the voltage on the first capacitor to a value of about 70 per cent of the peak, or about 1,000 volts in this case. The inverse peak voltage across the tube at the peak of the nonconducting half cycle will be about 2,400 volts, but will vary with different degrees of load.

The inverse peak values of high-vacuum diodes are equal to the insulation properties of the internal elements of the tube, since there is little or no gas in the tubes to ionize and arc back.

**10.17 Vacuum versus Mercury-vapor Diodes.** A summary of the advantages and disadvantages of high-vacuum and mercury-vapor diode tubes is listed in Table 10.1.

Table 10.1

| *High-vacuum* | *Mercury-vapor* |
|---|---|
| ADVANTAGES | ADVANTAGES |
| No warm-up time required for low-power tubes. | Constant-voltage drop of 15 volts across the tube. |
| May be used with any type of input-filter circuit. | Better voltage regulation possible. |
| Momentary overloads do little damage to the tube. | Cooler in operation. |
| Can utilize capacitive-input filter; therefore the output voltage can be greater for a given transformer. | Can use oxide-coated filaments in high-voltage applications, which are efficient electron emitters. |
|  | High current for size and filament power. |
|  | High efficiency. |
| DISADVANTAGES | DISADVANTAGES |
| May require ventilation in high-power applications. | Must be warmed up 15 to 20 sec. |
| Requires tungsten or thoriated-tungsten filaments for high-voltage applications: greater filament heating power required. | Low inverse peak voltage if operating overly warm. |
| Less efficient. | Insufficient gas pressure or momentary overloads cause double ionization and filament damage. |
| Varying voltage drop across the tube under heavy load conditions. | Usually require hash filters. |
|  | Usually not desirable for receivers. |
|  | Must use inductive-input filter. |
|  | Inductive-filter requirement decreases voltage output for a given transformer. |
|  | Requires equalizing resistors when two tubes are in parallel. |

**10.18 Ripple Frequency.** When designing filters for power supplies, the pulse frequency being filtered is important. The higher this ripple frequency, the easier it is to filter. For example, the usual power frequency of a-c is 60 cycles. A half-wave 60-cycle rectifier produces 60 pulses, or ripples, per second and requires a certain amount of inductance and capacitance to filter the pulses adequately. A full-wave 60-cycle rectifier produces 120 pulses/sec and requires only about half the capacitance and inductance to filter it. In aircraft, frequencies up to about 800 cycles may be used. This produces a full-wave ripple frequency of 1,600 cycles, requiring very little filter.

A full-wave 60-cycle rectifier may produce a 120-cycle ripple frequency (Fig. 10.24*a*), but if one of the two rectifier tubes is weak, the alternate pulses will be of different amplitudes and a 60-cycle component will occur (Fig. 10.24*b*). The 60-cycle component will be more difficult to filter than the 120-cycle ripple.

When three-phase a-c is investigated, it is found that a half-wave 60-cycle three-phase rectifier has a ripple frequency of 180 cycles. A full-wave 60-cycle three-phase rectifier has a ripple frequency of 360 cycles. It will also be found that the rectified current is in the form of varying d-c instead of pulsating and is therefore much easier to filter. For this reason three-phase a-c is often used in broadcast and other high-powered stations.

**10.19 Rectifier Filament Circuits.** The electric power to heat the filament or cathode of rectifier diodes in power supplies is usually obtained in one of four ways:

1. In low-power equipment, receivers, small amplifiers, etc., the power transformer consists of (*a*) a primary, (*b*) a high-voltage center-tapped secondary, (*c*) a filament winding for the tubes of the receiver or amplifier, and (*d*) a separate filament winding for the rectifier tube. An example of this type of power supply is shown in Fig. 10.27.

(*a*) (*b*)

FIG. 10.24. When one rectifier is weak, a half-frequency component is developed.

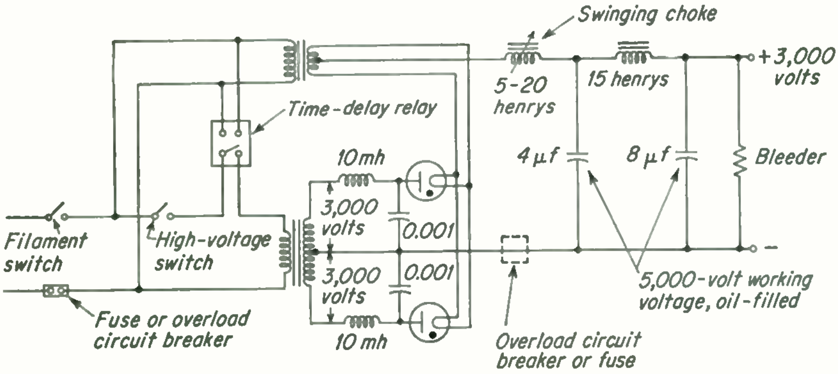


FIG. 10.25. A full-wave center-tap, high-voltage power supply, including possible component values.

2. In equipment operating from 6- or 12-volt batteries, the rectifier usually has an indirectly heated cathode, the filament or heater circuit being connected to the battery. The heater-to-cathode insulation of such tubes must be capable of withstanding half of the transformer-secondary peak-voltage value. An example of this form of power supply is shown in Fig. 10.38.

3. In higher-power equipment, the filament of the rectifier tubes must be heated for an appreciable time before the high voltage is applied across the tubes. As a result, a filament transformer separate from the high-voltage power transformer is used. Figure 10.25 shows a switching circuit and a full-wave mercury-vapor power supply of this type. After the filament circuit has been energized, the high-voltage transformer can

receive no voltage until the time-delay relay has closed and the high-voltage switch has also been closed.

4. In a-c/d-c equipment, in which there is no filament or power transformer, the filaments of all the tubes in the equipment are connected in series across the 120-volt source. All the tubes in this type of equipment must have heater cathodes.

In the chapter on Vacuum Tubes, center-tapping a-c filament leads was discussed. Failure to center-tap results in a periodic variation of the current through the tube. In power-supply-rectifier tubes the same thing occurs, except that the rectifier circuit is followed by a filter circuit, the chief function of which is to filter out *hum*, or current variations. Therefore, in power supplies center-tapping the filament may not be as necessary as in other circuits such as amplifiers or oscillators. When an absolute minimum of hum is required, the filaments of the rectifiers should be center-tapped, as in Fig. 10.25.

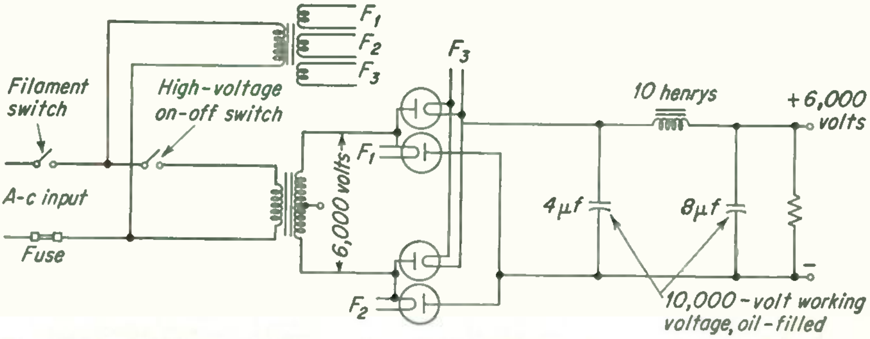


FIG. 10.26. A full-wave bridge-rectifier, high-voltage power supply, using the same power transformer as in Fig. 10.25. Output voltage is doubled.

**10.20 Practical Power Supplies.** Actually, there is no such thing as a "standard" type of power supply. However, the diagram in Fig. 10.25 is an illustration of a possible high-voltage transmitter supply utilizing full-wave, center-tapped rectification, choke-input filtering, a bleeder resistor, a time-delay relay to allow the filaments to heat before applying high voltage, and two possible places for fuses or overload relays.

The diagram in Fig. 10.26 illustrates a possible high-voltage transmitter power supply employing a bridge-rectifier circuit with capacitive-input filtering. Three secondary windings are required on the filament transformer (same power transformer as in Fig. 10.25).

The diagram in Fig. 10.27 illustrates a power supply that is used in many receivers and amplifiers to provide a well-filtered d-c voltage of perhaps 200 to 500 volts. The filament winding of the rectifier tube is a tertiary winding on the power transformer. The filament voltage for the other tubes of the receiver is taken from a fourth winding, as shown.

**10.21 Power-factor Compensation.** All power-transformer primaries have considerable inductance. When inductance is operating in an a-c circuit, current and voltage are out of phase. Any time the current lags or leads the voltage there is a lessening of the power factor in the circuit. A low power factor means less secondary power output per ampere of current flowing in the primary. For 60-cycle a-c, power factor may be disregarded in most power supplies. When 400- to 800-cycle a-c is used, as in aircraft, the power factor may decrease considerably. To overcome the inductive effect of the transformer, a large capacitor, 8 to 20 $\mu$f, can be connected in series with the primary of the transformer.

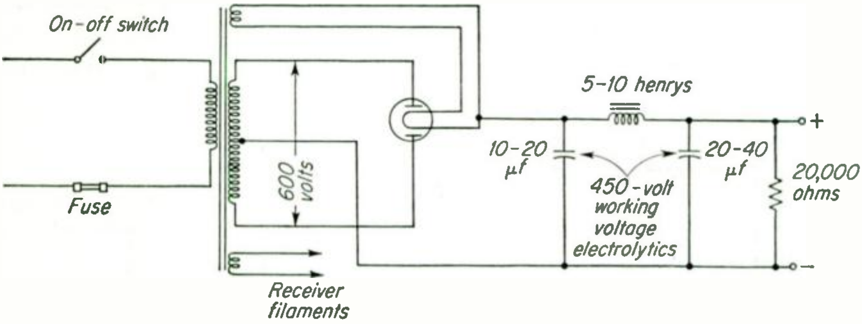


FIG. 10.27. Power-supply circuit similar to that used in many communication receivers.

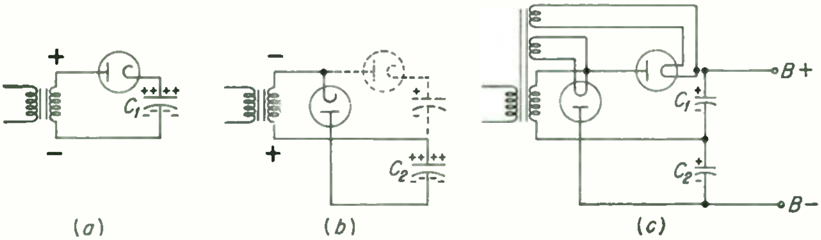


FIG. 10.28. Capacitors $C_1$ and $C_2$ charge on alternate half cycles and discharge in series into the load.

The current lead of the capacitor counteracts the current lag of the inductance, raising the power factor. The value of the capacitance may be made variable in steps to allow proper adjustment.

**10.22 A Voltage-doubler Circuit.** It is possible to rectify an a-c voltage and produce a d-c voltage almost twice the a-c value by using a circuit called a *voltage doubler*.

In Fig. 10.28*a*, when the top of the transformer secondary is positive, current flows through the rectifier and charges capacitor $C_1$ as shown. When the cycle reverses and the bottom of the transformer is positive, $C_2$ is charged by a second rectifier, as shown in Fig. 10.28*b*. The whole voltage-doubling circuit is drawn out in Fig. 10.28*c*, with the output d-c across the two charged capacitors in series. The larger the value of the two capacitors, the better the regulation and the higher the output voltage of the power supply under load conditions. Values in the range of 40 $\mu$f to more than 100 $\mu$f for each capacitor are used. The output voltage of the voltage-doubler circuit ranges from twice the peak value of the applied a-c at no load to about the peak value under heavy-load conditions. With 110 volts a-c input, this would produce a no-load voltage of 311 volts and a heavy-load voltage of about 156 volts.

The inverse peak voltage on the rectifiers is equal to approximately twice the peak a-c voltage of the secondary of the transformer.

When filament diodes are used, as shown, two filament windings are required. Heater-cathode duo-diode rectifiers, such as a type 6X5, may

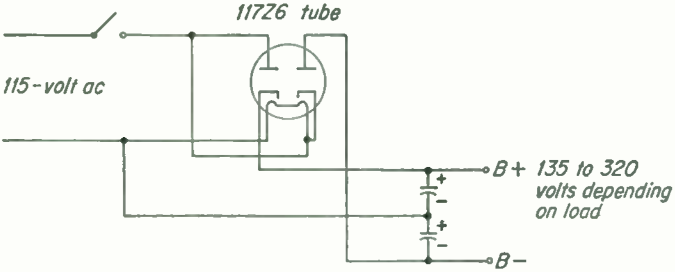


Fig. 10.29. Voltage-doubler circuit using a 117Z6-type tube.

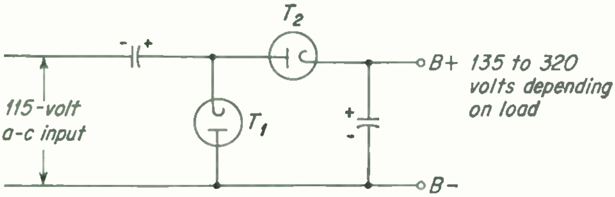


Fig. 10.30. Another voltage-doubler circuit that allows the negative d-c to be grounded.

be used with a single filament winding. Selenium, silicon, germanium, or copper-oxide rectifiers are often used in voltage doublers. With such rectifiers a 25- to 100-ohm resistor should be connected in series with each rectifier to limit surge currents that might otherwise damage them.

A frequent application of the voltage-doubler circuit is the power supply in ac-dc receivers, shown in Fig. 10.29. It requires no transformer and results in an output emf of approximately 170 volts under load when a 115-volt a-c line is used. A disadvantage of this type of voltage-doubler circuit is that *neither* side of the line can be used as B− or be connected to the chassis of the equipment if the chassis is grounded.

A doubler circuit in which a common ground may be used is shown in Fig. 10.30. When the top power line is negative, the input capacitor charges through $T_1$ to the voltage of the line, as indicated. When the line voltage reverses, the output capacitor, through diode $T_2$, is connected to the positive line voltage in series with the charged input capacitor. The output capacitor charges to almost twice the line voltage. Both capacitors can be electrolytics of 40 to 100 $\mu$f.

**10.23 The Bleeder Resistor.** It is standard practice in communication-equipment power supplies to use a *bleeder* resistor across the output of the supply. This resistor serves two purposes. First, it bleeds off the charge of the capacitors when the power supply is turned off, in order that servicing personnel will not receive electric shocks while they are working on supposedly "dead" equipment. (It is possible to turn off a transmitter with an open bleeder and several hours later receive a lethal shock from the charge still left in the filter capacitors.) Second, the bleeder resistor aids in holding the voltage output more nearly constant, as indicated in the simplified graph in Fig. 10.31.

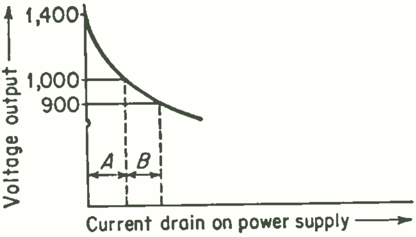


FIG. 10.31. Advantage of using a bleeder resistor.

According to the graph, with no current drain on the power supply, it has an output of 1,400 volts. When a current drain of the magnitude indicated by line *A* is drawn from the supply, the output voltage is reduced to 1,000 volts. This is a 40 per cent variation of voltage.

A bleeder resistance is connected across the power supply, and it draws a current of the magnitude shown by *A*. When a load, shown by *B* (equal to *A*), is added to the supply, the output voltage drops to 900 volts. This is an 11 per cent variation of voltage.

A power supply must be designed to have sufficient output power to accommodate not only the load demand but also the bleeder-resistor demand. The bleeder should take between 10 and 25 per cent of the total power-supply output *current*. Within limits, the lower the resistance value of the bleeder, the better the regulation.

A power supply designed to operate at 1,000 volts and 200 ma might have a bleeder current of 40 ma. The resistance of the bleeder, by Ohm's law $R = E/I$, equals 1,000/0.04, or 25,000 ohms. The power rating of the bleeder should be at least twice the computed power dissipation by the formula $P = EI = 1{,}000(0.04) = 40$ watts. A 100-watt 25,000-ohm resistor would probably be used.

**10.24 Power-supply Regulation.** When a power supply is operating into a load, it will have a certain output-voltage value. If the load is *removed*, the output voltage will increase. The percentage of voltage increase is considered the *regulation* of the power supply. For example, a power supply delivers 1,000 volts to a telegraph transmitter with the key down and 1,200 volts with the key up. The regulation is found by determining the ratio of the difference of voltages to the full-load voltage. The *percentage* of regulation is found by the formula

$$\% = \frac{(E_{nl} - E_{fl})100}{E_{fl}} = \frac{(1{,}200 - 1{,}000)100}{1{,}000} = \frac{200(100)}{1{,}000} = 20\%$$

where $E_{nl}$ is the no-load voltage; $E_{fl}$ is the full-load voltage; and % is the percentage of regulation. This same formula can be applied to batteries, motor generators, dynamotors, transformers, etc., to determine percentage of output regulation. The lower the percentage, the better the regulation.

The regulation formula can be rearranged to compute the full-load voltage, as in the following problem:

The no-load voltage is 140 volts, the regulation is 15 per cent, what is the full-load voltage?

$$\% = \frac{(E_{nl} - E_{fl})100}{E_{fl}}$$

$$\%(E_{fl}) = 100E_{nl} - 100E_{fl}$$

$$\%(E_{fl}) + 100E_{fl} = 100E_{nl}$$

$$E_{fl}(\% + 100) = 100E_{nl}$$

$$E_{fl} = \frac{100E_{nl}}{\% + 100} = \frac{14{,}000}{115} = 121.7 \text{ volts}$$

The regulation formula can be rearranged to compute the no-load voltage, as in the following problem:

Full-load voltage is 240 volts, regulation is 11 per cent, what is the no-load voltage?

$$\frac{(E_{nl} - E_{fl})100}{E_{fl}} = \%$$

$$(E_{nl} - E_{fl})100 = \%(E_{fl})$$

$$E_{nl} - E_{fl} = \frac{\%(E_{fl})}{100}$$

$$E_{nl} = \frac{\%(E_{fl})}{100} + E_{fl} = \frac{11(240)}{100} + 240 = 26.4 + 240$$

$$= 266.4 \text{ volts}$$

There are several factors which enter into the voltage regulation of electronic power supplies. In a power supply the following conditions may cause an increased percentage of voltage regulation, which is undesirable:

1. Resistance in the wires of the choke coils and transformer secondary. When the output current is increased, the voltage drop across the resistance increases, decreasing the output voltage of the supply.

2. Resistance in the primary of the power transformer and leads to it. When the load requires more current from the secondary, the resistance in the primary prevents the required primary current from flowing to adequately support the power demand of the secondary.

3. The voltage drop across a vacuum diode increases when the current through it increases, because of the internal resistance of such tubes. This is not true with mercury-vapor diodes, which have a constant 15-volt drop across them.

4. Use of capacitive-input filtering instead of inductive input.

5. Failure to use a swinging choke as the input-filter element.

6. Insufficient capacitance in the filter circuit. The load bleeds off the charge in the capacitors too rapidly.

7. Too *high* a bleeder-resistance value.

8. Use of half-wave rectification instead of full-wave.

**10.25 Voltage-regulator Tubes.** The constant-voltage drop across a gas-filled tube when the gas is ionized can be used as a means of regulating the output of a power supply. If a tube is constructed with two electrodes and is filled with neon gas at the proper pressure, the voltage across it is maintained at about 75 volts with any value of current flowing through it from 5 to 40 ma. The tube requires about 5 ma to keep it ionized properly. Therefore it can be used to regulate the voltage across a load drawing up to 35 ma of current. Figure 10.32 shows a *voltage-regulator* (VR) *tube* connected to a 300-volt power supply to provide a regulated 75 volts for a load.

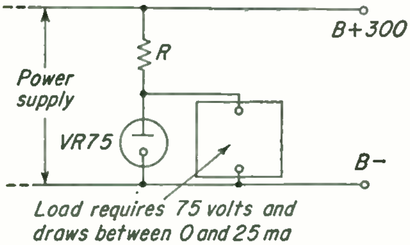


FIG. 10.32. Voltage-regulator circuit to feed a constant voltage to a load.

In the diagram, the load draws 20 ma and is expected to increase possibly 5 ma or to decrease possibly to zero. The maximum current through the dropping resistor $R$ will be 25 ma for the load, plus 5 ma to keep the tube ionized properly, or a total of 0.03 amp. The voltage drop to be developed across resistor $R$ is 300 volts less 75 volts, or 225 volts. By Ohm's law, $R = E/I$, or 225/0.03, or 7,500 ohms. When the power supply is turned on, the voltage across the VR tube will increase until it reaches about 90 volts, or the striking potential of the gas in the tube. The tube will ionize and immediately draw enough current through resistor $R$ to drop the voltage across the tube to 75 volts. As long as the load draws no more than 25 ma, the voltage across the tube, and therefore across the load, will hold very close to 75 volts. From zero load to 25-ma load the voltage will only vary about 4 volts.

If the load does not vary, but for some reason the power-supply voltage varies, the VR tube keeps the voltage across the load constant. As a result, the VR tube acts somewhat as a filter, feeding constant-voltage d-c to the load even if the power supply produces a varying d-c voltage.

Frequently used VR tubes are the VR75 (also known as an OA3), the VR90 (OB3), the VR105 (OC3), and the VR150 (OD3).

If it is desired to regulate a power supply to 300 volts, two VR150 tubes in series may be used. A VR150 in series with a VR90 produces a regulated 240 volts. For good regulation the power supply should have about twice the desired regulated voltage value.

If two VR tubes are connected in parallel to regulate more than 35 ma, it is necessary to add a 50- to 100-ohm equalizing resistance in *series* with each tube to insure both tubes ionizing (as in Fig. 10.22).

Note that the symbol of the VR tube in Fig. 10.32 shows the wider-area plate connected toward B+. Actually, the plate is a thin wire down the center of the tube, and the cathode is a large-area concentric metal cylinder around the wire. To assure proper ionization, some of the newer regulator tubes have a radioactive area on the anode, similar to the "radium" paint used on watch faces.

If the d-c potential across a VR tube is reversed, less current will flow through the tube, although it will ionize and hold the rated potential across it. The difference in current amplitude will be between 20 and 50 per cent, depending on the particular type of tube used. This difference in front-to-back current is produced by the difference in area of the two electrodes. The smaller an electrode, the greater the proportion of current that will flow to it. If the anode is made small enough, more than 10 times as much current can be made to flow in one direction than in the other. This essentially unidirectional behavior was used in the past in helium-filled type BH rectifiers, which used a large-area dish-shaped cathode electrode and two thin-wire anode electrodes. This produced a full-wave *cold-cathode* rectifier tube. A diagram of a cold-cathode full-wave rectifier is shown in Fig. 10.33.

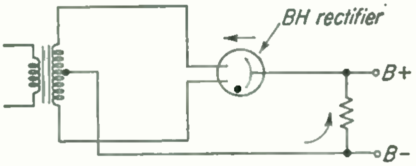


FIG. 10.33. BH, or OZ4, rectifier in a full-wave rectifier circuit.

**10.26 Voltage Dividers.** In many applications it is necessary to have two plate voltages, one higher than the other. It is possible to use a *voltage-divider* network of resistors to develop the lower voltage from the higher voltage of the power supply. The voltage divider may also serve as the bleeder resistance.

*Example:* A 500-volt power supply is being used in a two-tube transmitter. One tube requires 500 volts on the plate at a current value of 60 ma. The other tube requires 400 volts on the plate at a current of 40 ma. The bleeder current is to be 15 ma. What will the voltage-divider circuit require? Figure 10.34 illustrates this problem.

$R_1$ and $R_2$ in series form the voltage divider and bleeder circuit.

The voltage across $R_2$ is 400 volts, at a current of 0.015 amp. According to Ohm's law, $R_2 = E/I$, or 400/0.015, or 26,667 ohms.

The current through $R_1$ is the sum of the 0.015-amp bleeder current plus the 0.04 amp of the 400-volt load circuit, or 0.055 amp. The voltage drop across this resistor is 100 volts. The resistance of $R_1$, according to Ohm's law, is $R_1 = E/I$, or 100/0.055, or 1,818 ohms. The wattage rating for the resistors is usually *twice* the computed $I^2R$, the $EI$, or the $E^2/R$ values.

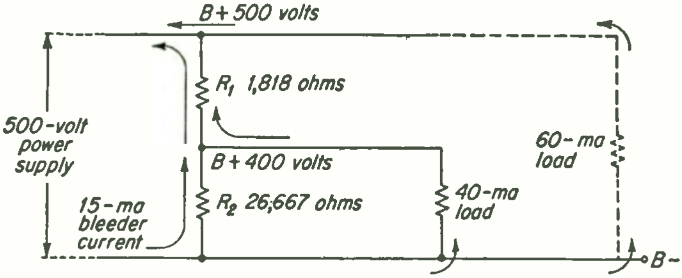


FIG. 10.34. Voltage-divider circuit to feed two different voltages to two different loads.

## 10.27 Copper-Oxide, Selenium, and Germanium Rectifiers.

If a sheet of lead and a sheet of copper covered with copper-oxide are pressed together, it will be found that current will flow much more readily in one direction (from the copper to the oxide) through the oxide coating than in the other, resulting in a rectifying action. Such a unit is called a *copper-oxide rectifier*. These units will stand only a limited inverse peak voltage. When used in high-voltage applications many units must be connected in series to give the desired inverse-voltage capabilities. The copper-oxide rectifiers have relatively long life and will rectify relatively heavy currents but have a fairly high initial cost.

When iron is coated with selenium, a rectifying unit will be produced. It is similar to the copper-oxide rectifiers, with the advantages of having a greater inverse voltage per unit and being slightly less expensive. Both of these rectifiers are used to rectify a-c in power supplies, in battery chargers, and in meters, to name a few applications.

In the last few years the germanium diode, or rectifier, has found wide acceptance. While it has no present application as a power-supply rectifier because of its low-inverse peak voltage and limited current-carrying capacity, it is used extensively in low-current circuits in receivers and transmitters. It consists of a small wire making a surface contact on a piece of germanium. The whole assembly can be made quite small and with almost no capacitance across the rectifier unit. This is in comparison with the considerable capacitance across the other dry rectifiers. Silicon rectifiers, a late development, surpass germanium diodes in both current-carrying ability and in inverse-peak-voltage ratings. Both of these rectifiers are quite small in comparison to previous rectifiers.

The diagrammatic symbol for these rectifiers is shown in Fig. 10.35. Note that the current direction through these rectifiers is *not* as apparently indicated by the arrowhead-like part of the symbol, but is in the opposite direction.

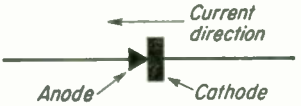


FIG. 10.35. Symbol of a junction rectifier, and direction of current flow through it.

While copper-oxide and selenium rectifiers are often used in half-wave circuits, they are also manufactured as a single group to be connected into a circuit as a full-wave bridge circuit. Four rectifiers are mounted on a single rod and interconnected in such a manner that when a-c is fed to the proper pair of external leads, d-c is obtained from the other two leads. Figure 10.36 shows, first, a bridge-rectifier circuit with each rectifier numbered. Second, it shows the physical interconnections of such a rectifier group, correspondingly numbered.

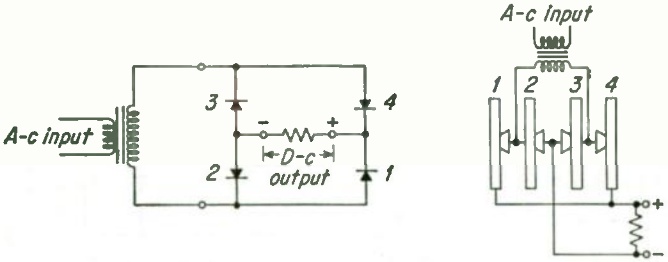


FIG. 10.36. Bridge circuit used with copper-oxide rectifiers, and how units are stacked.

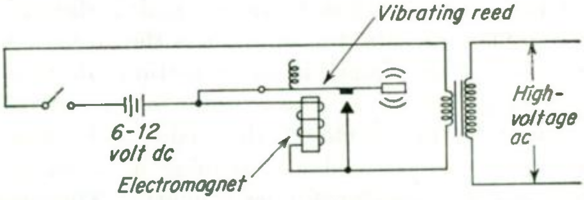


FIG. 10.37. Simple vibrator to produce high-voltage a-c from low-voltage d-c.

**10.28 Vibrator Supplies.** In many radio applications it is desirable to use a 6- or 12-volt battery as the power supply for low-power transmitters or for receivers. This is particularly true in mobile equipment on land or at sea. If 6 or 12 volts is all that is available, something must be done to convert this low voltage to a potential sufficient to operate the plate circuits of the tubes in the equipment. This can be done in several ways. One method is to use a vibrator power supply.

There are two basic types of vibrator supplies. By using a step-up transformer, it is possible to feed low-voltage pulsating d-c into the primary of a transformer and induce high-voltage a-c into the secondary. A simple vibrator circuit that will do this is shown in Fig. 10.37.

When the switch is closed, a relatively weak current flows through the electromagnet coil, the primary of the transformer, and the battery. The magnetism developed in the core of the electromagnet attracts the iron arm, or reed. When the iron reed is pulled down, it closes the open contacts in the diagram, shorts out the electromagnet coil, and allows a heavy current to flow through the primary of the transformer. With no current flowing through the electromagnet, the spring of the iron vibrator reed pulls the reed upward, opening the shorting contacts, decreasing the current in the circuit again, but developing magnetism once more. The reed is again attracted, closes the contacts, and sends another strong pulse of d-c through the primary. The vibrator continues to vibrate as long as the switch is closed, continually feeding interrupted varying d-c into the primary, inducing a like-frequency a-c in the secondary. While this simple circuit would operate, the current always flowing in the same direction in the primary would tend to magnetize the core of the transformer permanently and reduce the efficiency of the supply.

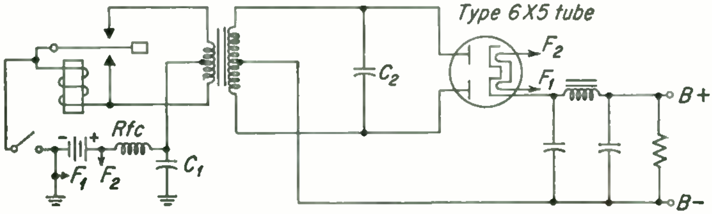


Fig. 10.38. Nonsynchronous-vibrator power supply.

A more practical *nonsynchronous* vibrator circuit is shown in Fig. 10.38. The nonsynchronous-type vibrator supply has the advantage of sending pulses of d-c through the primary in two directions alternately, thereby eliminating core magnetization. The vibrator reed is shown in the "off" position. When the switch is closed, the reed is pulled toward the electromagnet, shorting out the coil and sending a strong pulse upward through the lower half of the transformer primary. The weighted spring steel reed now springs back away from the lower contact, striking the upper contact, sending a strong pulse downward through the upper half of the primary winding. The electromagnet again pulls the reed downward, repeating the cycle. The primary has a current flowing alternately through it, first in one direction and then in the other, although the alternations occur in different halves of the primary winding. The polarity of the battery has no effect on the polarity of the d-c output voltage.

The radio-frequency choke coil (RFC) and capacitor $C_1$ form a low-pass-filter circuit to reduce impulse-type interference known as hash, produced by the vibrator contacts as they make and break the circuit. Without this filter a loud buzzing sound may be heard in an associated radio receiver. To further reduce this hash, the whole vibrator power supply must be completely shielded by encasing it in a metal box. All leads into and out of it must be bypassed.

Capacitor $C_2$ across the secondary of the transformer is required to reduce the sharp peaked waveform that would result because of the make and break of the vibrator contacts and to reduce sparking at the vibrator contacts, which might shorten the life of the vibrator. The value of this capacitance is quite critical. If this *buffer* capacitor becomes faulty, the vibrator will usually become faulty also. For this reason it should be replaced whenever the vibrator requires replacement.

The tube used for this type of supply must have a high heater-to-cathode insulation rating, such as in a 6X4- or 6X5-type tube.

The other form of vibrator supply is known as the *synchronous* type. It uses no rectifier tube, being a mechanical rectifier circuit. Its primary circuit is partly the same as the nonsynchronous vibrator circuit. Another set of contacts is added to the vibrating reed, as shown in Fig. 10.39.

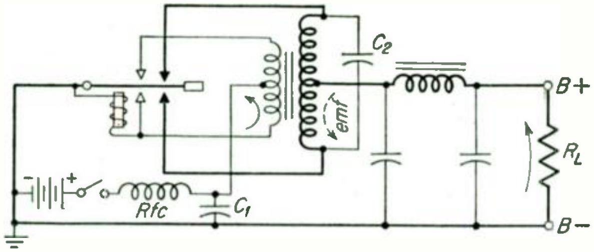


FIG. 10.39. Synchronous-vibrator power supply.

The reed is pulled down by magnetic attraction, making a contact that drives a pulse of d-c upward through the lower half of the primary, at the same time connecting the lower end of the secondary to ground through the second lower contact. The high-voltage emf developed in the secondary by the primary pulse forces current through the load $R_L$ in an upward direction, as shown by the arrow in the diagram.

The reed springs back, momentarily closing the two circuits through the upper contacts. This sends a d-c pulse downward through the upper half of the primary, inducing a high voltage upward in the secondary, connects the upper end of the secondary to ground, and forces current through the load $R_L$, again in the upward direction.

The current that flows in the load is always in the upward direction and is equivalent to a full-wave pulsating d-c. The low-pass capacitive-input filter smooths the pulses to a relatively pure d-c, suitable for receivers or transmitters.

The synchronous vibrator supply uses no tube, thereby saving the power necessary to heat the cathode, an advantage in mobile equipment.

As an aid to waveshaping, damping resistors of 50 to 100 ohms may be connected across the primary. A resistance having a value of a few thousand ohms is often connected in series with the buffer capacitor $C_2$ to protect the equipment if the capacitor becomes shorted.

Reversing the polarity of the battery will reverse the polarity of the output voltage.

**10.29 Filter Capacitors in Series.** In an emergency it is sometimes necessary to replace a high-voltage filter capacitor. If the only available capacitors have voltage ratings less than the value required, two or more may be connected in series. Two capacitors with equal capacitance will divide the total voltage across them equally. If one has more capacitance than the other, the one with the lesser capacitance will have the *greater* voltage drop developed across it. This can be illustrated by the three circuits in Fig. 10.40.

When the switch is closed, as shown in the second circuit, the same number of electrons flow in the whole circuit until the capacitors are charged. Since the two are both of 5-μf capacitance, they charge with the same number of electrons per square inch of plate area. The same number of electrostatic lines of force are developed across each square inch of dielectric, resulting in an equal voltage drop across each capacitor, in this case 500 volts.

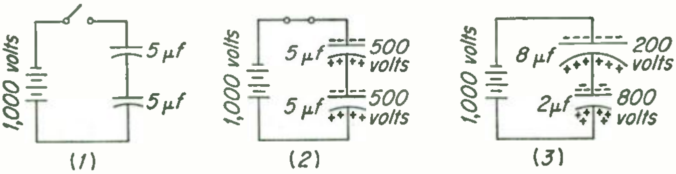


FIG. 10.40. Equal capacitors in series divide the voltage drop equally. Unequal capacitors divide the voltage inversely as the ratio of capacitances.

In the third circuit, the same charging current flows into both capacitors. The smaller must now hold more electrons per square inch of plate area. This produces more electrostatic lines of force through each square inch of dielectric, resulting in a relatively higher voltage drop across this one.

The voltage drop across two capacitances in series is inversely proportional to their respective capacitances. In the case of an a-c circuit, the voltage is directly proportional to their reactances.

If two 500-volt 5-μf paper or oil-filled dielectric capacitors are connected across 1,000 volts, they will operate satisfactorily. However, if one has slightly less capacitance than the other, more than 500 volts will be developed across it and it may short out. This will place the full 1,000 volts on the other one and blow it out also. To prevent this, an equalizing resistor should be connected across each capacitor, as shown in the diagram of Fig. 10.41. These two equal-value resistors tend to hold the voltage drop across each equal to half of the total voltage. The more nearly equal the capacitances, the higher the resistance value the equalizers may have (possibly 100,000 ohms). When the two capacitors are not of the same value, the resistors must be lower in value (10,000 to 50,000 ohms). Since these resistors tend to discharge the capacitors, thereby decreasing their effectiveness as filter components, the higher the resistance values that may be used the better.

The main advantages of electrolytic capacitors are their high capacitance, small size, and low cost. The leakage current that always flows through them is equivalent to shunting a resistor across them. If it is required that a 500-volt paper and a 500-volt electrolytic capacitor be connected in series across 1,000 volts, the paper capacitor must be shunted with a resistance equal to the leakage resistance of the electrolytic, and then equalizing resistors should be added across both. Such a circuit is not recommended except in emergencies.

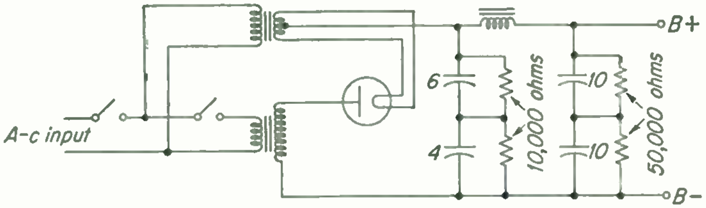


FIG. 10.41. Equalizing resistors across unequal and equal capacitors in series.

Since the leakage currents in two equal-capacitance electrolytic capacitors will normally vary somewhat, equalizing resistors should always be used across such capacitors when they are in series.

The equalizing resistances can also be useful as bleeder resistors. If it has been determined that a 30,000-ohm bleeder is required for a certain power supply, two 15,000-ohm equalizing resistors across two series-connected output capacitors will serve as both a bleeder and equalizing network. They must not be used as a voltage-divider circuit, however.

**10.30 Three-phase Power.** For high-power, high-voltage supplies in AF or RF stages of radio transmitters, three-phase (3-$\phi$) power has several advantages over the usual single-phase a-c:

1. It has a ripple frequency three times that of single phase. A 60-cycle single-phase full-wave rectifier has a ripple frequency of 120 cycles. A 60-cycle three-phase full-wave rectifier has a ripple frequency of 360 cycles. Half-wave three-phase with its 180 cycle ripple is easier to filter than full-wave single-phase.

2. The pulses of rectified current in either full-wave or half-wave three-phase circuits overlap, and the current value never drops to an instantaneous value of zero, making the three-phase rectified current still easier to filter. Power is present in the circuit at all times.

3. The output voltage of a three-phase system may be as much as 73 per cent higher than the turns ratio of the transformers would indicate.

Three-phase a-c is produced by special a-c generators, properly termed *alternators.* In effect, they are three single-phase alternators in one. A single-phase alternator has two leads coming from it (Fig. 10.42). A two-phase alternator would have four leads and a three-phase alternator would have six leads coming from it.

A simple three-phase alternator may have three separate pickup coils that rotate between electromagnetic-field poles. In each pickup coil a single-phase a-c is induced. These coils are set on the revolving part, called a *rotor,* or *armature,* in such a way that the voltages induced in the different coils are 120° apart. The three-phase alternator shown in Fig. 10.42 would be capable of supplying three separate single-phase circuits, or the outputs can be combined, as illustrated in Fig. 10.43, in one of two methods to produce a three-wire, three-phase circuit. The first diagram shows the Y connection (also known as *wye,* or *star,* connection). All three pickup coils are connected together at one point. The other ends of the coils form the leads that are brought out of the alternator. Any two of the output leads will carry voltages from *two* of the coils in series. Since the voltages in the coils are 120° out of phase, there will never be a time when the two voltages will be at a maximum together. With 100 volts as the peak in all coils, there will never be a time when 200 peak volts will appear across any two leads. Mathematically, and by actual trial, it is found that the peak voltage will rise to 173 volts between any two legs of a Y-connected, 100 volt/coil three-phase alternator. The voltage output from a Y-connected alternator can be found by multiplying the output voltage of one of its pickup coils by the factor 1.73.

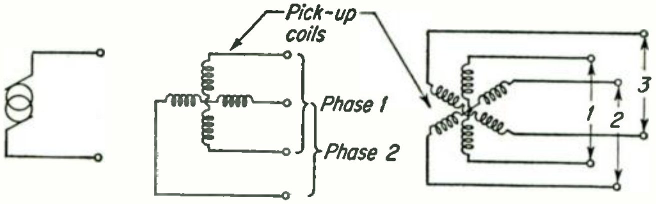


FIG. 10.42. Two terminals from a one-phase alternator, four from a two-phase alternator, and six from a three-phase alternator.

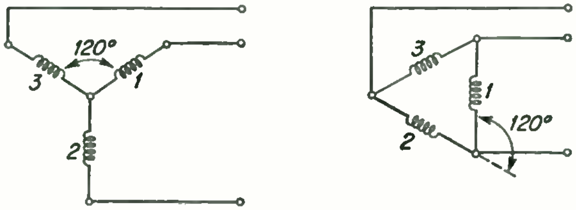


FIG. 10.43. Pickup coils connected in Y and in Δ.

Y

X

In the Δ-connected (delta) alternator, any two lines leading from the machine are directly connected across a pickup coil. If the coil has 100 volts induced in it, there will be 100 volts across the line. The other two coils have voltages induced in them, but these will be out of phase, with a resultant of 100 volts at the instant the first coil attains its peak value. This parallels the two 100 volts, resulting in a machine capable of producing 1.73 times as much *current* as any one pickup coil alone could carry.

A Y-connected alternator produces higher voltage at a lower current. The same generator Δ-connected produces lower voltage output but is capable of greater current.

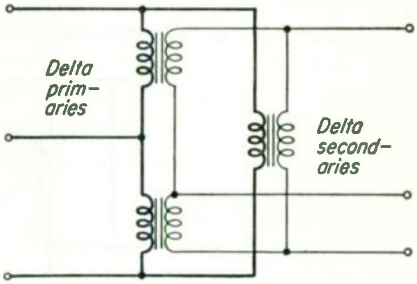


Fig. 10.44. Transformers connected Δ-Δ.

Three-phase power lines usually have three wires, although the center, or *neutral*, connection on a Y circuit may use a fourth, or this point may be grounded.

When either a single-core three-phase transformer or three separate transformers terminate three-wire three-phase lines, there are five methods of connecting the transformers: (1) Δ primary, Δ secondary, termed Δ-Δ, (2) Y-Y, (3) Δ-Y, (4) Y-Δ, and (5) open Δ, using two single-phase transformers only.

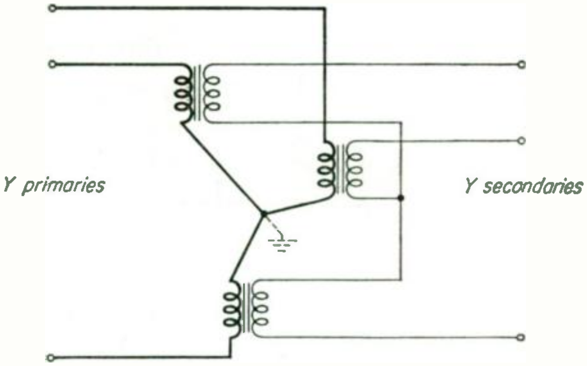


Fig. 10.45. Transformers connected Y-Y.

Figure 10.44 illustrates three transformers, primaries connected in Δ, and the secondaries also in Δ. Figure 10.45 illustrates three transformers, primaries in Y, and the secondaries also in Y.

If the transformers used have a 1:1 ratio, there will be no step-up or step-down in either the Δ-Δ circuit or in the Y-Y circuit. With the same transformers connected with primaries in Δ and secondaries in Y, as shown in Fig. 10.46, each output phase will have 1.73 times the *voltage* of the primary phases, as discussed previously. If the transformers have a 1:10 step-up ratio, the secondary-line voltage will be 17.3 times the primary voltage.

With the same transformers connected with primaries in Y, and secondaries in Δ, as shown in Fig. 10.47, each output phase will have a voltage equal to the reciprocal of 1.73, or 0.578, times the input- or primary-phase voltage. However, the current for each phase of the output will be 1.73 times the current in a primary phase.

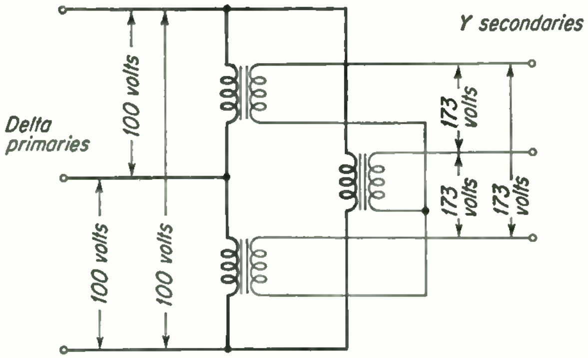


Fig. 10.46. Transformers connected Δ-Y.

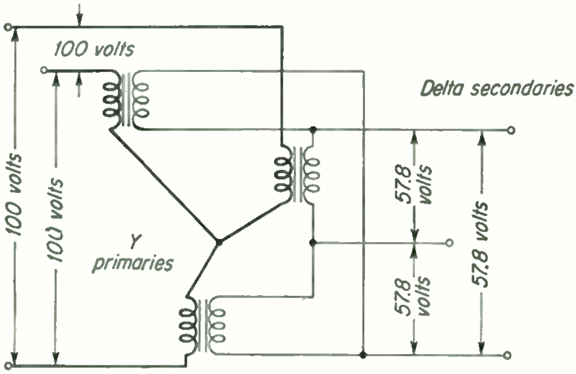


Fig. 10.47. Transformers connected Y-Δ.

It is possible to use only two transformers in a three-phase system. This configuration is known as an *open*-Δ circuit. It produces three-phase a-c by using the three secondary wires, as indicated in Fig. 10.48. It is equivalent to a three-transformer Δ circuit with one of the transformers open-circuited in either or both primary and secondary, or if one transformer is disconnected. In an emergency it is possible to change a Δ power system to an open Δ and operate at 58 per cent of the full-load capabilities of the three-transformer system.

The open-Δ and Y circuits can also be used as two or three single-phase circuits and can operate high-power motors, etc., with three-phase a-c from the same transformers at the same time, as illustrated in Fig. 10.49. Only the secondaries of the three-phase transformers are shown in this diagram.

In some applications one phase of a 240-volt Δ system may be center-tapped. The center tap is used as the neutral for two relatively low-power 120-volt single-phase circuits.

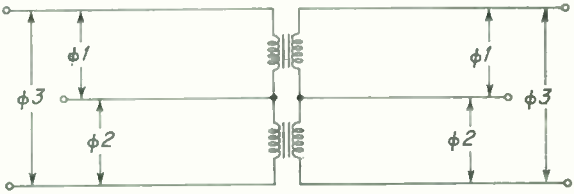


Fig. 10.48. Two transformers connected open-Δ.

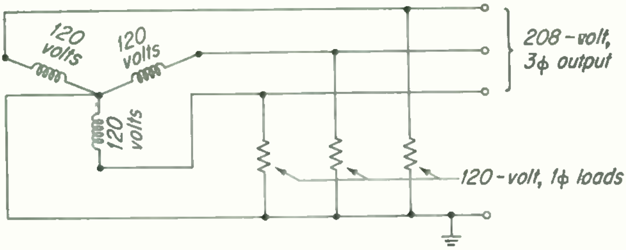


Fig. 10.49. A 208-volt three-phase Y with grounded neutral can be used as three 120-volt one-phase lines.

Computations of power become quite involved in three-phase circuits. However, in a reasonably well-balanced three-phase circuit, with each phase taking approximately one-third of the load, the total power can be determined by measuring the power in any two phases separately. If the power factor is more than 0.5, as is usually the case, the total power of the three phases is equal to the *sum* of the two power readings taken. If the power factor is less than 0.5, the total power is equal to the difference between the two readings. Figure 10.50 shows how two single-phase wattmeters can be connected to read the total power in a three-phase system. There are also three-phase wattmeters that consider all phases and indicate the true power of the whole circuit.

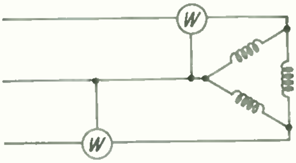


Fig. 10.50. Two single-phase wattmeters connected to read the power in a three-phase system.

**10.31 Three-phase Power Supplies.** When the three phases of three-phase a-c are plotted against time, they form the pattern shown in

Fig. 10.51. This can be resolved into three separate single-phase sine waves, separated by 120°. The heavy line indicates the resultant voltage or current when a three-phase a-c is half-wave-rectified. The pulse does not drop to zero at any time, making the waveform varying rather than pulsating d-c.

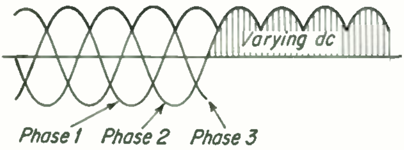


FIG. 10.51. Ripple from a half-wave-rectified three-phase Y output circuit.

A three-phase half-wave-rectified power-supply circuit is shown in Fig. 10.52. Note that the filament transformer is single-phase and may be taken from any one of the primary phases. The transformer connections are Δ-Y. This arrangement does not give the 1.73-voltage gain in the half-wave rectifier, since no two phases are in series across the load at any time.

A full-wave three-phase bridge-rectifier power-supply circuit is shown in Fig. 10.53. It requires four filament windings, not included in this diagram. The power transformers are connected Δ-Y. The neutral

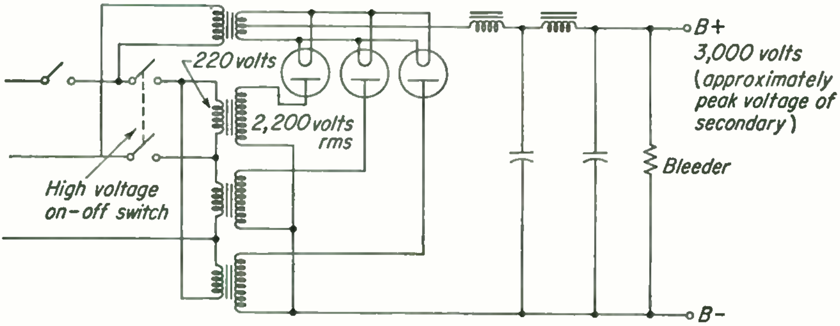


FIG. 10.52. Half-wave three-phase Y output power supply.

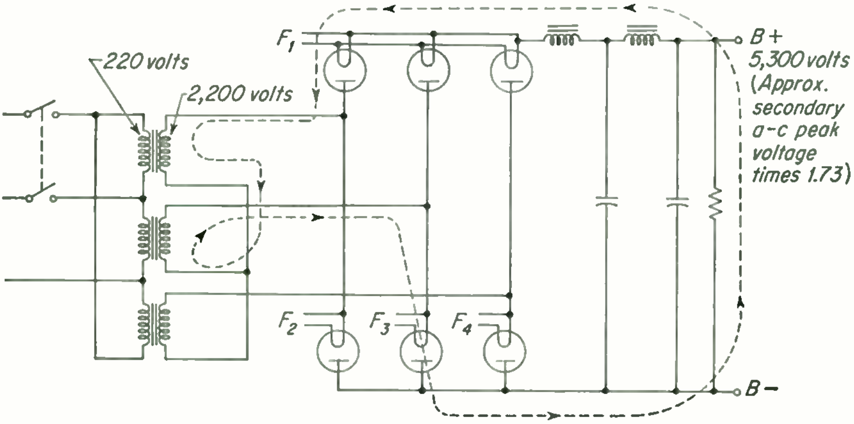


FIG. 10.53. Full-wave three-phase Y output power supply.

connection cannot be grounded if B− is. The dashed lines indicate one current path at one instant of maximum voltage in one phase. Two of the secondary windings are in series across the load. This results in a 1.73-voltage step-up over the turns ratio of the transformers used.

The waveform of full-wave-rectified three-phase a-c is shown by the heavy line in Fig. 10.54. Because of the small percentage of amplitude variation, this varying d-c is filtered adequately with relatively little capacitance and inductance.

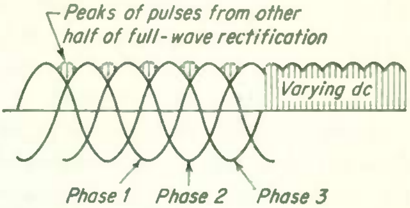


FIG. 10.54. Ripple from a full-wave-rectified three-phase Y output power supply.

**10.32 Indications of Power-supply Failure.** One of the important phases of an operator's duties is to be able to locate and repair failures in equipment when they occur, or are about to occur.

There are several indications of power-supply failures. Light gray wisps of smoke may curl up from under a chassis. Sparks may be seen in a rectifier tube. The hissing of an electric arc-over may be heard. Rectifier plates may turn red-hot. Mercury-vapor tubes may turn a brilliant blue-white. A faint purplish glow appears between filament and plate in a vacuum diode. Meters in associated equipment drop to zero or indicate excessive current. Transformers or chokes may hum ominously or start to smoke. Circuit breakers or overload relays may snap open. Fuses may burn out. In some cases, red lights may appear on panels; in others, alarm bells may ring.

Depending on the circumstances, the operator should immediately shut down all the equipment, *or* he should note the stages that indicate normal operation and then shut down the equipment and start looking for the trouble in the first stage that indicates improper operation.

In power supplies, tubes age and lose emission rather slowly, usually indicated by a slowly decreasing output current. However, it is also possible for a filament of a tube to burn out without warning. Vacuum tubes may become slightly gassy and develop a purplish glow between filament and plate even without excessive current flow through them. If the tube develops a rapid gas leak, it will suddenly turn milky, depositing a white oxide layer on the inside of the envelope. The filament will burn out immediately in this case. If the trouble is in a rectifier tube, it is unlikely that a fuse will burn out. Subnormal current in the associated equipment is the usual indication. Visual examination of the power supply may tell the operator which tube is at fault.

Smaller receiving-type rectifier tubes can be tested on a tube tester. Transmitting tubes can be tested by heating the filament of a good tube to a normal degree and connecting a d-c source, an ammeter, and a variable resistance in series with the plate-filament circuit of the tube. The resistance is adjusted until the maximum rated operating plate current flows through the tube. When a suspected tube is tested in place of the good tube, the plate current should be at least 80 per cent of that of the tube known to be good.

A short circuit in a power supply usually produces some of the more dramatic indications mentioned above (red plates, internal sparking in the tube, blown fuses). Such a short circuit may be produced when a filter capacitor *dielectric* arcs over and carbonizes. This results in a low resistance across the capacitor and a heavy current in the transformer-rectifier-filter circuit. Since chokes are usually installed in the positive-high-voltage lead with their cores and metal cases grounded, a short circuit to the core or case due to carbonization of the insulation on the wires will cause the same heavy current in the transformer-rectifier-filter circuit. A similar effect may be produced if the insulation of the filament-transformer winding breaks down. If the bleeder resistor shorts out, or if any of the positive terminal wiring touches the chassis, a short circuit results, with an accompanying high current and fireworks.

If any of the above-mentioned parts short to ground, an ohmmeter reading between ground and the positive terminal will read a very low resistance. If there is no short circuit, the ohmmeter reading should be the value of the bleeder resistor, usually between 10,000 and 40,000 ohms. (Be sure the equipment is off before using an ohmmeter for any tests.)

Sometimes a filter capacitor does not completely short out but develops a high resistance across it. It is said to have developed a *leak*. A leaking capacitor can be checked by connecting an ohmmeter across it. Any capacitor of 0.1 $\mu$f or more will produce a kick of the ohmmeter needle when first tested. This is the charging current flowing into the capacitor from the ohmmeter battery. If a paper capacitor registers less than about 10 meg after a second or two, it may be considered as leaking. An electrolytic will read low resistance the first instant it is tested, but should register more than 100,000 ohms after a few seconds. If an electrolytic capacitor is tested with the ohmmeter leads reversed, a different resistance value will usually be obtained. This is normal.

If one is available, a *capacitor checker* will give a reading of the capacitance, leakage, power factor, and whether the capacitor is open or shorted. This is obviously better than an ohmmeter test.

To test a capacitor alone in a power supply, one of its leads must be disconnected from the circuit and a meter connected across it, otherwise the whole filter circuit is being tested.

It is also possible that a short in the load circuit will produce the same symptoms in the power supply as a short in the power supply itself. Disconnecting the power supply from the load and checking both pieces of equipment with an ohmmeter will make it possible to localize the trouble more closely. If a B+ to ground reading across the load shows low resistance with the power supply disconnected, the short is in the load, not in the power supply.

Sometimes a turn or a few turns in the power transformer short together because of insulation breakdown. Heavy primary current will flow whether the shorted turns are in the primary or in the secondary, and fuses or overload relays will go out. Often the transformer will smoke. If it continues to heat or smoke with all parts disconnected from it, a new transformer is indicated.

If one-half of the secondary of a center-tapped transformer used in a full-wave rectification system burns out, the equipment may operate, but at reduced power, because of lower voltage output when the circuit operates as a half-wave power supply. A 60-cycle hum will usually be audible when the output of the equipment is checked.

If the tubes weaken or burn out, no heavy current flows in the power supply. However, if a short circuit occurs, dangerously high currents may flow. Sometimes the short circuit is an instantaneous one, caused by arcing across a moistened surface, or when an insect crawls between two points of high potential in the equipment. Sometimes a line surge can produce an overload that will burn out fuses or open-circuit breakers. Sometimes fuses themselves oxidize and burn out for no apparent reason. As a result, when a transmitter or receiver suddenly ceases operating and it is desirable that it be placed in operation as soon as possible, it may be expedient to replace the fuse, or close the circuit breaker and try momentarily turning on the equipment again. If there is nothing seriously wrong, the transmitter or receiver will operate normally. If not, the fuse or circuit breaker will go out again and it will be necessary to shut down to locate the trouble. In the first case, it would be well to examine the equipment closely for burns or signs of arcing the next time it is turned off, cleaning it thoroughly at the same time.

A possible and very dangerous fault in a power supply is the burning out of the bleeder resistor. When this happens the receiver or transmitter operates almost normally, but when the equipment is turned off, the filter capacitors may retain their high charge. Several minutes or hours later, personnel inadvertently touching the equipment during routine maintenance or cleaning may receive a lethal charge from the capacitors. After the equipment is turned off completely, the operator should *always* touch the positive terminals of all power supplies with a flexible wire that is fastened securely to ground at one end before servicing the equipment. If wire is not available, an insulated-handle screwdriver held across the filter-capacitor terminals will discharge such capacitors. The operator should make sure *he* is *not* grounded when he does this.

There have been occasions when radio equipment using a power transformer in the power supply has been plugged into a power line carrying

110 volts d-c instead of the required 110 volts a-c. Whereas the inductance of the primary limits the current flow with a-c, it has no opposition to d-c, and an excessively high current flows through the primary, burning out the primary or a fuse almost immediately.

The metallic shields and cores of power transformers and power-supply choke coils should be grounded to prevent them from picking up a static-electricity charge. Such a charge may be dangerous to personnel who might touch the equipment, or may add to voltages in the equipment and result in an arc-over and possible burnout of the equipment. Furthermore, such ungrounded equipment in transmitters may allow RF a-c to find its way into it and cause damage to internal insulation.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** List the comparative advantages and disadvantages of motor-generator and transformer-rectifier power supplies. (10.1) **[3]**

**2.** Explain the operation of a vacuum-tube-rectifier power supply and filter. (10.3, 10.9) **[3]**

**3.** What are the characteristics of a capacitor-input filter system as compared with a choke-input system? (10.8, 10.9) **[3]**

**4.** If the reluctance of an iron-core choke is increased by increasing the air gap of the magnetic path, in what other way does this affect the properties of the choke? (10.12) **[3]**

**5.** What is the effect upon a filter choke of a large value of d-c flow? (10.12, 10.13) **[3]**

**6.** What factors permit high-conduction currents in a hot-cathode type of mercury-vapor rectifier tube? (10.15) **[3]**

**7.** What effect does the resistance of filter chokes have on the regulation of a power supply in which they are used? (10.12, 10.24) **[3]**

**8.** What is the percentage regulation of a power supply with a no-load voltage output of 126.5 volts and a full-load voltage output of 115 volts? (10.24) **[3]**

**9.** Describe the theory of current conduction and rectification by means of cold-cathode, gassy-diode vacuum tubes. (10.25) **[3]**

**10.** What are the primary characteristics of a gas-filled rectifier tube? (10.15, 10.25) **[3]**

**11.** Draw a diagram of a synchronous-vibrator power supply. A nonsynchronous-vibrator power supply. (10.28) **[3]**

**12.** Describe the principle of operation of a synchronous type of mechanical rectifier. (10.28) **[3]**

**13.** May two capacitors of 500-volt operating voltage, one an electrolytic and the other a paper capacitor, be used successfully in series across a potential of 1,000 volts? Explain your answer. (10.29) **[3]**

**14.** When capacitors are connected in series so that the total operating voltage of the series connection is adequate for the output voltage of a filter system, what is the purpose of placing resistors of high value in shunt with each individual capacitor? (10.29) **[3]**

**15.** What is a desirable feature of an electrolytic capacitor as compared with other types? (10.29) **[3]**

**16.** In what circuits of a radio station are three-phase circuits sometimes employed? (10.30) **[3]**

**17.** What does a blue haze in the space between the filament and plate of a high-vacuum rectifier tube indicate? (10.32) **[3]**

**18.** If a high-vacuum-type, high-voltage rectifier tube should suddenly show severe internal sparking and then fail to operate, what elements of the rectifier filter system should be checked for possible failure before installing a new rectifier tube? (10.32) **[3]**

**19.** If the plate, or plates, of a rectifier tube suddenly became red-hot, what might be the cause, and how could remedies be effected? (10.32) **[3]**

**20.** What is the principal function of the filter in a power supply? (10.6) **[3 & 6]**

**21.** What is the principal function of a swinging choke in a filter system? (10.13) **[3 & 6]**

**22.** Compare the advantages and disadvantages of high-vacuum and hot-cathode mercury-vapor rectifier tubes. (10.14, 10.15, 10.17) **[3 & 6]**

**23.** List the main advantages of a full-wave rectifier as compared with a half-wave rectifier. (10.4, 10.8, 10.18, 10.24) **[3 & 6]**

**24.** Why is it desirable to have low-resistance filter chokes? (10.12, 10.24) **[3 & 6]**

**25.** What is the definition of voltage regulation as applied to power supplies? (10.24) **[3 & 6]**

**26.** What is the purpose(s) of a bleeder resistor as used in connection with power supplies? (10.23) **[3 & 6[**

**27.** When filter capacitors are connected in series, resistors of high value are often connected across the terminals of the individual capacitors. What is the purpose of this arrangement? (10.29) **[3 & 6]**

**28.** Draw a diagram of a rectifier system supplying two plate voltages, one approximately twice the other and using one high-voltage transformer with a single center-tapped secondary and such filament supplies as may be necessary. (10.5) **[4]**

**29.** How may a capacitor be added to a choke-input filter system to increase the full-load voltage? (10.9) **[4]**

**30.** Why is it important to maintain the operating temperature of mercury-vapor tubes within specified limits? (10.15) **[4]**

**31.** What is the value of voltage drop across the elements of a mercury-vapor rectifier tube under normal conducting conditions? (10.15) **[4]**

**32.** When mercury-vapor tubes are connected in parallel in a rectifier system, why are small resistors sometimes placed in series with the plate leads of the tubes? (10.15) **[4]**

**33.** How is the inverse peak voltage to which the tubes of a full-wave rectifier will be subject determined from the known secondary voltages of the power transformer? (10.16) **[4]**

**34.** What is meant by arc-back, or flash-back, in a rectifier tube? (10.15, 10.16) **[4]**

**35.** What is meant by the inverse-peak-voltage rating of a rectifier tube? (10.16) **[4]**

**36.** What is the predominant ripple frequency in the output of a single-phase full-wave rectifier when the primary source of power is 110 volts at 60 cycles? (10.18) **[4]**

**37.** Why is a time-delay relay arranged to apply the high voltage to anodes of mercury-vapor rectifier tubes sometime after the application of filament voltage? (10.19, 10.20) **[4]**

**38.** Draw a diagram of a bridge rectifier giving full-wave rectification without a center-tapped transformer. Indicate polarity of output terminals. (10.20) **[4]**

**39.** Draw a diagram of a voltage-doubling power supply using two half-wave rectifiers. (10.22) **[4]**

**40.** Why is it not advisable to operate a filter reactance in excess of its rated current value? (10.12, 10.24) **[4]**

**41.** If a power supply has an output voltage of 140 volts at no load and the regulation at full load is 15 per cent, what is the output voltage at full load? (10.24) [4]

**42.** If a power supply has a regulation of 11 per cent when the output voltage at full load is 240 volts, what is the output voltage at no load? (10.24) [4]

**43.** A rectifier-filter power supply is designed to furnish 500 volts at 60 ma to one circuit and 400 volts at 40 ma to another circuit. The bleeder current in the voltage divider is to be 15 ma. What value of resistance should be placed between the 500- and 400-volt taps of the voltage divider? (10.26) [4]

**44.** Draw a schematic wiring diagram of a three-phase transformer with Δ-connected primary and Y-connected secondary. (10.30) [4]

**45.** Three single-phase transformers, each with a ratio of 220:2,200 volts, are connected across a 220-volt three-phase line, primaries in delta. If the secondaries are connected in Y, what is the secondary-line voltage? (10.30) [4]

**46.** What system of connections for a three-phase three-transformer bank will provide maximum secondary voltage? (10.30, 10.31) [4]

**47.** What is the purpose of a choke coil? (10.7) [6]

**48.** What are the relative advantages of the capacitor-input and choke-input filter when used with rectifiers? (10.8, 10.9) [6]

**49.** What is the purpose of an air gap in the core of a filter choke coil? (10.12) [6]

**50.** What is the effect of loose laminations in a filter choke? (10.12) [6]

**51.** What action permits the high-conduction currents of a hot-cathode gas-filled rectifier tube? (10.15) [6]

**52.** Why are small resistors sometimes placed in series with each plate lead of mercury-vapor rectifier tubes connected in parallel? (10.15) [6]

**53.** What is the maximum allowable total secondary voltage of a transformer to be used as a center-tapped full-wave rectifier in connection with rectifier tubes having a peak-inverse-voltage rating of 10,000 volts? (10.16) [6]

**54.** What are the primary advantages of a high-vacuum rectifier as compared with the hot-cathode mercury-vapor rectifier? (10.17) [6]

**55.** What is the ratio of the frequencies of the output and input circuits of a single-phase full-wave rectifier? (10.18) [6]

**56.** Why should the temperature of the filament or heater in a mercury-vapor rectifier tube reach normal operating temperature before the plate voltage is applied? (10.15, 10.19) [6]

**57.** Indicate the approximate values of power-supply filter inductances encountered in practice. (10.8, 10.9, 10.12, 10.20) [6]

**58.** Draw a simple schematic circuit diagram of a rectifier and filter for supplying plate voltage to a radio receiver. (10.20) [6]

**59.** Why is a capacitor sometimes placed in series with the primary of a power transformer? (10.21) [6]

**60.** Draw a simple circuit diagram of a voltage-doubling power supply using two half-wave rectifiers. (10.22) [6]

**61.** What is meant by regulation of a power supply? What causes poor regulation? (10.24) [6]

**62.** What are the principal characteristics of a gas-filled rectifier tube? (10.15, 10.25) [6]

**63.** Draw a simple schematic diagram of a cold-cathode electron tube connected as a voltage regulator. As a rectifier. (10.25) [6]

**64.** Discuss the uses of copper oxide rectifiers. (10.27) [6]

**65.** What is the primary advantage to be obtained by shunting a high-resistance fixed resistor across each unit of a high-voltage series-capacitor bank in the power-supply filter circuit of a transmitter? (10.29) [6]

**66.** What precaution should be observed when connecting electrolytic capacitors in series? (10.29) **[6]**

**67.** Draw diagrams showing various ways by which three power transformers can be connected for operation on a three-phase circuit. Show how only two transformers can be connected for full operation on a three-phase circuit. (10.30) **[6]**

**68.** If part of the secondary winding of the power-supply transformer of a transmitter were accidentally shorted, what would be the immediate effect? (10.32) **[6]**

**69.** How may a filter capacitor be checked for leakage? (10.32) **[6]**

**70.** A radio receiver has a power transformer and rectifier designed to supply plate voltage to the vacuum tubes at 250 volts when operating from a 110-volt 60-cycle supply. What will be the effect if this transformer primary is connected to a 110-volt d-c source? (10.32) **[6]**

**71.** Why should the metallic case of a high-voltage transformer be grounded? (10.32) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**★1.** What is the purpose of a rectifier? (10.3)

**★2.** What is the purpose of a filter? (10.6)

**★3.** What is the purpose of a filter choke? (10.7)

**★4.** How can the hazard of electric shock from high-voltage capacitors remaining charged after the power supply is turned off be reduced? (10.32)

**5.** What are the relative output voltage and current capabilities of bridge and center-tapped full-wave rectifier systems using the same power transformer? (10.4)

**6.** What are the prime essentials of a good power-supply choke? (10.12)

**7.** What type of a filter choke maintains a substantially constant-voltage output with a varying load? (10.13)

**8.** What type of filter choke provides increased inductance with a decrease in current flowing through it? (10.13)

**9.** Draw a simple schematic diagram of a d-c plate supply utilizing a power transformer, full-wave rectifier system, bleeder, and a choke-input filter system. (10.15)

**10.** How can the noise, or hash, sometimes produced by mercury-vapor rectifier tubes and heard in local receivers be eliminated? (10.15)

**11.** What are the main advantages of mercury-vapor rectifier tubes over high-vacuum tubes having comparable filament ratings? (10.15)

**12.** How does the ripple frequency of a full-wave rectifier compare with the frequency of the source a-c? How does a half-wave rectifier compare? (10.18)

**13.** What are the inductance and capacitance values that might be suitable for a high-voltage power-supply filter system? (10.20)

**14.** Draw a simple schematic diagram of a d-c plate supply utilizing a power transformer, full-wave rectifier system, bleeder resistor, and capacitor-input filter system. (10.20)

**15.** What are two reasons why bleeder resistors are used in power supplies? (10.23)

**16.** If a filter capacitor in a power supply shorts out, what visible effect might be produced in the rectifier tube? (10.32)

**17.** What is the purpose of fusing the primary of a power-supply transformer? (10.32)

# CHAPTER 11

# MEASURING DEVICES

**11.1 Meters.** Meters, as used in radio and electronics, are instruments used to indicate current, voltage, power, resistance, frequency, decibels, volume units, watthours, ampere-hours, etc. Included in this discussion will be bridges used to measure resistance, inductance, and capacitance and the very important *oscilloscope*.

Since radio includes both a-c and d-c circuits, and since alternating and direct current behave differently, it has been found necessary to develop special meters for d-c and others for a-c. A few can be used on both, although there are limitations on their use.

It may be said that almost all meters in general use are current-type meters; that is, they depend upon a current of electrons flowing through them to move the indicator needle, or pointer, across the scale. The greater the current, the farther the needle moves. If the current ceases, the pointer will be pulled back to the zero reading by thin spiral springs attached to it.

Meters vary in size from the tiny 1-in. type used in portable equipment, through the more frequently found 2- to 4-in. *panel* meters, up to *switchboard* meters measuring as much as a foot across. The latter instruments are made for distant viewing, while the others are normally read at a distance of from 1 to 6 ft.

**11.2 D-C Meters.** Practically all the d-c meters used in commercial radio applications are of the same general type, known as the *moving-coil*, *galvanometer*, or *D'Arsonval* meter. This one type of meter can be used as a d-c ammeter, milliammeter, microammeter, voltmeter, or ohmmeter, and with rectifiers it will indicate alternating current and voltage.

The moving-coil meter is an electromagnetic device. It consists of the following essential parts:

1. A horseshoe-shaped permanent magnet
2. A round iron core between the magnet poles
3. A rotatable mechanism, which includes:
    - *a.* A lightweight coil
    - *b.* A pointer attached mechanically to the coil

  - *c.* Two delicate spiral springs to return the pointer to zero
  - *d.* Two precisely ground bearings

4. A calibrated paper or metal scale
5. A metal or bakelite case

A simplified drawing of the working parts of a moving-coil meter is shown in Fig. 11.1. The coil and pointer are shown away from their normal position in the circular slots between the magnet poles and the iron-core piece. The iron core does not rotate, but the coil assembly rotates in the spaces between the core and the magnet.

The distance between the magnet and the soft-iron core is only a few hundredths of an inch to reduce the reluctance of the path of the lines of force from north to south pole. This provides a stronger field in which the coil can move, reduces leakage lines of force from the magnet, and increases the sensitivity of the meter. It also decreases interaction between the lines of force and other outside magnetic fields that might tend to change the field strength of the horseshoe magnet.

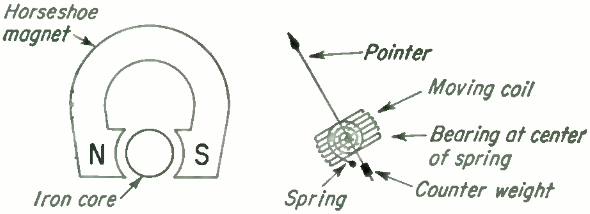


FIG. 11.1. Components of a D'Arsonval meter. The moving-coil assembly has been removed from its place between the magnet poles.

Each of the two spiral bronze springs is connected electrically to an end of the rotating coil. The other ends of the springs are attached mechanically to a point on the front or on the back of the coil assembly. Besides being used to *zero* the indicating needle, the springs provide the only path by which current is fed to and from the coil.

When a current of electrons flows through it, the coil becomes an electromagnet, with a north pole at one end and a south pole at the other. If the current is fed through it in such a direction as to develop an electromagnetic north pole at the upper end of the coil in the illustration, there will be a magnetic attraction between the top end of the coil and the south pole of the permanent magnet. At the same time the other end of the coil will have a south polarity and be attracted to the north pole of the magnet. This rotates the coil assembly and the pointer against the spring tension. If the current is small, the springs will not allow much rotation. The pointer and the coil assembly will rotate further, the greater the current flow.

Since the coil must be constructed of many turns of very fine wire, care must be taken never to feed an excessive current through it. The amount of current necessary for *full-scale* deflection of the pointer will not injure the coil, but a 100 per cent or greater overload may burn out the coil, or take the temper out of the springs or burn them out, or the very delicate aluminum needle may be bent if driven against the bumper usually placed past the ends of the calibrated scale.

When current through the coil ceases, the springs return the needle to the zero setting. Reversing the current through the coil moves the indicator needle backward, off the scale to the left. Connecting the meter so that the current is reversed will not necessarily cause damage, but in some of the more delicate meters it may bend the needle, particularly if the current is nearly the maximum rated value.

On most meters there is an adjustment screw brought out at the front of the meter. By rotating this screw, more or less torque, or twisting effort, can be placed on one of the centering springs. This provides a means of rotating the needle above or below the zero setting by a few degrees. With this adjustment the pointer can be accurately set to the zero point on the scale when no current is flowing through the meter. Once adjusted, the meter should not need readjustment.

Well-constructed and balanced meters will read the same whether held horizontally or vertically. Others, less accurately balanced, may require a zero readjustment if their operating position is changed. This can sometimes be corrected by adjusting the position of the counterweight shown in Fig. 11.1 to balance the coil and pointer assembly more accurately.

Meters are delicate instruments and must be handled gently. They should not be subjected to strong magnetic fields, since any change in the strength of the permanent magnet will result in erroneous readings. When treated properly, meters have been known to hold a satisfactory accuracy for sixty years or more.

Meters are made to be mounted on steel (iron) panels or on nonmagnetic panels (aluminum, bakelite, etc.). Those made to be mounted on nonmagnetic panels will have their permanent-magnet field strength affected if mounted on an iron panel and may not indicate accurately.

Most general-purpose meters are accurate to 2 per cent or better of their full-scale value. Meters are usually considered most accurate near the half-scale range. Many a-c meters are difficult to read below one-third scale.

There are other d-c meters operating on different electromagnetic principles, but they are not in wide use.

**11.3 Linear and Nonlinear Scales.** A moving-coil meter usually has good scale *linearity;* that is, if a current of 10 amp causes the pointer tip to move through an arc of 2 in., 5 amp will move the pointer tip through an arc of 1 in., 2½ amp will result in a ½-in. deflection, and so on.

Almost all other types of meters will have a nonlinear scale unless the parts are specially engineered to overcome this particular difficulty. Even then, the scale divisions near the zero value (on the left side of the scale) are usually crowded together and widen toward the higher values. Alternating-current and current-squared meters (explained later) are examples of such scales.

Figure 11.2 shows a possible linear meter scale and a possible nonlinear meter scale.

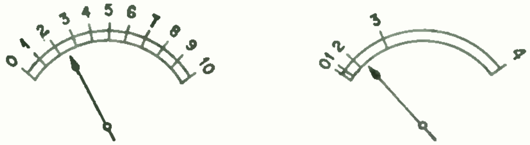


FIG. 11.2. Examples of a linear and a nonlinear (current-squared) meter scale.

**11.4 D-C Ammeters.** In most of the d-c meters calibrated to read in high values of current, a fairly sensitive instrument, a 0–1- to 0–10-ma meter, may be used. By placing a resistor across the meter, the current in the circuit is divided, part going through the meter and part going through the shunt resistor, as shown in Fig. 11.3.

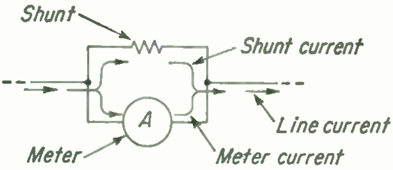


FIG. 11.3. Part of the line current flows through the shunt of an ammeter.

If a 0–1-ma-meter coil has 25 ohms resistance and a 25-ohm resistor is connected across it, half of any current flowing through this parallel circuit will pass through the meter and the other half will flow through the resistance. In this case, if 1 ma is flowing in the circuit, ½ ma flows through the meter. Only half as much electromagnetic effect will be developed in the meter coil, and only half deflection of the meter needle will result. The meter will read full deflection when 2 ma flows in the line. To make the meter read correctly, it will now be necessary to replace the 0–1-ma scale with a 0–2-ma scale.

By using the correct value of shunt resistance and scale calibration, it is possible to make a 0–1-ma meter read full-scale deflection with 50 ma, 500 ma, 1 amp, 10 amp, or any desired value above the 0–1-scale reading.

While the shunt resistor can be connected to the external contacts of the meter case, it is usually found inside the case. Meters are rarely changed in calibration in actual practice. The shunt is considered as an integral part of the meter and is not indicated in diagrams unless it is externally connected.

Ammeters (ampere reading meters) are always connected in series with one of the current-carrying wires of a circuit, as shown in Fig. 11.4. The meter indicates how much current is passing through that particular point in the circuit.

In a parallel circuit, one ammeter can be used to measure the total line current, or ammeters can be inserted in the parallel branches, as shown in Fig. 11.5. The sum of the parallel branches will always be the same as the line-current value.

Most metals heat when current passes through them, and their resistance values increase. To retain accuracy in an ammeter it is necessary to use metal shunts that will not change their resistance under a change in temperature. Special metal alloys are available that have an almost *zero-temperature coefficient of resistance* (variations of temperature have zero effect on the resistance of the metal). One such common alloy is constantan; another is manganin.

If the current flowing is more than the full-scale value of the ammeter connected in the circuit, it is possible to connect another ammeter in parallel with the first. The circuit current will be the sum of the two readings. The readings may not be equal if the sensitivity of the meters is not the same.

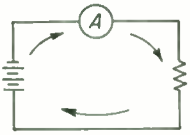


FIG. 11.4. An ammeter is connected in series with the line.

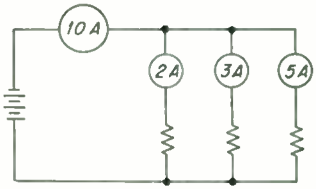


FIG. 11.5. Placement of an ammeter to read the total current of three branches.

If the accuracy of the ammeters on hand is not known, a fairly accurate assumed value can be obtained by connecting two ammeters in series and taking the average of the two readings. If they are both accurate, they should both read the same current, regardless of their sensitivity.

**11.5 Computing Shunt Resistances.** If a 0–1-ma (0–0.001 amp) meter is available, it is possible to convert it to a 0–10- or 0–100-ma reading meter merely by connecting a shunt resistor across it.

*Example:* It is desired to make a 0–1-ma meter with 25 ohms internal resistance read 0–10 ma full-scale. The shunt will have to carry 0.009 amp, and the meter 0.001 amp. Being in parallel, the meter and the shunt will have the same voltage across them. The current in any leg of a parallel circuit is inversely proportional to the resistance. Therefore, $\frac{1}{9}$ of 25 ohms will be required for the shunt, or 2.78 ohms. Whatever the meter reads must now be multiplied by 10. A reading of 0.6 on the meter indicates 6 ma flowing in the circuit.

If the meter is to be used as a 1–100 milliammeter, the shunt must be $\frac{1}{99}$ of 25 ohms, or 0.253 ohm. The scale reading must now be multiplied by 100. A reading of 0.74 indicates 74 ma.

Ammeters have a very low resistance value and must not be connected across a source of potential or an excessive current may flow through them.

It is possible to determine the current in a circuit if a meter is connected across a resistance in series with the circuit.

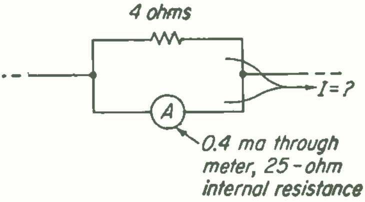


FIG. 11.6

*Example:* If a 25-ohm 0–0.001-amp meter is connected across a 4-ohm resistor in a circuit (Fig. 11.6) and it reads 0.0004 amp, the total current in the line can be determined by Ohm's law. The voltage drop across the meter (and the 4-ohm shunt) is equal to $E = IR$ or 0.0004(25), or 0.01 volt. The current through the shunt is equal to $I = E/R$, or 0.01/4, or 0.0025 amp. The shunt current is 0.0025, and the meter current is 0.0004, giving a total of 0.0029 amp or 2.9 ma, as the line current.

**11.6 Sensitivity.** The word *sensitivity* is often used when speaking of meters. A sensitive meter is one that requires very little current to produce full-scale deflection of the pointer. A meter that will swing to full scale when 1 ma of current flows through it is more sensitive than a meter that requires 2 ma to produce full-scale deflection.

If anything is done to a meter that makes it necessary to use more than normal current to obtain full-scale deflection (by shunting a resistor across it, for example), it is said to be desensitized, or less sensitive. Actually, shunting a resistor across a meter may make the meter operate as if it were less sensitive, but the movement sensitivity, the coil assembly, and the magnet's ability to produce full-scale deflection with a given current have not been changed.

The movement sensitivity of meters found in radio equipment and testing apparatus varies widely. Some of the more common d-c meters have sensitivities of 0–50 μa, 0–200 μa, 0–500 μa, 0–1 ma, 0–5 ma, and 0–10 ma, to mention a few.

Another means of expressing the sensitivity of a meter is in *ohms per volt*, discussed in Sec. 11.9.

**11.7 Damping.** Meters with no shunt resistors across them sometimes have very lively moving pointers. Those with very-low-resistance shunts may have slower-moving pointers. This slowing of the pointer movement is known as *damping*. Some damping is desired in most meters to prevent the pointer from oscillating back and forth when the current through the meter is changed a little. If a current is suddenly fed through a meter and the pointer moves up past the correct reading, the meter is less than *critically damped*. If it comes to the correct reading rapidly but does not overshoot, it is critically damped. If overly damped, it will rise slowly and will not indicate short pulse peaks adequately.

Damping can be produced electromagnetically. In ammeters, the coil is usually across the low-resistance shunt of the meter. This amounts to almost a dead short across the coil. When current flows through the coil, it is driven across the lines of force of the magnet and an emf is developed in it. This induced voltage will always be in a direction opposite to the direction of the current that produced the motion. The counter emf bucks the current flow through the meter coil, preventing the coil and pointer from swinging upward as rapidly as they normally might. The meter is damped in both upward and downward motions. The lower the resistance of the shunt, the greater the damping effect produced.

Damping is also produced by using an aluminum form for the moving coil. The metal form acts as a shorted turn. When the coil moves in the magnetic field, it induces a current in the shorted turn, setting up a counter field that tends to oppose the movement of the coil and the shorted turn.

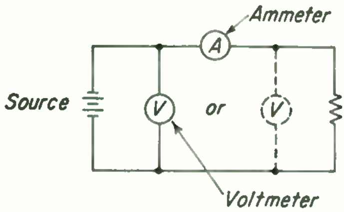


FIG. 11.7. A voltmeter is connected across the source (or load).

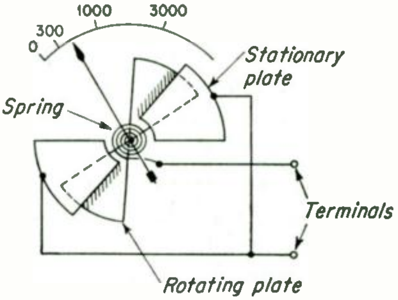


FIG. 11.8. Electrostatic voltmeter. When charged oppositely, the plates pull together and move the pointer.

A third method of producing damping utilizes small aluminum paddles attached to the coil assembly. The motion of the paddles through an enclosed air chamber prevents rapid rotation of the coil and pointer.

**11.8 The Electrostatic Voltmeter.** A voltmeter is an instrument that will indicate the difference of potential across a circuit, battery, generator, power supply, etc. It is always connected *across* the difference of potential, as shown in Fig. 11.7. Note the difference in connecting an ammeter and a voltmeter in a circuit. The ammeter is in *series* with the circuit; the voltmeter is *across* the circuit.

It might be said that the only real emf-indicating instruments are the oscilloscope (discussed later) and the electrostatic voltmeter. The electrostatic voltmeter is constructed in the form of a variable capacitor (condenser) with a pair of stationary metal plates and a pair of light, balanced metal plates that rotate on their central axis, as indicated in Fig. 11.8. A pointer is attached to the rotating plates. A delicate spiral spring returns the pointer to the zero point on the scale when no voltage is across the meter.

When the terminals connected to the two sets of plates of the meter are connected across a positive and negative source of voltage, the positive and negative charged plates will be attracted toward each other. The rotating plates will swing toward the stationary plates, overcoming the tension of the spring, and rotate the pointer across the scale.

Electrostatic voltmeters can be used to measure d-c or a-c emf values from about 100 volts to several thousand volts. The scale is not linear at the lower voltage readings, but can be made reasonably linear at the higher-scale readings by shaping the plates or by varying the spacing between the two sets of plates. These meters can be used to measure cathode-ray-tube anode voltages, or other high-potential circuit voltages, particularly when little or no current drain on the circuit is required. The electrostatic voltmeter requires no power or current flow *through* it to produce deflection, although it does require electrons as an initial charging current. When used to measure a-c, its capacitive reactance results in an apparent alternating current, although no electrons actually flow *through* the meter.

The electrostatic voltmeter is rare in radio, being confined to laboratory measurements.

**11.9 D-C Voltmeters.** The usual d-c voltmeter is composed of a sensitive moving-coil milliammeter with a resistance in *series* with the meter. Notice that the d-c ammeter usually has a low-value *shunt* resistor, while the voltmeter has a high-value *series* resistor. The series resistor, called the *multiplier*, is normally installed inside the voltmeter case, although in high-voltage and some laboratory meters the multipliers may be externally connected.

A common type of meter used in voltmeters is a 0–1-ma meter. It may have an internal resistance of about 25 ohms. If this meter is connected across a 100-volt d-c source, according to Ohm's law the current through it will be $I = E/R$, or 100/25, or 4 amp. Since the moving coil is wound for a maximum current of 0.001 amp, it will promptly burn out if connected across 100 volts. To limit the current to 0.001 amp, or 1 ma, the meter must have a resistance in series with it of $R = E/I$, or 100/0.001, or 100,000 ohms. The meter has approximately 25 ohms resistance in the coil. To this must be added 99,975 ohms (nominally 100,000 ohms). Such a meter with this value of resistance connected in series with it will give full-scale deflection when across 100 volts, half-scale deflection when across 50 volts, quarter-scale deflection when across 25 volts, and so on.

If it takes 100 volts to produce a full-scale deflection with 100,000 ohms, it will take 200 volts to produce full-scale deflection if the meter has 200,000 ohms internal multiplier resistance. For this reason, a 0–1-ma meter is said to have a sensitivity of *1,000 ohms per volt.* A 0–50-$\mu$a meter (0.00005 amp), being twenty times as sensitive as a 0–1-ma meter, has a sensitivity of *20,000 ohms per volt.* Since the resistance of the moving coil of the meter is such a small percentage of the total multiplier-resistance value, it may usually be disregarded. To produce a 0–150-volt meter, a 0–1-ma meter with 150,000 ohms resistance can be used, or a 0–50-$\mu$a meter with 3 million ohms as the multiplier resistance might be used.

When it is desired to measure the voltage across a circuit that is known to be more than the full-scale voltage of any of the meters on hand, it is possible to connect two voltmeters in series. The sum of the two voltage readings shown will be the voltage across the circuit. The readings may not be equal if the sensitivity of the meters is not exactly the same. This does not affect the accuracy of the readings. Each meter is actually indicating the voltage drop existing across itself.

If the accuracy of the voltmeters on hand is not known, two voltmeters can be connected in parallel across the circuit. The average of the two readings should produce a fairly accurate value. (In high-resistance circuits the addition of voltmeters can change the voltage across the line.)

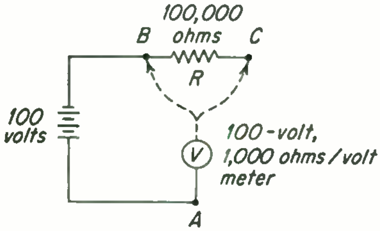


FIG. 11.9. Voltmeter reads 100 volts between $A$ and $B$, but only 50 volts between $A$ and $C$.

**11.10 Voltmeters in High-resistance Circuits.** A low-sensitivity meter may give correct readings when measuring circuits having low resistance values, but may give very inaccurate indications when used to measure voltages in high-resistance circuits. For example, consider the circuit shown in Fig. 11.9:

When a 0–100-volt 1,000 ohms/volt meter is connected across the source of emf, $A$ to $B$, it will read 100 volts. Since there is no current flowing through the 100,000-ohm resistance $R$, there is no voltage drop across it and there must be 100 volts between points $A$ and $C$. However, if the meter is now connected between points $A$ and $C$, the meter will indicate only 50 volts. In this case, current is flowing through the 100,000-ohm resistor $R$ and through the meter with its multiplier resistance of 100,000 ohms. With a source voltage of 100 across the total 200,000 ohms resistance, the current will be ½ ma ($I = E/R$, or 100/200,000, or 0.0005 amp). This value of current will make the meter read only half-scale. The meter is actually reading the correct voltage across its terminals. There is now a 50-volt drop across resistor $R$. As soon as the meter is disconnected, the voltage across points $A$ and $C$ rises to 100 volts again.

If a 100-volt 20,000 ohms/volt meter is substituted for the 1,000 ohms/volt meter in the same circuit, it will give a different reading. Across points $A$ and $B$ it will show 100 volts, as did the first meter, but when connected across points $A$ and $C$, it will read more nearly the actual voltage that exists across these points when there is no meter connected between them. The multiplier resistance of this 100-volt meter is 2 million ohms. The multiplier plus the resistance $R$ have a total of 2,100,000 ohms. Across this series combination of resistances is 100 volts. The current through the combination is found by using the formula $I = E/R$, or 100/2,100,000, or 0.0000476 amp. This is 47.6 $\mu$a. The meter, being a 50-$\mu$a meter, will read 47.6/50 of 100 volts, or 95.2 volts, an error of only about 5 per cent.

It can be seen that the more sensitive the meter used, the more accurate the voltage readings will be when high-resistance circuits are being measured. In radio there are many such high-resistance circuits. Two of the most commonly found are the automatic-volume-control (AVC) circuit in receivers and plate circuits of resistance-coupled amplifiers. It is possible that even the 20,000-ohms/volt meter might not give accurate enough readings in such circuits. It may be necessary to use a vacuum-tube voltmeter.

**11.11 Ohmmeters.** A standard piece of test equipment used in radio and electronics is an ohmmeter. With this meter it is possible to read directly the value of a resistor, the amount of resistance in a coil, the value of resistance in a circuit, and make continuity tests on filaments of vacuum tubes, capacitors, transformers, or entire circuits.

The ohmmeter can be a relatively simple piece of equipment, composed of a moving-coil meter, a low-voltage battery (usually 3 volts), a fixed resistor, $R_1$, and a rheostat, $R_2$, connected as shown in the diagram in Fig. 11.10.

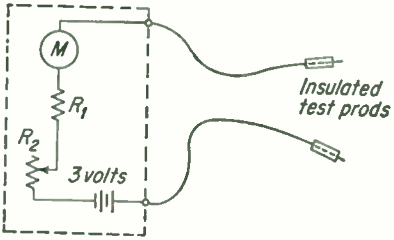


FIG. 11.10. Components of a simple ohmmeter.

The meter plus the two resistors $R_1$ and $R_2$ form a 3-volt voltmeter. When the two test prods are held together, the meter is connected across the battery and reads full-scale. The prods touching each other represent a zero resistance connection. Therefore this point is marked "0 ohms" on the meter scale. The zero-ohms point is on the *far right* end of the scale.

If the meter is a 0–1-ma meter with negligible resistance, the total of $R_1$ and $R_2$ will equal 3,000 ohms. If the prods are touched across a 3,000-ohm resistor, there are 6,000 ohms in the circuit and the current is ½ ma. The meter deflects to a half-scale reading. If the prods are held across 1,000 ohms, the total resistance in the circuit is 4,000 ohms and the meter will deflect to three-quarter scale. This can be computed by using the formula

$$D = \frac{R_m}{R_m + R_x} (100)$$

where $D$ is the percentage of deflection; $R_m$ is the resistance of the multiplier; and $R_x$ is the resistance of the unknown resistance.

If a 60,000-ohm resistance is measured, the meter deflects only one-twentieth of the full scale. The resistance values crowd together at the high-resistance end, with infinite resistance being equal to the zero-deflection setting, as indicated in Fig. 11.11. As a result, this particular meter will not read values above about 60,000 ohms accurately, nor will it give satisfactory readings of resistances under 100 ohms.

The rheostat, $R_2$, is made variable to compensate for battery aging. The dry cells that are normally used have about 1.5 volts each when new, but will drop in voltage to about 1.3 volts as they age. As a result, it is necessary to hold the test prods together and adjust the rheostat until the meter reads exactly zero ohms before taking a resistance reading. This calibration correction assures correct resistance readings with the ohmmeter.

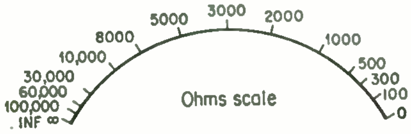


FIG. 11.11. Ohmmeter scale, zero ohms at one end, infinite ohms at the other.

A more adequate type of ohmmeter than the simple one explained is shown in Fig. 11.12.

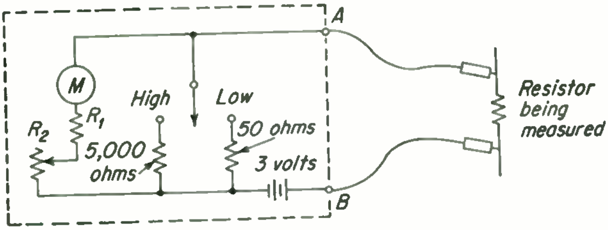


FIG. 11.12. Components of a multirange ohmmeter.

The meter and resistors $R_1$ and $R_2$ form a 3-volt meter as before. Test prods are connected to terminals $A$ and $B$. When the prods are held together, the voltmeter is across the 3-volt battery and the rheostat $R_2$ is adjusted to an accurate zero-ohms setting. If the "high-low" switch is in the low position, a 50-ohm resistance across the prods will produce a voltage-divider circuit and the meter will be across only 1.5 volts and will read half-scale. Fairly accurate readings can be obtained from zero to about 500 ohms with this setting. If the switch is in the high position, a 5,000-ohm resistance across the prods will give approximately half-scale deflection. Reasonably accurate readings can be expected up to about 100,000 ohms.

By using a 50-$\mu$a meter instead of the 0–1-ma meter and several values of calibrating resistors instead of only two, fairly accurate readings can be obtained from a few ohms to a million ohms or more.

CAUTION: The current through an ohmmeter of this type, particularly on the low-resistance settings, may be several hundred milliamperes. Milliammeters, microammeters, transistors, germanium diodes, or circuits which will not stand this much current through them *must not be measured or tested with an ohmmeter.*

CAUTION: When using an ohmmeter of any type, it is essential that the circuit being tested have no current flowing in it. If the circuit is not completely dead, the sensitive meter in the ohmmeter may be burned out by inadvertently connecting the ohmmeter across a relatively high voltage.

**11.12 Volt-Ohm-Milliammeters.** A handy piece of equipment for the radio or electronics man is a *volt-ohm-milliammeter* (VOM). This is usually a relatively sensitive d-c meter in a small box with a battery, switch, and several terminals. If connection is made across the proper terminals and the switch is set to the desired position, the single meter can be used as a voltmeter, an ohmmeter, or a milliammeter. The meter face will be marked with three separate scales. Figure 11.13 shows a simple VOM circuit.

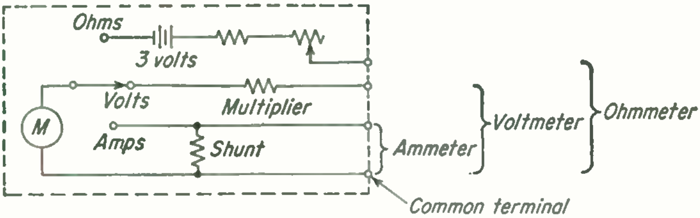


FIG. 11.13. Basic essentials of a simple volt-ohm milliammeter.

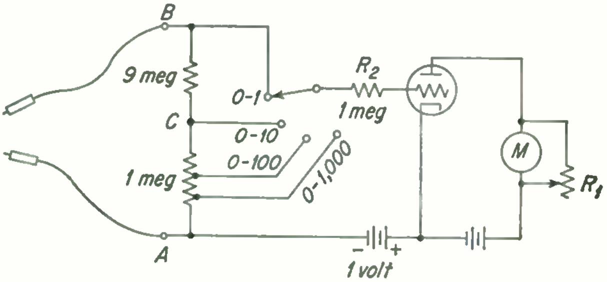


FIG. 11.14. Simple vacuum-tube voltmeter.

Many volt-ohm-milliammeters incorporate copper-oxide rectifiers to enable them to indicate a-c voltages. There will be a separate *a-c volts* scale on the face of the meter. There are usually three or four voltmeter ranges that can be selected, three or four milliammeter or ammeter ranges, and one or more ohmmeter ranges.

**11.13 D-C Vacuum-tube Voltmeters.** A voltmeter that may load a high-resistance circuit even less than the 20,000 ohms/volt meter does is the *vacuum-tube voltmeter* (VTVM). It utilizes the fact that a small variation in grid voltage can produce a relatively large variation of the plate current.

The simplest type of a VTVM is shown in Fig. 11.14. It consists of a high-$\mu$ triode with a 0–1-ma meter in the plate circuit. Any positive voltage connected to the grid across the input terminals *A* and *B* is in series with the 1-volt grid bias and will make the plate current increase.

If a 1-volt positive charge is placed across the input terminals $A$ and $B$, the grid bias will be neutralized and the plate current will increase to several milliamperes. If the shunt resistance across the meter is adjusted until the meter reads full-scale deflection, the meter can be calibrated to read from zero up to 1 volt at full deflection. Unfortunately, because of the bend in the $E_gI_p$ curve of a tube, the lower-scale indications will be crowded together, resulting in nonlinearity at the low-voltage end. The top three-quarters of the scale will be relatively linear, however.

The resistor $R_2$ prevents excessive current flow through the meter. If the voltage applied to the grid is greater than the 1-volt bias, the grid will draw current, producing a voltage drop across $R_2$, which maintains the grid-to-cathode voltage at essentially 1 volt. Therefore, if the meter is inadvertently connected across a high voltage, the meter will not be damaged, as it would be in a voltmeter using a D'Arsonval meter and multiplier resistances.

If the resistance between the bias battery and point $B$ is 10 meg, the meter sensitivity is 10,000,000 ohms/volt. This is 500 times better than the sensitivity of a 20,000-ohms/volt meter at 1 volt and 10,000 times better than that of a 1,000-ohms/volt meter.

To change from a 0–1-volt to a 0–10-volt meter, the 10-meg input resistance is tapped to form a 9- and 1-meg resistance, forming a voltage divider in the grid circuit, as shown. The grid is connected to the 1-meg resistor, and the meter now deflects to full scale when 10 volts is applied to the terminals $A$ and $B$. The meter face can carry a double calibration, one from 0 to 1 volt, and the other from 0 to 10 volts. The operator must note the voltage range being used to know which scale to read. The sensitivity of the meter is now 1,000,000 ohms/volt. If the 1-meg resistance is also made into a voltage divider, the meter can be made into a 0–100-volt meter. The sensitivity is then 100,000 ohms/volt. If the meter is made into a 0–1,000-volt meter the sensitivity will be only 10,000 ohms/volt, which is less than the 20,000 ohms/volt of a 50-$\mu$a meter used as a voltmeter. Above 500 volts it may be better to use a standard 20,000/ohm/volt meter unless the VTVM has special high-voltage circuits built into it. (Note that the VTVM *input impedance* is constant at 10,000,000 ohms on all ranges.)

Most modern VTVMs use two tubes in a balanced circuit similar to the diagram shown in Fig. 11.15. Triodes are shown for simplicity, although pentodes may be used. Some meters use twin-triode d-c amplifiers ahead of twin triodes in the balanced circuit, to produce greater sensitivity.

In the simplified circuit shown, if no voltage is being applied to the input terminals, the grids of both tubes are at the B− potential. Both tubes are conducting, the current through $R_1$ and $R_2$ should be equal, and the voltage drop across each should be the same. The meter is therefore connected across two points having no difference in potential (both plates are the same number of volts below the B+ value), and no current flows through the meter.

When a positive voltage is applied to the input circuit, the grid of VT-1 becomes less negative. Plate current through VT-1, $R_1$, and $R_3$ increases, increasing the voltage drop across $R_1$ and $R_3$. The increase in voltage across $R_3$ increases the bias on VT-2, and the plate current for this tube decreases, decreasing the voltage drop across $R_2$. The meter is now connected across a voltage drop. If the voltage drop across $R_1$ and $R_2$ was 10 volts with no input, now there may be 11 volts across $R_1$ and 9 volts across $R_2$. The meter is across a 2-volt differential, and current flows through it, making it deflect. The resistor in series with the meter is used to calibrate the meter when new tubes are installed. When the meter is once calibrated correctly, this control need not be adjusted again.

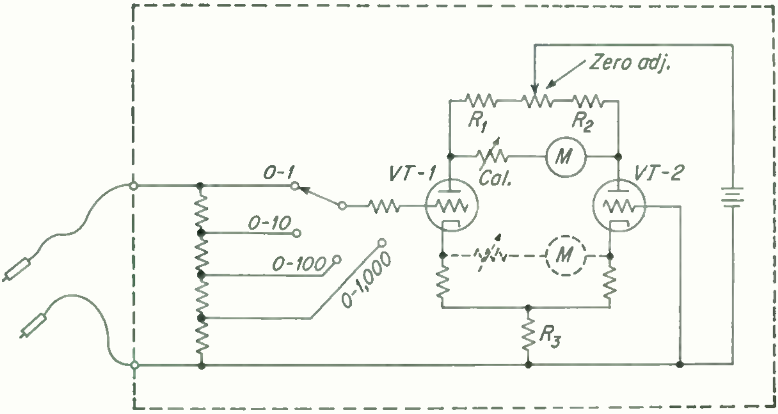


FIG. 11.15. A VTVM using a balanced tube circuit.

If the voltage drop across $R_1$ and $R_2$ is not exactly the same with no voltage applied to the input terminals, the "zero adjust" potentiometer, always mounted on the front panel, can be adjusted to compensate for this error and bring the indicator exactly to the zero mark on the scale of the meter.

The advantage of using two balanced tubes is that both are operating with plate current flowing at all times. This allows operation on the straight portion of the $E_gI_p$ curve, and linear-scale indications are possible. Furthermore, the cathode resistors produce a degenerative effect that further flattens any tendency toward nonlinearity.

In some VTVM circuits, the meter may be connected between the two cathodes, as indicated by the dotted lines in the diagram. The theory of operation is essentially the same.

The voltmeter probe of some meters has a 1-meg resistor at the tip. This allows the meter to be used on d-c circuits that are also carrying RF or AF a-c signals, without detuning the circuits or preventing them from operating normally.

Note that the VTVM ohmmeter scale reads zero ohms at the left side of the scale and infinite resistance at the right side. This is opposite from the ohmmeters previously explained.

An advantage when using a VTVM is the ability to measure d-c voltages without regard to polarity. On the front panel of a VTVM is a polarity-reversing switch. It reverses the connections of the indicator meter in its circuit, as shown in Fig. 11.16. If the VTVM reads backward during a test, it is only necessary to reverse the polarity of the meter by throwing the polarity-reversing switch. If operating correctly, the meter is as accurate one way as the other.

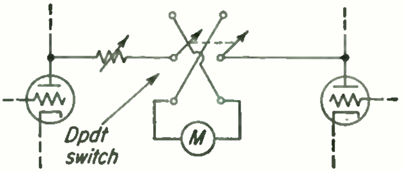


FIG. 11.16. Double-pole double-throw polarity-reversing switch for a VTVM.

A vacuum-tube voltmeter usually has a switch that allows the meter to function as an ohmmeter, and the meter face carries a special scale calibrated in ohms. When set to read resistance, a battery and two (or more) calibrating resistors, $R_a$ and $R_b$, are connected as shown in Fig. 11.17. As soon as the switch is thrown to the "ohms" position, the meter swings to full deflection, being connected across the battery ($R_a$ and $R_b$ have relatively little resistance in comparison with the input resistance of the VTVM). If the probes are held together, the pointer drops back to a zero reading. If the resistance range switch connects $R_a$ in the circuit, when a resistance equal in value to $R_a$ is connected across the probes, as shown, the pointer indicates half-scale. This is similar to the functioning of the previously explained ohmmeters.

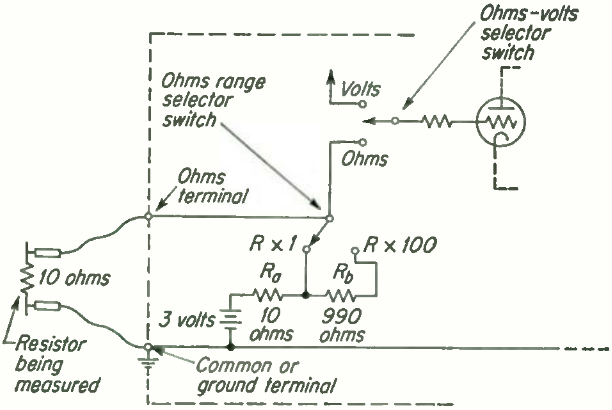


FIG. 11.17. Ohmmeter connections for a VTVM.

**11.14 A-C Vacuum-tube Voltmeters.** Most of the modern VTVMs will measure d-c voltages up to 1,000 volts or more, resistance from 1 ohm to possibly 1,000 meg, and a-c voltage up to about 1,000 volts. In some cases the a-c measurements merely use the sensitive meter in the VTVM in conjunction with a copper-oxide rectifier and the required multiplier resistances. They do not use the vacuum tubes at all. This results in a meter that will not respond accurately to a-c voltages above the AF range (about 15,000 cycles). Other meters utilize the VTVM and have diode-tube rectifiers *inside* the a-c voltage probe. These meters will satisfactorily measure RF a-c voltages up into the UHF range (300 to 3,000 Mc). It is this latter type that will be discussed.

At first thought, it would seem that a single-diode tube could be used to rectify the a-c being measured. The half-wave-rectified pulses could be filtered with a resistance and capacitance filter, as shown in Fig. 11.18, and the resulting d-c across it could be measured by the d-c VTVM. Essentially this is correct. However, as soon as the cathode of the probe diode is heated, electrons flow to the plate, forming a *contact potential* on the plate. This voltage is also read by the VTVM, making it impossible to obtain a zero-voltage reading on the meter.

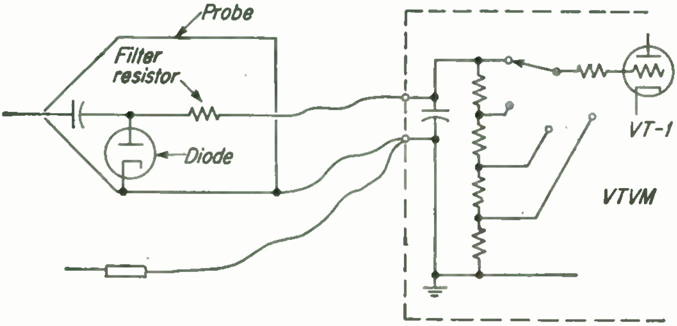


FIG. 11.18. A VTVM a-c probe subject to contact potential error.

By using twin diodes, one to provide the rectified a-c voltage to be read by the VTVM and the other to produce an equal value of contact potential to be applied to the other VTVM tube grid, it is possible to balance out the contact-potential indication. The contact potential of one tube equals the contact potential fed to the other tube, resulting in an equal decrease in both plate currents. This allows the meter to be brought to a zero reading with no voltage applied. The diagram in Fig. 11.19 illustrates a twin-diode voltmeter probe connected to a VTVM. Not shown, but required, are filament or heater leads to the diode and a shield around the probe-to-VTVM leads.

A VTVM having an a-c voltage function usually has a separate scale for the a-c voltages, calibrated in effective values. The probe-to-ground capacitance varies in different meters from about 3 to 10 μμf. When measuring tuned circuits they may be detuned slightly because of this capacitance. The input impedance is approximately the same as when the meter is used to measure d-c voltages.

Some a-c voltage probes contain germanium diodes. These tiny rectifying units can be used for practically any frequency, but are limited to about 100 volts. They have exceptionally low probe-to-ground capacitance, between 1 and 3 μμf, and require no filament wires in the probe leads.

**11.15 A-C Meters.** The D'Arsonval, or moving-coil, meter will deflect one direction or the other depending on the direction of the current flowing through it. With a one-cycle a-c, it will swing back and forth at a one-cycle rate. With 10-cycle a-c, it may attempt to swing back and forth 10 times a second, but because of damping and inertia, the pointer cannot move fast enough and will only vibrate a little above and below the zero reading. With any frequency higher than about 20 cycles, the needle will not move at all. It is possible to increase the a-c current through such a meter until the meter burns out and still have no deflection or indication at any time. Thus, the D'Arsonval meter alone is not suitable for a-c-circuit operation.

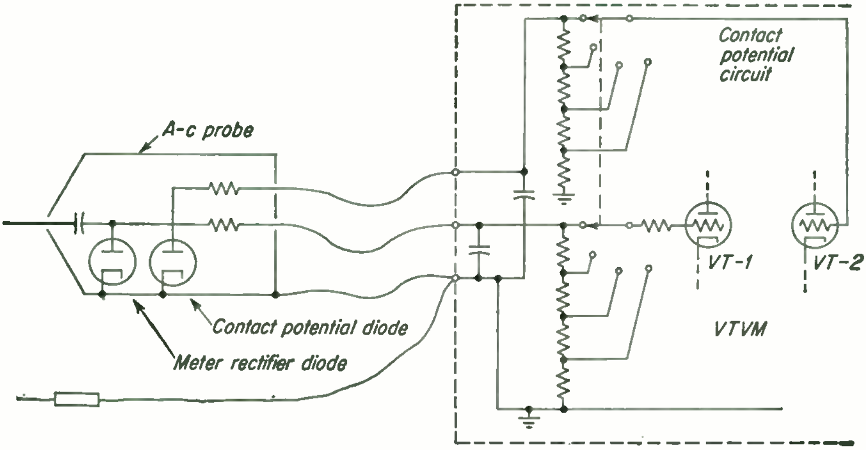


FIG. 11.19. A VTVM a-c probe with a contact-potential-canceling diode.

As previously mentioned, the electrostatic meter will give an indication with either d-c or a-c. The a-c indication given is the effective value, or 0.707 of maximum, *if the waveform is sinusoidal.*

**11.16 The Rectifier Meter.** In radio and electronic circuits, where the frequency involved is not above the audible frequency range (20,000 cycles), a moving-coil meter with a bridge rectifier is possibly the most frequently used. Four selenium or copper-oxide rectifiers are connected in a full-wave bridge-rectifying circuit to form an a-c voltmeter, as shown in Fig. 11.20. The bridge rectifier converts a-c into pulsating d-c. This current produces the same value of deflection regardless of frequency, within the audible limits above.

It is standard practice to calibrate the face scale of all a-c meters in effective values. Therefore the peak voltage value of sine wave a-c is always the meter reading times 1.414.

The rotation of the moving coil in a d-c meter is always proportional to the *average* value of the current or voltage being measured. When the voltmeter is connected across a 6.3-volt battery, the meter shows a reading of 6.3 volts. If a 2-volt peak a-c is added in series with the 6.3 volts d-c, the voltage varies from 4.3 to 8.3 volts alternately but the *average* is still 6.3. This is the value the meter will indicate. Therefore, whether a 2-volt a-c is added or not, the meter reads 6.3 volts.

As previously explained in the chapter on Alternating Current, the effective value of a sine-wave cycle of a-c is 0.707 of the peak value. The average value is 0.636 of the peak. To convert from the effective value to the peak value, the multiplying factor 1.414 (reciprocal of 0.707) is used. To convert from average to peak, the factor 1.57 is used.

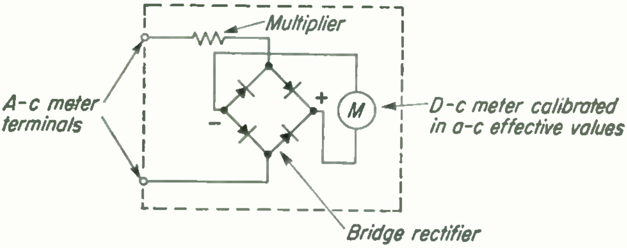


FIG. 11.20. Components of a rectifier-type a-c voltmeter.

If a 10-volt *d-c* meter is to be used to read *a-c* voltage by using a full-wave bridge rectifier, an indication of 10 volts on the *d-c scale* will actually be the average value of the d-c pulses flowing through it, or 0.636 of some peak voltage value. To find the peak value when the average is known, the multiplying factor 1.57 is used: 1.57 × 10 volts = 15.7 volts. Therefore the 10-volt d-c scale reading indicates 15.7 volts peak a-c. The effective value of 15.7 volts peak is 0.707 of it, or 11.1 volts. This is 1.11 times the average 10-volt value shown on the meter. Thus, when using a d-c meter to measure a-c using a full-wave rectifier, the d-c scale reading must be multiplied by 1.11 for the effective a-c value.

If a half-wave rectifier is used, the average value is half of the full-wave value of 0.636, or 0.318. Now a 10-volt reading on the meter indicates a 31.4-volt peak. The effective value of the a-c is 0.707 of the 31.4 volts, or 22.2 volts. This is obviously 2.22 times the 10-volt value. Therefore, to determine the effective a-c value, the conversion factor to use if a half-wave rectifier is used with a d-c meter is 2.22 times the scale reading.

Unfortunately, all rectifiers are somewhat nonlinear near their zero-current points. As a result, neither of these theoretical factors, neither 1.11 for full-wave nor 2.22 for half-wave, will give the exact values, although they may be close to the effective a-c values.

Meters using selenium or copper-oxide rectifiers are not accurate at higher frequencies because of the capacitance across the rectifier units. The higher the frequency, the more the capacitive reactance allows current to flow in both directions through the rectifiers. The less effective the rectifying action, the lower the meter reads. This can be partially overcome by using low-capacitance germanium diodes, but the inductive reactance of the moving coil increases with frequency, making the meter read low at higher frequencies.

It must be understood that D'Arsonval meters with self-contained rectifier units are normally calibrated for effective a-c values. A 10-volt reading on their scales indicates a 10-volt effective value of a-c. The peak value is found by multiplying the effective value by the factor 1.414. This is only accurate, however, when the waveform of the a-c is sinusoidal.

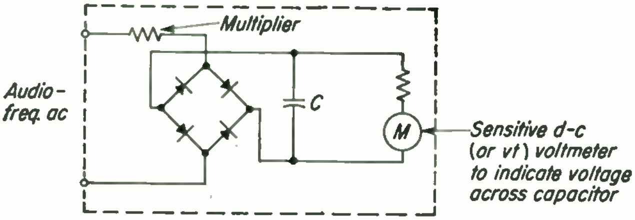


FIG. 11.21. Simple peak-reading a-c voltmeter.

**11.17 Peak Reading Meters.** In most audio work, as in broadcasting and recording, the waveform of the a-c used is rarely true sine wave. As a result, the effective values shown on the meters are rarely 0.707 of the peak values. If the peak value is desired, the normal a-c meter is not satisfactory. A *peak voltmeter* is required.

In general, peak reading meters rectify the a-c to be measured, charge a capacitor with the pulsating d-c obtained, and then measure the voltage across the charged capacitor. Figure 11.21 shows a meter suitable for reading peak voltages of AF a-c.

The meter used may be either a sensitive moving-coil meter or a vacuum-tube voltmeter. The high resistance of the meter circuit slowly leaks off the charge of the capacitor. The indicator rises rapidly as the capacitor charges, but hangs at or near the peak reading for a period of time. The less sensitive the meter, the less resistance it has and the quicker the capacitor discharges through the meter.

*Volume-unit* (*VU*), or volume-indicator, meters are essentially peak-reading meters. With a relatively rapid pulse, or steep wave, these meters rise to about 99 per cent of the peak value very quickly but fall off slowly.

Most a-c vacuum-tube voltmeters actually respond to the peak values of the a-c they are measuring because of the capacitance across the output of the a-c probe circuit, although the scale on the meter is calibrated in effective values. As a result, readings on these meters, when measuring speech or music signals, if multiplied by 1.414, will closely approximate the actual peak values.

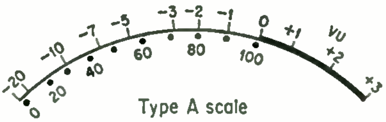
**11.18 Decibel and VU Meters.** The VU (volume-unit) meter is used in broadcast work as well as in other audio applications. It is an a-c *voltmeter* of the rectifier type used to monitor the amplitude of the AF program signals in different parts of the broadcast or other audio circuits. It must be connected across a 600-ohm impedance line, since it is calibrated to read relative *power* levels when across such a line.

In the past, different services used a different value of power as the reference, or 0, value. Some used 500 ohms and some 600 ohms as standard line impedances. Some used 0.006 watt as the 0 reference point, some 0.0125 watt, and others 0.001 watt. These meters are calibrated in decibel (db) units (Sec. 8.6), with the zero-power-level indication at about center scale. If the power in the line is more than the reference value, it produces a higher voltage across the line and the meter reads to the right of the zero mark. If the power is less than the reference value, the voltage is less, and the indicator needle moves to less than center scale.

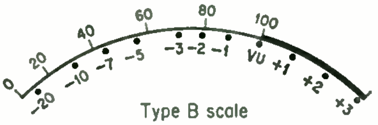
If a reference power of 0.006 watt is used, a +10-db indication on the meter indicates 10 times the reference power, or 0.06 watt, is being used by the circuit. A 20-db reading indicates 100 times 0.006, or 0.6 watt, etc. On the other hand, a −10-db reading on the meter indicates $\frac{1}{10}$ of 0.006, or 0.0006 watt. A −20-db reading indicates 0.01 times 0.006, or 0.00006 watt, etc.

In 1940, a standard type of power-level meter was decided upon. It is a rectifier-type meter having a specified degree of needle damping and definite scale calibrations. It uses 0.001 watt (one mw) as the zero reference level and must be connected across a 600-ohm impedance line. This is the VU meter and is now the standard in all broadcasting services. All VU meters are built with identical characteristics, whereas all decibel meters do not have the same scale markings, damping, or zero levels. The VU meter has a fairly high degree of damping, while the ordinary decibel meter usually has less. The decibel meter is still in use in applications where the power level being measured is not changing rapidly, as it does in circuits carrying speech and music signals.

There are two scale markings used in VU meters, as shown in Fig. 11.22. The VU meter is constructed to operate with a 3,600-ohm external series resistor, as shown in Fig. 11.23. When the power in the line being measured is higher than the +3 VU on the high end of the meter scale, three properly selected resistors forming a T-type *attenuation pad* can be inserted in the meter circuit to desensitize the meter by a predetermined number of VU (decibels) to prevent it from indicating off scale. If the attenuation pad is made to desensitize the meter 8 VU, any reading given by the meter will be 8 VU lower than the true value. An indication of −11 VU represents an actual line power of −3 VU, with an 8-VU attenuator pad in the circuit.



Type A scale



Type B scale

FIG. 11.22. VU meter scales, graduated in ±VU and 0 to 100 per cent modulation.

The 3,600-ohm external resistor is not incorporated in the meter in order that the user may include an attenuation pad in the meter circuit, if required.

**11.19 Thermocouple Ammeters.** A thermocouple ammeter consists of a d-c moving-coil meter connected across a thermocouple junction

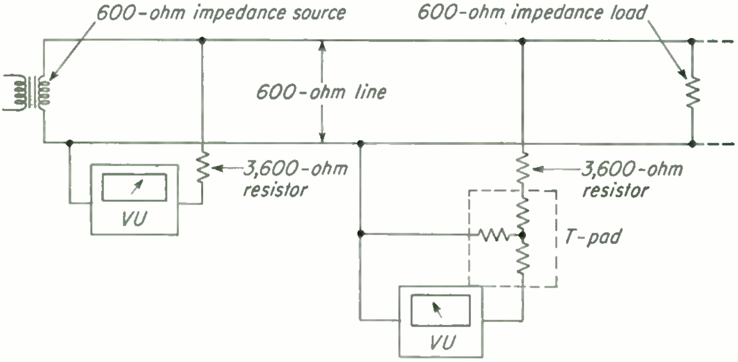


FIG. 11.23. VU meter connected across a 600-ohm line, and VU meter with an attenuation pad to desensitize it.

(Fig. 11.24). Current flowing from *A* to *B*, or from *B* to *A*, produces heat at the junction. The junction is heated whether the current through it is a-c or d-c, and heat produced is independent of frequency.

The junction is composed of two dissimilar metals welded together. When the welded joint is heated, different values of electron activity are developed in the two dissimilar metals. This results in a d-c emf between the two metals and an electron movement from one to the other. The heated junction becomes a thermal d-c generator. The current value developed is small, but with a sensitive meter and high enough junction current and temperature, satisfactory deflections are produced. The greater the alternating current through the resistance of the junction, the warmer it becomes and the greater the direct current through the meter circuit. A thermocouple ammeter indicator needle moves rather slowly because of the time required to heat the junction.

Thermocouple meters are normally calibrated to read effective a-c values. If calibrated at 60 cycles, the calibrations will be accurate up to 20 Mc or more. If used in d-c circuits, some meters may read either slightly high or slightly low, depending on the direction of the current through them. This is due to the small d-c voltage drop that is sometimes developed across the junction by the line current. This emf is in series with that produced by the junction and may either aid or buck it. The average of two readings, one with the current flowing in one direction and one with the current in the other, will give a correct value.

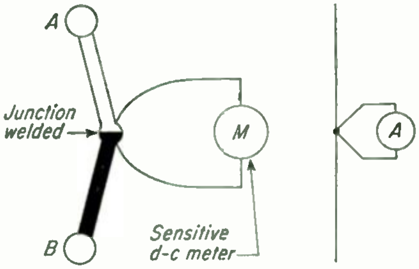


Fig. 11.24. Thermocouple ammeter consists of a sensitive d-c meter and a thermocouple junction. Symbol of thermocouple ammeter.

The range of a thermocouple meter can be varied several ways. Different junction metals will have different electron-activity capabilities and will produce different d-c emfs with the same heat. A resistance in series with the meter lead will reduce the current through the meter, decreasing the sensitivity of the meter as a whole. A shunt across the junction will reduce the current flowing through it. A shunt across the moving coil will reduce the current through it, desensitizing the meter as a whole. Deflection is essentially current squared.

In high-current meters, the thermocouple may consist of a short piece of hollow tubing made of a relatively high-resistance metal. This tube heats when current passes through it. The thermocouple-junction wires are welded together, and then welded to the surface of the tubing. As the tubing is heated the heat is transferred to the thermocouple junction, generating a d-c that is fed to the indicating meter.

Since they operate on practically any frequency, thermocouple meters can be used in d-c power and AF and RF circuits. They find their greatest use as antenna RF ammeters in radio transmitters.

**11.20 Hot-wire Ammeters.** During the early part of the twentieth century hot-wire ammeters were used, particularly in radio-transmitter antennas. It is a relatively simple meter and operates the same for d-c or a-c of any frequency. Because of its relatively high internal resistance, the effect of variations of air temperatures on its indications, its failure to always return to zero, and its slow movement, it is rarely seen today.

Figure 11.25 illustrates the basic principle of the hot-wire ammeter.

When current flows from $A$ to $B$, or $B$ to $A$, the resistance wire becomes warm and expands. When the wire expands, the spring tension pulls the center of the wire toward the right, at the same time pulling the pointer over. The greater the current flow, the greater the heat developed, the more the wire expands, and the greater the movement of the pointer. Deflection is essentially current squared.

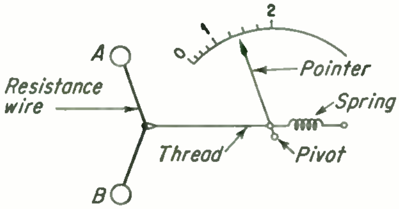


FIG. 11.25. Essentials of a hot-wire ammeter.

## 11.21 The Electrodynamometer.

The electrodynamometer, or dynamometer (pronounced dy-nah-mom-eter), is somewhat similar to the d-c moving-coil meter except that it has no permanent-magnet field. Instead, it has a pair of air-core field *coils* that produce an electromagnetic field when current flows through them. The pointer is attached to a moving coil that is returned to the zero position by a pair of spiral springs as in the D'Arsonval meter.

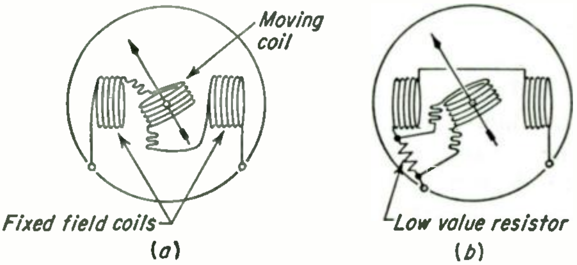


FIG. 11.26. (a) Low-current and (b) high-current dynamometer connections.

Figure 11.26 shows two methods of connecting the field and moving coils of an electrodynamometer. The series connection is used for voltmeters and low-current ammeters. The circuit with the moving coil across a low-value series resistance is used in higher-current ammeters. In either case, the currents in the moving and stationary coils are in phase. When current flows through one, it also flows through the others, producing a magnetic pulling effect that rotates the pointer against the tension of the springs. Because the polarity of both the fixed- and rotary-coil magnetic fields reverses with a reversal of current, the rotational pull is always in the same direction. For this reason, the meter can be used to indicate on either a-c or d-c. Because they are rather insensitive, in the range of a few ohms per volt, these meters find their greatest use in power-frequency circuits where power drain is of little importance.

Some of the electrodynamometers can be calibrated on d-c and will hold calibration when used on a-c up to about 500 cycles. At higher frequencies the inductive reactance of the coils may decrease the current flow through the meter and introduce errors. The electrodynamometer has no iron as a core and should not be operated near iron masses.

The electrodynamometer, as well as other power-frequency a-c meters, may use a step-down transformer when measuring potentials higher than 1,000 volts. When measuring heavy currents, a step-down *current* transformer can be connected in series with the line. The meter is connected across the secondary.

Because of their low sensitivity, low-range dynamometer voltmeters may require as much as ½ amp to produce full-scale deflection, or between 0.1 and 3 watts.

The deflection of the pointer against the spring tension requires current flow in the moving coil *and* the field coil. As a result, the deflection of the needle is small with low currents and increases as the square of the current, producing a current-squared scale.

**11.22 Repulsion-type Meters.** The repulsion-type moving-vane meter consists of a coil of wire, and inside the coil, two *vanes* made of thin sheets of highly permeable, low-retentivity soft iron that can magnetize and demagnetize easily. One of the vanes is stationary, and the other rotary, somewhat as indicated in Fig. 11.27. The pointer is attached to the rotary vane and is returned to the zero setting by a spiral spring (not shown).

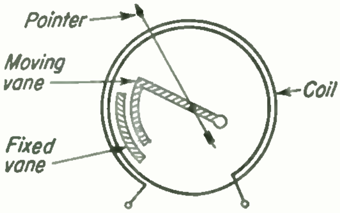


FIG. 11.27. Iron-vane type of repulsion meter.

When the coil is energized, it magnetizes both vanes by induction. Since they are lying in the same plane, the two vanes are magnetized with *like* polarity and repel each other. The moving vane is repelled from the fixed vane and against the tension of the restoring spring. Regardless of the direction of the current, the vanes continually repel each other as long as current flows in the coil.

Like the electrodynamometer, the moving-vane meter has low sensitivity and is normally used as a voltmeter or ammeter for power-frequency a-c, although it can be used to measure d-c. If the meter is used as an ammeter, the coil is made of a few turns of heavy wire. If used as a voltmeter, the coil has many turns of fine wire.

These meters would normally have current-squared calibrations, but by proper shaping of the vanes it is possible to produce fairly linear graduations over most of the scale. The lower values are always compressed. Calibrations are in effective values.

Another form of iron-vane meter has the vane set on an inclined plane inside the coil and fastened to the pointer. When magnetized, the vane tries to line itself in the lines of force, rotating the indicator needle against a spiral-spring tension. It will operate with d-c, although it is normally a power-frequency meter.

Another form of a-c meter is the inclined-coil, or inclined-loop, meter. Moving fields due to a-c flowing in the external coil induce a current into the internal shorted coil, or loop. The induced current in the loop produces a magnetic field of its own, in opposition to the external-coil field, rotating the loop and the indicator attached to it against a spring tension. This meter will operate on a-c only.

**11.23 The Wattmeter.** The value of power in a circuit can be determined by multiplying the voltage by the current. If an electrodynamometer-type meter is connected with its field coils in series with the line, as shown in Fig. 11.28, all the current to the load passes through the field coils and produces a magnetic field proportional to the current value.

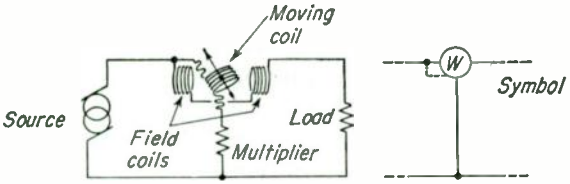


Fig. 11.28. Wattmeter and symbol. Connection shown dotted is sometimes used.

If the moving coil and a resistor are connected as a voltmeter across the line, the magnetic field around the moving coil is developed proportional to the voltage across the circuit. In the one meter, then, are represented both current and voltage effects. Increasing the current value will increase the deflection of the pointer. Increasing the voltage across the line will result in a greater current through the moving coil, a stronger magnetic field around it, and a greater scale deflection. In both cases, increases of either current or voltage, or both, will increase the power in the circuit and increase the scale deflection of the meter. The meter may be calibrated in watts or kilowatts. It may be used with d-c or a-c, provided the frequency is not over a few hundred cycles.

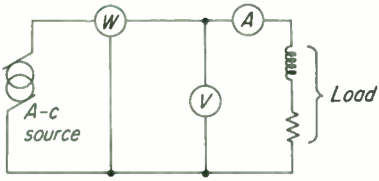


Fig. 11.29. Circuit with which the power factor of a load can be determined.

A wattmeter always indicates the *true power* in an a-c circuit. If the current and voltage are out of phase, the current-carrying fields and the voltage coil automatically allow for this and it is not necessary to multiply the indication by the power factor.

Figure 11.29 shows an ammeter and a voltmeter connected in an a-c circuit. The product of the current times the voltage gives the apparent power. Included in the circuit is a wattmeter, which reads true power.

By dividing the true-power reading by the apparent-power computation, the power factor of the circuit can be determined. The formula is

$$\mathrm{pf} = \frac{P}{\mathrm{VA}}$$

where pf is power factor; $P$ is the true power; and VA is the apparent power.

The power being used by a load in a d-c circuit can also be determined by a wattmeter, or by connecting a voltmeter and ammeter in the circuit, and multiplying the readings.

**11.24 Watthourmeters.** Electric energy is measured in watthours, wattseconds, or joules. Energy-measuring meters are known as *watthourmeters* or *kilowatthourmeters*.

The watthourmeter operates on a principle somewhat similar to that of a wattmeter. However, instead of moving an indicator needle, the current and voltage fields rotate an armature of a form of electric motor. The motor rotation gear-drives indicator hands that rotate like clock hands. A thousand watts operating for a minute will rotate the motor for a minute, gear-driving the hands through a small arc. The same power operating for an hour will move the indicator hand through an arc 60 times as great.

There are usually four indicator hands, each reduction-geared 10 times the preceding indicator. The first reads kilowatthours, the second 10s of kwhr, the third 100s of kwhr, and the fourth 1,000s of kwhr.

FIG. 11.30. Watthours of meter symbol.

The symbol for a watthourmeter is shown in Fig. 11.30.

**11.25 Frequency Meters.** There are four basic types of *frequency meters*. One is the vibrating-reed type, another is the induction type, another is the electrodynamic type, and the fourth is the beat-frequency type. The beat-frequency method is described in the chapter on Measuring Frequency.

Except for the beat-frequency type, all frequency meters are made to measure only a narrow band of frequencies. For example, the vibrating-reed type may only indicate from 58 to 62 cycles. It might be composed of nine vibrating steel reeds, having natural periods of vibration of 58 cycles, 58.5 cycles, 59 cycles, and so on. An electromagnet excited from the circuit being measured produces an alternating field at the frequency of the current in the circuit. The reeds are placed in this alternating magnetic field. If the frequency is 60 cycles, the reed tuned to 60 cycles falls into resonance with this frequency and vibrates with considerable amplitude, while adjacent reeds vibrate less. Observation of the reeds indicates the frequency of the a-c. If two adjacent reeds vibrate at the same amplitude, the frequency of the a-c is halfway between the frequency of vibration of the two reeds. In this way, it is possible to read such a meter to the quarter of a cycle.

The induction and electrodynamic types of frequency meters utilize a principle of balancing the indicator needle at the center of the meter scale by using the magnetic field of a resistive circuit and the magnetic field of an inductively reactive circuit to oppose each other. If the frequency increases, the current through the reactive circuit may decrease while the current through the resistive circuit remains the same. This pulls the needle toward the resistive-circuit side of the meter. A lower frequency may produce greater field strength of the reactive circuit, pulling the indicator toward the reactive-circuit side of the meter. Frequency meters are connected across the line being measured, similar to a voltmeter.

**11.26 Ampere-hour Meters.** Ampere-hour meters are rather specialized energy-indicating instruments. The d-c type is limited almost exclusively to battery-charging circuits in radio.

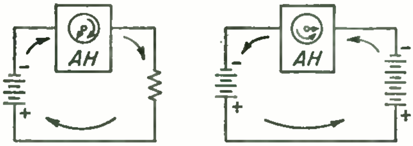


FIG. 11.31. Ampere-hour meters in a circuit in which a battery is discharging and in which the battery is being charged.

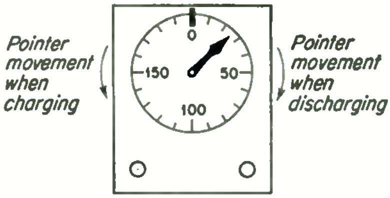


FIG. 11.32. Ampere-hour-meter pointer moves forward during discharge and backward during charge.

Briefly, when a battery is being *discharged*, current flows out of its negative terminal and into its positive. To *recharge* a battery, it is necessary to reverse the current flow through it by using an emf greater than that of the battery. This forces current into the negative and out of the positive terminals, as shown in Fig. 11.31.

If an ampere-hour meter is connected in series with the discharging battery, the current will flow through the meter in one direction. When the battery is charging, the current through the meter will be in the opposite direction.

The ampere-hour meter is a small mercury-pool motor. The direction of the motor rotation depends on the current direction through the meter. The speed of rotation depends on the current strength. The motor is geared to a rotating indicator needle (Fig. 11.32). As the battery is discharged the indicator needle rotates slowly clockwise. When the battery is charging, the indicator needle reverses its motion, moving counterclockwise. The more current flowing through the meter, the farther the indicator needle rotates in a given time. If the meter is set with its indicator at zero, and the battery is discharging at a rate of 2 amp, the needle may move ¼ in. in a clockwise direction in 1 hr. A discharge rate of 4 amp will move the needle ½ in. in the same time. In the latter case the battery has discharged *4 amp-hr*. To recharge this battery, it is necessary to feed at least 4 amp back into the battery for a period of 1 hr (4 amp-hr), or 8 amp for ½ hr (4 amp-hr), or 2 amp for 2 hr (4 amp-hr), etc. When the meter reads zero the battery is charged.

In actual practice it will be found that *more* than an equal number of ampere-hours of energy must be put back into the battery than was taken from it, because of heat losses, circuit losses, age of battery, etc., to bring it back to the original state of charge. To assure this greater number of ampere-hours during charging than during discharge, an internal magnetically operated shunting resistance is connected across the meter during the charging period. In this way some of the charging current flows through the shunt circuit and does not affect the rotation of the indicator needle. When the current reverses again, the shunting circuit becomes inoperative and all the current flows through the meter. The meter, then, is only reading accurately in ampere-hours during discharge of the battery.

**11.27 Current-squared-meter Scales.** In the electrodynamometer, the same current flows through the field and moving coils. Doubling the current in one coil results in a doubling of the current in the other and a quadrupled magnetic effect. It can be said that the deflection is proportional to the current squared. For example, if the pointer deflects 1 in. when 1 ma flows, it will deflect 4 in. with 2 ma, 9 in. with 3 ma, etc.

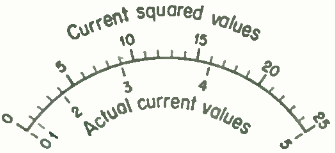


FIG. 11.33. Current-squared meter face, with actual current values also shown.

If the current values are *squared* and the squared markings are placed on the meter scale, it will be found that these markings are linear (Fig. 11.33). Current-squared markings may be equal-spaced indications, from 0 to 25, or 0 to 50, for example. These values may or may not relate to actual current values. However, if the full-scale current value is known, *or the current for any point* on the current-squared scale is known, the current for any other scale reading can be computed by using the formula

$$I_a = \sqrt{R_{kcs} \frac{I_{fs}^2}{R_{fcs}}}$$

where $I_a$ is the actual current at the specified current-squared-scale reading; $I_{fs}$ is the full-scale current value; $R_{kcs}$ is the known current-squared reading; and $R_{fcs}$ is the full-scale current-squared reading.

Figure 11.33 illustrates a possible current-squared meter with a 0–25 scale marking, and a 5-ma full-scale current value. It illustrates how the nonlinear actual current values, when squared, produce a linear current-squared scale. With this type of a scale it is only necessary to take the square root of the current-squared markings to find the actual current value.

A meter has a 0–50 scale, with the forty-fifth division known to equal a current value of 45 ma. What would be the actual current value when the meter indicates 25 on the current-squared scale? This meter can be considered as a 0–45 current-squared scale, and the problem can be computed by using the formula given above:

$$I_a = \sqrt{R_{kcs}\left(\frac{I_{fs}^2}{R_{fcs}}\right)} = \sqrt{25\left[\frac{(0.045)^2}{45}\right]} = \sqrt{25(0.000045)} = \sqrt{0.00\ 11\ 25}$$
$$= 0.0335 \text{ amp, or } 33.5 \text{ ma}$$

The thermocouple meter, being proportional to power (heat), is also proportional to current squared ($P = I^2R$). Sensitive RF a-c indicating devices may be thermocouple meters with current-squared scales. The full-scale deflection-current value is indicated somewhere on the meter face.

In general, the upper two-thirds of a current-squared meter is considered to have satisfactory accuracy. Below this the divisions on the scale may be too close together for accurate reading.

Although basically the deflection is proportional to the current *squared*, properly shaping the field magnets in the meter will make the greater part of the scale essentially linear.

**11.28 Bridges.** Any discussion of measuring instruments must include some mention of bridge-type devices. The Wheatstone bridge (Fig. 11.34) can be used to measure resistance values accurately from a fraction of an ohm to hundreds of thousands of ohms. The unknown resistance, $R_x$, is connected between points $A$ and $B$. A known variable resistance, $R_k$, is connected between points $X$ and $Y$. When the four resistances are proportional so that $R_1$ is to $R_k$ as $R_2$ is to $R_x$, the voltage drop across $R_k$ and $R_x$ will be equal. With no difference of potential across the meter, it will read zero. If the resistances are not proportional, the meter will indicate some value, plus or minus. The formula for the balanced circuit is

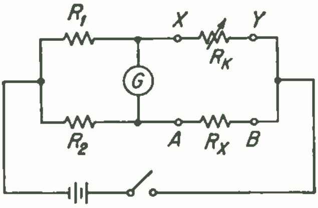


FIG. 11.34. Resistance-bridge circuit, for visual indications.

$$\frac{R_1}{R_k} = \frac{R_2}{R_x}$$

The resistance must be computed from the formula

$$R_x = \frac{R_kR_2}{R_1}$$

The bridge circuit requires a sensitive moving-coil meter constructed to give a zero setting in the center of the scale, instead of at the left end. This is usually known as a *galvanometer*-type meter.

The theory of using a proportional balance to produce a null indication is also used in other bridges. There are many different types, capable of measuring impedance, reactance, frequency, capacitance, and inductance. Space limits this discussion to one other type, an inductance bridge (Fig. 11.35). This bridge uses an a-c source, such as a vacuum-tube AF oscillator, transformer-coupled to the bridge. When $R_1$ is to $L_k$ as $R_2$ is to $L_x$, the difference of a-c potential across the earphones will be zero and no tone will be heard. If the proportions are not correct, a signal from the oscillator will be heard as a tone in the earphones.

The formula for determining the unknown inductance can be the same as used for the resistance in the Wheatstone bridge. Other variations are possible. For example, it might be more practical to use $L_k$ as a fixed value and use $R_1$ as the variable element. In measuring an inductance, resistance in the unknown inductance may result in some error.

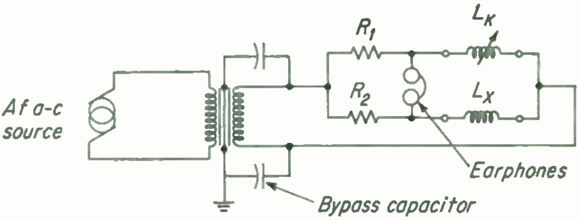


FIG. 11.35. Inductance bridge, giving aural indication of the null.

The variable resistances (inductances or capacitances) used to balance bridge circuits are available in *decade boxes*. A decade box may have five or more rotary switches, the first to select, for example, one of 10 resistances from 0.1 to 1.0 ohm. The second switch adds resistance in single-ohm units up to 10 ohms. The third switch adds resistance in 10-ohm units up to 100 ohms. The fourth switch adds resistance in 100-ohm units up to 1,000 ohms. The fifth switch adds resistance in 1,000-ohm units up to 10,000 ohms. By proper selection of the various switches, any value of resistance within 0.1 ohm can be selected. The name decade box is derived from *deca*, meaning "ten."

Resistor decades are very accurate. Capacitor decades are slightly less accurate. Inductance bridges may be accurate only to within 5 per cent, because of variations of $Q$ and saturation currents.

**11.29 The Oscilloscope.** An extremely useful measuring device is the *oscilloscope*, or *oscillograph*, as it is sometimes known. It presents a visual indication of instantaneous voltage excursions that no other measuring device can show. The indicator is known as a *cathode-ray tube*, similar to the picture tube in a television receiver, the basic difference being in the type of deflection used.

A cathode-ray tube consists of an *electron gun*, four deflection plates, a fluorescent screen, and the glass envelope.

The electron gun consists of a heater cathode, capable of emitting electrons when heated, a sheet of metal with a single hole in it, called the grid, and two metal cylinders, one named the focusing anode and the other the accelerating anode, as shown in Fig. 11.36. The grid is negatively charged in respect to the cathode by being connected to a more negative point on a voltage-divider resistor across a power supply of 600 to 1,500 volts.

The negative charge on the grid would normally prevent electrons from passing through the one small hole in it, except that the focusing anode on the other side is at a relatively high positive potential and attracts them. Some of these electrons strike the focusing anode and move to the power supply, but most of them pass on through the hole in the focusing anode, into the *electrostatic lens* that is formed inside this anode.

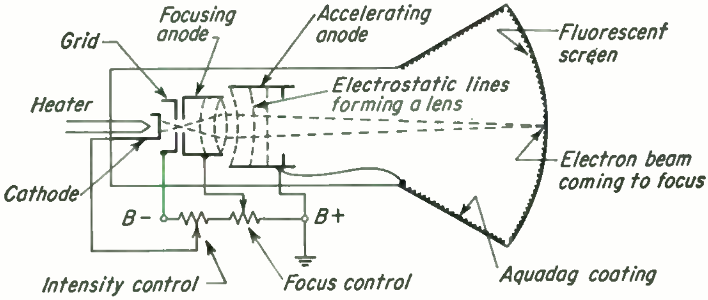


FIG. 11.36. Electron gun of an electrostatic-deflection cathode-ray tube. Deflection plates not shown.

Because of the difference in potential between the two anodes, the electrostatic lines of force in this area are bent, as shown. The electrostatic lines of *equipotential* across the opening between the anodes form an electrostatic lens. Electrons moving through this lens are made to converge at the screen, as light beams can be made to converge and focus when passed through a glass lens. By varying the voltage difference between the first and second anodes, the configuration of the lines of force of the field can be changed. This changes the shape of the electrostatic lens and changes the distance to the point where the electron beam will focus to a small spot.

Focusing is controlled by varying the voltage on the first anode, as shown by the arrowhead on the voltage divider in the illustration. By varying this control, the size of the spot produced on the screen may be decreased to a dot, smaller than the head of a pin.

The second anode, besides aiding in focusing the beam, tends to increase the speed of the electrons, and as a result is known as the accelerating anode. The more rapidly the electrons travel, the brighter the spot they produce when they strike the fluorescent screen at the front end of the tube.

The intensity of the spot is basically controlled by changing the potential on the grid. The more negative the grid, the fewer electrons that can be pulled through the hole in the grid and the less intense a spot produced on the screen. Control of the intensity can be accomplished by making the return lead from the cathode to the voltage-divider resistor as a variable control. This will also have a slight effect on the focus.

The electron beam can be deflected up or down by including two *vertical deflection plates* in the neck of the tube, above and below the beam, as shown in Fig. 11.37.

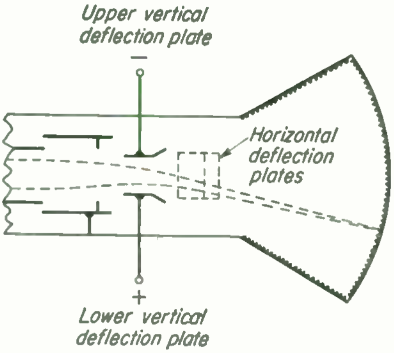


FIG. 11.37. Deflection plates of an electrostatic-deflection cathode-ray tube.

If the lower deflection plate is connected to the second anode (ground) and a positive potential in respect to it is applied to the upper deflection plate, the electrons in the beam will be attracted toward the upper plate and the spot on the screen will move upward. How far the spot moves is determined by the magnitude of the voltage applied to the deflection plate. If the upper plate is made negative in respect to the lower plate, the electron beam will be deflected downward a distance proportional to the voltage applied. Connecting a voltage to be measured between the two plates and watching the screen give an indication of its peak value. A transparent graph with millimeter spacing between lines can be laid over the face of the tube, and the length of the deflection measured. If the sensitivity of the deflection plate with a particular anode voltage is 0.33 mm/volt, for example, and the deflection of a pulsating d-c is 6 mm, the peak voltage applied to the plates must be 18.2 volts. The direction of deflection also indicates the polarity of the voltage if d-c is being measured. The indication will be a solid vertical line, 12 mm long for an 18-volt peak a-c, because of the continual reversal of polarity during alternate half cycles. The oscilloscope is an excellent peak-to-peak indicating device.

The cathode-ray tube also has a pair of *horizontal deflection plates*, placed at right angles to the vertical deflection plates, in the position shown by the dotted oblong in the illustration. Since these plates are closer to the screen, they will deflect the beam less and as a result have a slightly lower sensitivity. Voltages applied to the horizontal plates deflect the spot horizontally.

The *aquadag* coating, indicated in the illustrations, is a conductive coating sprayed on the inside of the tube and is connected to the accelerating anode. Electrons striking the phosphorescent and fluorescent painted surface, or screen, on the inner face of the tube cause a bright spot wherever they hit. These electrons bounce back, as a secondary emission, and are attracted to the positively charged aquadag coating, and from there move to the positive terminal of the power supply.

All the connections to all the elements are connected to pins at the cathode end of the tube. These pins usually fit into a 7- to 14-pin socket, depending on the tube type. There are many different types of cathode-ray tubes, having different face sizes, sensitivities, persistence of illumination, colors of screens, numbers of anodes, filament voltages, etc. Most oscilloscope tubes are 3- or 5-in. screen sizes, however.

There are many uses for the oscilloscope besides its use as a simple voltage indicator. In fact, in practically any electric or radio circuit the oscilloscope can be made to picture what is occurring.

Most oscilloscopes contain at least two other circuits. One is a variable-frequency saw-tooth a-c oscillator, used to produce horizontal deflection. The other is an amplifier stage to increase the voltage applied to the vertical plates. If the tube sensitivity is only ⅓-mm deflection per volt, it takes considerable amplification to produce adequate deflection when the amplitude of the a-c signal being viewed is only a small fraction of a volt.

Any frequency up to more than 50 Mc may be displayed satisfactorily when connected directly to the deflection plates. However, with most oscilloscopes, the vertical-deflection amplifiers will not produce undistorted amplification over a few hundred kilocycles, although more expensive models will amplify linearly up to many megacycles.

The saw-tooth oscillator voltage used for the horizontal *sweep* circuit is generated in the oscilloscope with some form of an RC oscillator. One type uses a thyratron, or gaseous triode. Another type uses two triodes in a multivibrator circuit. Such circuits are discussed in the chapter on Oscillators. The requirement for a sweep oscillation is a relatively slow, constantly increasing voltage, with a rapid return to zero. When such a voltage is applied to the horizontal deflection plates, the illuminated dot on the screen moves slowly and evenly across the screen, and then returns to the center so fast that it leaves no trace. It continually repeats this horizontal tracing and results in an apparent horizontal line on the face of the tube.

Consider what will happen when a 100-cycle sine-wave a-c is applied to the vertical deflection plates and a 100-cycle varying d-c saw-tooth wave is applied to the horizontal deflection plates. Each will be assumed to be starting at zero voltage. At first there is no deflection voltage present, and the illuminated dot should be in the center of the screen.

1. In $\frac{1}{400}$ sec the horizontal sweep moves the dot one-fourth of the distance to the right. At the same time the sine wave has risen to a maximum potential (assumed to be positive) and has pulled the dot upward, perhaps an inch, depending on the magnitude of the voltage, tracing the first quarter of a sine wave on the screen, as shown in Fig. 11.38*a*.

2. During the next $\frac{1}{400}$ sec, the horizontal sweep moves the dot to a position one-half the total distance to the right. At the same time, the sine wave has fallen to zero volts, allowing the dot to fall back to the starting level. The second quarter of a sine wave has been traced, as shown in Fig. 11.38*b*.

3. During the next $\frac{1}{400}$ sec the horizontal sweep moves the dot to a position three-fourths of the total distance to the right. At the same time, the sine wave has risen to a maximum negative, and the dot increases in a negative, in this case a downward, direction, tracing the third quarter of a sine wave on the screen, as in Fig. 11.38*c*.

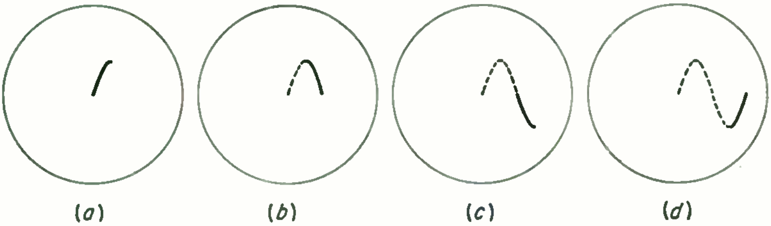


FIG. 11.38. Tracing a single cycle on an oscillograph screen.

4. In the next $\frac{1}{400}$ sec the horizontal sweep moves as far to the right as it is going, and at the last instant snaps back to the starting point. During this time, the sine-wave voltage drops back to the starting level, tracing the final quarter of the sine wave on the screen, as shown in Fig. 11.38*d*. Now the cycle is completed, and the next starts as before.

With the cycles occurring 100 times a second, to the eye a sine wave appears to be standing still on the screen. If the a-c applied to the vertical plates is nonsinusoidal, the display will be nonsinusoidal. In this way, the waveshape of any a-c or varying d-c applied to the vertical plates is made visible. It is only necessary to synchronize the horizontal-sweep frequency with the frequency of the wave being measured on the vertical and the pattern will stand still on the oscilloscope. It is also possible to use the sweep at some submultiple of the signal frequency and stop the motion of the figure displayed. For example, if the sweep is 50 cycles and the signal is 100 cycles, the sweep makes only one-half of its total excursion by the time the signal completes its first cycle. As a result, two cycles of the signal voltage will be shown along the line. If the signal and sweep voltages are not synchronized, the figures traced will appear to move to the right or to the left across the screen.

In practice, the sweep voltage is a saw-tooth a-c rather than a saw-tooth varying d-c, allowing the traced figure to be centered on the screen. There are controls to adjust the amplitude of the sweep voltage and to adjust its frequency.

It is possible to measure the frequency of an a-c by stopping the display of it on an oscilloscope, count the number of cycles shown, and multiply the cycles by the sweep frequency. However, this requires that the sweep frequency be known accurately.

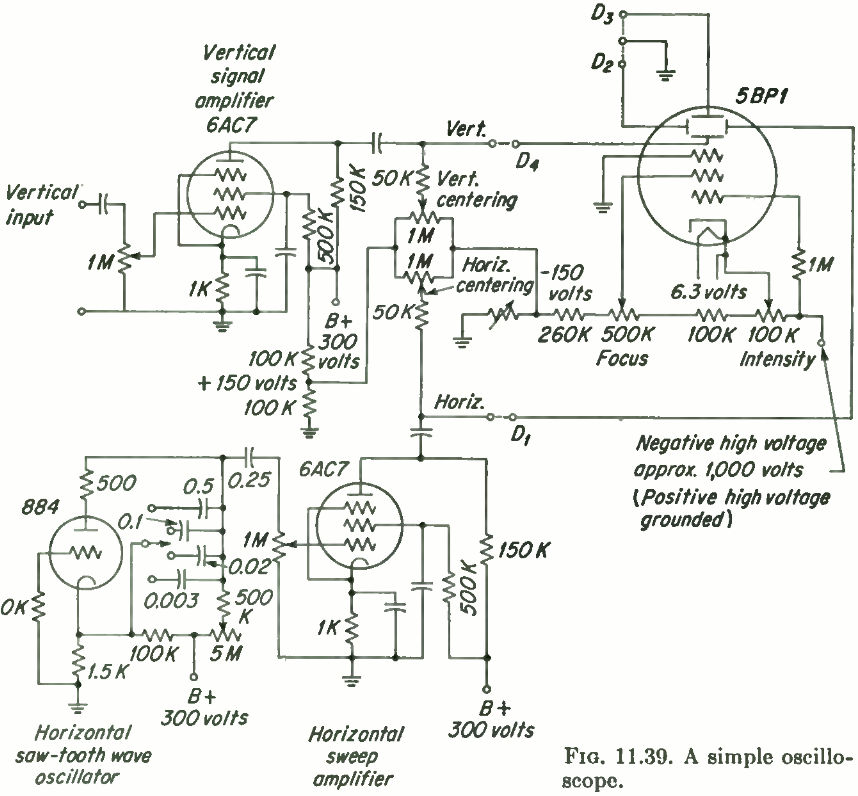


Fig. 11.39. A simple oscilloscope.

The uses of the oscilloscope are mentioned in subsequent chapters, particularly in the chapter on Amplitude Modulation.

The circuit of a simple oscilloscope is shown in Fig. 11.39. It consists of a 5BP1 5-in. cathode-ray tube, an 884 thyratron tube in a saw-tooth oscillator circuit, a 6AC7 horizontal-sweep amplifier, and a 6AC7 vertical-signal amplifier. (The operation of oscillators and amplifiers is discussed in subsequent chapters.)

The saw-tooth wave generated in the oscillator is amplified and fed to the horizontal-deflection-plate connection $D_1$. The other horizontal deflection plate, $D_2$, is connected to ground. Adjustment of the horizontal centering potentiometer centers the dot horizontally on the screen.

The signal to be measured is fed into the vertical input terminal, amplified, and fed to the vertical deflection plate $D_4$. The other vertical deflection plate, $D_3$, is connected to ground. The vertical signal can be centered by adjusting the vertical-centering potentiometer.

If RF a-c is to be measured, the connection between $D_4$ and "vert" can be opened and the RF a-c fed to $D_4$ and $D_3$ (which is grounded).

The oscilloscope requires one 300-volt and one 600- to 1,500-volt power supply.

The operation of magnetic-deflection cathode-ray tubes is discussed in the chapter on Television.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** If a 0–1 d-c milliammeter is to be converted into a voltmeter with full-scale calibration of 100 volts, what value of series resistance should be connected in series with the meter? (11.9) **[3]**

**2.** What type of indicating instrument is best suited for use in measuring RF currents? (11.19) **[3]**

**3.** What single instrument may be used to measure electrical resistance? (11.11) Electromotive force? (11.9) Electric-current flow? (11.4) Electric energy? (11.24) **[3 & 6]**

**4.** Describe the construction and characteristics of a D'Arsonval-type meter. (11.2) Repulsion-type ammeter. (11.22) Dynamometer-type indicating instrument. (11.21) Thermocouple-type meter. (11.19) **[3 & 6]**

**5.** What is the purpose of a shunt as used with an ammeter? (11.4) **[3 & 6]**

**6.** If two ammeters are connected in parallel, how may the total current through the two meters be determined? (11.4) **[3 & 6]**

**7.** If two ammeters are connected in series, how may the total current through the two meters be determined? (11.4) **[3 & 6]**

**8.** A milliammeter with a full-scale deflection of 1 ma and having a resistance of 25 ohms was used to measure an unknown current by shunting the meter with a 4-ohm resistor. It then read 0.4 ma. What was the unknown current value? (11.5) **[3 & 6]**

**9.** Why is a multiplier resistance used with a voltmeter? (11.9) **[3 & 6]**

**10.** How may a d-c milliammeter, in an emergency, be used to indicate voltage? (11.9) **[3 & 6]**

**11.** If two voltmeters are connected in series, how would you be able to determine the total drop across both instruments? (11.9) **[3 & 6]**

**12.** Draw a diagram of an ohmmeter and explain its operation. (11.11) **[3 & 6]**

**13.** Does an a-c ammeter indicate peak, average, or effective values of current? Explain. (11.15) **[3 & 6]**

**14.** Why are copper-oxide rectifiers, associated with d-c voltmeters for the purpose of measuring a-c, not suitable for the measurement of voltages at radio frequencies? (11.16) **[3 & 6]**

**15.** Which meters may be used to measure RF currents? (11.19, 11.20) **[3 & 6]**

**16.** Is the angular-scale deflection of a repulsion iron-vane ammeter proportional to the square or square root of the current, or merely directly proportional to the current? (11.22) **[3 & 6]**

**17.** Which voltmeter absorbs no power from the circuit under test? (11.8) **[4]**

**18.** What type of meter is suitable for measuring the AVC voltage in a standard broadcast receiver? (11.10, 11.13) **[4]**

**19.** What type of meter is suitable for measuring peak a-c voltages? (11.17) **[4]**

**20.** What unit has been adopted by leading program-transmission organizations as a volume unit, and to what power is this unit equivalent? (11.18) **[4]**

**21.** What are some purposes of T-pad attenuators? (11.18) **[4]**

**22.** What type of meter is suitable for measuring RF currents? (11.19, 11.20) **[4]**

**23.** A current-squared meter has a scale divided into 50 equal divisions. When 45 ma flows through the meter, the deflection is 45 divisions. What is the current flowing through the meter when the scale deflection is 25 divisions? (11.27) **[4]**

**24.** Why are permanent magnets used in d-c meters? (11.2) **[6]**

**25.** Indicate by a diagram how the total current in three branches of a parallel circuit can be measured by one ammeter. (11.4) **[6]**

**26.** By what factor must the voltage of an a-c circuit, as indicated on the scale of an a-c voltmeter, be multiplied in order to obtain the peak value? (11.16) **[6]**

**27.** If a d-c voltmeter is used to measure effective a-c voltages by the use of a bridge-type full-wave rectifier of negligible resistance, by what factor must the meter readings be multiplied in order to give corrected readings? (11.16) **[6]**

**28.** By what factor must the voltage of an a-c circuit, as indicated on the scale of an a-c voltmeter, be multiplied to obtain the average voltage value? (11.16) **[6]**

**29.** What is a thermocouple? (11.19) **[6]**

**30.** How may the range of a thermocouple ammeter be increased? (11.19) **[6]**

**31.** Show by a diagram how a voltmeter and ammeter should be connected to measure power in a d-c circuit. (11.23) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**★1.** What instrument is used to measure electric current? (11.4)

**★2.** What instrument is used to measure electric potential, or electromotive force? (11.9)

**★3.** What instrument is used to measure electric power? (11.23)

**★4.** What instrument is used to measure electric energy? (11.24)

**5.** What instrument is used to measure resistance? (11.11)

**6.** What instrument is used to measure frequency? (11.25)

**7.** What instrument is suitable to use when measuring RF current? (11.19)

**8.** What instrument can picture voltage or current waveshapes? (11.29)

## CHAPTER 12

# OSCILLATORS

**12.1 Types of Oscillators.** An oscillator circuit produces alternating current. When a-c for power transmission is required, electrodynamic alternators are used. For higher frequencies, such as audio and radio, vacuum-tube oscillator circuits are usually employed.

The first type of oscillator developed to generate RF was the spark circuit. It produced a damped, or decaying, type of a-c and was used up to about 2 Mc.

Another early radio oscillator was the arc circuit, which produced a constant-amplitude a-c. It could be used effectively only up to about 500 kc.

Still other early radio developments were the Alexanderson and the Goldsmith alternators. They were used to generate radio frequencies of less than 50 kc.

Next came vacuum-tube oscillators. These circuits can be made to operate at any frequency up to several hundred megacycles.

Since the 1930s, magnetron and klystron tubes have been developed to operate at frequencies above 300 Mc and are used in radar and other specialized fields. Recently, transistors have been used in oscillator circuits up to more than 100 Mc.

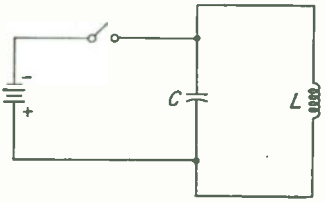


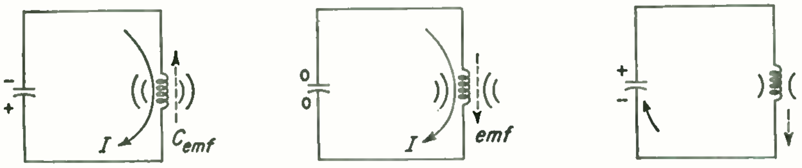
FIG. 12.1. Basic oscillator. Quickly closing and opening the switch charges the capacitor.

**12.2 Shock Excitation.** As a means of explaining the operation of oscillator circuits involving coils and capacitors (condensers), the shock-excitation, or flywheel, theory will be used.

If the switch in Fig. 12.1 is closed for an instant and then opened, electrons from the battery (1) flow to the top plate of the capacitor and charge it negative and (2) are pulled from the bottom plate, charging it positive. The inductance of the coil prevents any great current flow through it for the instant that the switch is closed. As the switch is opened, electrons on the negatively charged plate of the charged capacitor start to move toward the positive plate, downward through the coil. The battery has *shock-excited* the coil-capacitor circuit, and it starts into operation using the energy obtained from the battery as the motivating power.

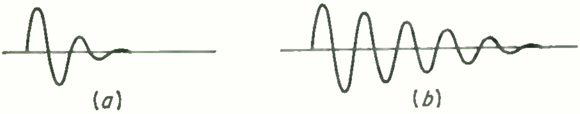
The current of electrons through the coil causes a magnetic field to expand outward (Fig. 12.2*a*), producing a counter emf in the coil which prevents the capacitor from discharging immediately.

As the capacitor discharges, it eventually reaches a point where there are the same number of electrons on both plates (Fig. 12.2*b*). With no emf across the coil, there should be no current in it and nothing to hold the field out around the coil. The field collapses back inward, inducing a downward-direction voltage in the coil. This forces free electrons in the wire of the coil and from the top plate of the capacitor down through the coil to the bottom plate, charging the bottom plate negative and the top plate positive (Fig. 12.2*c*).



(*a*) (*b*) (*c*)

FIG. 12.2. (*a*) Capacitor discharges through the coil, producing a magnetic field. (*b* and *c*) Collapsing field recharges capacitor to opposite polarity.



(*a*) (*b*)

FIG. 12.3. Alternating current damps out (*a*) rapidly in high-resistance circuits, and (*b*) slowly in a low-resistance circuit.

Now the capacitor is charged again, but this time with an opposite polarity. The amplitude of the charge is exactly the same as the original, *provided* there is no resistance in the circuit nor loss of energy due to the moving magnetic field inducing a current into nearby circuits. This charged condition will cause the current to reverse itself in the circuit, swing back up through the coil, and recharge the capacitor to a polarity the same as originally developed in it by the shock excitation of the battery. One cycle of a-c has been produced.

If there were no losses in the circuit, the current would *oscillate* back and forth, indefinitely, with a constant amplitude for each cycle. This would be a perpetual a-c generator. Because there are always losses in circuits, each succeeding half cycle has an amplitude a little less than the one before it. It is not long before the a-c is *damped out* entirely, as shown in Fig. 12.3. The less the resistance, the longer it takes the current to damp out.

The oscillation of electrons back and forth in an LC circuit is known as the flywheel effect. Practically all sine-wave-generating oscillators utilize this effect.

This explanation of shock excitation assumed that the capacitor was the part receiving the original shock of energy. It is also possible to shock-excite such a circuit by inducing a pulse of current into the coil, which would also produce an oscillation of the LC circuit.

If analyzed, it can be seen that the electrostatic energy in the capacitor is converted into electromagnetic energy around the coil, and then back to electrostatic energy in the capacitor, and so on. It can be said that the energy in an LC circuit oscillates from an electrostatic form to an electromagnetic form.

The spark oscillator originally used for radio communication inserted a spark gap in series with an LC circuit and fed a low-frequency a-c voltage across the capacitor (Fig. 12.4). When the emf reached a voltage sufficient to ionize the air between the electrodes of the gap, a spark flashed across, heating the air. The hot air ionized and acted as a conductor, allowing the charge that had built up in the capacitor to produce oscillations of a damped type at the natural frequency of resonance of the LC circuit. The spark oscillator is discussed in the chapter on Basic Transmitters.

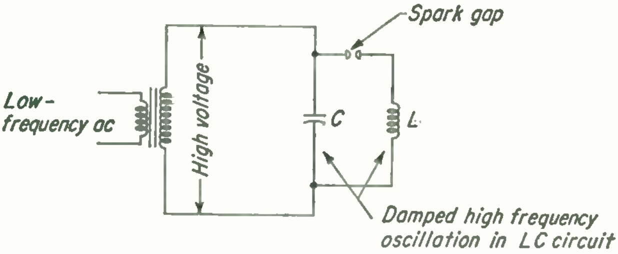


FIG. 12.4. Low-frequency a-c charges $C$ and breaks down the air of the gap, allowing damped high-frequency a-c to oscillate in the LC circuit.

**12.3 Vacuum-tube Oscillators.** The basic theory of the generation of sine wave a-c of continuous amplitude and frequency in most vacuum-tube oscillator circuits might be outlined as follows:

1. A tuned circuit is shock-excited into oscillation.
2. The a-c oscillation voltage from this circuit is amplified by a vacuum tube.
3. The amplified a-c voltage is fed back to the original tuned circuit by either inductive or capacitive coupling.
4. The fed-back voltage must be in such a phase as to aid the oscillating voltage in the tuned circuit.
5. The fed-back voltage keeps the shock-excited LC circuit oscillating at its fundamental frequency.

6. The oscillator circuit draws all its operating energy from the plate-circuit battery or power supply.

7. Alternating-current power produced in the oscillating circuit can be taken from it by either inductive or capacitive coupling (by transformer action or through a capacitor circuit).

**12.4 Armstrong Oscillator.** An Armstrong, or inductive-feedback, oscillator circuit is shown in Fig. 12.5.

When the switch in the B-battery circuit is closed, a surge of electrons begins to flow in the plate circuit. This surge of current through the *tickler coil* produces a rapidly expanding magnetic field around it. The field cuts across the turns of the coil of the LC circuit in the grid, inducing a voltage in it. This induced voltage shock-excites the tuned LC circuit, and it starts to oscillate at a frequency which depends upon the size of the coil and capacitor.

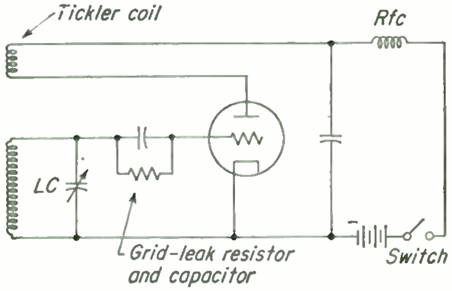


FIG. 12.5. Armstrong oscillator circuit.

As the LC circuit starts to oscillate, the a-c voltages developed across it are fed to the grid-cathode circuit of the tube, producing a relatively high-amplitude *variation* of direct plate current, producing, expanding, and contracting magnetic fields around the tickler coil, inducing an a-c back into the LC circuit, and keeping the circuit oscillating.

Note that the plate coil and the coil of the LC circuit form a transformer, with the plate coil as the primary.

All the a-c energy in the LC circuit is the result of induction from the plate coil. No energy is coming into the grid circuit from the B battery directly.

As long as the plate coil and grid coil are oriented in such a manner as to produce an aiding effect between each other, the oscillation of the LC circuit will continue to increase in strength until a maximum power of oscillation is reached. Actually, this maximum is reached during the first cycle. The maximum amplitude is determined by several factors—plate voltage, degree of coupling between the plate and grid coils, the $Q$ of the LC circuit, the amount of grid bias developed in the grid circuit, and the value of capacitance from tickler coil to cathode.

If the plate coil were wound in the opposite direction, the voltages induced into the grid circuit by the tickler-coil current would be out of phase with any oscillations in the LC circuit and the circuit would not produce sustained oscillations. If it cannot sustain oscillations, it will not act as an a-c generator.

Any LC circuit will have some losses because of resistance in it or induction into some external circuit. The energy fed back from plate circuit to grid circuit must be sufficient to overcome these losses to allow the LC circuit to oscillate at a constant amplitude and not damp out. Actually, considerably more feedback than the minimum requirement is used.

The in-phase feedback effect capable of producing oscillation is known as *regeneration*, while the out-of-phase feedback effect that will prevent oscillation is known as *degeneration*. If it is desired to make a radio circuit oscillate, it will be necessary to introduce regeneration in it. If it is desired to prevent a radio circuit from going into oscillation, it may be necessary to introduce degeneration in it, or *neutralize* it.

In the Armstrong circuit there are several methods by which the quantity of plate-to-grid feedback can be controlled: (1) by varying the tickler-coil coupling to the LC circuit; (2) by varying the d-c plate voltage, thereby varying the amplitude of the plate current flowing through the tickler coil; (3) by varying the tickler-to-ground capacitance, which completes the a-c path from plate circuit to cathode. The greater this capacitance, the greater the a-c component flowing in the tickler coil.

The Armstrong circuit can be used to generate a-c from a few cycles to several hundred megacycles.

**12.5 Grid-leak Bias.** As mentioned in the chapter on Vacuum Tubes, amplifier tubes require a negative d-c grid voltage called a *bias* to allow them to operate efficiently. Oscillator circuits can be operated with a battery supplying the required bias, but battery bias does not always allow the oscillator to be self-starting. Furthermore, it is rather costly. As a result, practically all oscillators use *grid-leak* bias.

In Fig. 12.6, all the parts of the Armstrong oscillator are shown that are needed to explain grid-leak bias. It will be assumed that the LC circuit is oscillating. An a-c voltage is fed across the grid capacitor and appears between grid and cathode. A 50-volt peak value will be assigned to it. When the grid is driven positive by this voltage, electrons from the space charge are picked up by the grid. When the grid is driven 50 volts negative on the next half cycle, the negative grid will not attract electrons. However, it still has the 50 volts' "worth" of negative charge picked up on the positive half cycle. At the peak of the negative half cycle, the

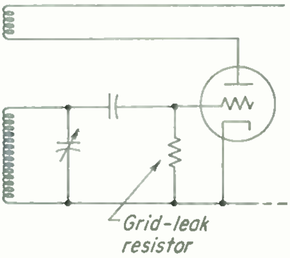


FIG. 12.6. Grid-leak biasing circuit.

grid has the sum of the negative 50 volts of the negative half cycle of LC-circuit oscillation, plus the negative 50 volts' worth of electrons picked up during the positive half cycle, or a 100-volt peak negative charge. During a positive half cycle, the grid has a zero charge (+50 volts plus −50 volts worth of electrons equals zero volts), and during the negative half cycle it has a negative 100 volts. The *average* bias for the whole cycle is therefore negative 50 volts. It can be said that the tube has biased itself to a negative 50-volt value.

If the grid-leak resistor has a value of many millions of ohms, the actual average operating bias value may be nearly 50 volts negative. However, if the grid-leak resistor has a 10,000-ohm value, it will allow the electrons trapped on the grid to leak off and back to the cathode rather rapidly, and the average bias will be considerably less than 50 volts. If it has a value of 1,000 ohms, it will leak off the electrons so fast that the grid will have almost no average bias value at all. The value of the grid bias will depend upon the grid-leak resistance and capacitance values as well as the a-c voltage developed across the LC circuit.

In general, the grid capacitor will have a value between 0.00005 and 0.00025 μf in most cases, and the grid-leak resistor will be 5,000 to 100,000 ohms in transmitter circuits where any a-c power output is required, and up to several megohms in some receiver applications where power is not important and where the grid attracts but few electrons.

It is found that when an oscillator is adjusted to operate with good efficiency and reasonable power output, the bias value will be about 1½ times the plate-current-cutoff bias value. According to definition, this is in the *class C* bias region.

The grid-leak resistor may be connected directly from grid to cathode, as in Fig. 12.6, or it can be connected across the grid capacitor, as in Fig. 12.5. As far as d-c is concerned, the grid-leak resistor is connected to the cathode when across the grid capacitor because the coil in the LC circuit usually has negligible resistance compared with that of the grid leak.

**12.6 Tuned-plate-tuned-grid Oscillator.** The Armstrong oscillator is an example of an inductively coupled oscillator. Energy from the plate circuit is induced into the grid circuit by transformer action of two inductively coupled coils. The tuned-plate-tuned-grid (abbreviated TPTG) oscillator circuit is an example of a capacitively coupled oscillator.

The reason the TPTG oscillator works is the reason many radio amplifiers may *not* operate satisfactorily. When it is understood why this circuit oscillates, it will also be evident why an amplifier using the same general circuitry will sometimes oscillate instead of amplify as it should.

In Fig. 12.7, a capacitor, $C_{gp}$, shown in dotted lines, is usually not needed. The grid-to-plate capacitance of the tube elements themselves is normally sufficient to couple back enough a-c energy capacitively from the plate circuit to the grid circuit to produce sustained oscillations of electrons in the tuned $L_1C_1$ circuit, which in turn keeps $L_2C_2$ oscillating.

The a-c grid circuit consists of the grid, the grid-leak capacitor, the LC circuit, and the cathode. The d-c grid circuit consists of the grid, the grid-leak resistor, and the cathode.

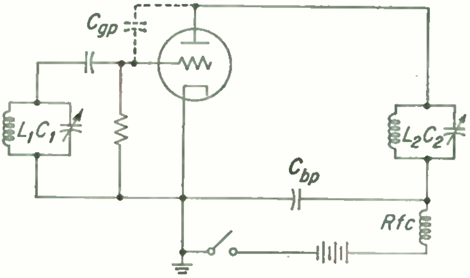


FIG. 12.7. A TPTG oscillator circuit.

The a-c plate circuit consists of the plate, the LC circuit, the bypass capacitor, $C_{bp}$, and the cathode. The d-c plate circuit consists of the plate, the LC circuit, the RF choke coil, the B battery, the switch, and the cathode. When you draw diagrams of radio circuits, it is always wise to check for complete grid and plate circuits for both a-c and d-c continuity.

The TPTG oscillator must have its grid LC circuit and its plate LC circuit tuned to the same frequency of oscillation. When the switch is closed (Fig. 12.7), a sudden surge of plate current begins to flow in the plate circuit. This shock-excites the plate LC circuit into oscillation at a frequency determined by the values of its inductance and capacitance.

When the LC circuit starts oscillating, an a-c voltage is developed across it. This a-c voltage is divided across the bypass capacitor, $C_{bp}$ (Fig. 12.8), the cathode-grid capacitance of the tube, $C_{gc}$, and the grid-plate capacitance of the tube, $C_{gp}$.

The bypass capacitor is relatively large (low reactance) and has very little of the total a-c voltage drop across it. As a result, practically all the a-c voltage across the plate LC circuit is also developed between cathode and plate in the tube. If the grid-cathode circuit and the grid-plate circuit capacitances were equal, then about half of the a-c would be developed across the grid-cathode circuit. In Fig. 12.7 the grid LC circuit is connected between cathode and grid through the grid-leak capacitor and is therefore subjected to a considerable fraction of the volt-

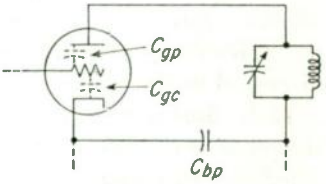


FIG. 12.8. Capacitive voltage divider across oscillating tank circuit.

age developed across the plate LC circuit. This voltage fed to the grid LC circuit from the plate forces the grid LC circuit into oscillation at the frequency of the plate circuit. Now both LC circuits are oscillating.

As mentioned previously, it is necessary that the two circuits be adjusted to approximately the same resonant frequency. If they are not tuned close enough, the feedback will be sufficiently out of phase so that the circuits cannot maintain sustained oscillations.

To change frequency in a TPTG oscillator, it is necessary to tune both the grid and plate circuits together to keep the feedback in proper phase.

Since there are two tuned circuits in the TPTG oscillator, there are two possible frequencies of oscillation if it is slightly out of tune. However, the circuit will normally operate on the frequency of the LC circuit having the higher $Q$.

Alternating-current energy is normally taken out of the oscillator from the plate LC circuit, although a smaller amount can be taken from the grid circuit.

When used to generate lower-frequency a-c, the TPTG circuit may not have enough energy fed back from plate to grid circuit by the interelectrode capacitances of the tube. To increase the value of feedback, a small capacitor of 10 to 50 $\mu\mu$f may have to be connected between grid and plate, as shown in dotted lines (Fig. 12.7). This allows a greater proportion of the feedback voltage to be divided across the grid and cathode, and therefore across the grid LC circuit.

This oscillator was popular in the early thirties, but has been superseded by other simpler circuits, although it may still be found in a few applications. A knowledge of its functioning is important to the radio operator because an *amplifier* circuit constructed in this general form, with grid and plate circuits tuned to the same frequency, may act as an oscillator if the capacitive feedback is sufficient. However, if the grid-plate capacitance can be reduced sufficiently, by using pentode tubes, for example, the circuit can be used as an amplifier with no danger of its breaking into self-oscillation. It is also possible to counteract the grid-plate feedback capacity and prevent oscillations by neutralization, discussed in the chapter on Radio-frequency Amplifiers.

**12.7 Series and Shunt Feed.** The route taken by the d-c in either the plate or the grid circuit determines the type of *feed* used in the circuit. There are two possible means of feeding vacuum-tube circuits, *series* and *shunt*. The latter is also known as parallel-feed.

*Rule:* If the plate current flows through the power supply, tube, and tuning coil in series, the plate circuit is series-fed.

*Rule:* If the tube, tank circuit, and power supply are all in parallel, the plate circuit is shunt-fed.

The TPTG circuits shown in Figs. 12.9 and 12.10 have tuned LC circuits as grid- and plate-circuit loads. Figure 12.9 illustrates a series-fed plate circuit and a series-fed grid circuit. Figure 12.10 illustrates a shunt-fed plate and shunt-fed grid circuit.

It is not necessary to use the same type of feed in both grid and plate circuits. While both grid and plate circuits can be either series- or shunt-fed, when a vacuum-tube circuit is said to be series-fed it normally means that the plate circuit is series-fed. It is rather rare to speak of the type of feed used in the grid circuit.

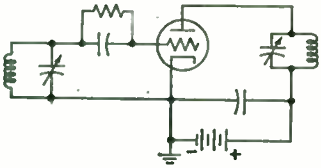


FIG. 12.9. Series-fed plate and grid circuits in TPTG oscillator.

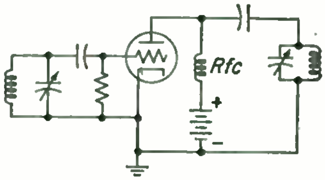


FIG. 12.10. Shunt-fed plate and grid circuits in TPTG oscillator.

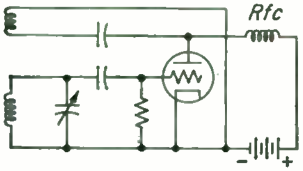


FIG. 12.11. Shunt-fed plate and grid circuits in an Armstrong oscillator.

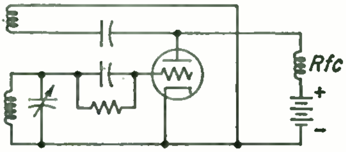


FIG. 12.12. Shunt-fed Armstrong oscillator with both grid and plate coil at ground potential, one end of each being connected to the cathode, or ground point, in the circuit.

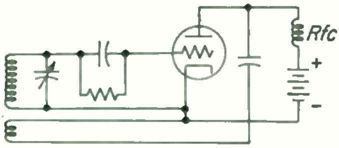


FIG. 12.13. Armstrong oscillator with tickler coil mounted below, instead of above, the LC circuit. Operation of the circuit is identical with Fig. 12.12. Note that the actual electrical connections have not changed in any way.

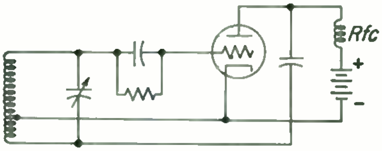


FIG. 12.14. The tickler coil has been incorporated in the LC circuit and the whole coil is being tuned, instead of only the grid coil. The Armstrong has now become a Hartley oscillator.

Figure 12.11 illustrates a shunt-fed Armstrong oscillator. Compare this diagram with that of Fig. 12.5.

If properly designed, an oscillator should work equally well whether series- or shunt-fed.

The radio-frequency choke coils (RFC) shown in the shunt-fed circuits have sufficient inductance and little enough distributed capacitance to exhibit considerable impedance to RF a-c or RF varying d-c. The higher this impedance value, the greater the RF a-c emf that can be developed across the associated tuned LC circuit. Note that an RFC is not necessarily needed in the series-fed circuits, although it is sometimes desirable to use one. If it is required, the RFC is connected between the positive terminal of the power supply and the tuned circuit, but as close to the tuned circuit as possible.

Series feed may put the tank circuit at high d-c voltages with attendant insulation and safety problems.

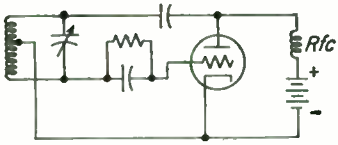


FIG. 12.15. Same Hartley circuit as Fig. 12.14, except that the positions of the parts are slightly rearranged, making the top of the coil the plate end instead of the grid end.

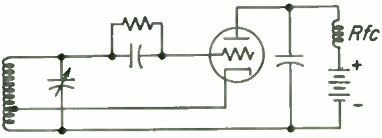


FIG. 12.16. In this rearrangement of the Hartley circuit, the bottom of the coil may be at ground potential, allowing one side of the tuning capacitor to be grounded, simplifying construction of the oscillator. Note that the cathode would be above ground potential.

**12.8 The Hartley Oscillator.** One of the most popular variable-frequency oscillators is the *Hartley* (Fig. 12.16). In its usual form it is an inductively coupled circuit; that is, plate-current variations in the plate half of the tank coil produce induced voltages in the grid half of the coil, which are in phase, or regenerative, and produce sustained oscillations of the tank circuit. However, the circuit will also oscillate if the grid and plate halves of the tank circuit are isolated from each other, indicating that part of the regenerative effect is produced by the capacitive coupling through the tuning capacitor in the tank circuit.

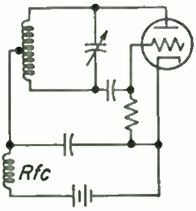


FIG. 12.17. The plate current is fed back to the battery through the plate coil. All Hartley circuits have the coil tapped, with the grid at one end, plate at the other, and cathode to the center tap.

The Hartley oscillator may be series- or shunt-fed, as with the other oscillator circuits. It has the advantage of having only one coil (center-tapped) and one tuning capacitor, thereby simplifying the construction of the circuit. Actually, the coil is not exactly center-tapped. The tap will be closer to the grid end of the coil for maximum power output, and nearer the plate end for best frequency stability.

Figures 12.11 to 12.17 show the evolution of several forms of the Hartley oscillator from an Armstrong oscillator. All these diagrams are actually practical oscillator circuits and may be found in use. Which circuit is to be used will depend on the requirements of the builder. If it is desired to keep the rotor of the tuning capacitor at ground potential to reduce *hand capacitance* (detuning of the oscillator frequency when any object is brought near the tuning capacitor), the diagram shown in Fig. 12.16 could be used. If it is desired to operate the oscillator without an RFC, both Figs. 12.16 and 12.17 could be used.

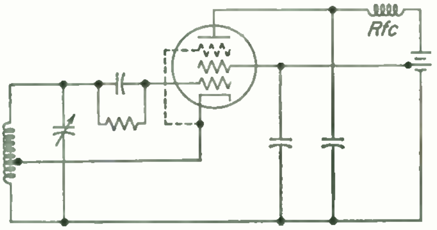


FIG. 12.18. Tetrode-tube Hartley circuit; also a pentode circuit if suppressor grid is used as shown in dotted lines.

Triodes, tetrodes, or pentodes can be used in any of these circuits. Compare the diagram in Fig. 12.18 with Fig. 12.16.

**12.9 The Colpitts Oscillator.** A frequently used variable-frequency oscillator is the *Colpitts* circuit. It is similar to a shunt-fed Hartley except that instead of the tank coil being center-tapped, two series capacitors are used in its LC circuit. The connection between these two capacitors is used as the center tap of the circuit, as shown in Fig. 12.19.

The Colpitts oscillator is normally shunt-fed, in both grid and plate circuits. While both $C_1$ and $C_2$ are shown in the diagram, the circuit will oscillate with either one shorted out. The circuit operates better with both in use, however. $C_1$ is the grid-leak capacitor and $C_2$ is the plate-voltage blocking capacitor. Without the latter, the d-c plate voltage would be across the tuning capacitors. Should any of these plates touch while the capacitance is being varied, the plate supply would be shorted and damage would result.

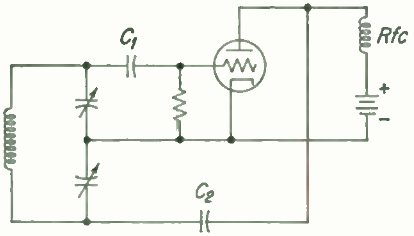


FIG. 12.19. Colpitts oscillator circuit.

The grid-end and the plate-end tuning capacitors in the Colpitts LC circuit usually have relatively large capacitance. Since they are in series, it is necessary that they each be twice the value of the tuning capacitor used in an equivalent LC circuit of a Hartley oscillator. These large capacitances across the cathode-to-grid and cathode-to-plate circuits of the tube mean that small changes in interelectrode capacitances that may occur in the tube as it warms up will have little effect on the frequency of oscillation of the LC circuit. Tube capacitances have only about half as much effect on the frequency of oscillation in the Colpitts as they do in the Hartley with any given LC-circuit coil.

In any of the variable-frequency oscillators, the greatest frequency stability is usually obtained at the lower-frequency end of the tuning range, because at this point the shunting capacitance of the tuning circuit is greatest and the ratio of interelectrode-capacitance change to tuning capacitance is at its highest.

As in the Hartley, the center-tapping of the tank circuit is not exactly in the center. If the grid-end tuning capacitor has the greater capacitance, the greater voltage drop will appear across the plate-end capacitor and the greater power output will be produced. Better frequency stability will result if the plate-end capacitor has more capacitance than the grid-end.

Besides the triode circuit shown, tetrodes or pentodes can also be used in a Colpitts circuit.

**12.10 The Ultraudion Oscillator.** The ultraudion oscillator circuit in its usual form is actually a series-fed Colpitts circuit. It is used only in very-high- or ultrahigh-frequency applications. It is a very simple circuit, operating on the same principle as the Colpitts, where the cathode is brought to the approximate center of the LC circuit capacitance. In the case of the ultraudion, these capacitances are the interelectrode capacitances of the tube. The interelectrode capacitances are shown in dotted lines in Fig. 12.20.

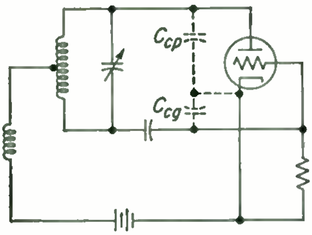


FIG. 12.20. Ultraudion oscillator circuit.

Since the circuit is used only at frequencies over 100 Mc, the required coils are quite small, as are the required capacitances. As a result the interelectrode capacitances are large enough to serve as the voltage-dividing network across the LC circuit. Although shown connected to the center of the coil, the circuit may operate with the RFC connected to either the grid or the plate end of the coil.

Note that a bypass capacitor connected between the center tap of the coil and the cathode makes a series-fed Hartley circuit out of the ultraudion.

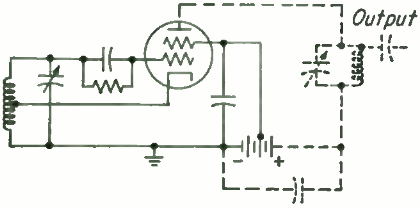


FIG. 12.21. Hartley-type ECO circuit.

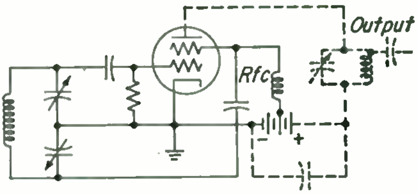


FIG. 12.22. Colpitts-type ECO circuit.

**12.11 Electron-coupled Oscillator.** The electron-coupled oscillator, or ECO, is in reality a combination of one of the previously described variable-frequency oscillators plus the amplification possible in the plate circuit of a tetrode or pentode tube (Figs. 12.21 and 12.22). It can be considered as similar to both an oscillator and an amplifier stage in one tube. The addition of the amplifier-stage effect produces more power output and also tends to isolate the oscillator from external circuits. This helps to prevent frequency changes due to variation in any circuits following the oscillator, which may be the biggest advantage of the ECO circuit.

Although the Armstrong or TPTG oscillator could be used in an electron-coupled circuit, usually the Hartley or the Colpitts, or a variation of one of them, is employed. (It is also possible to use a crystal ECO for fixed-frequency applications.)

The ECO is possibly the most used of the variable-frequency oscillators in transmitters today. The oscillating section will oscillate even if the output circuit, in dotted lines, is disconnected completely.

In the ECO diagrams it will be seen that the oscillating circuit is made up of the cathode, grid, and screen grid of the tube. The screen grid acts as the anode or plate of the oscillator circuit. When the oscillator is oscillating, the grid voltage will be varying at the oscillation frequency, which will vary the plate-circuit current at the same frequency. The only connection between the output coil in the plate circuit and the actual oscillating circuit is through the electron stream between screen grid and plate. Hence the name *electron-coupled* oscillator. The oscillator itself does not rely upon electron coupling, but the amplifying section does. Changing the output LC circuit tuning or loading should produce little effect on the frequency of oscillation, which is a highly desirable characteristic.

The plate-circuit load is shown as a tuned LC tank circuit. It may be found that when output is desired on the fundamental frequency of the oscillator, this circuit will be replaced with an RFC, or possibly a 2,000- to 10,000-ohm resistor. If output is desired on a harmonic frequency (twice, three times, four times, etc., of the oscillator), the plate tank should be tuned to the desired harmonic frequency for satisfactory output.

For simplicity, tetrode tubes are shown in the diagrams, but pentodes or other multigrid tubes are usually used. The suppressor grid is either connected directly to ground or, for greater output, to the cathode of the tube.

Notice that the bottom of the *output* tuned circuit is always bypassed to ground to complete the plate circuit as far as a-c is concerned.

**12.12 Crystal Oscillators.** Most modern commercial transmitters, either telegraph or telephone, use *crystal* oscillators because they will not drift more than a few cycles from the frequency for which they are ground. Tuned-circuit oscillators (*self-excited*) tend to drift considerably more.

An oscillating quartz crystal usually looks like a piece of frosted window glass cut into ½- to 1-in. squares and then ground smooth on all surfaces. Actually, window glass does not have the required properties to operate as an oscillator. Instead of glass, special crystalline quartz is cut in thin slices and ground smooth. Such quartz crystals have peculiar properties.

If a crystal is held between two flat metal plates and the plates are pressed together, a small emf will be developed between the two plates, as if the crystal became a battery for an instant. When the plates are released, the crystal springs back to its original shape and an opposite-polarity emf is developed between the two plates. In this way, physical energy is converted to electric energy by the crystal.

Furthermore, if an electric emf is applied across the two plates on either side of a crystal, the crystal will distort its normal shape. If an opposite-polarity emf is applied, the crystal will reverse its physical distortion. In this way, electric energy is converted to physical energy by the crystal.

These two reciprocal effects, physical energy converting to electric energy and electric energy converting to physical energy, in a crystal are known as *piezoelectric effect* (pronounced pie-ee-zo). A crystal oscillator circuit can be called a piezoelectric oscillator.

If a crystal between metal plates is shock-excited by either a physical stress or an electric charge, it will continue to vibrate physically at its natural frequency for a short while and at the same time produce an a-c emf between the plates. This is somewhat similar to the damped electron oscillation of a shock-excited LC circuit. Actually, a vibrating crystal will produce an alternating emf longer than an LC circuit will when shock-excited, because the crystal has a much higher $Q$ (fewer losses) than it is possible to obtain in ordinary LC circuits.

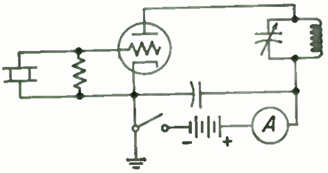


FIG. 12.23. Crystal oscillator, similar to a TPTG circuit.

To construct a practical crystal oscillator, it is only necessary to substitute a crystal, held between two plates, for the LC circuit of a TPTG oscillator (Fig. 12.23). In this circuit the crystal is operating as a high-$Q$ parallel-resonant circuit. Notice that no grid-leak capacitor is needed since the crystal will block any d-c flow.

When the switch is closed, the LC circuit in the plate circuit is shock-excited into oscillation by the sudden surge of plate current. The a-c developed across this LC circuit is fed back to the top crystal plate through the grid-plate interelectrode capacitance, and to the bottom plate of the crystal through the bypass capacitor from the LC circuit. When the crystal is excited by the a-c, it starts vibrating and working as an a-c generator on its own. The emf generated by the crystal is being applied to the grid and cathode and produces plate-current variations in phase with the plate LC circuit oscillations. With both crystal and LC circuit oscillating and feeding each other in phase, the whole circuit continues in sustained oscillation and acts as a very stable a-c generator.

If the plate LC circuit is not tuned close enough to the natural frequency of oscillation of the crystal, voltages developed in it will not be sufficiently in phase to produce the required mutual-aiding effect between the two circuits and no sustained oscillations will result. With no oscillation of the circuit, there will be no grid bias developed across the grid-leak resistor and the plate current will rise to a high value. When the plate circuit is tuned nearly to resonance with the crystal frequency, the circuit will be shocked into oscillating, because of minute changes in cathode emission, and a bias voltage will be developed that will decrease the average plate-current value. It is possible to tune this type of oscillator by watching the action of a milliammeter in the plate circuit. A decrease of plate current, as the plate LC circuit is tuned, is an indication that the circuit is oscillating and developing grid bias. The stronger the crystal oscillates, the greater the grid-leak bias developed and the lower the plate-current indication.

The minimum-plate-current reading may indicate strongest oscillation of a crystal-oscillator stage, but it does not necessarily indicate the optimum operating condition. For most satisfactory operation the plate-current value should be brought down about three-quarters of the way from maximum toward the minimum value. This will allow the circuit to be immediately self-starting, which may be very important in radiotelegraph transmitters. In practice, the plate circuit is not tuned exactly to the frequency of the crystal, but is detuned a few kilocycles.

When tuning a crystal stage, as the plate LC circuit is *increased* in frequency the plate current suddenly drops down to minimum. However, if the plate circuit is *decreased* in frequency while tuning, the plate current gradually decreases to the minimum value and then pops up to a maximum. This is a tuning characteristic of this type of crystal oscillator. Radio-frequency amplifier stages may also be tuned by watching their plate current, but unlike the crystal oscillator, as resonance is approached the current drops off gradually, whether tuning from high to low or low to high frequency.

The frequency of vibration, or oscillation, of a crystal is determined primarily by its physical size, thickness, angle of cut, and temperature. It is possible to vary the frequency of oscillation somewhat by changing the capacitance of the holder or by placing a small capacitance across it. Too large a capacitance will stop it from oscillating, but a small variable capacitor will allow adjustment of the frequency of oscillation by a few cycles (Fig. 12.24). Such a variable capacitor is often incorporated in modern commercial equipment.

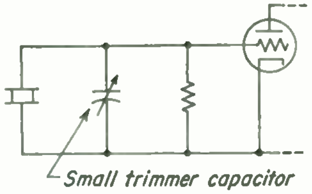


Fig. 12.24. Variation of capacitance across a crystal varies the oscillating frequency somewhat.

As the plate LC circuit is adjusted to the proper tuning point, it will be noticed that the frequency of oscillation may vary a few cycles or as much as a kilocycle. Replacement of the oscillator tube with a new one will often change the oscillation frequency a few cycles. Variation of the pressure on the crystal by the plates will shift the frequency of oscillation also. It can be seen that even if the manufacturer indicates a certain frequency of oscillation for a given crystal, it is quite possible that it may oscillate a few cycles one way or the other from the specified frequency.

For low-frequency crystals it may be necessary to add a small capacitor between plate and grid of the tube to increase the feedback sufficiently to produce oscillation. However, excessive feedback may cause excessive crystal excitation and fracture the crystal.

While *thickness* vibrations of thin crystals has been used in the explanations, if cut from quartz at the correct angle, a crystal will vibrate corner to corner (*shear*) or end to end (*longitudinally*). This results in a much lower frequency of oscillation using the same-size crystal. Such crystals are often silver-plated on the two flat surfaces, with a connecting wire soldered to the middle of each silvered surface. This allows shear or longitudinal oscillations but damps out thickness vibrations. Silvered crystals with connections made to the edges of the plates will produce thickness oscillations. Crystals may also vibrate *flexurally* (bending back and forth), *torsionally* (twisting movement), or in two or more different modes at the same time.

Although crystals are quite stable in frequency, changes in plate potential will shift the oscillation frequency. Because of this a separate power supply is advisable for the oscillator stage in a multistage transmitter.

**12.13 Crystals and Temperature Coefficients.** The manner in which a crystal is sliced from the natural raw quartz crystal will help to determine its natural oscillating frequency, its frequency stability, and its *temperature coefficient* and even to name the type of crystal.

Oscillating crystals are cut from six-sided quartz crystals that are found in nature. An end view of two such quartz crystals is shown in Fig. 12.25. The dotted lines indicate the *X* and the *Y* axes. The *Y* axis is from one flat face to the opposite flat face of the crystal. The *X* axis is from one corner to the opposite corner. A crystal sliced out of the quartz at *right angles* to the *Y* axis is called a *Y-cut* crystal. If cut at *right angles* to the *X* axis it is called an *X*-cut crystal. Figure 12.25 also shows the angle at which a *Y*-cut and an *X*-cut crystal is sliced from the raw quartz crystal.

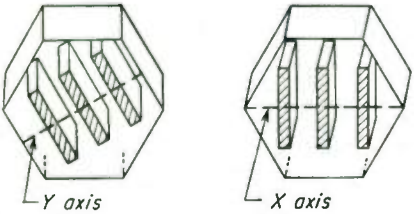


FIG. 12.25. Angles at which *Y*- and *X*-cut crystals are sliced from the raw crystalline quartz.

When crystals are cut at angles other than *X* and *Y* cuts they are given other names. Some other cuts are the *AT*, *BT*, *CT*, *Z*, etc. Some cuts operate more satisfactorily on high frequencies, others on lower frequencies. Different cuts have different temperature coefficients and oscillating characteristics.

The listing that follows should make clear the meaning of temperature coefficient of a crystal.

1. If a change in its temperature produces a relatively large variation in the oscillation frequency of a crystal, it has a *high* temperature coefficient.

2. If a change in its temperature produces a relatively small variation in the oscillation frequency of a crystal, it has a *low* temperature coefficient.

3. If a change in its temperature produces no variation in the oscillation frequency of a crystal, it has a *zero* temperature coefficient. (Actually no crystal has a true zero coefficient, although some cuts have a very low temperature coefficient over a fairly wide temperature range and are considered as zero-temperature-coefficient crystals.)

4. If an increase in its temperature produces an increase in its oscillating frequency, a crystal has a *positive* temperature coefficient.

5. If an increase in its temperature produces a decrease in its oscillating frequency, a crystal has a *negative* temperature coefficient.

Many crystals have a positive temperature coefficient when operated at about 70°F, nearly zero at about 110°, and negative at temperatures above 140°. Such crystals, if their temperature can be held at about 110°, will *operate* as though they had a zero temperature coefficient.

*Y*-cut crystals have a range of about $-25$ to $+100$ cycles/°C/Mc (cycles per degree per megacycle). They also have the disadvantage of having a second frequency at which they may oscillate. A frequency meter, explained in the chapter on Measuring Frequency, must be used when tuning such a crystal stage to make sure that the frequency of oscillation is the desired frequency.

*X*-cut crystals have a temperature coefficient range of about $-10$ to $-25$ cycles/°C/Mc.

Compare these ranges with those of a *GT*-cut, which has a $-1$- to $+1$-cycle/°C/Mc range. The *GT*-cut is almost a zero-temperature-coefficient crystal from freezing to boiling. However, it is useful at frequencies up to a few hundred kilocycles only.

An example of the use of temperature-coefficient information is indicated by the following problem:

A 600-kc *X*-cut crystal, calibrated at 50°C and having a temperature coefficient of $-20$ parts per million (ppm) per degree centigrade, will oscillate at what frequency when its temperature is 60°C?

First, the " $-20$ parts per million per degree" can be read as "a negative temperature coefficient of 20 cycles/°C/Mc"; 600 kc is only 0.6 Mc. Therefore the expression above can be read, " $-20$ cycles/°C/Mc × 0.6." The change in temperature is

10°. The change in cycles is then $-20$ times 10 times 0.6, or $-200 \times 0.6 = -120$ cycles. By increasing 10° in temperature the crystal loses 120 cycles from its 600,000-cycle calibration, or oscillates at a frequency of 599,880 cycles, or 599.88 kc. (If the crystal had the same value of positive temperature coefficient, the 120 cycles would have been added instead of subtracted.)

In many transmitters, the oscillator may be operating on a certain frequency, and the transmitter may be transmitting on some integral multiple, or harmonic, of the fundamental frequency. For example, if a transmitter uses a 1,000-kc crystal with a temperature coefficient of $-4$ cycles/°C/Mc, if the crystal temperature increases 6°, the crystal will decrease its frequency of oscillation $-4 \times 6$, or $-24$ cycles. If the output of the transmitter is supposed to be 5 times the fundamental, or 5,000 kc, the output frequency will decrease $5 \times (-24)$, or a change of 120 cycles. The output frequency will be 5,000,000 less 120 cycles, or 4,999.88 kc.

**12.14 Temperature-controlled Chambers.** If the crystal used in a crystal oscillator is held at a constant temperature, the frequency of oscillation will also remain constant. If the crystal varies in temperature, because of air currents across it or the natural increase in temperature when it is in operation, the frequency of the oscillator will change.

To prevent frequency drift due to changing temperatures, crystals may be operated in special airtight chambers. These chambers are held at a temperature higher than the crystal would normally operate, and higher than room temperature. Temperatures from about 110 to about 140°F are satisfactory. Such a chamber will have a resistor acting as an electric heater in it. This heater can bring the chamber to the desired temperature in a few minutes. It is necessary to turn on the chamber several minutes before operation is started if good frequency stability is desired. In many commercial stations the crystal chambers are never turned off, even if the transmitter is shut down for 6 to 8 hr each day.

In many radio services such exact frequency control may not be necessary, but in radio broadcasting the transmitter must never vary more than 20 cycles from its assigned frequency. In this case constant-temperature crystal chambers are practically mandatory.

A temperature-controlled chamber may consist of a box made of heat-insulating material, in which is located the crystal in its holder, the heating resistor, and either a *bimetallic element* or a special thermometer that makes an electric contact when the mercury column in it expands to a certain point and breaks the contact if the temperature drops below that point.

If the mercury thermostat is used, Fig. 12.26 shows a diagram of a possible temperature-controlled chamber and its associated equipment.

The important point about this circuit is the center-tapped transformer winding in the grid circuit. The center tap, because it is connected directly to the cathode, is always considered to be at zero potential. At any instant that the right side of the grid winding is positive, the left side will be negative in respect to the cathode. During the other half cycle the polarities will reverse.

The grid and plate windings of the transformer are connected in such a way that when the plate is positive and the thermometer contacts are open, the grid is connected through the grid resistor to the positive side of the grid winding. This places a positive voltage on the grid whenever a positive voltage is applied to the plate. If the grid and plate are both positive at the same time, plate current will flow and the resistor heats. The chamber starts to warm, and the thermometer column starts to rise. When the grid and plate are both negative, no plate current can flow. Therefore the resistor is only heating on one-half of each a-c cycle.

When the thermometer contact is closed by the rising mercury, the control grid is connected directly to the opposite end of the grid winding.

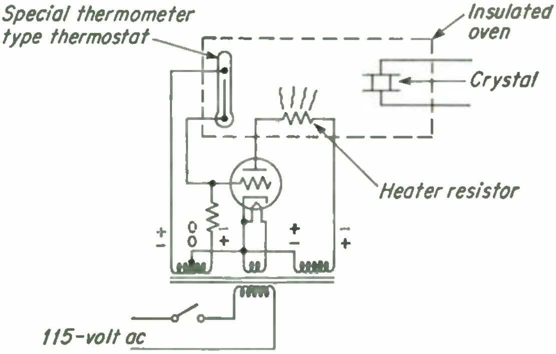


FIG. 12.26. Temperature-controlled chamber using a mercury thermostat.

Now when the plate potential is positive, the grid is negative and no plate current flows. With the thermostat open, the chamber heats, but with the thermostat circuit closed, the chamber cools. In actual operation the heating and cooling cycle may take from 10 to 60 sec. A small lamp can be included in the plate circuit. It will glow during the heating period and be dark during the cooling period, giving a visual indication of chamber operation.

A bimetallic element could be used in place of the mercury thermostat. A bimetallic element is composed of two thin strips of different metals bolted, riveted, or welded together. The metals are chosen so that one expands considerably when heated and the other expands very little. Such a strip can be arranged as shown in Fig. 12.27. When current flows through the resistance wire, the air or gas in the chamber, the crystal, and the bimetallic element all heat. If the bottom strip expands more than the top, the element will be forced to bend upward at the free end, opening the two contacts and breaking the heater circuit. When the chamber cools, the strip will bend down again and re-establish contact, starting the heating cycle again. An inert gas should be used in the chamber to prevent oxidation of the contacts due to sparking on the *make* and *break* of the circuit.

The mercury column is considered to make a more dependable contact, does not oxidize, and is more sensitive to temperature changes.

**12.15 Crystal Holders.** There are several types of holders used for crystals. The basic type of holder consists of a hollowed-out block of bakelite or other insulating material in which two perfectly flat metal plates and the crystal are mounted, as shown in Fig. 12.28. A spring against the top plate holds together the sandwich formed by the crystal between the two plates. An electrical connection is then taken from each plate.

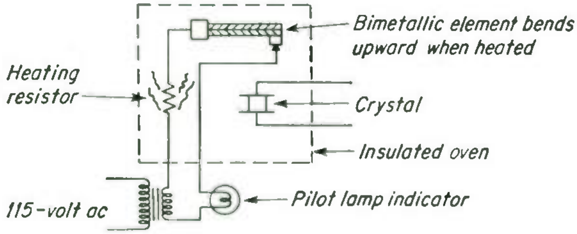


FIG. 12.27. Temperature-controlled chamber using a bimetallic element.

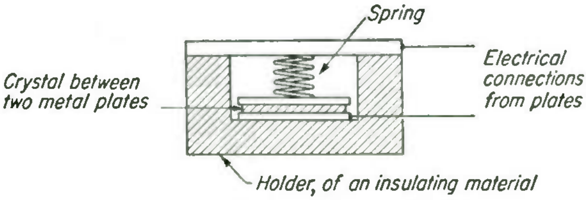


FIG. 12.28. Basic form of crystal holder.

Another type of holder is made in a similar manner, but the metal plates have raised corners. The raised corners touch the crystal, but the remainder of the plate has a slight air gap between it and the crystal. These air-gap mountings are often used with higher-frequency crystals.

Various types of holders are used with *plated* crystals. Instead of using plates against the flat surfaces of the crystal, many of the modern crystals are plated with a thin layer of metal on both of the flat surfaces. The holder makes a light pressure contact at some point on each plated surface.

When it becomes necessary to clean crystals, there are several ways to clean them satisfactorily. Two methods are: (1) wash with warm soap and water and rinse in clean water; (2) wash with carbon tetrachloride. In either method, the crystals should not be touched with the bare hands but should be handled with clean lint-free cloths, and by the edges rather than by the flat surfaces. The metal plates must also be cleaned. WARNING: Care must always be taken when using carbon tetrachloride for any reason. Its fumes are very poisonous. Assure adequate ventilation. If the liquid gets on the skin, it should be washed off immediately with soap and water.

Crystals are very fragile. They should be handled and operated with caution. They will fracture easily if dropped. If too much energy is fed back to them by a high value of coupling from the plate circuit, they may oscillate or vibrate so hard that they will fracture themselves. If the edge of a crystal becomes chipped, the crystal can usually be ground down on that edge but the frequency of oscillation will increase. Grinding is done on a flat surface such as on a piece of plate glass, using a mixture of very fine carborundum dust and water as the grinding compound. The frequency of a crystal can be raised by grinding its flat surfaces with such a compound. The frequency of a crystal can usually be lowered a few hundred cycles by marking an X from corner to corner on one or both flat surfaces with solder or lead.

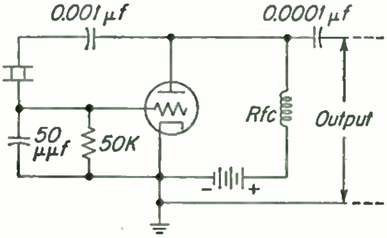


FIG. 12.29. Pierce crystal oscillator circuit.

### 12.16 Other Crystal Circuits.

Besides the basic TPTG-type crystal oscillator described, crystals can be used in other circuits. The *Pierce* circuit uses a crystal in place of the LC circuit in an ultraudion oscillator (Fig. 12.29). The Pierce oscillator has the advantage of not requiring any tuned circuits. However, it is harder on crystals, and relatively lower plate voltages must be used, limiting the output power from such a circuit. A small capacitor is usually inserted in series with the crystal to decrease the d-c voltage drop across the crystal.

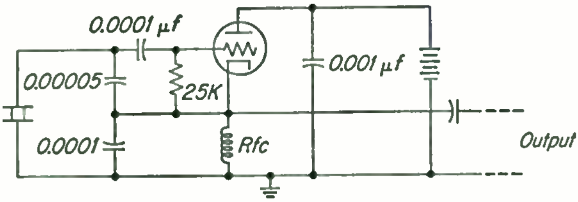


FIG. 12.30. Colpitts-like crystal oscillator circuit.

Another circuit in which a crystal can be used is the Colpitts. In this circuit the crystal is used in place of the usual coil and capacitor of a Colpitts oscillator (Fig. 12.30). This circuit has excellent stability. The value of the capacitance of the two capacitors across the crystal can control the degree of coupling between plate and grid.

The pentode tube was designed to reduce plate-grid capacitance. The TPTG crystal circuit depends on plate-grid capacitance to feed back energy from the plate circuit to the grid to support sustained oscillations. It would seem that a pentode crystal circuit would not be practical. However, the gain of a pentode tube is so great and the $Q$ of a crystal so high that even with the small value of plate-grid capacitance, enough energy can be fed back to produce oscillation of the circuit. A diagram of a pentode crystal oscillator circuit is shown in Fig. 12.31. Because so little RF a-c excitation is required to keep the crystal oscillating in a pentode circuit, it is possible to use relatively high plate voltage and obtain relatively higher power output from such a circuit than might be possible with a triode and still not overheat or fracture the crystal. A tetrode crystal oscillator is also possible.

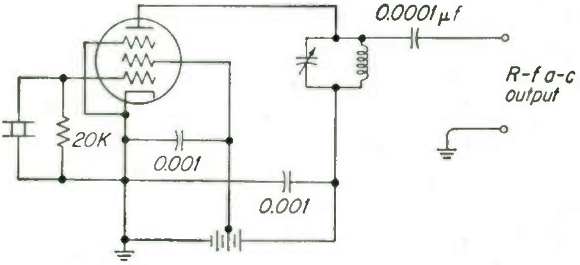


FIG. 12.31. Pentode crystal oscillator circuit.

**12.17 Some High-frequency Oscillators.** For the generation of audio frequencies, coils with iron cores are usually used. From 20,000 cycles up to around 500 kc, less inductance and capacitance are needed to attain resonance and maintain high $Q$. Cores with powdered-iron or air cores are usually used. From 0.5 Mc to more than 100 Mc, to obtain less inductance and still retain $Q$, air-core coils are usually employed, although powdered-iron cores are also in use. Above 100 Mc the inductance required is so small that only a few turns of a half-inch diameter are needed for tuned circuits. This small inductance shunted by the tube capacitance alone may resonate the circuit to this frequency. For frequencies above 300 Mc the coils bcome so small as to be impractical.

Consider some of the difficulties of 300-Mc operation. For example, it is desired to feed the grid and plate of a tube 180° out of phase at 300 Mc. At normal frequencies this can be done by using an LC circuit tuned to the frequency used. Across such a circuit the voltages are always opposite, or 180° out of phase. With normal tubes, the grid-plate capacitance may be so great and the inductance of the tube element leads so great that the added inductance of even a short piece of wire directly connecting the grid to the plate resonates at a lower frequency than the desired 300 Mc. Special high-frequency tubes have very short grid and plate leads and small grid-plate capacitance, so that it is possible to use small coils at 300 Mc and obtain circuit operation. As the frequency is increased a few hundred more megacycles, even these tubes may not operate.

One means of partially overcoming such difficulties is by the use of linear tank circuits. To explain this it is necessary to investigate the meaning of *wavelength*.

The speed of an electric impulse is 186,000 miles per second, or 300 million meters per second. A 300-Mc a-c completes its cycle in one three-hundred-millionth of a second. In this time an electric impulse will travel 1 meter, or 39.37 in.

If a 300-Mc generator is connected to a very long piece of wire, the instantaneous voltage values along the first 39.37 in. of the wire at one instant might be as shown in Fig. 12.32.

One-half meter from the starting point the voltage is 180° out of phase. Therefore, if a half-meter-long piece of wire is connected between grid and plate of a tube, it should take the place of a 300-Mc parallel-tuned LC circuit. The half-meter piece of wire could be bent into a *hairpin* and connected anywhere that an LC circuit is used and should operate as a tuned circuit.

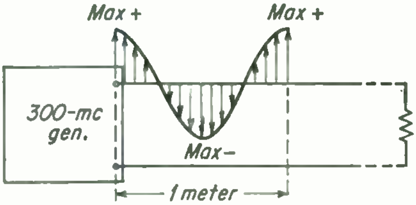


FIG. 12.32. Instantaneous voltage distribution of an a-c having a frequency of 300 Mc.

At 300 Mc a half-meter piece of wire is said to be a *half-wavelength* long. A full-wavelength wire is 1 meter long.

From the above information it can be generally stated that a half-wavelength of wire at any frequency can be used in place of a parallel-tuned LC circuit at that frequency.

The formula to find the full wavelength at any frequency is

$$\text{Wavelength} = \frac{\text{velocity}}{\text{frequency}} \qquad \text{or} \qquad \lambda = \frac{V}{F} \qquad \text{or} \qquad \lambda = \frac{300{,}000{,}000}{F}$$

where $\lambda$ is wavelength in meters; $F$ is frequency in cycles (per second); and $V$ is the velocity of a radio wave in meters/sec.

Applying this formula, the wavelength of a 30-Mc frequency is 300,000,000 divided by 30,000,000, or 10 meters long. A hairpin made of a wire 5 meters long will operate at 30 Mc as a parallel-tuned circuit. The length of the hairpin itself would be 2.5 meters, or a quarter-wavelength. Such linear hairpin tank circuits are usually considered to be two quarter-wavelength wires shorted together at one end.

A TPTG oscillator made up of quarter-wavelength lines ("linear tank") is shown in Fig. 12.33.

The interelectrode capacitances of the tube are across the hairpin ends. This effectively lowers the frequency of oscillation for a given-length hairpin. As a result, in practice it is necessary to use hairpins somewhat less than a complete quarter-wavelength. Such parallel-line tank circuits have high $Q$, which is an advantage. To tune these lines to resonate at a desired frequency, a small variable capacitor may be connected across the ends of the hairpin, as shown.

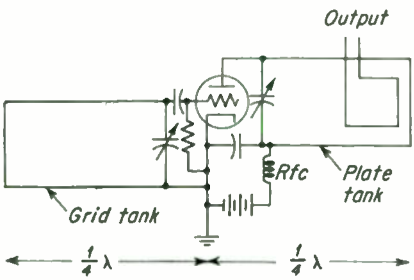


FIG. 12.33. A TPTG oscillator using quarter-wave hairpin tank circuits.

Besides the quarter-wave-long hairpin tank, it is also possible to use two parallel half-wave lines, open at the far ends, as a resonant circuit. The inductive and capacitive coupling between two parallel lines produces 180° out-of-phase voltages at the ends of the parallel wires. Oscillators of this form are shown in Fig. 12.34.

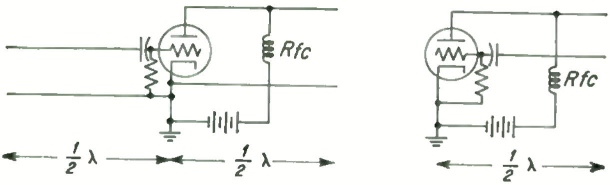


FIG. 12.34. Half-wave parallel-line TPTG oscillators.

Another variation of the hairpin form of tank circuit is the *coaxial* tank. It is composed of a thin conductor running up the center of a piece of copper tubing. The conductor is connected to the sealed end. A TPTG circuit using coaxial tanks is shown in Fig. 12.35. Such tank circuits isolate the oscillating electrons from outside effects. The electrons oscillate up and down the central wire and on the inner surface of the copper tubing, but not on the outside.

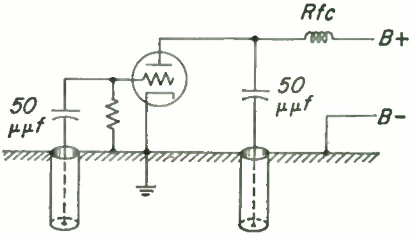


FIG. 12.35. Quarter-wave coaxial tanks in a TPTG oscillator circuit.

Another variation used at still higher frequencies is the *resonant-cavity*. As a simplified explanation, it may be seen as many hairpin circuits of the same dimensions laid side by side and soldered together, forming a single wide hairpin. Then the open sides of the hairpin are closed over with a sheet of metal, producing a metallic cavity (Fig. 12.36). The electrons now oscillate back and forth *inside* the cavity thus formed.

Cavity resonators will be discussed in the chapters on Radar and Television, in which services they are used extensively. The cavities are usually associated with klystron and magnetron tubes, rather than the usual triodes.

Energy is taken from all these circuits by using either a hairpin or a hook, shown in Figs. 12.33 and 12.36.

The higher the frequency, the greater the skin effect and the higher the effective resistance of a conductor. As a result, high-frequency circuits use large wires or large-area components such as resonant cavities. Since the current travels on the skin only of conductors at high frequencies, it is preferable to silver-plate the conductors. This increases the $Q$ of the circuits, which otherwise might be excessively low.

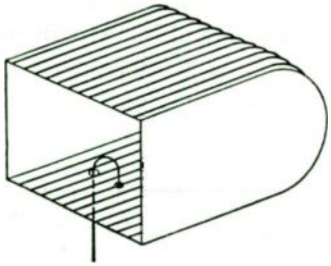


FIG. 12.36. Resonant cavities are equivalent to many quarter-wave hairpins side by side and soldered together.

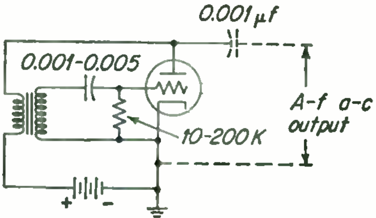


FIG. 12.37. Audio oscillator using the Armstrong circuit.

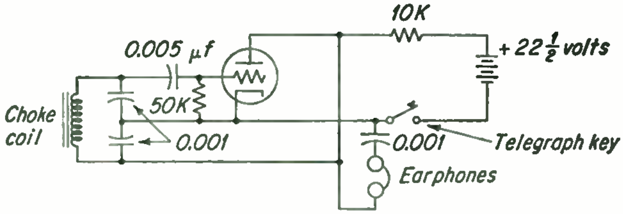


FIG. 12.38. Audio oscillator using the Colpitts circuit with a choke coil.

**12.18 Audio Oscillators.** The oscillators described have been RF types. The a-c generated is presumably well above the audible frequencies. An audible-frequency a-c may be desired for a code-practice circuit or as an audible-frequency source. If larger inductances (usually iron-core) are used, with larger capacitors, the oscillator circuits shown will generate an a-c that is audible as a tone in earphones or in a loudspeaker. As an example of an AF oscillator, an Armstrong circuit is shown in Fig. 12.37. The tickler coil and the tuned-circuit coil take the form of an iron-core transformer. The value of the grid-leak resistor helps to control the frequency of this circuit by changing the charge and discharge time of the grid-leak capacitor and resistor combination.

A Colpitts-circuit AF oscillator using a choke coil instead of a transformer is shown in Fig. 12.38. Note the use of a resistor instead of an RF choke or AF choke in the plate circuit. As long as only a little audio power is desired it is much more economical to use the resistance to obtain the required impedance across which the AF a-c voltage drop can be developed.

**12.19 Dynatron Oscillator.** In all the oscillator circuits described so far, an inductive or capacitive feedback of energy from plate to grid circuits is used to produce sustained oscillations. The dynatron oscillator operates on an entirely different basic principle, called *negative resistance*.

When a circuit has negative resistance it is working contrary to Ohm's law. For instance, according to Ohm's law an increase in emf in a circuit produces an increase in current. If an increase of emf in a circuit results in *less* current, the circuit is said to be exhibiting a negative-resistance effect.

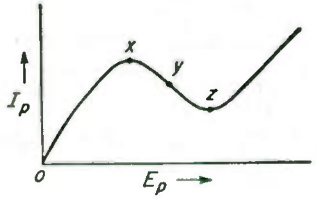


FIG. 12.39. $E_pI_p$ curve of a tetrode showing negative-resistance effect from $X$ to $Z$. Plate and screen-grid voltages approximately equal at point $Y$.

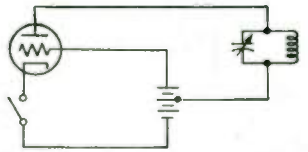


FIG. 12.40. Basic dynatron oscillator circuit using a triode.

A negative-resistance effect can be developed by operating the grid nearest the plate of a tube (screen grid in a tetrode) at a positive potential a little greater than the plate potential. If the grid is kept at a constant positive value, the plate current will increase as the plate voltage is brought up from zero to a certain point, $X$ in Fig. 12.39. Then, as the plate voltage is increased further, the plate current begins to decrease because of secondary-emission electrons from the plate traveling to the grid. (If more electrons are leaving the plate as secondary emission than arrive on it, the plate current is reversed.) If the plate voltage is increased still more, the plate is able to attract the secondary-emission electrons more than the grid, and the plate current will increase again with a further increase of plate voltage. The downward slope of the plate-current curve, $X$ to $Z$, indicates the range of plate voltages over which a negative-resistance effect is exhibited by the tube.

By the use of a tuned LC circuit between plate and grid, as shown in Fig. 12.40, a basic dynatron oscillator circuit is formed.

When the switch is closed, the plate LC circuit is shock-excited and the a-c voltages developed across the tuned circuit are added to the battery voltage being applied to the plate. If the battery voltage is adjusted to a value near point $Y$ on the curve, with the grid more positive than the plate, the plate voltage will be varying in the range $X$ to $Z$, (Fig. 12.39). The negative-resistance effect will be operating in such a phase as to aid the oscillations of the LC circuit, and the circuit will function as a generator of sustained oscillations.

Tetrode tubes were used in dynatron oscillators because control grids of triodes were not constructed ruggedly enough to stand the current they would have to carry in such a circuit. A practical dynatron oscillator circuit is shown in Fig. 12.41. Bypass capacitor $C_1$ affords a low-reactance a-c path from the LC circuit to the screen grid. $C_2$ brings one end of the LC circuit to ground potential as far as a-c is concerned. $C_3$ holds the control grid to a constant value.

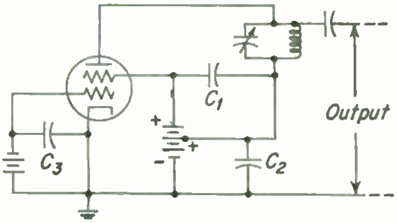


FIG. 12.41. Actual dynatron oscillator circuit using a tetrode.

Frequency stability of dynatron oscillators is very good. The circuit is relatively simple, but it has low power output. Since tetrode tubes of a desirable type for secondary emission are no longer manufactured, the dynatron circuit is rarely used any more. Over a long period of time the surface of the plate of the tube used in a dynatron oscillator may change somewhat, altering the secondary-emission characteristics and the frequency of the oscillator.

**12.20 RC Oscillators.** All the oscillator circuits described so far generate essentially sine-wave a-c. A true sinusoidal wave contains no harmonic (a multiple of the fundamental frequency) energy. A 6-Mc oscillator producing slightly distorted a-c will also be producing some 12-, 18-, 24-, 30-Mc, and so on, energy. These are the second, third, fourth, and fifth harmonics of the 6-Mc fundamental. The farther the wave deviates from the sine waveshape, the greater the proportion of harmonic energy generated.

An LC circuit, when oscillating, tends to produce sinusoidal a-c. When a minimum of harmonics is desired, LC oscillators are usually employed. If many harmonics are required, a jagged, saw-tooth waveform is best. Such a waveform is produced by *relaxation oscillators*. Since the rate of oscillation is dependent upon the values of resistance and capacitance in the circuit, they are also known as *RC oscillators*.

The simplest of the relaxation oscillator circuits is the neon-bulb circuit, shown in Fig. 12.42. When the switch is closed, the battery emf begins to force electrons through the resistor $R$ charging capacitor $C$. The higher the resistance value, the fewer electrons passed through it in a given time and the longer it takes to charge the capacitor.

In the circuit shown, the capacitor will never charge up to the 200 volts of the battery. The neon gas in the bulb ionizes when an emf of about 80 volts is across its two electrodes, which presents a low-resistance circuit to the capacitor. The capacitor now sees a short circuit across itself and immediately discharges through the bulb. In the diagram, electrons on the top plate will move through the bulb to the bottom plate, dropping the voltage across the capacitor rapidly. When the voltage across the neon bulb reaches a low value, the ionized gas *de-ionizes*, or extinguishes, and the capacitor is free to start recharging. When the voltage across the capacitor rises to 80 volts again, the capacitor is once more discharged by the ionized gas, and this oscillation continues, producing sustained saw-tooth varying d-c voltages across the capacitor, as shown in Fig. 12.43.

If greater or smaller saw-tooth voltages are required, tubes filled with gases having other ionization characteristics may be used.

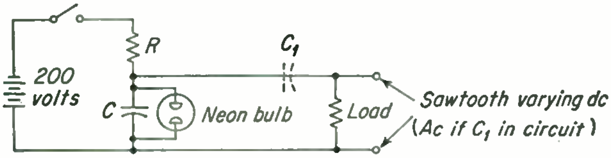


FIG. 12.42. Neon-bulb RC oscillator.

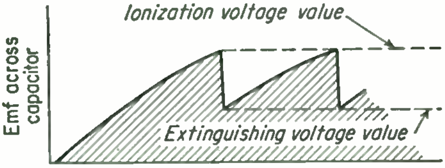


FIG. 12.43. Saw-tooth varying d-c wave from RC oscillator.

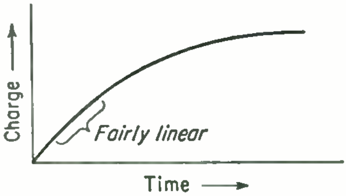


FIG. 12.44. Rise of potential across a charging capacitor.

Factors determining the time to charge the capacitor are: (1) size of the capacitor—the larger, the longer time taken to charge it; (2) the voltage of the battery—the higher the supply voltage, the greater the current through the resistance and the quicker the capacitor will charge to the ionization voltage; (3) resistance.

The charging-voltage curve of a capacitor is not a straight line (Fig. 12.44). To obtain a fairly linear (straight-line) rise of voltage, only a small part of the charging curve should be used. To assure this, a charging voltage several times the ionization voltage is required.

To change the saw-tooth varying d-c to a similar-shaped a-c, it is necessary only to couple to the load through a capacitance, shown in dotted lines (Fig. 12.42). The varying d-c waveshape of Fig. 12.43 would change to an a-c with a waveshape as shown in Fig. 12.45.

Triode or tetrode thyratrons filled with an ionizable gas may be used in an RC oscillator circuit. They operate on the same general principle as the neon-bulb oscillator, except that the negative potential applied to the grid will determine the ionization voltage of the tube. As the movable arm is adjusted on the potentiometer in Fig. 12.46, the grid bias, and therefore the ionization voltage of the tube, can be varied over relatively wide limits. The more negative the bias on the grid, the higher the voltage to which capacitor *C* will charge before the tube ionizes and discharges the capacitor. Type 884 and 885 tubes are gaseous triodes, usable in this circuit. A practical circuit requiring no bias supply is shown in Fig. 12.47.

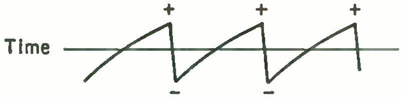


FIG. 12.45. Saw-tooth a-c produced from the saw-tooth varying d-c of Fig 12.43.

The resistance of an ionized neon bulb or gaseous tube is not an absolute short circuit. It has some resistance to current flow. Therefore it does not discharge the capacitor instantaneously. This slight time interval may be unimportant if the frequency is relatively low, but when the frequency of oscillation is increased to more than a few thousand cycles, the times to charge and to discharge the capacitor become equal. The waveform becomes more triangular. For harmonic generation this may still be satisfactory, but for sweep circuits requiring a slow linear rise and a rapid return it is unsatisfactory. Other circuits can be used. One of these is the *multivibrator*.

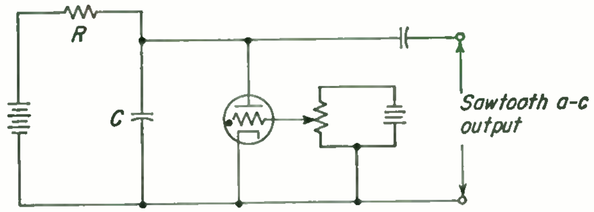


FIG. 12.46. Thyratron relaxation oscillator circuit. Frequency is controlled by the bias adjustment of the potentiometer.

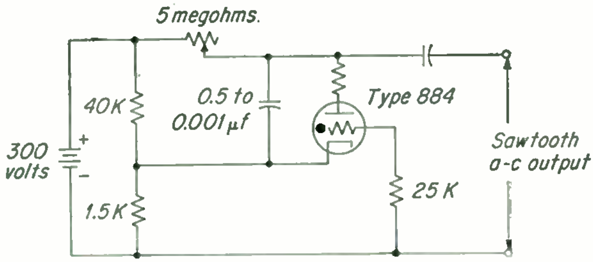


FIG. 12.47. Thyratron relaxation oscillator requiring no bias battery.

**12.21 Multivibrator Oscillators.** One of the many possible relaxation oscillators, or saw-tooth-wave generators, is the *multivibrator* circuit. It consists of two high-vacuum tubes connected in an RC coupled circuit (Fig. 12.48).

In any normal multistage amplifier there is a 180° phase change from the grid of one stage to the plate of that stage, or to the grid of the following tube. If the grid of the first tube suddenly goes more negative, the grid of the second tube goes more positive. As the grid of the second tube goes more positive, its plate is going more negative (less positive). If the output of the plate of the second tube is fed back to the first grid, the feedback voltage will be in phase and will increase the effect of the originating voltage change on the grid of the first tube. This in-phase feedback produces a slow charging of coupling capacitors through resistors, and then a rapid discharge when the tube begins to conduct. A sustained-relaxation form of oscillation is produced. Resistors in the grid and plate circuits and the coupling capacitors determine the frequency of oscillation. If LC circuits were substituted for the plate-load resistors, the resulting waveform would be essentially sinusoidal.

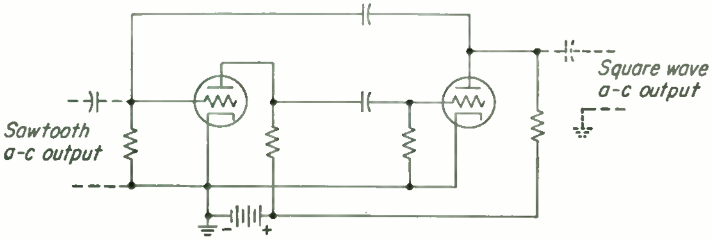


Fig. 12.48. Multivibrator oscillator circuit.

The saw-tooth waveform may be taken from across either of the *grid* resistors. A square waveform is developed across either plate-load resistor.

For some applications such as frequency measuring, the multivibrator circuit has too poor a frequency stability. To stabilize the circuit and force it to remain oscillating at one frequency it is possible to feed a stable, synchronizing sine-wave voltage from a crystal oscillator into any of the grid or plate circuits. The synchronizing voltage is either the same frequency or some multiple of the frequency of the multivibrator. A multivibrator can be held to 10-kc oscillation by using a 10-, 20-, 30-, and up to 100-kc crystal oscillator to produce the synchronizing, or stabilizing, voltage. Stabilization becomes more difficult as the stabilizing frequency increases. The stabilizing frequency is usually less than 10 times the frequency to be stabilized. Even though the synchronizing voltage is sinusoidal, the output of the multivibrator remains saw-toothed.

**12.22 Parasitic Oscillations.** Parasitic oscillations are unwanted, or parasite, oscillations in oscillator or amplifier stages. They occur frequently in transmitters, receivers, and audio equipment. They are very detrimental to the operation of the stage in several ways.

Parasitic oscillations are usually at a frequency considerably removed from that on which the stage is meant to operate. For example, a transmitter is operating on 6 Mc, but nearby receivers can hear signals from it every 100 kc from about 4 to 8 Mc. Furthermore, the transmitter tubes may overheat from overload, or tuning is found to be erratic. In all probability one or more stages are oscillating at 100 kc in some way. This is a low-frequency parasitic oscillation.

In another case a transmitter is operating, but tuning is erratic, the plates of the tubes show excessive color, plate current is not normal, and perhaps capacitors spark over for no apparent reason. It may be found that one or more of the stages are oscillating at possibly 100 Mc or some other very high frequency. This would be a high-frequency parasitic oscillation.

Sometimes, in audio amplifiers, undesired feedback effects will produce an oscillation at an audible frequency, at some subaudible frequency, or at a supersonic frequency. These are all forms of parasitic oscillations.

One possible method of producing a parasitic oscillation at a frequency lower than the operating frequency is illustrated in Fig. 12.49, which shows a TPTG oscillator, similar to a basic RF amplifier stage.

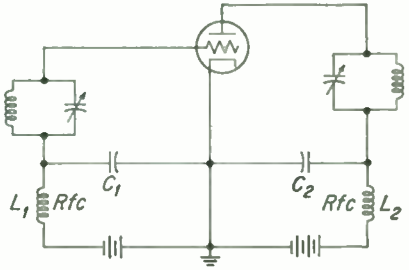


FIG. 12.49. TPTG oscillator (or amplifier) circuit in which low-frequency parasitic oscillations are possible.

In this diagram, if $L_1$ and $C_1$ happen to resonate at the same frequency as $L_2$ and $C_2$, the amplifier may oscillate at this particular frequency and at the same time work at the frequency of the two tank circuits. This would be a *low-frequency* parasitic since RF chokes have greater inductance than do the coils in the tuned circuits, and the bypass capacitors have a far greater capacitance value than the tuning capacitors of the LC circuits.

These parasitic oscillations can be stopped by using a resistance instead of the grid RFC, by using RF chokes of different values in grid and plate circuits, or by changing the values of the bypass capacitors.

The TPTG type of oscillator circuit is not the only one which may support parasitic oscillations. It is possible to have chance Hartley, Colpitts, and even dynatron parasitic circuits.

High-frequency parasitic oscillations may exist in an amplifier or oscillator and never be detected because they may exist at a frequency too high to be heard on any receiver in the area. However, television receivers make excellent detectors for any parasitic oscillations that fall anywhere near TV channels.

The two diagrams in Fig. 12.50 show the same circuit, first as normal

TPTG oscillations are concerned, and secondly as seen by the high-frequency parasitic oscillations.

The first diagram shows the elements of the stage which determine its normal frequency of operation, drawn in heavy lines. The second diagram shows a parasitic oscillation circuit at a frequency determined by two quarter-wave hairpin tanks, the tuning capacitors acting as connections across the ends of the quarter-wave lines. If the wiring of the grid circuit and of the plate circuit happens to have approximately the same-length leads, the circuit may produce oscillations at a high frequency at the same time that it is operating on the desired frequency. The inductances of the tuned circuits act as RF chokes for the high frequencies and are effectively out of the circuit.

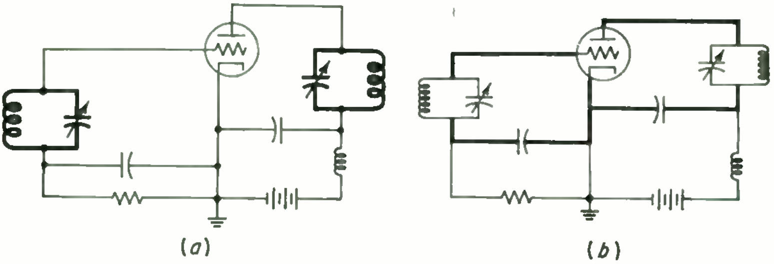


FIG. 12.50. (*a*) A TPTG circuit oscillating at the frequency of the tuned tank circuits. (*b*) Same circuit may form a quarter-wave parallel-line VHF parasitic oscillator circuit at the same time.

High-frequency parasitic oscillations can be stopped by winding a half dozen turns of wire around a 50 ohm 1-watt resistor and inserting this *parasitic choke* in either the grid or the plate lead of the circuit, as shown in Fig. 12.51.

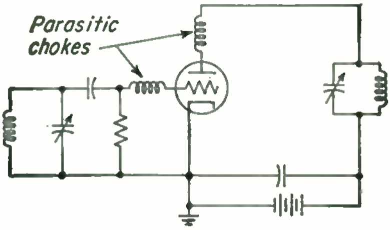


FIG. 12.51. Parasitic chokes may be placed at the plate or grid lead in the circuit.

Parasitic chokes should be installed as close to the terminals of the tube as possible. Sometimes a 100- to 300-ohm resistor in the plate or the screen-grid lead will accomplish the same result as the parasitic choke. Parasitic resistors in the grid circuit usually range from 100 to 1,000 ohms.

**12.23 Indications of Oscillation.** When an RF oscillator is turned on, several methods can be used to determine if the circuit is oscillating.

*Receiver.* A nearby radio receiver will indicate by a change of sound when an oscillator is tuned across the frequency to which it is adjusted. With the beat-frequency-oscillator circuit of the receiver turned on, the oscillator will be heard as a whistle.

*Bias Voltage.* Measure the d-c voltage developed across the grid-leak resistor with a 100-volt meter, using an RF choke connected to the probe to prevent detuning of the oscillator. Whenever the circuit is oscillating, it is developing grid bias.

*Grid Current.* When oscillating, grid current always flows through the grid leak and will produce an indication on any milliammeter in series with the circuit.

*Plate Current.* With TPTG and crystal oscillators, a decrease in plate current at any point across the tuning range indicates oscillation. If the plate current of an oscillator is normally 15 ma but suddenly jumps to 40 or 50 ma, it may indicate loss of bias due to cessation of oscillation.

*RF Indicator.* A flashlight globe in series with a loop of insulated wire will glow when the loop is coupled to the oscillator tank coil if the oscillator is producing a watt or more of RF power. A sensitive RF thermogalvanometer can be used instead of the globe. If no RF meter is available, a 0–1-ma meter with a germanium diode across it will act as an RF indicator.

*Oscilloscope.* Several turns of insulated wire coupled to the oscillator tank coil and connected to the vertical plates of an oscilloscope will show the presence of RF energy on the screen. With most oscilloscopes it is necessary that the RF be fed directly to the cathode-ray-tube plates and not through the vertical-signal amplifiers.

*Neon Lamp.* A neon lamp will glow if touched against the plate or grid lead of a low-power oscillating circuit, provided the oscillator is generating 80 or more volts in the tank circuit. The tester should hold the globe by the glass envelope, being careful not to touch any metal on the lamp. Several turns of wire connected to a neon lamp will work similarly to the flashlight-globe circuit.

*Lead Pencil.* A dangerous method, but sometimes practiced, is the use of a wooden pencil with soft lead. When touched to the plate or grid end of an oscillating tank circuit it will produce a small spark if the circuit is generating more than a few watts of RF energy. If you must use this, be sure you are not grounded.

For AF oscillators, the presence of grid bias or grid current is a reliable indication. A tone in earphones in series with two 0.0005-$\mu$f capacitors connected from ground to either grid or plate is a good indication. The output of the oscillator can be connected to an oscilloscope.

**12.24 Oscillator Stability.** The main requirement for an oscillator circuit, particularly for RF oscillators, is frequency stability. Factors for good frequency stability are the following:

1. Constant plate and screen-grid voltage. Use a separate oscillator power supply, if possible, or use a regulated voltage in a multistage transmitter.
2. Low plate current. The less plate current, the less heating of the tube and the less expansion of internal elements.
3. Low power output. Loose coupling keeps plate current low and tank $Q$ high, tending to hold the frequency constant.
4. Rigid mechanical structure. Vibration of almost any oscillator part produces frequency variation.
5. Oscillator should be followed by a buffer stage. The adjustment of stages following the buffer should not affect the oscillator.
6. Heavy wire for the oscillator coil. Results in higher $Q$, particularly if silver-plated, less contraction and expansion with heat, and less chance of vibration.
7. Drafts. Changing temperature of oscillator-stage parts because of air drafts produces a drift in the generated frequency.
8. Temperature-control chamber for crystals.
9. Tap coils properly. For Hartley, move tap to point on coil where best stability results. For Colpitts, adjust tuning capacitor ratios properly.
10. Use a high $C/L$ ratio. The more capacitance in the tuning circuit, the less effect external adjustments have on the frequency.
11. Shield parts. The tube, tank coils, and capacitors should be shielded with aluminum covering. This prevents parts from being affected by air currents, hand capacitance, and humidity. A shield acts as a shorted turn around a coil, reducing its inductance. Shields must be rigid to prevent vibration.
12. Grid leak. One of the most important factors is the correct values of grid-leak resistance and capacitance.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

1. Draw a simple schematic diagram showing a tuned-grid Armstrong-type triode oscillator with series-fed plate. Indicate power-supply polarity. (12.4) **[3]**
2. Explain how grid-bias voltage is developed by the grid leak in an oscillator. (12.5) **[3]**
3. By what means is feedback coupling obtained in a TPTG-type oscillator? (12.6) **[3]**
4. What is the purpose of an RF choke? (12.7) **[3]**
5. What are the differences between Colpitts and Hartley oscillators? (12.8, 12.9) **[3]**

**6.** Why is a high ratio of capacitance to inductance employed in the grid circuit of some oscillators? (12.9, 12.24) [3]

**7.** Draw a simple schematic diagram of an ECO, indicating power-supply polarities where necessary. (12.11) [3]

**8.** List the characteristics of an electron-coupled type of oscillator. (12.11) [3]

**9.** What are the principal advantages of crystal control over tuned-circuit oscillators? (12.12) [3]

**10.** What is the approximate range of temperature coefficients to be encountered with *X*-cut quartz crystals? (12.13) [3]

**11.** What is the purpose in maintaining the temperature of a quartz crystal as constant as possible? (12.14) [3]

**12.** Draw a circuit diagram of a one-tube audio oscillator using an iron-core choke. (12.18) [3]

**13.** List the characteristics of a dynatron type of oscillator. (12.19) [3]

**14.** Upon what characteristic of an electron tube does a dynatron type of oscillator depend? (12.19) [3]

**15.** What is a multivibrator, and what are its uses? (12.21) [3]

**16.** Describe how a vacuum tube oscillates in a circuit. (12.3, 12.4) [3 & 6]

**17.** Draw a simple schematic diagram showing a TPTG oscillator with series-fed plate. Indicate polarity of supply voltages. (12.16) [3 & 6]

**18.** Draw a simple schematic diagram showing a tuned-grid Armstrong-type triode oscillator, with shunt-fed plate. Indicate power-supply polarity. (12.7) [3 & 6]

**19.** Draw a simple schematic diagram showing a TPTG triode oscillator with shunt-fed plate. Indicate polarity of supply voltages. (12.7) [3 & 6]

**20.** Draw a simple schematic diagram showing a Hartley triode oscillator, with shunt-fed plate. Indicate power-supply polarities. (12.8) [3 & 6]

**21.** Draw a simple schematic diagram showing a Colpitts-type triode oscillator, with shunt-fed plate. Indicate power-supply polarity. (12.9) [3 & 6]

**22.** Draw a simple schematic diagram of an ECO. Indicate the circuit elements necessary to identify this form of oscillatory circuit. (12.11) [3 & 6]

**23.** Why is a quartz crystal used in a radio transmitter? (12.12) [3 & 6]

**24.** What will result if a d-c potential is applied between the two parallel surfaces of a quartz crystal? (12.12) [3 & 6]

**25.** Draw a simple schematic diagram of a quartz-crystal-controlled triode oscillator, indicating the circuit elements necessary to identify this form of oscillatory circuit. (12.12) [3 & 6]

**26.** What may result if a high degree of coupling exists between the plate and grid circuits of a crystal-controlled oscillator? (12.12) [3 & 6]

**27.** What crystalline substance is widely used in crystal-controlled oscillators? (12.13) [3 & 6]

**28.** What does the expression low-temperature coefficient mean as applied to a quartz crystal? (12.13) [3 & 6]

**29.** What is meant by negative temperature coefficient of a quartz crystal when used in an oscillator? (12.13) [3 & 6]

**30.** What does the expression positive temperature coefficient mean as applied to a quartz crystal? (12.13) [3 & 6]

**31.** Why is the crystal in some oscillators operated at constant temperature? (12.14) [3 & 6]

**32.** Is it necessary or desirable that the surfaces of a quartz crystal be clean? If so, what cleaning agents may be used which will not adversely affect the operation of the crystal? (12.15) [3 & 6]

**33.** Draw a simple schematic diagram of a pentode-type tube used as a crystal-controlled oscillator, indicating power-supply polarities. (12.16) [3 & 6]

**34.** Draw a simple schematic of a dynatron type of oscillator, indicating the circuit elements necessary to identify this form of oscillatory circuit. (12.19) [3 & 6]

**35.** What is a definition of parasitic oscillations? (12.22) [3 & 6]

**36.** What may be the result of parasitic oscillations? (12.22) [3 & 6]

**37.** Draw a diagram and describe the electrical characteristics of an ECO circuit. (12.11) [4]

**38.** Draw a diagram of a crystal oscillator. (12.12) [4]

**39.** For maximum stability, should the tuned circuit of a crystal oscillator be tuned to exact crystal frequency? (12.12) [4]

**40.** A 600-kc *X*-cut crystal, calibrated at 50°C and having a temperature coefficient of −20 ppm/°C, will oscillate at what frequency when its temperature is 60°C? (12.13) [4]

**41.** What precautions should be taken to insure that a crystal oscillator will function at one frequency only? (12.14) [4]

**42.** Why are quartz crystals in some cases operated in temperature-controlled ovens? (12.14) [4]

**43.** What are the advantages of mercury thermostats as compared with bimetallic thermostats? (12.14) [4]

**44.** Draw a simple schematic of a multivibrator oscillatory circuit. (12.21) [4]

**45.** What is meant by shock excitation of a circuit? (12.2) [6]

**46.** What is meant by the flywheel effect of a tank circuit? (12.2) [6]

**47.** What is an ECO? Explain its principle of operation. (12.11) [6]

**48.** What is meant by a harmonic? (12.11) [6]

**49.** Why is an additional plate-grid feedback capacitor sometimes necessary in a crystal oscillator? (12.12) [6]

**50.** A transmitter is operating on 5,000 kc, using a 1,000-kc crystal with a temperature coefficient of −4 cycles/Mc/°C. If the crystal temperature increases 6°, what is the change in the output frequency of the transmitter? (12.13) [6]

**51.** Draw a simple schematic diagram of a Pierce oscillator. (12.16) [6]

**52.** Draw a diagram of a crystal-controlled vacuum-tube oscillator using a tetrode-type tube. Indicate power-supply polarity where necessary. (12.16) [6]

**53.** What is a dynatron oscillator? Explain its operation. (12.19) [6]

**54.** What type of oscillator depends upon secondary emission from the anode for its operation? (12.19) [6]

**55.** How do multivibrator oscillators differ from a Hartley oscillator? In what circuits do multivibrator oscillators find application? (12.21) [6]

**56.** What determines the fundamental operating frequency of a multivibrator oscillator? (12.21) [6]

**57.** Draw a simple circuit diagram of a multivibrator oscillator. (12.21) [6]

**58.** Name four devices that could be used to indicate oscillation in a crystal oscillator. (12.23) [6]

**59.** What may be the effects of shielding applied to RF inductances? (12.24) [6]

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

★**1.** What is the relationship between a fundamental frequency and its second harmonic; its third harmonic; etc.? (12.20)

★**2.** What is the purpose of an oscillator? (12.1)

**★3.** What is meant by a parasitic oscillation? (12.22)

**★4.** What is the purpose of an RF choke? (12.7)

**★5.** What is the relationship between the frequency and wavelength of a radio wave if its velocity in space is 300 million meters/sec? (12.17)

**★6.** Radio waves travel at approximately what speed? (12.17)

**7.** Why is a crystal resonator used as a frequency-controlling element in a transmitter? (12.12)

**8.** Draw a simple schematic diagram of a piezoelectric crystal-controlled oscillator utilizing a pentode vacuum tube. (12.16)

**9.** Draw a simple schematic diagram of a Colpitts oscillator circuit. (12.9)

**10.** Why is a separate power supply advantageous for a crystal oscillator stage? (12.12)

**11.** How does the frequency stability of an ECO compare with other oscillators? (12.11)

## CHAPTER 13

# AUDIO-FREQUENCY AMPLIFIERS

**13.1 Audio Amplifiers.** The basic theory of an amplifier was discussed in the chapter on Vacuum Tubes, where it was pointed out that in a normal class A amplifier: (1) A variation of grid voltage produced a variation of plate current. (2) A negative grid-bias voltage determines how much plate current will flow with no signal input. (3) The bias prevents normal-amplitude signals fed to the grid circuit from driving the grid positive and producing grid current and distortion. (4) A proper grid-bias value will allow a tube to handle a maximum input-signal voltage without distortion. (5) With a bias value of 10 volts, a 10-volt peak a-c (7.07-volt rms) signal can be accommodated before grid current is produced. (6) The proper bias value is determined by the plate voltage and the $\mu$ (amplification factor) of the tube. (7) The higher the $\mu$ of a tube, the greater the signal-voltage amplification. (8) The higher the plate-load resistance, the greater the output-signal voltage.

This chapter expands this subject as related to audio-frequency (50 to 20,000 cycles) amplifying circuits.

**13.2 Voltage versus Power Amplifiers.** To increase weak a-c signals from microphones, turntables, detector stages of receivers, etc., an increase in the output a-c *voltage* amplitude with little or no change in the waveshape is required. To accomplish this, very little plate current may be necessary. High-$\mu$ triode (or pentode) voltage-amplifier tubes using resistance plate loads have plate currents of a fraction of 1 to possibly 5 ma. These tubes may be used as *low-power* output tubes also, to feed earphones or other low-level (weak-signal) audio circuits.

When it is necessary to drive the cone of a loudspeaker, to operate a recorder, or to modulate the plate circuit of a high-powered radio transmitter, more audio power is required, from one to sometimes thousands of watts. Tubes capable of producing such output power must be capable of handling very heavy plate currents, withstanding high plate voltages, as well as amplifying the signal voltage. When the electrical and physical characteristics of low-$\mu$ tubes are examined, it is found that they have widely spaced grids, a plate of relatively large area, and heavy filaments, capable of supplying a great quantity of electrons for plate current.

These features answer the requirements of power amplifiers for high plate current and some voltage amplification.

In general, low-$\mu$ triodes are used for *power* amplifiers and high-$\mu$ triodes for *voltage* amplifiers. Some pentodes and all beam-power tetrodes are used as power amplifiers.

**13.3 Distortion.** A simple amplifier, biased to class A (0.5 of the plate-current cutoff-bias value), is shown in Fig. 13.1. The resistor in the grid circuit would not normally be included, but may be considered as representing the direct-current resistance of the transformer secondary in this case.

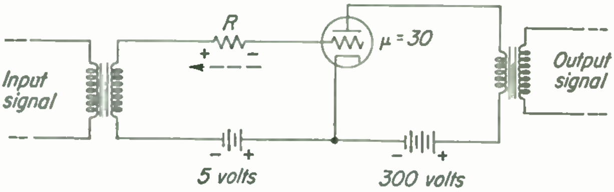


FIG. 13.1. A degenerative voltage is developed across any resistance in the grid circuit when grid current flows through it.

The triode tube has a $\mu$ of 30. The plate voltage is 300 volts. From the cutoff-bias formula (Sec. 9.18):

$$E_{co} = \frac{E_p}{\mu} = \frac{300}{30} = 10 \text{ volts}$$

The factor $0.5E_{co}$ will be used as the class A bias value to simplify the explanation. The bias is then $-5$ volts.

An input-signal voltage up to a peak of 5 volts a-c will be accommodated without drawing grid current or driving past the cutoff point on the curve (Fig. 13.2). The plate current is essentially undistorted.

When an 8-volt peak signal is fed to the grid, during part of the negative half cycle the plate current is completely cut off, resulting in serious distortion to this half cycle. During the positive half cycle, the grid is driven into the positive region and collects electrons from the space charge, and grid current flows backward, through the bias battery.

When grid current flows through any resistance in the grid circuit, it develops a voltage drop across the resistor. The greater the current flow, the greater the voltage developed. Because of the direction of current flow, the grid end of the resistor is negative and the transformer end is positive. Thus, as the grid is driven positive by the transformer (which would tend to increase plate current), a negative voltage is added in series with the grid circuit (which would tend to decrease plate current). As a result, the net grid voltage never reaches the 8-volt peak value but remains at essentially 5 volts. This produces a plate-current pulse with a badly flattened peak, as illustrated. Thus, both positive and negative half cycles are distorted.

(This explanation has neglected the fact that the plate current changing through the load impedance produces a varying voltage drop across the plate load, lowering the plate voltage on the positive half cycle and raising it during the negative. Raising the plate voltage moves the cutoff voltage to a more negative value. For this reason, practical amplifiers use a factor of $0.66E_{co}$ and can accommodate a greater input peak signal.)

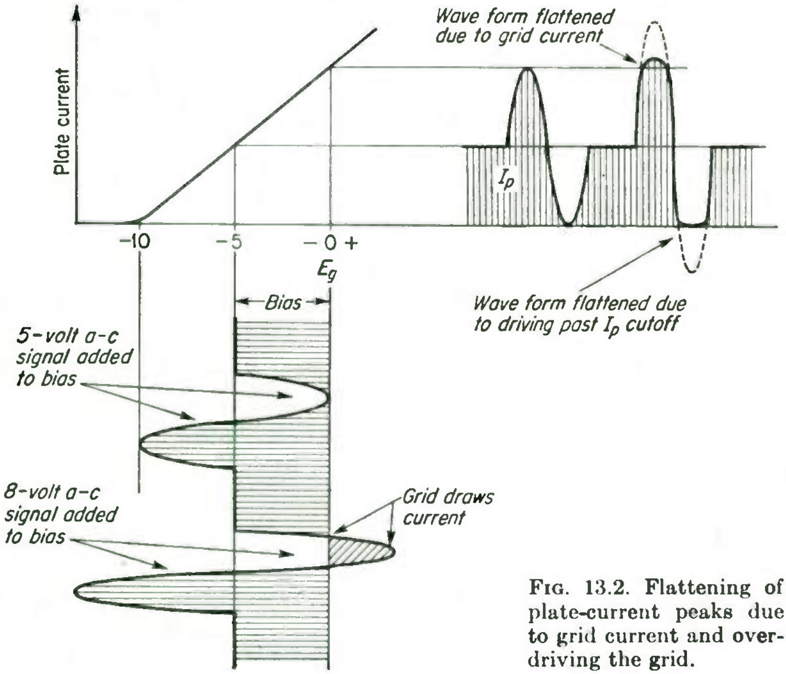


FIG. 13.2. Flattening of plate-current peaks due to grid current and overdriving the grid.

It can be seen that not only must a tube be biased correctly, but also the input a-c amplitude must be held within certain limits, or serious distortion of the input waveshape will be present in the plate or output circuit.

In some cases it may be possible to change circuit voltages to enable the circuit to handle input signals which might otherwise produce distortion. For example, in the last described case of overdriving the grid and producing both positive and negative peak *clipping*, if the plate voltage on the tube is increased, the cutoff point will be extended to the left a greater distance. This will require a greater value of negative grid voltage to attain cutoff, and consequently a higher bias to reach the proper class A bias value. If the plate voltage is increased enough, it may be that a bias point can be reached where the input a-c peaks of the input voltage described above will fall neither into the cutoff region nor into the positive grid region and the tube will operate without distorting or clipping the peaks. However, there are practical limits on the plate voltage.

If a given signal voltage is overdriving a tube, it may be possible to use a lower-$\mu$ tube. Low-$\mu$ tubes require considerably higher bias voltages to produce plate-current cutoff, thereby making it possible for them to accommodate greater grid-voltage amplitudes. However, a low-$\mu$ tube has an inherently lower voltage-amplification factor.

**13.4 $\mu$ versus Stage Gain.** The $\mu$, or amplification factor, of a triode tube is built into the tube by the manufacturer. In general, the voltage amplification to be expected in triode tubes using a resistor as the plate load depends on the $\mu$ of the tube used and will vary from about one-half to two-thirds of the $\mu$ value. A tube with a $\mu$ of 30 can be expected to produce an amplification of voltage between 15 and 20 times.

The number of times an input a-c voltage is amplified in passing through an amplifier stage is known as the *stage gain.* Low-$\mu$ tubes produce low stage gains, while high-$\mu$ tubes produce higher stage gains. The $\mu$ of a certain tube cannot be changed, but the stage gain can be varied within limits.

One factor in the voltage gain of a triode stage is the plate supply voltage used. The higher this voltage, the greater the possible gain. For example, a tube having a $\mu$ of 20 may give a stage gain of 12 with 90 volts as the supply, but may give a gain of 14 if the voltage is raised to 300.

Another factor is the plate-load resistance. The same tube may give a gain of 11 with a load resistance of 50,000 ohms, but may produce a gain of 14 with 500,000 ohms. The higher the load-resistance value, the greater the stage gain.

In an amplifier stage the resistance of the tube and the load resistance are in series across the power supply. The ratio of the load resistance to the total resistance of the tube and load, when multiplied by the $\mu$ of the tube, gives the stage gain. In formula form this may be expressed by

$$A = \frac{\mu R_L}{R_L + R_p}$$

where $A$ is stage gain; $R_p$ is the plate resistance of the tube; $R_L$ is the resistance of the load; and $\mu$ is the amplification factor of the tube.

*Example:* An amplifier has a $\mu$ of 24, a plate impedance of 5,000 ohms, and a load impedance of 10,000 ohms. What is the stage gain?

$$A = \frac{\mu R_L}{R_L + R_p} = \frac{24(10{,}000)}{10{,}000 + 5{,}000} = \frac{240{,}000}{15{,}000} = \text{gain of } 16$$

If a step-up coupling transformer is used in an audio-amplifier stage, the tube gain times the step-up ratio may easily be greater than the $\mu$ of the tube.

It may have been noted that each time the $\mu$ of a tube was mentioned the tube was specified as a *triode*. Tetrode or pentode tubes are also used as audio amplifiers, but the values of screen- or suppressor-grid voltages will affect the actual $\mu$ of the tube. For these tubes it is best to refer to tube-characteristics charts for the required resistances and capacitances to be used in practical cases. The $\mu$ of pentodes can be several hundred, making them highly desirable in some applications.

**13.5 Types of Coupling.** There are four major types of coupling circuits which are used in audio amplifiers: (1) transformer coupling (also known as inductive coupling), (2) resistance coupling (also known as capacitive coupling), (3) impedance coupling (another form of capacitive coupling), and (4) direct coupling.

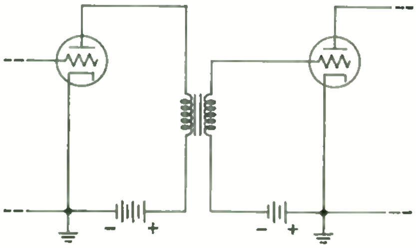


Fig. 13.3. Transformer, or inductive, coupling.

**13.6 Transformer Coupling.** Transformer, or *inductive*, coupling between two tubes is diagramed in Fig. 13.3. With inductive coupling, the output voltage of the first stage can be stepped up by the use of a step-up ratio transformer, and additional gain per stage is possible. The low resistance of the primary of a transformer results in a plate voltage almost equal to the supply voltage, an advantage in power amplifiers.

Transformers may be more costly than other forms of coupling, weigh more, be more bulky, and unless well shielded, be prone to pick up hum, or unwanted signal voltages, from nearby wiring. Less expensive transformers may introduce distortion into the signal.

If the signal voltage in an input transformer is amplified by one or two other stages and is inadvertently coupled back into the transformer by nearby fields, it may be induced in a degenerative phase and cause a weakening of the output, or in a regenerative phase and cause the stages to break into self-oscillation at some audible or supersonic frequency. The stages may *motorboat* (oscillate at a few cycles per second). To prevent this induction due to stray fields, audio transformers are encased in iron shields. The magnetic fields from nearby wires take the easier path afforded by the iron-shield cases rather than passing through the shields and across the coils inside.

Some transformers may also have *electrostatic* shielding between primary and secondary. This may take the form of a single layer of wire or a single turn of sheet brass (insulated to prevent forming a shorted turn) placed between primary and secondary windings. This shield is grounded or connected to the core. Such an electrostatic shield materially reduces the coupling of energy because of capacitance between primary and secondary coils. Since high frequencies pass through a capacitance better than low frequencies, any such capacitive feed will tend to increase the transfer of the higher frequencies into the secondary, and also produce a difference in phase between the capacitive and inductive couplings in the transformer. With this shield, any signal attempting to get from primary to secondary by capacitance effects encounters the shield first and is led to ground and prevented from appearing in the secondary. The only signal induced into the secondary is that produced by magnetic induction. The magnetic fields are not affected by the static shield.

Transformer coupling can be used in either voltage or power amplifiers.

In Sec. 9.22, it was pointed out that maximum output is produced when the impedance of the load matches the plate impedance of the tube. With *triode* tubes, slightly less output power, but less distortion, is produced by increasing the load impedance until it is two or three times the plate impedance. This is called the *optimum*, or *maximum undistorted*, output power.

Tetrode and pentode tubes have very high plate impedances. The primary impedance of a coupling transformer for these tubes is usually between one-fifth and one-tenth of the plate impedance of the tube. It is not generally feasible to produce transformers with primary impedances of much more than about 20,000 ohms.

The power output, either maximum or optimum, developed in the load of a vacuum tube, and the a-c voltage component, developed across the load, can be determined by the formulas

$$P_o = \frac{(\mu E_s)^2 R_L}{(R_p + R_L)^2} \qquad E_o = \frac{\mu E_s R_L}{(R_p + R_L)}$$

where $\mu$ is the amplification factor; $E_s$ is the signal voltage (rms) applied to the grid; $R_p$ is the plate impedance; $R_L$ is the impedance of the load; and $E_o$ is the output voltage developed across the load.

Matching impedances is only important in *power* amplifiers. Resistance-coupled amplifiers produce essentially undistorted output-signal *voltages* regardless of the plate-load-resistance value.

The general rule that d-c must not be fed to the primary of a transformer does not hold true with transformers when used as plate-circuit loads in vacuum tubes. The resistance of the tube in series with the transformer and the d-c power supply limits the current to a safe value for the primary wires. However, if the tube loses its bias and thereby lowers its resistance, sufficient plate current may flow to burn out the primary of the transformer. In any case, the d-c flowing through the primary of a single-tube amplifier tends to magnetize the core, although the results of such magnetization may not always be significant.

A form of inductive coupling that prevents plate current from flowing through the primary of the coupling transformer and saturating the core is shown in Fig. 13.4. This circuit uses a resistance in the plate circuit, across which the signal voltage is developed. The signal voltage is coupled to the primary by the capacitor $C$. For power amplifiers, an iron-core audio-frequency choke coil is used instead of the resistor. Isolating the transformer from the d-c component of the plate current in this manner can result in less distortion of the signal.

**13.7 Resistance Coupling.** A common method of coupling signals from the plate circuit of one audio voltage-amplifier tube to the grid of the next is by *resistance coupling* (Fig. 13.5). Since a capacitor (condenser) is also used in this circuit, it may also be known as resistance-capacitance coupling.

In this circuit, changes of grid voltage on the first tube produce a varying plate current through the plate-load resistor ($R_L$). Varying currents through this resistor produce varying voltage drops across it.

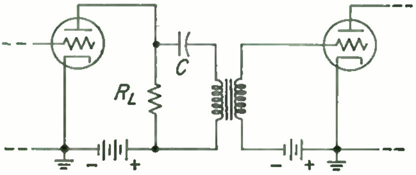


FIG. 13.4. Inductive coupling with no plate-current flow in the primary of the transformer.

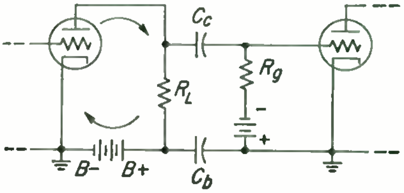


FIG. 13.5. Resistance coupling.

The grid resistor ($R_g$) of the next stage is dynamically connected across $R_L$, through two capacitors, the coupling capacitor $C_c$, at the top, and the bypass capacitor $C_b$, at the bottom. These two capacitors are large enough in value to have a low reactance to the lowest audio frequencies to be used in the circuit. The grid resistor $R_g$ is chosen to have at least twice the resistance of the plate load $R_L$. Varying d-c voltages produced across the plate-load resistor appear as similar-frequency a-c voltages across the grid resistor. Because the capacitors have low reactance and the grid resistor has high resistance, practically all the signal voltage will be reproduced across the grid resistor.

The grid of the second tube is connected to the top of $R_g$, and the cathode to the bottom. Any voltages across this resistance are in series with the grid circuit of the second tube and will cause the plate current of the second tube to vary in accordance with them.

The bypass capacitor $C_b$ may not be included in some circuits. Instead, the output-filter capacitor of the power supply may be used to bypass the bottom of the plate-load resistor to ground potential.

In practice, to keep the stage gain high, the value of the plate-load resistor is made several times the impedance of the tube. The higher the plate-load and grid resistances, the smaller the value of coupling capacitor needed. Two sets of component values that might be used in a resistance-coupled circuit using the same plate supply voltage and tube with a $\mu$ of 20 are:

| | |
|---|---|
| $R_L = 50{,}000$ ohms | $R_L = 250{,}000$ ohms |
| $R_g = 100{,}000$ ohms | $R_g = 500{,}000$ ohms |
| $C_c = 0.04\ \mu f$ | $C_c = 0.008\ \mu f$ |
| Stage gain = 11 | Stage gain = 14 |

Some of the important points regarding resistance coupling are as follows: The grid resistance should be at least twice the plate-load resistance. The larger the coupling capacitor, the better low-frequency signals will be passed to the grid. Too much coupling capacitance may cause cascaded stages (several stages, one after another) to break into self-oscillation. Resistance coupling is considered a method of coupling voltages, not power. The larger the value of the plate-load resistance, the greater the stage gain. The higher the plate voltage, the greater the stage gain. The higher the grid resistance, the more the grid-cathode interelectrode-capacitance (and Miller effect, Sec. 13.19) bypasses higher-frequency signals.

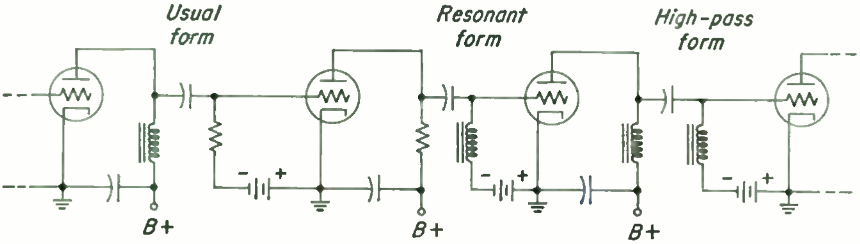


FIG. 13.6. Impedance-coupling methods, the usual, a resonant form, and a high-pass-filter form.

**13.8 Impedance Coupling.** Impedance coupling is somewhat similar to resistance coupling, using iron-core, AF choke coils in place of either the plate resistor, the grid resistor, or both (Fig. 13.6).

With the plate-circuit choke type of impedance, the plate voltage on the tube will be nearly the full voltage of the power supply, instead of less than half the power-supply voltage as is usual with resistance coupling. This results in considerably greater output-voltage possibilities. However, the choke may not present the same impedance to all audio frequencies, thereby producing a form of frequency distortion not as appreciable in resistance coupling.

The first circuit shown is the usual one for impedance coupling. The other two are possible forms. In the second, the coupling capacitor and choke may resonate at a certain frequency, accentuate that frequency, discriminating against all others. The third form may act as a high-pass filter, and also be rather expensive.

Choke coils may pick up stray fields and hum voltages, as do transformers. It is possible to use impedance coupling in voltage amplifiers, and also in power amplifiers when high impedance output is desired.

**13.9 Direct Coupling.** The capacitors used as the coupling element in resistance and impedance coupling and the transformers used in inductive coupling may not transfer all audio frequencies equally well, particularly frequencies below 50 cycles. To improve low-frequency response a circuit was devised which could be made to couple practically any AF because it coupled the plate circuit of one tube *directly* to the grid of the next. It is known as a *Loftin-White* circuit. A simplified version is shown in Fig. 13.7.

Plate current flowing out of the negative terminal of the power supply divides, the major portion flowing through resistor $R$ and a little flowing through the first tube and resistor $R_L$. These two currents join and as one current flow through the second tube, through the primary of the output transformer, and to the positive terminal of the power supply.

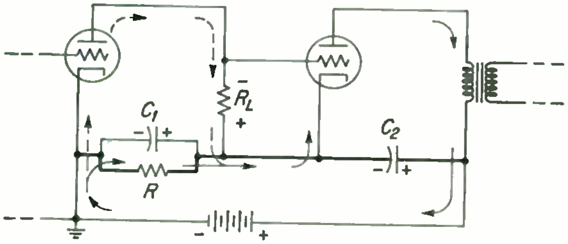


FIG. 13.7. Basic Loftin-White, or direct-coupling, circuit.

The plate current of the first tube, flowing through $R_L$, produces a voltage drop across it. The negative end of the resistor is at the top, the positive at the bottom. This negative potential is being applied to the grid-cathode circuit of the second tube and acts as a bias voltage.

When a signal voltage is fed to the grid of the first tube, its plate current varies, producing a varying potential across its plate-load resistor. This varying d-c potential is directly coupled or connected to the grid-cathode circuit of the second tube. The varying potential in its grid circuit causes the plate current of the second tube to vary. Varying current flowing through the primary of the output transformer produces the signal in the secondary.

The capacitor $C_1$ is large and tends to hold the voltage across $R$ constant. The voltage across $R$ and $C_1$ appears to the first tube as its power supply. The capacitor $C_2$ is large and tends to hold the voltage from the cathode of the second tube to B+ constant. The second tube sees the steady d-c potential across $C_2$ as its power supply. Effectively, then, there are two power supplies in series. The one actual power supply must supply enough voltage for the two stages in series.

This circuit is not in general use, but is capable of coupling between the two stages with very little distortion over the full audio spectrum.

**13.10 Types of Bias Used in Audio Amplifiers.** There are several methods of obtaining bias voltage for audio-amplifier stages. The following terminology will be used: (1) battery bias, (2) power-supply bias, (3) voltage-divider bias, (4) cathode-resistor bias, (5) contact-potential bias. (Grid-leak bias is not considered here, as it is not used in AF amplifiers.)

**13.11 Battery Bias.** The use of dry-cell C batteries for biasing AF amplifiers is usually limited to portable equipment. Wet, or storage, cells are sometimes used. See Figs. 13.4 and 13.5.

**13.12 Power-supply Bias.** In high-powered transmitting audio equipment electronic power supplies are usually used to supply the several hundred volts of bias that may be required by the powerful tubes used. In the past wet-cell batteries or d-c generators were used and may still be found in some equipment.

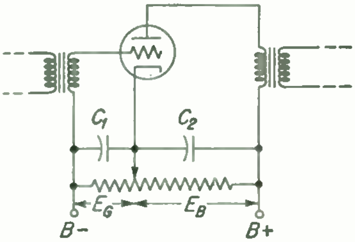


FIG. 13.8. Voltage-divider bias.

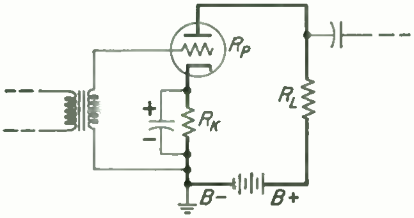


FIG. 13.9. Cathode-resistor bias.

**13.13 Voltage-divider Bias.** It is possible to connect a tapped resistor across a power supply (Fig. 13.8) and obtain both plate-potential and grid-bias voltage from the same supply.

As far as the right-hand, or B+, end of the voltage-dividing resistor is concerned, the cathode is at a considerably more negative point. The return of the grid circuit is to a more negative point than is the cathode. The amount that the grid is more negative than the cathode is the bias value. This can be adjusted to the desired value by moving the tap up or down the resistor. The greater the grid-bias voltage, the less the plate supply voltage.

The capacitors $C_1$ and $C_2$ are filter capacitors, holding the plate supply and the bias voltages constant when signals produce a varying plate current.

**13.14 Cathode-resistor Bias.** The most common type of bias in audio amplifiers is *cathode-resistor* bias (Fig. 13.9). In a way, it is similar to voltage-divider bias. The cathode resistor, the tube, and the plate load are all in series across the power supply. Starting from the positive end of the power supply, there is a voltage drop across the load resistance, another across the tube, and another across the cathode resistor. The sum of these voltage drops equals the supply voltage. Since the cathode is connected part way up this circuit toward the positive, it is more positive than the grid, which is connected to the bottom of $R_k$. The difference of potential across this resistor is the bias voltage. Changing the value of the cathode resistance changes the voltage drop across it, and the bias value changes.

When a signal is applied between grid and cathode, the plate (and cathode) current varies in accordance with the signal. This produces a varying voltage drop across the biasing resistor. A varying bias tends to oppose the input-signal voltage; that is, when the grid is driven slightly more negative by a signal voltage, the plate current will decrease. This decreases the voltage drop across the cathode resistor and produces less negative bias. Therefore, as the signal goes more negative, the bias becomes less negative. Actually, the bias voltage does not drop as much as the signal increases, so that the tube does function as an amplifier. If a large value of capacitance is placed across the cathode resistor, the bias voltage is filtered and held constant enough for the signal voltages applied to the grid to be effective. This results in full output from the tube with least input-signal voltage. Because the resistor across the capacitor tends to discharge it, the lower the resistance value, the larger the capacitance required to maintain a nearly constant voltage. If the capacitor is not large enough, the resistance will almost completely discharge it when low-frequency signals are being amplified but may be able to maintain the voltage relatively constant for high-frequency signals. This action will result in a lesser amplification of the low frequencies and full amplification of the high frequencies.

The value of the biasing resistance can be computed by Ohm's law $R = E/I$.

*Example:* A vacuum-tube handbook gives the following information on a triode tube: plate voltage = 250 volts, plate current = 9 ma, bias voltage = −8 volts, $\mu = 20$. What is the value of cathode resistance to produce the required −8-volts bias?

$$R = \frac{E}{I} = \frac{8}{0.009} = 889 \text{ ohms}$$

where $R$ is the cathode resistance; $E$ is the bias voltage; and $I$ is the plate current in amperes.

In practice a 900-ohm, or even a 1,000-ohm, resistor may be satisfactory. Note that this method of determining the bias resistance is only applicable when the plate-load resistance is small, as in a transformer or a choke coil. For resistance coupling, either refer to charts of resistor values for resistance-coupled stages or use the formula

$$R_k = \frac{R_L}{\mu}$$

where $R_k$ is the cathode resistance; $R_L$ is the plate-load resistance; and $\mu$ is the $\mu$ of the tube.

For pentodes (or tetrodes) the screen current as well as the plate current flows through the biasing resistance. As a result, the total of these two currents must be used in computing the value of the cathode resistor.

Assuming that the cathode resistance is 1,000 ohms, what size capacitor should be connected in parallel with it to hold the voltage across it sufficiently constant? The answer to this depends on the lowest frequency that must be amplified without excessive degeneration and other less obvious factors. A workable *approximation* for this capacitance is given by the time-constant formula (see Sec. 6.1) $T = RC$. For 1,000 ohms resistance and a lowest desired frequency of 100 cycles (0.01 sec), a satisfactory capacitance value is

$$T = RC$$

$$C = \frac{T}{R} = \frac{0.01}{1,000} = 0.00001 \text{ farad, or } 10\ \mu\text{f}$$

A 10-$\mu$f capacitor will satisfactorily filter a 1,000-ohm cathode resistor if the lowest desired frequency is 100 cycles. If the lowest desired frequency is 50 cycles, 20 $\mu$f should be used. (For exact values, refer to vacuum-tube handbooks.)

## 13.15 Contact-potential Bias.

*This type of bias is useful with high-$\mu$ tubes operating with very small input-signal voltages only.*

A diagram of a stage using contact-potential bias is shown in Fig. 13.10.

In the diagram shown there is apparently no bias on the grid. If the tube has a high $\mu$, 70 or more, and the resistance across the grid circuit is several megohms, a small negative voltage of 1 to 2 volts will be developed on the grid. This is produced by a few of the electrons from the cathode striking the closely spaced grid wires of the high-$\mu$ tube. These electrons are unable to leak back to the cathode through the high resistance fast enough to hold the grid at zero potential. This piling up of electrons on the grid forms the negative bias voltage. The diagram resembles grid-leak biasing used in oscillators and RF amplifiers, but the theory of operation is not the same. Grid-leak bias is not an audio-amplifier bias.

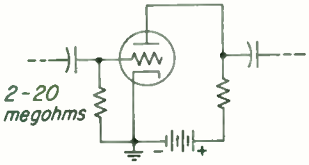


FIG. 13.10. Contact-potential bias.

Contact-potential bias is used only in the first stage of audio amplifiers, following microphones or detector circuits. It can decrease the hum sometimes developed when cathode-resistor bias is used with indirectly heated tubes using a-c as the heater current. The beginner should not use this form of biasing when drawing audio-amplifier diagrams, as its simplicity tempts him to use it where it may not be applicable.

**13.16 Biasing Filament Tubes.** So far, vacuum tubes with indirectly heated cathodes have been considered. When bias is applied to a directly heated, or filament-type, tube, using a-c as the heater current, the same theory applies except that the *center tap* of the filament circuit is used as the plate and grid return point (Sec. 9.7). The diagrams in Fig. 13.11 show two methods of returning to the center of the filament circuit. Either the center tap of the filament transformer or the center tap of a resistor across the filament circuit may be used. (The center-tapped resistor adds a quarter of its total value as a cathode-resistance bias.)

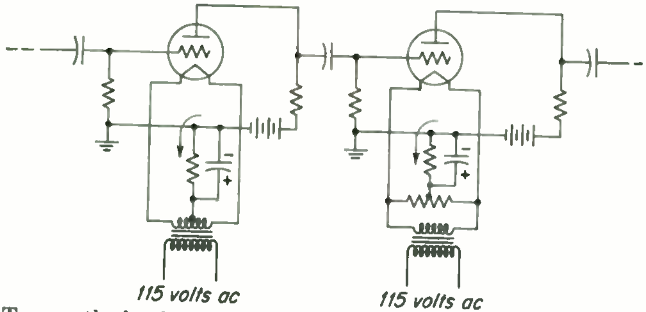


FIG. 13.11. Two methods of returning grid and plate circuits to the center tap of the filament.

When d-c is used to heat a filament-type tube, the filament circuit is not center-tapped, although it would operate satisfactorily that way. The voltage developed across a resistor in series with the power supply can be filtered with a capacitor and be used as a bias voltage (Fig. 13.12).

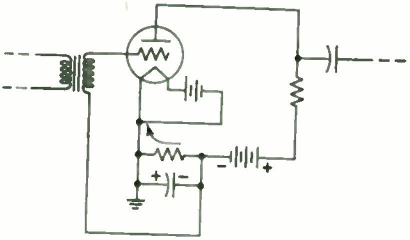


FIG. 13.12. Bias from a resistor in series with the plate circuit.

**13.17 Controlling Volume.** There are several methods of controlling volume which could be used in AF amplifiers. Some of them will introduce distortion into the signal as well as control the amplitude. For example, the simplest volume control would probably be the use of a rheostat across the grid circuit, as shown in Fig. 13.13*a*.

While the lowering of the resistance across the grid would certainly decrease the output of the tube, it is also changing the load on the plate circuit of the tube ahead. It will be remembered that it is good design to have the value of the grid-circuit resistance *twice* the value of the plate-load resistor. As the grid resistance is made less, this requirement is not met, and the lower audio frequencies will be weakened more than the high frequencies.

Another undesirable method of controlling gain is the inclusion of a rheostat in series with the signal to the grid of the tube (Fig. 13.13*b*). This has practically no control over the gain, since the signal being applied to the grid is a *voltage* and not a current signal. With no current flowing through the resistor, there can be no voltage drop across it, and therefore no matter what resistance is used, the voltage applied to the grid remains essentially the same.

These two undesirable methods are mentioned because beginners often "invent" them and wonder why they are not used.

The generally used method of controlling the signal to the grid of an amplifier (and thereby the output of the tube) is to use a voltage divider in the grid circuit. This takes the form of a *potentiometer* (Fig. 13.14).

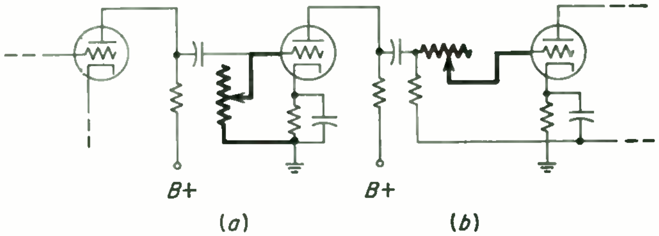


FIG. 13.13. Two undesirable methods by which volume might be controlled.

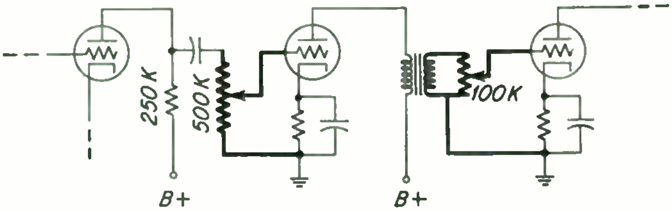


FIG. 13.14. Two practical methods of controlling volume or amplifier gain.

In the resistance-coupled circuit the potentiometer in the grid circuit should have twice the plate-load resistance. When the sliding contact is at the top of the potentiometer, the grid is receiving full output voltage from the first stage. When it is half down the potentiometer, it is receiving half voltage, and when at the bottom it is receiving no signal voltage.

The potentiometer across the secondary of the coupling transformer has a resistance high enough to reflect the proper impedance back to the primary. It is usually 10,000 to 500,000 ohms.

Potentiometers have different resistance *tapers*. A *linear-taper* potentiometer has the same resistance change for a given rotation angle of the arm regardless of whether the arm is at the lower end, the middle, or the top end. The potentiometer described above has such a taper. However, it will be found that when starting from zero signal and increasing the control slightly, the audio signal will rapidly increase at first. Above about mid-point there seems to be relatively little increase in volume. To overcome this undesirable feature, potentiometers are available with *audio tapers.* A small angle of rotation at the low end of the potentiometer moves the arm over a relatively small resistance change. As the arm is continued in rotation, more and more resistance change occurs for the same angle of rotation. This results in a volume control that has a less critical adjustment at the low-volume end. While there are several different audio tapers used, they all operate on this same theory.

In some portable, battery-operated, filament-type tube receivers the filament circuit of the audio amplifier may contain a rheostat. Variation of the filament current is a means of varying the amplitude of the signal, but does produce some distortion. It usually lessens filament-battery drain, however, which is the main reason for its use.

Other types of volume controls, such as varying the screen voltage, plate voltage, or the bias voltage, will control volume over only a small range. Past this they cause excessive distortion to the signal and therefore are not used in audio amplifiers. (Bias- and screen-voltage variations may be used to control the gain of *radio*-frequency amplifiers.)

**13.18 Tone Control.** Theoretically, an audio amplifier should amplify all frequencies fed to its grid equally well. It should amplify 50 cycles just as much as it amplifies 500 or 15,000 cycles. When correctly designed, modern amplifiers actually have such a response. They are said to have a *linear* (straight line), or *flat,* response. However, if any capacitance is connected across the grid-cathode (or plate-cathode) circuit the reactance of such a capacitance will form a path to *ground* for the signal voltage. Since the reactance of a capacitor varies inversely as the frequency, the same capacitor will bypass the high frequencies to ground more than it will the low frequencies. If part of the signal voltage is bypassed to ground instead of going to the grid, this part of the signal cannot affect the plate current.

The larger the capacitance across a grid circuit, the more it will attenuate the high frequencies. If the capacitor across a high impedance is very large (0.1 $\mu$f or more), it may effectively shunt *all* frequencies to ground, and the tube will have practically no signal to amplify.

The higher the *impedance* of the circuit across which the capacitor is placed, the more effect it will have on the loss of high frequencies. For example, a 0.0002-$\mu$f capacitor across a 500,000-ohm grid circuit will effectively decrease the higher audio frequencies. It may take a 0.001-$\mu$f capacitor to produce approximately the same effect across a 100,000-ohm circuit.

An amplifier in which the high frequencies are attenuated will sound to the listener as though the low frequencies are being highly amplified.

Many people prefer amplifiers with such a *bass* response. Noises, such as needle scratch of records, tube hiss, etc., usually range in frequency from 8,000 to 20,000 cycles and can be materially cut down by using a small capacitance across the grid (or plate) circuit of an amplifier carrying such signals.

While Fig. 13.15*a*, showing a variable capacitor as the tone control, is possible to use, the capacitor would be large and relatively expensive. Figure 13.15*b* is equally effective, is less expensive, and requires less space. It utilizes a fixed capacitor in series with a variable resistance. With an increase of resistance, the capacitance becomes less effective. With maximum resistance, perhaps 1 million ohms, the capacitance has practically no effect on the operation of the circuit. With the resistance adjusted to zero, the capacitor is directly across the grid-cathode circuit and effectively bypasses higher frequencies.

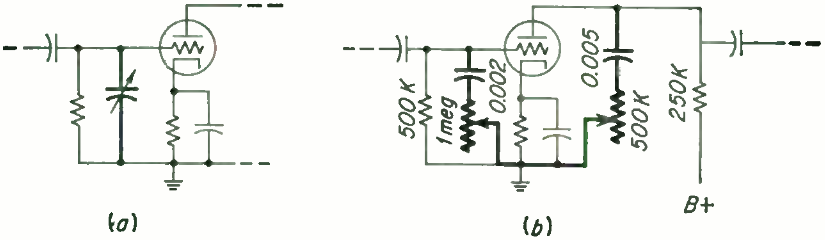


FIG. 13.15. Simple tone-control circuits.

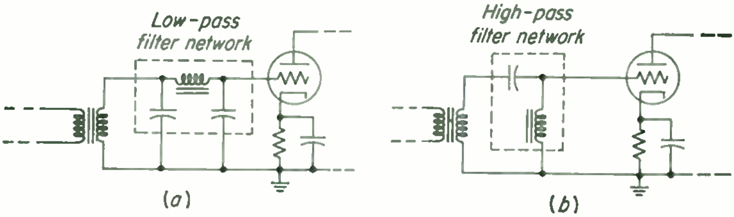


FIG. 13.16. Low-pass and high-pass filters can be used as tone-control circuits.

A tone control is often connected across the output of a tube, from plate to ground (Fig. 13.15*b*). The capacitor used in the plate circuit is slightly larger than would be required in the grid circuit, because the plate-load impedance is usually less than the grid-circuit impedance.

More effective types of tone controls are low-pass and high-pass filter networks. These utilize inductance, capacitance, and resistance to produce a filter network which will pass equally well all frequencies either below or above a predetermined frequency. These filters are discussed in the chapter on Resonance and Filters.

A simple low-pass (Fig. 13.16*a*) and a high-pass filter (Fig. 13.16*b*) are shown.

**13.19 Miller Effect.** When a high-gain resistance-coupled triode amplifier is constructed, it is sometimes found that the high-frequency response is poor, even with no capacitors across the grid-cathode circuit. This may be due to *Miller effect*, a capacitive effect present in the grid circuit of a tube having a resistive plate load. The value of the capacitive effect across the grid-cathode circuit is approximately indicated by

$$C_g = C_{gk} + (A)C_{gp}$$

where $C_g$ is the effective grid-to-ground capacitance in $\mu\mu$f; $C_{gk}$ is the grid-cathode tube capacitance in $\mu\mu$f; $A$ is the amplification of the stage; and $C_{gp}$ is the grid-plate tube capacitance in $\mu\mu$f.

As an example of the effective capacitance across the input circuit of an actual tube, the following values can be substituted in the formula: $C_{gk} = 4.2\ \mu\mu\text{f}$, $A = 12$, $C_{gp} = 3.8\ \mu\mu\text{f}$.

$$C_g = C_{gk} + (A)C_{gp} = 4.2 + (12)(3.8) = 49.8\ \mu\mu\text{f}$$

In the above example an amplification of 12 was assumed for a tube having a $\mu$ of 20. This can be controlled by selection of plate-load resistance, plate voltage, etc. It can be seen that although the tube itself may have only 4.2 $\mu\mu$f grid-cathode interelectrode capacitance, when operated in a circuit having several micromicrofarads of stray capacitance, the tube may be operating as though more than 50 $\mu\mu$f were present across the grid circuit. If the grid circuit has a high impedance, this effective capacitance may be enough to offer a fairly low reactance path to high-frequency signals and effectively bypass them to ground.

Miller effect varies directly as the stage gain. High-amplification stages will produce high effective capacitive effects, while low-gain stages will have proportionately less shunting-capacitance effect. This is one reason why high-fidelity (low-distortion) amplifiers may use lower-$\mu$ tubes.

While Miller effect is discussed here as being present in AF amplifiers having resistance plate loads, it is also present in circuits having impedance or reactive loads, such as in transformer-coupled stages and RF stages, although the effect may be lessened by an increase in the load-reactance value.

With their very low grid-plate capacitance, pentode tubes have little Miller effect even with relatively high stage gain.

Inverse feedback described later, decreases Miller effect.

**13.20 Filtering, or Decoupling, AF Stages.** The phase of any signal passing through a normal amplifier stage is changed 180°. As the grid of one tube in an amplifier is becoming *less* negative, the grid of the *next* tube is becoming *more* negative. This may be seen by following the step-by-step action of the circuit in Fig. 13.17.

1. Grid 1 goes less negative (more positive).
2. The plate current in this tube increases.

3. The voltage drop across the plate-load resistance increases because the resistance of the tube has decreased.

4. The top of the plate-load resistor is now closer to ground potential, or more negative than it was previously.

5. The plate side of the coupling capacitor is now more negative.

6. When the left side of the capacitor becomes more negative, it drives electrons out of the right side onto the grid of tube 2.

7. Electrons forced onto the grid charge it negatively.

The *plate currents* of two tubes in cascade, as shown, are also 180° out of phase. As the first increases, the other decreases. Any coupling, either capacitive or inductive, between grids of two adjacent stages, or between plates of two adjacent stages, will tend to cancel each other. This decreases the over-all amplification of the cascade amplifier, but also decreases any tendency for the stage to oscillate. This latter is usually desirable. On the other hand, any feedback from the third- to the first-stage plate circuits in a cascade amplifier is twice 180°, or 360°, and is in phase, or *regenerative*. This makes the stages form an oscillatory circuit. In some cases oscillations will be at audio frequencies, sometimes at a few cycles a second (called *motorboating* because of the "putt-putt-putt" sound produced) and sometimes at a supersonic frequency.

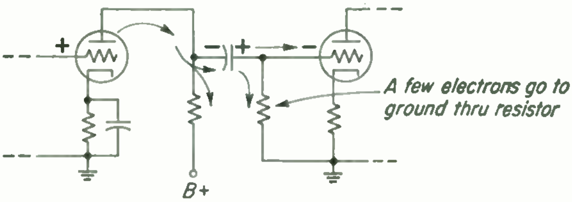


FIG. 13.17. As the grid of the first tube becomes positive, the second becomes negative.

The degenerative, or out-of-phase, type of feedback is usually not bothersome. In fact, many high-fidelity amplifiers incorporate circuits utilizing such *inverse feedback* to stabilize the circuits (prevent self-oscillations) and to decrease certain types of distortion.

The regenerative type of feedback is rarely desirable in audio amplifiers, since it increases noise in the circuit, increases distortion, may cause erratic operation of the stages, or produce oscillation. To decrease this effect it has been found that filtering the plate current for each stage separately will prevent current variations in one stage from producing plate-voltage variations in other tubes due to poor voltage regulation of a common power supply. Such plate-voltage variations from one stage can produce plate-current variations, and also (and this is often overlooked) grid-voltage variations if cathode-resistor bias is used in the stages. In some cases it may also be necessary to filter the grid circuit of the first tube in an amplifier.

Figure 13.18 shows an AF amplifier stage, employing both plate and grid RC filtering, or decoupling. The plate and grid circuits are decoupled from the power supply and from other stages as far as audio voltage variations are concerned.

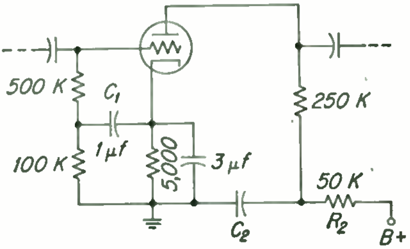


FIG. 13.18. Grid- and plate-circuit decoupling, or filtering.

The 100-kilohm resistor and $C_1$ form an RC *grid*-circuit filter. The 5,000-ohm cathode resistor is partially filtered by the 3-μf capacitor across it. Any voltage variations across the cathode resistor will be smoothed out by the action of $C_1$ and the 100-kilohm resistor, because of their long time constant. The voltage across $C_1$ will vary very little even with considerable variation of plate current through the cathode resistor.

The long-time-constant circuit, $R_2$ and $C_2$, holds the bottom of the 250,000-ohm plate-load resistor at a constant voltage above ground, regardless of instantaneous voltage variations from the power supply.

These filter circuits are also useful in decreasing hum if it is coming from an inadequately filtered power supply. For this reason, it is standard procedure to incorporate plate-circuit filtering in at least the first stage of practically all audio amplifiers.

**13.21 Classes of Amplifiers.** The final amplifier in a series of audio-amplifier stages is normally a *power* amplifier. It is so called because its output is used to do some form of work, such as operate a loudspeaker or modulate a transmitter.

A convenient method of partially describing the many conditions under which vacuum tubes can be used as amplifiers is to classify them by their approximate bias values as mentioned in "Vacuum Tubes."

These classifications are given in a generalized form in the following table:

| Class | Approximate bias used (× cutoff value) | Number of tubes required | Circuit |
|---|---|---|---|
| A | 0.5–0.66 | 1 or 2 | Single-ended, parallel, or push-pull |
| $AB_1$ | 0.85 | 2 | Push-pull |
| $AB_2$ | 0.90 | 2 | Push-pull |
| B | 1.00 | 2 | Push-pull |

The formula to determine the cutoff-bias voltage is (Sec 9.18)

$$E_{co} = \frac{E_p}{\mu}$$

The cutoff-bias value computed by this formula does not quite cut off the plate current, because of the curvature of the $E_gI_p$ curve in the region of cutoff.

It should be noted that the bias values given above are only approximate. There is actually considerable latitude in the selection of the bias value for an amplifier. There are other factors in determining the class in which the tube is operating. If no grid current is drawn during any portion of the input signal, the tube is considered as operating either as class A or $AB_1$. If the grid is driven positive so that grid current flows during a portion of the input cycle, the tube is operating either as a class $AB_2$ or as a class B amplifier.

There is one other classification of amplifier, the *class C*. This amplifier is used in RF power amplifiers almost exclusively and will be discussed in the chapter on Radio-frequency Amplifiers. Its bias value is 1½ to 4 times cutoff. During part of its input cycle no plate current flows at all, which would result in excessive distortion if used in audio applications.

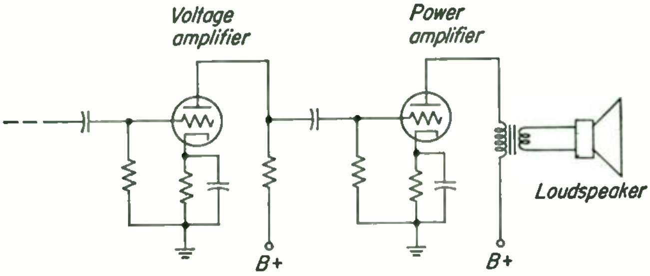


FIG. 13.19. A class A voltage-amplifier and a class A power-amplifier stage.

**13.22 Class A Audio Amplifiers.** Voltage amplifiers are always biased to class A. Bias for such stages can be obtained by any of the methods mentioned previously. Theoretically, the plate-circuit efficiency can be 50 per cent, but in actual circuits it is between 20 and 25 per cent. If the plate circuit draws 10 watts from its power supply, only about 2.5 watts of undistorted audio power can be produced. If the stage is resistance-coupled, the output in power is extremely low and is not considered.

The diagram in Fig. 13.19 shows a simple class A resistance-coupled voltage amplifier driving a class A power amplifier, inductively coupled to a loudspeaker. In this circuit a low-voltage AF signal fed through the coupling capacitor to the grid of the first tube is amplified and appears across the grid circuit of the second tube. The a-c voltage on the grid of this power amplifier produces variation of a relatively high-amplitude plate current flowing through the primary of the output transformer. This heavy current produces a strong magnetic field, which transfers considerable energy into the secondary and vibrates the loudspeaker diaphragm, producing air waves, or sound.

Class A power amplifiers may use a single tube, two tubes in parallel, or two tubes in push-pull. All other classes of audio power amplifiers must use two tubes in push-pull.

Class A stages have no grid-current flow. Therefore the stages ahead of them need only be voltage amplifiers. If a power-amplifier stage draws any grid current, the stage driving it must also be a power amplifier. If a class A stage draws grid current, it indicates either insufficient grid bias or excessive signal voltage.

The class A stage is limited to a peak signal input approximately equal to the bias value. The low-value signal requirement of a class A stage forces it to operate over only a limited but straight portion of the $E_gI_p$ curve, resulting in a low plate-circuit efficiency. However, when consideration is given to the ease of biasing, the lack of driving requirements, and the low distortion, the cost per watt of a class A power amplifier may not be much, if any, more than other classes of amplifiers.

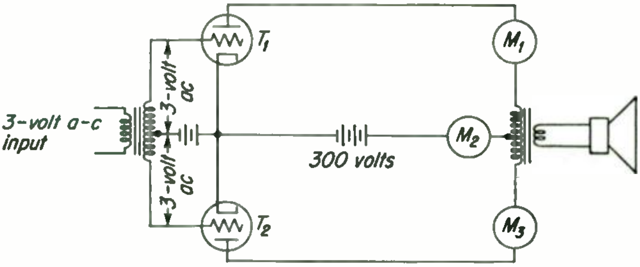


FIG. 13.20. Push-pull amplifier circuit.

**13.23 Push-Pull Class A Amplifiers.** Figure 13.20 shows a push-pull amplifier. If the bias-battery voltage is adjusted to about 0.66 of the cutoff bias, the stage is a class A amplifier. If the bias is adjusted to about 0.95 of the cutoff-bias voltage, the stage will be a class B amplifier. In other words, the *diagram* of class A push-pull and all other classes will be identical if battery bias is used. Furthermore, the general theory of operation is similar in many respects. At this time the circuit will be assumed to be biased for class A operation.

*No-signal Condition.* With no signal being applied to the grids, 300 volts as the plate supply, and a bias voltage of approximately 66 per cent of the cutoff value, a possible plate current for each tube might be 30 ma. $M_1$ and $M_3$ should both read 30 ma. If they read different values, the tubes should be changed until a pair is obtained which will give the same values. The tubes must be matched to reduce even-order harmonic generation. Meter $M_2$ should read 60 ma.

*Positive Signal Condition.* When an input signal of 3 volts is fed to the 2:1 step-up-ratio input transformer, on one-half of the input cycle the grid of $T_1$ will become 3 volts more *positive* (actually 3 volts less negative) than it was with no signal. This reduction in negative voltage on the grid of $T_1$ will increase its plate current, possibly by 6 ma. Now $M_1$ should read 36 ma. As $T_1$ becomes less negative, $T_2$, connected to the opposite end of the input transformer's secondary winding, will become 3 volts more negative than with no signal. The increase in negative charge on $T_2$ will produce a reduction in plate current through this tube of 6 ma. Now $M_3$ should read 24 ma. Note that as one tube draws more current, the other draws an equal amount less. The net result, as far as $M_2$ is concerned, is no change in current.

*Negative Signal Condition.* On the other half of the input-signal cycle, $T_1$ is driven more *negative* than with no signal, and its plate current drops. $T_2$ is driven less negative than with no signal, and its plate current increases. Again the total plate current as read in $M_2$ remains the same.

The signal voltages used have been considered to be a-c, but of such a low frequency that the meters $M_1$ and $M_3$ could follow their variations. Actually, AF signals produce very rapid variations in plate current in each tube, but any increase in current in either tube is followed so soon by the decrease due to the other half of the a-c cycle that the meter can only read the average of these high and low values. For this reason, under normal operating conditions, neither $M_1$, $M_2$, nor $M_3$ should change when a signal is applied to the input circuit. If a meter in the position of $M_2$ does change when signals are suddenly applied to a class A stage, *whether push-pull or single-ended,* it indicates that some form of distortion is being developed in the circuit. In the push-pull circuit the trouble might be in mismatched tubes. In the single-ended circuit the trouble might be in a faulty tube, incorrect bias value, excessive signal voltage, or poor power-supply voltage regulation.

A distinct advantage when using a push-pull instead of a single-ended circuit is the tendency to cancel the even-order harmonics (second, fourth, sixth, etc.) that may be developed in the stage, particularly if the two tubes are matched.

The d-c plate current of a single-ended amplifier tends to magnetize the core of the output transformer, resulting in distortion of the signal. In push-pull stages the plate currents are flowing in opposite directions, thereby preventing core magnetization or saturation, another reason why push-pull produces less distortion.

Push-pull stages can be operated in the more efficient classes of AB and B. This is another reason why push-pull is preferable to single-ended operation when large values of audio-power output are required.

Still another advantage is the ability of a push-pull stage to cancel hum due to any power-supply ripple (Sec. 13.39).

**13.24 Push-Pull Output-transformer Operation.** The operation of the currents and induced voltages in a push-pull output transformer should be understood. Figure 13.21 shows such a transformer and indicates the direction taken by the plate currents of the two tubes.

As the grid of $T_1$ becomes more positive, the current flowing down through its primary, $P_1$, increases, producing an expanding magnetic field of an assumed north polarity, which induces an upward voltage, $E_1$, in the secondary. At the same time the grid of $T_2$ is becoming more negative, and its plate current, flowing upward in $P_2$, *decreases*, producing a contracting magnetic field of south polarity. This also induces a voltage in the secondary in an upward direction. The expanding north field produces the same voltage effect as the contracting south field.

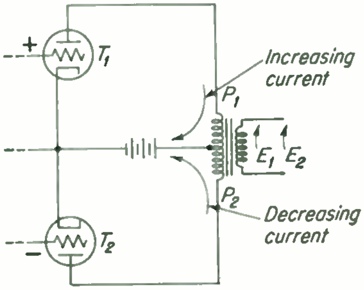


FIG. 13.21

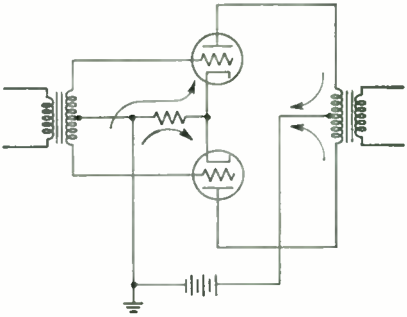


FIG. 13.22

FIG. 13.21. As the current increases in one-half of the primary it decreases in the other half, but induces voltages in the secondary that are additive.
FIG. 13.22. The cathode biasing resistor requires no filter capacitor in a class A push-pull stage.

When the grid of $T_1$ is going more positive, the plate current is increasing, inducing a counter emf in the upper half of the primary. Since this emf is in a direction opposite to the power-supply voltage, while it exists, the plate voltage of $T_1$ is *less* than the power-supply voltage. The increase in $T_1$ plate current also induces an emf in the other half of the primary that is in series with the power-supply voltage for $T_2$. Therefore the plate voltage of $T_2$ is considerably higher than the power-supply voltage as its grid is going negative.

**13.25 Push-Pull Class A Bias.** One of the advantages of the class A amplifier is the ease of biasing. The single-ended circuit was described in Sec. 13.14. How cathode-resistor bias is produced in a push-pull class A stage is shown in Fig. 13.22.

The plate current for both tubes flows through the cathode resistor. When a signal is impressed on the grid circuits, the plate current of one tube increases and the plate current of the other decreases a like amount at the same time. This results in a constant value of current through the cathode-biasing resistor at all times. A constant current produces a constant voltage drop. Therefore no filter capacitor is needed across the cathode resistor in a push-pull class A stage. One is often used in case the two tubes are unbalanced, however. Note which end of the bias resistor is grounded.

**13.26 If One Class A Push-Pull Tube Burns Out.** A push-pull *battery-biased* class A amplifier stage is actually two class A stages *back to back;* that is, the upper tube alone is a complete class A stage, as is the lower tube circuit. If one of the two tubes suffers a filament burnout and ceases to function, or is pulled out of its socket, the other tube continues to function as a normal single-ended class A amplifier. It will produce only about half the normal power output of the two tubes, but the output will remain relatively undistorted. Where only a small percentage of the audible output power of an amplifier is actually used, it may operate for long periods of time with one tube inoperative, and the difference may not be noted. (Other classes of amplifiers will produce considerable distortion if one tube ceases to function, since only about half of the input cycle will be properly amplified.)

When cathode-resistor bias is used in a push-pull class A stage and one tube ceases to operate, the current through the biasing resistance decreases, lowering the bias voltage. The average plate current is then higher than normal for the single tube, but less than it would have been for both tubes together. This will usually allow undistorted reproduction of low signal values. If there is no capacitor across the cathode-resistor biasing circuit, the degenerative feedback produced will further weaken the output signal. With only one tube operating, harmonic distortion increases.

**13.27 The Class $AB_1$ Audio Amplifier.** An audio amplifier biased a little higher than class A, and not driven to the point where grid current will flow, is considered to be a class $AB_1$ stage. On the negative half of the input cycle the peak signal usually adds enough negative voltage to the bias voltage to cut off the plate current for perhaps a quarter of the input cycle, as shown in Fig. 13.23.

The positive peak of the signal voltage does not quite reach the positive grid region during any portion of the cycle that is fed to the grid.

Because a signal strong enough to reach zero grid potential with the amplifier biased to class $AB_1$ will result in cutoff of plate current on the negative half cycle, class $AB_1$ amplifiers must use two tubes in push-pull. When one tube is cutting off for a short time, the other is reaching its high plate-current value and the output transformer has plate current flowing in it at all times to reproduce the signal voltage in the secondary. The output signal is relatively undistorted.

A pair of triode tubes capable of producing about 8 watts of audio in class A may produce about 16 watts of audio operating as class $AB_1$.

With the higher bias it is possible to use higher plate voltage without causing too much average plate current to flow. Increasing the plate voltage increases the cutoff voltage point. This allows a greater variation of grid voltage without driving into the positive grid region. With a greater grid-voltage swing, a much greater plate-current variation will take place, increasing the power output. Actually, during high negative signal peaks, the plate current ceases to flow for a portion of the cycle and the plate has a chance to cool. Because it is cooling or resting during part of the input cycle, when it is worked the tube can be worked much harder without increasing the average plate heat dissipation. As long as the tube is operated in such a manner that its plate does not exceed its rated-power (heat) dissipation, it should give satisfactory operation for a long period of time. When its plate dissipation is exceeded, its life expectancy is materially shortened.

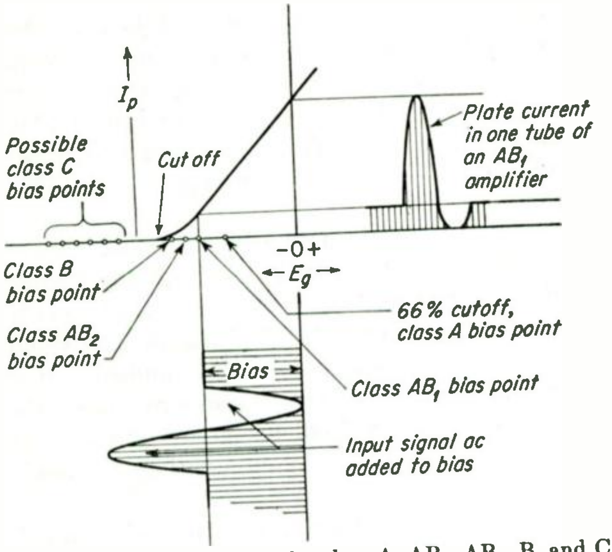


FIG. 13.23. Relative bias voltages for class A, $AB_1$, $AB_2$, B, and C stages.

Battery, power-supply, and voltage-divider biasing methods are satisfactory for class $AB_1$ stages. If the bias voltage is only a little more than class A values, cathode-resistor bias with a capacitor across the cathode resistor may be satisfactory.

The plate-circuit efficiency (d-c power input to a-c power output) for a class $AB_1$ amplifier is in the 25 to 50 per cent region.

**13.28 The Class $AB_2$ Audio Amplifier.** The class $AB_2$ amplifier is always a push-pull stage and may be biased nearer the plate-current cutoff point than the class $AB_1$ amplifier, although it may also use approximately the same bias value. An increased bias allows still higher plate voltage to be used on the tubes, and therefore greater grid-voltage swing than in class $AB_1$. The grid-circuit transformer must be designed to withstand grid-current flow as the high-amplitude input signals drive into the positive grid region on most peak signal voltages, and also cut off the plate current for a considerable portion of the negative half cycle. The cutting off of the plate current allows the plate to rest and cool. These factors produce greater efficiency and power output.

A pair of tubes capable of about 8 watts output in class A may be capable of about 16 watts output in class $AB_1$, and possibly 24 watts output in class $AB_2$.

In the class $AB_2$ amplifier the *no-signal plate current* is relatively low. If a milliammeter is connected in series with the plate-circuit power supply, it will read a fairly low value with no signals but will show an increase when strong signals are fed into the grid circuit. A class $AB_1$ stage will increase plate-current readings only when maximum signals are fed to it. The class A plate current remains the same with or without signals.

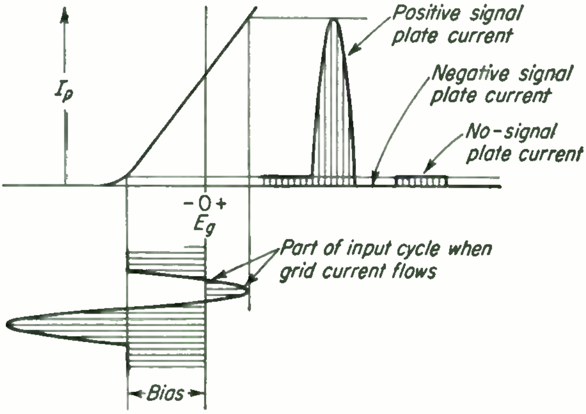


FIG. 13.24. Plate-current versus input-signal voltage for one tube of a class B stage. With no resistance in the grid circuit, the plate pulse is not flattened at the peak.

Battery-, power-supply, and voltage-divider bias can be used with class $AB_2$ stages, but not cathode-resistor bias.

**13.29 The Class B Audio Amplifier.** When two tubes connected in push-pull are biased almost to cutoff, they are considered to be operating as class B amplifiers. The $E_gI_p$ curve, the input-signal voltage, and the resulting plate-current pulse for *one* of the two tubes of a class B stage are indicated in Fig. 13.24.

Normal class B operation assumes high driving, or excitation, voltages applied to the grids of the tubes, enough to drive well up into the grid-current region. Considered alone, one of the tubes will operate with plate current for about 200° of the input-signal voltage cycle. No plate current flows during about 160° of the negative half cycle. The tube may be considered to be resting for almost the full half cycle. When it does work, a class B tube may be worked quite hard before its average plate-dissipation rating is exceeded. Since each tube in a class B AF amplifier handles only one half cycle, considerable distortion is produced if only one tube is operating. Grid current may flow for as much as 30° of the positive input cycle.

The bias for class B stages is more difficult to obtain than is bias for class A stages. It is necessary to use separate bias power supplies of low impedance (good voltage regulation) or batteries to produce the same bias voltage with and without grid current.

Both primary and secondary of the driver transformer of a class B stage should have low resistance to prevent formation of degenerative voltages in the secondary during the portion of the cycle that the grid is drawing current. The stage ahead of the class B amplifier should be a power stage to develop the necessary drive during grid-current periods.

A milliammeter in the plate circuit of a class B stage shows very little current with no signal, but its reading increases considerably when the stage is amplifying a signal. A rough estimate of how much power the stage is handling is given by the swing of the milliammeter needle. The greater the swing, the greater the power output.

It is possible to use special high-$\mu$ triode tubes, having $\mu$ values of 100 to 150, as class B tubes and use no bias voltage at all. This may be done because with no bias, high-$\mu$ tubes limit the plate current to very low values. The whole positive half cycle of the input voltage will cause grid current to flow in each tube. Most of the negative half cycle drives the grid beyond cutoff. With two tubes in push-pull, grid current flows for 360° of the input a-c cycle and considerable power is required from the driving stage. However, the requirement of no bias is a feature that makes this type of tube desirable in some applications. The tubes used must be specially constructed with grids which will handle the relatively high current flowing during the positive half cycles of the signal voltage.

The plate-circuit efficiency of class B audio amplifiers is usually between 50 and 60 per cent, depending upon the percentage of distortion that can be tolerated.

Beam-power tetrodes and pentodes are not operated in class B. They are usually limited to class A, $AB_1$, or $AB_2$.

Since a class B amplifier is biased almost to cutoff, a vacuum tube having a plate voltage of 1,000 volts and a $\mu$ of 25 will require approximately 40 volts of negative bias. This is computed from the cutoff formula given in Sec. 13.21.

**13.30 Earphones.** The task of converting varying-amplitude d-c or AF a-c into sound waves is accomplished by earphones or loudspeakers. Such instruments may be given the general name of *transducers.* They usually operate on an electromagnetic principle whereby a varying current produces a varying-strength magnetic field. The varying magnetic field attracts and releases a thin diaphragm of iron or other material. The vibration of the diaphragm sets up air-wave disturbances which are recognized as sound by the human ear.

Figure 13.25 illustrates the basic principle of the earphone. The significant parts are the *permanent* magnet type core, the coils surrounding the core, the thin iron diaphragm, and the protective case with a screw-on bakelite cap.

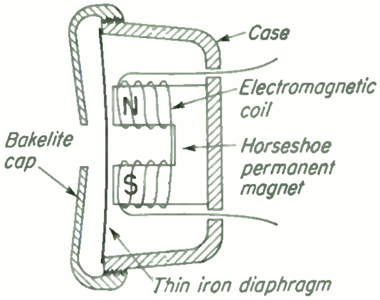


FIG. 13.25. Cross-sectional picturization of an earphone.

When no current is flowing through the coils, the magnet attracts the diaphragm and holds it in a strained position, bent slightly inward. If current flows through the coils, it will either add to the magnetism of the magnet and pull the diaphragm inward more, or partially cancel the magnetic field and allow the diaphragm to swing outward a little, depending on the current direction. If the current is varying or alternating, the diaphragm will swing back and forth, or vibrate, at the frequency of the current variations or alternations. The diaphragm vibrations cause air waves or sound to come out through the hole in the bakelite cap.

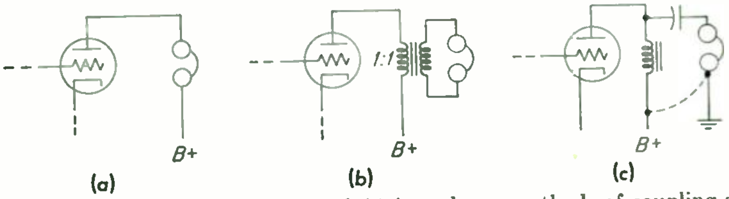


FIG. 13.26. (*a*) Direct, (*b*) inductive, and (*c*) impedance methods of coupling an earphone to the plate circuit of a tube.

Earphones are either high- or low-impedance types. High-impedance phones have many turns of fine wire around the core and are made to operate in series with the plate circuit, either through a 1:1 or step-up output transformer or impedance-coupled to the amplifier plate circuit (Fig. 13.26). The impedance ranges from 2,000 to 20,000 ohms to match the impedance of the tube plate circuit in which they operate.

When high-impedance earphones are connected directly in the plate circuit of an amplifier tube, care must be taken to connect them in such a way that plate current will flow in a direction that will increase the magnetic pull of the core. This tends to keep the permanent magnets from becoming demagnetized and results in louder signals. Earphone cords are usually marked with a red tracer to indicate which wire should be connected to the positive end of the power supply. When earphones are connected across the secondary of an output transformer they are fed a-c, and the polarity of the leads does not matter.

If earphones lose their permanent magnetism, each half cycle of AF a-c applied to them will produce one vibration, and this condition produces an extreme form of distortion.

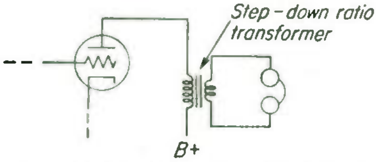


FIG. 13.27. Matching a low-impedance earphone to a high-impedance plate circuit requires a step-down transformer.

Low-impedance earphones have fewer turns of heavier wire and are made to operate with a higher current value. This is readily obtainable by the use of a step-down output transformer (Fig. 13.27). Low-impedance phones are not made to operate directly in the plate circuit of an amplifier tube, although they will produce weak signals if connected in such a manner. The impedance of the usual low-impedance phones is in the range of 75 to 600 ohms.

Besides the electromagnetically operated earphones, there are piezoelectric, or *crystal*, earphones. These are very-high-impedance types, ranging in the region of 20,000 ohms. They are made to operate from a high-impedance output transformer or with impedance coupling. Inside the earphone is a piezoelectric crystal attached firmly to a thin diaphragm. The two sides of the flat crystal are metal-coated. When an audio voltage is applied to the two opposite metallized surfaces of the crystal, the crystal bends, pushing the diaphragm inward or outward depending on the polarity of the audio voltages being applied. These phones are quite sensitive and have excellent fidelity.

Earphones should be handled carefully. A dented diaphragm will cause weak signal output or severe distortion if the diaphragm happens to touch the core during its vibrations. Any severe physical shock, such as is produced by dropping on the floor, tends to demagnetize the magnet core, causing weakened signal output as well as distortion of high-amplitude signals.

**13.31 Loudspeakers.** In the early days of radio the loudspeakers were made somewhat similar to the high-impedance electromagnetic-type earphones. They were made larger and had heavier wire in them to handle the greater plate currents they required. A horn, or large diaphragm area, was used to cause a larger mass of air to be vibrated, thereby producing louder sounds.

Today, most loudspeakers operate by either the permanent-magnetic or the electromagnetic field principle. The former is known as a p-m, or *dynamic*, speaker; the latter as an *electrodynamic* speaker. Figure 13.28 illustrates the basic principle of the p-m type.

When current flows through the coil attached to the diaphragm assembly, it makes an electromagnet out of the coil. The coil will now be attracted either inward toward the magnet or repelled outward away from it, depending upon the direction of the current in the coil, and therefore its magnetic polarity. Since the coil is attached to the diaphragm, any movement of the coil carries the diaphragm back and forth with it, producing the air vibrations necessary to make sound. The leads from the coil are attached to two points on the paper diaphragm. Flexible leads from these points are connected across the output transformer secondary. In this way a-c signal currents are carried to the coil from the transformer.

The impedance of loudspeakers of this type varies from 2 or 3 ohms to 30 or more ohms. They are made to operate from high-ratio step-down output transformers as shown in Fig. 13.19.

The electromagnetic-field loudspeakers are somewhat similar in construction to the p-m speakers except that the central core is made of soft iron and is a temporary magnet. On the rear of this core is a fixed *field* coil. This field coil, when energized, produces a strong field similar to that produced by the magnet in the p-m speaker. If the field coil is wound with many turns of small wire, it will have considerable resistance and can be connected across the d-c output of the power supply of the receiver or amplifier with which it is used. This d-c excitation will produce the desired strong constant magnetization of the core. If the field coil is wound of larger wire, with fewer turns, it will have less resistance and can be used as a smoothing choke in the power supply of the equipment in which the speaker is used. In this way the low-resistance field coil serves double duty, as a power-supply choke coil and a means of producing a strong unvarying magnetic field for the loudspeaker.

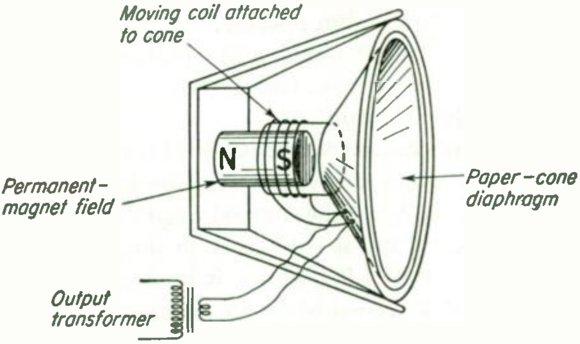


Fig. 13.28. Picturization of the working components of a p-m loudspeaker.

In mobile equipment, the field coil may be wound to operate from 6 or 12 volts d-c, or any other voltage used as primary power for the equipment.

**13.32 Impedance-coupled Output.** To prevent d-c from flowing through high-impedance types of loudspeakers, an impedance-coupling circuit can be used, as shown in Fig. 13.29. The varying plate current flowing through the choke coil develops an a-c voltage across the choke, which is fed to the loudspeaker through the capacitor *C*.

The lower connection on the speaker in the diagram could be connected to the lower end of the choke coil, shown in dotted lines, instead of to ground. The advantage of the method of connection shown keeps the speaker and its leads at ground potential as far as d-c is concerned.

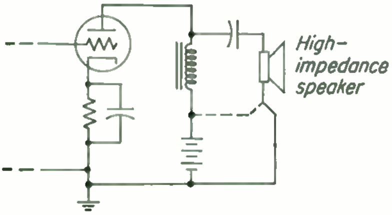


FIG. 13.29. Impedance-coupling a high-impedance speaker to a vacuum tube.

Earphones may also be coupled to an amplifier stage in a similar manner. In this case, because the earphones require little power to operate, them, the choke coil, which is rather expensive and heavy, may be supplanted by a 5,000- or 10,000-ohm resistor.

Should the choke coil short-circuit, the plate-current variations no longer have any impedance across which they could produce a voltage drop, resulting in no signal output.

**13.33 Matching Impedances with an Output Transformer.** When the maximum, or near-maximum, power output is desired from an a-c source, the load impedance should equal the source impedance. If the impedance of a loudspeaker is 4 ohms and it is to work in the plate circuit of a tube having a plate impedance of 4,000 ohms, it is obvious that quite a mismatch will be produced if the speaker is connected directly in the plate circuit. In such a case the speaker will produce almost no signal output.

As explained previously, transformers are used in a-c circuits to step up or step down voltages. The extent to which a transformer can step up or down voltages will depend almost entirely upon the turns ratio of the primary and the secondary. A 3:1 ratio transformer is assumed to either step up or step down the voltage 3 times.

Transformers can also be used to convert from one impedance value to another. As might be expected, a 1:1 ratio transformer will have the same impedance in the secondary as in the primary. However, when the turns ratio is anything other than unity (1:1), it is found that the impedance ratio of primary and secondary will be equal to the turns ratio *squared*. This is expressed in formula form by

$$\left(\frac{T_p}{T_s}\right)^2 = \frac{Z_p}{Z_s}$$

where $T_p$ is the number of primary turns; $T_s$ is the number of secondary turns; $Z_p$ is the primary impedance; and $Z_s$ is the secondary impedance.

This formula may also be expressed:

$$\frac{T_p}{T_s} = \sqrt{\frac{Z_p}{Z_s}}$$

The turns ratio of a transformer to match a source impedance of 500 ohms to a load of 10 ohms is

$$\frac{T_p}{T_s} = \sqrt{\frac{Z_p}{Z_s}} = \sqrt{\frac{500}{10}} = \sqrt{50} = \text{turns ratio of } 7.07:1$$

If a transformer has a turns ratio of 4:1, then the impedance ratio can be found by applying the formula as follows:

$$\frac{Z_p}{Z_s} = \left(\frac{T_p}{T_s}\right)^2 = \left(\frac{4}{1}\right)^2 = \frac{16}{1}, \text{ or impedance ratio of } 16:1$$

The answer obtained is the impedance *ratio* between primary and secondary. In this case it tells that the primary impedance is 16 times as great as the secondary. If the primary impedance were 16,000 ohms, the secondary would be 1,000 ohms.

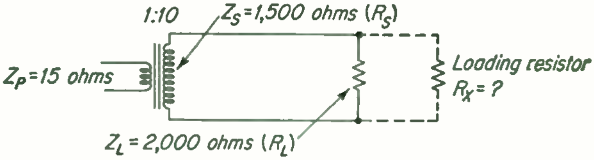


FIG. 13.30. Matching load to transformer.

If the requirement is to match a 4-ohm speaker to a 4,000-ohm power tube, what would the transformer turns ratio have to be? This can be solved by considering, first, that the primary impedance of the transformer should be at least *twice* the impedance of the tube. The requirement is then for a transformer with a primary impedance of 8,000 ohms (for optimum output) and a secondary impedance of 4 ohms.

The problem is solved as follows:

$$\frac{T_p}{T_s} = \sqrt{\frac{Z_p}{Z_s}} = \sqrt{\frac{8{,}000}{4}} = \sqrt{2{,}000} = \text{turns ratio of } 44.7:1$$

The primary of this output transformer should have about 45 times as many turns as the secondary, which would give the desired impedance ratio. Now the 4-ohm loudspeaker looks into a 4-ohm secondary winding, which satisfies this source-to-load impedance matching, the primary looks into the vacuum tube with the desired 2:1 unmatched source-to-load condition desirable for undistorted output from an amplifier.

The proper matching of primary impedance, secondary impedance, and load impedance sometimes requires additional loading of the secondary to utilize a transformer that does not have the desired turns ratio. This can be done by connecting a loading resistor across the secondary, as shown in Fig. 13.30.

In the case of a transformer having a step-up ratio of 10:1, with a 15-ohm primary impedance, the secondary impedance is equal to the turns ratio *squared*, or 100 times the primary in this case. The secondary impedance is therefore 1,500 ohms. If the load across the secondary is 2,000 ohms, there is a mismatch between secondary and load. However, if a loading resistor is paralleled across the 2,000-ohm load, it is possible to compute the required value of the loading resistance by utilizing the parallel-resistance formula:

$$R_s = \frac{1}{1/R_L + 1/R_x}$$

$$\frac{1}{R_L} + \frac{1}{R_x} = \frac{1}{R_s}$$

$$\frac{1}{R_x} = \frac{1}{R_s} - \frac{1}{R_L}$$

$$R_x = \frac{1}{1/R_s - 1/R_L} = \frac{1}{1/1{,}500 - 1/2{,}000} = \frac{1}{4/6{,}000 - 3/6{,}000} = \frac{1}{1/6{,}000}$$
$$= 6{,}000 \text{ ohms}$$

The addition of the 6,000-ohm loading resistor across the 2,000-ohm load results in a total load of 1,500 ohms, which matches the secondary impedance of the transformer.

**13.34 Parallel-connected Amplifier Tubes.** To double the output power of a class A amplifier, two similar-type tubes can be used. They can be connected in either a push-pull or a parallel circuit. The push-pull class A amplifier was discussed previously. The diagram for two triode tubes in a class A parallel circuit is shown in Fig. 13.31. (The first tube has only one physical connection to its grid. The connection apparently coming from the right side of the tube is merely a means of simplifying the diagraming.)

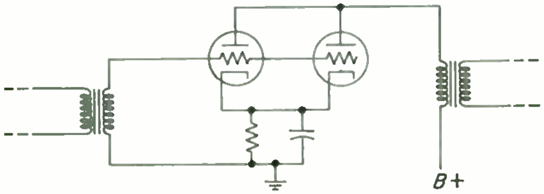


FIG. 13.31. Triodes in parallel.

In actual operation, two tubes in parallel act just the same as one larger tube of twice the power rating. With battery bias, if one tube burns out, the other tube continues to operate, delivering about half the power output and with little change in percentage of distortion. With cathode-resistor bias, when one tube burns out, the current through the cathode resistor decreases, decreasing the bias on the remaining tube. This causes the single tube to operate at a higher-than-normal plate current, at a little more than half the power output of the two tubes.

A disadvantage of parallel-tube operation is the doubling of the total plate current. This necessitates a transformer wound with much heavier wire in the primary. Since twice the current is flowing through the cathode-resistor biasing system, only half the resistance will be required to produce the proper class A bias value. With half the resistance, the filter capacitor across the cathode resistor will have to have twice the capacitance to produce an equivalent bias-voltage smoothing effect.

While transformer coupling is shown in the *grid* circuit of the diagram, it is also possible to use resistance coupling in any class A stage.

Parallel-connected tubes do not cancel even-order harmonics, or power-supply hum, as push-pull operation does.

It is also possible to use four tubes in a push-pull-parallel circuit. Push-pull-parallel can be used with class A, $AB_1$, $AB_2$, and B amplifiers.

**13.35 Types of Distortion.** When the waveshape of the output signal from an amplifier varies in any respect other than in amplitude from the waveshape of the signal fed into the amplifier, the amplifier is distorting the signal. There are three forms of distortion. These are (1) amplitude (also known as *harmonic*), (2) frequency, and (3) phase.

*Amplitude.* If a 3-volt sine-wave signal is fed into an amplifier and produces a 30-volt output signal but a 6-volt signal only produces a 40-volt output signal, the amplifier is not amplifying all signal amplitudes in the correct proportion. This is amplitude distortion. In this case the output waveshape of the 6-volt input signal will be flattened on the peaks. This same flattening of the peaks can be produced by adding to the signal just the correct number and amplitudes of harmonics of the signal frequency. Since the amplifier is doing the same thing to the waveform that addition of separate harmonics would have done, this form of distortion is also known as *harmonic distortion.* It is usually caused by overdriving the amplifier tube, or working on a nonlinear part of the curve of the tube.

*Frequency.* If a 3-volt 100-cycle signal is fed to an amplifier and produces a 30-volt output voltage but a 3-volt 5,000-cycle signal only produces a 20-volt output voltage, the amplifier is not amplifying all frequencies equally well. This type of distortion is known as *frequency distortion.* In this case, if a curve of frequency-versus-output amplitude is drawn, it will vary up and down. It is said to be *nonlinear* (not a straight line), or not *flat.* A perfectly flat amplifier will amplify all audio frequencies equally well.

*Phase.* If two different-frequency a-c signals are fed simultaneously into an amplifier with a certain time or phase difference between them, but are delivered at the output with different phase relationships, the amplifier is said to be producing *phase-shift distortion.* This differing amount of phase changing for different frequencies is caused by inductances and capacitances in the amplifier circuit working in conjunction with resistances. Phase distortion is not usually considered particularly bothersome in audio amplifiers since the ear does not distinguish this distortion easily. In TV, however, this distortion will produce a visual effect and is important.

The following are some of the possible causes of distortion in AF amplifiers:

1. Loss of cathode emission in a tube due to aging or to too low a filament current.
2. Overdriving a grid with too high a signal amplitude.
3. Tube becomes gaseous.
4. Leaking coupling or bypass capacitors.
5. Faulty resistors.
6. Improper control-grid-bias, screen-grid, suppressor-grid, or plate potentials.
7. Improper load-to-tube impedance matching.
8. Filament circuit not grounded at some point.
9. Poor-quality transformer or shorted turns in a transformer.
10. Hum introduced into amplifier circuits.

**13.36 Inverse Feedback in AF Amplifiers.** Signals fed into audio amplifiers are usually distorted somewhat as they pass through each vacuum-tube stage. This is particularly true when audio transformers are used. It is possible to decrease the amount of distortion produced in a stage by taking a small part of the output signal and feeding it back into the grid circuit. The feedback signal must be 180° out of phase with the signal being applied to the grid. This may be called *out-of-phase*, *inverse*, *degenerative*, or *negative* feedback. Any variations of the signal waveform produced in the stage and fed back out of phase will be materially reduced when *reamplified.* This results in a less distorted but weaker output signal. However, the input signal can now be increased, allowing the output of the stage to rise to its normal value.

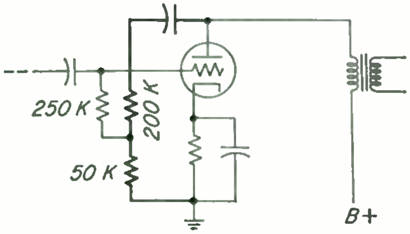


FIG. 13.32. Inverse voltage feedback circuit.

A circuit with inverse voltage feedback is shown in Fig. 13.32. The inverse circuit itself is shown in darker lines.

A signal applied to the grid circuit is amplified and appears across the primary of the output transformer. Since the bottom of the transformer primary is bypassed to ground, the output signal also appears between plate and ground. Connected across this output signal is a d-c blocking capacitor and the voltage-divider network made up of the 200-kilohm resistor and the 50-kilohm resistor. Approximately $\frac{1}{5}$ of the output signal a-c will appear across the 50-kilohm resistor. This small portion of the output is being developed in series with the grid circuit. Since the output voltage signal of an amplifier stage is always 180° out of phase with the signal on the grid, that part of the output signal across the 50-kilohm resistor represents an out-of-phase feedback from plate-to-grid circuit.

Another inverse-voltage feedback circuit takes the feedback voltage from the secondary of the output transformer (Fig. 13.33). If the voltage fed back to the grid is found to be regenerative and raises the gain, or causes the stage to oscillate, it can be made degenerative by reversing either the primary or the secondary connections of the output transformer.

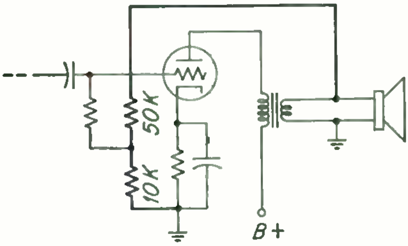


FIG. 13.33. Inverse voltage feedback circuit.

It is also possible to feed back the output voltage into the grid of the *driver* stage (Fig. 13.40). This tends to decrease distortion developed in both driver and power amplifier. Such a circuit is particularly adaptable when resistance coupling is employed between driver and final amplifier. With transformer interstage coupling, a phase reversal may occur at some frequency in the audio range, and increased distortion due to regeneration above a critical frequency may result.

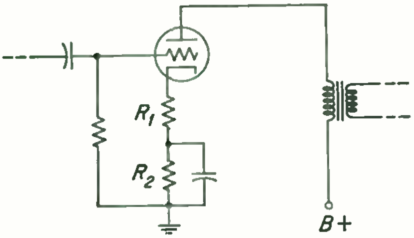


FIG. 13.34. Inverse current feedback circuit.

*Current feedback* is shown in Fig. 13.34. It utilizes the inverse voltage developed across the cathode-biasing resistor to produce the degeneration. In this circuit, the sum of $R_1$ and $R_2$ equals the necessary resistance to bias the stage to class A. The voltage developed across the unfiltered resistor will be out of phase with the signal applied to the grid and in series with the grid-to-cathode circuit. If all the cathode resistor is unfiltered, the degeneration developed may be more than desired. For this reason, only about half the resistance is filtered.

**13.37 Phase Inverters.** Push-pull grids must be fed two signals of equal amplitude but of opposite phase. As one grid is driven a few volts positive by the signal, the other must be driven an equal number of volts negative. The simplest form of a *phase inverter* is a center-tapped audio transformer (Fig. 13.35). If the center tap is in the electrical center of the secondary and is at ground potential, when one end of the secondary is more positive the other is an equal value more negative. If the secondary is connected to the grids of two push-pull tubes, the grids will be fed 180° out of phase, or with opposite-polarity signal voltages.

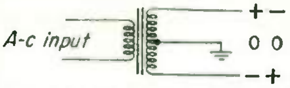


FIG. 13.35. Center-tapped transformer as a basic phase inverter.

Well-engineered transformers are relatively expensive, and even these may pass certain frequencies better than others. To produce the same phase inversion or reversal at less cost and at the same time attain a more constant frequency response, vacuum-tube phase inverters were developed. Two of these circuits are shown. It is important to understand that these vacuum-tube phase inverters can be used only with circuits that draw no grid current, which limits them to feeding class A or $AB_1$ push-pull stages.

In Fig. 13.36, the cathode resistor, the tube, and the plate resistor are all in series. The same current flows through them all. If both resistances are equal, the voltage drop across them will always have to be equal. Because of the bypass capacitor $C_{bp}$, B+ can be considered to be at ground potential as far as a-c is concerned. Note the relative potentials across the resistors. The cathode is positive in respect to ground. The plate is negative in respect to B+, which is at ground potential for a-c signal voltages. Now if the grid becomes a little more negative (1) the current through both resistors decreases; (2) the cathode becomes less positive in respect to ground; (3) the plate becomes less negative in respect to ground. Therefore the signals taken from the cathode and from the plate will be equal in amplitude but opposite in phase. These signals can now feed the two grids of two class A push-pull tubes.

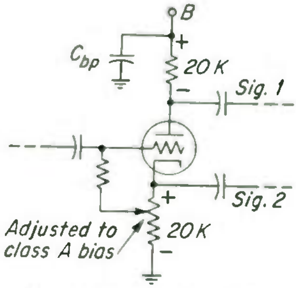


FIG. 13.36. Single-triode phase-inverter circuit.

In Fig. 13.37, $T_1$ is a normal resistance-coupled amplifier, feeding the grid of $T_2$. If $T_3$ is capable of amplifying 10 times, its grid will be fed from a point one-tenth of the way up the voltage-divider grid resistor $R_3$ of the second tube. The 10-times-amplified voltage across the plate-load resistor of $T_3$ will be equal in amplitude to the voltage applied to the grid of $T_2$, *but*, because it passed through the $T_3$ amplifier stage, it is 180° out of phase. (In a normal amplifier the output and input signals are always 180° out of phase.) Therefore $T_2$ and $T_4$ are being fed equal-amplitude but 180° out-of-phase signals.

The two plate resistors $R_1$ and $R_2$ must be equal in value, the two coupling capacitors $C_1$ and $C_2$ must be equal, and the two grid resistances $R_3$ and $R_4$ must be equal to produce equal signal voltages at the push-pull grids.

**13.38 Hum in AF Amplifiers.** Hum developed in AF amplifiers may fall into one of five general categories: (1) improperly filtered power supply, (2) improper functioning of some part in the amplifier, (3) capacitive coupling of hum voltages, (4) inductive coupling of hum voltages, or (5) low-frequency oscillation of the amplifier.

If an amplifier has been operating properly and either suddenly or slowly develops a constant low-frequency tone, or hum, the probabilities are that the power-supply capacitors are losing their effectiveness by drying out or a tube is developing a leak between filament and cathode. If the signal strength also drops at the same time, a filter capacitor may be leaking or shorted or a coupling capacitor may be leaking. In the latter case, considerable distortion will usually be present.

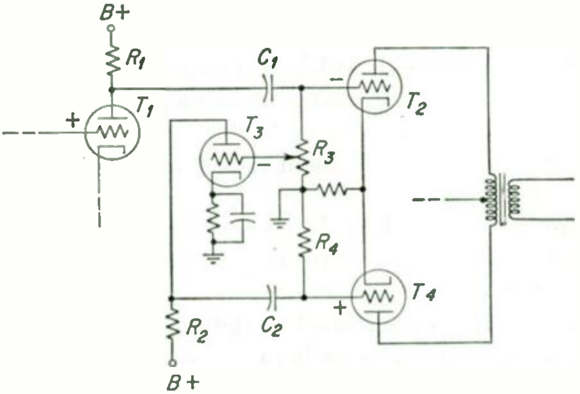


FIG. 13.37. The phase inverter tube $T_3$ feeds an inverted voltage to tube $T_4$.

If an amplifier is newly constructed or has been revamped in some way, it may be found to have a hum. The frequency of the hum should give a clue to the trouble. If the hum has a 60-cycle frequency, the trouble may be due to capacitive or inductive coupling from the filament leads to the grid leads of the first amplifier stage. The wires connecting a filament transformer to the filaments of tubes should always be twisted together to reduce hum pickup in the amplifier circuit. Any single wire carrying a heavy a-c current in it will induce that frequency in any other wire near it. However, if both filament wires are twisted together, an equal value of current is flowing in each wire but in opposite directions. The fields from the two wires will now produce equal and opposite induced voltages in any nearby wires, which cancel each other, resulting in zero hum pickup by the nearby wires. Relocation of the grid or the filament wiring may be necessary.

If a power-supply transformer is placed too close to the input amplifier stage, a 60-cycle hum may be induced into the wires of this stage—particularly into the grid-circuit wires.

The power-supply transformer will almost always induce a 60-cycle hum voltage into the coupling transformer of any low-level stage if the two transformers are less than 2 or 3 ft apart. Special iron shields completely surrounding the coupling transformer will allow closer operation. Often it is necessary to physically rotate the coupling transformer to find the position of minimum hum. Sometimes double shielding of the transformer is necessary.

If the cathode-biasing resistor in the first stages of an AF amplifier does not have a sufficiently large filter or bypass capacitor across it, hum may be produced because of the difference in potentials or leakage between cathode and filament. Some tubes will be much better than others of the same type and make. The selection of a quiet tube is necessary in the first stages in high-gain amplifiers.

Some part of the filament wiring is usually grounded to the chassis or the common ground point in the circuit. In many cases one side of the filament circuit is grounded, although grounding the center tap of the filament transformer is usually more effective in decreasing hum. If the filament transformer has no center tap, a center-tapped 20- to 50-ohm resistor connected across the filament circuit with its center tap grounded will be satisfactory.

If the frequency of the hum is 120 cycles, insufficient power-supply filtering is usually indicated. This may be caused by an amplifier tube drawing too much current for some reason. If the amplifier is drawing too much current, the trouble must be determined by test. To increase the filtering, more capacitance or inductance can be added to the power supply. It may be that only the first voltage-amplifier stages need more filtering. Plate-circuit decoupling networks composed of resistors and capacitors will effectively filter such stages. The degree of filtering required of the power-supply voltage decreases as the level of the amplified signal increases; that is, the first amplifier plate circuit requires the most filtering, and the last stage the least.

To prevent voltages induced on the chassis from being included in the grid or plate circuits of amplifiers, all connections to ground for each separate stage should be brought to a separate common ground point on the chassis.

When a long shielded input lead is used, as from a microphone or turntable pickup, it should be grounded at the grid end of the line, not at the microphone or pickup end.

**13.39 Hum Reduction in Push-Pull Stages.** One of the advantages of using push-pull, particularly in class A and $AB_1$ stages, is the ability of the circuit to cancel hum produced by power-supply ripple. In the push-pull circuit (Fig. 13.38) the plate current from both tubes is flowing in opposite directions in the primary of the output transformer. If the power-supply voltage varies downward, *both* plate currents decrease the same amount at the same time. Such a plate-current decrease in a single-ended stage produces an induced voltage output in the secondary. In push-pull, when both primary currents decrease at the same time, they produce two equal but opposite voltages in the secondary, which cancel each other. Signal voltages continue to be amplified in the stage, but the hum voltages are canceled in the output.

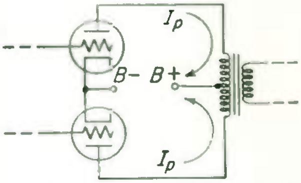


FIG. 13.38. Power-supply variations induce two voltages in the secondary that cancel each other.

**13.40 Miscellaneous Items Regarding AF Amplifiers.** The coupling capacitor between plate circuit and grid circuit in resistance- or impedance-coupled stages is often troublesome. The voltage difference across this capacitor is relatively high and may cause it to break down. As it ages it may become *intermittent*, operating correctly part of the time and either shorting or opening during the remainder of the time. This produces an amplifier which works normally part of the time, and then either distorts or drops its output. If it begins to leak (dielectric breaks down) a positive voltage from the power supply is applied to the grid of the tube connected to it. This increases the plate current of the second tube and usually produces considerable distortion. If this capacitor *opens* (one of the internal connections corrodes apart, the capacitance drops), the signal transferred across it drops to almost zero.

Another capacitor that often shorts out is the bypass capacitor on the screen grid. When it shorts out, the screen voltage will drop to zero and the plate current will decrease, reducing the output of the stage materially. A resistor in the screen circuit will heat and possibly burn out in this case. If a resistance in an amplifier begins to heat, it will rarely be the fault of the resistance. Look for a shorted capacitor, shorted tube, or two wires touching and shorting. Charred resistors should be replaced, as heat may change their resistance, or cause intermittent or noisy operation. This may take the form of clicks, crashes, or squeaks accompanying the signal.

Electrolytic capacitors dry and lose their capacitance. If the filter capacitor loses its capacitance, an increase in hum will occur or an audible oscillation may result because of poor regulation of the power-supply output. When a power-supply filter capacitor shorts, the plate voltage drops to zero on all stages and signals cease entirely. The power-supply transformer, tubes, and chokes may overheat. The tar in the transformer and choke may boil, smoke, and smell. Rectifier tube plates may become red; mercury-vapor tubes glow intensely blue. Always check for high resistance from B+ to B− before replacing a fuse or resetting the overload relay after repairing a damaged part.

If an electrolytic cathode bypass capacitor loses capacitance because of drying, the low-frequency response of the amplifier may decrease and signals may sound thin, or tinny. If this capacitor shorts, the tube has its bias voltage brought to zero, high plate current flows, and distortion may be considerable.

It is important to understand the difference between *plate supply voltage* and *plate voltage.* The plate supply voltage is the voltage reading when a voltmeter is placed across the power supply. The plate voltage is the voltage reading when the voltmeter is connected from cathode to plate at these terminals of the tube. These two voltages will differ by the amount equal to the voltage drop across any cathode-resistance bias circuit plus the voltage drop across the plate-circuit load resistance. It is possible, if battery bias is used, and the plate-load transformer primary has almost no resistance, that the plate voltage and the plate supply voltage will be essentially the same. However, normally there is considerable difference. This is particularly true of resistance-coupled stages.

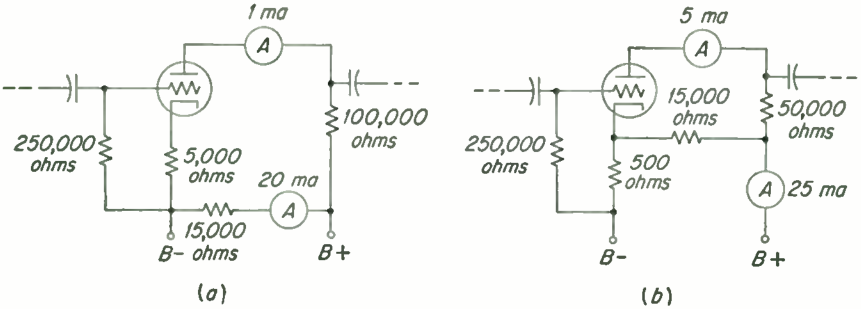


FIG. 13.39. Circuits for practice problems.

## Practice Problems

To test the understanding of these voltages, as well as bias computations, compute the following for Fig. 13.39*a* and *b*.

1. Grid-bias voltage = ?
2. Power-supply voltage = ?
3. Bleeder-resistor voltage = ?
4. Plate-load voltage = ?
5. Plate voltage = ?

**13.41 A General-purpose Amplifier.** The diagram of a five-tube general-purpose audio amplifier, shown in Fig. 13.40, includes a contact-potential-biased pentode input amplifier stage, suitable for amplifying weak signals such as produced by some microphones and low-level phonograph pickups. This is followed by a triode stage having a volume and a tone control and serving as the input stage for higher-voltage signals, such as developed in close-talking microphones, radio receivers, or high-level phonograph pickups. This stage is followed by a triode driver stage, transformer-coupled to two class A 6V6 beam-power tetrode tubes.

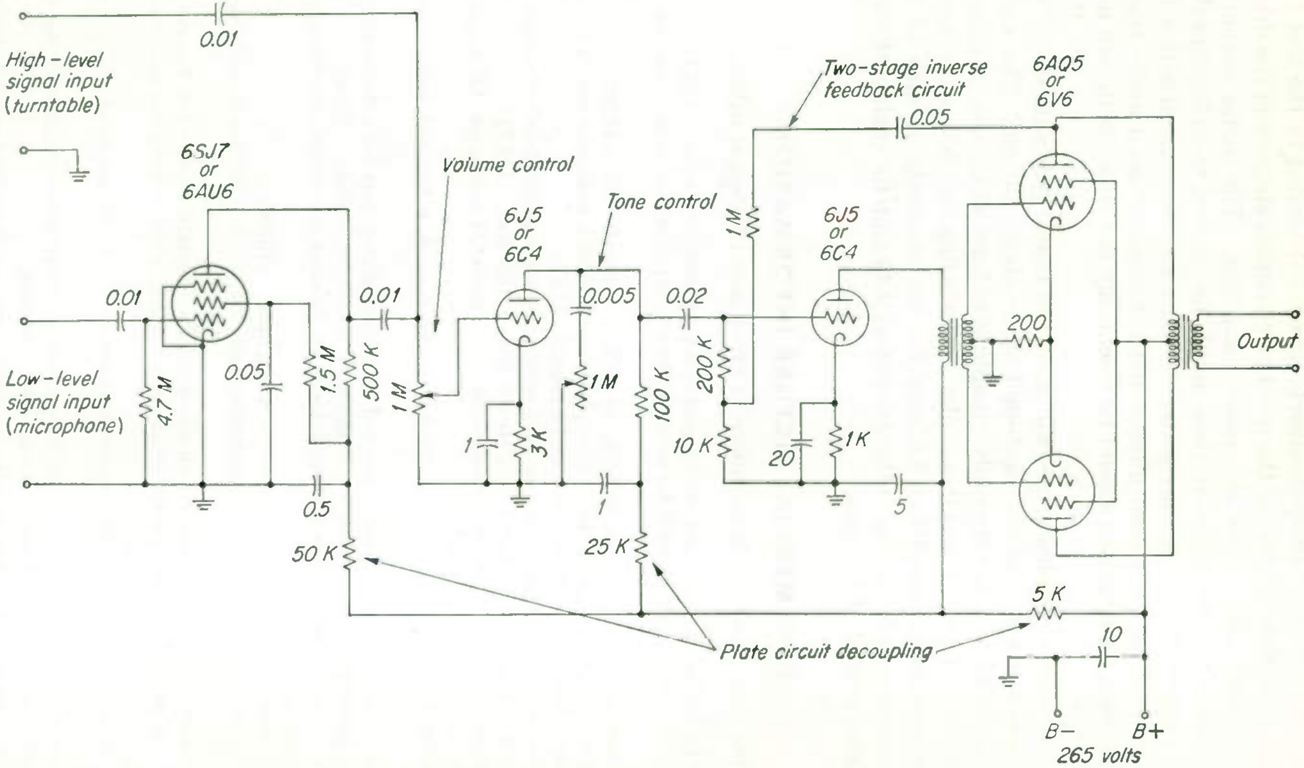


FIG. 13.40. A general-purpose 10-watt audio amplifier.

A two-stage inverse-voltage-feedback circuit is included in the last two stages. The plate circuits of the resistance-coupled stages and the driver stage are decoupled from the power amplifier. The audio output is approximately 10 watts, more than ample for normal room loudspeaker volume, sufficient to plate-modulate a 20-watt RF carrier, and with satisfactory power to cut record discs. With reasonably good audio transformers, such an amplifier should be essentially flat from 50 to well over 10,000 cycles.

The resistance-coupled stages will draw less than 1 ma each, the driver stage about 8 ma, and the push-pull stage about 75 ma. The whole amplifier requires a power supply capable of at least 85 ma output current at 265 volts, plus a 6.3-volt a-c filament winding on the power transformer capable of supplying 0.3 amp for the filaments of each of the resistance-coupled stages and the driver and 0.45 amp for each of the 6V6 filaments, a total of 1.8 amp.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** Why is bias voltage used on the grid of an AF amplifier tube? (13.1) **[3]**

**2.** What would be the effect if d-c were applied to the primary of an a-c transformer? (13.6) **[3]**

**3.** What may cause self-oscillation in an audio amplifier? (13.6, 13.20) **[3]**

**4.** If the value of capacitance of a coupling capacitor in a resistance-coupled audio amplifier is increased, what effect may be noted? (13.7) **[3]**

**5.** Draw a diagram of a resistance load connected in the plate circuit of a vacuum tube, and indicate the direction of electronic flow in this load. (13.7) **[3]**

**6.** What is the purpose of bypass capacitors connected across an AF amplifier cathode-bias resistor? (13.14) **[3]**

**7.** What is the purpose of a center-tap connection on a filament transformer? (13.16) **[3]**

**8.** Draw a diagram showing a method of obtaining grid bias for a filament-type vacuum tube by use of a resistance in the plate circuit of the tube. (13.16 ) **[3]**

**9.** What means are used to prevent interaction between the stages of a multistage AF amplifier? (13.20) **[3]**

**10.** Describe what is meant by a class A amplifier. (13.21) **[3]**

**11.** Compare the design and operating characteristics of class A, class B, and class C amplifiers. (13.21, 13.29) **[3]**

**12.** When a signal is impressed on the grid of a properly adjusted and operated class A AF amplifier, what change in average value of plate current will take place? (13.23) **[3]**

**13.** Discuss the input-circuit requirements for a class B AF amplifier grid circuit. (13.29) **[3]**

**14.** Why are high-reactance head telephones generally more satisfactory for use with radio receivers than low-reactance types? (13.30) **[3]**

**15.** Why are pairs of wires carrying a-c heater currents in audio amplifiers twisted together? (13.38) **[3]**

**16.** Is the d-c bias voltage normally positive or negative in a class A amplifier? (13.1) **[3 & 6]**

**17.** Does direct grid current normally flow in a class A amplifier employing one tube? (13.1, 13.3) [3 & 6]

**18.** What will be the effect of incorrect grid bias in a class A audio amplifier? (13.1, 13.3) [3 & 6]

**19.** What are the factors which determine the bias voltage for the grid of a vacuum tube? (13.1) [3 & 6]

**20.** What is the most desirable factor in the choice of a vacuum tube to be used as a voltage amplifier? (13.4) [3 & 6]

**21.** What circuit and vacuum-tube factors influence the voltage gain of a triode AF amplifier stage? (13.4) [3 & 6]

**22.** Draw a simple schematic diagram showing a method of transformer coupling between two triode vacuum tubes in an AF amplifier. (13.6) [3 & 6]

**23.** Draw a simple schematic circuit showing a method of resistance coupling between two triode vacuum tubes in an AF amplifier. (13.7) [3 & 6]

**24.** Draw a simple schematic diagram of a method of impedance coupling between two vacuum tubes in an AF amplifier. (13.8) [3 & 6]

**25.** Draw a diagram illustrating direct, or Loftin-White, coupling between two stages of AF amplification. (13.9) [3 & 6]

**26.** Explain how you would determine the value of cathode-bias resistance necessary to provide correct grid bias for any particular amplifier. (13.14) [3 & 6]

**27.** Draw a diagram showing a method of obtaining grid bias for an indirectly heated cathode-type vacuum tube by use of a resistance in the cathode circuit of the tube. (13.14) [3 & 6]

**28.** Describe the characteristics of a vacuum tube operating as a class A amplifier. (13.21) [3 & 6]

**29.** Why are tubes operated as class C amplifiers not suited for AF amplification? (13.21) [3 & 6]

**30.** Draw a simple schematic diagram of a triode vacuum-tube AF amplifier inductively coupled to a loudspeaker. (13.22) [3 & 6]

**31.** Does a properly operated class A audio amplifier produce serious modification of the input waveform? (13.22) [3 & 6]

**32.** What are the advantages of using two tubes in push-pull as compared to the use of the same tubes in parallel in an AF amplifier? (13.23, 13.34) [3 & 6]

**33.** What are the advantages of push-pull operation compared to single-tube operation in amplifiers? (13.23) [3 & 6]

**34.** Draw a grid-voltage–plate-current characteristic curve of a vacuum tube and indicate the operating points for class A, class B, and class C amplifier operation. (13.27) [3 & 6]

**35.** Describe the characteristics of a vacuum tube operating as a class B amplifier. (13.29) [3 & 6]

**36.** Why should polarity be observed in connecting head telephones directly in the plate circuit of a vacuum tube? (13.30) [3 & 6]

**37.** If low-impedance head telephones of the order of 75 ohms are to be connected to the output of a vacuum-tube amplifier, how may this be done to permit most satisfactory operation? (13.30) [3 & 6]

**38.** Draw a simple schematic circuit showing a method of coupling a high-impedance loudspeaker to an AF amplifier tube without flow of tube-plate current through the speaker windings and without the use of a transformer. (13.32) [3 & 6]

**39.** List four causes of distortion in a class A AF amplifier. (13.35) [3 & 6]

**40.** What would be the effect of a leaking or short-circuited coupling capacitor in a conventional resistance-coupled audio amplifier? (13.40) [3 & 6]

**41.** What is the stage amplification obtained with a single triode operating with the following constants: plate voltage 250, plate current 20 ma, plate impedance 5,000 ohms, load impedance 10,000 ohms, grid bias 4.5 volts, $\mu$ (amplification factor) 24? (13.4) [4]

**42.** Why is it preferable to isolate the d-c from the primary winding of an audio transformer working out of a single vacuum tube? (13.6) [4]

**43.** What will occur if one tube is removed from a push-pull class A AF amplifier stage? (13.26) [4]

**44.** What factor(s) determine the ratio of impedances which a given transformer can match? (13.33) [4]

**45.** In a transformer having a turns ratio of 10:1, working into a load impedance of 2,000 ohms and out of a circuit having an impedance of 15 ohms, what value of resistance may be connected across the load for an impedance match? (13.33) [4]

**46.** Draw a diagram of an audio amplifier with inverse feedback. (13.36) [4]

**47.** In a low-level amplifier using degenerative feedback, at a nominal mid-frequency, what is the phase relationship between the feedback voltage and the input voltage? (13.36) [4]

**48.** What is the purpose of deliberately introduced degenerative feedback in audio amplifiers? (13.36) [4]

**49.** Why is correct grid bias important in an AF amplifier? (13.1) [6]

**50.** What is the maximum permissible rms value of audio voltage which can be applied to the grid of a class A audio amplifier which has a grid-bias value of 10 volts? (13.2) [6]

**51.** Name four applications for vacuum tubes operating as class A audio amplifiers. (13.2) [6]

**52.** What is the principal advantage of transformer coupling compared with resistance coupling, as used in AF amplifiers? (13.6) [6]

**53.** Why is an audio transformer seldom employed as the output device to be used in the plate circuit of a tetrode audio-amplifier stage? (13.6) [6]

**54.** Explain how you would determine the value of cathode-bias resistor for a specific amplifier stage. (13.14) [6]

**55.** Draw a diagram showing a method of obtaining grid bias for a filament-type vacuum tube by use of resistance in the plate circuit of the tube. (13.16) [6]

**56.** What is the purpose of decoupling networks in the plate circuits of a multistage audio amplifier? (13.20) [6]

**57.** What is the chief advantage of class A audio operation as compared with other classes of AF amplifiers? (13.22) [6]

**58.** How may even-harmonic energy be reduced in the output of an AF amplifier? (13.23) [6]

**59.** In the operation of a class B audio-amplifier stage, should the plate current fluctuate or should it remain at a steady value? (13.29) [6]

**60.** During what portion of the excitation voltage cycle does plate current flow when a tube is used as a class B amplifier? (13.29) [6]

**61.** Why is it necessary to use two tubes in a class B audio amplifier? (13.29) [6]

**62.** What is the correct value of negative grid bias, for operation as a class B amplifier, for a vacuum tube of the following characteristics: plate voltage 1,000, plate current 127 ma, filament voltage 4 volts, filament current 5.4 amp, mutual conductance 8,000 $\mu$mhos, and $\mu$ (amplification factor) 25? (13.29) [6]

**63.** Why are permanent magnets used in head telephones? (13.30) [6]

**64.** Why do headphone receivers used in radio communication usually have high-impedance windings? (13.30) [6]

**65.** What is the relationship between the turns ratio and the impedance ratio of the windings of a transformer? (13.33) [6]

**66.** What turns ratio should a transformer have which is to be used to match a source impedance of 500 ohms to a load of 10 ohms? (13.33) [6]

**67.** What is the d-c plate voltage of a resistance-coupled amplifier stage which has a plate supply voltage of 260 volts, a plate current of 1 ma, and a plate-load resistance of 100,000 ohms? (13.40) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**★1.** What is the purpose of an amplifier? (13.2)
**★2.** What is meant by amplification? (13.2)
**★3.** What is the purpose of an AF choke? (13.8)
**4.** What are the operating characteristics of class A AF amplifiers? (13.21, 13.22)
**5.** Draw a simple schematic diagram of resistance coupling between two vacuum-tube amplifier stages. (13.7)

# CHAPTER 14

# RADIO-FREQUENCY AMPLIFIERS

**14.1 Purpose of RF Amplifiers.** An audio-frequency amplifier must amplify a relatively wide band of frequencies, from the lowest audible tones to the highest-pitched. The task of a *radio-frequency* (RF) amplifier is to amplify a relatively narrow band of frequencies and attenuate all others.

The usable limits of the RF spectrum are from about 10,000 cycles to approximately 300,000 million cycles. For certain radio services, such as radio telegraphic code, it is only necessary that a band of frequencies less than 1,000 cycles wide be amplified. In other services, such as voice transmissions, a band of 3 to 6 kc may be necessary. To transmit music by radio, a band of frequencies 10 kc wide will do fairly well, although if the amplifier will amplify a 30-kc bandwidth, the music may sound more natural. For FM broadcasting, a band 200 kc wide is used; for television 4.5 Mc; and radar requires even wider bandwidths. However, even the 4.5-Mc bandwidth of TV is only a small proportion of the 300,000-Mc radio spectrum.

To amplify one frequency, or more accurately, a small band of frequencies, resonant coil and capacitor (condenser) circuits are employed, as discussed in the chapter on Resonance and Filters. A tuned circuit will accept not only the frequency to which it is resonant, but also other nearby frequencies. The further the frequencies are from the resonant frequency, the less response they will produce in the tuned circuit.

In general, tuned circuits resonating in the range of 50 to 500 kc tend to be rather selective. They pass the resonant frequency and only a few cycles or kilocycles on either side. At higher frequencies, resonant circuits tend to accept signals further from resonance. The circuits are said to be broader-tuned. The broadness of tuning is related to the $Q$ of the circuits involved. The higher the $Q$, the more selective the resonant circuit. At higher frequencies it is more difficult to obtain high-$Q$ circuits. Table 14.1 gives some examples of possible bandwidths obtainable without too much engineering difficulty.

Increasing the frequency being amplified increases circuit difficulties. At higher frequencies the $Q$ of coils decreases because of skin effect and increased core losses. The dielectric losses in capacitors increase. Interaction between stages in receivers or transmitters increases. Shielding becomes more necessary. Wiring between parts of a circuit must be made shorter. Equipment must be made more compact. Insulating materials, such as bakelite, paper, cambric, black rubber, and cotton, usually satisfactory at lower frequencies, are found to have too much loss at higher frequencies. Special insulating materials such as mica, steatite, Isolantite, ceramics, and special plastics must be used. In general, at higher frequencies circuits become more cranky, more difficult to manage. However, new, smaller parts and more advanced circuitry are gradually widening the usable spectrum space. Before 1940 there was little commercial use being made of frequencies above 100 Mc. At present, frequencies up to 10,000 Mc are in daily commercial use. Radio-frequency amplifiers are not in general use, however, over about 500 Mc. Above this, most of the circuits are either oscillators or rectifiers.

Table 14.1

| Amplifier bandwidth | Approximate portion of the RF spectrum likely to be used | Possible uses |
|---|---|---|
| 1 kc | 30–50 kc | Radiotelegraphic code |
| 3 kc | 80–100 kc | Single-sideband voice |
| 6 kc | 150–300 kc | AM voice |
| 10–30 kc | 400–500 kc | AM music or FM voice |
| 200 kc | 5–15 Mc | FM music |
| 4.5 Mc | 20–70 Mc | TV and radar |

With the advent of radar and TV, a new type of amplifier came into being. It is neither a true AF nor a true RF amplifier, but a combination of both. It is called a *video* amplifier. Its function is to amplify all frequencies equally well from about 15 cycles to 4.5 Mc or more. These are discussed in the chapters on Television and Radar.

**14.2 Small-input-signal RF Amplifiers.** For the sake of simplification, RF amplifiers will be arbitrarily divided into two types. The first to be discussed will be amplifiers in which the signal input to the grid is rarely over a few volts and usually is only a fraction of a volt. These will be termed *small-input-signal RF amplifiers.* The other category will be termed *RF power amplifiers.*

Small-signal RF amplifiers include the amplifiers in radio or TV receivers. In some cases, RF amplifiers in a transmitter will fit into this category. However, these are basically receiver-type amplifiers. RF *power* amplifiers are found almost exclusively in radio and TV transmitters and will be discussed later.

Small-signal RF amplifiers are usually operated in class A. While they may have tuned circuits in both grid and plate circuits, it is more usual to find the grid circuit to be the one tuned. The diagram shown in Fig. 14.1 is a simple, practical RF amplifier as used in some types of receivers.

The tube normally used in a receiver RF amplifier is a pentode. The suppressor is connected directly to the cathode.

Screen-grid current flowing through the screen-grid dropping resistor (50,000 ohms in the diagram) produces a voltage drop across it, presenting a lower voltage to the screen than that applied to the plate. If the screen requires a current of 3 ma at a 100-volt potential but the power supply has 250 volts, the screen dropping resistor must lose 150 volts across it. According to Ohm's law, the resistance required to drop the voltage 150 volts when 0.003 amp flows through it is $R = E/I$, or 150/0.003, or 50,000 ohms. Different types of tubes having different screen voltage and current requirements may use other values of resistance, of course. When the power supply produces 100 volts or less, the screen-grid dropping resistor may be eliminated, allowing the screen to operate at the same voltage as the plate.

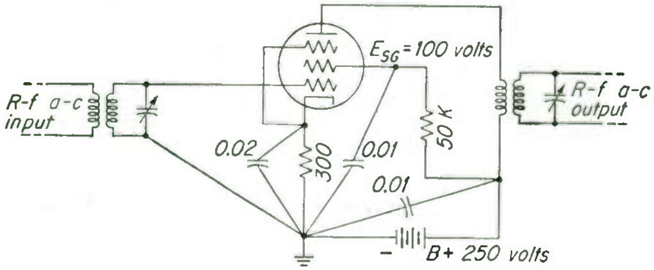


FIG. 14.1. Pentode circuit used to amplify low-amplitude RF signal voltages.

The 0.01-$\mu$f screen bypass capacitor and the resistor form an RC filter. They hold the screen-grid voltage essentially constant even when the current flowing through the tube varies because of the signal voltages applied to the control grid. Without the filter capacitor, a positive signal voltage on the control grid will produce an increase in plate *and* screen current. The increase in screen current will now produce a voltage drop of more than 150 volts across the dropping resistor, and therefore less than 100 volts between screen grid and cathode. When the screen-grid voltage is decreased, the plate current is also decreased. Therefore the screen grid will tend to decrease the plate current when the signal on the control grid should be increasing the plate current. This is a degenerative effect and results in considerable loss of amplification in the stage. For the short duration of one RF cycle, the charged 0.01-$\mu$f capacitor can maintain the screen voltage at approximately the 100 volts required. For an AF cycle, which lasts a much longer time, the 0.01-$\mu$f capacitance might be insufficient to hold the voltage steady enough. A 0.5-μf capacitor might be required.

The cathode resistor, usually about 300 ohms, is selected to produce a small bias voltage across it, biasing the tube to class A. Since the function of the receiver RF amplifier is to produce voltage amplification, a class A amplifier using a pentode tube (usually a variable-μ type) with high μ and high transconductance fills the requirements nicely. The 0.02-μf capacitor across the cathode-bias resistor holds the bias voltage essentially constant even when signal voltages on the control grid produce a variation in plate current through the resistor. It may also be considered as forming a low-reactance or low-impedance path from cathode to ground, resulting in a decrease in degenerative effect that would otherwise decrease the amplification of the stage.

The 0.01-μf bypass capacitor connected from the bottom of the plate-circuit load to ground tends to hold the voltage across it constant. It may also be considered as being the return circuit from the plate load to the cathode, as far as alternating-current signal voltages are concerned.

Notice that all leads of the RF amplifier are brought to *one* point. This is important. Using a single ground point for audio amplifiers is desirable in most cases, but in RF amplifiers it becomes a necessity if minimum interaction between stages is required. Each stage will have a separate ground point, and all the grounded parts of that stage should return to that point. The higher the frequency being amplified, the greater the necessity of using a single ground point. All grid, plate, and ground return leads must be as physically short as possible. Long leads at high frequencies will result in improper operation. Instead of amplifying, a stage may *take off* and produce self-sustained oscillations, or may interact through capacitive or inductive coupling with one or more other stages, forming some complex oscillator circuit.

In Fig. 14.1, the grid circuit is tuned and the plate is untuned. While the plate itself is not tuned, it is coupled close enough to the next stage's tuned-grid circuit so that a tuned-plate-tuned-grid (TPTG) oscillator may be produced if any capacitive feedback from plate to grid circuit exists. This is one of the reasons why the grid and plate leads must be kept short—to minimize stray capacitive coupling across the tube.

To prevent inductive coupling due to the fields of one tuned circuit inducing voltages into the other, both tuned circuits may be encased in metal shield cans. The best shielding material is the best conductor, which is silver. However, silver is expensive. Aluminum, being far less costly, is usually used. Copper is sometimes employed, but it is rather costly also. Since the high-frequency currents that are induced into the walls of the shield tend to travel on the inner surface only, because of skin effect, an excellent shield is produced by silver-plating the inside of a thin copper can. Practically all communications receivers shield all the RF coils to prevent erratic tuning, unwanted oscillations, or unwanted signals.

In most receivers there are RF amplifiers in which both the grid and plate circuits are tuned. These particular stages are known as *intermediate-frequency*, or IF, amplifiers. They are termed intermediate because they are lower than the frequency of the input radio signal being received but higher than the AF amplifiers forming the output circuits of the receiver. Regardless of what they may be called, they are a form of RF amplifier. Examples of some often-used intermediate frequencies are 50 kc, 85 kc, 175 kc, 456 kc, 1.5 Mc, 5 Mc, 10.7 Mc, 21 Mc, 30 Mc, 41 Mc, and 70 Mc. It can be seen that while they may be called intermediate, they are all within the RF spectrum.

Intermediate-frequency tuned circuits may be tuned by connecting small adjustable mica or air-dielectric capacitors across the coils, or by using fixed capacitors across the coils and screwing adjustable powdered-iron cores, or *slugs*, in or out of them. The input RF amplifiers of a receiver may be tuned from one signal to another, but the IF amplifiers remain on the one frequency to which they are tuned at the factory. A few receiver RF amplifiers, as well as some RF power amplifiers, also use slug tuning, having a mechanical means of pulling the slug into the desired position in the coil by a dial on the front of the equipment.

How and where RF and IF amplifiers fit into receivers is discussed in the chapters on AM Receivers, Radar, and Television.

**14.3 RF Power Amplifiers.** The remainder of this chapter pertains to RF amplifiers as used in transmitters. These amplifiers are designed to take a relatively higher-amplitude RF a-c input signal, amplify it, and produce enough power output from the plate circuit either to drive another RF power amplifier or excite a transmitting antenna and radiate RF energy.

While the small-signal RF amplifier is basically class A in operation, distorting the signal very little at any time, the RF power amplifier is usually biased from 1½ to 4 times the plate-current cutoff, allowing it to operate as a high-efficiency *class C* amplifier. Ten watts applied by the power supply to a class A stage may produce only about 2.5 watts useful RF a-c power output. The same tube, biased to class C, may be able to produce 6 or 7 watts output. To do this, however, it is necessary to distort the sine-wave input signal considerably, and then rely on the flywheel effect of the plate-circuit tuned coil and capacitor to restore the sine waveshape to the output signal.

In practically all cases where class C amplifiers are used, either class A or B could be used, with the lower efficiency of such operations. When it is desired to amplify the RF a-c signal without distortion, class A, AB, or B is used.

Bias for the different classes can be determined by the formulas

$$\text{Class A (0.66 cutoff)} = \frac{0.66E_p}{\mu}$$

$$\text{Class B (cutoff)} = \frac{E_p}{\mu}$$

$$\text{Class C } (1\tfrac{1}{2}\text{–}4 \times \text{cutoff}) = \frac{1.5E_p}{\mu} \quad \text{to} \quad \frac{4E_p}{\mu}$$

For example: For a tube with a plate voltage of 1,250 and a $\mu$ of 25,

$$\text{Class A} = \frac{0.66(1{,}250)}{25} = 33 \text{ volts}$$

$$\text{Class B} = \frac{1{,}250}{25} = 50 \text{ volts}$$

$$\text{Class C} = \frac{1.5(1{,}250)}{25} = 75 \text{ volts} \quad \text{to} \quad \frac{4(1{,}250)}{25} = 200 \text{ volts}$$

For transmitting tetrodes, the cutoff-bias voltage is approximately one-fifth of the screen-grid voltage, or $E_{co} = 0.2E_{sg}$. Class C bias $= 0.3E_{sg}$ to $0.8E_{sg}$.

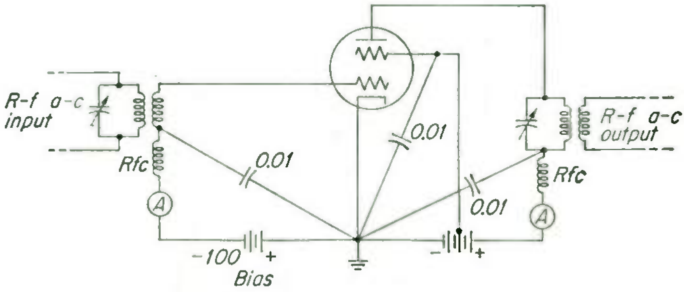


FIG. 14.2. Tetrode RF power amplifier with battery bias.

### 14.4 Battery-biased Class C RF Power Amplifier.

The first circuit to be considered as an RF power amplifier is a tetrode tube, using a battery to supply the bias voltage (Fig. 14.2). The plate-current cutoff bias is −50 volts. Since the grid is biased to a point past plate-current cutoff (−100 volts) the tube is biased to class C. With no signal voltage being applied from the RF a-c source, the bias holds the plate current to zero. It also holds the screen-grid current to zero. The stage is completely inoperative. This condition is indicated on the $E_gI_p$ curve (Fig. 14.3) as *condition 1*. The curve shows the cutoff-bias point as −50 volts, the actual bias point as −100 volts, and the zero bias point. The resultant plate current during condition 1 is zero.

In *condition 2* the RF a-c source is inducing a 50-volt peak in the grid-circuit coil. The a-c is added to the −100 volts bias, producing, in effect, a varying d-c bias. This varying bias ranges alternately from −50 to

$-150$ volts, but still no plate current flows in the tube because the grid voltage still is not driven to a lower value than cutoff.

In *condition 3*, the RF a-c source is able to induce a 100-volt peak into the grid coil. This, added to the $-100$ volts bias, produces a varying d-c that varies from zero to $-200$ volts. During the portion of the input-signal cycle that the bias is actually effective under the $E_gI_p$ curve, plate current flows as a steep, narrow pulse. Note that the width of the pulse is *less than a half cycle*. The plate current flows for less than 180° of the input cycle, actually for 120° in this case. So far, the grid has not been driven into the positive region, and therefore grid current does not flow in the grid circuit, even though the stage is biased to class C. This is a possible condition for a class C stage, but is not the optimum or normal operating condition.

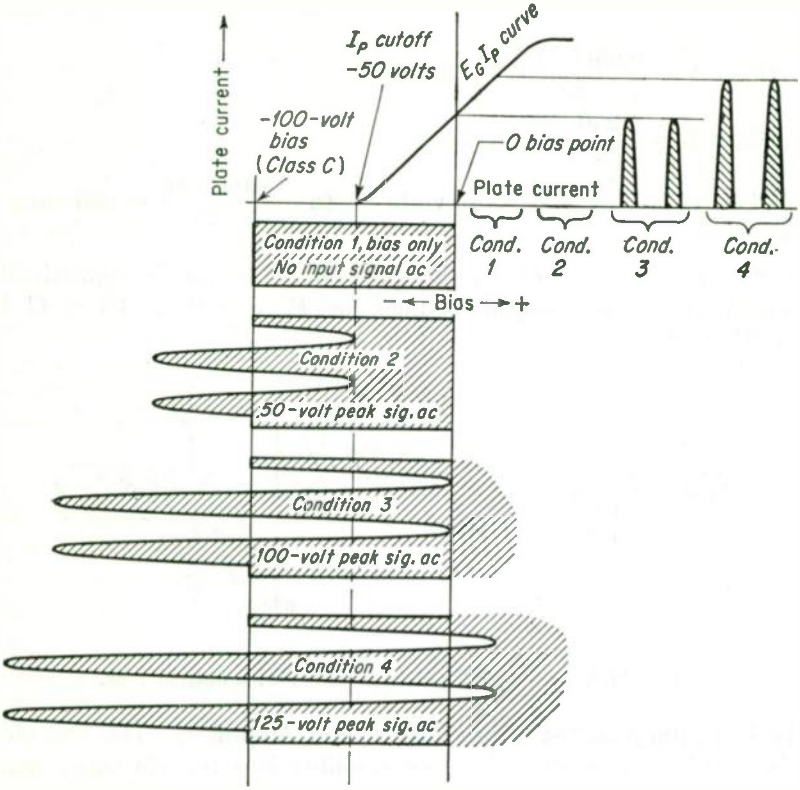


FIG. 14.3. Grid-voltage–plate-current curve and four possible conditions of a class C RF power-amplifier tube.

*Condition 4* represents the normally accepted condition for class C RF amplifiers. The RF source induces a voltage with a peak value considerably greater than the bias value. This drives the grid into the positive region for a portion of each cycle, causing a pulsating direct grid current to flow from the cathode through the tube to the grid, down through the grid coil, RF choke coil (RFC), the ammeter, and through the bias battery in a direction *opposite* to normal current flow for a battery. (This current forced backward through the bias battery will *charge* the battery rather than discharge it.) The plate-current peaks are considerably higher in amplitude and exist for slightly more than 120°. Increasing the bias voltage results in a decreased plate-current pulse duration. Less bias increases the duration of the pulses, provided the driving voltage remains the same.

Plate current heats the plate of a tube. The plate-dissipation rating of a tube expresses how much average heat the plate is capable of dissipating without overheating dangerously. The use of high bias voltages results in narrow plate-current pulses. Thus, class C amplifiers have a relatively long duration *between* pulses, allowing the tube to rest for a major portion of each cycle. During the time the tube is working it can be driven very hard and still its *average* plate dissipation may not exceed the plate-dissipation rating. For this reason class C amplifiers are high in efficiency. Class B amplifiers, biased to cutoff, have plate current flowing for a full half of the cycle, rest proportionately less, and are therefore less efficient. Class A amplifiers have plate current flowing all the time and tend to overheat their plates unless the plate voltage is held to a lower value than can be used with class B and C amplifiers.

It is notable that an RF power amplifier may be biased to the class A value but driven into the positive grid region and made to draw grid current. This is not the accepted *class A* operation, but is possible in RF amplifiers. It results in a considerable increase in efficiency in the stage, although it will result in less efficiency than if the stage were biased to class B or class C.

As in the small-signal RF amplifiers, the grid, screen-grid, plate, and cathode-resistor bypass capacitors return to a single ground point for most stable operation.

Current varies in the screen-grid circuit at the same time as does the plate current, although at a considerably lower amplitude. Two important points to remember about the screen grid in an RF amplifier are: (1) Use short leads on the bypass capacitor. (2) Do not apply higher screen-grid voltage than recommended in tube manuals. Excessive screen voltages produce excessive plate and screen current, which can decrease the life of the tube.

The two RF chokes shown in the grid and plate circuits may or may not be needed. If the bypass capacitors can maintain the bottom of the grid- and plate-circuit coils at essentially ground potential as far as RF a-c is concerned, the additional filtering of the RFC may be unnecessary. If both chokes are used, a low-frequency parasitic oscillation may be set up, as discussed in Sec. 12.22.

Radio-frequency chokes may be constructed as single-layer coils, perhaps ¾ in. in diameter and 5 in. long, with a hundred or more turns. However, it is found that an RFC may exhibit a parallel-resonant effect (high impedance) to certain radio frequencies, but will have an undesirable series resonance (low impedance) to other frequencies. The resonant peaks are usually harmonically related. To overcome the undesirable series-resonant effect, RF chokes may be made in different shapes. In one common form they are made up of three, four, or five separate *universal-wound pies* (one coil layer wound on top of other layers), with all the pies connected in series, as shown in Fig. 14.4. This form tends to produce a high-impedance, or a parallel-resonant, effect to practically all frequencies over the relatively wide band of frequencies for which the choke is manufactured.

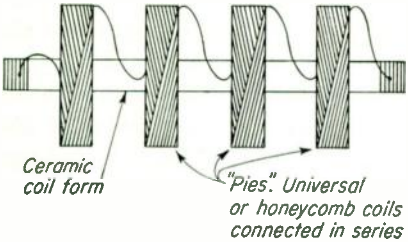


Fig. 14.4. RFC coil.

**14.5 Tuning the Plate Circuit.** The plate current flowing through the tube appears as short-duration pulses of d-c. These pulses appear to the LC circuit more as a distorted form of a-c than as a d-c. Consequently, it is reasonable to consider that the tuned circuit sees the tube and power supply as a source of quasi a-c energy. The LC circuit is then a parallel-resonant circuit connected across an a-c source. If the plate LC circuit is tuned to the same frequency as the plate-current pulses, it presents a high impedance to the pulses, thereby allowing little plate current at this frequency to flow through the source and itself. The ammeter in the plate circuit will read a low value in this case.

If the plate LC circuit is detuned from the frequency of the plate-current pulses, it presents a lower impedance to the pulses and allows a greater pulsating current to flow through the source and the LC circuit. The ammeter in the plate circuit will read a higher value. As a result, the plate-current ammeter makes a good indicator to determine when the plate LC circuit is tuned to resonance. At resonance the plate-current meter reads *minimum.* The further from resonance, the greater the plate-current value.

In a parallel circuit at resonance, a maximum number of electrons oscillate back and forth between the coil and capacitor of the LC circuit. Because they are oscillating at the same frequency as the incoming pulses from the source, little energy is required from the source pulses to maintain oscillations and the a-c voltage across the LC circuit is nearly equal to the voltage of the source. (Since the LC circuit is in parallel with the source, the RF a-c will not exceed the source voltage value.) At resonance it takes little energy, and therefore little plate current, to produce this a-c voltage value in the LC circuit. Thus maximum RF current is circulating in the LC circuit when the d-c plate-current indication is at a minimum.

Because the plate is taking a minimum number of electrons from the space charge of the tube when the plate load is tuned to the resonant frequency, the grid is free to attract a maximum number during its positive swing. As a result, the grid current, as read on a grid-circuit milliammeter, rises somewhat when the plate circuit is tuned to resonance. The grid current falls off as the plate circuit is detuned or if the plate current increases for any reason. As a result, a grid-current meter may be used to determine when the plate circuit is tuned to resonance. The screen-grid current will also increase when the plate current decreases. Meters are rarely included in the screen-grid circuit, however.

**14.6 Coupling the RF Amplifier to a Load.** The RF a-c energy oscillating in the plate LC circuit is coupled either into an antenna, into the grid circuit of another RF amplifier, or into some other kind of a load circuit. If the coupling between the plate LC circuit and the circuit that follows is very *loose*, little energy will be drawn from the plate tank circuit. In this case, the plate-current dip when the LC circuit is tuned to resonance will be very deep. For example, if the off-resonance plate-current maximum is 200 ma, the resonant value might dip to perhaps 20 or 30 ma (and the screen current may rise dangerously).

If the coupling between the plate tank and the following circuit is increased, the tank circuit will have more energy drawn from it. This lowers the parallel-circuit impedance value of the tank circuit, increasing the pulsating current flowing through the LC circuit and the source. The plate-current dip will no longer be as great. The off-resonance value may still be 200 ma, but the value at resonance may now be 100 ma.

If the load circuit is tightly coupled to the tank circuit, it may be found that no plate-current dip will be noticeable, and tuning by the plate-current meter is impossible.

How much coupling should be used? The best answer to this is to consult a manual giving the operating characteristics of the tube being used. Adjust the plate and screen voltages to the recommended values. Adjust the grid bias and grid drive to produce the recommended value of grid current. Then, starting with loose coupling, keep increasing the coupling and dipping the plate current by tuning the plate circuit until the plate-current minimum at the dip is that recommended in the manual. Recheck the plate, screen and bias voltages, and the grid-current value and readjust to the recommended values if necessary. This will usually require a recheck on the plate-circuit coupling.

In an emergency, where nothing is known except what is shown on the plate-current meter, it is probable that adjusting the coupling until the plate-current dip is about 75 per cent of the off-resonance maximum will give fairly good output. If the off-resonance value is 200 ma, the coupling should be increased until the maximum dip reads 150 ma. Proper operation of an RF amplifier rarely results with less than a 20 per cent dip in plate current from the off-resonance value. In most cases a greater current dip is required.

A more accurate method of determining the proper coupling to the output circuit is to use some means of measuring the output power, or of obtaining a relative indication of it. An RF ammeter in series with the load circuit (Fig. 14.5) will serve as an indicator of the relative power being taken from the amplifier circuit.

The plate-power input to the amplifier is equal to the product of the power-supply voltage times the plate current flowing through the amplifier, or $P = E_bI_p$ (or $E_pI_p$, since $E_b$ and $E_p$ are the same). With loose coupling to the load circuit, both the d-c plate input power at resonance and the RF a-c output-power value will be low. As the coupling is increased, both d-c input and RF output values will increase. A degree of coupling will be reached where the RF output power will show no further increase, whereas the d-c input power will continue to increase as coupling is increased. Further increase of coupling will usually result in a decrease in RF output and a still further increased input power. This indicates that the best point of coupling has been passed. The coupling should be reduced to the lowest value of d-c power that will give the greatest RF output. At this degree of coupling a condition of approximate impedance match between the plate impedance of the tube and the tank-circuit impedance occurs, resulting in a maximum power being developed in the load circuit. Furthermore, the impedance of the secondary of the output transformer should closely approximate the impedance of the load. The desirable condition of maximum power output by matching impedances, tube to tank and tank to output circuit, is being approached.

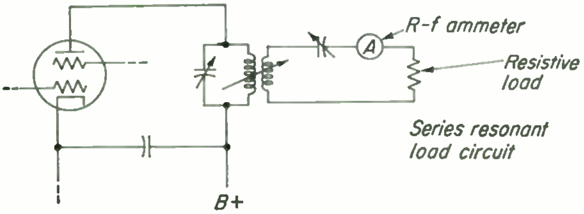


FIG. 14.5. RF power output can be determined by multiplying the load resistance by the current squared.

It is usually possible to obtain a still better impedance match and greater power output by increasing the capacitance and decreasing the inductance of the tank circuit, or vice versa, and running through the tests again. When maximum RF output results with as little d-c power as possible being used to produce it, optimum coupling has been attained.

It can be seen that finding the exact values for capacitance and inductance of the plate tank, degree of coupling, and load impedances is not easily accomplished. Fortunately, a rather wide variation of capacitance and inductance values from the optimum will produce output closely approaching that produced by the optimum values. The engineering required to compute optimum values is beyond the scope of this book.

While maximum output power is obtained when the load impedance matches the source, the higher the load impedance in comparison with the dynamic plate impedance of the tube, the greater the plate-circuit *efficiency*. In other words, the higher the ratio of load impedance to plate impedance, the higher the efficiency but the less the power output. A transmitter should not be adjusted for highest plate efficiency.

The plate-circuit efficiency can be determined by comparing the d-c plate-circuit input power to the RF output power. The percentage of efficiency is computed:

$$\%\ \text{efficiency} = \frac{P_{\text{rf}}}{P_{\text{dc}}} \times 100$$

where $P_{\text{rf}}$ is the RF a-c power output (see Sec. 20.30); and $P_{\text{dc}}$ is the d-c plate-circuit power input.

The d-c plate-circuit input power is the product of the plate voltage times the plate current. Of this total power input, some is dissipated as heat by the plate of the tube, a little is dissipated as heat in the LC circuit and other wiring in the circuit, and the remainder is RF output power. If the plate input power to a transmitting tube is 1,000 watts and the RF output power is 700 watts, it is normally assumed that the plate dissipation is 300 watts. In this case:

$$\%\ \text{efficiency} = \frac{P_{\text{rf}}}{P_{\text{dc}}} \times 100 = \frac{700}{1{,}000} \times 100 = 70\%$$

**14.7 Grid-leak Bias for RF Amplifiers.** Grid-leak bias (Sec. 12.5) can be used as the sole bias for a class C RF amplifier only if grid current flows. It cannot be used in receiver or other small-signal RF amplifiers in which there is no grid current.

Grid-leak bias depends upon the flow of grid current through a grid-leak resistor when the grid is driven into the positive region by the signal from the preceding stage. This requires a *power* amplifier as the driver stage to produce the required grid current.

The diagram in Fig. 14.6 shows a possible grid-leak-biased class C tetrode RF amplifier stage.

The grid-leak resistor is selected to have the correct resistance to produce the proper *average* class C bias voltage. It might be pointed out that the bias voltage developed by grid-leak bias varies in amplitude from the positive to negative peaks of the input RF a-c signal voltage, but the *average* value (held by the grid capacitor) is more than that required to produce plate-current cutoff. Therefore the stage is biased to class C.

The value of the bias voltage can be determined by Ohm's law $E = IR$, where $I$ is the grid current in amperes, and $R$ is the grid-leak resistance in ohms. If the average grid current, as read on the meter, is 10 ma and the resistance is 5,000 ohms, the average grid bias is 0.010 amp times 5,000 ohms, or 50 volts. If this bias voltage is less than is desired, the coupling from the RF a-c source can be tightened until the grid current times the resistance value equals the desired bias voltage. To vary the bias value the grid-leak resistance may be changed. It may be necessary to adjust both drive and resistance to obtain the desired results.

Grid-leak bias has one serious disadvantage. It is used in class C amplifiers normally operating with relatively high plate voltage. If the *driver* stage suddenly ceases operating for any reason, the RF amplifier is left with no input signal, zero bias, and high plate voltage. This will produce dangerously high plate and screen currents that may damage the amplifier tube unless some precaution is taken. Because of this danger, many class C amplifiers use either an external bias supply plus grid-leak bias or some cathode-resistance bias (Sec. 13.14) in addition to the grid-leak bias. In this way, if the drive is suddenly interrupted, the fixed bias will be sufficient to limit the plate and screen current of the amplifier to some safe value. An RF bypass capacitor should be connected across any cathode resistor to keep the cathode at ground potential as far as RF a-c is concerned. This prevents degeneration.

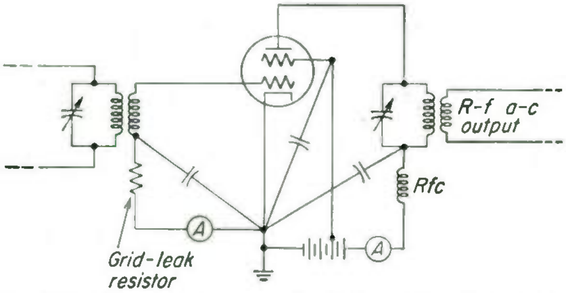


FIG. 14.6. Tetrode RF power amplifier with grid-leak bias.

Another safety precaution often used is a plate- or screen-circuit *overload relay*. If an excessively high plate current flows through the coil of an electromagnetic relay in series with the plate or screen circuit, the relay arm is pulled in, trips a latch, and automatically shuts off the plate and screen-grid power supplies.

**14.8 Parallel Operation of RF Amplifier Tubes.** The single-ended (one-tube) stages described so far have been used for simplification of discussion. To produce twice the power output possible from one tube, two tubes may be used in parallel or in push-pull.

A parallel RF amplifier circuit is shown in Fig. 14.7. Parallel-connected tubes have their similar elements connected together, cathode to cathode, grid to grid, etc. The small RF chokes connected as close as possible to the plate terminals of the tubes are used to discourage high-frequency parasitic oscillations (Sec. 12.22) which often occur in this type of amplifier circuit.

To test an amplifier stage for parasitic oscillations, the RF drive is first removed, and the stage then operated with grid-leak bias *only*. The plate and screen voltages are adjusted low enough to limit the plate and screen currents to values that will not exceed the plate and screen dissipation ratings of the tubes. An indication of any material value of grid current indicates the presence of parasitic oscillations. To stop parasitic oscillations occurring at higher frequencies than the operating frequency, parasitic chokes may also have to be added to the control-grid (points $X$) and/or the screen-grid leads (points $Y$). If the parasitic oscillation is occurring near the operating frequency, neutralization (discussed later) is required. If at a lower frequency than the operating frequency, RF chokes in the circuit are probably causing the parasitic oscillation.

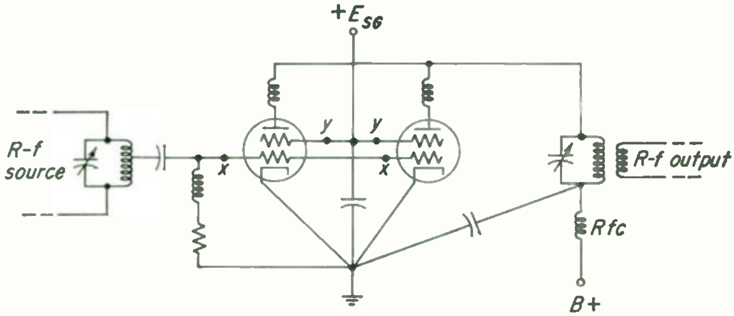


FIG. 14.7. Parallel tetrode tubes in an RF power amplifier.

Two tubes in parallel act somewhat as parallel resistors or impedances, lowering the operating-tube impedance as seen by the plate tank circuit. This will usually require lowering the value of inductance and raising the capacitance of the tuned circuit in order to match more closely the tube impedance to the load impedance. More oscillatory current will be flowing through the coil, which may require a coil made with larger-diameter wire.

The two tubes in parallel have twice the plate-to-cathode, plate-to-grid, and grid-to-cathode interelectrode capacitances, which may be a disadvantage for VHF operation.

**14.9 Push-Pull Operation of RF Amplifiers.** Two RF amplifier tubes can be connected in push-pull. The output power from two such tubes will be twice that obtainable from one tube in a single-ended circuit.

Figure 14.8 shows a pair of tetrode tubes connected in push-pull. The advantage of the use of push-pull stages is mainly their tendency to cancel *even-order* (second-, fourth-, etc.) harmonic energy in their output. However, to do this effectively, each tube has to be fed the same-amplitude signal voltage, the plate tank circuit must be accurately center-tapped, the coupling to the output should be taken equally from both halves of the plate tank circuit, and the characteristics of the two tubes must be matched.

The plate-to-cathode interelectrode capacitance effectively connected across the tuned plate circuit is made up of the capacitance of the two tubes acting in series. This results in only half the capacitance across the tuned circuit that would be present with one tube alone, a decided advantage for higher-frequency operation. For the same reason, the tuned grid circuit has only half of the tube capacitance across it that a single-ended stage would have.

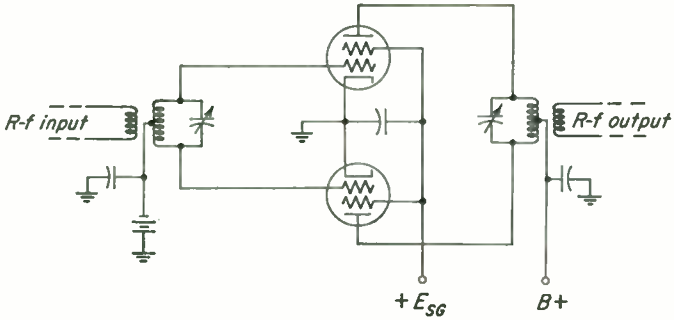


FIG. 14.8. Push-pull tetrode RF power amplifier.

Note the use of multiple ground indications to simplify the diagraming. This does not indicate that a single ground point is not necessary in the stage. In actual commercial diagrams such ground indicators are used, and it is assumed that the reader understands that each stage will have its single grounding point. Subsequent diagrams in this book will follow this reasoning.

**14.10 Types of Feed.** As mentioned in the discussion of types of feed in Sec. 12.7, it is possible to feed the plate current from the tube through the coil of the tuned tank circuit in the plate circuit (series feed) (Fig. 14.9*a*), or the plate current can be led off through an RF choke (shunt feed). In the latter case, the reactive a-c voltage drop across the RFC developed by the pulsating d-c flowing through it is coupled to a tuned circuit by a coupling capacitor $C_c$ (Fig. 14.9*b*).

In either series- or shunt-feed circuits, when the LC circuit is tuned to resonance with the frequency applied to the grid, the plate-current value will drop to a minimum.

Either series or shunt feed can be used in single-ended stages, in parallel-tube stages, or in push-pull stages.

With shunt feed, one side of the tuning capacitor is grounded. This is a mechanical advantage to the manufacturer of equipment in some cases. Also, there are no high d-c potentials on the coil or capacitor.

**14.11 Methods of Coupling RF Amplifiers.** The two stages shown in Fig. 14.10 are inductively coupled or transformer-coupled. This is only one of many possible methods of coupling RF energy from the output of one stage to the input of the next stage.

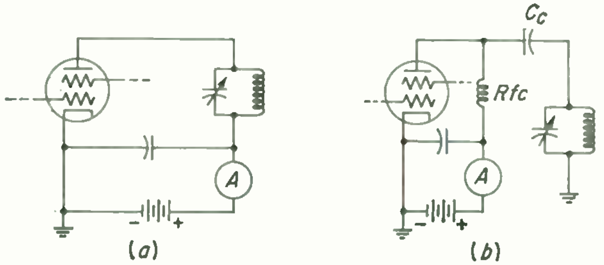


Fig. 14.9. (*a*) Series-fed and (*b*) shunt-fed RF amplifier plate circuits.

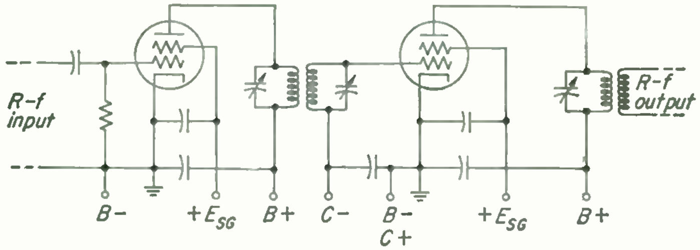


Fig. 14.10. Inductive or transformer coupling between two RF amplifiers.

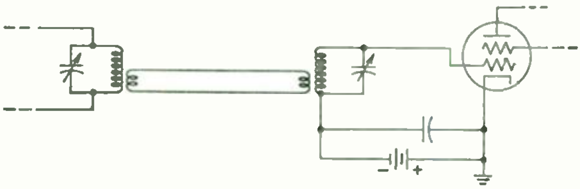


Fig. 14.11. Link coupling between two tuned circuits.

With tuned inductive coupling between two stages, as shown, it will be found that the circuits will require very loose coupling. They may have to be placed so far apart physically that they may require more space to construct them than is desired. It may be preferable to closely couple the two coils and tune only one of them.

A two-transformer method of coupling is known as *link* coupling. The plate coil is the primary of a step-down transformer, and the grid coil is the secondary of a step-up transformer, as shown in Fig. 14.11. This transformer effect reduces the impedance of the link line to very low values, allowing the energy to be carried long distances with little loss, particularly if coaxial cable is used between the terminating loops. As a result, the plate and grid circuits being coupled need not be physically close together, as is necessary with other forms of coupling. Link coupling also reduces stray capacitive coupling, thereby reducing possible coupling of unwanted harmonic frequencies generated in the plate circuit. This is considerably aided by grounding one side of the link line.

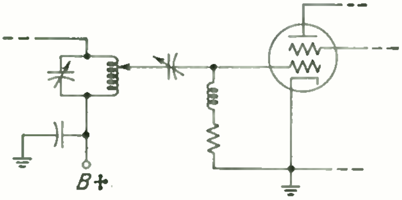


Fig. 14.12. Capacitive or impedance coupling in an RF amplifier.

A form of capacitive or impedance coupling is shown in Fig. 14.12. The degree of coupling can be determined either by adjustment of the capacitance of the coupling capacitor or by the placement of the tap on the coil. The closer the tap to the ground-potential end of the coil, the less the coupling. An RF choke, a grid-leak resistor, or both in series may be used in the grid circuit. This form of coupling finds wide use but tends to transfer any harmonics generated in the driving stage to the grid circuit of the following stage.

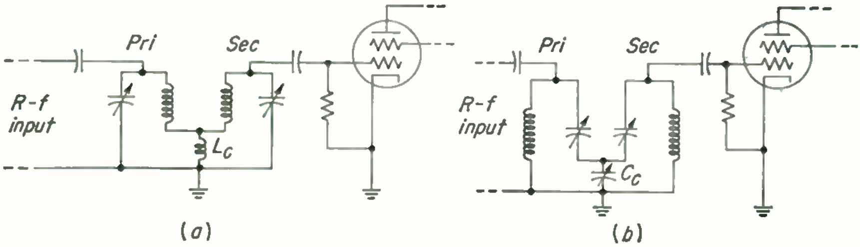


Fig. 14.13. (*a*) Direct-inductive and (*b*) direct-capacitive coupling circuits.

Two forms of direct coupling, inductive and capacitive, are shown in Fig. 14.13. The coupling coil $L_c$ and the coupling capacitor $C_c$ are common elements in these coupling systems. The reactive voltage developed across these coupling reactors by current in the primary circuit induces current in the secondary circuit. The smaller the inductance $L_c$ and the larger the coupling capacitance $C_c$ the less the coupling between the two circuits. There is no mutual inductance between coils.

**14.12 The Triode RF Amplifier.** Triode tubes are also used in RF power amplifiers, although tetrodes and pentodes have the advantage of greater sensitivity, require less RF drive to their grids, and do not require neutralization. So far, tetrode or pentode tubes have been used in the explanations of RF amplifiers because such tubes usually require no out-of-phase feedback, or neutralization. A triode-tube RF amplifier, with plate and grid circuit tuned to the same frequency, becomes a TPTG oscillator because of feedback from plate to grid circuits via the grid-plate interelectrode capacitance. If an oscillator is desired, this circuit may be satisfactory, but when the stage is supposed to be an RF amplifier, it must not break into self-oscillation. Introduction of the proper amount of neutralizing voltage into the circuit will prevent self-oscillation. If an RF amplifier is not properly neutralized, it may generate many spurious signals, interfering with other radio services. The plate current may not dip smoothly as the plate circuit is tuned past resonance—a common indication of an improperly neutralized stage.

There are several ways by which neutralization may be introduced into a stage to prevent it from oscillating. There are five methods of particular interest. These can be termed (1) plate neutralization, (2) grid neutralization, (3) direct neutralization, (4) inductive neutralization, (5) use of a *losser* resistor.

The general theory of the first four methods is somewhat the same. The energy fed back to the grid from the plate circuit by the grid-plate interelectrode capacitance is counteracted by using another equal but opposite voltage, resulting in a neutralizing of the feedback effect through the tube.

The losser method merely consists of a resistor in series with the grid lead, as shown in Fig. 14.14. The loss of energy in the grid resistor plus the out-of-phase, or degenerative, voltage developed across the resistor whenever current flows through it is great enough so that regeneration of energy into the grid circuit from the plate circuit is not sufficient to support oscillation of the stage. This method is useful mostly as a means of preventing parasitic oscillations in an RF amplifier in a transmitter, but is an inefficient method of neutralization against oscillation at the frequency to which the amplifier is tuned. The losser-resistor value should be as low as possible to produce the desired suppression of parasitic or circuit oscillation without too much loss of amplification. Values used may range from 50 to more than 1,000 ohms.

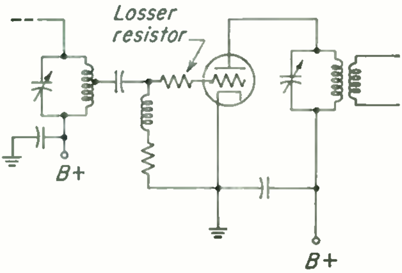


FIG. 14.14. Losser resistor in the grid circuit of an RF power amplifier.

Losser resistors are sometimes included in screen-grid and also in plate leads in place of parasitic chokes to stabilize the operation of the stage. The word *stabilize* in this sense means to allow the stage to act purely as an RF amplifier without generating parasitic oscillations or other undesirable effects.

An unbypassed cathode-biasing resistor also discourages self-oscillation of an amplifier stage.

**14.13 Plate Neutralization.** A common form of neutralization is *plate neutralization.* This circuit is shown in Fig. 14.15. It may also be known as a *Hazeltine balance* circuit.

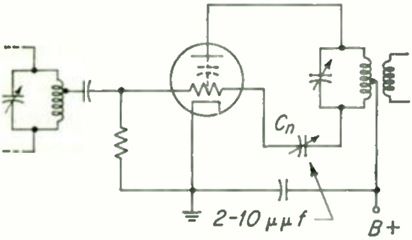


FIG. 14.15. Triode RF amplifier with plate neutralization.

The interelectrode capacitance between grid and plate (shown by the dotted capacitor inside the tube) can act as a conductor of RF energy from the plate tank circuit back to the grid circuit. As explained in the chapter on Oscillators, this will produce a sustained oscillation in the amplifier stage *if* the plate and grid circuits are tuned to approximately the same frequency. If they are not tuned to the same frequency, the stage will not oscillate, but neither will it effectively amplify the frequency fed to the grid by the source of RF a-c.

Notice that the plate tank circuit has its coil center-tapped, and the center tap is bypassed to the cathode and ground. This develops a zero RF-potential, or ground-potential, point at the center of the coil. With the center of the coil at zero RF potential at all times and with the tank circuit oscillating, one end of the LC circuit will be RF-positive at the same instant that the other end is RF-negative, and vice versa. As far as the coil is concerned, the two ends have equal amplitude voltages but are opposite in RF polarity at all times.

The top end of the tank circuit is feeding RF energy back to the grid via the grid-plate capacitance of the tube and is attempting to make the stage oscillate. When a *neutralizing capacitor* $C_n$, having the same capacitance as the interelectrode capacitance of the tube, is connected between the bottom of the tank circuit and the grid of the tube, the grid is fed two equal and opposite voltages at the same time, one through the tube and one through the neutralizing capacitor. The net result is zero effective feedback to the grid from the plate circuit, and the stage will not oscillate. It is neutralized.

In practice, the neutralizing capacitance is usually a variable capacitor in order that the proper capacitance can be obtained under operating conditions.

Actually, it is not necessary to exactly center-tap the plate coil. If the tap is closer to the bottom of the coil, a smaller neutralizing voltage will be developed across the lower part of the coil. However, this can be overcome by adjusting the neutralizing capacitor to a higher value of capacitance. This feeds more energy from the bottom of the tuned circuit to the grid, to equalize the greater feedback through the tube when the tap is moved down the coil.

Instead of center-tapping the plate coil, a *split-stator* capacitor may be connected across the tuning coil (Fig. 14.16). This is a dual variable capacitor with a common rotor connection for both sections. This may be thought of as center-tapping the capacitive half of the LC circuit. Center-tapping the tuning circuit in this manner again establishes a central ground-potential point, allowing the opposite ends of the coil to have equal potentials but opposite polarities. This neutralizing circuit resembles the one previously described in operation. One point regarding these two methods of center-tapping the tuned circuit: while both may work equally well, center-tap only the coil *or* the capacitor, *not both.*

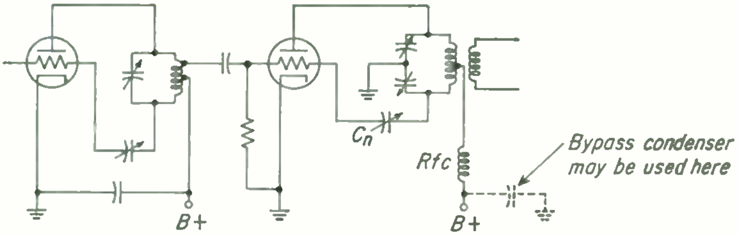


FIG. 14.16. Triode RF amplifier with split-stator capacitors and plate neutralization

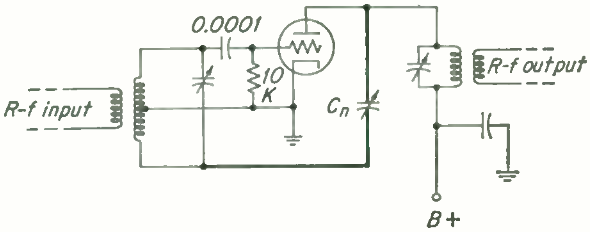


FIG. 14.17. Triode RF amplifier with grid neutralization.

If split-stator capacitors are used, the coil should not be bypassed to ground at the center, or the circuit tends to break up into two tuned circuits, one made up of the top capacitor and top half of the coil and the other of the bottom capacitor and bottom half of the coil. Instead, the center of the coil should be connected to the power supply though an RF choke, as shown.

**14.14 Grid Neutralization.** Another way of neutralizing a triode RF amplifier is to center-tap the grid circuit, as shown in Fig. 14.17. Amplified energy in the plate circuit will feed back to the top of the grid-circuit coil via the interelectrode capacitance between the grid and plate. The neutralizing capacitor $C_n$, if properly adjusted, will feed the same value of energy back to the *bottom* of the grid-circuit coil. Now the same voltage is being fed downward and upward in the grid coil at the same time, canceling any effective feedback of energy. The stage is neutralized.

As with plate neutralization, the tuned circuit may use a split-stator capacitor instead of center-tapping the coil.

**14.15 Neutralizing with an RF Indicator.** A method of neutralizing a low-powered triode RF amplifier stage in practice is outlined below:

1. Turn off the plate power-supply voltage. (Neutralization cannot be accomplished with an RF indicator if the B+ is on.)
2. Couple to the plate tank circuit some form of RF indicator that will indicate the presence of RF a-c in the tank circuit. (A loop of insulated wire in series with a sensitive RF thermogalvanometer, a loop and flashlight globe, a loop and an oscilloscope, a loop and a milliammeter with a germanium diode across it, any form of wavemeter having an RF indicating device in it, or a neon globe held to the plate end of the tank coil.
3. Make sure the grid circuit is being excited by RF a-c. (The presence of grid current is an indication of this.)
4. Rotate the neutralizing capacitor to either minimum or maximum capacitance. This should completely *de*neutralize the circuit.
5. Tune the plate circuit for maximum RF a-c indication. (The plate circuit is now being fed RF via the neutralizing capacitor or interelectrode capacitance of the tube and should give a strong indication on the RF indicating device when the plate LC circuit is in resonance with the input RF.)
6. Rotate the neutralizing capacitance to zero RF a-c indication.

The stage should now be neutralized and ready to operate as soon as plate voltage is applied to it. The RF indicator must be removed before applying plate voltage; otherwise the indicator will burn out.

How close to couple the indicator to the plate tank coil is determined by the power of the amplifier. For an amplifier of only a few watts, fairly tight coupling may be required. As the power is increased, the coupling will have to be decreased to prevent burnout of the RF indicator.

This method of neutralizing can be applied to either plate- or grid-neutralized RF amplifiers.

WARNING: Since the operator must reach inside the transmitter to couple the RF indicator to the plate tank coil, he should make sure the d-c plate voltage for the stage is off, or still better, that all power to the transmitter is off when the indicator is coupled or decoupled.

**14.16 Neutralizing with the Grid Current Meter.** Another method of neutralizing a triode RF amplifier involves the grid circuit meter only and requires no reaching into the transmitter. A recommended procedure is as follows:

1. Turn off the plate power-supply voltage of the stage to be neutralized.
2. Tune the plate-circuit tank capacitor through the resonance point and watch the grid-current meter. If the grid current fluctuates at all during the tuning, the stage is not neutralized.

3. Keep tuning the plate circuit and adjusting the neutralizing capacitor until a position is found for the neutralizing capacitor where the *grid current does not change* as the plate circuit is tuned past the resonant frequency.

The stage is neutralized. This method of neutralizing can be applied to either plate-neutralized or grid-neutralized RF amplifiers.

**14.17 Neutralizing Push-Pull Stages.** The neutralizing circuit used with push-pull RF amplifiers is shown in Fig. 14.18. It is a combination of both grid and plate neutralization. Note that $C_{n1}$ is acting as a plate neutralizing capacitor for the top tube and a grid neutralizing capacitor for the bottom tube. $C_{n2}$ acts as grid neutralizer for the top tube and plate neutralizer for the bottom. Both neutralizing capacitors are adjusted at the same time to maintain a nearly equal capacitance value for each.

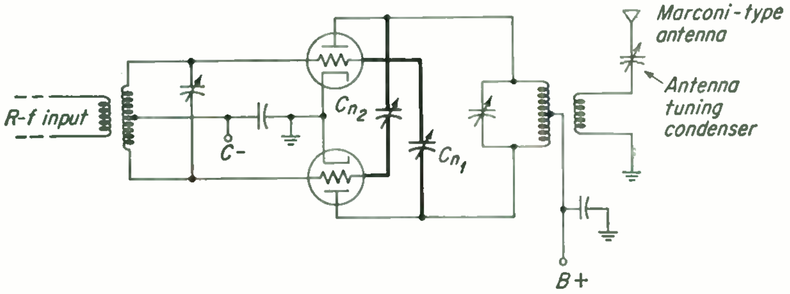


FIG. 14.18. Neutralization circuit with two triodes in push-pull.

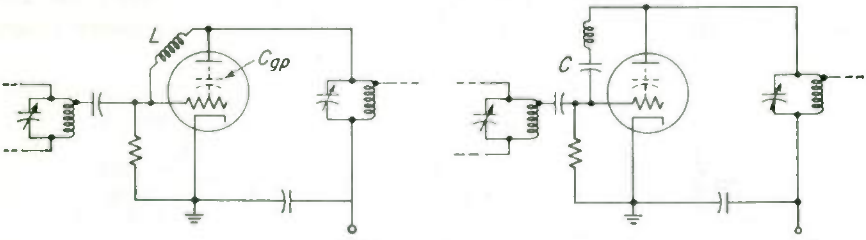
Because both grid and plate circuits are center-tapped and are assumed to be evenly balanced electrically, neutralization of push-pull stages tends to produce a neutralized condition over a relatively wide band of frequencies. A single-ended stage may require reneutralization if the frequency of operation is changed materially.

**14.18 Direct Neutralization.** A completely different method of producing neutralization is by the *direct*, or *coil*, method. This method operates on the theory that a parallel-tuned circuit has a very high impedance to the frequency to which it is tuned. Figure 14.19*a* shows a triode with a basic direct-neutralization circuit, and Fig. 14.19*b* illustrates a practical circuit.

If the correct value of inductance is selected and connected as shown by $L$, a parallel-resonant circuit is formed by $L$ and $C_{gp}$. If this circuit resonates at the desired frequency of operation, it forms a very high impedance to this frequency. The stage cannot oscillate since the usual capacitive susceptance of the grid-plate circuit is balanced out by an equal and opposite inductive susceptance. No a-c energy is conducted from the plate circuit to the grid circuit, and oscillation of the circuit is unlikely.

If the coil $L$ were connected as shown in Fig. 14.19*a*, it would place the plate circuit B+ voltage on the grid and the stage would not operate. To prevent this, a blocking capacitor $C$ is connected in series with the coil, as shown in Fig. 14.19*b*. This capacitor is selected to have a very low reactance to the operating frequency, so that the $L$ and $C_{gp}$ circuit will operate as if it were not there, as far as RF a-c is concerned. The d-c of the plate-circuit power supply will be blocked and will find no path to the grid.

Direct neutralization is theoretically only effective if the $L$ and $C_{gp}$ tune naturally to the frequency of operation. This means that a new value of inductance is required if another frequency of operation is desired. However, it is found that the circuit will operate over a small band of frequencies, so that a change of frequency of a few kilocycles will not prevent operation of the stage. It is not widely used.



(a) (b)

FIG. 14.19. Direct neutralization. (*a*) Basic circuit. (*b*) Actual circuit.

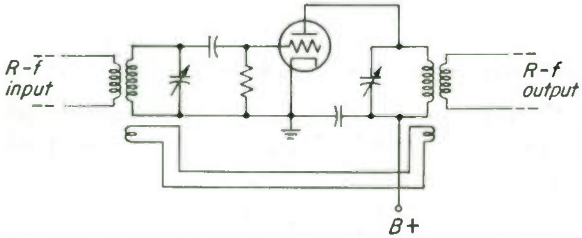


FIG. 14.20. Inductive neutralization of an RF amplifier stage.

**14.19 Inductive Neutralization.** An infrequently employed method of neutralizing an RF amplifier is *inductive neutralization* (Fig. 14.20).

The plate-to-grid capacitance of the tube is feeding RF energy from the plate circuit to the grid circuit, tending to make the circuit oscillate. To counteract and thereby neutralize this energy transfer, it is possible to loosely couple a pickup loop to the plate circuit. The energy picked up by this loop can be inductively coupled into the grid tank circuit by a second loop. If either the grid-circuit loop or the plate circuit loop is turned over, the phase of the inductive feedback can be reversed. With the loops coupled one way, the whole circuit is regenerative and will oscillate. When one loop is turned over, the feedback is degenerative. Varying the coupling of one or both loops produces neutralization. Proper neutralization can be determined by using either the RF indicator method or the grid-current-meter method.

Circuit operation is usually better if the loops are coupled to the *cold*, or ground-potential, ends of the tuned circuits, as shown. This is generally true of all RF transformers. The secondary should be coupled to the cold end rather than to the *hot*, or plate, end.

**14.20 Neutralizing Tetrode and Pentode Tubes.** In general, tetrode and pentode tubes made for use in RF circuits will need no neutralization at frequencies below 20 to 50 Mc. Above this, if the input and output circuits are not adequately isolated and shielded, it may be necessary to neutralize the tubes. The very small grid-plate capacitance in such tubes makes necessary very little neutralizing capacitance. For example, using grid neutralization, with the grid circuit below the chassis level and the plate circuit above, it may only be necessary to run a short wire from the grid coil up through a hole in the chassis to a position near the plate of the tube to produce the necessary capacitance to the plate to neutralize the tube.

Some of the newer high-frequency tetrodes are constructed in such a manner that they will operate up to more than 500 Mc without neutralization.

**14.21 Frequency Multipliers.** Operation of oscillator circuits, such as the Hartley or Colpitts, and even the crystal, shows that oscillators may have good frequency stability when operated on frequencies below 1 Mc but at higher frequencies the stability becomes poor. If the circuit is adjusted to oscillate at 2 Mc, its frequency stability may not be just twice as poor as at 1 Mc, but may be three or four times worse.

It is possible to operate the oscillator at a relatively low frequency and feed its output to a *doubler* or *multiplier* stage. Such stages will produce a frequency in their output circuit two, three, four, or five times the frequency fed to their grid circuits. The stability, as well as the frequency of the output, is an exact multiple of that of the oscillator. This will be considerably better than if the oscillator itself were used to generate the higher frequency directly. As a result, it is common to find multiplier stages in all high-frequences, VHF, and UHF transmitters.

Basically, a multiplier stage is a normal class C RF power amplifier with its plate circuit tuned to resonate at a frequency some whole-number multiple of that fed to its grid circuit (it cannot multiply 2.5 times, 3.5 times, etc.) Tetrode or pentode multipliers closely resemble normal RF amplifiers, as far as diagraming is concerned. It is necessary to label the plate circuit as being tuned to a multiple of the grid-circuit frequency to indicate that the stage is acting as a multiplier.

However, if a triode tube is used in a multiplier circuit, it is recognized as a frequency-multiplier stage because of the lack of any neutralizing circuit (Fig. 14.21). Since the plate circuit is not tuned to the same frequency as the grid circuit, the stage will not break into self-oscillation, and therefore needs no neutralizing. In special cases, where a stage may be required to act as an RF amplifier on one frequency of operation, and as a frequency multiplier for another frequency of operation, it may include a neutralizing circuit for the straight-through RF amplification. The neutralizing circuit is not particularly detrimental to the operation of the stage as a multiplier.

A tube operating as a frequency doubler usually has an RF output power about half of what might be expected from it if it were used as a straight-through RF amplifier. Its plate efficiency may range between 30 and 60 per cent

When the plate circuit is tuned to resonate at a frequency *three* times that applied to the grid, the stage is operating as a *tripler*, emitting energy at a frequency exactly three times that of the exciting frequency. The power output from a tripler is considerably less than that produced by the same tube and circuit operated as a doubler. Still higher multiplications produce progressively less power output. For this reason it is rather unusual to have a frequency multiplier operating at more than the third, or at the most the fifth, harmonic.

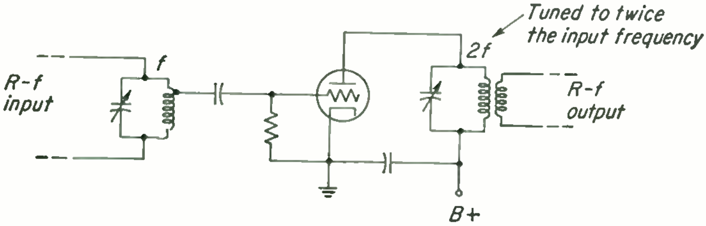


FIG. 14.21. Frequency doubler or multiplier stage.

Maximum harmonic output is produced in a doubler by using a high value of class C bias on the stage, usually two to four times the cutoff value, and driving well up into the positive grid region. This produces high-amplitude, narrow-width, plate-current pulses. A pulse excites the plate LC circuit. The electrons are driven down through the LC circuit, oscillate back up, then down, and then up again before the next d-c plate-current pulse arrives. In this way each pulse produces two cycles of nearly sine-wave a-c in the plate tank circuit. In the case of a tripler, the LC circuit must use the flywheel effect of a high-$Q$ circuit to allow three complete cycles to be formed for each plate-current pulse. Each succeeding unexcited oscillation, or a-c cycle, decreases in amplitude, resulting in a lowered average output power from the doubler and a greatly reduced output from the tripler.

The conditions for high-harmonic output from a *multiplier* stage can be summarized as: High harmonic output equals high bias voltage, high driving voltage, high plate voltage, and high-$Q$ tank circuit.

The opposite conditions are necessary when it is desired to reduce the harmonic output from an RF *amplifier*. These conditions are as follows: Use as little bias as possible and still operate class C. Use as little drive as possible and still obtain good efficiency. Do not use tight coupling between the output tank circuit and the load. Use a low $L/C$ ratio (low $L$ and high $C$) in the output tank circuit.

Note the difference between an RF amplifier transferring unwanted harmonics into the load circuit and the operation of a frequency multiplier that requires harmonic operation on one particular desired harmonic frequency. In both cases a fairly high-$Q$ tank circuit (not too tight an output coupling) is required.

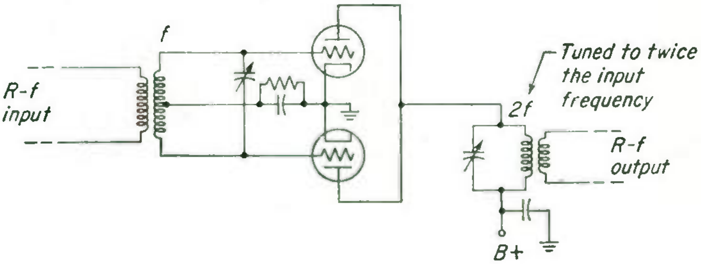


FIG. 14.22. Push-push frequency doubler or multiplier stage.

A circuit which will operate as a frequency doubler with practically the same efficiency as a normal class C RF amplifier is the *push-push* circuit. Figure 14.22 shows two triodes in a push-push amplifier circuit.

The grid circuits are connected in push-pull, and the plates are in parallel. The stage is biased to class C. The plate circuit is tuned to twice the frequency of the grid circuit. The two grids are being excited 180° out of phase.

When the grid of the top tube is positive, a plate-current pulse flows downward in the plate LC circuit, starting an oscillation at the LC circuit frequency. During this time the grid of the lower tube is highly negative, and this tube is inoperative. Between half cycles of the excitation voltage there is a period of time when neither tube is passing current and the flywheel effect of the tank circuit allows electrons to oscillate back up through the tank coil. When the cycle in the grid circuit reverses, the grid of the bottom tube becomes positive and a plate-current pulse again flows *downward* in the plate LC circuit, exciting the LC circuit again. In the push-push circuit only one half cycle of each plate-circuit oscillation depends on flywheel effect. In single-tube doublers, the flywheel effect must operate by itself for *three* half cycles before another excitation pulse occurs. This is the reason the push-push circuit can produce RF output at twice the grid frequency with almost the same efficiency as a single-ended, straight-through RF amplifier, in which only one half cycle of each plate-circuit oscillation is produced by flywheel effect also.

The push-push amplifier needs no neutralization. It will *not* operate as a tripler, but will produce power output on even-order harmonics, such as the second, fourth, and sixth, although rarely used for more than the fourth. The push-push stage has one particular disadvantage. It has a relatively high plate-to-cathode capacitance because the two plates are connected in parallel. Such high capacitance, effectively across the tuned circuit, makes high-frequency operation difficult.

Unlike the push-push amplifier, a *push-pull* stage will not operate as a doubler but makes an excellent tripler and will produce power output on odd harmonics, such as the third, fifth, and seventh. It is unusual to use it to produce more than the fifth harmonic.

While discussing harmonics, it should be pointed out that the first harmonic is the fundamental frequency. A harmonic is a whole-number multiple of some frequency. If a frequency is multiplied by 1, the answer is still the original, or fundamental, frequency. When a fundamental is multiplied by 2, the answer is the second harmonic. Thus, the second harmonic of 3 Mc is 6 Mc. The second harmonic of 380 kc is 760 kc. The third harmonic of 3,700 kc is 11.1 Mc. The seventh harmonic of 360 kc is 2,520 kc.

To develop output power on high frequencies, several frequency multipliers can be used in cascade (succession). The output frequency when three doublers are connected in cascade is 2 × 2 × 2, or 8 times the fundamental. If the output frequency of three doublers in cascade is 16,870 kc, the input frequency to the first doubler must be 16,870/8, or 2,108.75 kc.

If a tripler and two doublers are used with an input of 1 Mc, the output will be 3 × 2 × 2, or 12 Mc. The same output will result if the arrangement is a doubler, a doubler, and a tripler, or a doubler, a tripler, and a doubler.

**14.22 Capacitance and Inductance for Resonant Circuits.** When tuned circuits are described, the reader may wonder what size coil and what value of capacitance should be used. Actually, there is only one value of inductance and capacitance that will give maximum output for a given set of circuit conditions. However, so many of the factors in a circuit are variable that an accurate determination is rather involved. An old rule of thumb can be used to determine an approximate value of capacitance, and with the resonance formula explained in the chapter on Resonance and Filters, the required inductance can be computed.

First, it might be mentioned that in the earlier days of radio the frequency of oscillation was not used as much as it is today. Radiomen spoke and thought in terms of *wavelengths.* A wavelength is the distance that an electric impulse, or wave, will travel in the time it takes to complete one cycle of the a-c being considered (Fig. 14.23). For example, consider a frequency of 1,000,000 cycles. The period of one cycle is 0.000001 sec. It takes one-millionth of a second to complete one cycle of this alternating current. In that time, an electric impulse, or wave, will travel 300 meters (1 meter = 39.37 in.). The velocity of electric impulses, or radio waves, is 300 million meters/sec. It may be said that a wave having a frequency of 1 Mc has a *wavelength of 300 meters.*

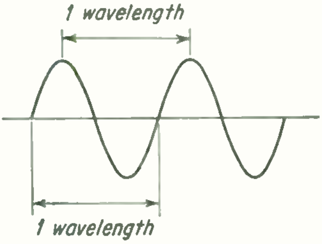


FIG. 14.23. One wavelength on a two-cycle a-c wave.

The formulas to convert frequency to wavelength, or wavelength to frequency, are:

$$\lambda = \frac{V}{F}$$

$$\lambda = \frac{300{,}000{,}000}{F}$$

$$F = \frac{300{,}000{,}000}{\lambda}$$

where $V$ is the velocity of propagation in meters per second; $F$ is the frequency in cycles (per second); and $\lambda$ is the wavelength in meters.

The rule of thumb mentioned above is: "For a resonant circuit, use 1 $\mu\mu$f of capacitance for each meter of wavelength." For a circuit resonant at 1 Mc, 300 $\mu\mu$f is a possible capacitance to be used in it.

What capacitance could be used in a tuned circuit operating on a frequency of 6,000 kc? The wavelength is

$$\lambda = \frac{300{,}000{,}000}{6{,}000{,}000} = 50 \text{ meters}$$

A possible value of capacitance to use is 50 $\mu\mu$f. It must be pointed out that this is unlikely to be the exact value of capacitance to produce the maximum efficiency of the tuned circuit. It is merely a simple method of arriving at an approximate value. In some circuits twice the value might be better; in others half might be better.

To determine the inductance required to resonate the 50-$\mu\mu$f capacitance to 6,000 kc, the resonance formula (Sec. 8.1) can be used:

$$L = \frac{1}{4\pi^2F^2C} = \frac{1}{4(9.86)(36 \times 10^{12})(50 \times 10^{-12})} = \frac{1}{70{,}900} = 14\ \mu\text{h}$$

If the coil must have 14 microhenrys ($\mu$h), what size and how many turns should it have? First, it is usual to build RF coils with a diameter and length approximately equal. In Sec. 5.2, a formula was given for such a coil:

$$L = \frac{r^2n^2}{9r + 10l}$$

The required coil might be made in many dimensions. For this problem, a 1-in. diameter and a 1-in. length will be tried. How many turns will be needed? Rearranging the above formula to solve for the number of turns $n$,

$$n = \sqrt{\frac{L(9r + 10l)}{r^2}} = \sqrt{\frac{14[9(0.5) + 10(1)]}{(0.5)^2}} = \sqrt{\frac{203}{0.25}} = \sqrt{812} = 28.5 \text{ turns}$$

On examination of a *copper-wire table* in a handbook, it is found that a No. 19 enamel insulated wire will wind approximately 27 turns to the inch. Therefore, a 1-in.-long coil wound with No. 19 enameled copper wire on a 1-in. diameter will produce an inductance of approximately 14 $\mu$h. This coil, when shunted with a 50-$\mu\mu$f capacitor, should form a resonant circuit at about 6,000 kc.

If No. 19 wire is too thin for the current that will be flowing, it will be necessary to increase the dimensions of the coil until the desired wire size can be accommodated.

The capacitance can be determined when the inductance value is known, as in the following problem:

If a frequency-doubler stage has an input frequency of 1,000 kc and the plate-circuit inductance is 60 $\mu$h, what value of plate capacitance is necessary for resonance? Since the stage is a doubler, the plate-circuit frequency is 2,000 kc. Using 60 $\mu$h and solving for the capacitance using the resonance formula rearranged,

$$C = \frac{1}{4\pi^2F^2L} = \frac{1}{4(9.86)(4 \times 10^{12})(60 \times 10^{-6})} = \frac{10^{-6}}{39.4(240)} = 0.000106 \ \mu\text{f, or } 106 \ \mu\mu\text{f}$$

This is the total capacitance, including tube and incidental circuit capacitances needed to resonate the 60-$\mu$h coil to 2,000 kc.

**14.23 Center-tapping the Filament.** Most high-power transmitting tubes use directly heated cathodes. The heating of these filaments is usually by 60-cycle a-c. As explained in the chapter on Vacuum Tubes, to produce as little variation of plate current, or hum modulation, as possible, the filament circuit is center-tapped and both grid- and plate-circuit returns are made to this center-tap point, as shown in Fig. 14.24.

It is important that the two bypass capacitors shown be connected from the filament terminals to ground with leads as short as possible. The center-tapping of the filament can be accomplished by using two equal-value resistors, $R_1$ and $R_2$ (10 to 50 ohms), or the center of the filament winding can be grounded as shown by the dotted line. Either method is satisfactory, but only one or the other should be used. In either case the capacitors are required. Since the capacitors complete the RF a-c circuit from filament to ground, the length of the filament wires to the transformer is not critical.

A milliammeter inserted at point $X$ will read the plate current. If inserted at point $Y$ it will read the grid current. If inserted at point $Z$ it will read the sum of both plate and grid currents, called the *cathode current,* since both currents flow to the filament center tap. In a tetrode it would read the sum of the plate, grid, and screen current. In a pentode it would also read any suppressor current, if the suppressor is grounded.

**14.24 Grounded-grid Amplifiers.** The higher the frequency of the RF used, the more critical the neutralization of an amplifier. If the grid of a triode is held at ground potential as far as a-c is concerned, the grid will act as an electrostatic shield between plate and cathode and neutralization may not be necessary, even in the VHF or UHF ranges. The basic *grounded-grid* amplifier circuit is shown in Fig. 14.25.

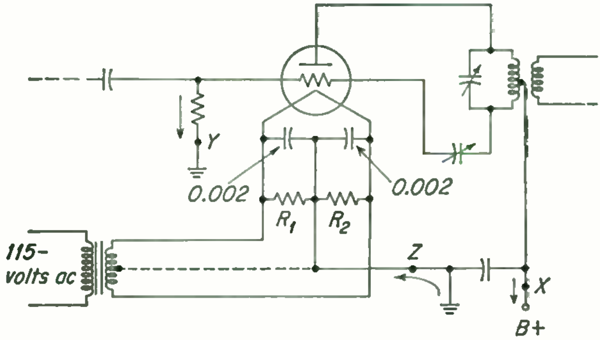


FIG. 14.24. Center-tapping the filament circuit of an RF amplifier tube.

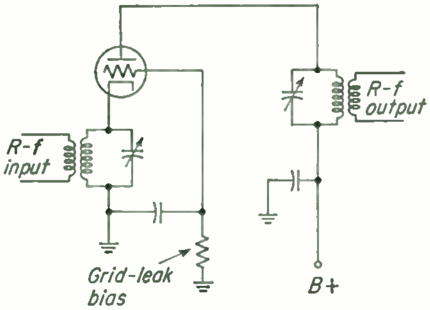


FIG. 14.25. Grounded-grid RF power amplifier.

Since the RF input must develop its signal in a circuit in which plate current is flowing, the cathode-ground tuned circuit should be designed to have a lower impedance than does the grid-ground circuit of normal amplifiers.

As far as the cathode is concerned, the grid is receiving a changing voltage when an RF is induced into the cathode coil. This allows the grid to vary the plate current, producing electron oscillation in the plate tank circuit. The output is taken from the plate LC circuit.

The grounded-grid power amplifier should have a plate-circuit efficiency similar to other class C amplifiers. However, it is found that the RF output power may be nearly equal to, or even exceed, the d-c plate-circuit power, which would indicate an efficiency of more than 100 per cent, an impossibility of course. The additional power in the output is the result of the input power being fed to the cathode coil. By examination of the diagram, it can be seen that the plate tank coil and the cathode tank coil are in series. The current that flows in the whole circuit can be considered to be the sum result of the normal power developed by the tube itself, plus the RF driving power, less any losses in the tube and other parts of the circuit.

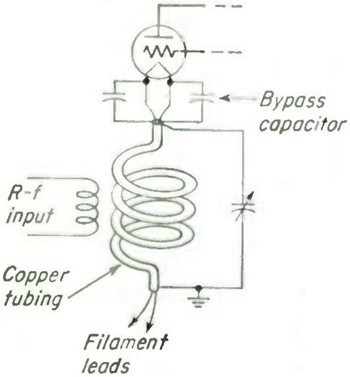


FIG. 14.26. A method of feeding the filament in a grounded-grid power amplifier.

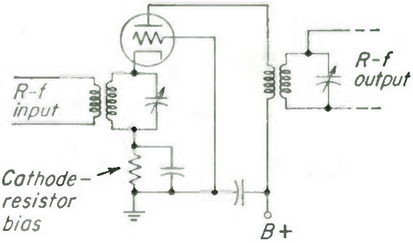


FIG. 14.27. Grounded-grid voltage amplifier used in VHF circuits.

A difficulty in feeding the filaments appears in this circuit. Although an indirectly heated cathode tube is shown for simplicity in the basic diagram, high-power tubes use directly heated cathodes. One method of feeding filament current to the filament without allowing RF a-c to appear in the filament transformer is to use an RF choke in each filament lead and bypass both terminals to the top of the cathode coil. Another possibility is to make the cathode coil of hollow copper tubing and feed both filament leads through the hollow center, again bypassing the filament terminals to the top of the cathode coil, as shown in Fig. 14.26.

The class A grounded-grid amplifier is sometimes used in VHF circuits, such as in TV receivers. A circuit similar to that shown in Fig. 14.27 may be used.

**14.25 Trouble Shooting an RF Amplifier.** When something goes wrong with an RF amplifier the radio operator must consider all the evidence given by meters, smoke, heat, and by whatever else can be seen or heard. The meters alone can help to localize the difficulty.

The plate-circuit milliameter indicates normal or improper operation by its reading. If it reads *low*, there are several possibilities (check the reasoning behind these): (1) The plate power-supply voltage has dropped off. (2) The *load* circuit is not tuned or is not operating correctly. (3) The bias voltage may be too high. (4) The filament voltage may have decreased, or the tube may have lost its emission. (5) The screen potential may be low. (6). There is loss of RF drive, if battery-biased.

If the plate-circuit milliammeter indicates *higher* current than normal, some possibilities are: (1) Screen or plate voltage is too high. (2) The plate circuit is detuned from the minimum plate-current value. (3) The antenna or other load is too tightly coupled. (4) There is loss of bias or insufficient bias. (5) There is excessive RF drive to the grid or lack of drive if the stage has grid-leak bias only.

The grid-circuit milliammeter is also a good indicator of the operation of the stage. If it reads abnormally *low* it may indicate (1) too much bias; (2) low filament voltage, or the tube is losing its emission; (3) lack of RF drive to the grid; (4) an excessive plate current.

If the grid-circuit milliammeter indicates *higher* than normal, some possibilities are: (1) loss of, or decrease in, bias voltage; (2) too much driving voltage; (3) plate and/or screen circuits open or not drawing current or shorted to ground; (4) the load is decoupled from the plate circuit.

## Practice Problems

The TPTG oscillator, link-coupled to a neutralized triode amplifier (Fig. 14.28), represents a possible transmitter. What would the different meters read (VH for very high, H for higher than normal, N for normal, L for lower than normal ,VL for very low, R for reversed reading, and 0 for zero) if the faults listed below occurred?

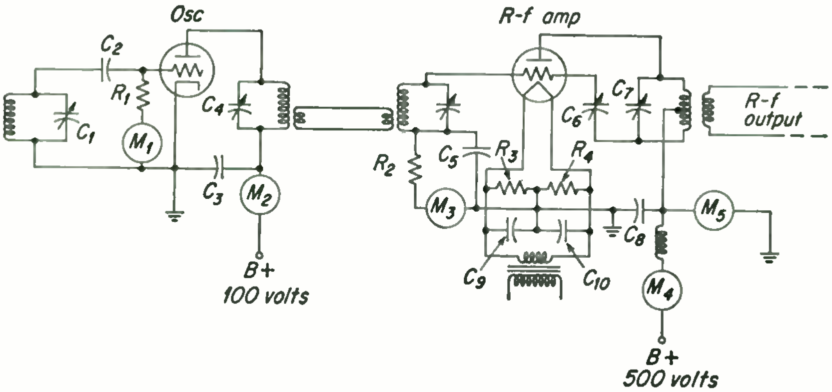


FIG. 14.28. TPTG oscillator, link-coupled to a triode RF amplifier.

| | $M_1$ | $M_2$ | $M_3$ | $M_4$ | $M_5$ |
|---|---|---|---|---|---|
| 1. If $C_1$ shorted out (example): | VL | H | VL | VH | L |
| 2. If $C_2$ shorted out: | | | | | |
| 3. If $C_3$ shorted out: | | | | | |
| 4. If $C_4$ shorted out: | | | | | |
| 5. If $C_5$ shorted out: | | | | | |
| 6. If $C_6$ shorted out: | | | | | |
| 7. If $C_7$ shorted out: | | | | | |
| 8. If $C_8$ shorted out: | | | | | |
| 9. If $C_9$ shorted out: | | | | | |
| 10. If $M_1$ burned out: | | | | | |
| 11. If $M_2$ burned out: | | | | | |
| 12. If $M_3$ burned out: | | | | | |
| 13. If $M_4$ burned out: | | | | | |
| 14. If $M_5$ burned out: | | | | | |
| 15. If the RFC shorted out: | | | | | |

16. If $R_1$ burned out: ____ ____ ____ ____ ____

17. If $R_2$ burned out: ____ ____ ____ ____ ____

18. If $R_3$ burned out: ____ ____ ____ ____ ____

19. If oscillator filament burned out: ____ ____ ____ ____ ____

20. If amplifier filament burned out: ____ ____ ____ ____ ____

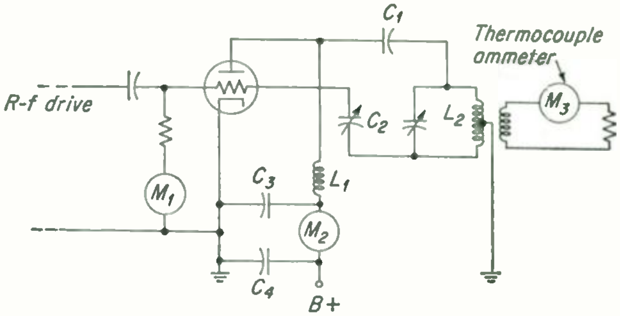


FIG. 14.29. Shunt-fed, plate-neutralized, triode RF power amplifier.

The triode RF amplifier shown in Fig. 14.29 represents a possible shunt-fed stage in a transmitter. Meter $M_3$ reads the RF current drawn by the load and is an indicator of the relative power output of the stage.

What would the different meters read (VH for very high, H for higher than normal, N for normal, L for lower than normal, VL for very low, R for reversed reading, and O for zero) if the faults listed below occurred?

$M_1$ $M_2$ $M_3$

1. $C_1$ shorted out: ____ ____ ____

2. $C_2$ shorted out: ____ ____ ____

3. $C_3$ shorted out: ____ ____ ____

4. $C_4$ shorted out: ____ ____ ____

5. $L_1$ shorted out: ____ ____ ____

6. $L_2$ shorted out: ____ ____ ____

7. $L_1$ open circuits: ____ ____ ____

8. $L_2$ open circuits: ____ ____ ____

9. Drive drops to zero: ____ ____ ____

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** Compare the design and operating characteristics of class A, class B, and class C amplifiers. (14.3) **[3]**

**2.** Draw a grid-voltage–plate-current characteristic curve of a vacuum tube and indicate the operating point for class C amplifier operation. (14.4) **[3]**

**3.** Why is the plate-circuit efficiency of an RF amplifier tube operating as class C higher than that of the same tube operated as class B? If the statement above is false, explain your reasons for such a conclusion. (14.4) **[3]**

**4.** What are the advantages of using a resistor in series with the cathode of a class C RF amplifier tube to provide bias? (14.7) **[3]**

**5.** How may the generation of even-harmonic energy in an RF-amplifier stage be minimized? (14.9, 14.21) **[3]**

**6.** Draw a simple schematic diagram showing a method of coupling between two tetrode vacuum tubes in a tuned RF amplifier. (14.11) **[3]**

**7.** Describe what is meant by link coupling. For what purpose(s) is it used? (14.11) **[3]**

**8.** Draw a diagram illustrating inductive coupling between two tuned RF circuits. (14.11) **[3]**

**9.** Draw a diagram illustrating capacitive coupling between two tuned RF circuits. (14.11) **[3]**

**10.** Does a pentode vacuum tube usually require neutralization when used as an RF amplifier? (14.12) **[3]**

**11.** What is the principal advantage of a tetrode over a triode as an RF amplifier? (14.12) **[3]**

**12.** Explain the purposes and methods of neutralization in RF amplifiers. (14.12–14.20) **[3]**

**13.** Draw a simple schematic diagram of a system of neutralizing the grid-plate capacitance of a single electron tube employed as an RF amplifier. (14.13) **[3]**

**14.** Draw a simple schematic diagram showing a method of coupling between two triode vacuum tubes in a tuned RF amplifier and a method of neutralizing to prevent oscillation. (14.13) **[3]**

**15.** What instruments or devices may be used to adjust and determine that an amplifier stage is properly neutralized? (14.15) **[3]**

**16.** What tests will determine if an RF power-amplifier stage is properly neutralized? (14.15, 14.16) **[3]**

**17.** Explain the process of neutralizing a triode RF amplifier. (14.15, 14.16) **[3]**

**18.** Draw a simple schematic diagram showing a method of coupling the RF output of the final power amplifier stage of a transmitter to an antenna. (14.17) **[3]**

**19.** Draw a simple schematic diagram of a push-pull, neutralized RF amplifier stage coupled to a Marconi-type antenna system. (14.17) **[3]**

**20.** What class of amplifier is appropriate in an RF doubler stage? (14.21) **[3]**

**21.** What are the characteristics of a frequency-doubler stage? (14.21) **[3]**

**22.** Draw a simple schematic circuit of an RF doubler stage, indicating any pertinent points which will distinguish this circuit as a frequency doubler. (14.21) **[3]**

**23.** How may the production of harmonic energy by a vacuum-tube RF amplifier be minimized? (14.21) **[3]**

**24.** What is the seventh harmonic of 360 kc? (14.21) **[3]**

**25.** Draw a simple schematic diagram indicating a link-coupling system between a TPTG oscillator stage and a single-electron-tube neutralized amplifier. (14.25) **[3]**

**26.** What would be the result of a short circuit of the plate RFC in an RF amplifier? (14.25) **[3]**

**27.** Describe the characteristics of a vacuum tube operating as a class C amplifier. (14.3, 14.4) **[3 & 6]**

**28.** During what approximate portion of the excitation voltage cycle does plate current flow when a tube is used as a class C amplifier? (14.4) **[3 & 6]**

**29.** What is the purpose of an RF choke? (14.4) **[3 & 6]**

**30.** Given the following vacuum-tube constants: $E_p = 1{,}000$ volts, $I_p = 150$ ma, $I_g = 10$ ma, and grid leak $= 5{,}000$ ohms. What would be the value of d-c grid-bias voltage? (14.7) **[3 & 6]**

**31.** What is the primary purpose of a grid leak in a class C amplifier of a transmitter? (14.7) **[3 & 6]**

**32.** Why must some RF amplifiers be neutralized? (14.12) **[3 & 6]**

**33.** Draw a circuit of a frequency doubler and explain its operation. What points distinguish this as a frequency doubler? (14.21) **[3 & 6]**

**34.** For what purpose is a doubler amplifier stage used? (14.21) **[3 & 6]**

**35.** If the period of one complete cycle of a radio wave is 0.000001 sec, what is the wavelength? (14.22) **[3 & 6]**

**36.** What is the formula for determining the wavelength when the frequency, in kilocycles, is known? (14.22) **[3 & 6]**

**37.** What material is used in shields to prevent stray magnetic fields in the vicinity of RF circuits? (14.2) **[4]**

**38.** What is the principal advantage of a class C amplifier? (14.3) **[4]**

**39.** If upon tuning the plate circuit of a triode RF amplifier the grid current undergoes variations, what defect is indicated? (14.5, 14.16) **[4]**

**40.** In a class C RF amplifier, what ratio of load impedance to dynamic plate impedance will give the greatest plate efficiency? (14.6) **[4]**

**41.** In adjusting the plate tank circuit of an RF amplifier, should minimum or maximum plate current indicate resonance? (14.6) **[4]**

**42.** Indicate by a simple diagram the shunt-fed plate circuit of an RF amplifier. (14.10) **[4]**

**43.** Indicate by a simple diagram the series-fed plate circuit of an RF amplifier. (14.10) **[4]**

**44.** What is the purpose of neutralizing an RF amplifier stage? (14.12) **[4]**

**45.** Why is it necessary or advisable to remove the plate voltage from the tube being neutralized? (14.15) **[4]**

**46.** If an oscillatory circuit consists of two identical tubes, the grids connected in push-pull and the plates in parallel, what relationship will hold between the input and output frequencies? (14.21) **[4]**

**47.** Under what circumstances is neutralization of a triode RF amplifier not required? (14.21, 14.24) **[4]**

**48.** If a frequency-doubler stage has an input frequency of 1,000 kc and the plate inductance is 60 $\mu$h, what value of plate capacitance is necessary for resonance, neglecting stray capacitances? (14.22) **[4]**

**49.** Why are grounded-grid amplifiers sometimes used at very high frequencies? (14.24) **[4]**

**50.** Draw a diagram of a grounded-grid amplifier. (14.24) **[4]**

**51.** Why are bypass capacitors used across the cathode-bias resistors of an RF amplifier? (14.2, 14.7) **[6]**

**52.** What is the purpose of shielding between RF amplifier stages? (14.2) **[6]**

**53.** What is the approximate efficiency of a class A vacuum-tube amplifier? Class B? Class C? (14.3) **[6]**

**54.** A triode transmitting tube, operating with plate voltage of 1,250 volts, has filament voltage of 10, filament current of 3.25 amp, and plate current of 150 ma. The amplification factor is 25. What value of control-grid bias must be used for operation as a class C stage? (14.3) **[6]**

**55.** Define a class C amplifier. (14.3) **[6]**

**56.** What load conditions must be satisfied in order to obtain the maximum possible output from any power source? (14.6) **[6]**

**57.** In a self-biased RF amplifier stage having a plate voltage of 1,250, a plate current of 150 ma, a grid current of 15 ma, and a grid-leak resistance of 4,000 ohms, what is the value of operating grid bias? (14.7) **[6]**

**58.** Draw a simple schematic diagram showing a method of inductive or transformer coupling between two stages of an RF amplifier. (14.11) **[6]**

**59.** Draw a simple schematic diagram showing a method of coupling between two tetrode vacuum tubes in a tuned RF amplifier. (14.11) **[6]**

**60.** Draw a simple schematic diagram showing a method of link coupling between two RF amplifier stages. (14.11) **[6]**

**61.** Draw a simple schematic diagram showing a method of impedance coupling between two stages of an RF amplifier. (14.11) **[6]**

**62.** What is the principal advantage of a tetrode over a triode as an RF amplifier? (14.12) **[6]**

**63.** Draw a simple schematic diagram showing a method of coupling between two triode vacuum tubes in a tuned RF amplifier and a method of neutralizing to prevent oscillation. (14.13) **[6]**

**64.** Name three instruments which may be used as indicating devices in neutralizing an RF amplifier stage of a transmitter. (14.15) **[6]**

**65.** Describe how an RF amplifier stage may be neutralized. What precautions must be observed? (14.15, 14.16) **[6]**

**66.** Does a pentode vacuum tube usually require neutralization when used as an RF amplifier? (14.21) **[6]**

**67.** Draw a simple schematic circuit of an RF doubler stage, indicating any pertinent points which will distinguish this circuit as that of a frequency doubler. Describe its operation. (14.21) **[6]**

**68.** What factors are most important in the operation of a vacuum tube as a frequency doubler? (14.21) **[6]**

**69.** What is the crystal frequency of a transmitter having three doubler stages and an output frequency of 16,870 kc? (14.21) **[6]**

**70.** What is meant by a harmonic? (14.21) **[6]**

**71.** What is the second harmonic of 380 kc? (14.21) **[6]**

**72.** Indicate by a drawing two cycles of an RF wave and indicate one wavelength thereof. (14.22) **[6]**

**73.** What is the velocity of propagation of RF waves in space? (14.22) **[6]**

**74.** What currents will be indicated by a milliammeter connected between the center tap of the filament transformer of a tetrode and negative high voltage (ground)? (14.23) **[6]**

**75.** When an a-c filament supply is used, why is a filament center tap usually provided for the vacuum-tube plate and grid return circuits? (14.23) **[6]**

**76.** Why might an RF amplifier tube have excessive plate current? (14.25) **[6]**

**77.** In a series-fed plate circuit of a vacuum-tube amplifier, what would be the result of a short circuit of the plate bypass capacitor? (14.25) **[6]**

**78.** In a shunt-fed plate circuit of a vacuum-tube amplifier, what would be the effect of an open circuit in the plate RF choke? (14.25) **[6]**

**79.** In a shunt-fed plate circuit of a vacuum-tube amplifier, what would be the result of a short circuit of the plate RFC? (14.25) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

★**1.** What is the relationship between a fundamental frequency and its second harmonic; its third harmonic; etc.? (14.21)

★**2.** What is the purpose of an RF choke? (14.4)

★**3.** How is the actual power input to an RF amplifier tube determined? (14.6)

★**4.** What is a frequency multiplier? (14.21)

★**5.** What is the relationship between the frequency and wavelength of a radio wave if its velocity in space is 300 million meters/sec? (14.22)

★**6.** What is the second harmonic of 380 kc? (14.21)

★**7.** What is the fundamental frequency if the third harmonic is 3,700 kc? (14.21)

**8.** Does a high- or low-$Q$ circuit discriminate against harmonic energy? (14.21)

**9.** What operating conditions are favorable to harmonic generation in an RF doubler amplifier? (14.21)

**10.** Will a large or small $L/C$ ratio in the tuned plate circuit of a vacuum-tube RF amplifier minimize the production of harmonics? (14.21)

**11.** What are the relative plate-current indications for resonance and off-resonance tuning of the plate tank circuits of an RF power amplifier? (14.5)

**12.** To obtain optimum output power from an RF amplifier, what should be the relationship between the output circuit impedance and the rated tube impedance? (14.6)

**13.** What formula is used to determine the d-c plate power input to a vacuum tube when the plate voltage and plate current are specified? (14.6)

**14.** Why is it necessary to neutralize a triode RF amplifier having input and output circuits tuned to the same frequency? (14.12)

**15.** How is the proper neutralization of an RF amplifier indicated? (14.15)

**16.** How is the plate efficiency of a vacuum tube determined when the plate input and the RF output power are given? (14.6)

**17.** How is the plate efficiency of a vacuum tube determined when the output power and power loss in the plate element are known? (14.6)

**18.** What are some of the results of operating an unneutralized RF amplifier? (14.12)

**19.** Describe a method of neutralizing an RF amplifier. (14.15)

**20.** What are some causes of excessive plate current in an RF amplifier? (14.25)

**21.** Why is a filament center-tap connection usually provided for a transmitting-tube plate and grid return circuit when a-c is used to heat the filament? (14.23)

**22.** What is link coupling in RF amplifier stages? (14.11)

**23.** When may a class C triode RF amplifier be considered neutralized? (14.15, 14.16)

**24.** What class of amplifier makes the most satisfactory harmonic generator? (14.21)

**25.** Draw a simple schematic diagram of a plate-neutralized RF stage utilizing a triode vacuum tube. (14.13)

**26.** Draw a simple schematic diagram of an RF amplifier stage having a series-fed plate circuit. A parallel or shunt-fed plate circuit. (14.10, 14.13, 14.25)

**27.** Draw a simple schematic diagram of a class C push-pull amplifier stage using triode tubes, including a circuit for proper neutralization. (14.17)

**28.** What advantage does a pentode tube have over a triode when used as an RF amplifier? (14.12)

# CHAPTER 15

# BASIC TRANSMITTERS

**15.1 Radio Transmitters.** So far, the study of radio and electronic circuits has been confined to basic units, such as oscillators, audio-frequency amplifiers, radio-frequency amplifiers, power supplies, meters, and vacuum tubes. In this chapter, these circuits are connected together to form a complete radio transmitter. For example, a radiotelegraph transmitter used for commercial radio telegraphic communication may consist of an oscillator, an RF buffer amplifier, one or more doubler or multiplier stages, an RF power amplifier, an audio oscillator and amplifier acting as a tone modulator, one or more power supplies, and an antenna.

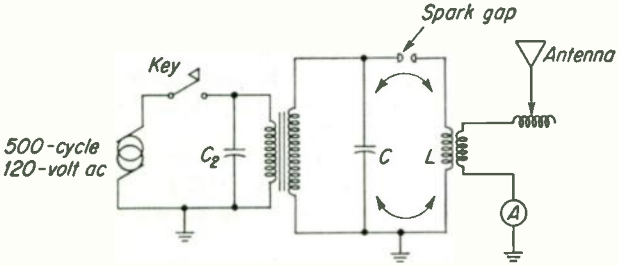


Fig. 15.1. Basic spark transmitter. The frequency of the antenna circuit determines the transmitting frequency.

That part of the frequency spectrum in which radiotelegraph communication is used normally lies between 10 kc and about 30 Mc. The transmitters discussed in this chapter will fall into this frequency category. Higher-frequency equipment is discussed in the chapters on Frequency Modulation, Television, and Radar.

**15.2 Spark Transmitters.** The first communication by radio was accomplished with a *spark*-type transmitter, mentioned in the chapter on Oscillators. A diagram of a simple spark oscillator used as a radio transmitter by coupling it to an antenna is shown in Fig. 15.1.

When the key is pressed, the relatively low voltage, 500-cycle alternating current is fed to the primary of the step-up transformer. An a-c potential of several thousand volts is developed across the secondary.

This high voltage is applied across the capacitor (condenser) $C$ and across the series circuit made up of the coil $L$ and the spark gap. As the 500-cycle voltage rises, capacitor $C$ charges. When the voltage across $C$ rises high enough to ionize the air in the gap, a spark, or arc of ionized air, is developed across the gap. The ionized air acts as a conductor of electric current. Ionizing of the gap connects the coil across the charged capacitor, and the LC circuit so formed operates with flywheel effect, producing several cycles of rapidly decaying RF a-c, the frequency of which is determined by the value of $L$ and $C$.

When the low-frequency a-c drops in voltage as its cycle progresses, the gap de-ionizes and the coil is no longer connected across the capacitor. When the next half cycle occurs, the voltage builds up across capacitor $C$ again, the gap ionizes, and another *train* of damped RF cycles occurs. Therefore; for each cycle of power frequency a-c, there are two trains of damped RF a-c waves developed in the LC circuit.

Figure 15.2 shows a series of four damped wavetrains that would be produced by two cycles of the power-frequency a-c. This damped, or decaying, waveform in radio communication is known as a *type B emission*.

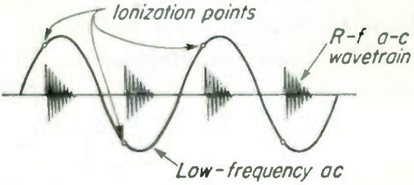


FIG. 15.2. Four damped waves of RF a-c produced by two cycles of low-frequency a-c.

The LC circuit has electrons oscillating back and forth in it at the RF rate. Some of this high-frequency energy is induced into the antenna coil and circuit by transformer action and is radiated from the antenna as a *radio wave*.

Capacitor $C_2$ is to bypass any RF a-c picked up by the primary circuit, to prevent it from flowing in the transformer primary.

If the 500-cycle a-c primary has 120 volts, the operator is opening and closing a 120-volt circuit with the key. If he inadvertently places his finger across the metal parts of the key, he receives a 120-volt shock, which is most unpleasant. Also, if the transmitter is drawing 2,400 watts, the key must be carrying 20 amp through its contacts. Such a current is relatively high and requires a heavy key with large contacts. The difficulties of danger to personnel and having to use a slow, heavy key can be overcome by using a *keying relay* (Fig. 15.3). When the operator presses the key, current flows through the electromagnet relay coil, pulls the relay arm down, and closes the primary circuit to the transformer. The keying circuit may use as little as 6 volts, which is insufficient to produce a shock to the operator. The keying-relay contacts can be made quite heavy to allow the passage of the necessarily heavy current.

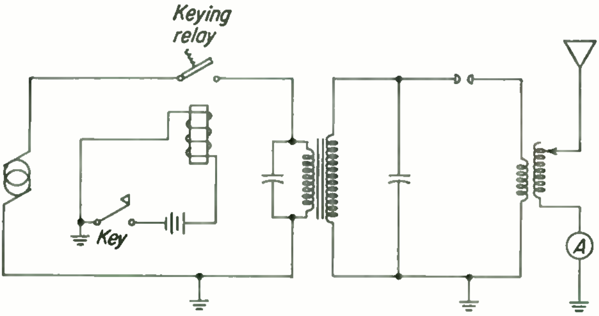


FIG. 15.3. Keying relay in a spark transmitter circuit.

Although spark transmitters are no longer used, many sources of radio interference are actually small spark-type oscillators, radiating a broad band of interference signals.

**15.3 Break-in Operation.** In many manual radiotelegraph circuits, one frequency is used for both transmission and reception. Usually it is desirable that the same antenna be used for both transmitter and receiver. However, if the receiver is connected to the antenna while the transmitter is in operation, power from the transmitter will feed into the receiver and damage it. It is necessary to disconnect the antenna from the receiver when transmitting and reconnect it when receiving. This can be done with the circuit shown in the *block diagram* of Fig. 15.4.

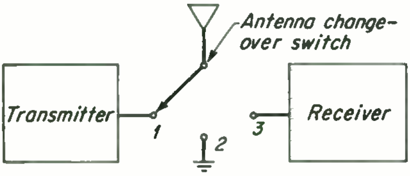


FIG. 15.4. Antenna change-over switch.

The antenna *change-over* switch has three positions: (1) antenna to transmitter, (2) antenna to ground (in case of lightning storms), and (3) antenna to receiver.

The disadvantage of the antenna-change-over-switch method of communicating is the inability to hear the other station as long as the antenna is connected to the transmitter, even if the key is up. This can be remedied in some cases by using separate antennas for receiver and transmitter, but does not solve the requirement of using one antenna for both. The *break-in relay* was developed to overcome this difficulty. The diagram in Fig. 15.5 shows a break-in relay connected to a spark transmitter and a receiver.

When the key is open, the keying relay is not energized. The antenna is connected to the receiver, and no primary power is being fed to the primary of the spark transformer.

When the key is pressed "closed," the relay coil is energized, making an electromagnet of the iron core, pulling both relay arms toward the core. This disconnects the antenna from the receiver and connects it to the transmitter. At the same time the lower arm closes the contacts in series with the power-frequency circuit energizing the transmitter.

Each time the key is closed or opened, the antenna is thrown from receiver to transmitter, or vice versa. Now when the key is in the open position, the operator can hear any signals picked up by the receiver, even on the frequency of his transmitter. In fact, he can be sending a message, and if the receiving operator wants to stop him, the distant operator holds the key down on his own transmitter. The sending operator suddenly hears a tone from his receiver between his own dot-and-dash sending and stops to find out what the other operator wants. This is known as *break-in* operation, as either operator can break in on the other's sending and ask for repeats or corrections.

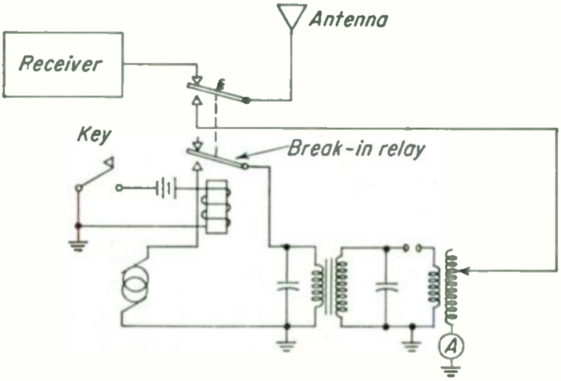


FIG. 15.5. Break-in keying relay in a spark-transmitter circuit.

The break-in relay shown in the diagram might actually feed considerable power into the receiver because of the capacitance between the open-relay contacts. To prevent this, another set of contacts, not shown on the simplified diagram, can be used to short out the input to the receiver while the transmitter is on.

Break-in relays are often employed even if separate antennas are used for transmitting and receiving, to preclude the possibility of the receiving antenna picking up sufficient power from the transmitting antenna to cause receiver burnout.

Relay contacts may be made of such metals as silver, nickel, or tungsten. The relay arms are usually made in such a manner that the contacts slide or wipe across each other slightly. This is accomplished by having a certain amount of resiliency in the relay arm or by spring-loading the contacts. The self-wiping motion assures better contact by continually polishing the contacting areas.

Silver makes an excellent contact material, but tends to *pit* if the contacts are used in circuits where an arc is produced when the contacts open. This leaves a small depression in one contact and a small mound on the other. The mound may form to such an extent that eventually the contacts may not open at all. Such relay contacts must be burnished, or filed with a fine, flat file every so often. Over a long period of time they may have to be replaced with new contacts.

It is advantageous to use vacuum relays whenever possible. These relays have all their working parts in an evacuated bulb and will stand extremely high voltages and currents without sparking or deteriorating. Tungsten, a very hard contact metal, is usually used in such relays.

**15.4 RF Alternators.** The spark transmitter was relatively simple and afforded reliable communication, but it had its disadvantages. If the antenna was too closely coupled to the oscillating LC circuit, the wavetrains damped, or died out, too rapidly. This caused signals, called *sidebands*, to be emitted on many frequencies above and below that of the carrier frequency. In fact, even with minimum coupling between antenna and transmitter, the spark was very *broad*, according to today's concept of transmissions. If a receiver with a nonoscillating detector was used to detect spark signals, a relatively pleasing tone was heard. However, when maximum sensitivity was required of the receiver, it had to be put into oscillation, and the spark signal in this case had a rather unpleasant scratching sound, with little or no tone.

A more nearly sine-wave RF signal was required, one which could produce a clear whistle with an oscillating detector. One of the methods first used to produce sine-wave RF a-c was an RF alternator, made with dozens of field poles and rotated fast enough to generate a-c at a frequency high enough to be suitable for transmitting radio signals. The RF alternator was capable of generating from 10 kc to only about 30 kc. The antenna was connected to one of the two output terminals of the alternator and the ground to the other.

It was difficult to key these machines and at the same time to hold the alternator at constant enough speed to assure a steady output frequency. Such machines were very heavy and costly. Repairs and maintenance required specialists.

**15.5 Arc Transmitters.** At about the beginning of the twentieth century it was found that high-frequency oscillations could be produced by incorporating the negative-resistance effect of an ionized gas arc into an inductance and capacitance circuit. Sustained oscillations resulted at the resonant frequency of the LC circuit.

A shock-excited LC circuit should continue to oscillate at its resonant frequency without stopping. However, resistance in the circuit soon damps out the oscillations. When the current through an arc increases, the resistance of the arc *decreases*, opposite to the general concept of Ohm's law. This is a *negative-resistance* effect. An LC circuit with negative resistance tends to increase its oscillation strength rather than damp out. The oscillations in the arc transmitter increase immediately to the maximum attainable by the circuit and remain at that amplitude as long as the d-c power is applied to the arc. This results in a strong sine-wave RF a-c oscillating in the arc LC circuit (Fig. 15.6). The d-c generator produced 300 to 1,000 volts. The electromagnet acted as an RF choke and at the same time produced a strong electromagnetic field. This field caused the arc to take a curved path between the electrodes, greatly lengthening the arc path and increasing the negative-resistance effect. The two arc contacts became very hot. One, the anode, connected to the positive side of the generator, was hollow, made of copper, and was cooled by an internal distilled-water cooling system. The other arc contact, the cathode, was made of carbon and had to be slowly rotated, automatically or manually.

To produce an ionized gas rich in hydrogen, alcohol was dripped into the hot arc chamber. If stray oxygen found its way into the closed chamber, the hydrogen and oxygen exploded when the arc was first *struck* (electrodes touched together for an instant to start the arc). Arc-chamber tops were hinged to allow free movement when the chamber blew up. Both the transmitter-room walls and the operators often wore horizontal black soot lines produced by these explosions.

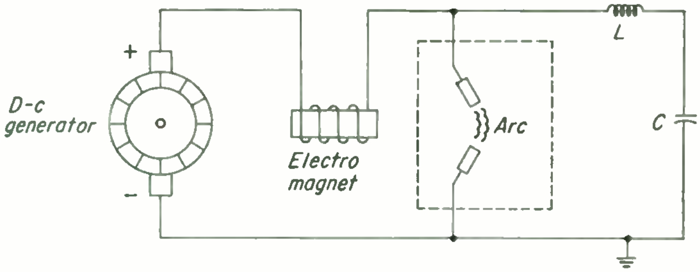


FIG. 15.6. Basic-arc-transmitter circuit.

The arc produced a fairly sinusoidal wave of continuous amplitude (A1), and not damped as a spark emission. The abbreviation *CW*, meaning continuous-amplitude wave, indicates such an emission.

A disadvantage to arc operation is the requirement that the arc oscillate continuously. The first type of keying used was a form of frequency shift keying, called *compensation wave.* When the key was open, the arc transmitted on one frequency, and when the key was closed, it transmitted on some other frequency, using twice as much space in the radio spectrum as it should.

An improvement on compensation wave was *back-shunt* keying, which connected the arc to a nonradiating resistance load, or a *dummy antenna*, when the key was open. When the key was closed, the arc fed its energy into the antenna instead of into the dummy load.

Figure 15.7 shows a simplified diagram of a compensation-wave-keyed arc transmitter, and Fig. 15.8, a back-shunt-keyed arc transmitter. The antenna coil and the antenna wire take the place of the inductance in the basic arc diagram (Fig. 15.6), and the capacitance present between the antenna wires and ground takes the place of the capacitor in the basic diagram.

Another form of keying employed a *chopper wheel.* The rim of this motor-driven wheel was broken up into alternate segments of insulating and conducting materials. A contact wiped over the segments as the wheel rotated. As the contact was made and broken between the wheel conductor and the wiping brush, a very small portion of the antenna inductance was alternately shorted and opened. This changed the frequency of oscillation a few kilocycles, producing a varying-frequency carrier. This frequency variation, or frequency *modulation,* occurred at the rate of the make-and-break contact on the wheel. If the wheel made and broke 500 times a second, the carrier was modulated at a 500-cycle rate. Back-shunt keying may be used, or the leads to the chopper wheel can be keyed as shown in Fig. 15.9.

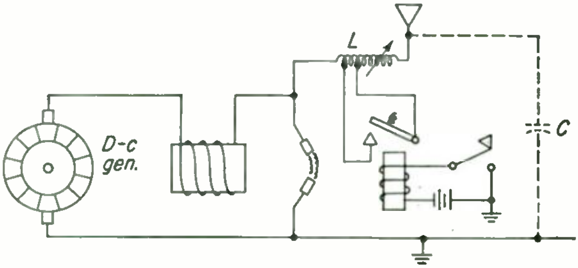


FIG. 15.7. Arc transmitter with compensation wave keying.

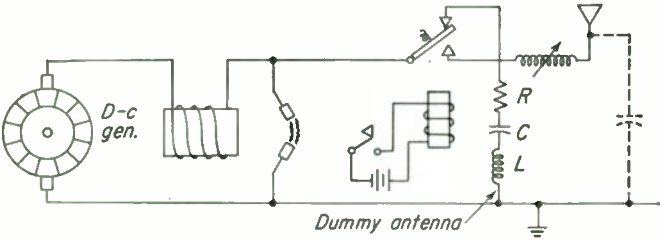


FIG. 15.8. Arc transmitter with back-shunt keying.

The chopper wheel changes the A1-emission characteristic of the arc to what was originally called an A2 emission. Today it would be classed as an F2 emission (a keyed, frequency-modulated carrier). It was also previously termed modulated CW (MCW) or interrupted CW (ICW). It was possible to have an arc transmitter with two or more systems of keying. The operator used the method which worked best under the prevailing conditions.

While the arc produced continuous amplitude waves of more or less pure sine-wave output, it had considerable harmonic output as well as spurious side signals called *mush* near the fundamental and the harmonic frequencies.

With the requirements of dripping alcohol, water-cooling the anode, continual rotation and feeding of the cathode, high-power magnets, and conditions of poor operation at 500 kc or higher, exploding chambers, harmonics, mush, and keying difficulties, more satisfactory methods of producing RF energy were obviously required. In the early 1920s the vacuum tube began to be used, and the days of the spark, arc, and RF alternators were numbered.

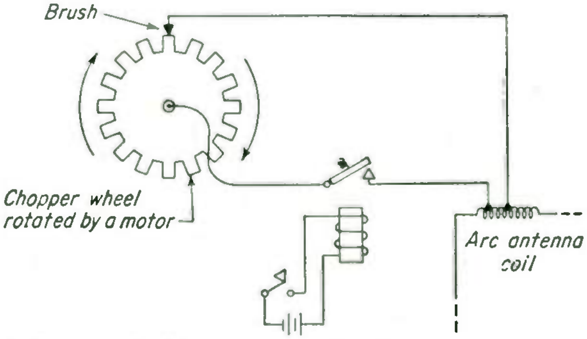


FIG. 15.9. A chopper wheel in an arc circuit to frequency-modulate the wave.

### 15.6 Tuning Low-frequency Tank Circuits.

The spark, arc, and RF alternator were all used in the low-frequency (30–300 kc) range, or in the medium-frequency (300–3,000 kc) range, but for the most part below 1,000 kc. Note that the diagrams of these transmitters show no variable capacitors. The frequency is changed by varying the inductance instead. Lower-frequency resonant circuits require considerable capacitance change for a given frequency change. It conserves space to build variable inductors for these frequencies rather than large variable capacitors. A low-frequency LC circuit may be composed of a fixed capacitance and a *variometer*. A variometer is constructed by using two air-core coils *connected in series,* the smaller one rotating *inside* the larger. As the center coil is rotated, it can be made either to add to the total inductance or, by 180° rotation, cancel the inductance. The symbols for a variometer are shown in Fig. 15.10.

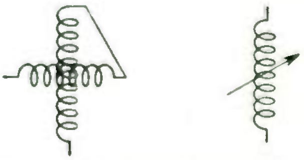


FIG. 15.10. Symbols used for variometers.

For low-frequency circuits powdered-iron cores, or *slugs,* can be slid into and out of a coil to produce a change of inductance. This requires no moving electrical connections to vary the frequency and may be useful where the climate is damp and sliding contacts tend to corrode.

For frequencies above 500 kc, variable capacitors and fixed coils are usually employed in tuned circuits.

**15.7 The Carrier.** A radio transmitter in operation sends out energy in the form of a radio wave at some basic frequency known as the *carrier frequency*, and the energy radiated is known as the *carrier wave.*

If the carrier wave is broken into dots and dashes, intelligence can be transmitted by telegraphic or teletype codes. If the carrier amplitude or frequency is varied (modulated) at a voice or music frequency, voice or music can be reproduced from the modulated carrier wave by a receiver.

A0 emission is the carrier wave alone, not keyed or modulated.

A1 emission is the carrier wave keyed on and off into dots and dashes. Also known as continuous wave (CW).

A2 emission is the carrier wave being keyed, but modulated with a steady tone at the same time.

A3 emission is the carrier wave modulated in amplitude by voice or music a-c voltages. (A3a is single sideband.)

A4 emission is the carrier-wave amplitude modulated by facsimile (pronounced fak-sim-ill-ee) signal voltages (voltages produced when a still picture is scanned for dark and light areas).

A5 emission is the carrier-wave amplitude modulated by television video signals (voltages produced when a moving scene is scanned rapidly for its dark and light areas).

F1 emission is the carrier wave keyed in frequency as dots and dashes.

F3 emission is the carrier wave modulated in frequency by voice or music a-c voltages.

B emission is the damped wave of a spark transmitter.

**15.8 Vacuum-tube Transmitters.** When vacuum tubes were first used, they were rather small and could not compete with RF alternators delivering up to 200 kw or arcs having power ratings up to a million watts. However, as vacuum-tube experiments increased, larger and larger tubes were constructed, until by the early thirties they were supplanting the high-powered arc transmitters. Because the tubes were more efficient, it was not necessary to have as much power input to the tubes as was required for the arcs. The plates had to be water-cooled in larger applications, but there was little mechanical difficulty, less harmonic output, and no mush. These transmitters produced clean CW signals. They could be operated at frequencies up to more than 20 Mc, opening up from 15 to 40 times as much usable RF spectrum space. As time went on, the usable spectrum has been expanded up to well over 30,000 Mc. Keying high-powered tube circuits can be relatively simple and inexpensive. Furthermore, vacuum-tube transmitters can be made much more compact than alternators and arcs.

The discussion of vacuum-tube transmitters will first consider the simplest type of oscillator coupled to an antenna to form a *CW transmitter.*

In the twenties, such a relatively simple circuit would have been considered quite practical.

The keying considered throughout the following discussions will be assumed to be hand keying, accomplished by manually operating a telegraph key. In modern commercial equipment the keying is often accomplished by feeding special coded tapes into the transmitter, or the transmitter may be connected to a teletypewriter which may use a make-and-break (MAB) circuit to transmit teletype signals by radio.

**15.9 A Simple Code Transmitter.** The transmitter circuit, shown in Fig. 15.11, represents a possible low-power emergency transmitter for use on low or high frequencies. The circuit is a shunt-fed Hartley oscillator using a triode tube with an indirectly heated cathode. The A battery serves as both a filament and relay-coil voltage supply. The keying relay is shown breaking the plate-circuit B− lead, although keying at either of the two points marked $X$ would be as effective. The antenna, being grounded at one end, is known as a *Marconi* antenna.

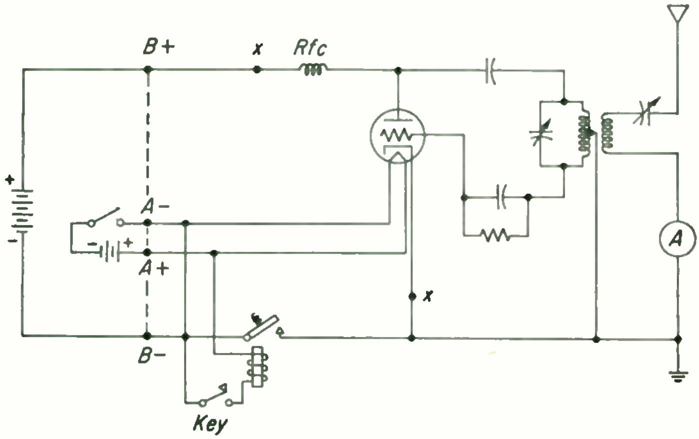


FIG. 15.11. A simple Hartley triode oscillator transmitter.

To place this transmitter into operation the following procedure might be used:

1. Close the filament circuit switch and allow sufficient time for the cathode to heat.
2. Press the key and rotate the oscillator-tank tuning capacitor until the transmitter is on the desired frequency.
3. Couple and tune the antenna circuit until a maximum antenna current reading is obtained on the antenna meter.
4. Recheck the frequency, because changing the antenna tuning will affect the oscillation frequency of this type of oscillator. The transmitter is ready to use.

The main disadvantage of the simple *self-excited* oscillator-type transmitter is its relatively poor frequency stability. Any variation of the antenna-circuit inductance or capacitance reflects a change into the LC circuit of the oscillator and will shift its frequency to some extent. The frequency of transmission will vary if the antenna wire swings in the wind, or if the ship or boat on which it might be installed rolls from side to side in rough weather.

Changes in plate voltage will change the frequency of oscillation somewhat. The voltage regulation of the power supply will affect the frequency. When the key is open, the power-supply voltage is usually at a maximum. When the key is closed, the oscillator draws current from the supply, and the supply voltage decreases rather slowly. The relatively slow decrease in plate voltage results in a relatively slow frequency shift of the oscillation frequency. The changing frequency causes a changing tone, called a *chirp*, to be heard at the receiving station. The change of frequency at the make and break of the key may appear as a chirp if it is fairly slow, or as a *click* if the frequency change is very rapid. Both are undesirable but are usually present in simple transmitters such as this, particularly when operated at frequencies above 1 or 2 Mc.

Increasing the power of this type of transmitter only aggravates the frequency instability, so that the circuit is usually confined to low-power output.

A battery is used in the circuit diagrams described. Batteries and dynamotors might actually be used if the equipment was used as a portable or mobile transmitter. Otherwise, electronic power supplies are generally used.

The antenna coupling must be as loose as possible. If the coupling is too tight, chirping and frequency instabilities due to antenna changes will be excessive, or the oscillator may fail to oscillate at all.

An overcoupled antenna can produce *split tuning*, or the double-peaked response curve discussed in Sec. 8.7. In the case of the simple oscillator transmitter, the oscillator frequency may be pulled toward one or the other peaks, or in aggravated cases, the frequency of oscillation may jump from one peak frequency to the other.

**15.10 The MOPA Transmitter.** To increase the frequency stability of a simple oscillator transmitter, an RF-amplifier stage may be added. A diagram of an oscillator coupled to a triode RF amplifier is shown in Fig. 15.12.

When an amplifier stage is added to an oscillator, the transmitter can be called an *MOPA*, meaning *master-oscillator power amplifier*. The MOPA shown incorporates a shunt-fed Hartley oscillator with a plate-neutralized class C triode amplifier. The B− lead for both the oscillator and amplifier is broken, and the keying relay has been inserted. When the key is closed, both oscillator and amplifier stages are energized at the same time. This has the advantage of producing no signal when the key is open, but may produce chirps because the oscillator circuit is being keyed. If the oscillator is allowed to run all the time, and the power to the amplifier alone is keyed by inserting the keying relay in the *B+ high* lead, little or no chirp will be produced, but in the immediate vicinity of the transmitter a signal will be audible on a receiver as long as the oscillator is allowed to run. Such a locally audible signal usually makes break-in operation impossible. This local signal can be decreased materially by completely shielding, or boxing in, both stages in aluminum or copper containers, allowing only the antenna connection to be exposed to the outside. If the amplifier is properly neutralized, very little signal from the oscillator should pass through the amplifier when the plate voltage is disconnected from the amplifier.

The MOPA circuit has the advantage of isolating the *oscillator* stage from the antenna. If any changes are made to the antenna circuit, it may affect the plate circuit of the amplifier but will have almost no effect on the oscillator. However, if the amplifier stage is not properly neutralized, there may be a considerable frequency pulling effect on the oscillator, because of capacitive feed from the plate circuit through the amplifier tube, through the interstage coupling capacitor to the oscillator tank circuit.

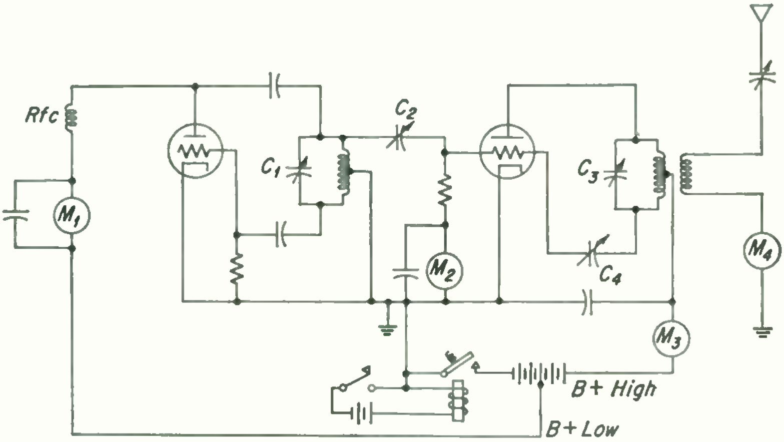


FIG. 15.12. An MOPA transmitter.

One advantage of an MOPA over a self-excited oscillator-type transmitter is in power output. Although an oscillator tube may operate at high-power output, its frequency stability will be poor. With an MOPA it is possible to operate the oscillator at a relatively stable, low-power output and obtain high-power output from a highly efficient class C power amplifier.

Since the power to the plate circuit is being keyed, this system may be classed as *plate-circuit keying.*

Direct-current meters in a transmitter are bypassed with mica or ceramic dielectric capacitors of 0.001- to 0.005-$\mu$f capacitance. This prevents RF a-c from flowing through the fine wires and hairsprings of the meter and burning them out. Although d-c meters are never placed in the "hot" parts of RF circuits (between the plate and the RF choke, or between the grid and the grid-leak resistor), there is still the possibility that some RF a-c may flow through them. The bypass capacitors act as a good conductor for high-frequency currents, while the meter with its resistance and inductance will offer a much higher impedance path. To further protect the meter, it may also be bypassed to ground.

The RF ammeter in the antenna circuit must not be bypassed, of course, or it will read a lower value of current than is actually flowing in the circuit.

Neutralization of the amplifier is important. If improperly neutralized, there will be a strong local signal when the key is open, the oscillator frequency will pull (shift) as the amplifier or antenna is tuned, and the stage may break into strong self-oscillation and emit signals on frequencies near the operating frequency. Often, if the grid drive from the oscillator is sufficiently high, the stage may stay in synchronism and operate satisfactorily if only slightly out of neutralization. If the drive is low, or drops to zero, the stage may break into oscillation, particularly if bias is produced by the grid-leak method.

**15.11 Tuning the MOPA Transmitter.** Tuning an MOPA transmitter, such as in Fig. 15.12, to operate on a desired frequency involves several steps. The procedure outlined below is not the only possible one but is normally quite satisfactory.

1. Disconnect the B+ lead of the amplifier. Decouple the antenna coil. Adjust the interstage coupling capacitor to minimum capacitance.
2. Turn on the filaments, and after a few minutes warm-up time, close the key, energizing the oscillator. The oscillator-plate current meter $M_1$ will usually read between 5 and 20 ma. The grid current meter $M_2$ should read very little. The amplifier-plate current meter $M_3$ and the antenna meter $M_4$ will both read zero.
3. Select the desired frequency on a receiver or frequency meter and rotate the oscillator tuning capacitor $C_1$ until the signal heard is a low-pitched tone.
4. Couple energy to the grid of the amplifier by increasing the capacitance of $C_2$ until the grid current on meter $M_2$ is about 10 per cent more than required for normal operation of the amplifier tube. The oscillator-plate current should increase 10 to 50 per cent. Retune the oscillator if necessary.
5. Neutralize the amplifier stage by either the RF indicator or the grid-current method, explained in Sec. 14.15.
6. Connect the amplifier plate-circuit lead to the power supply and

immediately tune the plate tank-circuit capacitor $C_3$ for minimum amplifier-plate current.

7. With very *loose* coupling between antenna and amplifier tank, tune the antenna by adjusting the variable capacitor in the antenna for a *maximum* peak indication of the amplifier-plate current, or for maximum indication of RF current in the antenna meter $M_4$. (The antenna is now tuned to resonance and usually needs no further adjustment.)

Note that it is necessary to tune the final amplifier *before* the antenna circuit can be tuned, otherwise the final amplifier-plate current will be at a maximum, and the RF output will be little or nothing, resulting in little or no RF indication in the antenna ammeter.

8. Increase the antenna coupling. This will increase the antenna current and the amplifier-plate current at the same time. Both are indications that the antenna is taking RF power from the amplifier plate circuit.

9. Redip the amplifier plate current by adjusting the plate tank capacitor $C_3$, and readjust the antenna coupling until the desired plate current occurs with tank-circuit resonance (plate-current dip).

10. Recheck the grid current, adjusting capacitor $C_2$ if necessary to bring the grid current to the desired value.

11. Recheck the amplifier plate tuning for desired plate current.

12. Recheck the frequency once more, and the transmitter is ready to operate.

Note that it is necessary to watch the oscillator frequency closely to prevent off-frequency operation of the transmitter. If the oscillator stage is a crystal oscillator, no frequency adjustment may be necessary since crystals will normally oscillate on only the frequency for which they are ground.

**15.12 Frequency Stability.** Self-excited oscillator circuits, such as Hartley, Colpitts, and others, may have rather poor frequency stability and may not hold a constant frequency of oscillation. The reasons for this are many. Some of the possible causes of an *abrupt* frequency variation in an oscillator are (1) plate-voltage changes due to power-line voltage variations; (2) loose connections in the oscillator, amplifier, or antenna circuit; (3) poor soldered connections in the oscillator or in the stage following; (4) poor connections between the tube base pins and the tube socket; (5) faulty fixed capacitors; (6) faulty resistors; (7) faulty tubes; (8) poor electric contact between the bearing surfaces of variable capacitors; (9) loose shield cans; (10) parts which, when heated, expand and either make or break a contact.

When a quartz crystal oscillator is employed, it is found that many of these faults produce very little change in the frequency of oscillation. They may affect the output power somewhat, however.

Some of the causes of a *slow drift* of frequency in a self-excited oscillator are: (1) Heating of the oscillator coil due to RF a-c flowing in it causes it to expand and change inductance slightly, changing the LC circuit resonant frequency. (2) Heating of the basically air-dielectric tuning capacitor of the oscillator causes heating and expansion of the dielectric material used to mount the plates, changing the capacitance. (3) Heating of the oscillator tube causes its elements to expand and change its electrical characteristics and the oscillation frequency. (4) RF a-c heats mica or other types of dielectrics in a fixed capacitor and produces an expansion of the dielectric and a capacitance change, which can affect the frequency of oscillation if the capacitor is in the oscillator or in the stage following it. (5) Direct current or RF alternating current heats resistors, causing them to change values slightly (grid-leak resistor, for example), possibly changing the loading on the oscillator and therefore its frequency. (6) As a tube ages, its characteristics change, resulting in a slight frequency change.

Practically all these frequency changes can be effectively eliminated by using a quartz crystal oscillator instead of a self-excited oscillator.

Every commercial radio station is assigned one or more exact frequencies on which it may operate. Crystals ground to operate on an assigned frequency, or on some submultiple of this frequency, result in little chance of off-frequency operation.

Where the *frequency tolerance* (the number of cycles a transmitter may operate away from the assigned frequency) is small, it may be necessary not only to use crystal oscillators but to keep the crystals in special temperature-controlled ovens, discussed in Sec. 12.14.

A source of frequency variation, present even in crystal oscillators to some extent, is variation of the plate voltage. This difficulty can be overcome by using a separate power supply for the oscillator stage. In this way, the voltage of the oscillator will be independent of all the other stages of the transmitter, regardless of how they may be tuned or operated. To further improve the frequency stability, it is common practice to use voltage-regulator tubes on oscillator and *buffer* amplifier stages that follow the oscillator. The buffer isolates the oscillator, allowing it to oscillate completely independent of the rest of the transmitter.

All oscillators will have a warm-up period, during which some frequency variation will be present. With temperature-controlled crystals, the period is the time required for the oven and crystal to attain their operating temperature. With self-excited oscillators, half an hour to several hours may be required before no further frequency drift is noticeable. These oscillators can be more quickly stabilized if they are operated in a temperature-controlled chamber, or if they utilize specially designed capacitors to counteract the effect of heating in the circuit.

A sudden cold draft striking a self-excited-oscillator stage may cause several hundred cycles change in frequency, but may cause only a few cycles drift in a crystal stage.

**15.13 Using a Dummy Antenna.** The discussion of the back-shunt keying method of the arc transmitter mentioned the dummy-antenna action of the coil, capacitor, and resistor in the back-shunt circuit. This same type of circuit is used when it is desired to tune a transmitter, or to test it without transmitting a radio wave and interfering with other stations on the same frequency. A dummy, *artificial*, or *phantom*, antenna is connected across the antenna circuit in place of a real antenna (Fig. 15.13).

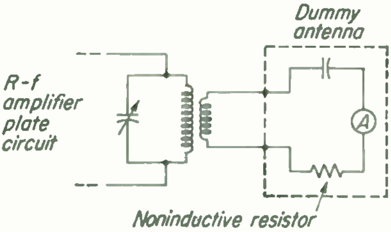


FIG. 15.13. A dummy antenna circuit.

The capacitor of the dummy antenna should have a reactance value similar to that of the reactance of the antenna coupling coil. The *noninductive* (not made in coil form) resistor should have a resistance value similar to the impedance expected to be exhibited by the antenna when it is connected to the transmitter. With the dummy antenna coupled to the amplifier tank circuit, the resistor should dissipate, in heat, the amount of energy the antenna will dissipate in radiated radio waves.

The power output of the transmitter can be approximated by using the power formula $P = I^2R$ and using the current value shown by the ammeter in the dummy antenna and the resistance value of the noninductive resistor. When the antenna is connected in place of the dummy and the coupling is varied until a similar amplifier plate-current value results, the antenna should be emitting a power approximately that computed for the dummy circuit.

A simple dummy antenna for low-powered transmitters is sometimes constructed by using an electric-light globe and a capacitor. The RF power heats the filament of the lamp. By comparing the brilliance of the lamp with its normal brilliance on a 120-volt circuit, a rough approximation of the power output can be obtained.

Preliminary tuning of any transmitter, either with or without a dummy antenna, should be done at reduced power, usually obtained by using one-half to one-quarter the operating-plate (and screen-grid) voltage for the stage. This not only helps to protect the equipment from inadvertent overloads during tuning operations, but decreases possible interference to other stations operating on the same or adjacent frequencies.

**15.14 Keying the Plate Circuit.** One method of sending dots and dashes with a radio transmitter is to open and close the *plate* circuit with a telegraph key, or better, with a keying relay. The key can be inserted in series with the negative end of the plate power supply, at point *X* (Fig. 15.14), or in series with the positive terminal, at point *Y*.

If the key is connected in series with the plate and grid circuits by being placed between cathode and ground, point *Z*, the stage is said to be *cathode-keyed*. The cathode must be bypassed to ground.

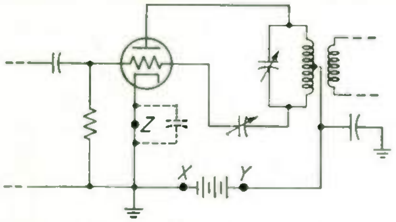


FIG. 15.14. Keying at point *X* or *Y* produces plate-circuit keying; at *Z*, cathode keying.

Simple keying methods such as these may produce serious *key clicks* in receivers, at frequencies near and possibly far removed from the carrier frequency. This is a serious fault in a CW transmitter and must be corrected.

Figure 15.15 shows a diagram of three points, *X*, *Y*, *Z*, where the plate circuit may be keyed if a directly heated (filament) tube is used in the keyed stage.

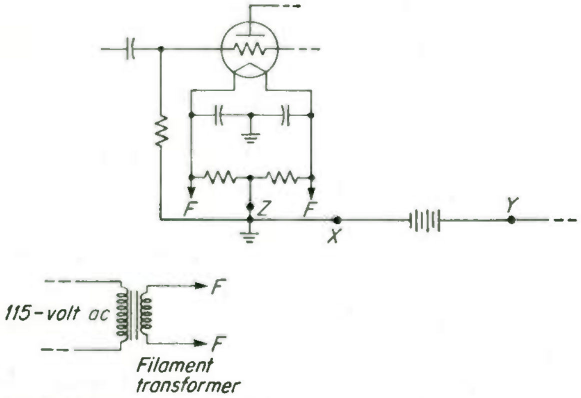


FIG. 15.15. Points at which a filament-type tube can be keyed.

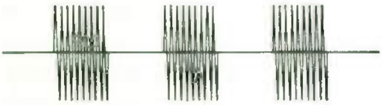


FIG. 15.16. Three keyed bursts of RF a-c forming the telegraphic letter *S*.

FIG. 15.17. How the letter *S* appears to the detector of a receiver.

## 15.15 Shaping or Filtering the CW Signal.

When the key of a code transmitter is closed, RF a-c is transmitted. The RF a-c of the letter *S* (three dots) can be represented as shown in Fig. 15.16.

The waveshape of the letter *S*, as shown, has a square waveshape. Figure 15.17 shows the sharp corners of the square wave, as it looks at the receiver.

Transmission of this type of square-wave signal will produce sidebands, or frequencies on both sides of the carrier frequency. The reason for this can be explained by showing what constitutes a square wave.

Figure 15.18 shows, first, a sine wave, second, the result of adding the third harmonic, and finally, the result of adding up to the ninth harmonic.

By starting with a fundamental frequency, 10 cycles, for example, and adding the first 9 harmonics in proper phase and amplitude, it is possible to produce a fairly square waveform. If the first 50 harmonics are added in the proper proportions, an excellent square wave will be produced. The more harmonics involved, the *squarer* the *corners* of the square-wave signal. Working backward with this theory, it can be seen that if a fundamental plus harmonics can produce a square wave, then a square wave can be considered to be made up of a fundamental plus many harmonics of that fundamental frequency.

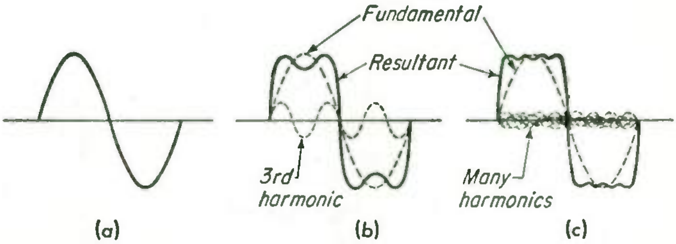


Fig. 15.18. Formation of a square-wave cycle. (*a*) Fundamental. (*b*) Addition of third harmonic. (*c*) Addition of several harmonics.

If a series of square-wave dots are transmitted from a code transmitter, the signal will be made up of the dots plus many *harmonics* of the *dot frequency* (not to be confused with possible harmonics of the RF carrier frequency). If the dots are made at a speed of 10 per second, they form a 10-cycle fundamental keying frequency. If the square waveshape of the dots is good, there may be up to 50 or more strong harmonics present. This means that there will be harmonics present 500 cycles on both sides of the carrier (10 cycles × 50 = 500 cycles). If there are 20 dots per second, harmonics will be generated out to 1,000 cycles or more on each side of the carrier. It can be seen that the amount of RF spectrum space is directly proportional to the speed of the sending. High-speed sending takes up more of the spectrum space than does low-speed. Proper shaping of the transmitted square-wave signals rounds them off slightly, representing fewer harmonics present, and produces good readable signals up to 25 or 35 words per minute without involving a spectrum band of more than 100 to 200 cycles in width.

The generation of harmonics by keying, while somewhat objectionable because of radiation of harmonics on frequencies on both sides of the carrier, may be considerably exaggerated by variations of the power-supply voltage of the transmitter. When the key is pressed, a heavy load is suddenly applied to the power supply and its output voltage drops. Actually, the voltage sags and rises several times in a fraction of a second. This *transient* variation of the power-supply voltage imposes another waveshape on the transmitted signal. The mixture of the transient waveshape on the normal waveshape can produce extremely high-order harmonics which may produce objectionable harmonic energy hundreds of kilocycles on both sides of the carrier. These *key clicks* produce spurious responses in receivers tuned far off of the fundamental frequency of the transmitter.

If the square-wave code signal can be shaped in such a way that the sharp corners are rounded off, this rounded shape will represent the fundamental and fewer harmonics and will mix with the power-supply transient voltages to produce considerably fewer objectionable harmonics.

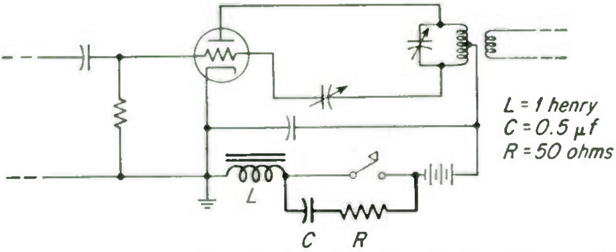


FIG. 15.19. Key-click filter in the plate circuit of an RF amplifier.

The rounding of the corners of a CW signal is said to produce *soft* keying. *Hard* keying has a sharp-cornered square waveform.

Hard keying can be softened by the use of a *key-click filter*. One possible filter is shown in Fig. 15.19.

When the key is closed, the inductance $L$ acts to oppose the rise of plate current, rounding off the sharp *make* corner of the signal. When the key is opened, the capacitor allows current to flow for a time in the plate circuit, until the capacitor becomes charged to the power-supply potential. The resistance $R$ decreases sparking at the key contacts when the key is closed again. The values of $L$, $C$, and $R$ vary with plate-current values. A characteristic waveshape with such a filter is shown in Fig. 15.20.

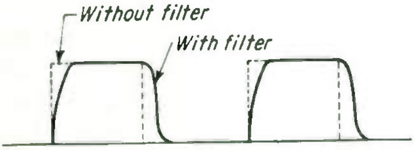


FIG. 15.20. Shape of square-wave plate-current pulses when a key-click filter is in the circuit.

If sparking is excessive at any switch contacts, a capacitor and resistor may be connected in series across the switch, as in Fig. 15.19, to decrease this sparking. Series inductance may not be required.

**15.16 Primary Keying.** Another method of producing radiotelegraph transmissions with little or no key clicks is to use *primary keying.* A diagram of this type of a circuit is shown in Fig. 15.21 connected to an RF amplifier of a code transmitter.

This circuit can be recognized as a full-wave center-tapped rectifier with inductive-input filtering. The key makes and breaks the power to the primary of the power transformer. The filtering action of the choke coil prevents the plate voltage from building up rapidly, thereby rounding off the *make* corners of the square waveshape of the transmitted dot or dash. The capacitance of the capacitor determines how long the transmitter will continue to operate after the key is opened, thereby preventing a sharp decrease in plate current, resulting in a rounded characteristic of the *break* corner of the transmitted dot or dash.

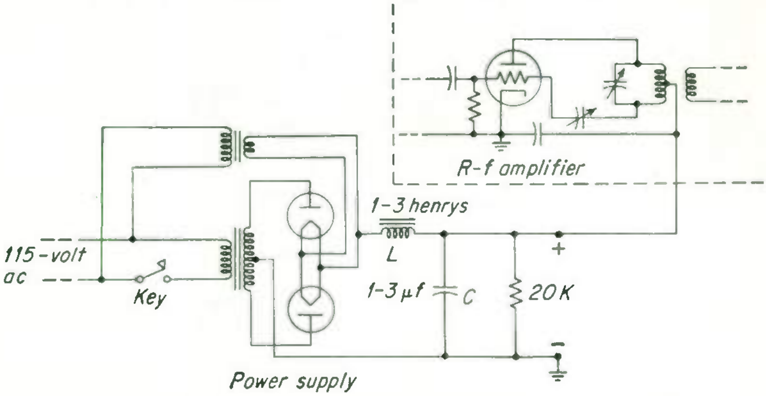


FIG. 15.21. Primary-keying circuit connected to an RF amplifier.

The values of the inductance and capacitance will vary with plate current requirements as well as the frequency of the power a-c. For 60-cycle power, the inductance may be between 1 and 3 henrys, and the capacitance between 1 and 3 μf.

In practice this type of keying sometimes softens the transmitted signal to such an extent that rapidly made dots and dashes become blurred together and unintelligible. If less $L$ and $C$ filter is used to improve the intelligibility, the ripple content of the power-supply voltage may increase sufficiently to produce, in the case of 60-cycle power sources, a 120-cycle modulated-tone transmission, which is usually undesirable. If 400-cycle or higher a-c power is available, less $L$ and $C$ filtering is required to produce a smooth d-c output from the power supply. This type of keying can then be used with higher keying speeds. If a modulated-tone (A2) emission is desired, very small $L$ and $C$ values will produce a pleasant-sounding 800- or 1,000-cycle tone signal from power frequencies of 400 or 500 cycles.

**15.17 Vacuum-tube Keying.** One method of controlling the emission of a telegraph transmitter is by using *vacuum-tube keying*. This method of keying has the advantage of being able to form the dots and dashes without physically making or breaking a circuit carrying either high current or high voltage. By varying resistance and/or capacitance values, satisfactory waveshaping may be accomplished.

The circuit to be keyed is opened, and a low-$\mu$ triode tube is connected in series with the circuit in such a way that current will pass through the triode in the same direction as current normally flows, as shown in Fig. 15.22.

In the vacuum-tube keyer circuit shown, the keyer tube is in series with the plate supply voltage of the RF amplifier. If the keyer tube can be made to stop all current flow through it, the RF amplifier stage will also have no current flowing through it and will have no RF output.

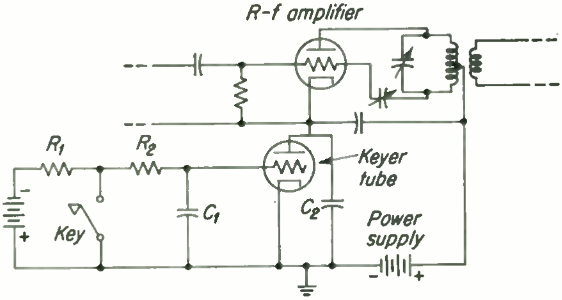


FIG. 15.22. Vacuum-tube-keying circuit.

With the key open, the full bias voltage is applied to the keyer grid-cathode circuit, biasing the tube past cutoff, preventing any plate-current flow, and preventing the RF amplifier stage from operating. $C_1$ charges to the full bias voltage.

When the key is closed, three things happen: (1) All the bias voltage is developed across $R_1$, preventing a short circuit of the battery. (2) Capacitor $C_1$ discharges through $R_2$ at a rate dependent upon the $R_2$ and $C_1$ values, lowering the negative bias value on the grid to zero. (3) With no bias on the keyer tube, current can flow through the keyer tube and the RF amplifier, allowing the amplifier to operate and transmit a signal.

When the key is opened, $C_1$ begins to charge at a rate dependent upon the values of $C_1$, and $R_1$ plus $R_2$. Since $C_1$ is connected between the grid and cathode, when the voltage across $C_1$ builds up to the cutoff value of the tube, the keyer tube stops passing current and the RF amplifier stops operating.

Large values of $R_2$ and $C_1$ and a relatively low bias voltage produce a slow increase and decrease of bias voltage and result in very soft keying.

Small values of $R_2$ and $C_1$ and a high bias voltage result in harder keying.

If one keyer tube will not pass enough plate current to satisfy the requirements of the RF amplifier, two or more tubes may be used in parallel.

Capacitor $C_2$ is a bypass capacitor, keeping the cathode of the RF amplifier at ground potential as far as RF a-c is concerned. It has little effect on shaping the transmitted wave.

**15.18 Grid-block Keying.** So far, only plate- or cathode-circuit keying has been discussed. However, if the bias applied to the grid circuit of an RF amplifier is sufficiently negative to prevent plate current flow in the tube, regardless of how high the driving RF a-c voltage may be, the amplifier stage cannot operate. The blocking of the plate current by applying a high negative charge to the grid is known as *grid-block*, *blocked-grid*, or *grid-bias* keying.

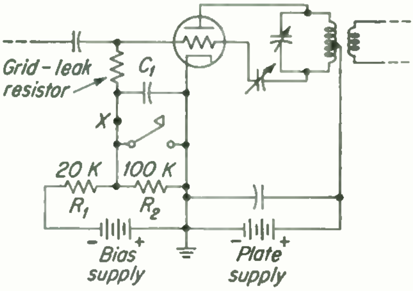


Fig. 15.23. Blocked-grid keying using a bias supply.

A diagram of a blocked-grid system of keying requiring a separate bias supply is shown in Fig. 15.23.

When the key is open, $R_1$ and $R_2$ form a voltage divider across the bias supply. The voltage drop across $R_2$ must be high enough to cut off the plate current of the stage, preventing any RF output.

When the key is closed, all the bias-supply voltage is across $R_1$ and none across the key or in series with the grid circuit. The only working bias in the grid circuit is that developed by the grid-leak resistor. The stage will now operate normally, emitting an RF signal.

Capacitor $C_1$ is an RF bypass, holding the bottom of the grid-leak resistor at cathode potential as far as RF a-c is concerned. If sparking is produced at the key contacts as the key is closed across the charged capacitor, a resistance of a few hundred ohms inserted in the circuit at point $X$ should reduce it.

Should the bias-supply voltage fail for any reason, the stage will continue to emit a signal even with the key in the up, or open, position. The emission will be slightly less when the key is open. It may appear to the operator that the key is shorted, since the local signal will be extremely strong under both conditions. Pitted contacts that refuse to open on the keying relay will also allow the emission to continue with the key contacts open.

Another circuit in which the grid is blocked with the key open but which requires no separate bias supply is shown in Fig. 15.24.

When the key is open, the 20-kilohm and the 40-kilohm resistors form a voltage-divider circuit across the power supply. One-third of the power-supply voltage is placed on the grid to block it.

When the key is closed, the 20-kilohm resistor is shorted out and the only bias voltage in the grid circuit is that developed across the grid-leak resistance. The full voltage of the power supply is now connected between cathode and plate, and also across the 40-kilohm resistor. With the key down, the current flowing in the 40-kilohm resistor is a waste, unless this resistor is considered as an auxiliary bleeder resistor on the power supply.

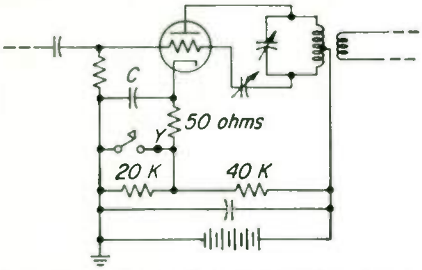


FIG. 15.24. A blocked-grid keying circuit requiring no bias supply.

Since the voltage across the key is high a keying relay should be employed rather than a simple telegraph key.

In some installations it might be more advantageous to ground the cathode instead of the negative terminal of the plate supply. Either will operate satisfactorily.

A possible method of keying, but one that is rarely used, is screen-grid keying. Another even less practical form is suppressor-grid keying.

An A2 emission can be produced by connecting a chopper wheel into the circuit at point *Y*. If the chopper makes and breaks contact 500 times a second and the key is held down for $\frac{1}{10}$ sec to transmit a dot, the carrier will be turned on and off 50 times. This results in an interrupted CW signal, composed of pulses of square-wave RF a-c, only slightly rounded off by the filtering effect of the capacitor *C* and 50-ohm resistor across the key and chopper. It will be a rather broad emission, but can be detected by any type of receiver tuned to the frequency. For this reason it would be satisfactory for distress transmissions in an emergency.

**15.19 Frequency-shift Keying.** The usual radio receiver is sensitive to changes in amplitude. When a carrier of a transmitter is turned on and off, as when sending dots and dashes of telegraphic code, the receiver should produce a sound for each dot or dash and be quiet between times. Unfortunately, man-made static as well as natural static are also occurring as changes in amplitude and produce noises in the receiver when the transmitter is off. If the received signal is strong enough, it will be well above this noise level, and the dots and dashes can be easily distinguished. However, when signals are only slightly stronger than the noise level, instantaneous crashes of noise between dots and dashes can confuse the reception of the code.

As long as there is a carrier, the receiver is quieted somewhat. Therefore, if the carrier can be left on at all times, some of the effect of background noise can be overcome. If the carrier is to be on all the time, how can dots and dashes be made? One method is to shift the carrier back and forth from one frequency to another. When no code is being sent, the carrier is left on one frequency, called the *space* frequency. When a dot or dash is transmitted, the carrier is shifted over to another nearby frequency, called the *mark* frequency. This is known as *frequency-shift keying*, or *FSK*. If the mark and space frequencies are relatively close, 60 to 900 cycles, the receiver remains in a quieted condition, since it receives both signals on one setting of the dial.

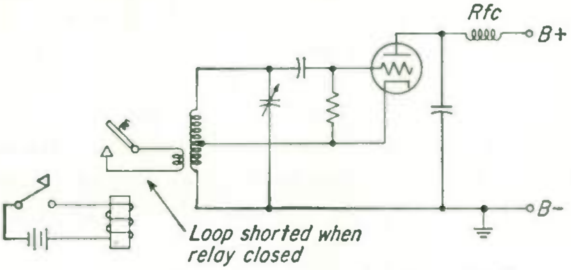


FIG. 15.25. Shorting a loop to produce FSK.

By making the receiver sensitive to frequency changes only, rather than to amplitude changes, further improvement on reception can be realized.

Figure 15.25 shows a basic keying circuit by which mark and space signals can be produced. The closer the coupling of the loop, the greater the frequency variation when the relay shorts the loop. A shorted loop coupled to an inductance lowers the effective inductance and will raise the frequency of oscillation of an associated tank circuit.

Another method of shifting the frequency is to connect and disconnect a small capacitor across part of the tuned circuit of an oscillator. The capacitance lowers the frequency. A possible circuit for this is shown in Fig. 15.26. Adjusting the capacitance $C_1$ controls the frequency variation.

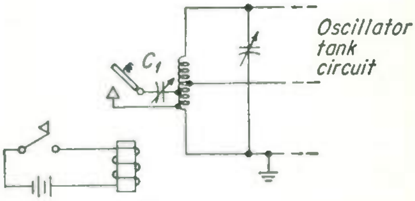


FIG. 15.26. Shunting a capacitance across the tank to produce FSK.

An FSK circuit using two diode tubes *biased* by having their plates more negative than their cathodes is shown in Fig. 15.27. With the two tubes biased to a value determined by the voltage divider composed of $R_1$ and $R_2$ so that they cannot conduct, capacitor $C_1$ is not effective. However, when the key is closed, the bias voltage is decreased enough so that some of the peaks of both halves of the RF a-c cycles produced in the oscillator are greater than the bias. During these portions of the cycle the capacitor is effectively coupled across part of the tuned circuit, lowering the frequency of oscillation. The lower the bias value on the diodes, the greater the proportion of the cycle during which the capacitor is effective and the greater the frequency variation.

A coil can be substituted for $C_1$. When the diodes conduct, the frequency will increase.

The double-diode method of shifting the frequency is usually better than the simpler shorted loop or shunt capacitor, because no relay is necessary. A relay mounted close to the oscillator coil may cause a physical jarring of the circuit parts and will produce an undesired frequency vibration on both mark and space signals unless pains are taken to prevent it. Another advantage is the possibility of remote frequency-shift control. The rheostat adjustment may be located any desired distance from the oscillator. In the other circuits, frequency-shift adjustments must be at the site of the oscillator tank circuit.

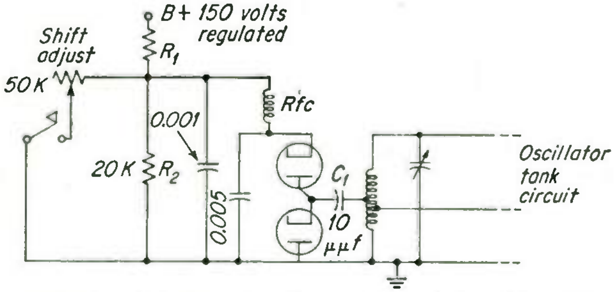


FIG. 15.27. Double-diode circuit to produce FSK. $R_1$ = 100 kilohms.

Another possible method of shifting the frequency is by the use of a *reactance-tube modulator circuit*, discussed in the chapter on Frequency Modulation. The reactance tube is connected across the tank circuit of the master oscillator.

It is possible to frequency-shift a crystal oscillator, although the number of cycles it will move is usually only a few hundred. This can be done by keying a small inductance in and out of the crystal circuit itself, or keying a small capacitor across the crystal, with either a relay or a double-diode circuit. Crystals in the frequency range of 500 kc will shift only a few cycles. Crystals in the 4-Mc region will shift about 400 cycles and still give good output on both mark and space frequencies.

**15.20 Modulated Code Signals (A2).** Short-wave signals, either radiotelegraph or radiotelephone, are often subject to very rapid and deep fading. Two frequencies separated by only a few hundred cycles may fade at different rates. To take advantage of this, code signals are sometimes *tone-modulated*. This may be accomplished by several methods.

One method consists of adding an AF a-c voltage in series with the d-c plate voltage of the final RF amplifier stage, resulting in a varying d-c plate voltage for this tube. The strength of the RF a-c output will now vary up and down in amplitude at the a-c rate. The chopper wheel, previously mentioned, produces a similar effect. The RF carrier is said to be *amplitude-modulated* at the AF rate.

If an 800-cycle a-c is added in series with the d-c plate voltage of an RF amplifier, the output RF power will increase and decrease in amplitude 800 times a second. The addition of this modulation to the carrier wave produces two other RF signals, one having a frequency 800 cycles higher than the carrier and the other a frequency 800 cycles lower than the carrier frequency. These new RF signals are called *sidebands*, since they appear on each side of the carrier frequency.

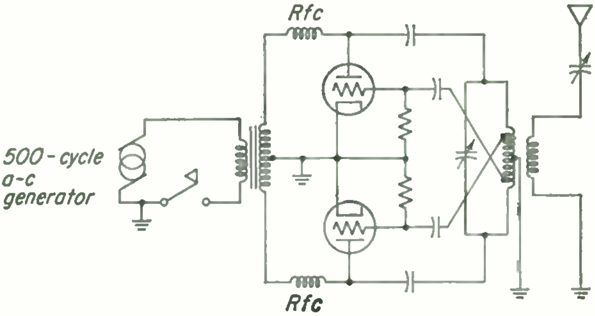


FIG. 15.28. A self-rectified Hartley oscillator transmitter.

Under conditions of severe fading, it may be that the carrier frequency will fade out completely but one or the other sidebands will not be completely faded. As a result, with the usual CW receiver, a readable signal may be heard even when the carrier frequency has faded out completely. While this may help at some times, it is not a cure for fading. Modulated CW signals (A2) may be more consistent than unmodulated CW signals (A1), but they will also fade out completely at times.

**15.21 The Self-rectified Transmitter.** The high-voltage power supply of a transmitter is usually an expensive part of the equipment. The power supply usually steps up an available a-c voltage, rectifies it, and then filters it, producing a d-c suitable for the plate circuit of the transmitting tube. When modulated oscillators were commonly used as CW transmitters, to decrease the cost of the power supply, a self-rectified oscillator circuit was developed. Such a circuit is shown in Fig. 15.28.

The self-rectified circuit with 500-cycle a-c, usually generated at the station by a motor-generator set, produced a 1,000-cycle modulation of the oscillator output. The circuit is similar to a shunt-fed push-pull Hartley. The only difference is the means of feeding plate voltage to the tubes. On one half cycle of the 500-cycle a-c, one end of the power transformer is positive, and that tube produces the oscillation in the tuned tank circuit. When the a-c cycle reverses, the other tube works, keeping the tank circuit in oscillation. This results in a carrier wave that varies up and down from zero amplitude to maximum and back to zero again, twice for every cycle of the 500-cycle a-c. The carrier is modulated at a 1,000-cycle frequency. The emission is classified as A2.

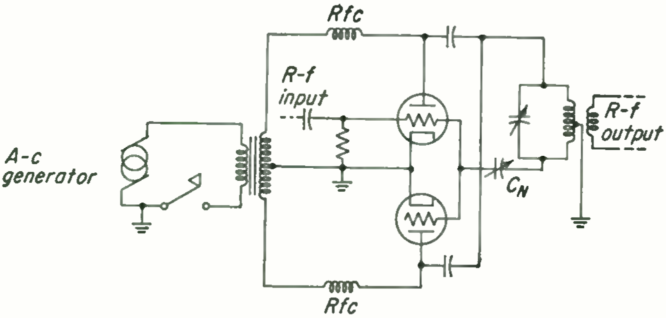


Fig. 15.29. A self-rectified RF amplifier circuit.

The emission of the self-rectified transmitter will be the same as a transmitter using an unfiltered full-wave-rectified power supply. There is no way to filter the 500-cycle a-c applied to the self-rectified circuit to decrease or prevent modulation of the output.

The emission from this type of oscillator will not only be amplitude-modulated but, because of varying plate voltage, will be frequency-modulated as well. This results in a broad emission.

Self-rectification can be used in an RF amplifier also. Figure 15.29 shows one possible circuit. Unfortunately, the emitted wave of any self-rectifying circuit will be rich in harmonics of the *modulating* frequency, resulting in an excessively broad wave. This is undesirable, and as a result these circuits are rarely used.

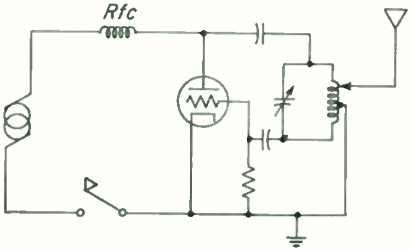


Fig. 15.30. Simplest type of self-rectified transmitter, with direct-coupled antenna.

The simplest form of a self-rectified transmitter circuit consists of an oscillator being fed directly by an alternator, as shown in Fig. 15.30. During the half cycle when the a-c generator places a positive charge on the plate of the tube, the oscillator circuit oscillates. During the half cycle when the plate is negative, there is no output from the oscillator. Such a transmitter has extremely poor emission characteristics, is broad, sounds raspy, and has relatively low output power. The only acceptable use of such a transmitter would be in cases of distress, when it is the only piece of radio equipment that can be placed in operation. In cases of distress, when lives are at stake, any form of emission is acceptable.

**15.22 The Buffer Amplifier.** The MOPA, or master-oscillator power amplifier transmitter, represents a decided improvement over a simple oscillator in both power output and frequency stability, as well as chirpless and clickless keying. Even so, varying the amplifier tuning, as well as varying the antenna coupling, tends to cause less-than-perfect frequency stability. Failure to neutralize the amplifier perfectly exaggerates the instability.

More nearly perfect operation is possible in a transmitter consisting of an oscillator, an intermediate powered amplifier, and a high-powered final amplifier. A diagram of such a transmitter is shown in Fig. 15.31.

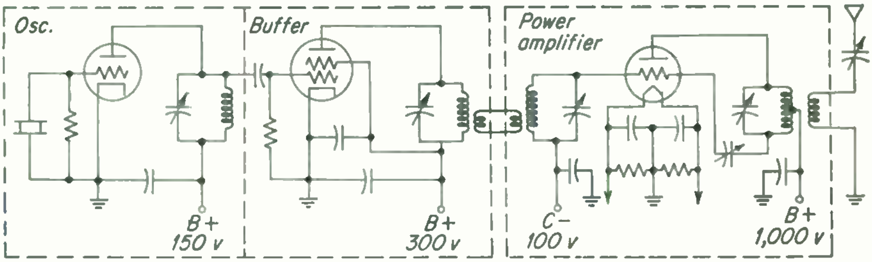


FIG. 15.31. Crystal oscillator, tetrode buffer stage, and triode power-amplifier transmitter.

The intermediate amplifier is called a *buffer* amplifier. It has two duties: (1) to amplify the weak output of the oscillator enough to adequately excite the grid of the final amplifier; (2) to prevent interaction between the final amplifier and the oscillator, which might result in frequency instability.

A buffer amplifier can be a standard triode, tetrode, or pentode RF amplifier. It is relatively low powered, usually employing indirectly heated, or cathode-type, tubes. The final, or power-amplifier, stage usually uses directly heated, or filament-type, tubes, particularly if the power output is over one or two hundred watts. Most commercial-type CW transmitters have an output ranging from 200 watts to more than 10,000 watts.

When the oscillator and the buffer stages are both properly shielded and the buffer neutralized (if necessary), tuning the final amplifier or antenna circuits should have little or no effect on the oscillator frequency. If the oscillator and buffer operate from a power supply separate from the final-amplifier supply, keying the final amplifier should produce excellent keying characteristics.

Fairly good keying can be produced by keying the buffer, particularly if it has a power supply separate from that of the oscillator. Keying an intermediate *driver* amplifier between the buffer and the final amplifier is to be preferred, however. In general, the oscillator and buffer stage should be considered together as a frequency-determining pair and should not be keyed in radiotelegraph nor amplitude-modulated in radiotelephone transmitters.

The three-stage transmitter shown consists of a triode crystal oscillator, capacitively coupled to a tetrode buffer stage, link-coupled to a plate-neutralized triode final amplifier, inductively coupled to an antenna. A probable power input to the final-amplifier plate circuit is about 200 watts, with about 140 watts of RF power output.

As discussed in previous chapters, the a-c filament circuit of any directly heated final amplifier tube must be center-tapped and bypassed to ground to prevent a-c hum modulation of the transmitted wave.

Buffer amplifiers are usually biased to class C, although class A or B is sometimes used.

The generally accepted procedure for tuning multistage transmitters such as the one shown is as follows:

1. Start with the plate voltage off on all stages.
2. Connect the plate voltage to the oscillator and tune this stage. (Neutralize next stage, if required.)
3. Connect the plate voltage to the next stage and tune it. Recheck the previously tuned stage.
4. Progress stage by stage as in step 3 to the final amplifier and the antenna.
5. Tune the final amplifier to a plate-current dip with very loose antenna coupling.
6. Tune the antenna to resonate with the final amplifier (if a tunable antenna is used), indicated by a slight peaking of the final plate current.
7. Increase the antenna coupling to the desired final-amplifier plate-current value or required antenna-current value.

It is good procedure to recheck each stage again, starting at the oscillator stage and working up to the final amplifier and antenna.

All triode buffer or final-amplifier stages (except multiplier or grounded-grid amplifiers) must be neutralized before they are tuned, to prevent self-oscillation, generation of spurious oscillation frequencies, erratic tuning, excessive plate current, or poor isolation of the stages ahead of or after them. Once neutralized, a stage may require no reneutralization for a long period of time. Tetrodes and pentodes may not require neutralization when operated on frequencies less than about 30 Mc.

**15.23 Grid-leak Bias in CW Transmitters.** A grid-leak-biased stage has no bias when there is no RF excitation to the grid, as in an amplifier following a keyed stage in a CW transmitter. Without bias, the stage may draw too much plate current and damage the tube.

There are three methods of protecting a grid-leak-biased stage in a CW transmitter when a lower-level stage is keyed:

1. By using batteries, or a bias supply. The amplifier may be biased to class C, or to some lesser value of bias, to limit the plate current to some safe value when the key is up and no RF excitation is being applied to the stage and no grid-leak bias is being developed.
2. The stage may employ cathode-resistor bias to produce a safety bias when no RF excitation is applied, limiting the plate current to some safe value. However, the active plate voltage on the stage is equal to the plate supply voltage minus the drop across the cathode-bias resistor.
3. A *clamp* tube may be used in screen-grid amplifier tubes (Fig. 15.32).

The clamp tube should have a high amplification factor, a relatively low cutoff-bias value, and the ability to pass a relatively heavy current. A type-6Y6 beam-power tetrode is often used as a clamp tube. When there is no excitation to the RF amplifier, there is no grid-leak bias, and the clamp tube, which also derives its bias from the grid leak, having no bias, passes a high value of current through itself and the screen dropping resistor $R_1$. This high current produces a large voltage drop across $R_1$, producing a low voltage across the clamp tube, and therefore a low screen voltage for the RF amplifier. With a low screen voltage, the plate current cannot be high.

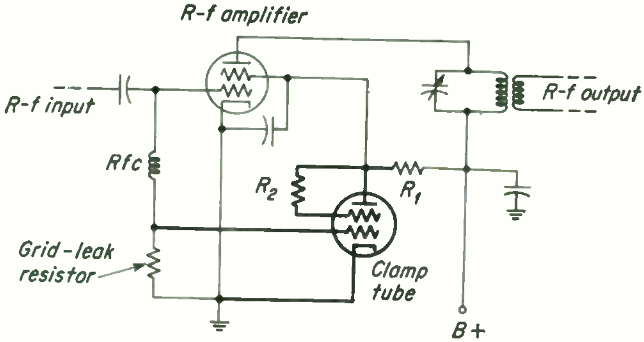


FIG. 15.32. Clamp-tube circuit used when a preceding stage is keyed.

When excitation is applied to the grid of the amplifier, grid-leak bias is produced, biasing the clamp tube and stopping its plate current. This allows the normal screen-grid current to flow through $R_1$, and the amplifier stage operates as though the clamp tube were not in the circuit.

Resistor $R_2$ is to prevent excessive screen-grid current from flowing in the clamp tube.

Clamper circuits are also used in radar, TV, and other systems.

**15.24 Frequency Doublers or Multipliers.** The lower the frequency of oscillation, the more stable the oscillator and the less it is likely to drift (Secs. 12.9, 12.24). To take advantage of this better frequency stability, the oscillator is often operated at a lower frequency than the frequency of operation of the final amplifier. For example, it is desired to transmit on a frequency of 8,070 kc. If the oscillator operates on 2,017.5 kc stably, the 2017.5-kc signal can be fed into a pair of frequency-doubler stages. The output of these stages will drive the final amplifier at the desired 8,070-kc frequency with greater stability than if the oscillator had been on 8,070 kc. A block diagram of such a transmitter is shown in Fig. 15.33.

Since the final-amplifier frequency is not the same as the frequency of the oscillator, there is much less chance of interaction between the two stages. It is not quite as necessary to rely upon shielding and proper neutralization of the intermediate stages.

Transmitters operating in the VHF band, 30 to 300 Mc, usually use three or more multiplier stages. For example, to transmit a signal on

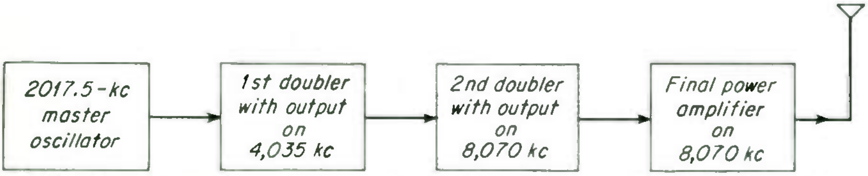


FIG. 15.33. Block diagram of a transmitter with an output on 8,070 kc and an oscillator frequency of 2,017.5 kc.

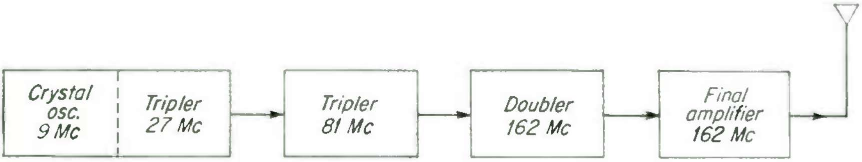


FIG. 15-34. Block diagram of a system to produce 162-Mc output.

162 Mc, a possible arrangement is shown in the block diagram in Fig. 15.34. A crystal is the only commercially acceptable type of oscillator to maintain adequate frequency stability when the fundamental is multiplied this many times. A crystal oscillator of the electron-coupled type will give good output on either the second or third harmonic, and some special crystal oscillator circuits will give good output on the fifth or seventh harmonic. Very-high-frequency mobile equipment is an example of oscillator-multiplier-amplifier equipment such as described here.

If the frequency of the oscillator stage in a multistage transmitter changes for any reason, the multiplier stages multiply the frequency change.

*Example:* A 1,000-kc crystal is used in a transmitter operating on an assigned frequency of 8,000 kc. The transmitter must have three doubler stages. If the crystal changes 5 cycles in frequency, the first doubler changes 10 cycles, the second doubler changes 20 cycles, and the third doubler changes 40 cycles. The 5-cycle oscillator change produces a 40-cycle change in the output signal.

If the crystal has a temperature coefficient of −4 cycles/Mc/°C and the temperature of the crystal increases 6°C, the output frequency will *decrease* 4 cycles (−4 cycles indicates a negative temperature coefficient) times 1 (1,000 kc equals exactly 1 Mc) times 2, times 2, times 2 (because of the three doubler stages) times 6 (temperature increase in degrees), or 192 cycles. If the output frequency had been 8,000,000 cycles, increasing the temperature of the crystal 6° decreases the frequency of the output 192 cycles, to 7,999,808 cycles, or 7,999.808 kc. If the crystal had a *positive* temperature coefficient of +4 cycles Mc/°C, the rise in temperature would have *increased* the frequency to 8,000,192 cycles.

### 15.25 Decreasing Harmonic Radiation.

No RF amplifier will emit a pure sine-wave RF a-c. Inasmuch as any deviation from the pure sine wave represents harmonic content, RF amplifiers can be expected to transmit some harmonic energy as well as the fundamental frequency. In many cases, harmonic energy from a transmitter will fall on frequencies used by other radio services, causing them interference. This is against communication laws and must be eliminated.

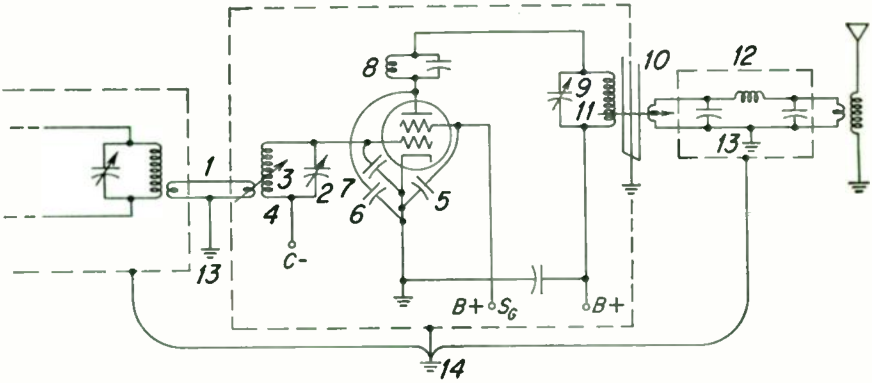


FIG. 15-35. Methods of decreasing harmonic output from a power amplifier.

There are several possible methods of decreasing harmonic generation and radiation. Figure 15.35 illustrates some of these.

Each of the numbered items in the illustration will be briefly described.

1. The use of link or any other form of inductive coupling discriminates against the passing of higher frequencies, whereas most forms of capacitive coupling will couple higher (harmonic) frequencies better than it will the lower fundamental frequency.
2. A circuit tuned to the fundamental in the grid circuit decreases the possibility of transferring harmonics generated in the driving stage to the final-amplifier grid.
3. The coupling to the grid circuit should be held to a low enough value to prevent driving the grid to the point of plate-current saturation at the

peak of the RF voltage, which inevitably results in a high percentage of harmonic output.

4. The bias voltage should be as low as possible, no more than 1½ times the cutoff value for class C amplifiers, to produce plate current flow as near 180° of the RF cycle as possible without materially decreasing the efficiency of the stage.

5, 6, 7. Small mica or air-dielectric capacitors, 3 to 50 $\mu\mu$f, are connected to ground from the grid, screen, and plate terminals of the tube and effectively bypass harmonic frequencies that fall in the VHF range.

8. A small coil and capacitor tuned to any VHF being interfered with tends to decrease harmonic transfer through the tube to the plate tank circuit, although it is probably more effective as a parasitic-oscillation stopping device.

9. The tank circuit should have as high a $Q$ as practical, to produce good flywheel effect.

10. A *Faraday shield* may be installed between the final tank and the antenna. It is a gridwork of thin parallel wires, not connected together at the top but soldered together at the bottom and grounded. This *electrostatic shield* materially decreases capacitive coupling, thereby decreasing possibility of harmonic transfer to the antenna circuit.

11. As loose a coupling as possible should be used between final tank circuit and the antenna and still maintain the desired output power. Overcoupling lowers the $Q$ of the tank circuit, materially increasing the harmonic output.

12. A low-pass filter with a cutoff frequency slightly below the second-harmonic frequency of the transmitter may be added to the antenna feed line. All frequencies above its cutoff frequency will be materially decreased, will not be delivered to the antenna, and therefore will not be transmitted. (An *m*-derived filter would be preferable to the simpler constant *k* type shown.)

13. One side of a link-coupling circuit should always be grounded.

14. All stages, as well as the low-pass filter, should be separately shielded and then grounded to a common ground point, such as an underground waterpipe or some other adequate ground.

Not shown in the illustration, but particularly effective in reducing even-order harmonics, is a well-balanced push-pull stage.

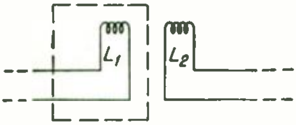


FIG. 15.36. Coil $L_1$ is shielded from $L_2$.

**15.26 Shielding.** The advisability of *shielding* stages, circuits, or parts has been mentioned several times. Shields must do two things: (1) shield one circuit electromagnetically from other circuits; (2) shield one circuit electrostatically from other circuits.

As a simple case of shielding, consider the two coils in Fig. 15.36.

The dotted lines surrounding the first coil indicate that this coil is encased in a metal container. It is shielded.

Assume, first, that there is no shield present. Coils 1 and 2 are mutually inductive. Alternating current in the first will induce alternating current into the second because of expanding and contracting *magnetic* fields. If a metallic box is now placed around the first coil, no current is induced into the second coil. The expanding and contracting magnetic fields induce an alternating voltage and current in the metal shield. This induced current produces a field, according to Lenz's law, opposite in phase to that of the field that produced it. If the shield metal was a perfect conductor, the strength of the opposing field would equal the inducing field and there would be zero resulting field to move outward toward the second coil. The shielding would be perfect.

Unfortunately, there is no such thing as a perfect conductor. Therefore shielding of magnetic fields can never be perfect. However, silver is near enough to a perfect conductor to produce very good shielding. Copper is only a little less effective. Then, in order, come gold, aluminum, zinc, iron, and lead, to mention some common metals. Because of the high cost of silver, copper, and gold, most shielding is done with aluminum, except in circuits operating at frequencies over about 100 Mc, when silver-plated copper or brass is used.

Once again, consider the two coils without the shield. Each coil is a conductor, and the air between them is a dielectric. They form a capacitor. Alternating current can travel from the first coil to the second via the electrostatic lines of force of capacitance. Actually, energy is being transferred from one circuit to the other by both electromagnetic and electrostatic lines of force.

When the metallic shield is placed around the first coil, there is capacitance between the first coil and the shield, and also between the shield and the second coil. Again, there may be some electrostatic transfer of energy; but if the shield is connected to ground, the electrostatic energy flows back and forth between the first coil, the shield, and ground and practically none reaches the second coil. Electrostatic shielding is almost complete with any of the common metals.

What is true of shielding between the two coils is also true between two or more RF stages, between an RF amplifier and an antenna, and between an RF and an AF stage.

Proper shielding can prevent degeneration, regeneration, oscillation, distortion, parasitics, instability, hand capacitance, detuning, and other undesired effects. All communications equipment is made of metal to provide solid physical construction as well as good shielding.

Properly constructed transmitters and receivers have no high-voltage carrying leads external to the equipment. All exposed metal parts are engineered in such a way that they can be connected to the chassis and grounded, thereby preventing operating personnel from shocks. Grounding the metal parts of a transmitter also prevents the accumulation of a static charge on them. As a further protection to personnel, interlock switches may be incorporated in doors, to automatically interrupt all high-voltage circuits if the doors of the transmitter are opened. All possible controls to adjustable parts are brought outside, making it unnecessary for the operator to reach inside the cabinet, or housing, to tune or adjust the circuits. When fuses are used, they are usually available from outside the equipment. When overload relays are used instead of fuses, the restore mechanisms are usually available from outside. The operator determines the operation of the equipment by meter readings alone. The meters to be found on a transmitter are power-line voltmeter, filament voltmeter, plate-current meter(s), plate-voltage meter(s), grid-current meter(s), antenna-current meter.

**15.27 Transmitters Today.** Modern transmitters might be catalogued as to whether they operate on one assigned frequency, on several assigned frequencies, or in bands of frequencies.

Broadcast, police headquarters, and some fixed point-to-point stations are examples of transmitters assigned to operate on one frequency only. They all use crystal-controlled oscillators. The RF sections of such transmitters are tunable, but once tuned, are not expected to be adjusted for long periods of time. Police, taxicab, and other *mobile* equipment fall in the same category, except that they are constructed to operate from 6- or 12-volt d-c sources, are built as light and rugged as possible, and have minimum power drain per watt output. These usually operate on assigned frequencies from 30 to 500 Mc.

Shipboard radiotelegraph or radiotelephone, aircraft, and many point-to-point transmitters are examples of transmitters that operate on certain assigned frequencies during one time of the day and on other frequencies at other times of the day to communicate over the same or different distances. Crystal-controlled oscillators are used. There may be a separate crystal for each assigned frequency, or the frequencies may be harmonically related, and frequency multiplier stages can be utilized. The use of crystals in these transmitters simplifies selection of the correct frequency, as well as assuring good frequency stability. The desired crystal is chosen by rotating a selector switch. The same switch may shift the RF stages to pretuned settings, requiring only antenna and final-amplifier trimming to assure proper operation of the transmitter. In some equipment the tuning is done automatically. In others, each buffer, multiplier, and amplifier requires individual retuning by the operator.

In the early days of radio, all transmitters used variable-frequency-type oscillators. Today, amateur, military, and marine equipment are the only transmitters with variable-frequency oscillators. Commercial equipment has changed to crystals to assure operation within the strict frequency tolerances set by national and international communications agreements.

Since the amateur has been assigned bands of frequencies, such as 3.5 to 4 Mc, 7 to 7.3 Mc, 14 to 14.35 Mc, etc., his transmitter may have a variable-frequency oscillator to allow him to operate on any frequency within the band limits. Crystal-controlled oscillators may be used, but they restrict his ability to move away from interfering signals or to shift to any particularly desirable frequency. The amateur transmitter should be capable of operating on several bands at the choice of the operator and on any desired frequency in these bands.

The single-frequency-type transmitter is discussed in the chapter on The Broadcast Station. The multifrequency-type transmitter is discussed in the chapter on Shipboard Radio Stations. A variable-frequency-oscillator radiotelegraph transmitter circuit suitable for amateur band operation will be discussed in this chapter.

**15.28 A VFO Transmitter.** The *variable-frequency oscillator*, or VFO, radiotelegraph-transmitter diagram shown in Fig. 15.37 represents an amateur-band transmitter capable of between 200 and 400 watts input. By adjusting the ganged three-pole four-position band-selector switch (SW), operation on any one of four amateur bands is possible. The switch is shown in the 14.0–14.35-Mc position.

The Hartley-type electron-coupled oscillator operates on the "160-meter," or the 1.750–2.0-Mc band. $C_1$ is the tuning capacitor, while $C_2$ is a padding capacitor to add capacitance to the tuned circuit. As mentioned in the chapter on Oscillators, the more capacitance in the tuned circuit, the less the frequency of the oscillator is likely to drift. The output plate circuit of the oscillator is *broadly tuned* by using a tightly coupled, low-$Q$ resonant circuit which is tuned by adjusting the powdered-iron core, or slug, in the inductance. The oscillator tube is a pentode and might be a 6AG7, 6SK7, 6AG5, or other similar type.

The second stage is a buffer amplifier operating on the same frequency as the oscillator. It is keyed with a system of blocked-grid keying. The screen-grid voltage is made variable as a means of controlling the excitation to the stages that follow. With the switch in the position shown, the output of the buffer feeds the grid circuit of a tetrode doubler stage. The buffer and the multiplier stages are tetrodes, such as the 6V6, 6AQ5, 6L6, or other similar types.

The third stage is a doubler, with the plate circuit tuned to the "80-meter," or 3.5–4.0-Mc band. The cathode-resistor bias holds the plate current to some safe value while no signal is applied to the grid of the tube. When the key is closed, the grid is excited and a class C bias value is developed across the grid-leak resistor. The tube now acts as a frequency doubler, feeding a 3.5–4-Mc signal to the next stage.

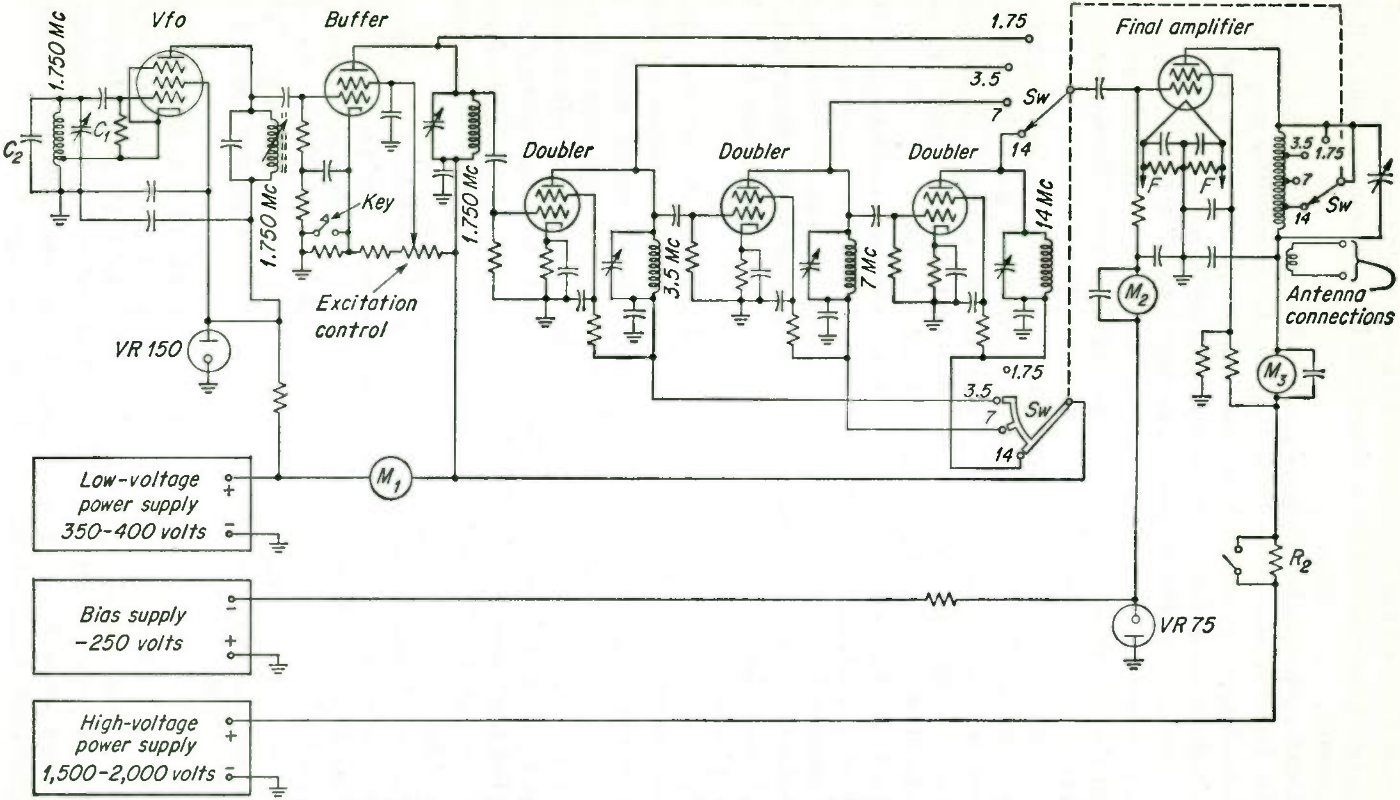


FIG. 15.37. Schematic diagram of a possible four-band VFO amateur transmitter.

The fourth stage is similar to the third except that the plate circuit is tuned to cover the "40 meter," or 7.0–7.3-Mc amateur band. Note that 7.3–8.0 Mc is not included in the amateur band, and the transmitter must not be operated in this range.

The fifth stage is similar to the fourth except that the plate circuit is tuned to cover the "20 meter," or 14.0–14.35-Mc amateur band. While it is also possible to operate the transmitter from 14.35 to 16.0 Mc, these are not amateur frequencies and must not be used.

The sixth stage is the final amplifier, which feeds RF power to the antenna. It is a beam-tetrode power amplifier, biased by a separate power supply to slightly more than plate-current cutoff.

*Tuning.* To tune this transmitter, first the high-voltage power supply is turned off. The remainder of the transmitter is turned on. After a warm-up period of a few minutes, the desired frequency of operation is selected on the oscillator tuning dial.

When the key is pressed, the buffer begins amplifying and feeding RF a-c to the first doubler, which excites the second doubler, and so on. The final-amplifier grid circuit draws current when excited by the last doubler. The buffer and doubler stages can be tuned by watching either the plate current meter $M_1$ or the grid meter in the final-amplifier grid circuit $M_2$. Meter $M_1$ will show lower current values as the buffer or multipliers are tuned to resonance, while meter $M_2$ will show an increase when the stages are properly tuned. When the buffer and doublers have been tuned properly, the *excitation control* in the screen-grid circuit of the buffer can be adjusted to the required grid current for the final amplifier.

Now the high-voltage power supply is turned on, but at a low-power setting. The usual method of obtaining low-power input is by controlling the plate voltage, either with a variable autotransformer (see Fig. 15.38), or by inserting a variable or fixed resistor in series with the high-voltage lead $R_2$ in Fig. 15.37. The plate tank circuit is tuned to a plate-current minimum. The antenna circuit is tuned to resonance, indicated by a slight rise in plate current. The antenna is coupled a little tighter, and the plate tank redipped, as coupling the antenna usually detunes the final plate tank a little. The full plate voltage is applied to the final amplifier, and the antenna coupling increased until the desired plate current, as specified in a tube manual, is attained. The grid current must be rechecked during the tune-up procedure to assure a proper value.

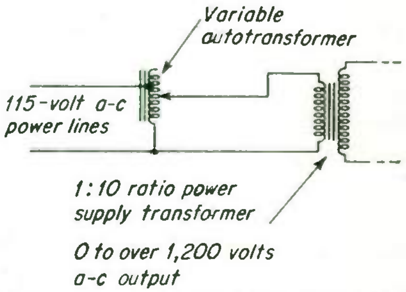


FIG. 15.38. Autotransformer connected between the power-supply transformer primary and the power line.

It is possible to have the tuned-plate tank circuit of the last multiplier stage resonate from 22 to 14 Mc and operate the last multiplier as a *tripler*. If the final amplifier has a plate tank circuit capable of tuning over this same range, the transmitter can operate on the "15 meter," or 21–21.45-Mc band. Care must be exercised by the operator not to tune, inadvertently, to the wrong harmonic frequency.

If it is desired to operate on the 7.0-Mc band, the band-selector switch can be turned to the 7-Mc setting. This disconnects the plate supply from the last multiplier, connects the final-amplifier grid to the 7-Mc stage, and shorts out less of the final-amplifier plate coil, allowing it to resonate at a lower frequency. Operation on the 3.5- and 1.75-Mc bands is similarly obtained.

Shifting the fundamental frequency of the transmitter a few kilocycles may not require retuning of all the stages. This is particularly true of the higher-frequency multipliers, because of the normally lower $Q$ of the circuits at higher frequencies. However, if the frequency is changed 50 or more kilocycles, at least the 1.75- and 3.5-Mc tuned circuits may have to be retuned. It is possible to *gang* all tuned circuits so that satisfactory operation can be obtained on four bands with a single tuning control for oscillator buffer and multipliers. Separate controls will have to be used with the final plate and the antenna circuits, however.

**15.29 Emergency Repairs.** There are many possible sources of trouble in a transmitter. Any part can become faulty and prevent proper operation of the equipment. When something does go wrong, it is up to the radio operator to determine the fault as soon as possible and make the necessary repairs. When a faulty part is found, it is best to use an identical replacement. Unfortunately, identical replacements are not always immediately available, and emergency repairs must often be made. This sometimes tests the ingenuity of the operator.

Some of the many possible troubles encountered in transmitter operation will be mentioned and discussed briefly. In most radio stations there will be at least a volt-ohm-milliammeter with which equipment can be tested. Between voltage readings on all stages and continuity readings with the ohmmeter, most troubles can be located.

*Tubes.* Vacuum tubes wear out. Excessive filament voltage and current shorten their lives. An indication of loss of filament emission is a permanent decrease of grid and plate current. The excitation to the next stage may show a decrease. If the tube has a glass envelope, a blue or purple haze may be seen between filament and plate, indicating gas. The grid, screen grid, or plate may become red-hot. If the envelope develops a crack in it, air will rush in and a white coating will form on the inside of the glass as the filament wire burns up. Loose elements may sag and short to adjacent elements, causing sparks and high-current indications on meters. Often the terminals of tubes become oxidized and develop a poor contact. If the tube is pulled out and replaced, the equipment may work normally again. The terminals of the tube and the socket contacts should be lightly sanded with fine sandpaper. If there is any question as to whether the filament is burned out, a continuity check with an ohmmeter will tell. An ohmmeter may also be used to test a tube for element-to-element shorts. Receiving-type tubes can be checked in a tube tester, if one is available, but transmitting tubes usually must be replaced with identical replacements to determine if they are faulty. In some cases, tubes of somewhat similar construction and similar socket-pin connections can be substituted temporarily. For example, a 6L6 can often be used in place of a 6V6, 6F6, or 6K6, or vice versa.

*Tube Sockets.* These may short out internally or open-circuit. They usually give the operator trouble because they so seldom become faulty that they may be overlooked when they do. Ohmmeter tests will usually indicate the difficulty.

*Transformers.* Power transformers often give trouble. If they become damp, the insulation around the internal wires may ionize and spark across, sometimes starting a fire. Radio-frequency a-c sometimes finds its way into a transformer, jumps from one conductor to another, burns the insulation, or short-circuits the transformer. If charred insulation is found before the transformer burns up, it is sometimes possible to scrape all the blackened part away and coat the wires with an insulating material, such as clear lacquer, insulating paints, or quick-drying household cement. The transmitter may operate under lowered power for long periods of time with such a temporary repair. If RF is suspected, the transformer should have bypass capacitors connected across both primary and secondary windings. It is not unusual to find transformer wires corroded to the extent that they finally part, open-circuiting the transformer. If the wires are within reach, it is sometimes possible to scrape them clean and solder them together again. Sometimes a transformer with several taps for different voltages will burn out. It is often possible to jumper the open part and use the remainder of the winding, operating at reduced power. An ohmmeter is handy for checking continuity of windings in suspected transformers. A transformer can be checked by putting a low-voltage a-c across the primary and measuring the secondary voltage. If there is no voltage output, the transformer is probably burned out or shorted. If burned out, it will remain cool; if shorted internally, it will soon become hot.

*Resistors.* Resistors often burn out. In some cases they may become excessively heated over a long period of time and increase resistance to a high value, or *open*. In many cases, they overheat because some other part is faulty. For example, a screen-grid dropping resistor suddenly becomes hot and burns out. It will usually be found that the screen bypass capacitor is shorted, connecting the resistor from ground to B+, increasing the current through it, and burning it out. In many cases, as in grid or screen-grid circuits, replacement of resistors with others of half or twice the resistance of the burned-out part will produce a temporary repair that will be satisfactory. Sometimes it will not. In some cases, wire-wound resistors can be temporarily repaired by holding aluminum or tin foil against the burned-out section with a wrapping of cord or wire. It is possible to make a heavy-current rheostat out of a metal bucket of salt water with a metal shaft hung into the water. The resistance between the shaft and the metal bucket will vary inversely as the length of the shaft immersed in the water.

*Capacitors.* These are one of the main sources of trouble in radio equipment. When capacitors are at work, the dielectric is under constant strain. If there is a weak spot in the dielectric, eventually it will spark, short the capacitor, and produce trouble. Sometimes the short circuit is intermittent, making it very hard to find. Electrolytic capacitors can dry out and lose their capacitance, but still not short out. When tested with an ohmmeter these capacitors will not show the charging current that a good capacitor will. They will not show a low resistance as a shorted capacitor will. If a 0.001-$\mu$f mica capacitor in an RF circuit shorts out, it may be possible to use two 0.002-$\mu$f paper capacitors in series in place of the mica, although paper capacitors are not usually considered satisfactory in transmitters, particularly at frequencies of over 2 or 3 Mc. The bearings, or sliding contacts, on variable capacitors often become clogged with dirt and oil, producing a poor connection. They can be cleaned with solvents such as gasoline, kerosene, naphthalene, or carbon tetrachloride. (WARNING: The fumes of carbon tetrachloride are very poisonous, and those of the others are quite flammable.) In many cases, two or three hundred per cent or more variation in the capacitance of bypass capacitors will not have any noticeable effect on the operation of a transmitter. If the bypass-capacitor values of a CW transmitter are 0.002 $\mu$f, a 0.001- or a 0.01-$\mu$f value will probably operate satisfactorily. In the case of filter capacitors in power supplies, more than the original capacitance is almost always satisfactory. In an emergency, a power supply can be operated with little or no filter, particularly in CW transmitters.

*Choke Coils.* RFC coils sometimes oxidize and burn out. If the faulty layer, or pie, can be found with an ohmmeter, it can be jumpered and the choke should work satisfactorily on most frequencies, if used in a multifrequency transmitter. In many cases, a handmade RF choke can be made by winding several hundred turns of wire onto a pencil-sized piece of dry wood. A choke coil in a power supply may burn out or short to the core. If burned out, it may be jumpered, or the primary or secondary of a spare power transformer may be used in its place. If shorted to the core, the core can be loosened from the metal chassis of the power supply, insulated from the chassis by many layers of waxed or dry paper, and operated temporarily. The core will be "hot" electrically when the power supply is on and must not be touched.

*Meters.* Direct-current ammeters or milliammeters usually have shunt resistors in them. The moving coil can burn out or oxidize apart, and the meter will still carry current through the shunt. When this happens, the transmitter continues to operate satisfactorily, but with no current indication. If a shunt burns out, the moving-coil element always burns out too. In a voltmeter, the series multiplier resistor can oxidize and open, but the moving part may not be damaged. Installation of a new series resistor of approximately the same resistance in the meter will result in fairly accurate readings by the voltmeter. Since the plate- and grid-current values are functions of the filament temperature, if the filament circuit has a voltmeter across it and the meter burns out, it is possible to arrive at a good approximation of the correct *filament* voltage by adjusting the filament rheostat until normal grid and plate current is indicated on the grid and plate meters or until the color of the hot filament seems normal. In an RF thermocouple meter, if the thermocouple circuit becomes faulty, RF a-c may still flow through the thermocouple, but no d-c will be fed to the meter and no indication of RF will be given. If the RF ammeter is used as the only means of indicating when the antenna and final amplifier are correctly tuned, it is possible to substitute a 150- to 300-watt electric light for the meter if it burns out. Care must be taken not to operate the equipment at a power level that will burn out the light. When the transmitter is properly tuned, the light can be shorted out and the transmitter can be run at full-power output. A 6-volt pilot light may be shunted across 6 to 10 in. of the antenna wire and be used as a tuning indicator.

*Antennas.* Any kind of wire will work as an antenna in an emergency. (Even wet rope soaked in salt water has been used for transmission and reception for short periods.) While copper wire is better, iron wire will radiate almost as well, and the difference in reception is not noticeable. No wire is too thick, and any wire that does not burn out is satisfactory for emergency communications. Dry string; rope; most plastic materials; dry, oiled, or waxed wood make satisfactory temporary antenna insulators.

*Relays.* If a relay coil burns out, it can often be taken apart and rewound (Sec. 3.20). If it has two coils in it, one can be used if the relay voltage can be reduced or if a resistor can be connected in series with it to limit current. The spring tension may have to be weakened to allow the relay to operate. If the relay contacts become so badly worn that they are inoperative, it is sometimes possible to solder pieces of silver coins or sheet silver to the worn contacts.

**15.30 Indications of Trouble.** Obvious indications of trouble in transmitters are the hiss or crackle of an electric spark jumping, the blue curl of smoke, the flicker of a flame, the smell of burning insulation, a loud humming sound from a transformer, lack of filament glow in tubes, failure of the keying relay to close when the key is pressed, and the clatter of an overload circuit breaker opening. Less obvious, but telling as significant a story, are the meters on the panel of a transmitter. They can tell the operator much about the operation of his equipment. Some of the possible troubles and meter indications are outlined below, stage by stage.

*Oscillator.* PLATE-CURRENT METER READING INCREASES. Stage probably not oscillating, because of inoperative crystal, detuned plate circuit, shorted grid circuit or tube. Unlikely that the power supply voltage will increase materially.

PLATE-CURRENT METER READING ZERO. The power supply may not be functioning, the meter may be burned out, the oscillator tube filament may be burned out, there may be a poor connection in the plate circuit, a fuse may be burned out, the screen or control grid may be open.

PLATE-CURRENT METER READING DECREASES. The coupling to the next stage may be loosened, the tube may be faulty, or the filament or plate voltage may be low.

*RF Amplifiers.* GRID-CURRENT METER READING INCREASES. Loss of bias supply voltage, excessive RF drive from preceding stage, or low plate current. When the plate is taking no electrons, the grid is free to collect more of them than normal. Therefore low plate voltage, low screen voltage, decreased coupling to next stage, or open plate circuit will all result in an increased grid current.

GRID-CURRENT METER READING ZERO. Burned-out filament in tube, no filament voltage, resistor or RF choke in grid circuit burned out, insufficient excitation if power-supply bias used, no excitation if grid-leak-bias used, or burned-out meter.

GRID-CURRENT METER READING DECREASES. Decreased excitation to grid, driving circuit detuned, low filament voltage, low filament emission from tube, or increased plate current. (As the plate current increases, the grid current decreases. Therefore anything that will produce high plate current such as a detuned plate circuit, high screen voltage, or tight coupling to next stage will produce a lowered grid current.)

PLATE-CURRENT METER READING INCREASES. Loss of power-supply bias voltage, loss of RF excitation from previous stage if grid-leak bias is used, a detuned plate circuit, an increased coupling to the next stage, a soft, or gassy, tube, or a high screen-grid voltage will produce high plate current.

PLATE-CURRENT METER READING ZERO. No plate supply voltage because of burned-out fuse in power supply, shorted filter capacitor, open RF choke or power-supply choke, open overload relay in plate circuit, no filament voltage, burned-out filament in tube, screen-grid voltage zero, or an open in the plate circuit will result in zero plate current.

PLATE-CURRENT METER READING DECREASES. May be caused by low plate supply voltage, decreased coupling to plate-circuit load, low filament emission, low filament voltage, low screen-grid voltage, excessive bias on the grid, or an open in the antenna or other load circuit.

*Antenna.* AMMETER READING INCREASES. Plate voltage inadvertently increased, or faulty ammeter. If an antenna wire falls to the ground, the antenna meter will drop to zero, but in some cases when the antenna is retuned, the meter will register more than normal current.

ANTENNA AMMETER READING ZERO. Either there is no RF output from final amplifier, the antenna wires or connections are faulty, the coupling circuit is faulty, or the meter is burned out. It is possible to have the antenna meter moving coil burn out and still have the transmitter emitting normally. The meters in the final amplifier will read normally in this case.

ANTENNA AMMETER READING DECREASES. This is the usual indication when something is wrong in the transmitter. It may be caused by a low degree of coupling to the antenna, an excessive degree of coupling, a detuned plate circuit of the final amplifier, low plate voltage on the amplifier tube, low grid excitation to the final amplifier, an excessive grid bias on the final, low filament emission from the tube, low filament voltage, insufficient or excessive screen-grid voltage, or loss of battery bias on the amplifier.

*A Pinned Meter.* When a meter is suddenly *pinned* (the pointer driven to the stop pin past the maximum scale indication), there is usually a shorted part in the stage involved. A bypass capacitor may be shorted, an RF choke may short to ground, a variable capacitor may short to ground, or the tube may develop a short circuit by internal elements loosening and touching. If there is no fuse, circuit breaker, or overload relay in the circuit, the meter may be burned out before the transmitter and power supply can be turned off. After completely disconnecting all electricity to the stage involved, an ohmmeter can be used to determine what part of the circuit is shorted.

Many transmitters incorporate overload relays that restore automatically a certain number of times before staying open. These relays were designed for transmitters where, sometimes, for no accountable reason, a spark will jump a gap and momentarily cause a surge of high current in the circuit. The overload relay in that circuit opens, the spark extinguishes, and the overload closes again. If the spark occurs again, or if the fault does not clear itself, the overload will fall out again. After the second or third restoration, the relay may automatically hold open until manually restored after the fault has been found. Lightning striking on or near a transmitting antenna will often cause an instantaneous interruption of this type.

If the RF excitation to an amplifier is removed but the antenna meter indicates the presence or RF, either the amplifier is improperly neutralized and has broken into self-oscillation on some frequency near the assigned frequency or the meter needle may be stuck.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** What are the lowest radio frequencies useful in radio communication? (15.1) **[3]**

**2.** What is meant by carrier frequency? Carrier wave? (15.7) **[3]**

**3.** Define the following types of emission: A0, A1, A2, A3, A4, and A5. (15.7) **[3]**

**4.** What is the effect of a swinging antenna upon the output of a simple oscillator? (15.9) **[3]**

**5.** What are the principal advantages of crystal control over tuned-circuit oscillators in transmitters? (15.12) **[3]**

**6.** What is the purpose of a dummy antenna? (15.13) **[3]**

**7.** Describe three methods for reducing the RF harmonic emission of a radiotelephone transmitter. (15.25) **[3]**

**8.** How may the production of harmonic energy by a vacuum-tube RF amplifier be minimized? (15.25) **[3]**

**9.** What is the purpose of a Faraday screen between the final tank inductance of a transmitter and the antenna inductance? (15.25) **[3]**

**10.** What would be the possible indications that a vacuum tube in a transmitter has subnormal filament emission? (15.29) **[3]**

**11.** If the transmitter-filament voltmeter should cease to operate, how may the approximately correct filament-rheostat adjustment be found? (15.29) **[3]**

**12.** In a class C RF amplifier stage of a transmitter, if plate current continues to flow and RF energy is still present in the antenna circuit after grid excitation is removed, what defect would be indicated? (15.30) **[3]**

**13.** What material is frequently used for relay contacts? Why? (15.3) **[3 & 6]**

**14.** What are the advantages of an MOPA type of transmitter as compared with a simple oscillator transmitter? (15.10) **[3 & 6]**

**15.** Why is a separate source of plate power desirable for a crystal oscillator stage in a radio transmitter? (15.12) **[3 & 6]**

**16.** What is meant by a blocked grid? (15.18) **[3 & 6]**

**17.** What is the purpose of a buffer amplifier stage in a transmitter? (15.22) **[3 & 6]**

**18.** Why should all exposed metal transmitter parts be grounded? (15.26) **[3 & 6]**

**19.** What are some possible indications of a defective transmitting vacuum tube? (15.29) **[3 & 6]**

**20.** Draw a circuit diagram showing the principle of operation of a telegraph keying relay. (15.2, 15.3, 15.9) **[6]**

**21.** What is meant by break-in operation at a radiotelegraph station, and how is it accomplished? (15.3) **[5 & 6]**

**22.** What is meant by self-wiping contacts as used in connection with relays? (15.3) **[6]**

**23.** What are the general characteristics of the emission of a radiotelegraph transmitter which uses a chopper to obtain A2 emission? (15.5, 15.9) **[6]**

**24.** What is the purpose of the iron-compound cylinders which are found in the inductances of certain marine radiotelegraph transmitters? The position of these cylinders, with respect to the inductances, is adjustable for what purpose? (15.6) **[6]**

**25.** Why do many marine transmitters employ variometers rather than variable capacitors as the tuning elements? (15.6) **[6]**

**26.** List the various points in a radiotelegraph transmitter where keying can be accomplished. (15.9, 15.14, 15.16, 15.17, 15.18, 15.19) **[6]**

**27.** What are the disadvantages of using a self-excited oscillator type of transmitter for shipboard service? (15.9) **[6]**

**28.** What is the effect of excessive coupling between the output circuit of a simple oscillator and an antenna? (15.9) **[6]**

**29.** Draw a simple schematic diagram showing a method of coupling the RF output of the final-power-amplifier stage of a transmitter to an antenna. (15.9, 15.10) **[6]**

**30.** What is the result of excessive coupling between the antenna and output circuits of a self-excited type of vacuum-tube transmitter? (15.9) **[6]**

**31.** What is meant by split tuning? (15.9) **[6]**

**32.** Draw a complete schematic diagram of a system of inductive coupling between the output of an RF amplifier and an antenna system. (15.10, 15.25) **[6]**

**33.** How is the keying of a simple oscillator type of emergency marine transmitter usually accomplished? (15.9, 15.10) **[6]**

**34.** What class of amplifier should be employed in the final amplifier stage of a radiotelegraph transmitter for maximum plate efficiency? (15.10) **[6]**

**35.** How may instruments used to indicate various direct currents and voltages in a transmitter be protected against damage due to stray RF? (15.10) **[6]**

**36.** Should the antenna circuit of an MOPA type of transmitter be adjusted to the resonant frequency before the plate tank circuit of the final stage? Give the reasons for your answer. (15.11) **[6]**

**37.** What effect upon the plate current of the final amplifier stage will be observed as the antenna circuit is brought into resonance? (15.11) **[6]**

**38.** What is the principal advantage to be gained by the use of a crystal-controlled oscillator in a marine radiotelegraph transmitter? (15.12) **[6]**

**39.** Name four advantages of crystal-control oscillators over tuned-circuit oscillators. (15.12) **[6]**

**40.** What is the function of a quartz crystal in a radio transmitter? (15.12) **[6]**

**41.** Why is the crystal in some oscillators operated at constant temperature? (15.12) **[6]**

**42.** Why is an artificial antenna sometimes used in testing a transmitter? By what other names is this instrument known? (15.13) **[6]**

**43.** What precautions should be observed in tuning a transmitter to avoid damage to components? (15.13, 15.28) **[6]**

**44.** Why should a transmitter be tuned initially at reduced power? (15.13) **[6]**

**45.** Does the code speed, or number of words per minute transmitted, have any effect on the bandwidth of emission from a radiotelegraph transmitter? (15.15) **[6]**

**46.** Draw a simple schematic diagram of a key-click filter suitable for use when a vacuum-tube transmitter is keyed in the negative high-voltage circuit. (15.15) **[6]**

**47.** Describe a means of reducing sparking at the contacts of a key used with a radiotelegraph transmitter. (15.15) **[6]**

**48.** Draw a simple schematic diagram of a system of keying in the primary of the transformer supplying high voltage to a vacuum-tube transmitter. Indicate any values of inductance, resistance, and capacitance which may be deemed necessary to fully understand the correct operation of this type of keying. (15.16) **[6]**

**49.** Draw a simple schematic diagram showing how a radiotelegraph transmitter may be keyed by the grid-blocking method. (15.18) **[6]**

**50.** In a radiotelegraph transmitter employing a d-c generator as a filament supply and grid-bias keying, if it is noted that when the key contacts are open the emission continues, what could be the trouble? (15.18) [6]

**51.** What is frequency-shift keying and how is it accomplished? (15.19) [6]

**52.** A marine transmitter uses 500-cycle a-c for plate supply. It is rectified by a full-wave rectifier circuit but is not filtered. How would the emission be classified? (15.20) [6]

**53.** What is meant by a self-rectified circuit, as employed in marine vacuum-tube radiotelegraph transmitters? (15.21) [6]

**54.** Draw a simple circuit diagram of a transmitter using an oscillator coupled to the antenna, with the oscillator using a self-rectifying circuit for operation directly from an a-c generator. (15.21) [6]

**55.** In a transmitter involving a master oscillator, intermediate amplifier, and final amplifier, describe the order in which circuits should be adjusted in placing this transmitter in operation. (15.22) [6]

**56.** Draw a block diagram of an MOPA radiotelegraph transmitter with the master oscillator operating on 2,017.5 kc and the transmitter output on 8,070 kc. (15.24) [6]

**57.** How may harmonic radiation of a transmitter be prevented? (15.25) [6]

**58.** What is the purpose of an electrostatic shield? (15.25) [6]

**59.** What is the primary function of the power amplifier stage of a marine radiotelegraph transmitter? (15.28) [6]

**60.** How is the power output of a marine vacuum-tube radiotelegraph transmitter ordinarily adjusted? (15.28) [6]

**61.** Name four indications of a defective vacuum tube in a transmitter. (15.29) [6]

**62.** What emergency repairs may be made to an inductance coil having burned or charred insulation? (15.29) [6]

**63.** If the plate current of the final RF amplifier in a transmitter suddenly increased and radiation decreased although the antenna circuit was in good order, what would be the possible causes? (15.30) [6]

**64.** An MOPA type of transmitter has been operating normally. Suddenly the antenna ammeter reads zero, although all filaments are burning and plate and grid meters are indicating normal voltages and currents. What would be the possible causes? (15.30) [6]

**65.** Define type A1, A2, A3, A4, and B emissions. (15.7) [6]

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**★1.** What is the recognized abbreviation for continuous wave? (15.7)

**★2.** What is the purpose of an RF amplifier in a transmitter? (15.10)

**★3.** What is the purpose of a key-click filter, and when should it be used? (15.15)

**★4.** What precautions should be taken to avoid the danger of shock from high-voltage electric circuits? (15.26)

**★5.** What symbol is used to designate amplitude-modulated telegraphy without the use of modulating AF (on-off keying)? (15.7)

**6.** How may the final amplifier be treated to prevent harmonic radiations from falling in TV (VHF) bands? (15.25)

**7.** Explain the tuning procedure and plate-current indications for an RF power amplifier in a transmitter. (15.11)

**8.** Why is it advantageous to use a crystal resonator as a frequency-controlling device in a transmitter? (15.11)

**9.** Explain the use of interlock switches on access doors of a transmitter to prevent accidental contact with high-voltage circuits. (15.26)

**10.** Why is it advisable to use a separate power supply for the oscillator stage of a transmitter? (15.22)

**11.** What may cause off-frequency emissions in a radiotelegraph transmitter? (15.10)

**12.** What is the purpose of a Faraday shield between the power amplifier and the antenna circuit? (15.25)

**13.** Why is it undesirable to couple oscillators or amplifiers with high harmonic output directly to an antenna? (15.25)

**14.** What can be used to protect receivers and transmitters from damage due to atmospheric electricity? (15.3)

**15.** Where can link coupling be utilized in a radio transmitter? (15.22)

**16.** What are the most commonly used types of emission in radio? (15.7)

## CHAPTER 16

# AMPLITUDE MODULATION

**16.1 Principle of Amplitude Modulation.** The term *modulation* may be considered to imply or mean "variation." If a direct current is being made to vary in amplitude 500 times a second, it is being amplitude-modulated at a 500-cycle rate.

If an RF a-c carrier wave is being made to vary in amplitude 500 times a second, it is being amplitude-modulated at a 500-cycle rate (AM, or A3, type or emission).

If an RF carrier wave is made to vary in *frequency* 500 times a second, it is being frequency-modulated at a 500-cycle rate. This is *frequency modulation* (FM, or F3) which is discussed in the chapter on that subject. Simultaneous frequency and amplitude modulation is undesirable, although either, separately, is a method of transmitting speech and music.

**16.2 Why the Carrier Is Modulated.** Under normal circumstances, the carrier wave emitted by a radio transmitter cannot be heard on a receiver made for speech or music reception. If such an inaudible carrier wave is made to vary in amplitude at speech or musical tone rates, it is said to be modulated by the speech or music. With the proper type of receiver, the voice or musical-tone modulated radio-frequency carrier can be *demodulated* to reproduce the speech or music variations alone, thereby reproducing the original sounds for the listener.

There are many methods by which the speech or music can be made to amplitude-modulate a carrier, but, first, there are some basic concepts regarding sound and microphones that must be understood.

**16.3 Sound.** When a firecracker is lighted, thrown up into the air, and explodes, a *sound* is heard. If the firecracker is near, it sounds *loud.* If someone else far away explodes the firecracker, it sounds *weak.* When the firecracker explodes, it suddenly and violently pushes the air away. This creates a hollow ball of compressed air all around the firecracker. Compressing molecules of air as it goes, the ball of compressed air begins moving outward in all directions, at a speed of approximately 1,100 ft/sec. If examined closely, it would be found that just inside, and next to, the compressed air molecules of the ball is a rarefied area of air molecules. This compression with its attendant rarefaction forms a *sound wave.*

As the sound wave travels outward it is constantly expanding. The mechanical energy it contained when it was confined in a small area near the firecracker rapidly becomes less for any given square inch or square foot of the wavefront. If the wave travels only a short distance, it strikes the eardrum with considerable energy. If it travels a long distance it strikes the eardrum with very little energy.

A sound wave of mechanical energy striking the eardrum causes the outer-ear diaphragm to vibrate. This transmits a mechanical vibration into the *inner ear*, in turn actuating delicate nerve endings that relay an electrochemical impulse to the brain. If the person is "conscious," he is made aware of the "sound." By past experience, this particular nerve-to-brain impulse from an explosion is recognized as a bang.

Any musical instrument producing a constant, single tone sets up a continuous series of waves at a definite frequency. These waves, striking the diaphragm of the ear, are transferred to the inner ear and energize the nerve endings *resonant* to this particular frequency, making the listener aware of this tone.

The higher the frequency of sound waves, the higher the *pitch*, or tone, the listener hears.

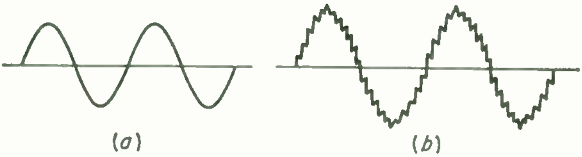


FIG. 16.1. Two signals of the same fundamental frequency. (*a*) A pure tone. (*b*) A fundamental with harmonics, or overtones.

The greater the energy content of a wave striking the eardrum, the stronger the nerve impulse generated and the *louder* the sound to the listener.

A sound wave, then, has both amplitude (loudness) and frequency (pitch). It also has what may be termed quality, or purity (great or little harmonic content). A sine-wave a-c signal generator adjusted to 256 cycles (*middle C*) coupled to a good loudspeaker produces a nearly pure 256-cycle tone. A musical instrument playing a fundamental 256-cycle tone will sound different because it cannot produce a pure vibration. It may produce a fundamental 256-cycle vibration, but many harmonics, or *overtones*, are generated at the same time. The number and amplitudes of the different harmonics produced indentify the type of instrument being played. Thus, a piano, an oboe, and a saxophone, all sound different even though they may all be playing the same fundamental tone. Two singers singing the same tone will also sound different because their vocal cords have different dimensions and produce different harmonics.

Most sounds are highly complex, being made up of fundamentals and many harmonics. Figure 16.1 shows, first, a representation of a pure tone, and, secondly, a possible musical or speech tone having the same fundamental frequency.

Sound waves are often represented by sine waves for pure tones and jagged waveforms for speech or musical tones. The half of the drawing above the zero, or time line, may indicate the compression of air molecules, in which case that shown below the line will represent the rarefaction part of the sound wave. The jagged form indicates high-frequency harmonics (or other tones) added to a fundamental frequency.

To transmit audio-frequency modulation on a carrier wave, it takes the greatest amount of power to produce a given peak value of sine-wave modulation. All less pure, natural sound waveshapes produce the same peak value with less average power. Therefore, a transmitter engineered to handle sine-wave audio-power values will be capable of handling any waveforms of normal sounds. For this reason, explanations are made in terms of sine-wave-modulating a-c. In actual practice, it takes about half as much average audio *power* to fully modulate a transmitter with speech sounds as it does to fully modulate it with pure sine-wave tones.

The amount of sound power transmitted to a diaphragm can be measured in microwatts per square centimeter. For example, the lowest audible intensity, or threshold value, of sound for the human ear is approximately $1 \times 10^{-10}$ $\mu$w/cm$^2$. On the loudness scale, this is given a zero value. Ten times this sound power is said to be 1 *bel* louder. Ten times more sound (100 times the threshold value) is again 1 *bel* louder, or has an absolute value of 2 bels. If you are familiar with mathematics, you will see that this is a *logarithmic* increase. The logarithmic ratio is used because the human ear responds closely to this ratio; that is, an increase in a weak sound of 1 *decibel* (one-tenth of a bel, abbreviated *db*) is barely noticeable to a listener. Actually, this is an increase in power of 26 per cent (Sec. 8.6). A loud sound, containing considerably more power, when increased 26 per cent, will also result in a barely discernible change in sound intensity to the listener.

The ear of a person of any age responds best to sounds between 1,000 and 4,000 cycles. The response of the ear is *down* about 20 db at a frequency of 200 cycles, and down about 40 db at a frequency of 100 cycles. Usually, the older a person is, the less response the ear produces at the higher frequencies. For teenagers, sounds of 15,000 cycles may be down 20 db, and 18,000 cycles may be down 40 db. For elderly persons, there may be little or no response above 10,000 cycles.

**16.4 The Single-button Microphone.** A microphone is a device used to convert mechanical sound energy into electric energy of equivalent frequency and amplitude.

The *single-button*, or *carbon-button*, microphone is the original microphone. It is still used in telephones, and in many radio applications, such as mobile or portable equipment, where fine quality of reproduction is not essential. It will convert voice sounds into electric voltages fairly well, but will not faithfully reproduce over a wide enough frequency range to be used for high-fidelity music. It is in reality a variable resistor. When its resistance is changed, the current flowing through it varies accordingly.

The illustration in Fig. 16.2 gives a general idea of the construction of a single-button microphone. The carbon or metal button is electrically insulated from both the diaphragm and the frame of the microphone. One electrical connection is made to the frame and diaphragm, and the other to the metal button. Sand-sized particles of carbon are held between diaphragm and button by fluffy cotton washers. This light cotton packing allows the diaphragm to vibrate toward and away from the stationary button without allowing the carbon particles to drop away from between them. If the diaphragm is moved toward the button, the granules are compressed and the diaphragm-to-button resistance is decreased.

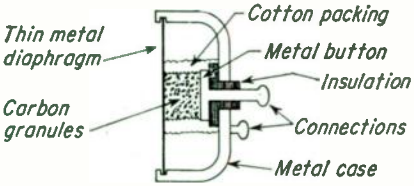


Fig. 16.2. Cross-section picturization of a single-button carbon microphone.

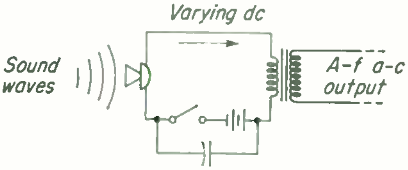


Fig. 16.3. Single-button microphone circuit.

Sound waves in air, being alternate compressions and rarefactions of the air molecules, beat against the diaphragm. The compressions push the diaphragm inward. The rarefactions pull the diaphragm outward. Sound waves, then, cause the resistance of the microphone to vary at the rate of the compressions and rarefactions. High-frequency tones vibrate the diaphragm rapidly; low frequencies vibrate it slowly. Weak sounds cause little vibration. Loud sounds produce relatively wide movements of the diaphragm, and therefore relatively large resistance changes. Pure tones produce an even, smooth, inward and outward swing. Harmonic-containing sounds produce a jerky inward and outward swing of the diaphragm.

The single-button microphone circuit in Fig. 16.3 shows a microphone, a battery, a switch, and a microphone transformer.

The battery keeps current flowing through the microphone and transformer primary at all times. Resistance variations, due to sound waves, produce corresponding current variations (varying d-c) in the microphone circuit. The varying d-c in the primary produces an a-c in the secondary with a frequency and amplitude equal to the variations of the current in the primary. Therefore the sound waves are represented in the secondary of the transformer by an a-c whose frequency and amplitude will vary with the frequency and amplitude of the sound itself.

If earphones are connected either in place of the primary of the transformer or across the secondary, the electrical variations will reproduce the original sound with recognizable clarity, although the sound will not be very loud.

The single-button microphone has several advantages. It is relatively inexpensive to manufacture. It is fairly indestructible, withstanding rather rough handling, and is not subject to deterioration due to heat or cold. It has a relatively high output power in comparison with many other types. It can be spoken into at close range, allowing the voice to override background noises. It is usually made to be most sensitive to voice frequencies, which range from about 200 to 3,000 cycles.

Once in a while the carbon granules will either pick up moisture or weld together and *pack*. The microphone may have to be shaken or jarred lightly to free the granules. Another disadvantage is the requirement of a battery in the microphone circuit. It also distorts sounds more than most other types of microphones. When direct current flows through the granules, they move very slightly, producing a random, high-frequency variation in the microphone current. This results in a constant, weak *hissing* sound in the output. The lower the d-c voltage used in the microphone circuit, the lower the hiss level, although the signal output drops somewhat also. If one or two volts is used in the microphone circuit (5 to 15 ma), satisfactory results are usually obtainable.

**16.5 Loop, or Absorption, Modulation.** The oldest, and one of the simplest, methods of modulating a radio carrier wave with voice frequencies is called *loop*, or *absorption*, modulation (Fig. 16.4).

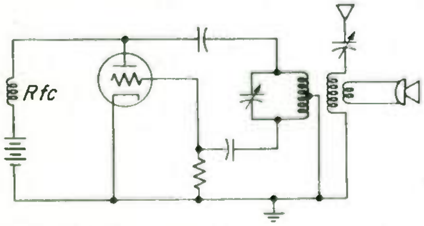


Fig. 16.4. Loop, or absorption, modulation circuit.

In loop modulation, an RF oscillator is necessary to provide a constant RF a-c signal to the antenna. In the case shown, a Hartley oscillator is used.

A single-button microphone is inductively coupled to the antenna circuit. Most of the RF carrier energy being fed into the antenna circuit by the oscillator is radiated. However, some of the energy of the oscillator is fed into the loop and is dissipated by the resistance of the microphone as heat.

The resistance of the microphone varies at the audio rate of any sound causing its diaphragm to vibrate, and as a result, the amount of RF energy being absorbed and dissipated into heat by it is varying.

If the power output of the oscillator is essentially constant but the microphone is absorbing alternately more and less power from the oscillator, the antenna finds itself with alternately less and more power to be radiated. This variation of RF power output at an audio rate from the antenna produces the modulated carrier of the system. Since the *power* is being varied in accordance with the sound waves, the modulation is known as *amplitude modulation.*

Diagrammatically, the effect of the microphone on the output RF carrier power can be shown as in Fig. 16.5. This form of modulation is of interest mainly because it is a fairly simple demonstration of amplitude modulation. It is impractical by present standards and is no longer used.

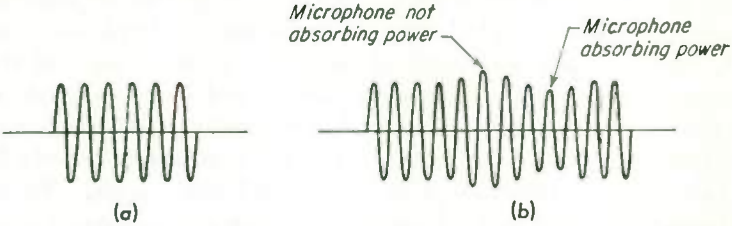


FIG. 16.5. Antenna current. (*a*) With constant amplitude, no modulation. (*b*) When the microphone is alternately absorbing more and less power from the circuit.

The variation of the resistance across the loop changes the inductance reflected back on the tuned circuit of the oscillator, changing the oscillation frequency of the LC circuit. This results in simultaneous FM and AM and the generation of an excessive number of sidebands, or products of modulation. This produces a distorted-sounding received signal, as well as taking up many times the spectrum space that would be required by transmitting AM alone. With loop modulation of a self-excited oscillator, the signal is actually more frequency-modulated than amplitude-modulated.

### 16.6 A Simple Series Modulation.

A system of modulation which will be called *simple series modulation* utilizes the single-button microphone in another manner. This is a type of *plate-circuit modulation,* since the plate current is varied by the microphone. A diagram of such a system is shown in Fig. 16.6.

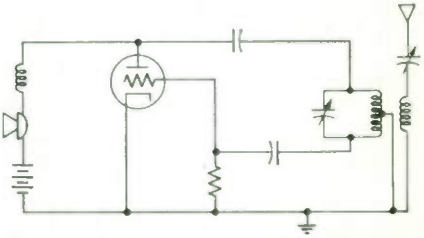


FIG. 16.6. Carbon microphone in series with plate circuit produces a form of plate modulation.

The plate current of the oscillator flows through the tube, B battery, and microphone. This current flow results in the operation of the oscillator in a normal manner. An RF oscillation is produced, fed into the antenna circuit, and radiated.

When spoken into, the microphone varies its resistance, in turn varying the plate current in the plate circuit of the tube, and thereby varying the output power of the oscillator. If a 500-cycle sound wave strikes the diaphragm of the microphone, the output RF carrier will be amplitude-modulated at a 500-cycle rate because of the variation of the resistance of the microphone at this frequency.

Although this is a possible method of modulation, it is not used. It has many disadvantages, mainly the small amount of modulation that can be produced.

It will be remembered that any variation of plate voltage or current in self-excited (variable-frequency) oscillators, and even crystal oscillators to some extent, will produce a frequency change in the output. Therefore the amplitude modulation of an oscillator by simple series modulation will also produce considerable *frequency* modulation, and thereby objectionable distortion. This simultaneous FM and AM produced by varying the plate voltage or current of an oscillator must be remembered. It is for this reason that oscillators are never modulated directly in any form of amplitude modulation in commercial radio work. To reduce such frequency modulation it is necessary to use a separate oscillator and modulate an RF amplifier stage (MOPA), as in Fig. 16.7.

If the plate circuit of the RF power amplifier (rather than the grid circuit) is modulated, there will be much less frequency shift, or FM. Any such frequency shift is usually termed *dynamic instability*. The term dynamic instability refers to the carrier frequency and indicates that the frequency, for some reason, is not stable under operating conditions. Some of the possible causes of dynamic instability, or FM, in an MOPA transmitter are Miller effect, imperfect power-supply regulation during modulation, imperfect neutralization of the amplifier, unwanted feedback effects, vibration of parts of the oscillator if the transmitter is jarred, faulty parts causing sudden frequency changes, and loose connections.

It is impossible to prevent FM entirely, even in the MOPA, unless a separate power supply is used for the oscillator and one or more buffer stages are between the oscillator and the modulated stage, with all stages adequately shielded and neutralized.

**16.7 Series Modulation.** One of the simplest of the satisfactory methods of producing AM is *series modulation* (Fig. 16.7). In action, it is basically similar to the simple series modulation previously described. A continuous RF carrier is provided by an oscillator and an RF amplifier. The output of the class C RF amplifier is fed into an antenna and is radiated.

The RF amplifier stage directly involved in the modulation process is the *modulated stage*, or the *modulated amplifier*.

The final audio-amplifier stage coupled to the modulated amplifier is the *modulator stage*, or the *modulator*.

The stage or stages preceding the modulator are known as the *speech amplifiers*. They amplify the weak AF emf from the microphone to a value that will adequately drive the grid of the modulator tube.

In series modulation, the plate circuit of the modulator tube, the plate circuit of the modulated stage, and the power supply are all connected in series. A variation of the resistance in any part of this series circuit will affect the d-c current flowing through the whole circuit. Varying the plate current in the RF amplifier will vary the RF output power of that stage.

The modulator tube in series modulation might be termed an *electronic variable resistor*, since AF voltage variations applied to its grid vary the d-c plate resistance of the tube.

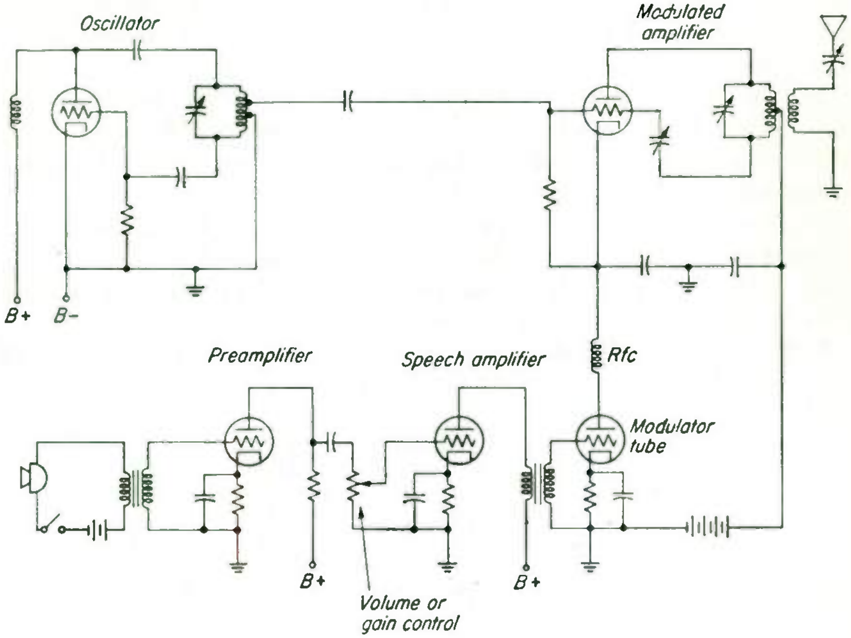


FIG. 16.7. Transmitter circuit using series modulation.

When a sound strikes the microphone, a weak AF a-c is developed across the microphone transformer secondary. This is amplified by the speech amplifiers and applied to the grid of the modulator tube. When the grid of the modulator is driven *less* negative than normal, the current flowing through the modulator increases, the voltage drop across it decreases, and the RF amplifier is across a greater proportion of the plate supply voltage. More current flows through the RF amplifier now and the RF output from the stage increases.

When the grid of the modulator is driven *more* negative, plate current through the modulator decreases and a greater voltage drop is developed across the modulator. Less of the total power-supply voltage is across the RF amplifier, and the RF output from the stage decreases. In this way, AF variations of the grid voltage of the modulator vary the power output of the RF amplifier.

Series modulation is not widely used in the United States, although it i capable of good, undistorted modulation. It has the advantage of no requiring an expensive, heavy modulation transformer required by othe plate-modulation systems, to be discussed later. It has the disadvantag of requiring approximately twice the plate voltage from the power suppl since both tubes, modulator and modulated amplifier, are in series acros the supply. Also, if the cathode of the modulator is at ground potential the cathode of the RF amplifier will be at a high d-c potential abov ground, producing an insulation problem in high-powered equipment If the cathode of the RF amplifier is connected to ground, then the modulator cathode will have to be at a high-voltage negative potential, which is usually even less desirable.

The audio voltage applied to the grid of the modulator must never b high enough in amplitude to produce plate-current cutoff of the stage This places the operation of this stage in the class A category. It can us cathode-resistor bias, as shown, or some type of a bias supply.

The RF amplifier shown is a class C stage, receiving its bias because o the grid current which is made to flow by the output of the oscillato stage. This grid-leak bias value remains essentially constant with o without modulation of the plate circuit.

**16.8 The Modulated Envelope.** Practically all modulated RF stages are biased to class C. As a result, the plate current will always b narrow pulses of d-c that occur during the positive half cycle of the RF a-c grid excitation. These pulses of plate current produce a flywhee effect in the plate tank circuit, resulting in a very nearly sinusoida RF a-c output waveform.

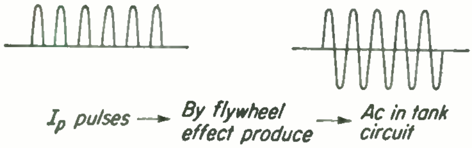


FIG. 16.8. Constant-amplitude pulses of plate current by flywheel effect of the tank circuit produce constant-amplitude RF a-c.

If the modulator suddenly allows more plate current to flow through the RF amplifier, the plate pulses increase in amplitude, and the RF output amplitude also increases. Note that both the positive and the negative halves of each RF a-c cycle are increased. Figure 16.8 illustrates the result of flywheel effect when constant-amplitude plate-current pulses are flowing in the plate circuit.

Figure 16.9 illustrates the result of flywheel effect on the output a-c when *varying*-amplitude plate-current pulses are flowing in the plate circuit. The illustration of the RF varying in amplitude during modulation shows the *modulation envelope.*

Producing an RF a-c cycle with *both* positive and negative half cycles of essentially equal amplitude when the tuned circuit is excited by pulses of d-c is an important concept for the reader to comprehend. With push-pull RF circuits, there are plate-current pulses flowing in opposite directions alternately in the plate tank circuit to aid in producing RF a-c. In single-ended circuits, flywheel action alone is responsible for the reproduction of the second half of the RF a-c cycle. Furthermore, each cycle of the RF of the modulated envelope produced by flywheel action has an almost perfect sine waveshape.

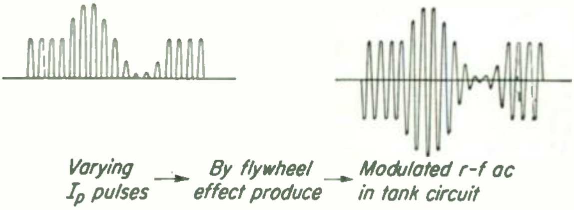


Fig. 16.9. Varying-amplitude plate-current pulses produce modulated RF a-c in the tank circuit.

**16.9 Simple Plate Modulation.** It is possible to produce modulation of the carrier wave of a low-power oscillator by adding an AF a-c in series with the plate circuit, as shown in Fig. 16.10. This is a basic plate-modulation circuit. Sound waves striking the diaphragm of the microphone produce an AF a-c voltage in the secondary of the microphone transformer.

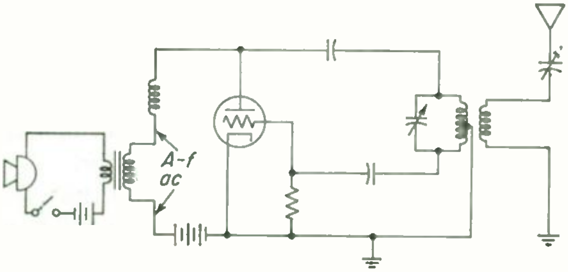


Fig. 16.10. Basic plate-modulation circuit.

On one half cycle (the *positive*) of the AF a-c, the audio emf will be in the same direction as the plate supply emf, and the two will be additive. The resultant plate-circuit voltage is increased. When the plate voltage increases, the plate current and the RF output increase.

On the other half cycle (the *negative*), the audio emf will be opposing the plate supply emf, and the plate-circuit voltage will be the difference between the two. The resultant plate-circuit voltage is decreased, the plate current decreases, and the RF output decreases.

During the positive half cycle of the modulating AF a-c, the *positive peak of modulation* of the carrier is produced, as shown in Fig. 16.11. During this half cycle, both positive and negative half cycles of the RF a-c output are greater than the unmodulated values.

During the negative half cycle of the modulating a-c, the *negative peak of modulation* is produced, also shown in Fig. 16.11. During this half cycle both positive and negative half cycles of RF a-c output are less than the unmodulated values. It may seem peculiar that the negative *peak* should actually be the lowest point as far as the RF a-c voltage in the emitted wave is concerned.

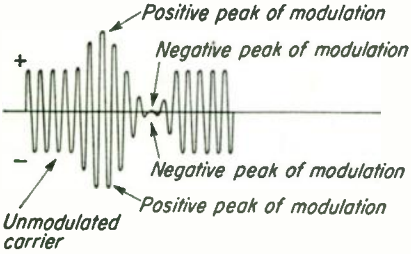


FIG. 16.11. Illustrating positive and negative peaks of modulation.

The explanations have been given in terms of voltage. The illustrations representing carrier voltages are valid illustrations of the carrier currents also, since current is directly proportional to voltage. They are not correct representations of power, however. If the carrier voltage is doubled, the carrier current is also doubled. At the instant the voltage and current are doubled, the output power is four times the carrier value. The illustration of *power* at the positive peak of modulation would have to be drawn four times as high as the carrier value.

If sufficient a-c voltage is used to modulate a self-excited oscillator circuit to a high degree, the variation of plate voltage will produce considerable FM, or dynamic instability. Furthermore, during the peaks of high-amplitude *negative* half cycles of the modulating a-c, the plate voltage may drop so low that the oscillator will stop oscillating completely for a short period of time. This produces an extremely objectionable distortion. For these reasons, a high percentage of modulating voltage is undesirable when applied to a *self-excited* oscillator.

The simple plate-modulation system shown is not practical. The voltage output of a microphone alone will not be sufficient to produce much modulation. However, by adding an audio-amplifier stage or two, it is possible to increase the audio power and voltage to the point where high values of modulation are possible.

**16.10 Percentage of Modulation.** The *loudness* of the modulation on a carrier wave is determined by how much the carrier voltage or current varies in amplitude. A strong carrier with a low percentage of variation may give a weaker response in a receiver than a weaker carrier with a greater percentage of variation.

The variation value is expressed as a *percentage of modulation,* with 100 per cent being the highest possible undistorted modulation.

Figure 16.12 illustrates several percentages of sine-wave modulation of an RF carrier. The unmodulated carrier (Fig. 16.12*a*) represents 0 per cent modulation.

A carrier is modulated 50 per cent if its positive *peak* voltage value rises to a value 50 per cent greater than the unmodulated-carrier-voltage maximum value and drops 50 per cent at the negative *peak* of modulation (Fig. 16.12*b*).

An RF carrier is modulated 100 per cent if its positive *peak* voltage value rises to a value twice the unmodulated-carrier-voltage maximum value and also drops 100 per cent (to zero) at the negative peak of modulation (Fig. 16.12*c*).

If too much modulating voltage is applied to the modulated stage, *overmodulation* occurs. The positive peak rises to more than twice the carrier level, and the negative peak drops to zero and remains at zero for a time (Fig. 16.12*d*). The 50 and 100 per cent modulation illustrations show a sine-wave modulation. The overmodulated signal is not a sine wave at the negative peak and therefore will produce many undesirable harmonics of the modulating frequency, known as *splatter*, or *buckshot*, as well as *distortion*.

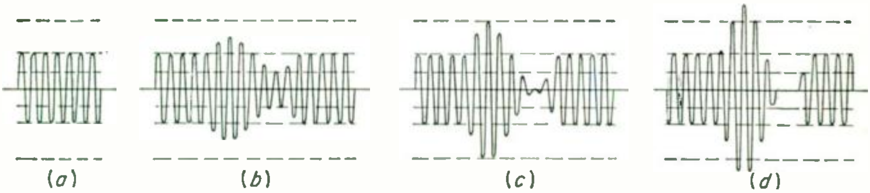


FIG. 16.12. (*a*) An unmodulated carrier. (*b*) A 50 per cent–modulated carrier. (*c*) A 100 per cent–modulated carrier. (*d*) An overmodulated carrier.

The undesirable effects produced by overmodulation may cause interference to other radio services on frequencies above and below the carrier frequency, as well as a distorted, harsh-sounding transmitted signal. As a result, overmodulation is illegal. Care must be exercised that no more than 100 per cent modulation of the negative peaks occurs in radiotelephone transmitters. As long as the positive peaks of modulation maintain an undistorted waveform, they are not considered responsible for distortion if the overmodulation is not excessive. It is the abrupt arrival of the negative peak at zero output and its abrupt rise from zero that produce the undesirable by-products of overmodulation.

Because the percentage of modulation is directly related to the loudness of the signal produced in a receiver, the higher the average percentage of modulation that can be maintained without producing distortion, the more effective the communication can be. To maintain as high a percentage as possible, an *audio peak limiter* is usually incorporated in the modulation system of commercial radiotelephone equipment. Such a device may decrease the amplification of one of the audio stages when the signal voltage peaks passing through it rise over a predetermined value. While this clips off, or distorts, the peaks and generates AF harmonics, the latter can be filtered with low-pass filters. The distortion becomes hardly noticeable, and the emission is not broadened. Excessive limiting, or clipping, of the waveform will produce noticeable distortion.

**16.11 Plate Modulation.** One of the popular AM methods is transformer-type plate modulation. A diagram of a simplified, but workable, circuit is shown in Fig. 16.13. With this circuit most of the basic requirements of a plate-modulation system can be explained.

In the diagram, a triode RF amplifier stage is being modulated by adding an AF a-c voltage in series with the plate power-supply voltage of the RF amplifier. The RF output power will vary with any AF voltages developed in the secondary of the modulation transformer. The power-supply voltage of the RF amplifier is 2,000 volts. The peak value of the AF voltage output of the modulation transformer must be 2,000 volts, alternately positive and negative, to produce 100 per cent modulation. Under these conditions, the plate voltage will vary from 4,000 to zero volts, producing a positive voltage peak of modulation twice the value of the carrier voltage peaks and a negative peak of modulation of zero output.

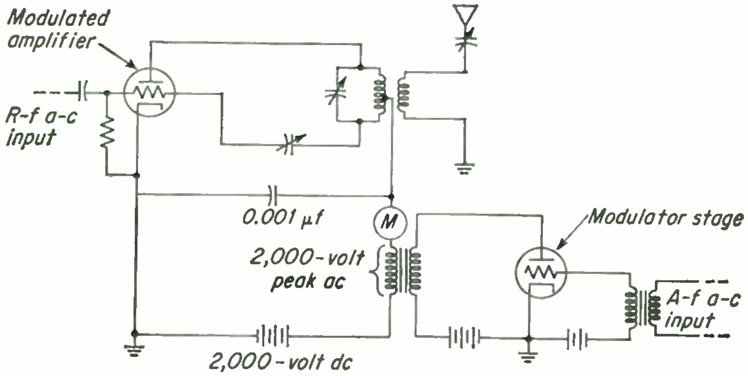


FIG. 16.13. Practical plate-modulated RF amplifier.

The RF amplifier stage is grid-leak-biased to class C by a constant-amplitude RF being applied to the grid of the RF amplifier from an oscillator, buffer, doubler, or driver stage. The output of the RF amplifier is coupled to a Marconi-type antenna.

The modulator tube is shown as a class A triode, for simplicity. In actual transmitters it is more likely that push-pull triodes in class A, AB, or B or beam-power tetrodes in class $AB_2$ would be used to develop the relatively high audio power required to produce the desired modulation and reduce even-order harmonic generation.

One of the important factors in producing plate modulation is the determination of the required audio power to produce a desired percentage of modulation (usually 100 per cent). It will be assumed that the modulated RF amplifier is operating under the following conditions:

$$E_p = 2{,}000 \text{ volts}$$
$$I_p = 0.5 \text{ amp (500 ma)}$$

Where $E_p$ is the d-c plate supply voltage; and $I_p$ is the plate current in amperes as read on the plate circuit ammeter $M$.

A step-by-step explanation of how to determine the audio power required to modulate the RF amplifier, shown in the diagram, to 100 per cent is as follows:

1. According to the power formula $P = EI$, the d-c power input to the RF stage is 2,000 × 0.5, or 1,000 watts.
2. According to Ohm's law $R = E/I$, the resistance of the plate circuit of the RF stage is 2,000/0.5, or 4,000 ohms.
3. To produce 100 per cent plate modulation, the sum of the instantaneous AF a-c peak voltage, plus the d-c plate voltage, must equal twice the unmodulated d-c voltage value in the RF amplifier plate circuit and zero volts, alternately.
4. Twice the voltage on the plate of the RF tube will produce twice the plate current, or 1 amp.
5. Twice the voltage and twice the current produces a *peak* power of 4 times the d-c power input, or, in the amplifier above, 4 × 1,000 or 4,000 watts.
6. Even at 100 per cent modulation, the plate current meter $M$ will not visibly vary; therefore the *average* power being drawn from the RF amplifier power supply must remain constant, in this case at 1,000 watts. The additional power to produce the peak of 4,000 watts must be supplied by the modulator and must be the result of the AF power. At first, it would seem that the modulator must furnish 3,000 watts, which, when added to the 1,000 watts d-c, would give the 4,000-watt peak power. However, this is far from correct. Consider what the modulator is actually doing.
7. The modulator tube is feeding its power output, through the modulation transformer, into the 4,000-ohm plate circuit of the RF amplifier.
8. The modulator must develop a 2,000-volt peak a-c voltage into the 4,000-ohm resistive RF amplifier plate circuit to produce 100 per cent modulation. How much power will it take to produce 2,000 volts peak a-c across this apparent 4,000-ohm resistor?
9. The power formula $P = E^2/R$ assumes *effective* voltage values. The peak voltage value must be converted to the effective value by multiplying the peak by 0.707, as discussed in the chapter on Alternating Current. In this case, 2,000 × 0.707 = 1,414 volts effective AF a-c.

10. Substituting these figures in the formula for power:

$$P = \frac{E^2}{R} = \frac{(1{,}414)^2}{4{,}000} = \frac{2{,}000{,}000}{4{,}000} = 500 \text{ watts}$$

11. It takes 500 watts of sinusoidal audio power from the modulator to 100 per cent plate-modulate an RF amplifier with a plate power input of 1,000 watts.

12. Since 500 watts is exactly one-half of 1,000 watts, the modulator must provide an AF power equal to one-half of the d-c plate supply power to the modulated amplifier. This represents a 50 per cent increase in power delivered to the modulated stage.

13. Note that the audio power must be delivered into the RF amplifier plate circuit. Any AF power lost, because of inefficiency of the modulation transformer, will not reach the RF amplifier. As a result, the modulator must feed slightly more than one-half the d-c plate power into its output transformer primary to produce the required secondary power.

It is possible to apply the same reasoning and formulas to determine the required AF power to produce any percentage of modulation. It must be understood that the percentage of modulation will be directly proportional to the *peak* a-c emf added to the d-c plate supply voltage. For example:

A peak a-c equal to 100 per cent of the d-c $E_p$ produces 100 per cent modulation.

A peak a-c equal to 75 per cent of the d-c $E_p$ produces 75 per cent modulation.

A peak a-c equal to 50 per cent of the d-c $E_p$ produces 50 per cent modulation.

To find the required audio power to plate-modulate an RF amplifier with 2,000 volts plate voltage and 0.5 amp plate current ($R_p = 4{,}000$ ohms) to 50 per cent:

$$P = \frac{E^2}{R} = \frac{(1{,}000 \times 0.707)^2}{4{,}000} = \frac{(707)^2}{4{,}000} = \frac{500{,}000}{4{,}000} = 125 \text{ watts}$$

Therefore 50 per cent modulation requires only one-quarter of the power that is required for 100 per cent modulation. This represents a 75 per cent decrease in required audio power between 100 and 50 per cent modulation.

A simpler method of determining the required audio power to produce a given percentage of modulation is to use the formula

$$P_{\text{af}} = \frac{m^2 P_{\text{dc}}}{2}$$

where $P_{\text{af}}$ is the audio power needed; $P_{\text{dc}}$ is the d-c plate power input; and $m$ is the percentage of modulation expressed as a decimal, such as 50 per cent = 0.5.

*Example:* To modulate an amplifier 100 per cent when the d-c power input is 1,000 watts, the audio power is

$$P_{af} = \frac{m^2P_{dc}}{2} = \frac{1^2(1{,}000)}{2} = 500 \text{ watts}$$

To produce 50 per cent modulation in the same amplifier,

$$P_{af} = \frac{m^2P_{dc}}{2} = \frac{(0.5^2)(1{,}000)}{2} = \frac{0.25(1{,}000)}{2} = 125 \text{ watts}$$

If a given amount of audio power is available, it is possible to determine the amount of d-c power which can be modulated to a desired percentage, by rearranging the above formula:

$$P_{af} = \frac{m^2P_{dc}}{2}$$
$$2P_{af} = m^2P_{dc}$$
$$\frac{2P_{af}}{m^2} = P_{dc}$$

*Example:* An AF power of 500 watts will modulate what d-c power input to an RF amplifier to 50 per cent?

$$P_{dc} = \frac{2P_{af}}{m^2} = \frac{2(500)}{(0.5)^2} = \frac{1{,}000}{0.25} = 4{,}000 \text{ watts}$$

How much modulator power input is required to produce a given AF a-c power? If the modulator stage is class A, it will be only about 25 per cent efficient. If class B, it may be more than 60 per cent efficient. If the transmitter has an output power of 100 watts and the final RF amplifier is 50 per cent efficient, the plate input power must be 200 watts. It will require 100 watts of sine-wave AF a-c to modulate the 200 watts of d-c plate input. The AF power output from the modulator stage will be equal to its plate-power input times the percentage of efficiency of the stage, or

$$P_o = P_{in}(\%)$$

where $P_o$ is a-c power output; $P_{in}$ is d-c power input; and % is the efficiency of the stage.

This formula can be rearranged to

$$P_{in} = \frac{P_o}{\%}$$

If the modulator is a class B audio amplifier with an efficiency of 66 per cent, to produce the needed 100 watts of audio, the required d-c power input to the modulator is

$$P_{in} = \frac{P_o}{\%} = \frac{100}{0.66} = 151 \text{ watts}$$

It must be pointed out that these figures are considering the modulation as being sinusoidal. Because of the jagged, high-peaked characteristics of speech and musical sounds, their *average* power is far below the average power required to produce a given peak value of sine-wave voltage. It is generally considered that if 500 watts of audio will produce 100 per cent sine-wave modulation, half of 500 watts, or 250 average watts, of voice-type audio power will produce 100 per cent modulation on peaks. However, this is not always true. With some voices the 250 average watts of audio may not produce an audio voltage peak high enough to produce 100 per cent modulation at any instant, while other voices may have many peaks overmodulating the transmitter when an average of 250 watts is produced.

At the positive peak of modulation, in the circuit of Fig. 16.13, the plate potential rises from the 2,000-volt carrier value to 4,000 volts. This should produce exactly twice the plate current, and therefore four times the RF power output. However, the $E_pI_p$ curve is not a straight line. As the plate voltage is doubled, the plate current does not quite double. As a result, the output power is not quite four times, and the positive peak will not rise as much as it should. If a power-supply bias alone is used, this distortion of the positive peak will always occur. Using grid-leak bias, as shown, will decrease the distortion. With grid-leak bias, when the plate current increases, fewer electrons will be available to flow to the grid, reducing the grid current, and therefore the bias value. Reducing the bias increases the plate current, tending to maintain a positive peak of modulation at the proper amplitude. For this reason, plate-modulated stages should always either use power supply *and* grid-leak bias or use grid-leak bias alone.

The value of the RF grid excitation is quite important. A grid-leak-biased amplifier having 2,000 volts on the plate has no grid bias with no RF grid excitation. Excessively high plate current will flow. With a relatively small RF grid excitation there will be only a little bias and the signal voltage will only operate over a small portion of the $E_gI_p$ curve of the tube. This will result in low efficiency and only a little RF a-c power output. If the plate circuit is modulated, the grid is not being driven positive enough to lower the impedance of the tube and the positive peaks of modulation will not be developed, although the negative peaks may be. If the excitation is increased, the RF power output will increase up to a point. The tube is approaching the point of saturation. A further increase of excitation will not materially increase the RF output.

If modulation is now applied, low percentages of modulation are satisfactorily produced, but the positive peaks of modulation will not be adequately developed at high percentages. The excitation must be increased until the tube is operating in a saturated condition to allow high-percentage positive peaks to be produced linearly. The correct RF excitation will be the minimum value required to produce a positive voltage peak of modulation twice the carrier value and a negative peak just to zero, as indicated on an oscilloscope (Sec. 16.21). If an oscilloscope is not available, the approximate values can be approached by adjusting the stage according to the operating data for the tube being used, such as the plate voltage, plate current, grid-leak bias resistance, grid current, and other information given by the tube manufacturer.

As explained in the chapter on Audio-frequency Amplifiers, the primary of a modulation (audio) transformer should have an impedance value between two and three times the impedance of the modulator tube or tubes for undistorted output. The secondary impedance of the transformer must match the plate resistance of the class C modulated stage. The following is an example of a possible problem in determining the impedance and turns ratio of a modulation transformer:

A certain class C amplifier has a plate voltage of 1,000 and a plate current of 0.15 amp. The class A modulator tube has a plate impedance of 15,000 ohms. What turns-ratio transformer will match the modulator to the modulated stage?

If the modulator plate impedance is 15,000 ohms, about 2½ times this value, or a 37,500-ohm primary, will be suitable.

The secondary impedance must match the impedance of the class C plate circuit and is computed

$$R_p = \frac{E_p}{I_p} = \frac{1{,}000}{0.15} = 6{,}670 \text{ ohms}$$

From the turns-ratio formula in Sec. 13.33,

$$\text{Turns ratio} = \sqrt{\frac{Z_1}{Z_2}} = \sqrt{\frac{37{,}500}{6{,}670}} = \sqrt{5.62} = 2.37{:}1$$

The primary should have approximately 2.37 times as many turns as the secondary. In practice, a ratio between 2:1 and 2.5:1 would operate, although reasonably undistorted 90 to 100 per cent modulation is only produced when the impedances match properly. Excessive mismatch results in distortion of the modulation, or inability to produce high percentages of modulation.

**16.12 Plate-modulating Tetrodes and Pentodes.** It is sometimes advantageous to use tetrode or pentode tubes as the modulated RF amplifiers, rather than triodes. Triodes must be neutralized, whereas tetrodes and pentodes do not usually require neutralization below 30 Mc. Tetrodes and pentodes have higher-power sensitivities, requiring less RF driving power and less bias voltage.

When a modulated voltage is applied to the plate circuit of a tetrode or pentode and a constant voltage is applied to the screen grid, 100 per cent modulation is not possible without excessive distortion, since plate current is fairly independent of the plate voltage. It is necessary to modulate simultaneously the plate *and* screen-grid circuits to produce undistorted high percentages of modulation. This can be done several ways. Three methods are described here.

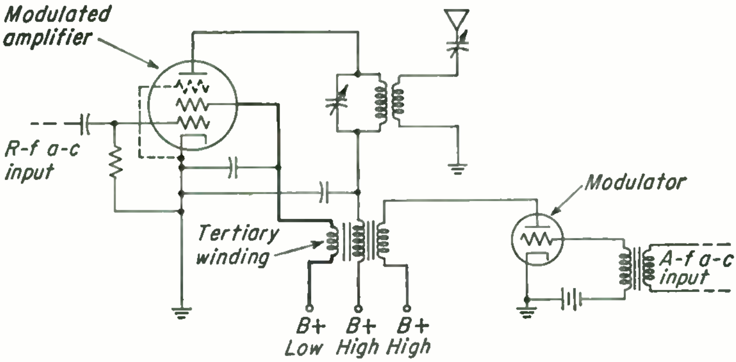


FIG. 16.14. Plate modulation of a tetrode (or pentode) using a modulation transformer with a tertiary winding.

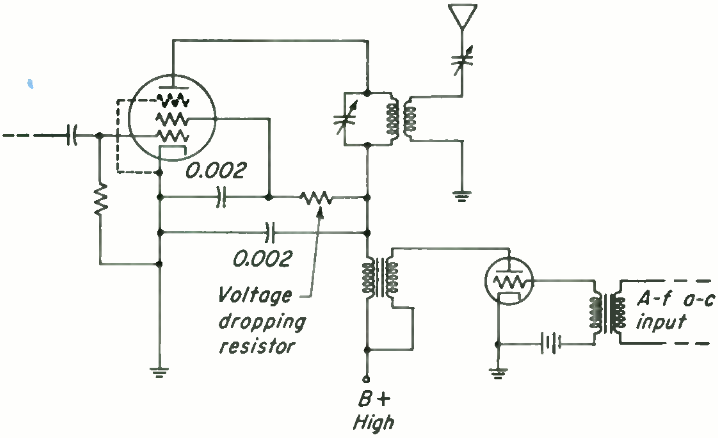


FIG. 16.15. Plate modulation of a tetrode (or pentode) using a voltage-dropping resistor and one power supply.

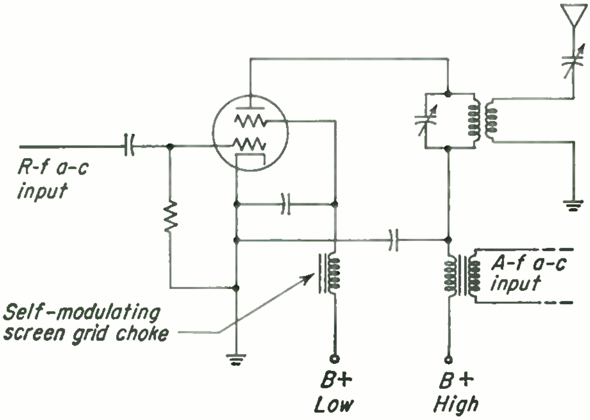


FIG. 16.16. Self-modulating screen-grid circuit for plate modulation of a tetrode.

The modulation transformer may have a secondary and a tertiary winding producing a high AF a-c voltage for the plate circuit and a lower modulating voltage for the screen-grid circuit (Fig. 16.14). The plate and screen modulating voltages must be in phase.

The screen grid may be fed a modulating voltage through a voltage-dropping resistor connected to the plate end of the modulation transformer secondary, as shown in Fig. 16.15. If the resistor is erroneously connected to the power-supply end of the transformer, no modulating AF a-c will be fed to the screen grid.

A high-inductance, low-resistance choke coil in series with the screen-grid supply lead (Fig. 16.16) will produce self-modulation of the screen-grid voltage. Increased positive potential on the plate causes increased plate current and decreased screen-grid current. Decreasing screen current allows the magnetic field of the choke to collapse, inducing a more positive voltage on the screen. Thus the screen and plate become more positive at the same time.

**16.13 Input Power and Operating Power.** A plate-modulated RF amplifier with 2,000 volts plate potential and 0.5 amp plate current has a 1,000-watt input to the plate circuit. How much of this 1,000 watts input is actually radiated?

Whatever the power input to a class C RF amplifier, it is usually assumed that the RF output will be at least 70 per cent of the plate-circuit input power. For 1,000 watts input, about 700 watts of output, or *operating*, power will be produced.

If the transmitter is licensed for more than 5,000 watts, the 70 per cent factor may be raised to 85 per cent. A transmitter licensed for 8,500 watts operating power will require an input power of 10,000 watts.

The percentage of modulation does not enter into the computation of operating power. The efficiency of the amplifier should remain constant regardless of the modulation percentage, provided the tubes are operated within their rated values. A 1,000-watt input transmitter has a 700-watt carrier-power rating whether modulated or not. However, when 100 per cent sine-wave-modulated, the d-c plus the audio a-c power input is 1,000 plus 500 watts, or 1,500 watts. The actual RF power output with 100 per cent modulation is 70 per cent of 1,500 watts, or 1,050 watts. The carrier is still only 700 watts. The other 350 watts of RF power is in the sidebands, two other completely different RF signals being emitted at the same time the carrier is transmitted.

**16.14 Sidebands.** It has been repeatedly stated that the sine wave is the perfect a-c. An RF carrier consisting of perfect sine-wave a-c will have no harmonics nor any other frequency components. If such a carrier has a frequency of 1,500 kc, the only possible emission from it would be a 1,500-kc signal.

When the illustration of the modulated envelope (Fig. 16.11) is examined, it can be seen that during the time the carrier is constant in amplitude and not modulated, the RF a-c might have a substantially sine waveshape. However, when modulation is applied, each succeeding cycle is higher or lower in amplitude than the one before it. It is impossible to have a progressive increase or decrease in amplitude such as this without changing the sine waveshape slightly. The change that occurs when a 2,000-cycle sine-wave modulating signal is applied is such that two frequencies, completely different from the carrier, are developed along with the carrier. These two new frequencies are called the sidebands and occur, one 2,000 cycles (2 kc) above the carrier frequency, the other 2,000 cycles below the carrier, as shown in Fig. 16.17.

The explanation of sidebands deals with the theory of *mixing*, *beating*, or *heterodyning* one frequency with another frequency in a "nonlinear" circuit, such as in the plate circuit of an RF amplifier. The result is always at least four output frequencies: (1) one of the original frequencies, (2)the other original frequency, (3) the *sum* of the two frequencies, and (4) the *difference* between the two frequencies.

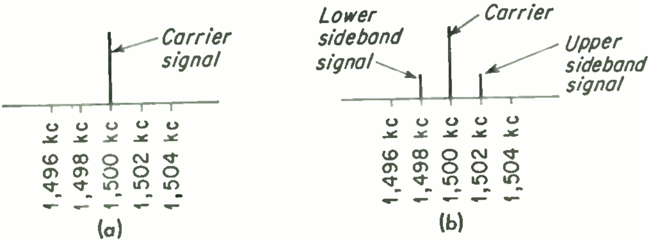


FIG. 16.17. (*a*) Representation of a 1,500-kc carrier. (*b*) The sidebands formed when the carrier is modulated by a 2-kc signal.

In a modulated RF amplifier plate circuit, the four frequencies might be a 1,500-kc carrier and 2,000 cycles AF from the modulator. When mixed they will result in the four frequencies (1) 1,500,000 cycles, (2) 2,000 cycles, (3) 1,502,000 cycles, and (4) 1,498,000 cycles.

Since the RF amplifier tank circuit and the antenna circuit have practically zero impedance to the 2,000 cycle frequency, no voltage of this frequency can develop and the 2,000 cycle frequency is lost.

The other three frequencies, the carrier and the two sidebands, are all close enough in frequency so that the amplifier tank circuit and the antenna will tune to them, accept them all, and radiate them.

All the intelligence or transmitted sounds are represented by the sidebands produced during modulation. If there are 350 watts of RF power radiated in the sidebands, each sideband will have half of this total, or 175 watts. An extremely "sharp," or frequency-selective, receiver can tune in the carrier or either sideband signal alone. With a 2,000-cycle constant tone as the modulation, the receiver will produce no tone from any of the three signals alone. However, a broader receiver, one which will accept all three signals at once, will produce a 2,000-cycle tone because the carrier frequency and the sideband frequencies recombine in the *receiver* circuits, mixing and reproducing the missing 2,000-cycle resultant. It is also possible to have a sharp receiver pick up the carrier and only one sideband. These two frequencies can combine in the receiver to produce the 2,000-cycle tone, although not quite as loud as if both sidebands and the carrier are received.

If the 2,000-cycle tone modulation is distorted for any reason, harmonics of 2,000 cycles will be present in the modulated envelope. Instead of confining all the energy to one frequency 2,000 cycles on either side of the carrier, spurious *harmonics of 2,000 cycles* will be produced as additional sidebands far out, above and below the carrier frequency. This results in a *broad* wave and is very undesirable. It produces interference to other radio services and unpleasant sounding signals.

In plate modulation, the power output of the modulator can be considered to be producing the sidebands only. The sideband power present in a modulated signal can be determined by using the same formula as is used to determine the amount of audio power required to produce a given percentage of modulation:

$$P_{af} = \frac{m^2 P_{dc}}{2}$$

where $P_{af}$ is the sideband power produced by the audio modulating power; $P_{dc}$ is the carrier power produced by the d-c power supply of the RF amplifier; and $m$ is the percentage of modulation divided by 100.

*Example:* If the carrier output of a transmitter is 1,000 watts, how much power is in the sidebands when the carrier is modulated 80 per cent by a sine-wave audio signal?

$$P_{af} = \frac{m^2 P_{dc}}{2} = \frac{(0.8)^2(1{,}000)}{2} = \frac{0.64(1{,}000)}{2} = \frac{640}{2} = 320 \text{ watts in the sidebands}$$

**16.15 Bandwidth.** The *bandwidth* of an amplitude-modulated radiotelephone transmitter is determined by the highest-frequency audio a-c being transmitted. The bandwidth is the difference in frequency between the lowest-frequency sideband and the highest-frequency sideband. A carrier modulated with an 800-cycle audio tone has a bandwidth of 1,600 cycles. If modulated with a 3-kc tone, the bandwidth is 6 kc.

If the modulating frequency is 3 kc but the audio is distorted, the bandwidth will be determined by the number of harmonics of 3 kc that are significantly strong. If the fifth harmonic is still relatively strong, the bandwidth is at least 30 kc. Near the transmitter, where even the weak harmonics are receivable, it will appear to be considerably wider.

For radiotelegraph transmitters keying at 30 to 40 words per minute, the bandwidth should not be more than about 250 cycles. For speech transmission, where 3,000 cycles is the highest frequency to be transmitted, the bandwidth should not be much more than 6 kc. For music transmission, where the highest frequency to be transmitted is 5,000 cycles, the bandwidth should not be much more than 10 kc. For high-fidelity transmissions, where the highest frequency is 15,000 cycles, the bandwidth is 30 kc.

**16.16 Heising Modulation.** The most popular method of plate modulation in the early days of broadcasting was the Heising system. It has now been generally superseded by the transformer method previously described. A simple diagram of Heising modulation is shown in Fig. 16.18.

The plate currents of both the modulator and the RF amplifier flow downward through the modulation choke. The same plate voltage is being applied to both modulator and modulated amplifier. The modulator is a class A stage, and the RF amplifier is a class C stage.

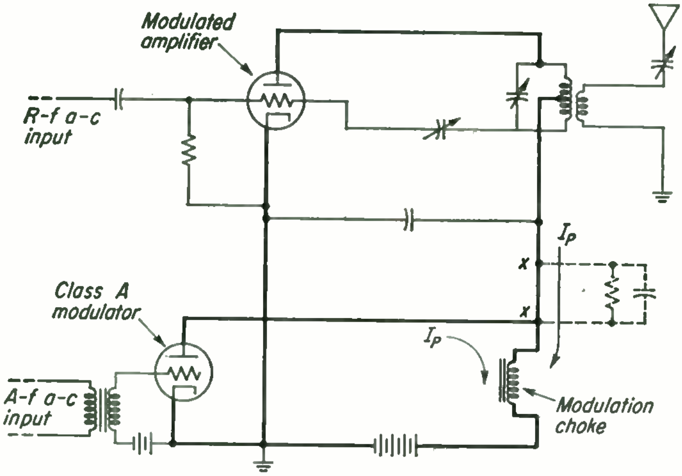


FIG. 16.18. Heising, or constant-current, modulation circuit.

The modulation choke has a large enough inductance value (30 to 100 henrys) to present a very high impedance to any AF current variations that attempt to flow through it.

With no modulation, there is a steady average d-c flowing through the choke, part being the modulator plate current and part being the RF amplifier plate current, a constant average d-c.

When the grid of the modulator is driven less negative, the plate current of the modulator tube increases. The current increase (downward) through the choke develops a counter emf (upward voltage) across the choke. This counter emf is in series with the power-supply voltage and the plate circuit of the RF amplifier. However, the counter-emf-pressure direction is opposite to the power-supply voltage, therefore partially canceling out the plate voltage on the RF amplifier. This decreases the RF amplifier plate current and the RF a-c output. The average RF amplifier plate current decreases just as much as the modulator plate current increases.

When the modulator grid is driven more negative, the modulator plate current decreases, producing a collapsing magnetic field and an induced emf (downward) in the choke, adding to the power-supply voltage for the RF amplifier, and increasing its plate current and the RF a-c output. As before, the RF amplifier plate current increases as much as the modulator plate current decreases. This results in a constant-current value in the choke and power supply and accounts for the reason why Heising modulation is also known as *constant-current modulation.*

The AF a-c voltages developed across the choke coil in a Heising modulation system can never quite equal the source voltage, in this case the plate supply voltage. If the RF amplifier voltage cannot be doubled at the peaks of modulation, 100 per cent modulation cannot be obtained in the Heising circuit shown.

If a resistor, with an AF bypass capacitor across it, is connected in series with the plate circuit at the points marked $X$ in the diagram, the voltage drop across the resistor will lower the d-c plate voltage on the RF amplifier plate, but not on the modulator plate.

If the power supply is 1,000 volts and the modulator can develop 800 volts peak AF a-c across the choke, the series resistor must have a value large enough to provide a voltage drop of at least 200 volts, if 100 per cent modulation is desired.

The capacitor across the resistor will have to have a low reactance to all the audio voltages in order not to attenuate them. The resistor alone will produce a d-c voltage drop across itself, but the modulating AF will also produce a voltage drop across it, preventing the full AF voltage from being applied to the RF amplifier tube plate unless the capacitor (condenser) is present.

**16.17 Grid Modulation.** In plate modulation, an AF a-c is added to the d-c plate supply voltage, forming a varying d-c that modulates the amplitude of the output wave.

In grid modulation, or grid-bias modulation, an audio voltage is added in series with the bias supply of the modulated amplifier, as shown in Fig. 16.19. Since the bias voltage can control the output power of the amplifier, variations of the bias voltage can produce AM of the output. In plate modulation, the modulating a-c is working into a plate circuit having a definite resistance value ($R = E/I$). In grid modulation, the bias and modulating-signal values may be adjusted so that the grid will not be drawing current at any time during modulation. The modulator tube is then working into practically an infinite-ohms load resistance, and almost no power is required to produce the modulation. This very small audio-power requirement is one of the main advantages of grid modulation.

The grid-modulated stage is biased to class C and always uses some type of bias supply, never using grid-leak bias. The reason for this becomes evident when it is recalled that grid-leak bias requires grid current flowing through the grid-leak resistance to produce the bias voltage. With no grid current, there will be no bias voltage.

Figure 16.20 illustrates the $E_gI_p$ curve of a grid-modulated amplifier in which no grid current flows.

The bias is adjusted to about 1½ times the plate-current cutoff value, *condition A*, with no RF excitation or modulating voltages.

The RF excitation voltage is increased to the point where the peaks are at the mid-point of the $E_gI_p$ curve, between zero grid volts and the cutoff value, as shown by *condition B*.

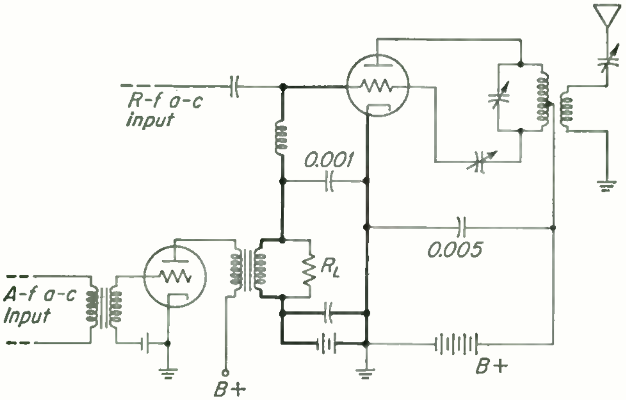


FIG. 16.19. Control-grid, or grid-bias, modulation circuit.

When the bias voltage is modulated, the RF excitation peaks are made to move toward and away from the zero grid voltage line, as shown in *condition C*. The plate-current pulses vary in amplitude as the modulating voltage changes. Note that the RF excitation voltage does not vary in amplitude, but the whole excitation signal is swung back and forth under the curve by varying the bias voltage, thereby producing the varying-amplitude plate-current pulses.

At first computation, there seems to be an inconsistency in grid modulation. The plate power-supply voltage is not modulated, but is constant. At the point of 100 per cent modulation, the amplitude of the plate-current pulses is twice the carrier value. Since the plate voltage does not change, apparently voltage times current results in only twice the power output from the tube at 100 per cent modulation peaks. It has been previously explained that the positive peak of modulation requires four times the power, instead of the apparent doubled power. However, when the excitation voltages are swung back and forth, the tube is being operated over a greater portion of the curve and the efficiency of operation of the tube increases. When the bias is swung sufficiently to produce 100 per cent modulation values, the efficiency is doubled. As a result, at 100 per cent modulation the tube is twice as efficient and the peak current is twice as much. This results in a fourfold increase of RF power output at the instant of 100 per cent positive peak modulation. Because of the variation of efficiency, grid modulation is also known as *efficiency modulation.*

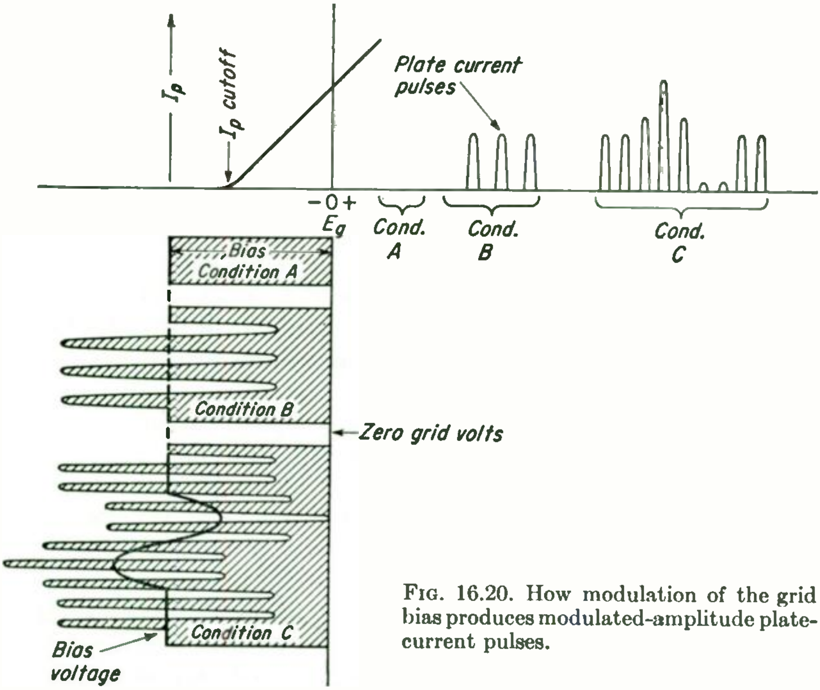


FIG. 16.20. How modulation of the grid bias produces modulated-amplitude plate-current pulses.

During modulation, the plate-current pulses increase as much as they decrease, resulting in a constant average plate current. A milliammeter in the plate circuit will not show any material variation during modulation, unless distortion is present.

Operating a grid modulated amplifier as explained will produce reasonably undistorted modulation up to about 95 per cent. The stage will operate at only about 20 per cent efficiency when producing the carrier alone, rising to a peak of about 40 per cent under 100 per cent modulation conditions. To increase the efficiency of the amplifier stage, the RF excitation may be raised to the point where the peaks of the driving voltage approach the zero grid voltage point. This operates the tube over a greater proportion of its curve, and about 35 per cent efficiency is possible. When modulated to 100 per cent, the positive peak of modulation will be produced while the tube is operating at about 70 per cent efficiency. Under these conditions, grid current flows during most of the positive peaks of modulation. This current throws a greater load on both the modulator tube and the RF driver. Loading one-half of the cycle of both of these stages tends to decrease the positive peaks of modulation. To partially overcome this type of distortion, the resistor $R_L$, in Fig. 16.19, maintains a fixed load on the modulator stage at all times. A similar loading resistor may be connected across any grid LC circuit to load both halves of the RF cycle from the driver. The d-c resistance of the modulated-amplifier grid circuit is kept as low as possible to decrease degeneration when grid current flows. The amount of audio power required for grid modulation is relatively insignificant, rarely being more than a watt or two.

To produce the highest possible power output and the best linearity of modulation, the plate voltage on the modulated stage should be as high as the tube will stand.

One of the disadvantages of grid modulation is the rather critical adjustments for proper operation. The degree of coupling to the antenna, the correct LC ratio in the plate tank circuit, the bias voltage, the excitation voltage, and the modulating voltage are all more critical than in plate modulation.

In comparison with plate modulation, grid modulation requires less audio power, and as a result has simpler circuits, but may produce a less linear modulation. It is more difficult to adjust and keep in adjustment, requires a higher plate voltage, is easily overmodulated, is more likely to frequency-modulate the carrier if no buffer stage is used, and will produce a carrier of about one-third as much power from the same RF amplifier tube with the same plate voltage supply as plate modulation. Regardless of this apparent advantage of plate modulation over grid modulation, actually, for speech communication from a fixed station, considering efficiencies, cost, size, and weight, one type of modulation may be very little better than the other.

**16.18 Suppressor-grid Modulation.** When a pentode tube is being used, either the control grid or the suppressor grid may be modulated. The operation of suppressor-grid modulation is essentially the same as control-grid modulation, with one main difference. With suppressor-grid modulation the RF excitation voltage is applied to the control grid, which may use either power-supply bias or grid-leak bias. The AF modulating voltage is added in series with the suppressor-grid circuit. This circuit must be biased from a power supply. A diagram of a suppressor-grid modulated pentode RF amplifier is shown in Fig. 16.21. The modulating voltage value for suppressor-grid modulation is considerably greater than for control-grid modulation because of the lower $\mu$ of the suppressor grid. Very little modulating power is required.

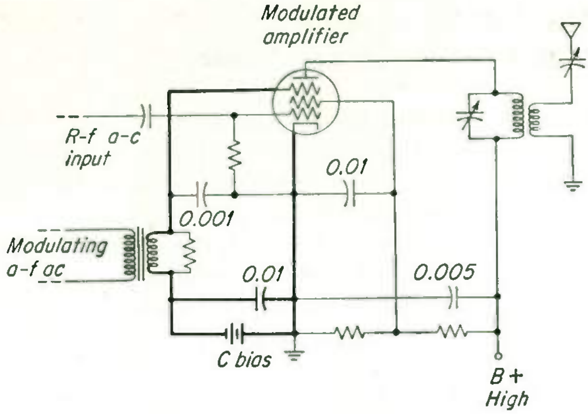


FIG. 16.21. Suppressor-grid modulation circuit.

**16.19 Screen-grid Modulation.** Modulating the screen grid of a beam-power tetrode or a pentode is similar in some respects to both grid modulation and plate modulation. The audio power requirement is considerably lower than for plate modulation and greater than for grid. The AF a-c is added to a positive potential from a d-c power supply, as it is in plate modulation (Fig. 16.22). The plate voltage of the stage should be maintained at as high a value as permissible for maximum output. The screen voltage must be lowered to about two-thirds of its normal operating value, and varied from that point by the modulating voltage. To increase linearity at higher percentages of modulation, a portion of the modulating voltage can be applied to the screen and control grids simultaneously. With undistorted output, the plate current meter should not vary materially. However, the screen current meter usually rises slightly during modulation.

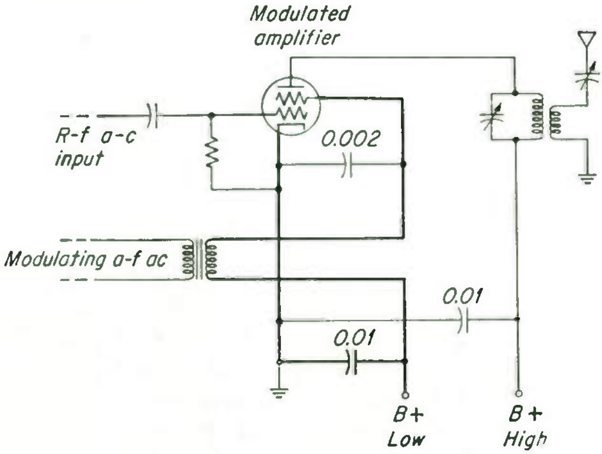


FIG. 16.22. Screen-grid modulation circuit.

Screen-grid modulation requires relatively little control-grid drive and rather tight coupling between the plate tank and the circuit to which it is coupled.

**16.20 High-level and Low-level Modulation.** Modulated stages can be divided into three separate categories. These are as follows:

1. High-level modulated stages, in which the modulated stage is plate-modulated and its output feeds the antenna.
2. Low-level modulated stages, in which the modulated stage is either plate- or grid-modulated but feeds the modulated carrier wave to a *linear* amplifier. The linear stage amplifies the modulated carrier without distorting it in any way and feeds the amplified modulated signal to the antenna.
3. Grid modulation, in which the final amplifier is grid-modulated.

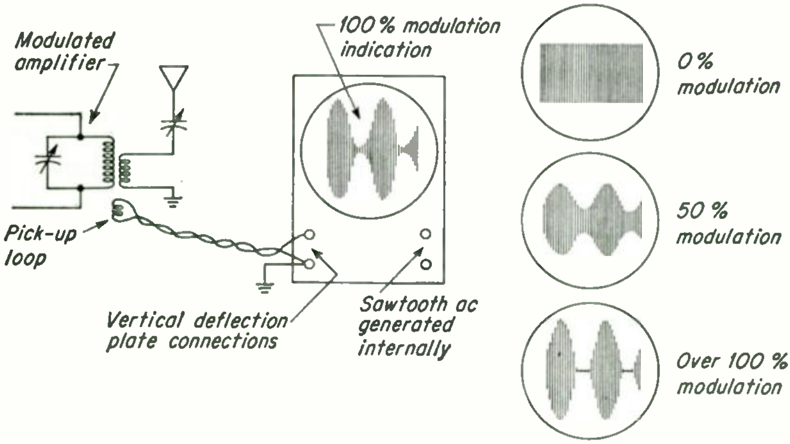


FIG. 16.23. Circuit to produce a modulated envelope display on an oscilloscope and four possible displays.

**16.21 Checking Modulation with an Oscilloscope.** The operation of an oscilloscope was described previously, in the chapter on Measuring Devices. This piece of equipment is one of the most satisfactory of all the simpler methods of determining the percentage of modulation on a carrier, as well as indicating the presence of certain types of distortion. There are many methods of using the oscilloscope. Only two will be mentioned here. One shows the modulation envelope. The other produces a *trapezoidal* figure on the screen.

The modulation envelope is displayed by using a saw-tooth a-c of 50 to 200 cycles on the horizontal-deflection plates. This is usually supplied by the saw-tooth a-c generating circuit incorporated in the oscilloscope. Radio-frequency a-c is picked up inductively by loose-coupling a two- or three-turn loop to the antenna or final-amplifier coil, as shown in Fig. 16.23. The loop is connected *directly* to the vertical deflection plates

(A short antenna with an accompanying tuned circuit can also be used as the RF pickup device.)

With no modulation, the carrier wave produces a wide band across the face of the cathode-ray tube. When modulation is applied, the band is modulated, the positive peaks increasing the height of the band and the negative peaks decreasing the band to a narrow line. If the saw-tooth sweep voltage has a frequency of 200 cycles and the modulation is a sinusoidal 400-cycle signal, the modulated carrier will appear with two sine-wave cycles on the top and bottom of the carrier band. If modulated 100 per cent, the negative peaks will show as a spot on the screen, and the positive peaks will have twice the vertical amplitude of the carrier alone, as shown in Fig. 16.23. The oscilloscope shows the modulation envelope as it was explained at the beginning of this chapter. If the transmitter is being modulated by a sine-wave signal, any deviation from the sine waveshape of the modulated envelope indicates that distortion is being produced in the modulation system. It is possible to check back, stage by stage, with the oscilloscope and determine where the distortion first appears and correct it at that point. To do this a 0.1-μf capacitor can be connected to the ungrounded vertical plate where the RF pickup loop was previously connected. By touching the capacitor to the plate or grid terminal of each tube in the audio section of the transmitter, an indication will be given of the waveshape at that point. Care must be taken when touching plate-circuit terminals because dangerously high voltages may exist at those points. Furthermore, the modulator AF a-c will be too high in amplitude for the plates of the cathode-ray tube. A voltage-divider circuit as shown in Fig. 16.24 can be used to decrease the voltage applied to the oscilloscope vertical plates.

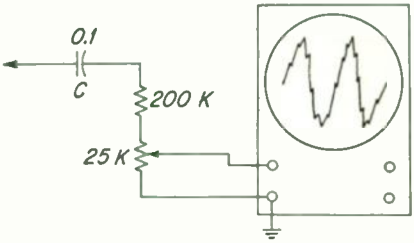


Fig. 16.24. Circuit to display an AF voltage.

WARNING: Adequate insulation must exist around the test circuit capacitor and the 200,000-ohm resistor, if the circuit is used while the transmitter is in operation. It is much safer to turn off the transmitter, fasten the capacitor to the desired point, and then turn on the transmitter again for a test.

The pattern on the oscilloscope will stand still only if the modulating frequency is some exact multiple of the saw-tooth sweep frequency. Voice and music will produce a jagged, jumping series of waveforms on the face of the tube. If the positive or negative peaks are badly flattened, it is sometimes apparent to the trained observer.

If bright spots are developed on the modulated envelope at the negative peaks of modulation, this is an indication of overmodulation, and consequently distortion and broadening of the bandwidth of the emission.

Precise neutralization of the modulated stage can be accomplished by overmodulating the negative peaks. If the negative-peak indication does not drop to a fine line, adjustment of the neutralizing capacitor to the point of proper neutralization will decrease the width of the line.

The trapezoidal display is produced by feeding modulated RF directly to the vertical plates of the oscilloscope, as before, and by feeding a small fraction of the *modulating* a-c to the horizontal plates from the modulation transformer *secondary* (Fig. 16.25).

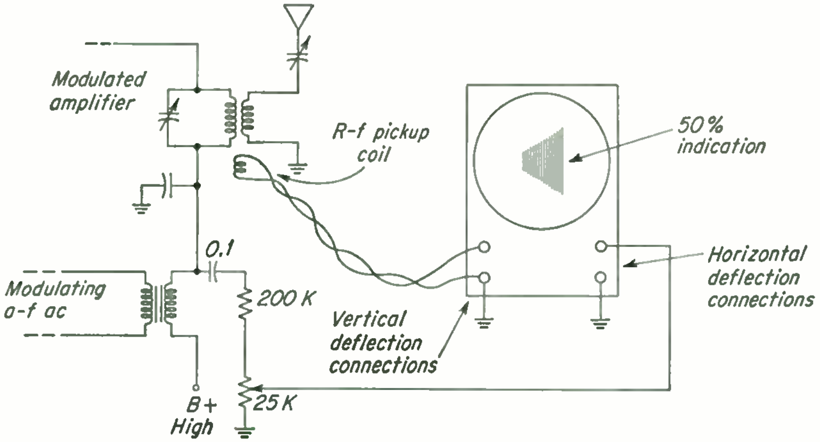


FIG. 16.25. Circuit to produce a trapezoidal display on an oscilloscope.

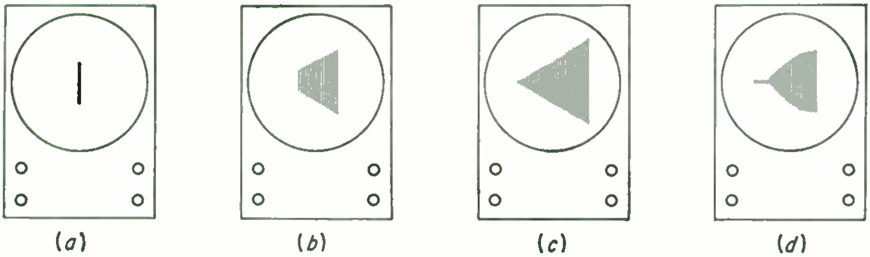


FIG. 16-26. Four possible trapezoidal displays on an oscilloscope.

With no modulation, the carrier produces a thin vertical line on the screen of the oscilloscope. When modulation is applied, the line thickens to the right and left sides. The negative peaks of modulation are indicated by the side that drops off in amplitude, and the positive peaks by the side that increases in amplitude. At 100 per cent modulation, the trapezoid forms a point at one side and is twice the carrier amplitude on the other side (a triangle). Figure 16.26 shows how an unmodulated carrier (*a*), a 50 per cent modulated carrier (*b*), a 100 per cent modulated carrier (*c*), and an overmodulated carrier (*d*) appear with a trapezoidal display on the oscilloscope. If the slanting sides of the trapezoid are not perfectly straight, distortion is indicated. If the positive peaks show a flattening instead of rising to a sharp point, *negative carrier shift* is indicated, as shown on the illustration of overmodulation. This is the usual result with severe overmodulation.

It is important to understand that the displays on the oscilloscope show the results of adding the sidebands to the carrier, but cannot show the sidebands themselves. The beginner often believes that the part of the display above the carrier level is a sideband, which is not true at all. The oscilloscope only represents a carrier and how the voltage in the carrier varies from instant to instant.

**16.22 Linear RF Amplifiers.** A linear amplifier is one which will amplify a weak signal voltage in relatively the same proportion as it will amplify a stronger signal voltage.

*Example:* An amplifier amplifies a 2-volt signal to 20 volts, a 3-volt signal to 30 volts, and a 4-volt signal to 40 volts. This amplifier is operating as a linear amplifier.

Another amplifier amplifies a 2-volt signal to 20 volts, but when fed a 4-volt signal it only amplifies it to 30 volts. This amplifier is operating as a nonlinear amplifier and is distorting the signal.

Linearity can be obtained only by operating the amplifier tube over the straight portion of the $E_gI_p$ curve. If the tube is operated over a portion of its curve that is nonlinear, distorted amplification will result.

The only amplifiers that produce undistorted audio signals are the class A, AB, and B. Class C amplifiers are considered nonlinear because they are not usually operated on the straight portion of the $E_gI_p$ curve for the whole input cycle. There is an exception to this, known as the *class BC* amplifier, to be explained later.

In a high-level modulated transmitter, where the output of the modulated stage feeds into an antenna, no linear amplifiers are needed. If the modulated RF stage is *not* the final RF amplifier, all stages after the modulated stage will have to be linear amplifiers to enable them to amplify the modulated RF carrier without distorting it in any way. This means that all RF amplifiers following a modulated stage will have to be linear RF amplifiers and, therefore, theoretically, biased to class A, AB, or B. A simple block diagram of a low-level modulated transmitter using a linear amplifier is shown in Fig. 16.27.

In practice it is found that class A amplifiers are too low in efficiency. Therefore class AB or B amplifiers are more likely to be used as RF linear amplifiers.

In audio, a class B amplifier must be a push-pull type to utilize both halves of the input cycle. However, in RF amplifiers a class B amplifier can operate with only one tube. The missing half of each RF cycle is reproduced by the flywheel action of the tuned plate tank circuit of the stage. However, class B radio-frequency amplifiers *may* use two tubes in a push-pull circuit.

Figure 16.28 shows a 100 per cent modulated envelope impressed on the $E_gI_p$ curve of a class B linear amplifier, with the resulting plate-current pulses produced by the modulated carrier.

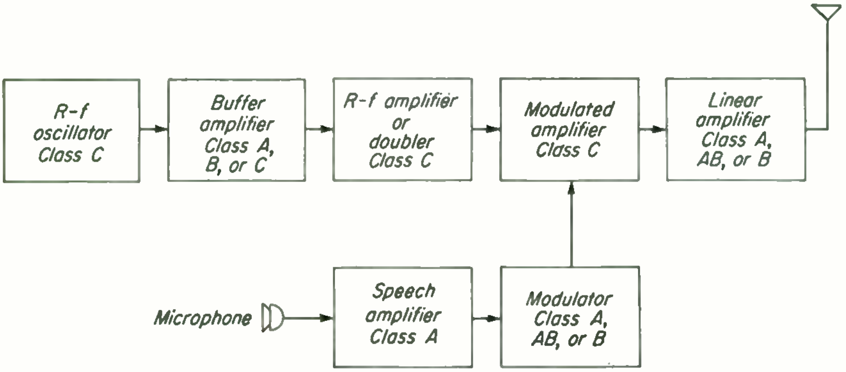


FIG. 16.27. Block diagram of a radiotelephone transmitter using low-level modulation and a linear amplifier.

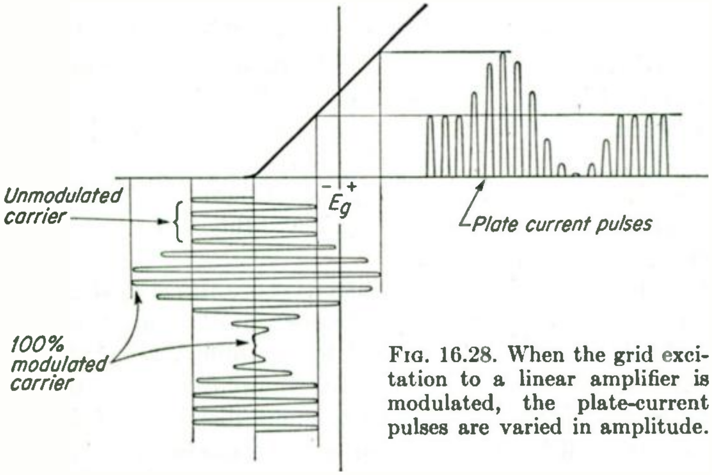


FIG. 16.28. When the grid excitation to a linear amplifier is modulated, the plate-current pulses are varied in amplitude.

The class B linear amplifier in Fig. 16.28 is excited almost to zero grid volts by the carrier signal. Much of the positive peaks of modulation fall into the positive grid region and will produce grid-current flow. This type of amplifier requires a bias supply with very good regulation as well as low d-c resistance between grid and cathode of the amplifier.

In linear RF amplifiers, a resistance is usually connected across the grid coil of the stage. This resistance acts as the load on the circuit ahead of it, usually the modulated stage. To produce undistorted modulation from any modulated amplifier it is necessary for it to work into a constant load, such as is presented by an antenna in high-level modulation systems. To produce such an unvarying impedance load on the modulated stage, the circuit following it is usually loaded with a noninductive resistance of such a value as to reflect the desired impedance on the plate circuit of the low-level stage. The resistor is shown in the diagram of a low-level modulated stage coupled to a linear amplifier (Fig. 16.29).

To take advantage of the characteristic higher efficiency of a class C stage, a linear amplifier is sometimes biased to class C but is made to operate on the linear portion of the $E_gI_p$ curve. The signal fed to the grid must be of the proper amplitude, and also it must *not* be modulated to a high percentage. This is actually an advantage, because it is not difficult to produce low percentages of essentially undistorted modulation with most systems. In Fig. 16.30 the linear amplifier is biased to about 1½ times cutoff and requires an excitation carrier modulated to only about 70 per cent to produce 100 per cent–modulated output RF a-c.

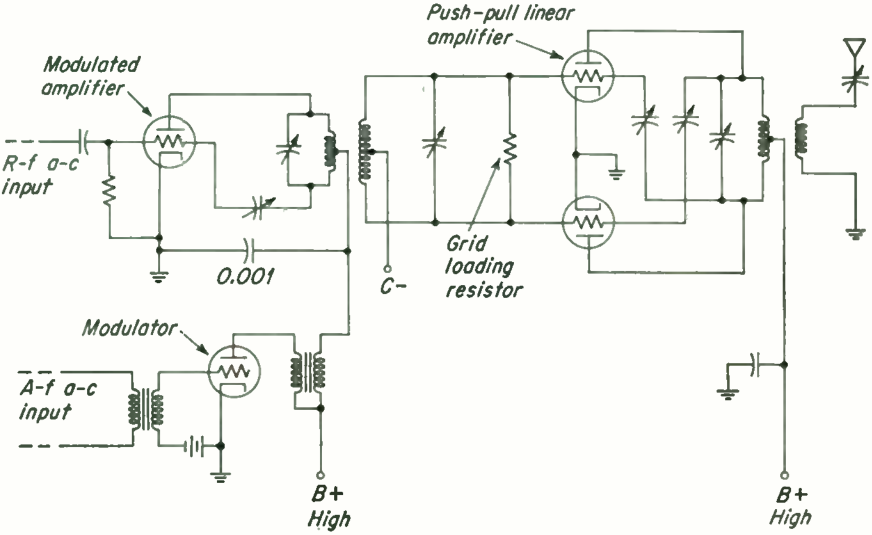


FIG. 16.29. A plate-modulated stage and a push-pull linear amplifier.

Since the stage is biased to class C but operates over the same portion of the curve as is used if it were biased to class B, this type of operation is known as *class BC*.

Notice that in Fig. 16.30 the positive peaks of modulation do not operate into any saturated, or bent, portion of the $E_gI_p$ curve. If excitation due to the carrier alone is increased up to the point of saturation, no positive peak of modulation can produce higher plate-current pulses than the carrier does. The negative-peak variations can be produced in the output, but the positive peaks will be flattened. This is a serious form of distortion and must be avoided. In such a case, the milliammeter in the linear-amplifier plate circuit will decrease sharply when the stage is amplifying a modulated input signal. With no distortion and proper bias and drive voltages, the plate current milliammeter should remain steady, or only vary slightly as the percentage of modulation changes.

To hold distortion to a minimum in a linear amplifier, the plate, screen grid, and grid bias supplies must all have very good voltage regulation.

A tube used in a linear-amplifier circuit can operate with higher plate voltage than would be used if the same tube were plate-modulated. For example, a tube operating with 2,000 volts on the plate as a plate-modulated amplifier can use approximately 2,500 volts as a linear amplifier.

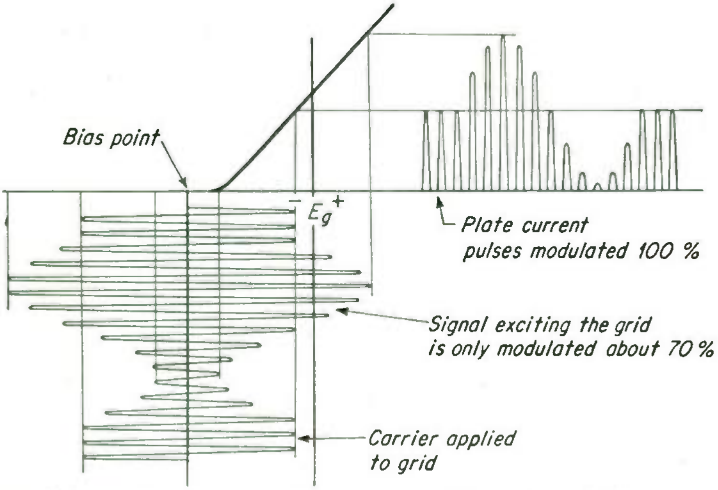


FIG. 16.30. Biasing the linear amplifier to class BC produces 100 per cent plate-current-pulse modulation with only a 60 or 70 per cent modulated input.

According to the FCC, the d-c plate power input times 0.35 equals the operating power output of a class B linear amplifier. This indicates that such an amplifier operates with an efficiency of approximately 35 per cent. Compare this with the factor of 0.7 to 0.85 for plate-modulated stages. When linear amplifiers are used with *single-sideband suppressed-carrier* emissions, the efficiency of the stage may be more than 60 per cent.

If the final class B linear amplifier of a transmitter has an RF output power of 50 kw and operates with a plate-circuit efficiency of 33 per cent, how much power is being dissipated in heat by the plates of the final-amplifier tube or tubes? From the formula (Sec. 16.11),

$$P_{\text{in}} = \frac{P_o}{\%} = \frac{50\text{ kw}}{33\%} = 150\text{ kw} \qquad \text{(approx.)}$$

The total plate power input is equal to the RF power output plus the power dissipated, or

$$P_{in} = P_o + P_d$$

where $P_d$ is the plate power dissipation. Solving for $P_d$

$$P_d = P_{in} - P_o = 150 - 50 = 100 \text{ kw dissipated in heat}$$

If there were six tubes in push-pull-parallel in the amplifier, each would have to dissipate 16.7 kw.

The linear amplifier in a radiotelephone transmitter is similar to a grid-modulated stage in some respects. The d-c plate voltage does not change. When the excitation voltage is doubled, the plate-current pulses double in amplitude. This should produce twice the output power, but the output increases *four* times. The output power is therefore proportional to the excitation voltage squared. With an increased percentage of modulation, the plate current varies over a wider portion of the $E_gI_p$ curve and the efficiency of the amplifier increases. With the increased power *and* efficiency, the proper output power is developed. Whereas the plate of a plate-modulated tube may turn red-hot at a high percentage of modulation, a linear-amplifier plate will cool under modulated conditions.

**16.23 Adjusting a Linear RF Amplifier.** It is possible to tune a class B linear RF amplifier stage using the following steps.

1. Bias the stage to cutoff by applying full operating plate voltage and observing the plate current as the bias voltage is decreased from a value known to be more than is necessary for plate-current cutoff. (Use no RF excitation while determining the cutoff bias value.) When the plate current begins to read a few milliamperes, the bias value is approximately correct.

2. Apply a weak unmodulated RF excitation to the grid, and tune the plate circuit to minimum plate current. (Then neutralize the stage if needed.)

3. Increase the RF excitation until some grid current begins to flow. At this value of RF excitation note the plate current. (For example, at a very low grid-current value the plate current is 300 ma.)

4. Decrease the RF excitation until the plate-current value is one-half the above-noted value (150 ma). This should be approximately the correct unmodulated carrier-excitation value.

5. Couple the antenna to the amplifier. Check the modulation percentage and linearity as shown on an oscilloscope, with a sine-wave signal generator feeding into the speech amplifier, making adjustments on bias, RF excitation, and antenna coupling until essentially undistorted 100 per cent modulation is produced at the desired power output.

**16.24 The Doherty Amplifier.** Much of the advantage of being able to modulate a low-level, or low-power, stage is overcome when it becomes necessary to operate the modulated signal into a linear amplifier with only

30 to 35 per cent plate efficiency. The *Doherty* amplifier has the advantage of operating as a linear amplifier with an efficiency of more than 60 per cent. It consists of two separate tube circuits. A basic schematic diagram is shown in Fig. 16.31.

The class B stage operates all the time. The class C stage operates only during the *positive* half cycles of modulation. With the carrier alone, and during negative halves of the modulated cycle, the class C tube does nothing.

The class B stage is excited to the point of saturation with the carrier alone. As a result of the relatively wide swing of plate current, it operates at about 60 per cent efficiency, but into a plate tank load of twice the tube impedance. This mismatch decreases the possible power output of the stage somewhat, but gives good efficiency. The class B stage produces all the output power of the carrier alone and of the negative half cycle of modulation.

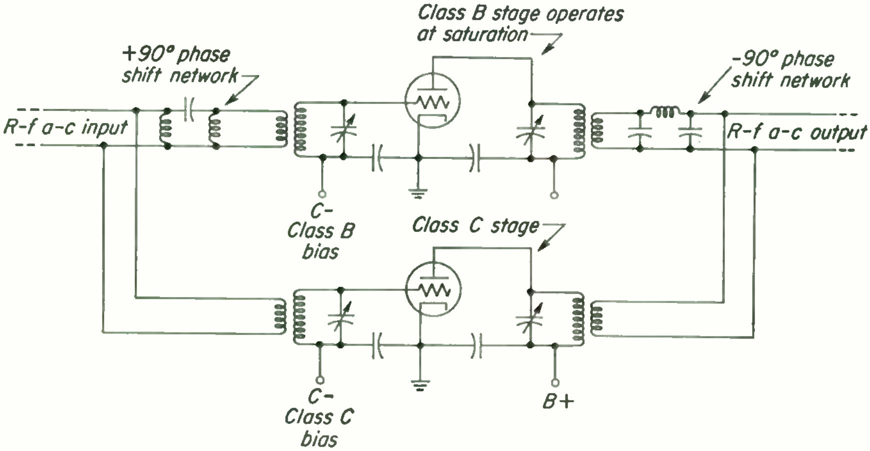


FIG. 16.31. Doherty high-efficiency linear RF amplifier circuit.

During the positive half cycle of modulation the class B stage is in a saturated condition and assumably would not materially increase its output. The class C stage goes into operation, producing RF power, feeding it into the output circuit. This reflects a lowered impedance back on the tank circuit of the class B stage, forcing the tube and load impedance to match and additional power to come from the class B stage. As a result, at the positive peak of modulation the necessary RF power peak of four times the carrier value is produced by the action of both tubes.

To produce the necessary impedance matching in the output circuit of the Doherty amplifier, the equivalent of a quarter-wave line must be inserted in the output of the class B tube. This also changes the phase of the output by 90°, necessitating an opposite change of phase, either in the grid of the class B stage, as shown, or in the grid circuit of the class C stage, in order that the output of both stages be in phase.

Such an amplifier is used in broadcast stations or lower-frequency applications where operation on only a single frequency is required. Tuning from one frequency to another becomes complicated because of the required adjustments of the phase-shift networks.

**16.25 Carrier Shift.** Distortion of modulation in an amplitude-modulated radiotelephone transmitter may result in *carrier shift*, either *positive* or *negative*.

With undistorted modulation, the carrier voltage increases as much during the positive peaks of modulation as it decreases during the negative peaks. The *average* carrier *voltage* remains constant with or without modulation.

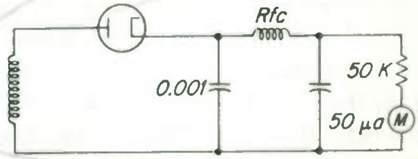


FIG. 16.32. Carrier-shift meter.

A meter capable of indicating the average carrier voltage is shown in Fig. 16.32. A d-c voltmeter, composed of a 50 μa meter and a multiplier resistance in series with it, is connected across the output of an RF pickup coil and a half-wave rectifier. The output of the rectifier is d-c, pulsating at the RF rate. The RF choke and the two capacitors form a low-pass filter for RF, but have little smoothing effect on frequencies as low as audio.

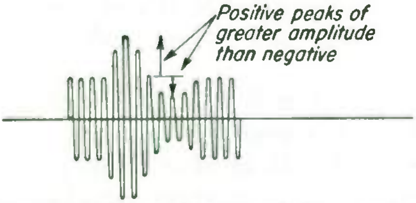


FIG. 16.33. A carrier with positive carrier shift.

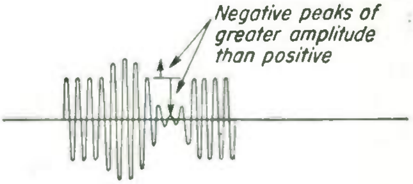


FIG. 16.34. A carrier with negative carrier shift.

The pickup coil is coupled close enough to the modulated RF output of a transmitter to give approximately half-scale reading on the voltmeter.

When undistorted modulation is produced by the transmitter, the increased positive peaks and decreased negative peaks of modulation are equal. Since the meter cannot swing fast enough to follow the audio variations of the modulated envelope, and since the average remains constant, the meter needle does not change with or without modulation.

If during the positive *peak* of modulation the voltage of the carrier increases more than it decreases during the negative *peak*, the result is a shifting of the *average* carrier voltage upward, or in the positive-peak direction, shown in Fig. 16.33. Positive carrier shift is present. The average carrier voltage being higher during modulation, the carrier-shift meter indicates a higher value. As modulation is applied the meter swings upward.

If during the negative peak of modulation the voltage of the carrier decreases more than it increases during the positive peak, the result is a shifting of the average carrier voltage downward, or in the negative-peak direction, shown in Fig. 16.34. Negative carrier shift is present. The average carrier voltage being lower during modulation, the carrier-shift meter indicates a lower value as modulation is applied. Negative carrier shift is also known as *downward modulation*, particularly if excessive.

In Figs. 16.33 and 16.34, if the original AF voltage were sinusoidal, but the modulating output voltage is no longer sine-wave-shaped, this indicates the modulating voltage has been distorted. It may be said that the modulating wave is *asymmetrical*, or nonsymmetrical.

When there is carrier shift present, there is distortion of the signal. Less than about 5 per cent of carrier shift is probably not noticeable to the average listener. More than this may be. If considerable negative carrier shift is present, the signals have a compressed, choked, and weak sound, as if the percentage of modulation were low.

With negative carrier shift the antenna ammeter will not increase normally, or may even decrease. With positive carrier shift the antenna ammeter will increase more than normally.

WARNING: There is a tendency, when seeing the words *carrier shift*, to visualize a shifting of the *frequency* of the carrier. This is not correct. Any frequency variation may be termed frequency shift, dynamic instability, or frequency modulation. Carrier shift refers to amplitude variations of the carrier, not frequency.

For voice communication, some positive carrier shift in the transmission is an advantage, provided the negative peaks are not materially distorted in shape. In this way, a greater proportion of sideband power can be radiated for a given carrier value and the receiver produces louder signals.

**16.26 Causes of Carrier Shift.** There are many causes of the type of distortion called carrier shift. The discussion of these will be listed under the types of circuits in which it is produced.

*Plate-modulated Stages.* Insufficient RF excitation to the grid is one o the most frequent causes of negative carrier shift. Battery bias alone or the modulated stage will produce some negative carrier shift at hig percentages of modulation. Distorted audio from the modulator stag may produce either negative or positive carrier shift. If a speech amplifie is overdriven, or overexcited, and produces distortion in the modulatin waveform, either form of carrier shift can result, depending upon th phasing of the connections to the modulation transformer. Imprope impedance match between the modulator and the modulated stage ca reflect back onto the modulator tube and produce distortion (usuall negative carrier shift). Improper antenna coupling reflects back an improper impedance match onto the modulator, or produces an improper LC ratio in the plate tank circuit, producing distortion, usually negative carrier shift. Low filament voltage or an old tube in the RF amplifier will not produce enough electron emission from the filament to allow sufficient plate current to flow at the positive peaks of modulation, and negative carrier shift will result. Excessive screen voltage, or failure to modulate the screen of a tetrode or pentode tube, will result in negative carrier shift. If one of the two tubes of a push-pull modulator burns out, severe distortion and carrier shift will occur. Insufficient or no plate voltage on the modulated amplifier will result in an overmodulated condition and considerable positive carrier shift. Overmodulation due to too high a setting of the gain control in the speech amplifier may produce a positive carrier shift. Poor voltage regulation in power supplies may result in negative carrier shift.

*Grid-modulated Stages.* Either form of carrier shift is easily produced if the grid-modulated stage and the modulator are not carefully adjusted. Too high a bias can produce positive carrier shift, as can too little RF grid excitation. Too low a bias can produce negative carrier shift, as can too much RF grid excitation. Excessive audio modulating voltage will result in positive carrier shift under certain circumstances, and negative shift in others. A distorted audio waveform can produce either positive or negative carrier shift, regardless of whether the distortion is developed by overexciting the microphone, preamplifier, speech amplifier, or modulator or in mismatching impedances through the modulation transformer. A weak tube or low filament voltage in the modulated stage can produce negative carrier shift. Improper antenna coupling can produce either form of carrier shift, depending upon other circuit factors.

*Linear Amplifiers.* These stages are similar to grid-modulated stages. Proper bias and RF excitation values are very important. Unless care is taken not to overexcite the grid, severe negative carrier shift will be produced. If the modulated stage has a certain type of carrier shift in its output, the output of the linear amplifier normally has the same. It is possible to partially balance out small values of carrier shift as the signal passes through a linear amplifier. If the original modulated signal has a slight negative carrier shift, the linear amplifier can be adjusted to produce a slight positive carrier shift.

If an RF amplifier tuning circuit or the antenna circuit insulation breaks down and sparks across on positive peaks of modulation, the indication given by the carrier-shift meter will be downward.

Microphones have a tendency to react differently to different voices. It is not uncommon to have one voice produce some negative carrier shift while others will produce a positive shift. It is advantageous to phase the output connections of microphones in such a way that voices tend to produce positive carrier shift rather than negative. This can be done by reversing the microphone wires at the input to the preamplifier.

**16.27 Radiotelegraph and Radiotelephone with the Same Tube.** If a tube or transmitter is to be used for both plate-modulated radiotelephone and radiotelegraph emissions, the carrier output for radiotelephone will usually have to be held between 65 and 75 per cent of that used for radiotelegraph. The differential in output is necessary to allow for the additional power being handled by the tube under modulated conditions. If a tube is capable of 1,000 watts in radiotelegraph service, it should be operated at approximately 700 watts carrier power if modulated, to allow for the 350 watts of sideband power that will be added to the carrier under 100 per cent sine-wave-modulation conditions. Running at 700 watts carrier, the tube is actually being overdriven if continually operated at 100 per cent sine-wave modulation. However, it is unusual to have a transmitter operating under this particular condition for any period of time. The average modulation for speech and music will produce far less than 350 watts of average sideband power for a 700-watt carrier.

If the same tube is grid-modulated, instead of 1,000 watts carrier output, about 200 to 250 watts will be all that can be expected as the carrier power. If the grid excitation is not decreased sufficiently to drop the carrier to this low a level, negative carrier shift will be developed when the stage is modulated.

To decrease power output of an RF amplifier, lower plate voltage or a lower degree of coupling to the antenna is employed.

**16.28 What the Antenna Ammeter Tells.** If a transmitter is turned on, the antenna ammeter will rise to some value and remain there until the transmitter is turned off again.

If the transmitter is turned on and then modulated 100 per cent by a constant sine-wave AF a-c, the antenna meter will rise to a higher value than with the carrier alone. The modulation being applied to the RF amplifier appears in the radiated wave as sideband power, which is added to the carrier power in the antenna. The added power is responsible for the increase in the antenna current reading. (An RF voltmeter will show the same degree of increase, although such meters are rarely seen.)

How much will the antenna current rise for 100 per cent sine-wave modulation? Assume a carrier power of 100 watts in the antenna. For simplicity, the antenna resistance will be assumed to be 1 ohm. The antenna resistance is constant and will not vary with changes of power.

1. The current in the antenna, from the power formula; is

$$P = I^2R \qquad \text{or} \qquad I = \sqrt{\frac{P}{R}} = \sqrt{\frac{100}{1}} = 10 \text{ amp}$$

2. With 100 per cent modulation, the sideband power will be equal to one-half the carrier power (Sec. 16.11). The total power in the antenna at this time is 100 watts carrier plus 50 watts sideband, or 150 watts.

3. The antenna current with 150 watts is found from the same formula:

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{150}{1}} = 12.25 \text{ amp}$$

4. The antenna current increases from 10 amp unmodulated to 12.25 amp when 100 per cent modulated. This is a 22.5 per cent increase.

Any time an antenna ammeter indicates an increase of 22.5 per cent over the unmodulated value, provided a sine-wave modulation signal is used and provided no distortion is present, the transmitter can be assumed to be modulated 100 per cent. An 8-amp unmodulated carrier should read 8 × 0.225 + 8, or 9.8 amp when modulated 100 per cent.

For 50 per cent sine-wave modulation, assume the same 100-watt carrier and antenna as above:

1. Fifty per cent modulation produces only one-fourth as much sideband power as is developed at 100 per cent (Sec. 16.11).

2. At 100 per cent, the sideband power was 50 watts. At 50 per cent the sideband power is 12.5 watts.

3. At 50 per cent, the total power in the antenna is 100 + 12.5, or 112.5 watts.

4. From the formula above, the antenna current will be

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{112.5}{1}} = 10.6 \text{ amp}$$

5. The increase from 10 to 10.6 is 0.06 greater than the original carrier value. Therefore the antenna ammeter will rise only 6 per cent over the carrier value for a 50 per cent-modulated signal.

Note that sine-wave modulating voltages are specified in all cases. These ratios hold true only in such cases. Pure tones of music are somewhat sinusoidal, but speech and normal music are far from sine-wave-shaped. When a transmitter is voice-modulated, the antenna ammeter may hardly move at all, although some of the peaks of modulation may actually be 100 per cent or more. If the antenna ammeter shows a 22.5 per cent increase when voice modulation is being applied to the transmitter, it is an indication of overmodulation and distortion.

If the antenna meter decreases when modulation is applied, downward modulation, or severe negative carrier shift, is present.

If the meter does not appear to move when modulation is applied, it may indicate low percentage of modulation, or some negative carrier shift, or both.

Sometimes the ammeter will move upward with low percentages of modulation, but begins to decrease with an increase of modulating voltage. This may indicate nearly normal modulation to a certain percentage, and then distortion sets in, and negative carrier shift results.

**16.29 Microphones.** There are several different principles upon which microphones can be built. In each basic type, the mechanical energy of the sound wave is converted into electrical variations or alternations, containing the same frequency and relative amplitudes that were present in the sound waves. Some basic principles that are used for microphones are varying resistance, magnetic induction, piezoelectric effect, electrostatic induction, and possible, but not used, magnetostriction.

**16.30 The Double-button Microphone.** The single-button microphone described in Sec. 16.4 is an example of a variable-resistance type of microphone. The double-button type was a more advanced form of microphone operating on the same principle and was the first microphone capable of reproducing music well. It had a fairly flat frequency response from about 100 to more than 5,000 cycles. The output power was about $-20$ to $-30$ db for loud sounds near it, whereas the single-button microphone will produce about zero db with close talking. The double-button microphone had several disadvantages. It required a battery to operate it. A background hiss was produced by the current flowing through the loosely packed granules—a serious disadvantage. The carbon granules were subject to packing together. It required critical current balancing and button-pressure adjustments. It had to be handled gently and was slung in a special spring-mounted ring to prevent noise when it was touched or jarred. It was large and fairly heavy. It was not sensitive to the whole audio range.

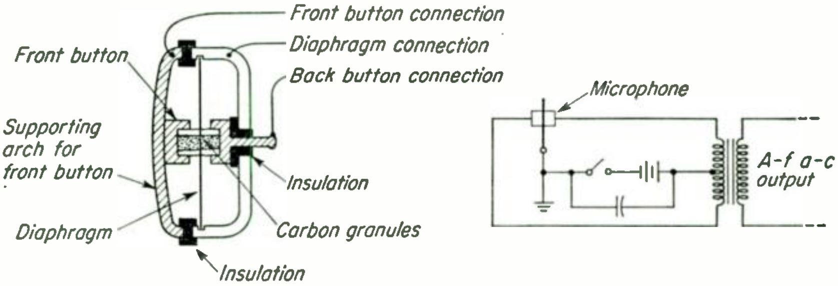


FIG. 16.35. Cross section of a double-button carbon microphone, and the circuit in which it is used.

The cross-section illustration and diagram in Fig. 16.35 shows a simplified version of the double-button microphone and a possible circuit.

When the diaphragm is vibrated inward by sound waves, it compresses the granules between the diaphragm and the back button, at the same time loosening the granules between the diaphragm and the front button. As a result, more current flows through the back button and less through the front. Since the buttons are connected to opposite ends of the microphone transformer, a push-pull effect is obtained whereby the current variations in each half of the primary are in such phase as to be additive and produce an increased voltage in the secondary winding.

Although it appears that the two buttons working in push-pull should produce more secondary voltage than a single-button microphone, the additional damping due to the second button desensitizes the microphone. Vibrations in both directions, being equally damped, result in a decrease in the distortion of the output. The double-button microphone is an obsolete type.

**16.31 Magnetic-induction Microphones.** There are several types of microphones that fall into the general category of magnetic-induction microphones. They all operate on the principle that sound waves striking a diaphragm produce a relative movement between a magnetic field and a conductor, thereby inducing a voltage in the conductor. Only the *dynamic* microphone will be discussed. It is similar in general construction to a permanent-magnet dynamic loudspeaker (p-m), described in the chapter on Audio-frequency Amplifiers. It is a popular broadcast microphone, having an essentially flat frequency range from about 60 to well over 8,000 cycles in the better models. It requires no battery, as the carbon-button microphones do, being a form of a-c generator in itself. It can be built light, small, and rugged and at a comparatively low cost. It has an output power of −50 to −60 db.

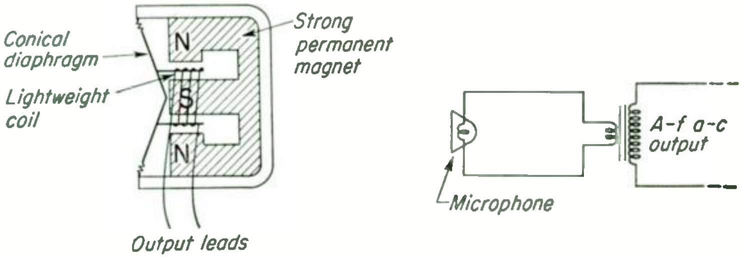


FIG. 16.36. Cross section of a dynamic microphone, and the circuit in which it is used.

The cross-section illustration and diagram of Fig. 16.36 shows a simplified construction and the dynamic-microphone circuit.

A conical diaphragm has a small coil attached to it, but is free to move in and out of the space between north and south poles of the magnet. Vibration of the diaphragm by sound waves moves the coil back and forth across the lines of force, inducing an a-c in the turns of the coil. The a-c will have a frequency equal to the diaphragm-vibration frequency and an amplitude proportional to the extent of the diaphragm vibration.

The moving-coil impedance is very low, only a few ohms. A step-up transformer, usually built into the microphone case, is required to enable the output of the microphone to match the input circuit transformers of amplifiers with which it is to be used. In broadcast equipment, the input impedance of such amplifiers will be between 30 and 600 ohms.

*Sound-powered microphones*, used for voice communications in special telephone lines, are dynamic-microphone types. Since high fidelity is not a factor for voice transmission, it is possible to obtain relatively high-power output, from zero to plus 10 db, by close talking into such microphones. When earphones are connected across these microphones, the resulting signal is loud enough to operate the earphones satisfactorily. Such a microphone can also be used as an earphone, operating the same as a p-m loudspeaker.

Dynamic microphones must be kept away from a-c fields. If the coil is held near a power transformer or any fairly strong alternating field, a hum will be induced in the microphone. It is sometimes possible to minimize such hum by turning the microphone in a different direction.

Other microphones operating on the magnetic-induction principle have various names: magnetic, variable-reluctance, ribbon, velocity, etc. Even an earphone will operate as a microphone, although with poor fidelity.

When it is necessary to use long microphone leads, the lower the impedance of the lines, the less extraneous noise will be picked up and the less high-frequency attenuation due to capacitance between the conductors making up the line. This rule of low impedance for long lines is true for all types of microphones and audio lines in general.

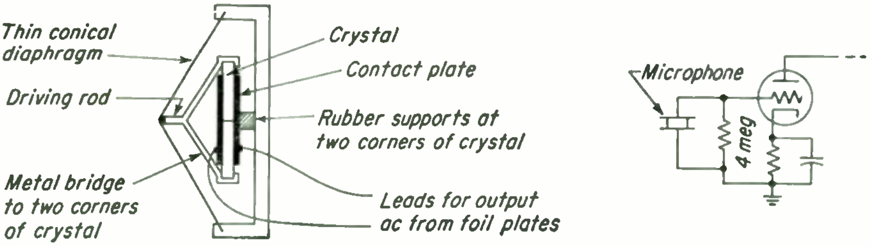


FIG. 16.37. Cross section of a crystal microphone, and the circuit in which it is used.

**16.32 The Crystal Microphone.** The crystal microphone is found mostly in public-address, amateur-communication, and home-recording systems. It has good frequency response, from about 50 to 8,000 cycles, and relatively good sensitivity, −40 to −50 db. It is fairly rugged mechanically, is satisfactory when used as a hand microphone, and may be spoken into from close range. It is rarely used in broadcasting.

The crystals used in crystal microphones are subject to two troubles. Moisture or a temperature of more than 120°F, (easily produced by summer sun striking the microphone) will ruin them. Newer developments with ceramics are overcoming these difficulties.

The *rochelle-salts* crystals of these microphones have piezoelectric properties similar to quartz crystals used in oscillators. When the crystal is vibrated mechanically, an a-c emf is developed between any two metal plates held against opposite surfaces of the crystal. This a-c will be proportional to both the vibration frequency and amplitude.

Sound waves striking the conical aluminum diaphragm of the crystal microphones shown in Fig. 16.37 will cause it to vibrate. These vibrations are mechanically transmitted by a small driving rod to two of the opposite corners of a thin, square crystal. The mechanical vibrations alternately bend the crystal in and out, producing an AF a-c between the two foil plates cemented to the two flat sides of the crystal. The output leads from the microphone are connected to the two plates.

The output impedance of the crystal microphone is high, in the range of several million ohms, necessitating relatively short leads to the input circuit of the microphone amplifier to prevent loss of the higher audio frequencies, or hum pickup. The leads must be well shielded, and not more than about 20 ft long.

**16.33 The Condenser Microphone.** In the late 1920s, the best broadcasting microphone was probably the electrostatic, or condenser (capacitor), microphone. Its frequency response was good, from about 50 to 10,000 cycles. However, it required a high-voltage battery to operate it, and because it had an exceptionally high impedance, the leads of the microphone had to be very short. The first amplifier stages were constructed in the microphone case for this reason. This made it quite bulky, because of the size of the tubes and parts in use at that time. When dynamic and other microphones were developed, the condenser microphone lost favor and was no longer produced.

During the Second World War great strides were made in reducing the size of radio tubes and parts. After the war, TV increased in popularity, and along with it a demand developed in other fields for a small, thin microphone which would not hide a performer behind it. By utilizing a tiny condenser head mounted above subminature-tube amplifiers, a microphone was developed that had a diameter of about ¾ in. at the top and tapered out to an inch or so a few inches lower. The cable to the microphone contains not only the output lines from the microphone unit, but also the required power-supply lines for the tubes and condenser head. The diaphragm of this type of microphone faces upward, giving it an *omnidirectional* (all-direction) response. The diaphragm is tightly stretched to prevent it from resonating at any audible frequency and reproducing sounds at the resonant frequency with excessive output.

The cross-section illustration and diagram in Fig. 16.38 shows the elements of a condenser-microphone head, accompanied by a possible one-tube-circuit diagram.

When sound waves strike the tightly stretched diaphragm of the condenser microphone, it vibrates, changing the capacitance between front and back plates. This capacitance changes in accordance with the frequency and amplitude of the sound waves. In this way, sound waves produce a variation of capacitance.

When the circuit is operating, electrons move down through the resistor

$R$, until there is a difference of electron charge equivalent to 200 volts across the capacitor. Then the current ceases to move, but an excess of electrons remains on the front plate and a deficiency on the back. If the capacitor had a greater capacitance, it would have taken more electrons on the front plate to produce the 200-volt charge.

If the charged capacitor suddenly changes to a greater capacitance by the plates being forced closer together, a current of electrons will flow through the resistor until the charge on the capacitor becomes 200 volts again. This capacitor-charging current through the resistance produces a voltage drop across it, the value being equal to $E = IR$. As the capacitance varies, because of diaphragm vibration, electrons are forced to flow back and forth through the resistor as the capacitor charges and discharges and an a-c emf is developed across the resistor. The emf will vary in frequency and amplitude in accordance with the sound waves striking the diaphragm. The condenser microphone has a sensitivity of about $-90$ db.

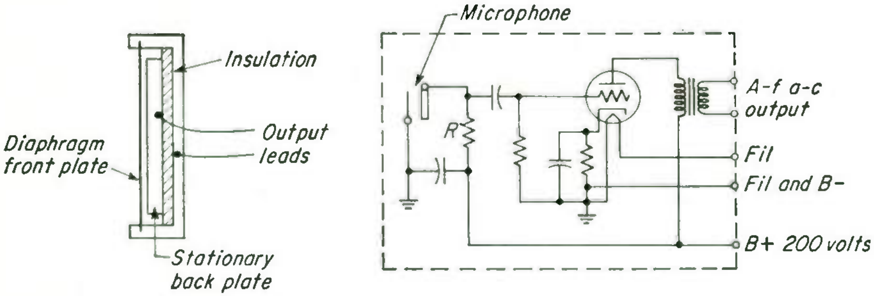


FIG. 16.38. Cross section of a condenser microphone, and the circuit in which it is used.

**16.34 Tuning a Radiotelephone Transmitter.** The diagram in Fig. 16.39 represents a simplified but workable radiotelephone transmitter. As a general review of radiotelephone circuits, a short description of the operation of each stage is given. At the start, the filaments of all tubes are on, but all plate voltage supplies are off.

The crystal-oscillator power supply is turned on. The plate tank circuit of this stage is tuned to a plate-current dip, or minimum, as indicated by meter $M_1$. The grid current meter $M_2$ will usually read maximum when the $M_1$ reading is slightly off the minimum value. If the $M_2$ reading is too low, the capacitance of coupling capacitor $C_1$ may be increased.

The buffer is neutralized, and then the power supply is turned on. The buffer-plate tank circuit is tuned to a dip as indicated on meter $M_3$. The grid tank $LC_3$ is tuned to a maximum grid current as shown by meter $M_4$. If the grid current is not the desired value, the link coupling to $LC_3$ can be tightened or loosened as required.

The modulated-amplifier power supply is set for low-voltage output and turned on. The shunt-fed final plate tank circuit is tuned to a minimum plate current reading as indicated by plate current meter $M_5$. The plate voltage is raised to the operating value.

The antenna is loosely coupled to the final tank circuit and tuned to resonance, indicated by a peak reading of the RF current meter $M_6$, or a peaking of the plate current on meter $M_5$. The coupling is increased until the desired antenna current is produced, or until the desired plate current value is shown by $M_5$.

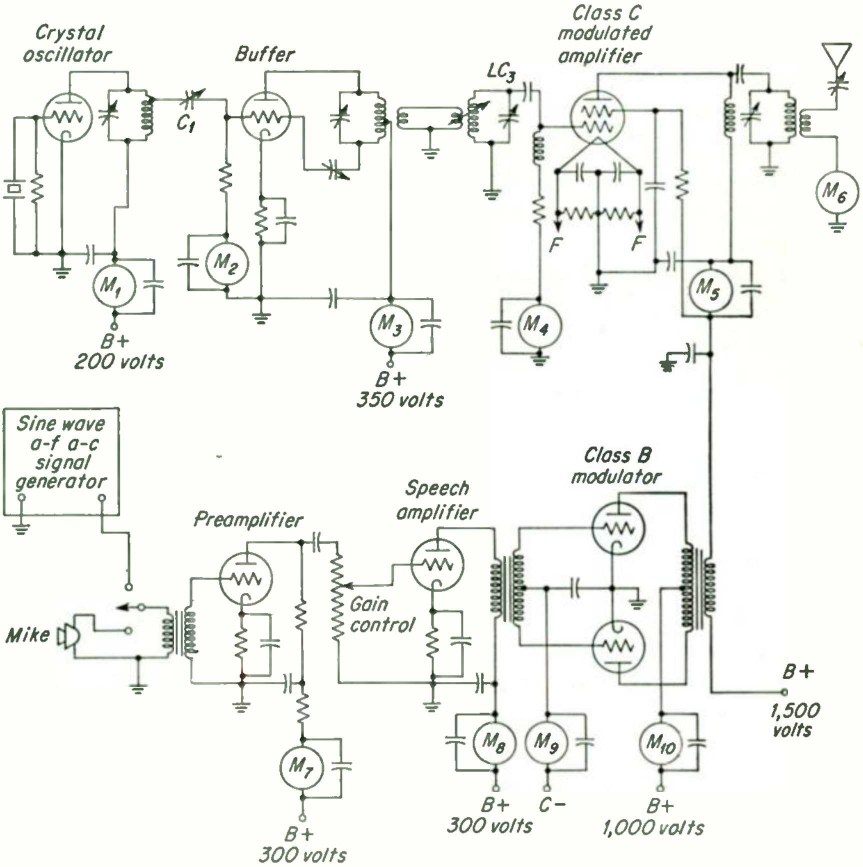


FIG. 16.39. Schematic diagram of a radiotelephone transmitter, and meters that indicate its operation.

The *preamplifier* stage (the audio amplifier before the audio gain control) is turned on and a sine-wave signal generator is fed to the input transformer of the preamplifier. The signal-generator output is increased until a change of plate current is noted in meter $M_7$ and is then decreased slightly. The class A preamplifier is probably not distorting at this signal-input level.

The speech-amplifier gain control is turned down to the bottom, and the stage is turned on. The gain control can be increased up to the point where plate current begins to change, as shown by meter $M_8$. The change in average plate current in this class A stage indicates distortion is being produced in the stage. This is as high as the gain control may be turned with the signal generator set at its present level.

The bias voltage value of the modulator stage should be checked. If the modulator is to be operated as push-pull class A, there should be no indication of grid current in meter $M_9$. It may be necessary to reduce the gain control to a point where no grid current flows. If the modulator is biased for operation as class $AB_2$ or class B, grid current should flow with the gain control set to its maximum allowable point, as determined previously.

With the gain control again turned down, the modulator is turned on. If the modulators are biased to class A, the plate current in meter $M_{10}$ should read the value indicated in the tube manufacturer's data sheet for the type tubes used in the modulator stage. If biased to class $AB_2$, there will be considerably less *static* (no input signal) plate current. If biased to class B, there will be very little static plate current.

When the gain control is turned up, the RF ammeter should rise, and *all other meters*, except possibly the modulator stage grid and plate meters, should *remain steady*. If the modulator is biased to class A, neither of its meters should move. However, if biased to class $AB_2$ or B, at a low-gain-control setting the grid current may not indicate, but the plate current may increase with modulation. At a high-gain-control setting, the plate current and the grid current will both rise.

The average plate current of the modulated amplifier should remain constant, with or without modulation. Any material change of meter $M_5$ indicates the presence of carrier shift and distortion of the modulated envelope. Actually, at high percentages of modulation this current value will usually drop a little, but not more than 1 or 2 per cent. This plate-current-meter action is the same for plate- or grid-modulated stages, as well as for linear amplifiers.

If an oscilloscope is available, a check on percentage of modulation and linearity of the modulated waveform can now be made.

The microphone can be switched on and spoken into. The antenna current should rise slightly. It will probably be necessary to raise the gain-control setting to produce a high percentage of modulation because of the low-amplitude output of microphones. In fact, a second preamplifier or speech-amplifier stage would undoubtedly be needed to bring the weak output of the microphone up to the required level to modulate the transmitter completely. The percentage of modulation of speech is best checked with an oscilloscope.

If the modulation transformer suddenly develops one or more shorted turns in either the primary or secondary, all meter readings will be normal with no modulation. When modulation is applied, a heavy current will be induced in the shorted part, lowering the impedance of the primary, increasing the modulator plate current, and distorting the audio signal. The plate-current indication in meter $M_{10}$ will increase excessively, the percentage of modulation will drop off, negative carrier shift will be produced, and the antenna current will not increase as much as normally. The shorted transformer may buzz audibly, become excessively warm, may smoke after a short time, and may burn up. The plates of the modulator tubes may become hotter than normal.

With the modulator stage biased to class B, the plate-current indication varies directly with the signal output of the stage. The modulator plate meter $M_{10}$ can be used as a relative indication of the percentage of modulation. A small plate-current increase indicates a low percentage of modulation. A large plate-current increase indicates a high percentage of modulation.

When tuning a transmitter, the operator must keep in mind that the equipment contains lethal voltages. As a general rule, while tuning, keep one hand in a pocket. Do not touch the microphone. Touching the antenna leads on high-powered transmitters can result in severe burns, or worse. Most commercial transmitters have built-in safety devices to protect personnel and equipment, such as door interlocks that disconnect the high-voltage supplies if the doors of the transmitter are opened, and overload relays that automatically shut down the equipment if excessive current flows. In some cases lights flash on or bells ring if trouble occurs in any circuit. Such relays can be set to sound the alarm if either more or less than normal current flows.

If the operator knows the circuits in his equipment, he can tell by the various meter readings if and where any trouble occurs.

**16.35 Single-sideband Radiotelephone.** Fading signals have always been one of the main difficulties in radio communications, particularly when the transmission path is several hundred or thousand miles long. Radiotelephone signals not only fade up and down in strength, but some sideband frequencies fade up as others fade down, or the carrier may fade at different rates and times from either sideband. This results in varying signal strengths and a characteristic rolling distortion effect. For a time, the signals may have few low AF components, and in another instant it may have few high audio components. This may produce voice transmissions that are completely unintelligible at times, regardless of how loud they are. The difficulty is due to the upper and the lower sidebands fading at different rates. This can be partly overcome by producing both sidebands at the transmitter, but eliminating one by using very sharp RF filter circuits. Now the transmitter radiates only a carrier and one set of sideband signals.

The difficulty of the carrier and the sidebands fading at different rates still exists. It can be eliminated by balancing out the carrier at the transmitter, filtering out one sideband as before, and transmitting only the remaining sideband frequencies. This is known as *single-sideband suppressed-carrier* (SSSC, SSB, or A3a) emission. Figure 16.40 shows a double-sideband signal, the same emission with one sideband filtered out, and lastly, the same signal with one sideband and the carrier filtered out.

A3a signals produce a muffled noise in the normal radiotelephone receiver and cannot be understood because there is no carrier for the sideband signals to beat against to produce heterodyne, or beat, frequencies in the receiver. At the receiver it is possible to use an oscillator adjusted to the frequency that the carrier would have if it were transmitted and feed this frequency into the receiver at the same time as the sidebands are received. Now the sideband signals can beat against a correct-frequency local carrier and produce the proper audio tones to reproduce the original intelligence or sounds.

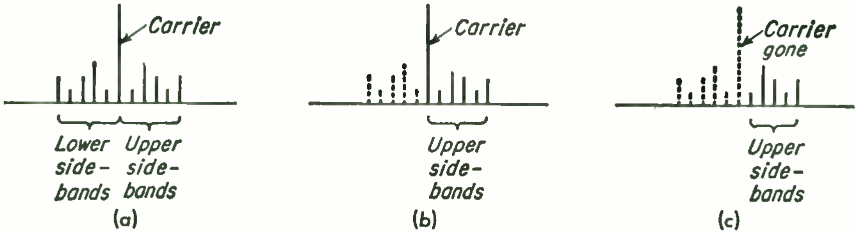


FIG. 16.40. (*a*) A carrier and sidebands due to multitone modulation. (*b*) Single sideband with carrier. (*c*) Single sideband with suppressed carrier.

Inserting a nonfading carrier signal at the receiver is quite a saving for the transmitter and results in better sounding signals. In normal double-sideband transmissions, at 100 per cent modulation, two-thirds of the power transmitted is in the carrier and one-third is in sidebands. With A3a, little or no power is wasted in transmitting a carrier, and only half of the sideband power is required. Furthermore, all the radiated power is in sidebands, which is the only part of the transmission carrying any intelligence.

At present, most single-sideband emissions are used for voice communication. Music is still transmitted with double sidebands because of the lack of adequate receiving equipment by the general public.

Voice transmissions on single sideband may still fade up and down in strength, and at different instants the high or the low frequencies may predominate, but the rolling distortion fade of short-wave signals may be eliminated. Only a few years ago, radio news transmissions relayed across the oceans were hardly understandable at times. Today, by the use of single-sideband transmissions, they may fade but are usually of relatively good quality.

It is somewhat difficult to construct filters sharp enough to eliminate one set of sideband signals without taking out some of the other sideband signals too. In the past it was necessary to start at lower radio frequencies (10 to 100 kc) because at these frequencies the filters can be made sharper more easily. If the carrier starts at a low frequency, it is necessary to heterodyne, or beat, the signals to the higher frequencies where they are normally transmitted. Frequency multipliers *cannot* be used, as they would multiply the spacing of the sideband signals and produce an output that would be unintelligible when mixed with the carrier frequency.

Figure 16.41 is a block diagram of a possible single-sideband transmitter to operate on a (suppressed) carrier frequency of 8,000 kc.

The 50-kc crystal oscillator and buffer provide the carrier to be modulated. The microphone and speech amplifiers provide the audio modulating signal, usually from 150 to 3,000 cycles. The RF and AF voltages are fed simultaneously into a special mixer circuit called a *balanced*, or *ring*, modulator, which amplitude-modulates the 50-kc carrier but cancels the carrier at the same time. The output of this stage contains the upper and the lower sidebands, 50–53 kc and 47–50 kc (actually 50,150–53,000 cycles and 47,000–49,850 cycles), but no carrier.

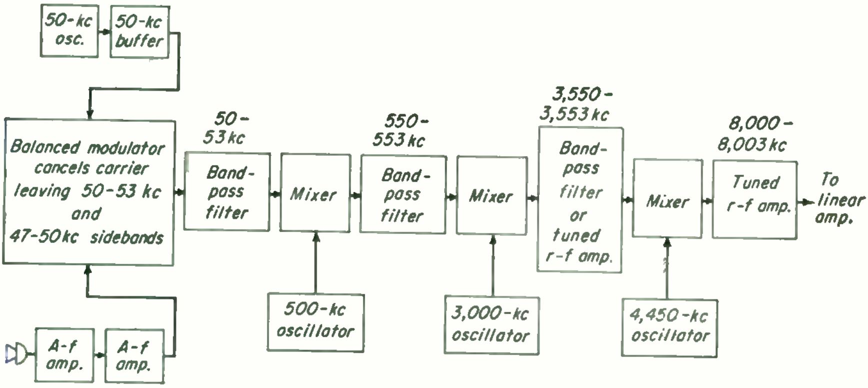


FIG. 16.41. Block diagram of a filter-type single-sideband transmitter.

The upper and lower sidebands are fed to a sharp bandpass filter that passes the upper sideband frequencies, 50–53 kc, but filters out the lower. The output from this filter will be 50–53-kc signals only.

The 50–53-kc sideband signal is mixed with a 500-kc signal. These beat together and produce a sum and difference frequency. The sum frequencies of 550–553 kc, the difference frequencies of 447–450 kc, and the 500-kc oscillator signal are all present in the output. These are fed to a bandpass filter that passes the 550–553-kc signals, but not the others. Note that this filter can pass frequencies of 501–600 kc and still not pass the oscillator or lower sideband signals. It is only the first filter that must have a narrow bandpass and sharp cutoff characteristic. The original sidebands of 50–53 kc have now been moved 500 kc up the RF spectrum, but still exist in their original spacing and form.

The 550–553-kc signal is mixed with a 3,000-kc signal, again producing a sum and difference frequency. The sum frequency of 3,550–3,553 kc is so far removed from the oscillator frequency of 3,000 kc that a simple tuned amplifier stage can now act as the bandpass filter and pass only the sum frequency to the next mixer stage.

The 3,550–3,553-kc signals are finally mixed with a 4,450-kc oscillator to produce 8,000–8,003-kc signals. The original sidebands have now been moved up to 8 Mc in the RF spectrum. The 8,000–8,003-kc signals are amplified with linear amplifiers and are transmitted as the single-sideband signal.

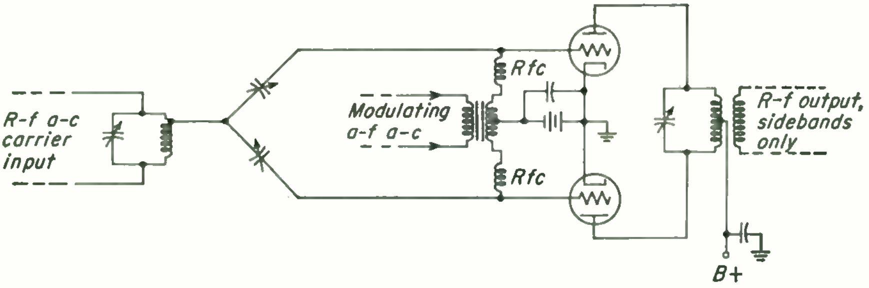


FIG. 16.42. A balanced modulator circuit.

To change the output frequency of the transmitter it is only necessary to change the frequency of the last oscillator stage (the 4,450-kc oscillator in the system described) and the tuning of the linear amplifiers.

There are many different circuits used as balanced modulators. The one shown in Fig. 16.42 feeds an RF carrier to the two grids in parallel, and the audio modulating voltage (control-grid modulation in this case) is fed to the two grids in push-pull. The RF carrier balances out in the plate circuit (both grids are driven positive at the same time, producing equal and opposite current flow in the plate coil). Since the tuned circuit has practically zero impedance to audio frequencies, there can be no audio output. However, the results of modulation, namely, the upper and lower sidebands, are not canceled. The output of the circuit consists of the sidebands only, if the circuit is properly balanced.

Filters using several quartz crystals or specially constructed high-$Q$ components have been developed that are sharp enough in the 500-kc region to filter one sideband adequately. This results in a somewhat simpler transmitter. The basic principle remains the same as that of the older transmitters, however.

In commercial work, a *vestigial* (pronounced ves-tij-ee-al, meaning "slight trace") carrier is usually transmitted. Instead of completely canceling the carrier at the balanced modulator, a little of it is allowed to remain in the transmitted signal. At the receiving station the local oscillator is made to lock in, or synchronize on the frequency of the carrier, preventing the distortion that results if the local carrier is a few cycles off frequency.

In some commercial sideband communications the voice is scrambled, heterodyned, or *inverted* before modulation, in such a manner that the casual listener is unable to reproduce the intelligence with any simple device such as a local oscillator.

By the use of more complex transmitters, it is quite possible to transmit one conversation with one sideband and another on the other sideband, using the same carrier frequency. This is known as an *A3b emission.*

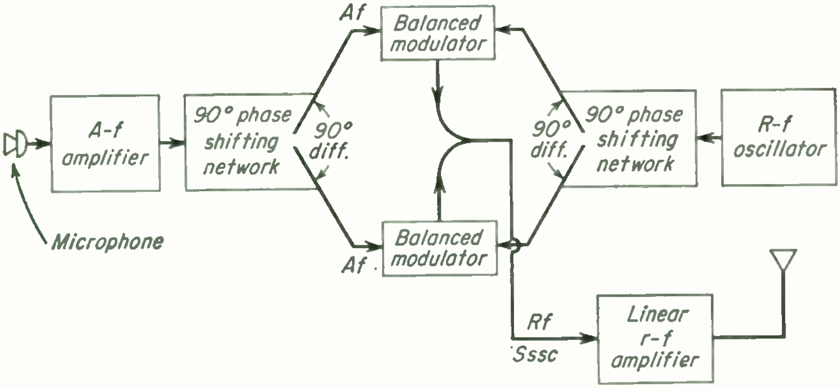


FIG. 16.43. Block diagram of a phasing system that produces an SSSC emission.

It is possible to have several conversations in progress at the same time, as well as a few radioteletype transmissions, all using the same carrier frequency. The voice emission may require the first 3 kc of sideband out from the carrier. A teletype signal can use the next 500 cycles out, a second teletype can use the next 500 cycles, and so on. At the receiving station, filters separate the information transmitted on each section of the sideband. The other sideband can be similarly modulated. (Radio is beginning to become complex!)

Another entirely different method of producing a single-sideband suppressed-carrier emission is to use 90° phasing networks. A block diagram of a phasing type SSB transmitter is shown in Fig. 16.43.

The audio frequency from a microphone is amplified and fed into a resistance-capacitance (RC) phase-shifting network that passes it along one of its circuits and produces a 45° lag in the signal, and at the same time passes it along another circuit and produces a 45° lead in the signal. The result is the same audio signal being emitted from two different parts of the network with a phase difference of 90°.

Radio frequency a-c from an oscillator on the desired frequency of operation is fed into a 45° RL and into a 45° RC phase-shifting network, resulting in two similar RF signals, except that they are 90° out of phase.

One of the AF signals and one of the RF signals are fed into a single balanced modulator stage. At the same time the other AF and RF signals are fed into another similar balanced modulator. When the outputs of the balanced modulators are combined, the carrier frequency has been balanced out, one sideband has been emphasized, and the other has been minimized to such an extent that it is practically nonexistent. This is assuming proper balancing of the respective circuits involved.

The resulting SSSC emission is fed into one or more linear amplifiers until the output power is at the desired level.

It is possible to switch from one sideband to the other by connecting the two out-of-phase audio signals to the opposite balanced modulators.

The phasing-type system has the advantage of not requiring any heterodyning to operate on high frequencies. Its carrier frequency may be the frequency generated by the RF oscillator, or frequency multipliers may be used between the oscillator and the RF phase-shifting circuits. The RF phase-shifting network will have to be changed if the frequency of operation is changed, however.

It is not too difficult to produce audio phase-shifting networks that will hold close enough to 90° phase difference over a range of 200 to 3,000 cycles, which is the voice frequency range. Extending the AF range and maintaining a precise 90° phase difference to produce proper balancing and cancellation of one sideband becomes difficult.

The phasing system of SSB is used in amateur radio communication to a great extent, while the filter systems are used commercially.

Besides the elimination of distortion fade, there are two other advantages of SSB over the simpler double-sideband AM. One is the considerably smaller power required to transmit only one sideband instead of two sidebands plus the carrier, and the other is the relatively small spectrum space required. As a comparison, an A3 amplitude-modulated voice transmission requires a bandwidth equal to twice the highest modulating frequency, or about 6 kc. An SSB, A3a emission requires only about 2.8 kc to transmit the same voice signals.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** What form of energy is contained in a sound wave? (16.3) [3]

**2.** What characteristic determines the pitch of a sound? (16.3) [3]

**3.** Describe the construction and characteristics of a carbon-button-type microphone. (16.4, 16.30) [3]

**4.** What was the first type of microphone that is still in use? (16.4) [3]

**5.** What may cause packing of the carbon granules in a carbon-button microphone? (16.4) **[3]**

**6.** Why is a separate source of plate power desirable for a crystal-oscillator stage in a radio transmitter? (16.6) **[3]**

**7.** What is meant by frequency shift, or dynamic instability, with reference to a modulated RF emission? (16.6) **[3]**

**8.** What might cause FM in an amplitude-modulated radiotelephone transmitter? (16.6) **[3]**

**9.** Draw a diagram of a microphone circuit complete with two stages of audio amplification. (16.7) **[3]**

**10.** Why is a high percentage of modulation desirable in amplitude-modulated transmitters? (16.10) **[3]**

**11.** Draw a diagram of a carrier-wave envelope when modulated 50 per cent by a sinusoidal wave. Indicate on the diagram the dimensions from which the percentage of modulation is determined. (16.10) **[3]**

**12.** What are some of the possible results of overmodulation? (16.11) **[3]**

**13.** What is meant by plate modulation? (16.11) **[3]**

**14.** Draw a simple schematic diagram showing a method of coupling a modulator tube to an RF power-amplifier tube to produce plate modulation of the amplified RF energy. (16.11) **[3]**

**15.** What is the relationship between the average power output of the modulator and the modulated-amplifier plate-circuit input, under 100 per cent, sinusoidal plate modulation? (16.11) **[3]**

**16.** Draw a simple schematic diagram showing the proper method of obtaining d-c screen-grid voltage from the plate supply in the case of a modulated-pentode, class C amplifier. (16.12) **[3]**

**17.** Draw a simple schematic diagram showing a Heising modulation system capable of producing 100 per cent modulation. Indicate power-supply polarity where necessary. (16.16) **[3]**

**18.** What is meant by grid modulation? (16.17) **[3]**

**19.** Draw a simple schematic diagram showing a method of coupling a modulator tube to an RF power-amplifier tube to produce grid modulation of the amplified RF energy. (16.17) **[3]**

**20.** Draw a simple schematic diagram showing a method of suppressor grid modulation of a pentode-type vacuum tube. (16.18) **[3]**

**21.** How may the distortion effects caused by class B operation of an RF amplifier be minimized? (16.22) **[3]**

**22.** What is the effect of carrier shift in a plate-modulated class C amplifier? (16.25) **[3]**

**23.** What are causes of downward fluctuation of the antenna current of an amplitude-modulated transmitter when the transmitter is modulated? (16.26) **[3]**

**24.** What may cause upward fluctuation of the antenna current of an amplitude-modulated transmitter when the transmitter is modulated? (16.26) **[3]**

**25.** What might be the cause of a decrease in antenna current of a high-level amplitude-modulated radiotelephone transmitter when modulation is applied? (16.26) **[3]**

**26.** What are possible causes of negative carrier shift in a linear RF amplifier? (16.26) **[3]**

**27.** Describe the construction and characteristics of a crystal-type microphone. (16.31) **[3]**

**28.** In the adjustment of a radiotelephone transmitter, what precautions should be observed? (16.34) **[3]**

**29.** What is the purpose of a preamplifier? (16.34) **[3]**

**30.** Should the plate current of a modulated class C amplifier stage vary or remain constant under modulation conditions? Why? (16.34) **[3]**

**31.** What might be the cause of variation in plate current of a class B type of modulator? (16.34) **[3]**

**32.** What would be the effect of a shorted turn in a class B modulation transformer? In a class A modulation transformer? (16.34) **[3]**

**33.** Define the term decibel. (16.3) **[3 & 6]**

**34.** Draw a diagram of a single-button carbon microphone circuit including the microphone transformer and source of power. (16.4) **[3 & 6]**

**35.** What is the ratio of modulator a-c power output to modulated amplifier d-c plate power input for 100 per cent amplitude modulation? (16.11) **[3 & 6]**

**36.** If a 1,500-kc radio wave is modulated by a 2,000-cycle sine-wave tone, what frequencies are contained in the modulated wave? (16.14) **[3 & 6]**

**37.** What is meant by low-level and high-level modulation? (16.20) **[3 & 6]**

**38.** If the first speech-amplifier tube of a radiotelephone transmitter were overexcited but the percentage modulation capabilities of the transmitter were not exceeded, what would be the effect upon the output of the transmitter? (16.26) **[3 & 6]**

**39.** In a modulated class C RF amplifier, what is the effect of insufficient excitation? (16.26) **[3 & 6]**

**40.** What percentage of antenna-current increase would be expected between unmodulated conditions and 100 per cent sinusoidal modulation? (16.28) **[3 & 6]**

**41.** Name four methods for generating an electric potential. (16.29) **[3 & 6]**

**42.** What precautions should be observed in the use of a double-button carbon microphone? 16.30) **[3 & 6]**

**43.** What precaution should be observed when using and storing crystal microphones? (16.31) **[3 & 6]**

**44.** What is the most serious disadvantage of using carbon microphones with high-fidelity amplifiers? (16.4, 16.30) **[4]**

**45.** Why is FM undesirable in the standard broadcast band? (16.5) **[4]**

**46.** What is the last AF amplifier stage which modulates the RF stage termed? (16.7) **[4]**

**47.** What is the ratio of unmodulated carrier power to instantaneous peak power at 100 per cent modulation at a standard broadcast station? (16.9, 16.11) **[4]**

**48.** What undesirable effects result from overmodulation of a broadcast transmitter? (16.10) **[4]**

**49.** What are the results of using an audio peak limiter? (16.10) **[4]**

**50.** State advantages and disadvantages of class B modulators. (16.11) **[4]**

**51.** If you decrease the percentage of modulation from 100 to 50 per cent, by what percentage have you decreased the power in the sidebands? (16.11) **[4]**

**52.** What percentage increase in average output power is obtained under 100 per cent sinusoidal modulation as compared with average unmodulated carrier power? (16.11) **[4]**

**53.** Discuss the characteristics of a modulated class C amplifier. (16.11, 16.17) **[4]**

**54.** A certain transmitter has an output of 100 watts. The efficiency of the final modulated amplifier stage is 50 per cent. Assuming that the modulator has an efficiency of 66 per cent, what plate input to the modulator is necessary for 100 per cent modulation of this transmitter, assuming that the modulator output is sinusoidal? (16.11) **[4]**

**55.** How is the load on a modulator which modulates the plate circuit of a class C RF stage determined? (16.11) **[4]**

**56.** Given a class C amplifier with a plate voltage of 1,000 volts and a plate current of 150 ma which is to be modulated by a class A amplifier with a plate voltage of 2,000 volts, a plate current of 200 ma, and a plate impedance of 15,000 ohms. What is the proper turns ratio for the coupling transformer? (16.11) **[4]**

**57.** If a frequency of 500 cycles is beat with a frequency of 550 kc what will be the resultant frequencies? (16.14) **[4]**

**58.** Draw a simple schematic diagram of a grid-bias modulation system, including the modulated RF stage. (16.17) **[4]**

**59.** In a properly adjusted grid-bias modulated RF amplifier, under what circumstances will the plate current vary as read on a d-c meter? (16.17) **[4]**

**60.** Define high-level and low-level modulation. (16.20) **[4]**

**61.** What pattern on a cathode-ray oscilloscope indicates overmodulation of a standard broadcast station? (16.21) **[4]**

**62.** If tests indicate that the positive modulation peaks are greater than the negative peaks in a transmitter employing a class B audio modulator, what steps should be taken to determine the cause? (16.21, 16.26) **[4]**

**63.** Draw a simple sketch of the trapezoidal pattern on a cathode-ray oscilloscope screen indicating low per cent modulation without distortion. (16.21) **[4]**

**64.** Draw a diagram of a class B push-pull linear amplifier using triode tubes. Include a complete antenna coupling circuit and antenna circuit. Indicate points at which the various voltages will be connected. (16.22) **[4]**

**65.** What do variations in the final-amplifier plate current of a transmitter employing low-level modulation usually indicate? (16.22) **[4]**

**66.** What may be the cause of a decrease in antenna current during modulation of a class B linear RF amplifier? (16.22) **[4]**

**67.** A 50-kw transmitter employs six tubes in push-pull-parallel in the final class B linear stage, operating with a 50-kw output and an efficiency of 33 per cent. Assuming that all the heat radiation is transferred to the water-cooling system, what amount of power must be dissipated from each tube? (16.22) **[4]**

**68.** With respect to the unmodulated values, doubling the excitation voltage of a class B linear RF amplifier gives what increase in RF power output? (16.22) **[4]**

**69.** Draw a schematic diagram of test equipment which may be used to detect carrier shift of a radiotelephone transmitter output. (16.25) **[4]**

**70.** What may cause unsymmetrical modulation of a standard broadcast transmitter? (16.25) **[4]**

**71.** In a modulated amplifier, under what circumstances will the plate current vary as read on a d-c meter? (16.26, 16.34) **[4]**

**72.** What could cause downward deflection of the antenna-current ammeter of a transmitter when modulation is applied? (16.26, 16.28) **[4]**

**73.** Name four causes of distortion in the output of a modulated amplifier stage. (16.26) **[4]**

**74** In a class C RF amplifier stage feeding an antenna system, if there is a positive shift in carrier amplitude under modulation conditions, what may be the trouble? (16.26) **[4]**

**75.** If a transmitter is modulated 100 per cent by a sinusoidal tone, what percentage increase in antenna current will occur? (16.28) **[4]**

**76.** What type of microphone employs a coil of wire, attached to a diaphragm, which moves in a magnetic field as the result of the impinging of sound waves? (16.31) **[4]**

**77.** Why are the diaphragms of certain microphones stretched? (16.33) **[4]**

**78.** Draw a diagram of a complete class B modulation system, including the modulated RF amplifier stage. Indicate points where the various voltages will be connected. (16.34) **[4]**

**79.** Draw a simple schematic diagram of a class B audio high-level modulation system, including the modulated RF stage. (16.34) **[4]**

**80.** During 100 per cent modulation, what percentage of the average output power is in the sidebands? (16.35) [4]

**81.** What are the advantages of the single-button carbon microphone? (16.4) [6]

**82.** Why is a speech amplifier used in connection with the modulator of a radiotelephone transmitter? (16.7) [6]

**83.** Draw a circuit diagram showing how a microphone can be connected to an audio amplifier. (16.7, 16.30–16.32) [6]

**84.** The d-c plate input to a modulated class C amplifier with an efficiency of 60 per cent is 200 watts. What value of sinusoidal audio power is required in order to insure 100 per cent modulation? 50 per cent modulation? (16.11) [6]

**85.** What is the total bandwidth of a transmitter using A2 emission with a modulating frequency of 800 cycles and a carrier frequency of 500 kc? (16.14, 16.15) [6]

**86.** What is the purpose of the plate choke in Heising modulation? (16.16) [6]

**87.** Why is a series resistor used in the d-c plate supply of a modulated RF amplifier, between amplifier and modulator, in a Heising modulation system? (16.16) [6]

**88.** Should the efficiency of a grid-bias modulated stage be maximum at complete modulation or zero modulation? Explain. (16.17) [6]

**89.** Does grid current flow in the conventional grid-bias modulated stage of a radiotelephone transmitter, under modulated conditions? (16.17) [6]

**90.** How should the bias of a grid-modulated RF stage be adjusted? (16.17) [6]

**91.** Compare the characteristics of plate and grid-bias modulation. (16.17) [6]

**92.** Under what "class" of amplification are the vacuum tubes in a linear RF amplifier stage, following a modulated stage, operated? (16.22) [6]

**93.** If a final RF amplifier operated as class B linear were excited to saturation with no modulation, what would be the effects when undergoing modulation? (16.22) [6]

**94.** What is the meaning of carrier shift? (16.25) [6]

**95.** Name the effects of overexcitation of a class B amplifier grid circuit. (16.26) [6]

**96.** What might be the causes of a positive shift in carrier amplitude during modulation? (16.26) [6]

**97.** What may cause a positive carrier shift in a linear RF amplifier output? (16.26) [6]

**98.** If a transmitter is adjusted for maximum power output for telegraph operation, why must the plate voltage be reduced if the transmitter is to be amplitude-modulated? (16.27) [6]

**99.** A transmitter has an antenna current of 8 amp using A1 emission. What would the antenna current be when this transmitter is 100 per cent modulated by sinusoidal modulation? (16.28) [6]

**100.** What types of microphones have a high impedance output? (16.32, 16.33) [6]

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

★**1.** What is the maximum permissible percentage of modulation of a radiotelephone station? (16.10)

★**2.** What is the recognized abbreviation for frequency modulation? (16.1)

★**3.** What is the recognized abbreviation for amplitude modulation? (16.1)

★**4.** What is the purpose of a modulator? (16.11)

★**5.** What is meant by modulation? (16.1)

★**6.** What are the undesirable effects of overmodulation in radiotelephony? (16.10)

**7.** What are the adverse effects of overmodulation on intelligibility and proper use of spectrum space? (16.10)

**8.** What are the relative bandwidths of types A1 and A3 emissions? (16.15)

**9.** What are the relative bandwidths of SSB and double-sideband AM? (16.35)

**10.** What is the amount of modulator sinusoidal power output required for 100 per cent amplitude modulation of a specified unmodulated power input of a class C amplifier? (16.11)

**11.** Why is simultaneous AM and FM in a radiotelephone transmitter undesirable? (16.5)

**12.** What is the meaning of the term sidebands with respect to AM? (16.14)

**13.** Draw a simple sketch of the RF envelope which will appear on the screen of a cathode-ray oscilloscope when connected to show a trapezoidal pattern with 100 per cent modulation. With 50 per cent modulation. With overmodulation. (16.21)

**14.** What may cause the antenna current to decrease when the carrier of a radiotelephone transmitter is plate-amplitude-modulated? (16.26)

## CHAPTER 17

# AMPLITUDE-MODULATION RECEIVERS

**17.1 Receivers.** There are many types of receivers. Some detect amplitude-modulated signals, some detect telegraph signals, others detect frequency-modulated signals, and still others will display a picture when tuned to a television signal. For each type of transmission there is some type of receiver that will detect it best.

This chapter considers receivers capable of detecting amplitude-modulated signals and radiotelegraph signals. Those used for FM and TV are discussed in the chapters on Frequency Modulation and Television.

A receiving system consists of an antenna, in which all passing radio waves induce an emf, a means of tuning the desired signal, a means of detecting, or *demodulating*, the modulation in the signal, and a means of making the detected electrical signal audible.

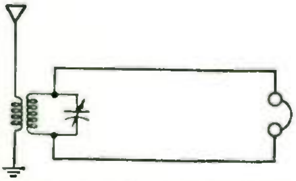


Fig. 17.1. Earphones alone across a tuned circuit will not detect radio signals.

A wire may serve as the antenna. The desired signal can be selected by using a resonant circuit. A detector can change the modulated RF a-c to an AF a-c or varying d-c. A pair of earphones or a loudspeaker can produce an audible response when fed the AF a-c.

At first it might be thought that a pair of earphones across a tuned circuit, as shown in Fig. 17.1, would operate as a receiver.

When the circuit is analyzed further, it is seen that such a circuit is unworkable. If the resonant circuit is tuned to the desired frequency, perhaps 1,000 kc, a voltage of that frequency is being developed across the tuned circuit and a current of that frequency may be flowing through the earphones. However, even if the earphone diaphragms could vibrate at that rate and produce air waves at a frequency of 1,000,000 cycles per second (cps), nothing would be heard. The ear is not sensitive to sound (air) waves higher than about 20,000 cps. If the carrier is modulated, the carrier frequency is still 1,000 kc, the sidebands are a little higher and lower, and are all inaudible.

The missing circuit component to change the inaudible RF to an electric impulse, either varying or alternating at an audible frequency, is a *detector*.

**17.2 Demodulating a Modulated Wave.** If the received carrier wave is amplitude-modulated by voice, tone, or music, it is possible to detect the variation of the carrier amplitude with a simple half-wave rectifier circuit, similar to those discussed in the chapter on Power Supplies. A diode-tube rectifying detector or receiver is shown in Fig. 17.2.

When the secondary is tuned to the frequency of a local modulated transmitter, RF a-c at this frequency is developed in it. The modulated RF is also illustrated. The high-impedance earphones and the rectifier form a load on the tuned circuit. Because of the rectifier, only unidirectional pulses can flow through the earphones. The resultant pulsating d-c is also shown.

With an unvarying carrier, constant-peak-amplitude d-c pulses flow through the earphones, pull the diaphragm inward a little, and hold it there. When the carrier is amplitude-modulated, the average current of the pulses varies with the modulation and the earphone diaphragm is pulled further inward or is released and moves outward. This controlled movement of the earphone diaphragm produces air waves which can produce the sensation of sound in the ear.

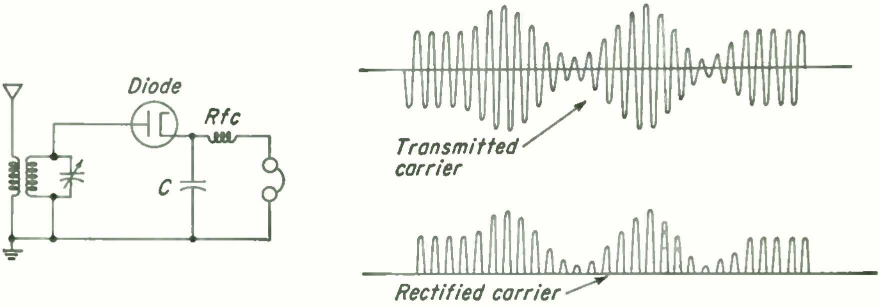


FIG. 17.2. A diode detector circuit, and a modulated carrier wave and the rectified (demodulated) carrier.

The *average* amplitude of the sinusoidal half-wave pulses is equal to one-half of the average value (½ of 0.636 maximum), or roughly one-third of the peak value. The average value can be increased to nearly the peak value by using a capacitive-input LC filter circuit (Fig. 17.2). The 0.0005- to 0.002-μf capacitor (condenser) charges to the peak value and tends to hold this value until the next RF pulse arrives. As a result, the average current through the earphones is increased, and a louder reproduction of the signal is heard. In many cases the RF choke (RFC) is not needed, the inductance of the windings of the earphones serving as the inductive filter.

The lower the impedance of the load, the greater the filter capacitance required. If this capacitance is too great, the capacitor will not discharge rapidly enough and the waveform of a cycle of high-frequency modulation may drop and rise again before the capacitor has time to discharge. As a result, current fed to the load will not vary at high-frequency audio rates and these high frequencies will be lost. With correct capacitance, this circuit can reproduce AM with high fidelity and is being used in almost all broadcast or voice receivers.

Note that in this detector there is no plate-circuit supply. The signal coming from the antenna supplies all the power that appears in the earphones. As a result, only relatively strong or local signals are audible.

The diode detector described has been a series-type half-wave rectifier. It is possible to connect the diode in a shunt circuit and demodulate equally well. A diagram of a shunt-type rectifier detector circuit coupled to a triode amplifier stage is shown in Fig. 17.3. In this circuit an RF emf from the tuned circuit is applied across the diode. When the plate is positive, electrons flow, and are stored on the right-hand plate of $C_1$. On the next half cycle the plate is driven negative and does not draw electrons. Those that had been drawn to it during the positive half cycle may now discharge through the RFC, charging capacitor $C_2$. This capacitor discharges through the primary of the audio transformer. If the carrier is modulated, the charge across capacitor $C_2$ varies, producing a varying direct current through the transformer primary and an alternating current in the secondary. The a-c is amplified by the triode, and relatively loud signals are now audible in the earphones. The RFC is required in the shunt circuit to prevent the coupling capacitor $C_1$ and the filter capacitor $C_2$ from being in series across the tuned circuit and detuning it.

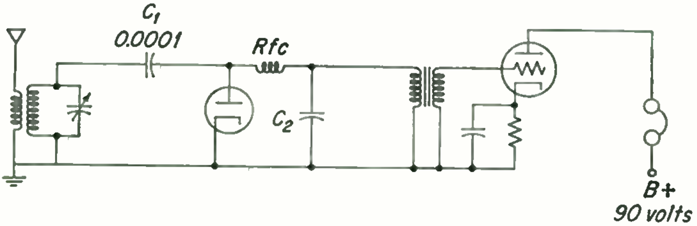


FIG. 17.3. A shunt-type diode detector with a stage of audio amplification.

**17.3 Crystal Detectors.** One of the first widely used rectifying demodulators was the *crystal detector*. Rectifier crystals are usually metallic crystals, such as galena, iron pyrites, germanium, silicon, and carborundum, to mention a few. (These must not be confused with quartz or rochelle-salts crystals used in oscillator circuits or in microphones.)

The crystal itself is usually embedded in a lead mounting. A thin pointed wire, called a *cat whisker*, is pressed against the surface of the crystal. If a *sensitive* spot is found on the crystal, considerably greater current will flow in one direction than in the opposite through the junction of the cat whisker and the crystal material, and effective rectification will be produced. A crystal rectifier can be connected in place of the diode tube in the previously explained circuits. A diagram of a crystal-detector receiver is shown in Fig. 17.4.

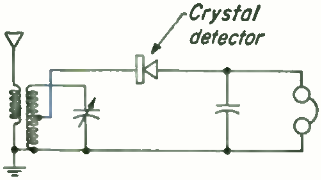


FIG. 17.4. A crystal-detector circuit. Tapping down the coil produces a higher-$Q$ tuned circuit.

Note that the crystal rectifier and the earphones are shown tapped part way down the tuned circuit. This results in less loading of the tuned circuit, allowing it to have a higher $Q$. With higher $Q$, the circuit will tune sharper, and little or no decrease in signal strength will be noted. This also allows the impedance of the load to match more closely the impedance of that part of the source across which it is connected. The diode detector and other tuned circuits used in radio receivers may also benefit by such tapping down.

**17.4 Plate and Power Detectors.** With the rectifying detectors described so far, the power of the signal in the earphones is always somewhat less than the RF power picked up by the antenna wire. When triode tubes are used in suitable circuits it is possible to obtain detection and also amplification of the input signal.

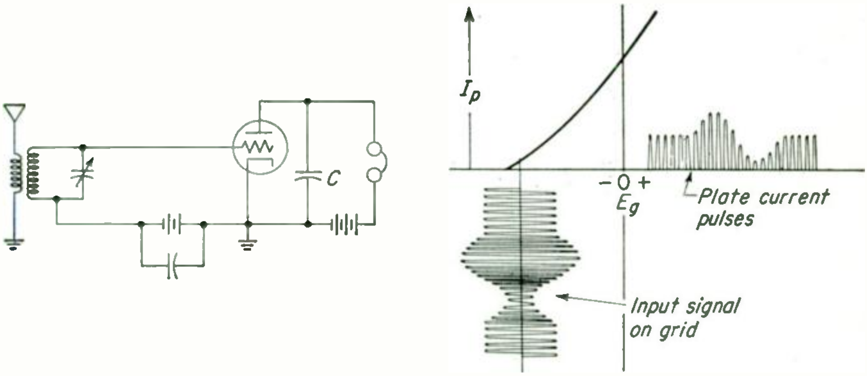


FIG. 17.5. A battery-biased power-detector circuit, and the rectification effect of the plate current.

One such circuit is called a *plate*, or *power*, detector. It is known as a plate detector because the *rectification effect* responsible for the demodulation of the signal takes place in the plate circuit of the tube. It is called a power detector because with a high plate voltage and a relatively high-amplitude signal voltage applied to the grid circuit a relatively high output audio power can be produced.

The power detector can be considered to consist of a class B biased RF grid circuit and a normal AF amplifier plate circuit. A diagram of a plate detector is shown in Fig. 17.5.

The grid circuit is biased almost to cutoff, as illustrated in the $E_gI_p$ graph. With no signal input there is almost no plate current. When a carrier is received, the positive half cycles of the signal produce plate-current pulses and the negative half cycles have practically no effect on the plate current. This is essentially rectification in the plate circuit. The bypass capacitor $C$ in the plate circuit filters the pulses and produces a higher average d-c flow in the plate circuit.

When the carrier is amplitude-modulated, the pulses in the plate circuit vary in amplitude. The voltage across the capacitor varies in accordance with the modulation, and the current flowing through the earphones varies similarly.

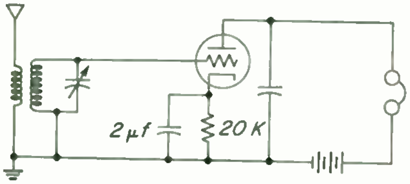


FIG. 17.6. A cathode-resistor-biased power-detector circuit.

The grid circuit of the power detector has relatively high bias, and grid current does not flow under normal signal conditions. As a result, the tuned circuit operates as though it had no load on it. With no load the $Q$ can be quite high, allowing a relatively high signal voltage to be developed with a given input signal and affording a fairly sensitive and selective tuning circuit. The power detector is considerably more selective than a diode or crystal receiver.

Instead of using a bias battery, a cathode resistor of about 20,000 to 50,000 ohms with a 1- or 2-μf capacitor across it will produce the necessary bias for the stage. This is the usual form of a plate detector and is shown in Fig. 17.6.

**17.5 Linear and Square-law Detectors.** The graph in Fig. 17.7 illustrates a plate current that is relatively linear (*a*) and a plate current that graphs according to the *square law* (*b*).

In the first, or linear, case (*a*), each time the voltage is doubled, the plate current is doubled. In the second (*b*), each time the voltage is doubled the plate current increases *four* times, or as the square of the voltage increase.

A linear rectifier circuit will produce a current waveshape essentially the same as the voltage waveshape. Little distortion is produced. With a square-law rectifier the waveshape of the output current will differ from the input-voltage waveshape, and distortion is produced. The same signal input may produce considerably more output from the square-law detector, however.

A diode tube is a nearly linear device, except when operated close to the zero-voltage–zero-current point, where it rounds off in a square-law manner. As long as the diode is operated well up in its curve, it will produce reasonably undistorted output. However, when it is operated near the zero-current value, it becomes a square-law device and produces distortion of the signal.

The power detector has considerably more curve to its $E_gI_p$ curve than does the diode. As a result more distortion can be expected from the power detector. With strong signals, the power detector is operating on the straightest portion of its curve and relatively little distortion is produced.

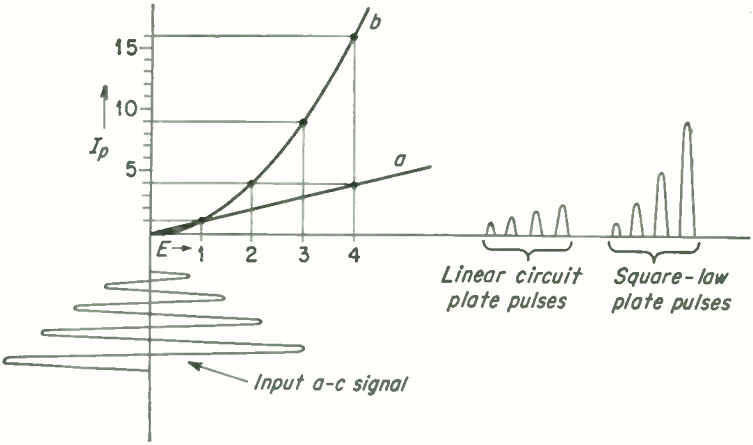


FIG. 17.7. Plate currents in (*a*) a linear rectifying circuit and (*b*) a square-law rectifying circuit.

High *percentages* of modulation may drive any of these detectors into the nonlinear part of their curves, and some distortion will be produced.

Actually, neither a diode nor a triode has a true square-law or linear curve.

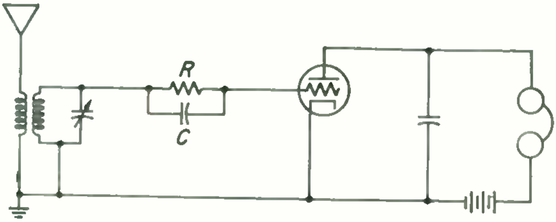


FIG. 17.8. A grid-leak detector circuit.

**17.6 Grid-leak Detectors.** The grid-leak detector was popular in the past because it had high over-all sensitivity. It may be considered to have a diode rectifier grid circuit and a normal AF amplifier plate circuit. A diagram of a grid-leak detector receiver is shown in Fig. 17.8.

Observation of the grid circuit shows it to consist of a tuned circuit (the RF a-c source), a rectifier (the cathode and *grid*), a resistance as a load, and a bypass or filter capacitor across the load. (If earphones were substituted for the resistor, signals would be heard in the diode detector circuit thus formed.) Received signals produce a varying d-c voltage across the grid-leak resistor $R$ (0.5 to 5 meg) and grid-leak capacitor $C$ (0.0001 to 0.0003 $\mu$f). Rectified current flows from grid, through the resistor, to cathode, making the grid end of $R$ negative. This negative d-c voltage acts as a bias for the triode. With no signal input, there is almost no current flowing in the grid circuit and almost no bias. The plate current is relatively high. Therefore a low plate voltage is always used. When an unmodulated carrier is tuned in, rectified current flows through the grid-leak resistor, a bias voltage is developed, and the plate current decreases. When the carrier is modulated, the bias varies in accordance with the modulation waveform, producing a relatively wide plate-current *variation* in the earphones.

Since the impedance of the load in the *grid* circuit is approximately equal to the grid-leak value, it is relatively high. This results in a high-$Q$ tuning circuit, high-amplitude signal voltages, and good selectivity, much better than if earphones are connected as the diode load.

The lower the plate voltage used in a grid-leak detector, the closer to the operation of a square-law detector and the relatively greater effectiveness as a detector of weak signals. The higher the plate voltage, the less the distortion and the greater the output from the detector with stronger signals. As a compromise, a plate supply of about 22 volts is usually used, although it will operate with 5 to 100 volts.

This detector is found only in special types of equipment today. It should have selectivity and sensitivity nearly equal to a power detector, provided the grid-leak resistance value is high.

**17.7 Regenerative Detectors.** To increase the sensitivity and selectivity of the grid-leak detector, a plate-circuit *tickler coil* can be used to regenerate, or couple, energy from the plate circuit into the grid circuit. The diagram of a regenerative detector using a *three-circuit tuner* (antenna, grid, and plate circuits) is shown in Fig. 17.9.

Normally, the tuned circuit has the fairly high $Q$ of a grid-leak detector. However, there are always losses in the LC circuit and the grid-leak resistor. If an RF signal voltage appears in the grid circuit, it is amplified and fed back in phase by the tickler coil. The portion of the signal energy that was lost because of grid-circuit losses is partially made up. The result is an apparent lessening of the losses and a higher $Q$. With no regeneration (no coupling between tickler and grid circuit) the stage operates as a straight grid-leak detector. As regeneration is increased, the detection efficiency and the signal output increase. If enough regeneration is present, all the losses in the grid circuit will be made up and the LC circuit will begin to oscillate at its natural frequency of resonance. The regenerative detector is now an Armstrong oscillator. The bypass capacitor *C* completes the a-c plate circuit, increasing regeneration. Variation of this capacitance is a means of controlling regeneration and oscillation.

A factor in the sensitivity and selectivity of the regenerative detector is the grid-leak resistor. The higher the resistance, the more sensitive and selective the detector, although the more distortion that may be produced with strong received signals.

Both the sensitivity and selectivity of the detector increase with an increase in regeneration. Maximum sensitivity and selectivity, for detection of A2- or A3-modulated signals, occur when the regeneration is just under the value required to produce oscillation. As soon as the stage oscillates, it is no longer satisfactory as a detector for A3 modulated signals.

As the regeneration and the *Q* of the LC circuit increase, the coupling requirement from antenna to tuned circuit decreases. Set at maximum sensitivity, the required coupling is remarkably small. Considerable signal strength may be obtainable from distant stations by using only a short wire as an antenna.

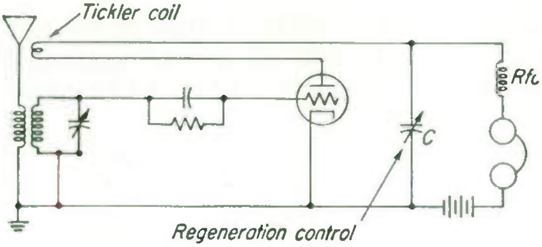


FIG. 17.9. A regenerative detector circuit.

As soon as the regenerative detector breaks into oscillation it becomes an *autodyne* (*auto* meaning "self," *dyne* from "heterodyne") detector. In this condition it can be satisfactorily used to detect radiotelegraphic code, either A1 or A2 emission. The basis of detection changes from rectification to heterodyne.

When two different-frequency a-c signals are mixed, or heterodyned, in a nonlinear circuit, such as the grid circuit of a vacuum tube, at least four frequencies will appear in the plate circuit: (1) the first frequency, (2) the second frequency, (3) the sum of the first and second frequency, (4) the difference between the first and second frequency.

If an autodyne detector (a regenerative detector in oscillation) is operating at a frequency of 1,002,000 cycles and a signal is being received that has a frequency of 1,000,000 cycles, the difference frequency between these two is 2,000 cycles. This 2,000-cycle frequency and the three other heterodyne signals appear in the plate circuit. Since the plate circuit has an RF filter composed of capacitor *C* and the RFC (Fig. 17.9), the three higher-frequency signals do not pass through the plate circuit load. Only the 2,000-cycle *beat* signal flows through the earphones. The beat note can be changed by tuning the autodyne LC circuit. If the 1,000,000-cycle incoming signal is in dots and dashes, the audible beat will reproduce the dots and dashes as 2,000-cycle tone signals in the plate load.

The autodyne detector is most sensitive to weak A1 or A2 signals when oscillating weakly. Maximum beat response is produced when the two signals being heterodyned have the same amplitude. Since two separate frequencies operating in the same circuit tend to synchronize into one frequency of oscillation, a weakly oscillating LC circuit may be forced to synchronize with a strong incoming signal and no beat note will be produced. The detector is said to be *blocking*. To prevent such blocking and frequency *pulling* it is necessary to loosen the coupling to the detector and to increase the regeneration until the autodyne circuit is in strong oscillation. However, strong oscillation desensitizes the heterodyne circuit by making the LC oscillations much stronger than the incoming signal.

When necessary to copy weak signals through strong signal interference, the antenna coupling should be loosened, increasing the $Q$ of the LC circuit, and the detector should be set into fairly strong oscillation to prevent frequency pulling.

The degree of regeneration and oscillation can be controlled by the value of capacitance $C$, the degree of coupling between tickler and LC circuit, or the plate-supply-voltage value.

When regeneration is increased, a faint swishing sound should audibly mark the point of oscillation. If improperly operating, the oscillation point will be indicated by a "pop." If the circuit is oscillating, touching the grid, plate, or the top of the LC circuit should result in a clicking noise in the earphones. If the regenerative detector is oscillating and it is tuned across the frequency to which another nearby receiver is set, the receiver will either produce a down-and-up whistle or the background noise level will be heard to change. The ability of an autodyne to radiate a signal is one of its disadvantages. If coupled directly to an antenna, such a detector may radiate a receivable signal for many miles. During the war such receivers had to be banned, as enemy submarines and surface vessels could take radio direction-finder bearings on the radiated signal and track down a ship using such a receiver. Since such detectors can interfere with neighborhood broadcast reception, they are rarely used. Their place has been taken by the more easily operated superheterodyne. The regenerative, or autodyne, detector still has some special uses, however.

If an autodyne detector will not oscillate, there are several possible reasons: The plate voltage may be too low. The coupling between tickler and LC circuit may be too loose. The antenna-to-grid coupling may be too tight, coupling in too much loss in the circuit. The tube may be faulty. The tickler turns may be connected in reverse. The grid-leak resistor or capacitor may be shorted or open.

Sometimes, at the point of oscillation, the circuit will set up an audio howl, resulting from the inductance of the load and the various capacitances in the circuit, forming an audio oscillation when the circuit is adjusted to its most sensitive condition. This howl may be stopped by (1) connecting a 50,000-ohm resistor across the transformer or earphones in the plate circuit, (2) changing the RFC value, (3) changing the grid-leak or capacitor value, (4) reducing the number of turns on the tickler, or (5) reducing the plate voltage.

The plate supply voltage must have good regulation, and there must be very little resistance in the plate circuit. A resistance cannot be used as the plate load if proper control of the oscillation point is to be expected.

If the grid-leak resistor or capacitor shorts, the detector operates without a load in the grid circuit. The detector may not oscillate, but it will detect modulated signals a little, working as a square-law detector on a bent portion of the $E_gI_p$ curve for such operation.

**17.8 The Superregenerative Detector.** A demodulator sometimes used in the VHF range is the superregenerative detector. It is the most sensitive single tube detector ever developed. Basically, it is an autodyne detector with either its plate or grid circuit overmodulated by a supersonic a-c emf. As a result, the autodyne circuit is effectively turned on and quenched, possibly 20,000 or more times a second. Figure 17.10 illustrates a plate-quenched superregenerative circuit.

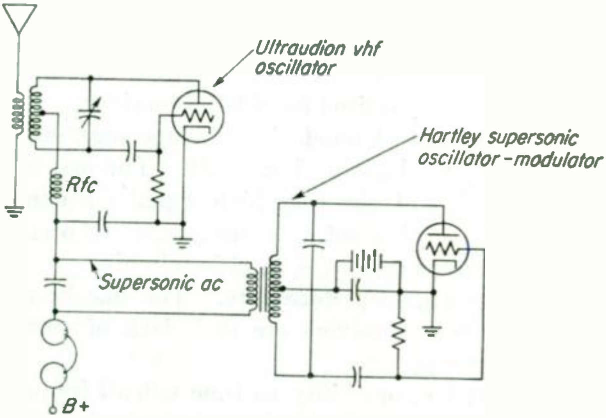


FIG. 17.10. An externally quenched superregenerative detector.

Each time the supersonic quenching voltage allows the ultraudion circuit to start oscillating, it produces a burst or pulse of RF a-c at the very high frequency to which the LC circuit is tuned. With no signal being received, noise in the grid circuit of the VHF oscillator circuit allows random starting time for the VHF pulses, and therefore random *length* pulses. All pulses will be forced to cease when the quenching voltage drops off. This random pulse length results in a rather loud hissing noise in the output of the detector. When a carrier signal is received, the RF voltages from the carrier force all the pulses to start at a constant time interval, quieting the noise output. When modulation appears on the carrier, the variation of the amplitude of the signal voltage changes the *time* that it takes to start the VHF pulse. Modulation on the carrier produces modulated *duration* pulses, and therefore a modulated *average* energy output.

A relatively weak carrier signal will suppress the background noise, and its modulation will produce almost as much output-signal strength as the modulation of a strong carrier. High-amplitude impulse noises, usually very strong in the VHF range, are effectively limited in amplitude. They will not appear at all if they do not start an RF pulse and are therefore not detected.

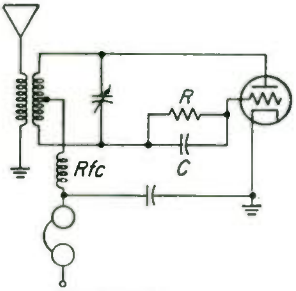


FIG. 17.11. A self-quenching superregenerative detector.

The superregenerative detector is extremely broad, even with a relatively high-$Q$ LC circuit. The demodulation contains a high percentage of distortion. When coupled to an antenna, the superregenerator radiates a very broad signal. As a result, it is rarely used except where a minimum number of stages is required for a VHF receiver.

A much simpler superregenerative circuit is shown in Fig. 17.11. The one tube oscillates at the very high signal frequency while the grid-leak resistor and capacitor set up a supersonic RC oscillation at the same time. This is known as a *self-quenching* circuit.

**17.9 Tuned-radio-frequency Receivers.** The disadvantages of the simpler detectors alone as receivers are their lack of sensitivity, selectivity, and output audio power.

The required selectivity, or ability to tune out all frequencies except the one desired, is readily obtainable by using a series of two or more loosely coupled tuned circuits. Figure 17.12 illustrates a possible tunable filter system of this type. These circuits must be *gang*-tuned in order that both be tuned to identical frequencies regardless of the setting of the tuning capacitor. Each circuit must *track* with the other over the portion of the frequency spectrum it is desired to tune.

Unfortunately, cascading tuning circuits of this type decreases the signal amplitude or the sensitivity of the system. The loss of signal strength can be made up by adding several audio amplifiers after the detector stage, as was done in some of the earlier receivers. Such receivers operated satisfactorily for local station reception. Weaker signals were attenuated too much in the tuned filter system and were lost in the input noise of the detector circuit.

In place of the link-coupling system a vacuum tube was used to couple from one tuned circuit to the next. The vacuum tube also amplified the input signal so that any loss in the signal as it passed through the filter was more than made up by the amplification of the vacuum tube. Figure 17.13 illustrates a block diagram of a three-tube *tuned-radio-frequency* amplifier, or TRF, receiver.

The *neutrodyne* receiver was used in the mid-twenties. It consisted of a neutralized class A triode RF amplifier, usually a grid-leak or regenerative detector, and one or more stages of triode audio amplification.

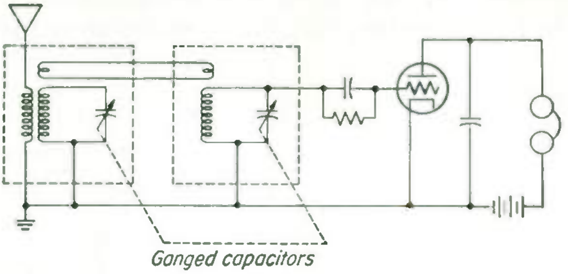


FIG. 17.12. A method of increasing selectivity by cascading tuned circuits.

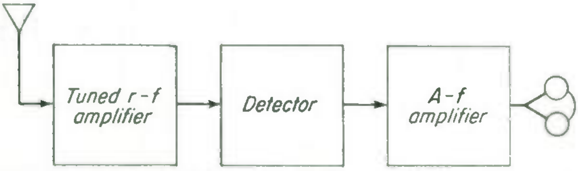


FIG. 17.13. Block diagram of a three-tube TRF receiver.

As soon as tetrodes and pentodes were developed, they were used as the RF amplifier to do away with the requirement of neutralizing and to raise the gain of the amplifier. It was found that more gain with less distortion could be produced with pentode RF amplifiers than was possible with audio amplifiers. Some receivers used two or three RF amplifiers ahead of the detector. However, the more stages, the greater difficulty experienced in making them track properly and in preventing them from breaking into oscillation. Only two or three audio stages are needed to bring the output up to loudspeaker volume. In many earlier receivers there was often an output jack in the detector stage for earphones and an output jack in each amplifier stage. This was sometimes handy in localizing trouble. If no signal came from the audio amplifier but one was heard in the detector stage, trouble was indicated in the audio stage.

The three-tube TRF receiver in Fig. 17.14 represents a popular inexpensive broadcast or short-wave receiver of the early thirties, often used as a portable receiver. It consists of a pentode RF amplifier stage, with a variable bias resistor to control the gain or sensitivity of the RF stage. $R_1$ is the minimum value of resistance required to bias the tube to class A. Any additional resistance added in series with $R_1$ increases the bias and decreases the sensitivity of the stage. The detector stage is a regenerative type, permitting rectification detection for A2 and A3 modulated signals and autodyne detection for A1 or A2 radiotelegraphic signals. The audio stage is a standard type of volume-controlled amplifier.

Note that A2, or tone, modulated radiotelegraphic code can be received as either a modulated signal or by beating it with the detector in oscillation. Regardless of how the detector is adjusted, A2 signals can be detected and copied. For this reason, SOS, or telegraphic distress signals, are required to be transmitted with an A2 emission whenever possible. If the A2 signal is weak, it is more easily copied with the detector in weak oscillation.

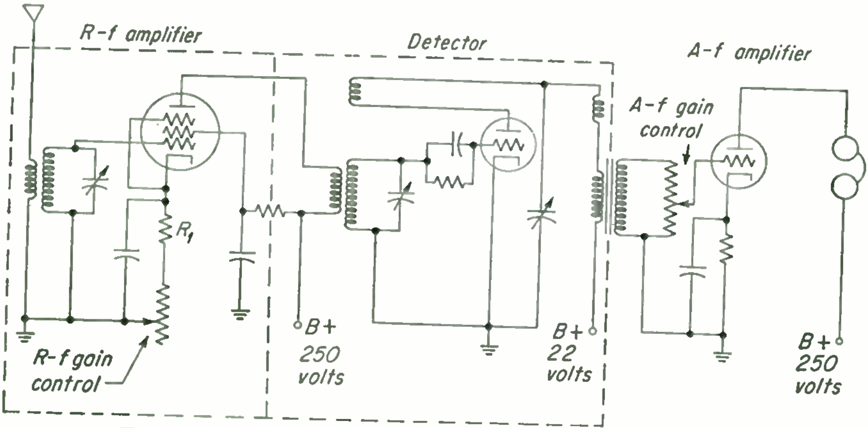


Fig. 17-14. Schematic diagram of a three-tube TRF receiver.

The detector stage should be completely shielded in a grounded metal box to prevent signals from reaching it directly and decreasing the selectivity gained by using the tuned RF amplifier. It is desirable to shield the RF amplifier also.

A few TRF receivers use the heterodyne principle instead of the autodyne for A1 or A2 reception. This requires a separate oscillator stage that must track with the detector and RF amplifiers. When a signal is received, the oscillator produces a heterodyne, or beat, tone, making A1 signals audible. Heterodyning with a separate oscillator has the advantage of less frequency pulling when a strong signal is being received. To receive modulated signals the oscillator is switched off. Some marine radio direction-finder receivers use this system.

TRF receivers may still be found in use in simple emergency equipment and in some broadcast receivers.

The use of a well-shielded RF amplifier ahead of the autodyne or superregenerative detectors prevents oscillations in the detector stage from reaching the antenna. With a shielded RF amplifier stage the autodyne or superregenerative receiver will not radiate a signal.

TRF receivers are fairly satisfactory up to about 10 Mc. Above this frequency both sensitivity and selectivity fall off because of the lower $Q$ of the tuned circuits.

**17.10 The Superheterodyne.** Practically all radio receivers built today are superheterodynes. While the superheterodyne circuit is more complicated than the simpler TRF, the ability to operate satisfactorily on any frequency with a constant value of selectivity and good sensitivity makes it highly desirable. A block diagram of a communications superheterodyne receiver capable of detecting A1, A2, or A3 emission signals is shown in Fig. 17.15.

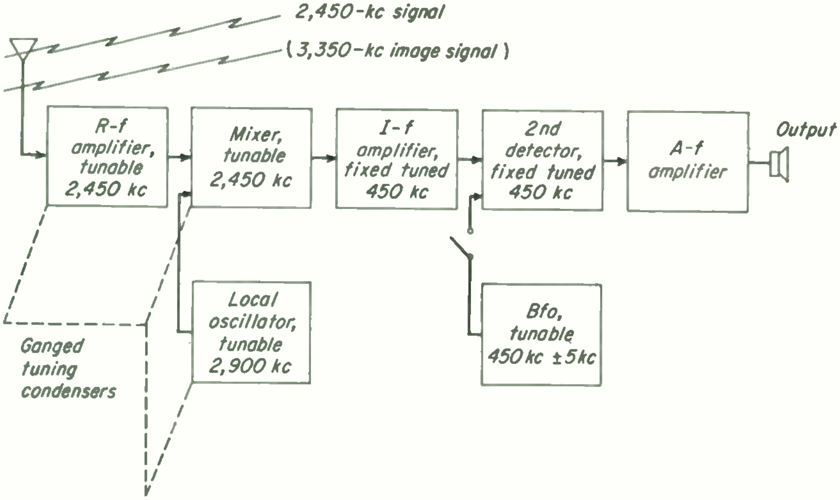


FIG. 17.15. Block diagram of a relatively simple short-wave communications superheterodyne receiver.

A brief explanation of the basic operation of the stages of the superheterodyne is as follows:

The receiver happens to be tuned to a frequency of 2,450 kc and to a station on that frequency.

The RF amplifier is tuned to 2,450 kc and amplifies the received signal. The output from this stage is fed to a heterodyne detector, known as the *first-detector*, *mixer*, or *converter* stage.

The mixer stage is also tuned to 2,450 kc and is being fed two signals. One is the received signal from the RF amplifier, and the other is a constant-amplitude oscillation from the *local-oscillator* stage. These two frequencies are heterodyned in the mixer stage where the sum and the difference frequencies are developed in the mixer plate circuit. If the local oscillator is tuned to 2,900 kc and the input signal frequency is 2,450 kc the difference frequency is 450 kc. In the superheterodyne the difference frequency is known as the *intermediate frequency* (IF). This IF is fed into an IF amplifier stage.

The IF amplifier has both its grid and plate circuits tuned to 450 kc to accept the difference frequency but to reject the original signal, the local oscillator signal, and the sum frequency, which are all present in the plate circuit of the mixer stage. The selectivity of the superheterodyne is primarily determined by the number and $Q$ of the tuned circuits used in the IF amplifier stage or stages. The IF amplifier amplifies the difference frequency of 450 kc and feeds it to the second detector.

The second detector usually consists of a simple diode detector circuit that rectifies the 450-kc IF signal. If the signal contains modulation, the output of the diode rectifier is an AF varying d-c that is changed to an AF a-c by a resistance-capacitance coupling circuit and fed to the AF amplifier, where it is finally amplified and fed to earphones or loudspeaker.

If the signal is an A1 emission, it will be necessary to change the second detector from a rectifying detector to a heterodyne detector. This is accomplished by switching on the *beat-frequency oscillator*, or BFO.

The BFO is tunable a few kilocycles above and below the 450-kc IF. By tuning the BFO it is possible to produce any beat tone desired by the listening operator. The beat tone is amplified and fed to the output device.

If a strong local station should be transmitting on 3,350 kc and the RF amplifier cannot attenuate this frequency, it will also be fed to the grid of the mixer stage, mix with the 2,900-kc local oscillator, and produce a 450-kc difference frequency that will also be amplified by the IF stage, be detected, and be audible in the output. This frequency is known as an *image signal* and is one of the disadvantages of a superheterodyne circuit.

To prevent interaction between all the stages and to prevent interference from undesired signals, all RF, IF, and oscillator stages should be completely shielded. If the tubes are not of the metal-envelope type, they should also have separate shields around them.

**17.11 The RF Amplifier.** The first stage in a communications superheterodyne usually consists of a remote-cutoff, or variable-$\mu$, RF pentode tube, such as a 6SK7 or 6BA6, etc., in a circuit similar to the one shown in Fig. 17.16.

The grid circuit is tuned to the signal frequency. The plate circuit is untuned. The screen-grid voltage is obtained from a voltage-divider network to give as good a voltage regulation as possible. The stage obtains its class A bias from the cathode resistor, and also additional bias from the automatic-volume-control (AVC) voltage, explained later. A sensitivity control may also be incorporated in this stage, which may consist of either a rheostat in series with the cathode-bias resistor, as shown in Fig. 17.14, or some means of varying the screen voltage.

The coupling capacitor $C$ prevents the d-c AVC bias voltage from being shorted to ground by the coil. The bias voltage developed across the cathode resistor comes to the grid through the AVC circuit, one end of which is grounded.

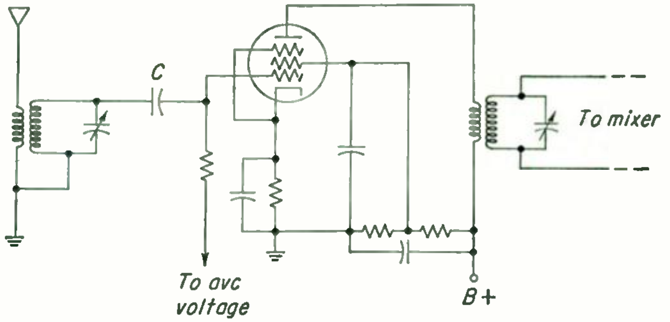


FIG. 17.16. An RF amplifier circuit in a superheterodyne.

Since all the stages following the RF amplifier amplify any noise generated in it, the tube and its circuit must be selected for minimum noise output, or highest signal-to-noise ratio.

The output of the RF amplifier is fed to the mixer stage.

**17.12 The Mixer Stage.** The mixer, converter, or first-detector stage is a heterodyne detector in which the difference frequency is a relatively low radio frequency rather than an audio frequency. A simple type of mixer stage is shown in Fig. 17.17.

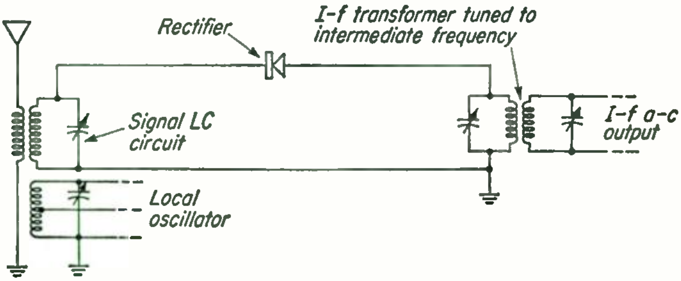


FIG. 17.17. Diode, or crystal mixer, circuit.

In this circuit a diode-tube, a germanium, or a silicon rectifier can be used. The signal and the local oscillator frequency are inductively coupled and appear in the signal circuit. They are fed through the nonlinear rectifier to the difference-frequency tuned circuit. All but the difference frequency, now called the intermediate frequency, are attenuated by the tuned circuits of the IF transformer. The disadvantage of such a "mixing" circuit is the lack of amplification of the IF signal produced.

Mixing can be accomplished in the grid circuit of a triode, and amplification of the difference frequency in the plate circuit can be produced.

Special tubes have been developed to mix two frequencies efficiently in the electron stream between cathode and plate of the tube. One such tube is shown in Fig. 17.18 and another is used in the diagram of the complete communications superheterodyne receiver in Fig. 17.32.

The *pentagrid-converter* tube shown, a 6SA7, 6BE6, etc., employs the cathode and first and second grids as a cathode, control grid, and plate in a Hartley-type triode oscillator circuit.

If the frequency of the IF amplifier is set at 450 kc and the signal frequency is 2,450 kc the local oscillator will have to be on either 2,000 or on 2,900 kc. In receivers operating up to about 20 Mc, it is standard practice to use an oscillator operating on a frequency *higher* than the signal frequency to simplify tracking. If the oscillator is operated at a frequency lower than the signal frequency, using a 450-kc IF, the oscillator would be on 450 kc to receive a station on 900 kc. The strength of the local oscillator signal would completely block the 450-kc IF amplifier and nothing would be heard when the receiver was tuned to 900 kc.

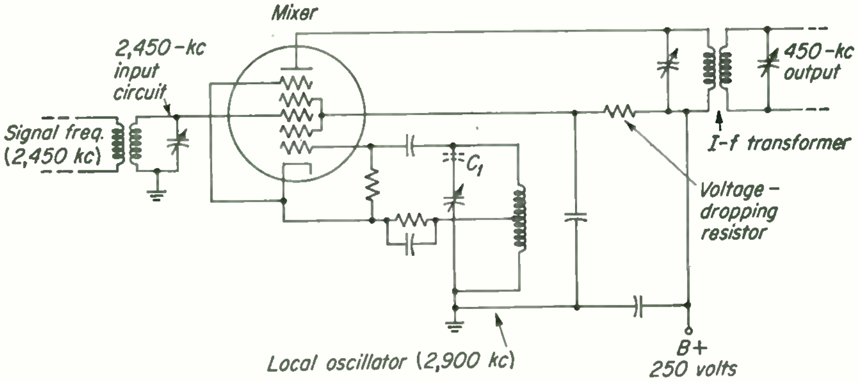


Fig. 17.18. A pentagrid converter circuit used to produce the IF.

The oscillator circuit is usually a Hartley or Armstrong in tunable receivers. For fixed-frequency reception, the local oscillator may be a crystal oscillator, making off-frequency operation unlikely.

It is necessary to track the tuning of the oscillator, the mixer, and the RF amplifier(s) in such a way that when the mixer and RF amplifier are tuned to the desired frequency, the oscillator will always be exactly 450 kc higher. To do this the capacitor plates of the oscillator stage can be manufactured specially to allow proper tracking. However, for all-frequency operation the tracking may be accomplished by inserting a tracking capacitor at the position of the capacitor $C_1$, allowing three similar, ganged variable capacitors to be used for RF amplifier, mixer, and oscillator stages. The higher the frequency band being tuned, the greater the capacitance required in these tracking capacitors to allow the oscillator to cover the same frequency band that the mixer does at its lower frequency. Above 20 Mc no capacitor may be necessary. In more elaborate receivers having two RF amplifiers, four ganged circuits must all be tracked properly by means of small trimmer capacitors across all tuned coils, and some method of varying the inductance of the coils, such as adjustable brass or powdered-iron cores, is used.

The stability of the oscillator frequency is an important item in communications superheterodynes. All insulating materials used in the oscillator should be ceramic or other low-loss types. Mica or ceramic rather than paper capacitors should be used for bypassing. All oscillator components should be rigidly mounted and shielded to prevent frequency wobble when the receiver is physically jarred.

While a signal gain is produced in the mixer stage it is not as much as in an RF or IF amplifier. RF pentode tubes have transconductance values from 2,000 to 12,000, whereas the conversion transconductance of mixer tubes ranges from about 450 to 900.

**17.13 The IF Amplifiers.** The superheterodyne is the most practical of any tunable receiver chiefly because the IF amplifiers do not require tracking. They can be adjusted to the IF and remain that way, regardless of the frequency to which the *front end* is tuned. Since the IF is a relatively low RF, the amplifier circuits are stable and require no neutralization. Both grid and plate circuits are tuned, resulting in high gain for the amplifiers and an effective rejection of all frequencies except those on the IF and a few kilocycles on each side. Figure 17.19 is a diagram of an IF amplifier. Except for the tuned plate circuit it appears identical with the RF amplifier. Note that the AVC voltage is shown as series-fed in this diagram, whereas it was shown as shunt-fed in the RF amplifier to allow the rotor of the RF tuning capacitor to be grounded.

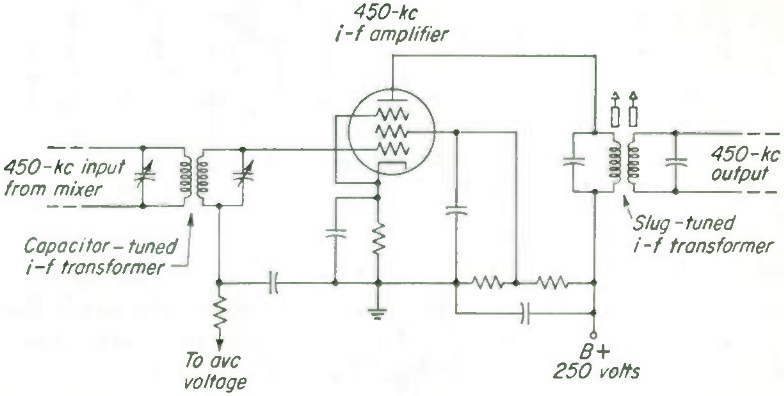


FIG. 17.19. An IF amplifier circuit used in a superheterodyne receiver.

The IF transformers themselves usually consist of two multilayer coils wound on ¼- to ⅜-in. cylinders of insulating material. The coils may be tuned with two adjustable mica or air capacitors, all enclosed in an aluminum shield can. Some IF transformer coils have *fixed* mica capacitors across them, and powdered-iron slugs are screwed into or out of the cores of the coils to tune them by a variation of their inductance. By using low-loss, high-permeability core materials, the coils require only a fraction of the number of turns needed for air-core coils. This can result in higher-$Q$ circuits with narrower bandwidth and higher output voltages.

There are several methods used to produce either a narrower or a variable IF bandwidth. In some receivers a mechanical means is provided whereby the coupling between primary and secondary of the transformers can be varied from less than critical coupling for a narrow bandwidth to an overcoupled condition for a broad bandwidth. In other receivers, resistances can be switched in series with some of the tuned circuits of the IF amplifiers to lower the $Q$ of the circuits and broaden the bandwidth. In general, the more tuned circuits in the *IF strip*, the narrower the passband. Two top-coupled transformers may be used between stages as shown in Fig. 17.20. Tapping down the secondary coil raises the $Q$ of the output circuit, further narrowing the frequency response.

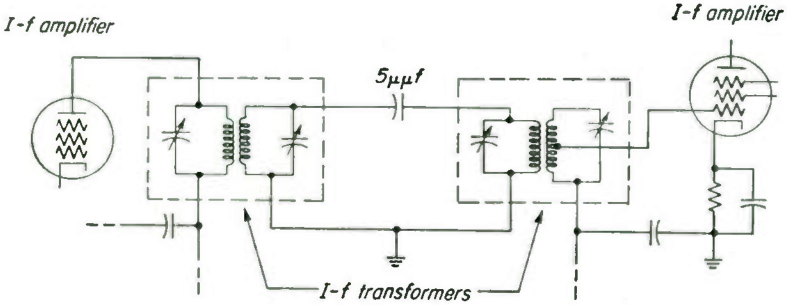


FIG. 17.20. IF selectivity can be increased by cascading and tapping down tuned circuits.

If one filter, such as an $m$-derived bandpass inductance-capacitance circuit, can carve out a desirable bandpass response by itself, the amplifiers that follow it need not be narrow-bandwidth circuits.

Some receivers use special electromechanical magnetostrictive input filters which feature highly desirable response curves with extremely steep-sided *skirts* with narrow, flat tops. Special IF filters are available with passbands of 800 cycles for A1 reception to more than 30 kc for FM communications. A *crystal filter* and *double conversion,* both explained later, are in common use in communication receivers to obtain narrow-bandwidth IF strips.

Remote-cutoff-type tubes, such as 6SK7, 6BA6, etc., are used in IF amplifier stages. Smaller receivers may use only one IF amplifier. Most communication receivers use two IF stages, and in some cases three. However, it is often found that the addition of the third stage is unnecessary as it may only produce self-oscillation or may bring up the background-noise level without improving the signal-to-noise ratio.

A rheostat may be connected in series with the cathode-bias resistor, or the screen-grid voltage may be made variable to act as a manual gain control for both RF and IF amplifier stages when receiving A1 or single-sideband signals.

**17.14 The Second Detector and AVC Circuit.** The highly amplified signal from the last IF stage is fed to the second detector, which is usually a diode rectifier, similar to the circuit shown in Fig. 17.21.

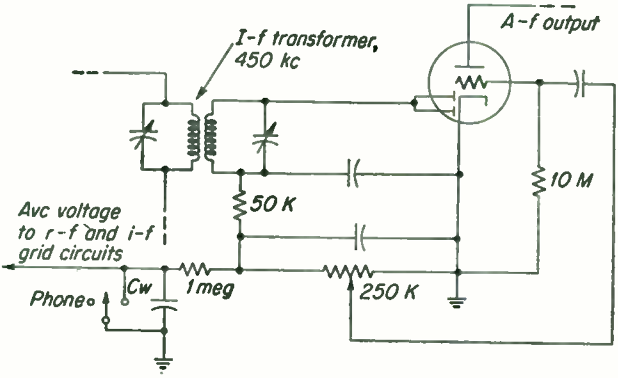


FIG. 17.21. Second detector, first audio amplifier, and AVC circuit.

The usual tube for the second-detector–first-audio-amplifier–AVC circuit is a twin-diode–high-$\mu$ triode, such as a 6SQ7, 6AT6, etc. In the diagram shown, the two diode plates are connected together to form a single diode. The 250-kilohm potentiometer is the load on the diode rectifier circuit. Two 0.0001-$\mu$f capacitors and a 50,000-ohm resistor form an RC-type RF filter, resulting in an audio varying d-c across the potentiometer. The setting of the potentiometer (the volume control) determines how much of the audio signal is coupled to the grid of the triode amplifier.

Since the direct current flows from left to right through the potentiometer, the left end is negatively charged. The stronger the signal received, the more negative this end becomes. This negative voltage, which varies with the strength of the incoming signal, is taken off through a long-time-constant RC filter, composed of a 1-meg resistor and a 0.01-$\mu$f capacitor that filters out the AF variation of the d-c. The voltage across this capacitor will vary only with average carrier variations. This is the AVC voltage for the RF and IF amplifiers. A strong signal produces a high AVC voltage and biases the remote-cutoff amplifier tubes to a point on their $E_gI_p$ curves where the slope is slight and they amplify very little. With a weak signal there is very little AVC bias and the tubes operate at full gain. This tends to make all signals of nearly equal amplitude at the second detector. Thus it may not be necessary to adjust the audio volume control when tuning from a stronger station to a weaker one.

When copying code signals, A1 or A2, or single-sideband suppressed carrier, the AVC voltage should be disconnected. A *phone-CW* switch shorts out the AVC voltage that would be fed to the amplifiers, leaving them with only the class A bias developed by their respective cathode-resistor bias circuits and their RF gain controls.

Even on weak signals, the AVC circuit in Fig. 17.21 produces bias, thereby weakening such signals. To prevent this, an AVC circuit that does not go into operation until the signal reaches a certain amplitude may be used. This system is known as *delayed AVC*, or *DAVC*. A diagram of one such circuit is shown in Fig. 17.22.

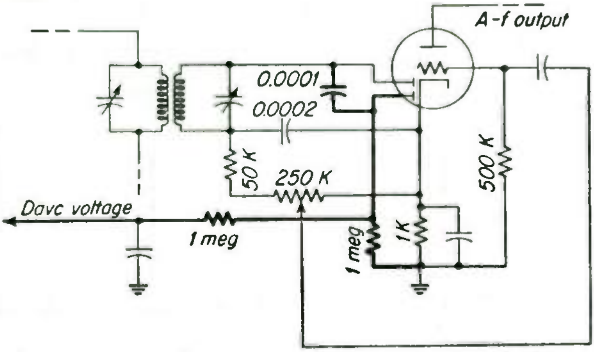


FIG. 17.22. A DAVC circuit.

The top diode plate, the IF transformer secondary, and the potentiometer form a normal rectifier detector. Triode plate current flowing through the cathode resistor develops a bias of about 1 volt across it. This bias voltage is applied to both the triode grid and the lower diode plate. Until the lower plate receives a signal greater than 1 volt positive, current will not flow to it from the cathode. If the signal strength is over 1 volt, current flows to the diode plate, through the 1-meg resistor, developing a negative biasing voltage across it. This DAVC voltage is filtered and fed to the grid circuits of the RF and IF amplifiers. With this circuit, weak signals receive full amplification, and only stronger signals developing more than a 1-volt peak at the second detector have AVC applied to them.

In general, AVC is not fed to the mixer stage of a communication receiver, since a changing bias on the grid of such tubes tends to pull or vary the oscillator frequency as the signal fades up and down. Small broadcast receivers having no RF amplifiers usually do have the AVC fed to the mixer. Their IF passband is so broad that a little detuning is not noticeable.

**17.15 The Beat-frequency Oscillator.** To change the second detector from a rectifying to a heterodyne detector to receive A1, A2, or single-sideband signals, the BFO is turned on. This is a variable-frequency oscillator, using a Hartley, Colpitts, or Armstrong circuit. It is tunable to the IF and two or three kilocycles higher and lower. The BFO heterodynes with any signal coming through the IF strip, producing an audible beat tone in the detector. The BFO must have good frequency stability to prevent drifting of the beat tone.

The BFO is usually capacitively coupled to either the diode plate of the tuned circuit of the second detector or to the plate circuit of the last IF amplifier (Fig. 17.32).

Since many BFO circuits are simple oscillators, strong signals delivered to the second detector will tend to pull their frequency, resulting in a changing beat tone with fading signals. Reception of signal-sideband signals will be very poor under such conditions. It is preferable to use an electron-coupled oscillator circuit to prevent such pulling. A diagram of such a BFO circuit is shown in Fig. 17.23.

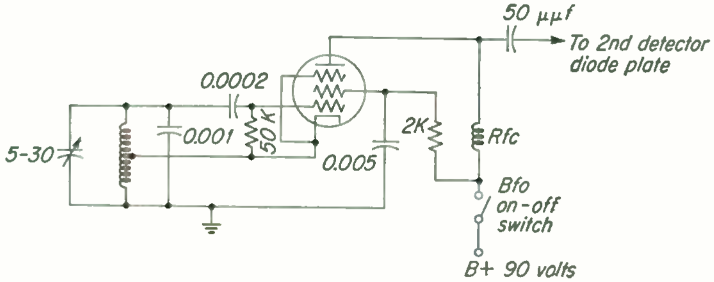


Fig. 17.23. An ECO-type beat-frequency oscillator circuit.

For single-sideband reception it is sometimes preferable to isolate the BFO and the second detector more adequately. A buffer amplifier, usually untuned, may be connected between the two stages. A more effective detector for single sideband may be a pentagrid converter in a circuit similar to the mixer stage.

The BFO tuning circuit consists of a coil, a relatively large fixed mica capacitor for a high $C/L$ ratio (to give good frequency stability), and a small variable capacitor to tune the oscillator over the relatively small band of frequencies near the IF.

It is possible to use a regenerative second detector and use autodyne rather than heterodyne detection. This type of detector has the disadvantages of not developing sufficient AVC, shifting frequency as the regeneration is increased, pulling the frequency of oscillation with fading

A1 signals, and relatively poor fidelity, if this is important. It has the advantage of being considerably more sensitive than diode detection and requires less IF amplification. It is sometimes used in portable equipment.

**17.16 The Squelch Circuit.** One circuit that can operate from the AVC voltage is the *squelch*, or Q (quieting), circuit. Modern communication receivers have high gain. When no signal is tuned in, there is a considerable buzzing and crackling background noise developed. To quiet the receiver until a signal appears on the frequency to which the set is tuned, a squelch circuit is used. One possible squelch circuit is shown in Fig. 17.24.

With no signal there is no negative AVC voltage and the squelch tube allows current to flow through it, through part of $R_1$, and to the +250 voltage point. The current flow through $R_1$ produces a d-c voltage drop across it. This voltage is negative at the top and is in series with the amplifier grid circuit, biasing the high-$\mu$ amplifier tube past cutoff, preventing it from operating. There is then no output from the amplifier.

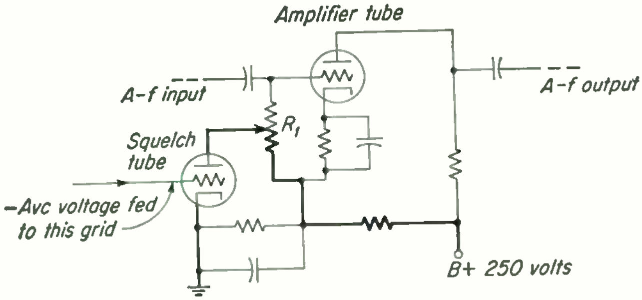


FIG. 17.24. A squelch interstation quieting, or Q, circuit.

When a signal is received, AVC voltage is developed, biasing the high-$\mu$ squelch tube to cutoff, stopping its plate current flow. The biasing voltage across $R_1$ ceases to exist. The amplifier can now operate as a normal resistance-coupled amplifier as long as the signal develops AVC voltage. The position of the tap on $R_1$ helps to determine the quieting point.

**17.17 The Tuning Eye.** Another circuit that operates from the AVC voltage is the *electron-ray tube*, or the *tuning-eye tube*. It may be considered as a special double-triode tube. One triode is a normal amplifier, but the other has a specially formed, circular, shallow, cone-shaped *target plate*, with a hole in the center. The common cathode extends through the hole. The target plate is coated with a substance that glows bright green when electrons strike it. A third element, a straight wire called the *target grid*, is also brought through the hole, between the cathode and the target plate, as indicated in the cross-section side view in Fig. 17.25.

When the cathode is hot, it emits electrons that are attracted to the positively charged target plate. If the target grid has no charge, the whole target-plate area will appear green. If the target grid wire is charged negatively, it repels the electrons from the cathode, effectively shielding a portion of the plate area from electron bombardment. This segment of the plate area appears dark.

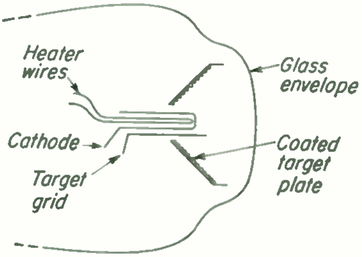


FIG. 17.25. Cross section of the components of a tuning-eye tube.

A circuit used with a tuning-eye tube such as a 6E5 is shown in Fig. 17.26. When there is no signal at the second detector of the receiver, there is no AVC voltage, the tuning-eye triode grid has no bias, and plate current flows through resistor *R*. Because of the current direction through *R*, the triode plate, and therefore the target grid, is more negative than the target plate, shielding a segment of the target plate, as illustrated.

When a signal is received, AVC voltage applies a negative charge to the triode grid and decreases the voltage drop across *R*, resulting in a smaller area of shielded or dark target area. If the signal is strong enough, all the target area will glow, as shown. The width of the shaded area is a visual indication of signal intensity. When the receiver is tuned to the frequency of a station, maximum AVC voltage is developed and the eye closes to the greatest degree.

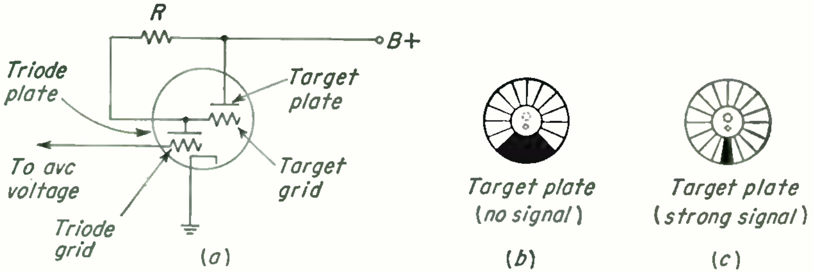


FIG. 17.26. (*a*) Circuit of a tuning-eye tube. (*b*) How it appears with no signal. (*c*) Appearance with a strong signal.

**17.18 The S Meter.** Another visual indicator of signal strength is the S meter. It also depends on the amplitude of the AVC voltage developed at the second detector. The simplest S meter consists of a 0–10-ma meter in series with an RF or IF amplifier plate or cathode circuit. With no signal received, there is no AVC bias voltage and maximum plate current flows in the tube and through the meter. With a signal, the AVC biases the tube, reducing the plate current and the indication on the meter. The stronger the signal, the less current the meter indicates. The meter face can be calibrated in relative signal strengths, usually 6 db per calibration unit. The disadvantage of this meter is that it reads downward for increased signal strength. With some meters this may be corrected by removing the case and moving *both* hairspring adjustments until the meter needle zeros at the right-hand side of the scale. Now when the meter is inserted in the circuit, with correct reversed polarity, plate current deflects it to the left and it will read upward with increased signal strengths. A more sensitive meter may be used if a shunt resistor is connected across it.

More often, a bridge circuit is used as a signal-strength indicator. Figure 17.27 shows an S meter connected in the plate circuit of an RF or IF amplifier tube. If the impedance of the tube with no signal and no AVC voltage is equal to $R_1$ and if $R_2$ equals $R_3$, the voltage drop across the meter will be zero and no current will flow through it. With a signal and AVC voltage, the plate current through the tube and $R_3$ decreases, developing less voltage drop across $R_3$. A voltage difference now appears across the meter, and current flows through it. Either $R_2$ or $R_3$ should be variable, and it is advisable to have a variable shunt across the meter to allow proper zero and maximum adjustments.

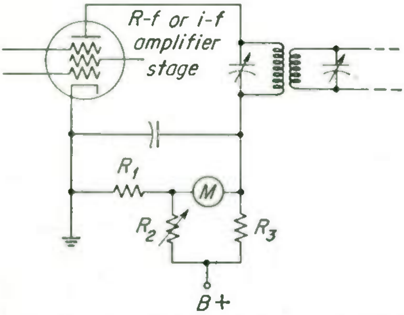


FIG. 17.27. An S-meter bridge circuit.

**17.19 Noise Limiters.** Impulse noises, such as automobile ignition, sparking of motors, switching heavy-current circuits on and off, lightning, and power leaks, can completely cover signals that might otherwise be perfectly readable. These all represent an amplitude-modulated form of signal and are detected by the usual communications receiver. Since an FM receiver does not detect amplitude variations, such noises may cause little or no difficulty with FM reception.

While noise impulses may be of extremely short duration, they may have amplitudes 10 to 1,000 times the strength of the signal it is desired to hear.

A particularly effective circuit that can be used to clip off, or limit, such pulses to an amplitude the equivalent of only about 85 per cent modulation is called the *series noise limiter*. Because the impulses have such a short duration, even with an 85 per cent modulation amplitude they are not too noticeable when receiving a highly modulated signal.

The series noise limiter uses a diode that conducts signals to the audio amplifier as long as they are lower than about 85 per cent modulation. As soon as signals of greater amplitude than this come through the detector, the diode stops conducting and no signal is passed to the audio amplifier until the amplitude decreases to the cutoff value again. Figure

17.28 shows a series noise limiter connected between the second detector and the first audio amplifier.

The varying d-c audio signal of the second detector is developed across the two 100-kilohm resistors in series. If the carrier signal produces 10 volts negative at the AVC takeoff point, the plate of the diode is then 5 volts positive in respect to this point (or 5 volts less negative than this point). The cathode of the diode is connected to the −10-volt point through the 250-kilohm and the 1-meg resistors. The 0.1-μf capacitor between these two resistors holds an average −10-volt charge whether the carrier is modulated or not. (Actually it is not quite −10 volts because of the current flowing through the resistors.) Since the plate is more positive than the cathode, the diode acts as a conductor. The AF signals developed across the lower 100-kilohm resistor are passed by the diode through the 0.05-μf coupling capacitor to the volume control in the grid circuit of the AF amplifier.

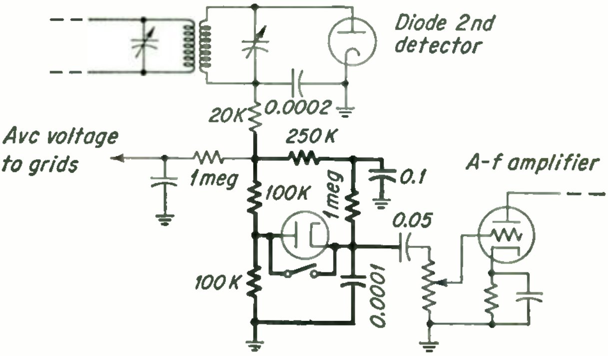


FIG. 17.28. Series noise-limiter circuit.

A peak of 100 per cent modulation will produce a −20 volt peak of d-c at the top of the two 100-kilohm resistors. At this instant the plate of the limiter diode (at the center of the 200,000-ohm voltage divider) will be −10 volts, *the same voltage as its cathode* since the cathode is obtaining its charge from the 0.1-μf capacitor. The diode ceases to conduct, and no impulse of this amplitude or higher can be transferred to the audio stage. A very small signal can be passed across the diode by the cathode-plate interelectrode capacitance. The 0.0001-μf capacitor effectively bypasses any such leakage signal.

There is a small amount of distortion developed in this limiter, even at less than 100 per cent modulation.

A switch across the limiter diode stops the limiting action. Use of this type of limiter decreases the possible signal-voltage amplitude from the second detector to one-half what it would be without the limiter.

A limiter of this type will not operate with the BFO on, since the BFO produces so much rectified voltage that the diode conducts all the time.

As a result, this limiter does not function when copying code or SSB signals.

To decrease impulse noise when receiving A1 signals, an amplifier stage can be made to saturate at some controlled amplitude. An audio amplifier having 100-volt power supply cannot produce more than 100 volts variation across its plate load regardless of how much signal is fed to its grid. If the plate voltage of an amplifier is reduced to some low voltage, it cannot produce more than this output, regardless of the input amplitude. If the plate voltage of an audio amplifier is made variable, when low values are used the maximum output peaks will be considerably limited. By varying the volume control at the second detector, and also the plate voltage of one of the audio amplifiers, an effective peak limiting can be produced for radiotelegraphic-code reception.

**17.20 The Audio Amplifiers.** The audio amplifiers in a receiver may have a relatively flat response if high-fidelity music is to be received. Communication receivers may limit the audio response of all frequencies above approximately 5,000 cycles to decrease noise response.

In some cases, where code or other single-tone reception is required, the audio stages may incorporate a tuned filter to accentuate one desired or a narrow band of frequencies.

A *tone control,* described in the chapter on Audio-frequency Amplifiers, may be used.

Most receivers are constructed to operate into loudspeakers, with either a 3- to 8-ohm or a 600-ohm impedance.

When it is desired to use earphones, they may be connected across the final-audio-amplifier output transformer secondary, or provision may be made to plug them into the output of the stage before the final amplifier. In some cases, when the earphones are plugged in, the loudspeaker is automatically disconnected.

**17.21 The Crystal Filter.** One of the standard circuits included in many modern communication receivers is a crystal filter, the basic element being a quartz crystal ground to series-resonate at the IF. A characteristic of an oscillating-type quartz crystal is its extremely high $Q$ when used as a resonant circuit. Advantage is taken of this high $Q$, and resulting narrow bandwidth, by inserting a crystal between the mixer and the first IF amplifier. A possible crystal-filter circuit is shown in Fig. 17.29.

A signal on the resonant frequency of the crystal will pass through it with practically no attenuation. Signals on frequencies only a few hundred cycles removed from the crystal frequency should be greatly attenuated. Unfortunately, the capacitance between the metal plates that hold the crystal passes all the frequencies near the IF equally well. As a result, not only the frequency of resonance is passed by the crystal, but other adjacent frequencies are passed by the capacitance of the crystal holder. To neutralize this capacitive-signal transfer, another similar capacitive signal from the opposite end of the input transformer, 180° out of phase, is also fed to the IF amplifier. If the two signals are of equal amplitude and the capacitance of the crystal holder equals the capacitance of the neutralizing capacitor *Cn*, the only signal transfer will be that accomplished by the crystal, and an extremely narrow passband can be developed.

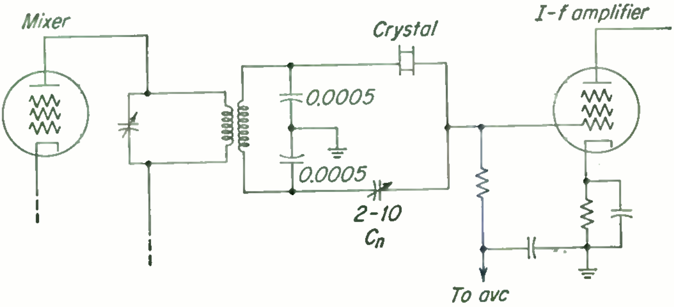


Fig. 17.29. A basic IF crystal-filter circuit.

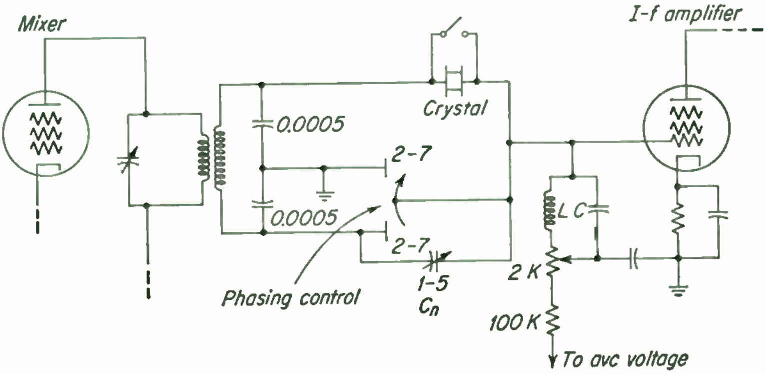


Fig. 17.30. An improved IF crystal-filter circuit.

A switch across the crystal removes the crystal filter from the circuit, broadening the IF response considerably.

An improved crystal-filter circuit is shown in Fig. 17.30.

With the phasing capacitor set for equal capacitance to both stator plates, and with an incoming signal in the center of the IF passband, the neutralizing capacitor $C_n$ is adjusted for complete neutralization of the crystal-holder capacitance. This capacitor is never changed. When the phasing capacitor is turned one way or the other, the *parallel* resonant condition of the crystal will be tuned to one side or other of the IF center frequency. The parallel resonant condition produces extremely high attenuation to any signal on its particular frequency.

If the receiver is tuned to the carrier of a voice-modulated station and another station is 2 kc to one side, the phasing control can be adjusted until the 2-kc beat tone is decreased to nearly zero. This does not cancel the sidebands of the interfering station but eliminates the beat tone which can be very objectionable.

The ability of the crystal filter to eliminate the beat tone is most noticeable when copying radiotelegraph signals, which are heard as beat tones only. It is possible to select one station and phase out another on an adjacent frequency almost completely.

The crystal filter alone is far too sharp for good A3 reception, even for voice. The passband of the crystal filter can be materially broadened by adding a tuned LC circuit between the crystal and the next grid. The *less* the resistance in this circuit (the higher its $Q$), the *broader* the characteristics of the crystal filter. The variable resistance shown in this circuit acts as a variable-bandwidth control.

**17.22 Wavetraps.** When undesired local signals produce a response in a receiver, either a series- or parallel-resonant circuit wavetrap may be used to advantage.

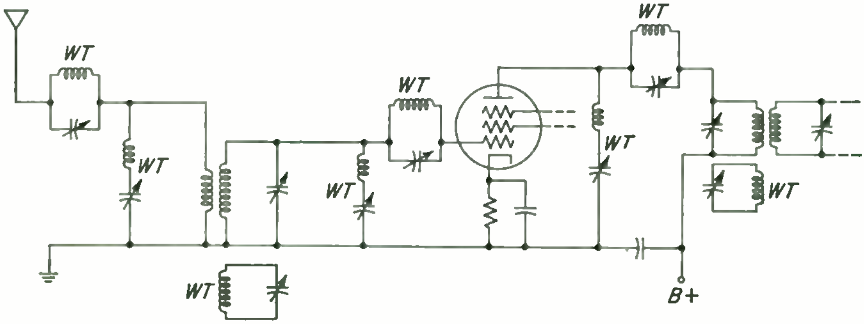


Fig. 17.31. Possible placement of series- and parallel-tuned wavetraps in an RF amplifier.

A series-resonant wavetrap utilizes the *low* impedance of a series circuit to its resonant frequency. A series trap connected across a circuit will effectively reduce the formation of any resonant-frequency voltage across it. Such a wavetrap may be connected across the input (antenna and ground) circuit of a receiver, from grid to ground, or from plate to ground, as shown in Fig. 17.31, and sometimes across the power lines where they enter the receiver. As long as the desired signal is not too close to the wavetrap frequency, the wavetrap will not reduce the desired signal materially.

A parallel-resonant wavetrap utilizes the very *high* impedance developed across a parallel LC circuit at its resonant frequency. A parallel wavetrap may be connected in series with the antenna input terminal, in series with a grid or plate circuit lead in an amplifier, or in series with one or both power lines as they enter the receiver. This introduces so much impedance to the frequency to which the trap is tuned that very little energy at this frequency will be able to flow in the circuit in which the trap is connected. Placing a trap in a circuit may detune it somewhat.

Figure 17.31 illustrates several places where wavetraps can be placed in an antenna and an RF amplifier circuit.

As indicated in the diagram, a resonant-circuit wavetrap may also be inductively coupled to any tuned circuit. Signals having the same frequency as the wavetrap are induced into the trap, produce an oscillation in it, absorbing energy, and reinduce back into the tuned circuit of the receiver a voltage of the same frequency but approximately 180° out of phase. This effectively cancels or attenuates the signal to which the wavetrap is tuned.

**17.23 Image Frequencies.** Image frequencies have been mentioned previously. Any frequency besides the signal that will beat with the local oscillator and produce a frequency equal to the intermediate frequency (IF) is an image. In most cases only one image is considered. As an example, if the IF is 450 kc and the *local oscillator* is oscillating on 8,000 kc, a signal on either 8,450 or on 7,550 kc will beat against the oscillator and produce the IF.

The relationship between the signal, the oscillator, the IF, and the image frequencies can be expressed in formula form:

$$\begin{aligned} f_i &= f_o + f_{if} \\ f_i &= f_o - f_{if} \\ f_i &= f_s + 2f_{if} \\ f_i &= f_s - 2f_{if} \end{aligned}$$

where $f_i$ is the image frequency; $f_o$ is the oscillator frequency; $f_{if}$ is the intermediate frequency; and $f_s$ is the signal frequency.

At a frequency of 7,550 (or 8,450) kc, the mixer tuned circuit usually has a low $Q$ and is quite broad. Alone, it may not reject a strong signal on the image frequency to any great extent. The addition of a tuned RF amplifier before the mixer produces considerable image rejection. A second RF amplifier will reject the image very well. However, at frequencies in the 30-Mc range, for example, even the two RF amplifiers may not reject images satisfactorily.

The IF of 450 kc is too low for proper high-frequency reception. The image signal is only 2 times 450, or 900 kc, from the signal frequency. If the IF is at 2,000 kc, the image will be twice 2,000 kc, or 4 Mc from the signal frequency. Even a relatively low-$Q$ circuit in the normal RF range will reject a signal 4 Mc removed.

The problem of image rejection is being solved today by using *double-conversion* superheterodyne circuits. The first IF may be in the 2.5-Mc region. After an IF stage at this frequency, a second mixer stage is used, with a crystal-controlled oscillator to convert to a second, much lower IF, usually in the 50- to 100-kc region. It is relatively simple to produce a high-$Q$ tuned circuit at these low frequencies. As a result two low-frequency IF stages may produce a very narrow passband. Expensive filters with their rather high insertion losses are not needed, and image rejection is obtained in the first conversion stage.

If the local crystal oscillator used in conjunction with the second conversion stage is not adequately shielded and isolated, harmonics of this oscillation may produce images or signals on higher-frequency bands. This is somewhat similar to many broadcast receivers with unshielded oscillators hearing higher-frequency police or amateur stations apparently in the broadcast band. Actually, the stations are beating against the second or third harmonics of the local oscillator in the receiver and are producing image signals in the improperly shielded set. A wavetrap can be very effective in decreasing image response caused by such a strong local signal.

**17.24 A Simple Double-conversion Superheterodyne.** The diagram of the receiver in Fig. 17.32 represents the minimum number of stages and functions that will qualify it to be termed a *double-conversion* (two mixer, or converter, stages) or double-superheterodyne communication receiver. Only single RF and IF stages have been included. No limiters, crystal filters, audio filters, or specialized circuits have been shown. To further simplify the diagram, band switching (switching in different coils to receive different parts of the RF spectrum) is not shown.

The receiver consists of a remote-cutoff RF amplifier with an RF gain control in the cathode. This is followed by the first triode-hexode converter stage, using an Armstrong local oscillator to produce a first IF of about 2.5 Mc. This is followed by a similar-type tube in the second converter stage, using a Pierce-type local crystal-oscillator circuit. (To isolate the first and second conversion stages better, a stage of IF amplification might be added between them, tuned to the first IF of 2.5 Mc.) The second converter is followed by a stage of lower IF, usually between 50 and 450 kc. This feeds into a second-detector stage in which is developed the AVC voltage. The triode part of this duplex diode-triode tube is also the first AF amplifier, which is resistance-coupled to a beam-power tetrode AF power amplifier. An ECO-type BFO is coupled into the plate circuit of the last IF amplifier. A full-wave rectifier with a single-section pi filter with a voltage divider makes up the power supply for the receiver.

If the second conversion stage is deleted, the diagram is of the simpler and more common single-conversion superheterodyne.

The first IF must be one that is not included in the tuning range of the receiver, since signals near the IF will tune broadly and the IF section may break into oscillation as the front end is tuned close to this frequency.

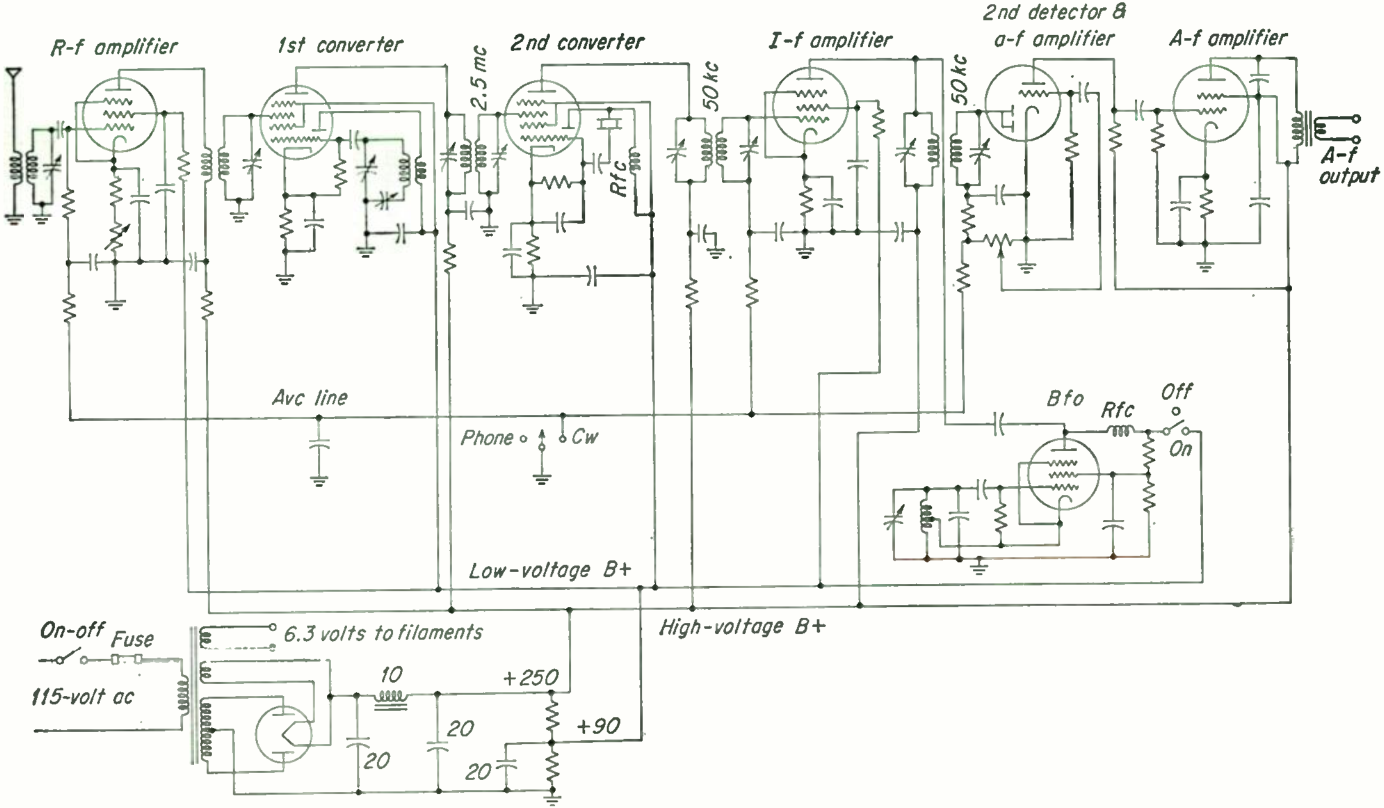


Fig. 17.32. A double-conversion superheterodyne circuit.

**17.25 Operating a Superheterodyne.** The small broadcast-band superheterodyne is quite simple to operate. It has an on-off switch, usually on the same shaft as the volume control, and a tuning knob. Some have tone controls. There is usually only one band of operation, the *standard broadcast band,* from 560 to 1,600 kc, and one type of emission, A3. The tuning knob is rotated to the desired station, the volume is adjusted to the desired level, and the tone control may be adjusted.

Receivers manufactured to monitor a single frequency, as in police, fire, taxicab, and other communication services, have an on-off switch, volume control, and usually a squelch-circuit on-off switch, possibly with an accompanying noise-threshold adjustment. Tuning is accomplished by internal screwdriver controls that are set once and left alone. Operation is as simple as possible.

The communication receiver may be another matter. It may have an on-off switch, a band-selector switch, a wideband tuning control, a vernier control to tune over a narrow band of frequencies, a crystal-filter on-off switch, a crystal phasing control, a variable IF bandwidth control, an AVC on-off switch, an RF gain control, an audio volume control, a tone control, a BFO on-off switch, a BFO tuning control, a limiter for use with A3 signals, a limiter for use with A1 signals, an audio filter switch, an earphone or loudspeaker switch or jacks, and a standby switch used when a local transmitter is in operation but which leaves the filaments of the receiver on.

As the band-selector switch is turned, different-sized coils are simultaneously connected across the RF amplifier, mixer, and local oscillator tuning capacitors, allowing the receiver to tune over a different portion of the radio spectrum. *Low-frequency receivers* will tune from about 15 to 550 kc in possibly four bands. *All-wave* receivers usually tune from 560 kc to 30 or 40 Mc in four to seven bands, depending on how wide a frequency coverage is desired on each band. In some receivers, band changing is accomplished by shorting out part of each tuning coil simultaneously. This is not considered particularly good engineering. However, it is better than merely tapping down the coils to change frequency, because the unused upper portions may fall into parallel resonance at some frequency and act as a wavetrap at that frequency. *Short-wave* receivers tune from about 2 to 30 or 40 Mc.

To tune in a *broadcast* signal where relatively high fidelity is desired, the crystal filter is turned off, the bandwidth is set to 10 to 15 kc, the AVC is turned on, the RF gain control is turned up full, the audio volume control is advanced to the desired sound level, the tone control is set to maximum high-frequency response, the noise limiters are normally left off, and the BFO is off.

To tune in an A3 *voice* signal on the higher-frequency bands where sidebands up to only 3,000 cycles are desired, the crystal filter is usually off, although it may be set to a broad position, the bandwidth should be set to about 6 kc, the AVC is turned on, the RF gain is turned on full, the tone control is set to reduce the high-frequency audio response, the noise limiter is on or off as required, the CW audio filter is off, and the BFO is off. Loudness is controlled with the AF volume control. If interference appears on one sideband of the desired signal, it is possible to reduce the bandwidth and/or set the crystal filter to a sharper position. The receiver is tuned to pick up the carrier and the set of sidebands that are not being interfered with. This is single-sideband-with-carrier reception and is possible on any double sideband transmission with some loss of signal strength and quality.

To tune in an A3b voice signal (single-sideband suppressed-carrier), the bandwidth of the receiver is adjusted to 3 kc by using the crystal and/or the bandwidth control. The AVC is switched off. The *audio* volume control is set to *maximum*, the tone control is set to decrease high-frequency response, the noise limiter and CW filter are turned off. The RF gain control is used to control the volume of the received signal, *not* the audio volume control. The BFO is turned on and set to a frequency 1.5 kc higher or lower than the IF center frequency. The BFO is now inserting a carrier in place of the missing carrier of the transmitted signal, and the 3 kc of sideband signals is passing through the IF amplifiers. The receiver is tuned very slowly and carefully until the voice is readable. If the voice cannot be detected, the BFO is tuned 1.5 kc on the other side of the IF center frequency and the receiver is again tuned. It will be noted that as much as 10-*cycle* variation in the setting of the vernier tuning control or of the BFO can make the received signal sound unnatural. Two hundred cycles off, and the signal is difficult to understand. For this reason receivers used for SSSC (SSB) reception must have exceptional frequency stability of local and beat-frequency oscillators.

To tune in A1 or A2 radiotelegraph signals the crystal filter may or may not be used, depending on the interference from adjacent frequency signals. The bandwidth control may be adjusted to as narrow a setting as possible. The AVC is turned off, the audio volume is set at maximum, the BFO is turned on and adjusted to a frequency near the center of the IF channel, the tone control is adjusted to remove as many high audio frequencies as possible, the A3 noise limiter is turned off, the A1 noise limiter may be turned on if necessary. The audio filter may be used if interference is bothersome or if the signal is extremely weak. The *RF gain control* is used to control the volume of the received signal. If adjacent frequency signals interfere, the crystal filter can be placed in a sharper condition and the interfering signals phased out.

In general, when trying to copy through interference with a superheterodyne or a TRF receiver (whether the interference is from a nearby noise-generating source or from adjacent frequency signals), as low a degree of coupling as possible should be used between antenna and receiver to increase the $Q$ of the input circuit. The RF gain control should be operated as low as possible, and any interstage coupling that can be varied should be at a minimum to prevent overloading of the tuned circuits. The narrower the bandwidth of the IF strip, the better. The more it is restricted, the less noise present in the output.

To relieve listening fatigue due to continued listening to a single tone while copying code signals, the operator can tune either the BFO or the main tuning dial very slightly to change the beat tone of the received signal, preferably about half an octave.

Strong CW signals are prevented from blocking the receiver by turning down the RF gain control.

**17.26 Diversity Reception.** To overcome the effects of fading, the AVC circuit was developed. While this is partially effective, signals can still fade in and then out completely. It has been found that two antennas a few hundred feet apart may have two entirely different amplitude signals in them from the same distant station at any particular instant. It is possible to connect a separate receiver to each of two or three widely spaced antennas and feed them to a common output. If the two or three receivers have a common AVC line, the receiver with the strongest signal in it takes over and the output is mainly derived from this one receiver. If, at another instant, one of the other receivers has a higher-amplitude signal, it produces a higher AVC, desensitizing the other receivers, and only its output is delivered. This results in a much more even intensity output signal. Signals that might have been fading severely on one receiver may have almost no signal-strength variation using diversity reception.

Two receivers with antennas directly adjacent will also give a certain amount of diversity reception, although the farther they are apart, the better the diversity action.

**17.27 Aligning a Superheterodyne.** Tuning the RF, mixer, oscillator, IF, and detector stages of a superheterodyne to their correct frequencies is known as *aligning* the receiver. Fortunately, superheterodynes rarely need realignment. When tubes are changed, only on the higher-frequency bands may the local oscillator be detuned enough to require realignment. In many cases, inexpert attempts to realign will result in greater misalignment. However, once in a while a do-it-yourself mechanic will decide that the screws in the receiver are too loose and tighten them all, including the RF and IF trimmer capacitors. In this case no signals will be audible, even if the receiver circuits are electrically perfect. Sometimes one or more stages in a receiver are changed to include new parts, higher-gain tubes, and so on. In these cases realignment will be necessary.

To align a superheterodyne, the operator should have at least a tone-modulated RF signal generator capable of being tuned across the IF frequency and across that part of the radio spectrum the receiver is supposed to tune; a small screwdriver made of insulating material; and two 0.0001- to 0.0005-$\mu$f fixed capacitors. A vacuum-tube voltmeter or a 20,000 ohms/volt meter can be used to measure the AVC voltage during alignment.

The basic procedure is to work from the second-detector input circuit back to the RF input circuits, checking each stage in turn.

To align a small broadcast receiver, one procedure might be as follows:

The tone-modulated RF signal generator is adjusted to the desired IF, usually 455 to 465 kc, and is connected to the grid and to ground (or negative terminal of the power supply) of the last IF stage, using the 0.0001-$\mu$f capacitors in series with the signal-generator leads. The detector stage should demodulate this signal, and a tone should be heard in the loudspeaker. A sensitive voltmeter connected between the AVC line and ground will read any d-c voltage developed across the diode detector load. The output of the RF signal generator should always be readjusted to as weak an output as possible and still obtain an audible or visual tuning indication.

The primary and the secondary of the IF transformer between the last IF amplifier and the detector are tuned for maximum audible or visual indication, using the insulating-material screwdriver to prevent detuning by *hand capacitance* and to prevent shorting the adjusting screws of the IF transformers against the shield cans.

After this transformer is tuned, the signal generator is moved to the grid of the mixer stage (or to the grid of the IF stage ahead, if there is one). A wire is connected across the local oscillator tuning capacitor to prevent it from oscillating. The IF transformer primary and secondary between the mixer and IF stage (or between any two IF stages) are tuned for maximum audible or visual indication. This completes the alignment of the IF section.

The alignment of the mixer and oscillator stages involves tracking these two. Although there are many different circuits employed as mixer stages, the tracking procedure is somewhat similar in all. The various capacitors involved in most circuits are shown and labeled in Fig. 17.33.

After the shorting wire has been removed from the oscillator capacitor, the receiver dial is set to some high-frequency point, such as 1,400 kc. The signal generator is set to the same frequency and coupled to the external *antenna terminal*. If the signal generator is not heard on the receiver, the oscillator *trimmer* capacitor can be varied until the signal is heard. Then the input trimmer capacitor of the mixer is tuned until a peak is indicated audibly or visually. The receiver is next tuned to a calibrated point at the low-frequency end of the dial, such as 600 kc.

The signal generator is then set to 600 kc. If the signal generator cannot be heard in the receiver, the oscillator is not tracking with the dial markings. At the low-frequency end of the dial the oscillator *tracking* capacitor is adjusted until the signal is heard. Then the receiver and signal generator are returned to the 1,400-kc settings, and the oscillator *trimmer* capacitor is readjusted for maximum indication. The high- and low-frequency points are rechecked until the signals track with the dial readings, adjusting the oscillator *trimmer* capacitor on the high-frequency point and the oscillator *tracking* capacitor on the low-frequency point. The receiver is now aligned to the dial markings.

Note that it may not be necessary to attempt to track the mixer input circuit of the smaller receivers. In many receivers there is no way to track this circuit, and it is assumed that the dial has been calibrated to follow the tuning characteristics of this input circuit. If the input trimmer is adjusted at the high-frequency end and found to be off tune at the low-frequency end, the receiver may be set to a frequency of about 1,200 kc and peaked. The input circuit will probably be tuned close enough on all other frequencies to produce satisfactory operation. If the input circuit tuning capacitor has slotted outer plates, it is possible to bend out one or more slotted sections at one end or the other, reducing the capacitance at either the high- or the low-frequency end as desired, to produce better tracking. This will require more trimmer adjustments.

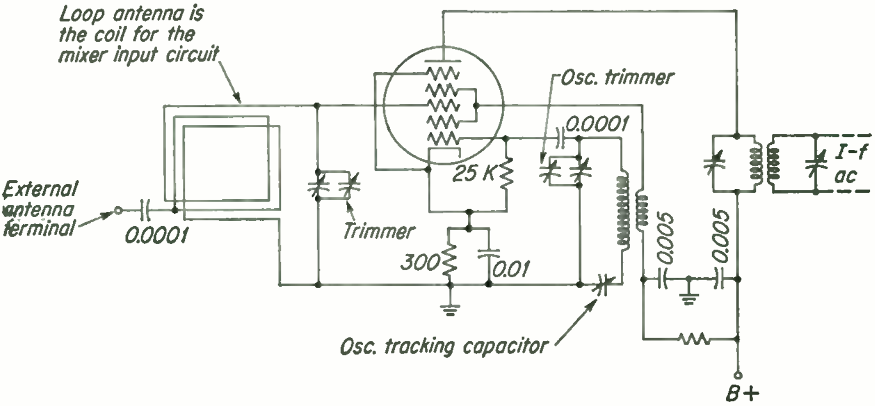


FIG. 17.33. An input-mixer stage of a loop-antenna broadcast-band receiver.

In the more expensive receivers, there are trimmer capacitors across each coil and a means of changing the inductance of each coil, usually by running either brass or powdered-iron-compound slugs into or out of the core area of the coils. (Brass slugs lower inductance, acting as shorted turns, whereas iron increases inductance when used as a core.) After the oscillator stage has been tuned to conform to the dial markings, the mixer input stage is made to tune over the same band of frequencies, adjusting the *inductance* at the *low-frequency* end of the band and the *capacitance* at the *high-frequency* end. With receivers having RF amplifiers, the signal is fed into the antenna and the RF amplifier is tuned to cover the same band of frequencies, using the same method as was used with the mixer input circuit. The basic steps are tune oscillator, tune mixer input, then tune RF amplifier(s).

While the audible-output method is satisfactory for small broadcast receivers, an unmodulated-signal-generator output is required for the sharper communication receivers, which are always aligned in their sharpest condition. With sharp receivers, the sidebands of the modulated signal can give confusing indications both audibly and visually. A visual indication from a vacuum-tube voltmeter is one of the best methods of determining peak tuning. The S meter in the receiver can also be used.

When a crystal filter is the input circuit of the IF section, it should be adjusted for minimum bandwidth (best capacitive neutralization) and the signal generator fed into the mixer stage and varied until a maximum visual indication is obtained. The signal generator is now on the crystal-filter frequency. All IF amplifiers are then trimmed to this frequency.

**17.28 Trouble Shooting in Receivers.** One of the requirements of many of the radio operating jobs is the servicing of equipment when it ceases to function properly. Many books have been written on the subject of servicing radio equipment. Only a few basic ideas regarding it can be included here. Experience with previous breakdowns is probably as important as anything else. However, if the operator has not had experience, what is he to do? Consideration of the outward evidences may indicate the possible trouble. What shows that the equipment is not operating properly? If it is smoke, the equipment must be turned off immediately. If the signals are weak, distorted, or nonexistent, the steps taken may vary considerably. In any case, the operator should first try to *see* what is not normal.

Regardless of the number of jokes made on the subject, in an emergency one of the first steps taken when a receiver suddenly stops working is to deliver a sharp blow with the heel of the clenched fist to each side of the receiver, to the top, and to the front panel. In a remarkable number of cases the receiver will start operating again—but it is not fixed. As soon as possible the equipment should be checked thoroughly. Something is loose. It may be due to oxidized pin connections in a tube or other part, or some screw or solder connections may have loosened. Each tube should be worked back and forth gently in its socket with the receiver on, to see if the cause of the intermittent operation can be localized. Tapping the parts will often help to localize the trouble.

Fuses should be checked, as well as line-cord connections if there is no heating of filaments or dial lights. It is discouraging to find, after spend-ing many minutes testing tubes and parts, that the line cord has a broken connection or that the fuse blew out when the receiver was turned on, as it often will. An old fuse may burn out for no apparent reason. In case of a blown fuse, it is usually a good practice to renew the fuse and turn on the equipment. If there is something wrong with the equipment, the fuse will burn out again.

Failure of a tube is probably more often the reason for improper operation of a receiver than any other cause. If possible, test each tube, noting the physical condition of the tube pins and the socket and surrounding chassis. Clean the dust from around the tubes. If a tube tester is not available, substitute each tube singly with a similar tube, taking care to replace all the tubes to their original sockets if not proved faulty. Mixing up the arrangement of even the same types of tubes in a communication receiver may cause improper operation of the equipment because of slight capacitance variations between supposedly similar tubes.

If the steps outlined above have all been taken and the equipment still does not operate, something may have burned out, opened, or shorted. The receiver should be removed from its cabinet, turned upside down at a test bench, and the bottom plate removed. Careful scrutiny of the parts may show a burned resistor, evidences of excessive heat, bulging fixed capacitors, or loose wires.

In a surprising number of cases, the trouble in a receiver can be localized, using nothing more complicated than a fairly sensitive volt-ohm meter. The voltmeter is used if the receiver is turned on and the power supply is found to be operating. The ohmmeter is used *only* when the receiver is turned off and the a-c line cord pulled out of the service outlet.

If the power supply is found to be operating and the normal 100 to 300 volts is being produced, the voltage between the plate pin of each tube and B− can be tested. The plate of every triode, tetrode, and pentode should read a positive voltage. If not, there may be an open in that circuit or the plate circuit may be shorted to ground. The plate voltage of resistance-coupled amplifiers will normally read lower than other stages. Screen-grid terminals should also show a voltage reading. Touching the voltmeter to the plates and grids of audio-amplifier tubes may result in an audible click in the loudspeaker, telling that the audio stages are operating. Each cathode of an amplifier stage should be checked for voltage. If the tube is not passing current for some reason, there will be no bias voltage developed, although there may be voltage at the plate terminal. However, an open cathode resistor may produce a high-voltage reading between cathode and ground. Each control grid can be tested and should read zero volts to ground. A positive voltage on a control grid may indicate a leaking coupling capacitor.

To check whether an oscillator stage is oscillating, an RF choke or a 100,000-ohm carbon resistor can be connected to the end of the ungrounded voltmeter probe and held against the control grid of the oscillator tube. If there is plate voltage on the tube but no negative d-c grid voltage, the oscillator must not be oscillating.

If all measured voltages seem within reason and still no signals can be heard, an audio signal generator can be connected across each audio amplifier in turn, starting at the final amplifier, working back to the second detector. If this does not localize the trouble in an audio stage, a tone-modulated RF signal generator can be connected to the IF amplifiers and RF circuits, following a procedure of circuit checking similar to alignment, each stage being checked until one is found that produces little or no output when fed an input signal.

Distortion in the audio amplifiers can be checked with earphones in series with a 0.005-$\mu$f capacitor. When the stage is reached in which the distortion is produced, it will be audibly evident. It is then necessary to determine what part is faulty. Open grid resistors, leaking capacitors, and shorted transformer turns are all possibilities.

Sometimes the AVC line becomes grounded, and overdriving of the IF stages occurs, distorting all but the weakest signals. Sometimes the diode load resistor opens, and all signals may be weak and distorted. Volume-control potentiometers often become faulty.

If the power supply does not have any output voltage, the power-supply switch should be left on and the power-line plug pulled out. An ohmmeter test across the plug and line cord should give a reading of 3 to 10 ohms. If a very-high-resistance reading is indicated, something in the primary circuit is burned out, a fuse or the primary winding, or the connecting wires may be disconnected.

The secondary of the power transformer should show continuity and resistance values of 25 to 350 ohms. The B+ to ground circuit should read several thousand ohms, or whatever the bleeder resistance is. If it reads nearly zero, a filter capacitor in the power supply, or a bypass capacitor in the receiver, may be the trouble. The output lead of the power supply can be unsoldered, and the B+ to ground of the power supply checked. If it shows a relatively high resistance, the receiver B+ lead must show the low-resistance reading. Whichever end of the B+ line reads low resistance has the shorted capacitor or part in it. It will be necessary to continue disconnecting circuits from the B+ line until the low-resistance circuit is found.

Noisy operation of a receiver can be caused by many things. Sometimes it is from poor connections and vibration of the equipment. It can be due to intermittent breaking down of the dielectric of coupling or bypass capacitors. It can be due to faulty resistors or tubes. If the equipment is battery-operated, noise can be produced by polarization of old, worn-out batteries. When old batteries are replaced with new, care must be taken that the battery polarity is correct, since a reversed-polarity B battery will place a negative potential on the plates of the tubes and they will not operate.

**17.29 Emergency Repairs.** Sometimes there are no spare parts for a receiver when it burns out. The operator's problem is to put the receiver into some kind of working condition.

If the first RF amplifier stage or tube becomes faulty, it is possible to capacitively couple the antenna directly to the next RF amplifier grid, or to the mixer input grid, by wrapping an *insulated* wire around any exposed wiring in the grid circuit. This forms a *gimmick*, which has a few micromicrofarads of capacitance to the wire around which it is connected. It is also possible to remove the faulty tube and couple the antenna through a 50- or 100-$\mu\mu$f capacitor to the plate pin hole in the tube socket. The primary of the plate-circuit RF transformer then acts as an antenna coil. However, it is still connected to a high positive potential and must be treated with caution.

If an RF or IF amplifier tube becomes inoperative and there are no replacements, the plate and grid connections of this stage can be connected together with a gimmick or small capacitor, and signals may be heard.

If the second-detector tube fails, audible signals may be heard by connecting earphones between the cathode and the AVC end of the second, or even the first, IF amplifier transformer. It may be possible to couple the grid circuit of an audio stage to this point through a capacitor and produce amplified output.

If one of the audio amplifiers becomes faulty, it may be possible to jump the signal over this stage with a capacitor of any value between 0.001 and 0.1 $\mu$f, or earphones can be connected across the second-detector diode load resistor.

If the local oscillator ceases to oscillate, earphones can be connected in series with the mixer-stage plate circuit, or in series with the last RF stage. These circuits will act as detectors, and strong *modulated* signals can be demodulated.

If test equipment is not available, a continuity checker can be rigged by connecting a 1½- to 6-volt battery in series with a pair of earphones. When leads from these are connected and disconnected across a coil or the primary or secondary of a transformer, for example, clicks will be heard. If the winding is open, little or no click will be audible. Capacitors of more than 0.002-$\mu$f capacitance can also be tested. A capacitor such as a 0.1-$\mu$f or larger will click loudly on the first contact, charge to the battery voltage, and produce almost no click if the connection is made to it again immediately. If it continues to click, it is possibly leaking or shorted. The higher the resistance tested with this continuity checker, the lower the amplitude of the click. Tubes can be tested for filament continuity or for shorts between elements with such emergency equipment.

A pair of earphones in series with a 0.0001- to 0.01-$\mu$f capacitor can be used to test whether AF signals are present in different stages. When connected from cathode to the AVC connection of an RF or IF transformer, modulated signals should be audible if the receiver is operating up to that point. From the second detector on, the audio signal can be traced to each grid and plate circuit of the different audio stages, indicating where a loss of signal occurs.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** Draw a simple schematic diagram of a diode vacuum tube connected for diode detection and showing a method of coupling to an audio amplifier. (17.2) **[3]**

**2.** Describe the operation of a crystal detector (rectifier). (17.3) **[3]**

**3.** What effect does the reception of modulated signals have on the plate current of a grid-leak, grid-capacitor type of detector? On a grid-bias type of detector? (17.4, 17.5) **[3]**

**4.** What are the characteristics of plate detection? (17.7) **[3]**

**5.** What feedback conditions must be satisfied in a regenerative detector in order to obtain sustained oscillations? (17.7) **[3]**

**6.** How does the value of resistance in the grid leak of a regenerative-type detector affect the sensitivity of the detector? (17.7) **[3]**

**7.** Why is it necessary to use an oscillating detector for reception of an unmodulated carrier? (17.7) **[3]**

**8.** Explain what circuit conditions are necessary in a regenerative receiver for maximum response to a modulated signal. (17.7) **[3]**

**9.** How may a regenerative-type receiver be adjusted for maximum sensitivity? (17.7, 17.9) **[3]**

**10.** What feedback conditions must be satisfied in a regenerative detector for most stable operation of the detector circuit in an oscillating condition? (17.7) **[3]**

**11.** What is the principal advantage of the tetrode as compared to the triode, when used in a radio receiver? (17.9) **[3]**

**12.** What type of radiotelephone receiver using vacuum tubes does not require an oscillator? 17.9) **[3]**

**13.** Draw a diagram of a TRF-type radio receiver. (17.9) **[3]**

**14.** What type of radio receivers contain IF transformers? (17.10) **[3]**

**15.** What is meant by double detection in a receiver? (17.10) **[3]**

**16.** Draw a block diagram of a superheterodyne receiver capable of receiving amplitude-modulated signals and indicate the frequencies present in the various stages when the receiver is tuned to 2,450 kc. What is the frequency of a station that might cause image interference to the receiver when tuned to 2,450 kc? (17.10) **[3]**

**17.** What type of radio receiver is subject to image interference? (17.10) **[3]**

**18.** What is the purpose of shielding in a multistage radio receiver? (17.10) **[3]**

**19.** What is the purpose of an oscillator in a receiver operating on a frequency near the IF of the receiver? (17.15) **[3]**

**20.** Show by a diagram how to connect a wavetrap in the antenna circuit of a radio receiver to attenuate an interfering signal. (17.22) **[3]**

**21.** What advantages are obtained from adding a TRF amplifier stage ahead of the first-detector (converter) stage of a superheterodyne receiver? (17.23) **[3]**

**22.** If a superheterodyne receiver is tuned to a desired signal at 1,000 kc and its conversion oscillator is operating at 1,300 kc, what would be the frequency of an incoming signal which would possibly cause image reception? (17.23) [3]

**23.** Explain the relation between the signal frequency, the oscillator frequency, and the image frequency in a superheterodyne receiver. (17.23) [3]

**24.** Discuss methods whereby interference to radio reception can be reduced. (17.25) [3]

**25.** What is the purpose of a diversity-antenna receiving system? (17.26) [3]

**26.** What would be the effect upon a radio receiver if the vacuum-tube plate potential were reversed in polarity? (17.28) [3]

**27.** Explain the operation of a diode type of detector. (17.2) [3 & 6]

**28.** What is the principal advantage in the use of a diode detector instead of a grid-leak-type triode detector? (17.2) [3 & 6]

**29.** What operating conditions determine that a tube is being used as a power detector? (17.4) [3 & 6]

**30.** Explain the operation of a power- or plate-rectification-type of vacuum-tube detector. (17.4) [3 & 6]

**31.** Draw a simple schematic diagram of a triode vacuum tube connected for plate, or power, detection. (17.4) [3 & 6]

**32.** List and explain the characteristics of a square-law type of vacuum-tube detector. (17.5) [3 & 6]

**33.** Explain the operation of a grid-leak-type detector. (17.6) [3 & 6]

**34.** Draw a simple schematic diagram of a triode vacuum tube connected for grid-leak-capacitor detection. (17.6) [3 & 6]

**35.** Is a grid-leak type of detector more or less sensitive than a power detector (plate rectification)? Why? (17.6) [3 & 6]

**36.** Do oscillators operating on adjacent frequencies have a tendency to synchronize oscillation or drift apart in frequency? (17.7, 17.13) [3 & 6]

**37.** Draw a simple schematic circuit of a regenerative detector. (17.7) [3 & 6]

**38.** What might be the cause of low sensitivity of a three-circuit regenerative receiver? (17.7) [3 & 6]

**39.** What effects might be caused by a shorted grid capacitor in a three-circuit regenerative receiver? (17.7) [3 & 6]

**40.** Compare the selectivity and sensitivity of the following types of receivers: (*a*) TRF receiver. (*b*) Superregenerative receiver. (*c*) Superheterodyne receiver. (17.8, 17.9, 17.13) [3 & 6]

**41.** Describe the operation of a regenerative-type receiver. (17.9) [3 & 6]

**42.** Explain the purpose and operation of the first detector in a superheterodyne receiver. (17.10, 17.12) [3 & 6]

**43.** How is AVC accomplished in a radio receiver? (17.14) [3 & 6]

**44.** What type of modulation is largely contained in static and lightning radio waves? (17.19) [3 & 6]

**45.** What is the purpose of a wavetrap in a radio receiver? (17.22) [3 & 6]

**46.** If a tube in the only RF stage of your receiver burned out, how could temporary repairs or modifications be made to permit operation of the receiver if no spare tube were available? (17.29) [3 & 6]

**47.** Draw a diagram showing how AVC is accomplished in a standard broadcast receiver. (17.14) [4]

**48.** Describe how to adjust a communications radio receiver for the reception of weak CW signals. (17.7, 17.25) [5]

**49.** What adjustment should be made to a radiotelegraph receiver if the receiver blocks on the reception of strong signals? (17.7, 17.25) [5]

**50.** How should a radiotelegraph receiver be adjusted for the reception of type-A2 emissions? (17.9, 17.25) [5]

**51.** How should the AVC switch be set for reception of CW radiotelegraph signals on a communications receiver designed for both radiotelephone and radiotelegraph reception? (17.14, 17.25) [5]

**52.** Explain the use of the crystal-filter switch on a communications receiver. (17.21) [5]

**53.** Sometimes a given radiotelegraph transmitting station can be heard at more than one place on the tuning dial of a receiver. Is this always an indication that the station is transmitting on more than one frequency? (17.23) [5]

**54.** After long periods of listening to a CW telegraph signal of constant tone, what adjustment can the operator make to a radio receiver to relieve hearing fatigue? (17.26) [5]

**55.** Name four materials which can be used as crystal detectors. (17.3) [6]

**56.** Draw a circuit diagram of a crystal-detector receiver and explain its principle of operation. Name two substances that can be used as the crystal in such a receiver. (17.3) [6]

**57.** Why is it sometimes necessary to provide an RF filter in the plate circuit of a detector tube? (17.7) [6]

**58.** What effect does an incoming signal have upon the plate current of a triode detector of the grid-leak type? (17.6) [6]

**59.** What controls determine the selectivity of a three-circuit receiver? (17.7) [6]

**60.** Using a regenerative receiver without RF amplifier stages, describe how you would adjust to receive radiotelegraph signals through interference. (17.7) [6]

**61.** How may a regenerative-type receiver be adjusted for maximum sensitivity? (17.7) [6]

**62.** What are the objections to the operation of a regenerative oscillating-detector receiver when directly coupled to an antenna? (17.7) [6]

**63.** If a ship's regenerative receiver failed to oscillate when the regeneration control was advanced, explain the possible causes and remedies. (17.7) [6]

**64.** Describe how you could test a regenerative receiver to determine if the detector is in an oscillating condition. (17.7) [6]

**65.** Name three causes of an audio howl in a regenerative receiver. (17.7) [6]

**66.** Give four reasons which would prevent a regenerative receiver from oscillating. (17.7) [6]

**67.** In the operation of a regenerative-type receiver, how is oscillation of the detector indicated? (17.7) [6]

**68.** Describe the principle of operation of a superregenerative receiver. (17.8) [6]

**69.** If signals are heard with the headphones plugged into the detector plate circuit of a receiver but no signals are heard when phones are plugged into the first AF amplifier-stage plate circuit, what might be the cause and how could it be remedied? (17.9, 17.28) [6]

**70.** Draw a block diagram of a TRF-type receiver. (17.9) [6]

**71.** Discuss the relative advantages and disadvantages of a stage of RF amplification as compared with a stage of AF amplification for use in connection with a regenerative receiver. (17.9) [6]

**72.** In a TRF receiver, what is the advantage of heterodyne reception as compared with autodyne reception? (17.9) [6]

**73.** What is the purpose of a TRF amplifier stage ahead of the mixer stage of a superheterodyne receiver? (17.10, 17.11, 17.23) [6]

**74.** What is the purpose of an oscillator in a receiver operating on a frequency near the intermediate frequency of the receiver? (17.10, 17.15) [6]

**75.** What is the mixer tube in the superheterodyne receiver? (17.10, 17.14) [6]

**76.** Draw a block diagram of a superheterodyne receiver capable of receiving CW radiotelegraph signals. (17.10) [6]

**77.** A superheterodyne-type receiver is adjusted to 2,738 kc. The IF is 475 kc. What is the frequency to which the grid circuit of the second detector must be tuned? (17.10) [6]

**78.** Why do some superheterodyne receivers employ a crystal-controlled oscillator in the first detector? (17.12) [6]

**79.** What is the advantage of using iron cores of special construction in RF transformers and inductances? (17.13) [6]

**80.** What types of radio receivers are not affected by static interference? (17.19) [6]

**81.** What is the main advantage of a tuned AF amplifier in a receiver used for the reception of radiotelegraph signals? (17.20) [6]

**82.** What is a crystal filter as used in a superheterodyne receiver? (17.21) [6]

**83.** What is the purpose of a crystal filter in the IF stage of a superheterodyne communications receiver? Under what conditions is this filter used? (17.21) [6]

**84.** If broadcast signals interfered with your reception of signals on 500 kc while aboard ship, how would you reduce or eliminate such interference? (17.22) [6]

**85.** Why should a superheterodyne receiver used for the reception of A1 signals be equipped with at least one stage of RF amplification ahead of the first detector? (17.23) [6]

**86.** Knowing the IF and the signal to which a superheterodyne receiver is tuned, how would you determine the most probable frequency on which image reception would occur? (17.23) [6]

**87.** What is the chief advantage to be gained in the utilization of high intermediate frequencies in a superheterodyne receiver? (17.23) [6]

**88.** How may image response be reduced in a superheterodyne receiver? (17.23) [6]

**89.** If a superheterodyne receiver is receiving a signal on 1,000 kc and the mixing oscillator is tuned to 1,500 kc, what is the IF? (17.23) [6]

**90.** Explain the reasons why a superheterodyne receiver may not be successfully used for reception of frequencies very near that of the IF amplifier. (17.24) [6]

**91.** Draw a circuit diagram of a superheterodyne receiver with AVC and explain the principle of operation. (17.24) [6]

**92.** Why are the unused portions of inductances in receivers sometimes shorted? (17.25) [6]

**93.** How should a superheterodyne communications receiver be adjusted for maximum response to weak CW signals? To strong CW signals? (17.25) [6]

**94.** Explain how you would test the various components of a receiver of the three-circuit regenerative type in trouble shooting. (17.28) [6]

**95.** What may be the cause of noisy operation of a regenerative three-circuit receiver having two stages of AF amplification? (17.28) [6]

## AMATEUR LICENSE INFORMATION

Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer the following question.

**1.** Draw a simple schematic diagram of a wavetrap that can be connected between the antenna and receiver to decrease interference from a local transmitter. (17.22)

## CHAPTER 18

# FREQUENCY MODULATION

**18.1 Purpose of Frequency Modulation.** From the time it was first used, there has been a constant search for better methods of utilizing radio as a means of communication. By 1930 the superheterodyne had been developed, as had high-powered amplitude-modulated transmitters. Since that time communication equipment has become less bulky and somewhat better as far as sensitivity and selectivity are concerned. The difficulty of man-made and natural static still exists. As far as radio broadcasting is concerned, the sponsor is usually interested in a coverage of only a few miles, so that the standard broadcast band (560–1,600 kc), with its 1,000- to 50,000-watt stations, is quite satisfactory. However, at a distance of only a few miles from a 50-kw station, a lightning storm can still make reception unpleasant.

In order to prevent noises that vary in amplitude from interfering with reception, it is necessary to make the receiver unresponsive to amplitude variations.

As previously stated, an alternating current can be changed in only three ways: (1) in amplitude, or strength, (2) in frequency, (3) in phase. The study so far has been almost entirely limited to transmitters and receivers that produce and demodulate amplitude modulation. The short discussions on frequency-shift keying (FSK) indicated that it is possible to transmit intelligence by changing the carrier frequency without changing the carrier amplitude. Frequency modulation, or FM, is somewhat similar to FSK, in that the carrier is made to swing back and forth in frequency, but at an audio rate. If the carrier sweeps back and forth 1,000 times a second, the carrier is being frequency-modulated at a 1,000-cycle frequency. When the audio voltage that produces the FM of the carrier is no longer present, the carrier comes to rest at the *center frequency* and remains there until another modulating voltage is applied.

An FM receiver is quite similar to an AM receiver. It is usually a superheterodyne, but has a special second detector that will demodulate frequency instead of amplitude variations. The IF stages feeding the second detector are amplifiers, but also act as *amplitude limiters.*

Since the FM receiver is not sensitive to amplitude variations in normal operation, static crashes are not demodulated and are therefore not audible. This is also true of many other types of high-impulse interference that make AM reception difficult.

**18.2 The Four Fields of FM.** There are four major fields in which FM is in use. One is in the FM broadcast band, 88–108 Mc, in which FM stations broadcast programs to the everyday radio listener. These programs may be the same as or similar to those transmitted on the standard AM broadcast band. While FM transmissions may have greater fidelity of transmission than the same programs being transmitted simultaneously on the standard AM broadcast band, it is only because the AM signals are passed through a low-pass audio filter system that prevents frequencies higher than 5,000, or in some cases 7,500, cycles from modulating the transmitter and interfering with adjacent channel transmission on the AM band. The FM transmitters need not attenuate any frequencies under 15,000 cycles, since nearby stations are not assigned to adjacent channels on the FM band.

The second use of FM is in television transmissions. The video, or visible, signals are amplitude-modulated, but the voice and music are transmitted on a separate transmitter that is frequency-modulated. Therefore a TV receiver must be both an AM and an FM receiver at the same time.

The third use of FM is in the land mobile or emergency services, such as taxicabs, police, and fire communications. These communications are all voice-type and are not interested in transmitting audio frequencies above about 3,000 cycles.

The fourth use of FM is in the amateur bands, where *narrow-band FM* is usually used. In some bands wideband FM is allowed. Here again, only voice frequencies are transmitted.

**18.3 Basic Concepts of FM.** In AM, the louder the sound striking the microphone, the greater the variation of the strength of the carrier and the louder the signal developed in the detector stage of the receiver. In FM, the louder the sound, the greater the variation of the frequency from the assigned or center frequency, and the louder the signal developed in the FM detector stage, the *discriminator*.

If the carrier is made to deviate 75 kc on each side of the center, or resting, carrier frequency (a total swing of 150 kc), a satisfactorily loud signal will be developed, and a not excessive amount of frequency spectrum will be used. This is the maximum carrier excursion allowed by the FCC for FM broadcast stations. It is considered as *100 per cent modulation*, although any value frequency excursion could have been selected as the 100 per cent value. If the carrier is 50 per cent modulated, the swing is 37.5 kc on each side of the center frequency; 60 per cent modulation produces a *deviation* of 45 kc; 80 per cent modulation produces a deviation of 60 kc. Doubling the percentage of modulation always doubles the frequency swing. As long as the percentage of modulation remains the same, the frequency swing remains the same, regardless of the tone of the modulation (disregarding pre-emphasis).

A simple system by which FM could be developed is shown in Fig. 18.1. The circuit shows a series-fed Hartley oscillator with a condenser microphone connected across the tuned circuit. When sounds strike the diaphragm, it swings in and out, changing the capacitance across the microphone, which changes the frequency of the oscillator. The amplitude of the RF a-c generated by the oscillator will not change, however.

The louder the sounds striking the microphone, the greater its capacitance change and the farther the swing of the carrier from its resting, or center, frequency. If the tone of the sound is 500 cycles, the microphone diaphragm vibrates 500 times a second and the frequency of the oscillator swings back and forth 500 times a second. If the *same*-strength sound, but having a frequency of 1,000 cycles, strikes the microphone, the diaphragm will vibrate twice as rapidly, producing a carrier that increases and decreases frequency 1,000 times a second. Since the strength of the tone is the same, the deviation of the carrier from the center frequency should be the same. If the sound striking the microphone is not as strong, regardless of the frequency or tone, the deviation, and therefore the percentage of modulation, will be less.

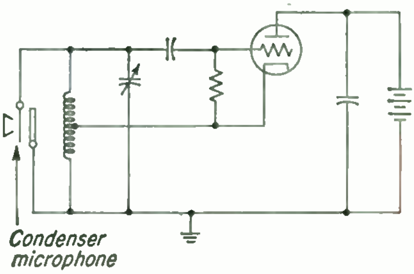


FIG. 18.1. A possible method of producing FM.

The usual amplifier stage reverses the phase of the signal applied to its grid. This represents a 180° phase change between input and output signal. If some control can be included in the amplifier which will change this phase difference to some other value, perhaps 90°, the transmitted output signal will have the same frequency and amplitude as with the 180° shift. To a receiver there would be no distinguishable change in the signal. If the control circuit is modulated by an audio-frequency signal, the phase might be shifted from 90 to 100° and then to 80° alternately at an audio rate. Each output cycle of RF a-c would be forced to have a slightly longer or slightly shorter wavelength than the input unmodulated signal. As long as the AF modulation was applied, the transmitted wavelength would be forced to vary. This produces an indirect FM known as *phase modulation* or PM.

In AM, the addition of the AF to the carrier produces sidebands. Any single tone used to modulate the carrier produces a sideband on each side of the carrier frequency. During modulation each succeeding RF a-c cycle is slightly greater or less in *amplitude* than the one before. This distortion of the RF wave can be considered as producing the sidebands.

In FM the swinging of the carrier from one frequency to another means that each RF a-c cycle cannot be a pure sine wave, since each succeeding cycle is at a slightly higher or slightly lower frequency than the one preceding it. This results in sidebands also. Instead of only one pair of sidebands for any one tone (as in AM), the number of sidebands produced by FM will depend on how far the carrier is swung. The greater the swing, the greater the number of sidebands. Theoretically, there are an infinite number of sidebands produced by an FM transmitter, but only the first few are strong enough to be significant.

Considering 15 kc as the highest AF necessary to be transmitted and 75 kc as the widest frequency deviation allowed, the ratio of the deviation to the modulating frequency is 75:15, which is known as the *deviation ratio* of an FM broadcast transmitter. The ratio of the maximum deviation allowed (75 kc) to the modulating frequency (10, 5, 7 kc, etc.) is known as the *modulation index*. Note that the deviation ratio and the modulation index are only the same at the maximum 75-kc deviation with the maximum modulating signal frequency of 15 kc.

Mod Index of 5

$MI = \frac{Dev}{Mod\ Freq}$

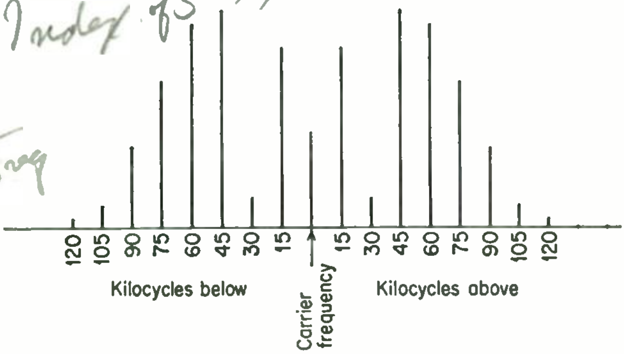


FIG. 18.2. Sidebands developed by a 15-kc tone swinging the carrier 75 kc above and below the center frequency.

The deviation ratio of 5 that is used in FM broadcasting will produce eight significant sidebands above and eight below the center frequency with a 15-kc modulating tone. (The number of significant sidebands is mathematically determined by *Bessel functions*, which are beyond the scope of this book.) A 15-kc modulating tone, forcing the carrier to deviate 75 kc, produces eight significant sidebands, each one 15 kc from the adjacent sidebands, as shown in Fig. 18.2. Such a modulating signal will produce significant sidebands 120 kc each side of the center frequency, or will require a total bandwidth of 240 kc. However, since the fundamental tones of all musical instruments are below 5 kc, only the relatively weaker overtones, or harmonics, are in the range of 5 to 15 kc. It is unlikely that a strong signal will ever be transmitted at as high an audio frequency as 15 kc. As a result, only the first four or five sidebands may be developed, requiring only about 120–150-kc bandwidth.

If a 10-kc tone is transmitted, its modulation index will be $^{75}/_{10}$, or 7.5. This will produce about 11 significant sidebands, or a bandwidth of 2 × 10 × 11, or 220 kc. So high a frequency is again probably greater than will ever be transmitted at full volume by a station, and therefore a bandwidth of 200 kc will still suffice.

When a 5-kc tone is transmitted, its modulation index is $^{75}/_{5}$, or 15. A modulation index of 15 has 20 significant sidebands and will require a bandwidth of 2 × 5 × 20, or 200 kc, provided the carrier is deviated a full 75 kc by a 5,000-cycle tone. While this is still a rather high frequency, it *is* possible that it *may* be applied to the transmitter with enough amplitude to produce a full 75-kc deviation (particularly if preemphasis is being used).

Tones between about 100 and 4,000 cycles include the strongest tones picked up by a microphone from voice and music and will all have a modulation index of more than 15 and produce many more than 20 significant sidebands when the transmitter is being modulated to the 100 per cent value. As long as the lower tones are not overmodulating, there is little chance that the fewer higher frequencies will have sufficient power to overmodulate or produce significant sidebands out past 200 kc.

Because of this, an FM broadcast channel is 200 kc wide, in comparison with the 10-kc channel width of the standard AM broadcast band. Using the region of the spectrum where the signals travel only slightly more than line of sight (88–108 Mc) daytime or nighttime, and usually less than 100 miles, enables FM stations to use wide channels.

The FM band is 20 Mc wide, and each channel is 200 kc. The first channel has a center frequency of 88.1 Mc, 88.3 Mc for the second, etc. There is room for 100 FM channels in this band. However, in one geographical area, stations are never assigned adjacent channels, to prevent interference or overlapping of some of the outermost sidebands. This reduces the possible number of channels in one area to 50. At a distance of 50 to 200 miles away, the unassigned channels may be assigned.

Since only the frequency of the oscillator is modulated in FM, only a fraction of a watt of audio power is required to produce 100 per cent modulation. Compare this to the 500 watts of audio required to amplitude-modulate 1,000 watts of d-c plate-power input to an RF amplifier. In AM, the audio sidebands are added to the carrier power; but in FM, the carrier power is used to form the sidebands. As a result, the antenna current of an FM transmitter should not change whether the carrier is modulated or not. However, if the tuned circuits of the RF amplifiers of the transmitter, or of the antenna, have too high a $Q$, the bandpass of these circuits may be too narrow and sidebands widely displaced from the center frequency may be attenuated. In this case, the antenna current may drop off slightly at high percentages of modulation. This may also occur if the stages are not properly tuned.

The various frequency-shift or frequency-modulated types of emissions are as follows:

F0. A steady carrier of a frequency-modulation transmitter.

F1. A carrier that is shifted or keyed in frequency according to some code, such as International Morse, or radioteletype.

F2. An on-off keyed carrier that is shifting in frequency at some audible rate.

F3. Frequency-modulated voice or music transmissions.

F4. A carrier shifted in frequency in accordance with still-picture elements. Facsimile transmissions.

F5. A carrier shifted in frequency in accordance with moving-picture elements. Television transmissions. (Used only experimentally, not on commercial TV channels.)

**18.4 Receiving the FM Signal.** Any AM receiver can be used to demodulate an FM emission, provided the FM does not deviate more than the width of the skirts of the IF passband of the receiver. The theory of demodulation in this case is called *slope detection.* For example, consider the IF response curve of an AM receiver shown in Fig. 18.3.

The top of the passband curve may be relatively flat, but the skirts slope off in both the higher- and lower-frequency directions. If the receiver is tuned to a frequency to either side of the center of the IF band, FM signals will be audible. With the center carrier of an FM transmitter tuned to point $F$ (or $F_1$), relatively undistorted FM will be produced by a diode or any other AM detector. As the carrier is modulated it swings up in frequency, producing greater signal strength at the detector, and then swings down in frequency, producing less strength at the detector. The variation of amplitude of the signal at the detector in accordance with the frequency swing of the FM signal reproduces the modulation. As long as the more or less linear slope of the curve covers a greater frequency band than the excursion of the carrier during FM, the demodulation will be fairly linear, *but* the advantage of FM reception of discriminating against amplitude noises will not be present. With slope detection, FM is just as subject to noise as is AM. Furthermore, if the FM carrier swings past the limits of the slope,

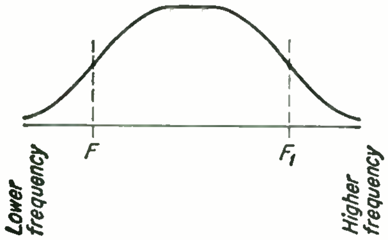


FIG. 18.3. Two possible tuning points to produce slope detection of an FM signal on an AM receiver.

considerable distortion will be present, since all wider-deviation signals will not be reproduced at the detector.

When an FM carrier is tuned to the center of the passband of an AM detector, no modulation should be heard. It may be considered that the sidebands produced by FM are of such polarity that their sum is at all times equal in amplitude and opposite in phase, resulting in zero audio output from an AM detector when tuned to pick up an equal number on both sides of the center frequency. AM sidebands *add* together to produce a greater resultant signal in the AM detector.

To reproduce audio from an FM signal a special frequency-sensitive *discriminator* circuit should be used.

**18.5 The Foster-Seeley Discriminator.** While there are quite a few different types and forms of FM detectors, only two, the Foster-Seeley discriminator and the *ratio* detector, will be discussed here.

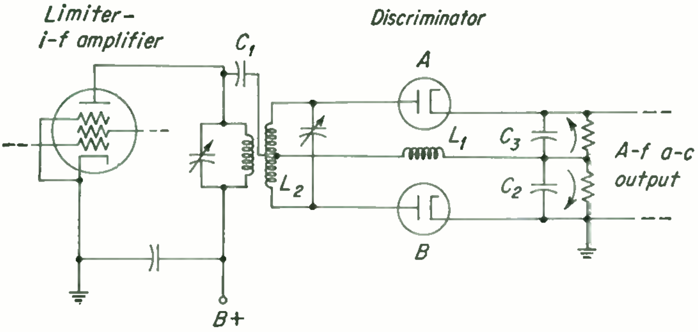


FIG. 18.4. The basic Foster-Seeley discriminator circuit.

The Foster-Seeley discriminator has many possible variations of the basic form shown in Fig. 18.4. It follows the IF stages of a superheterodyne, although it could be tuned to the transmitting frequency.

When the secondary of the discriminator transformer is tuned to resonance with the incoming signal, it is series-resonant. The current that flows in the secondary will be in phase with the voltage induced in it by the current of the primary.

Because of the low reactance of $C_1$ and $C_2$ to intermediate frequencies, $L_1$ is parallel to the primary circuit, and the voltage across it is in phase with the primary voltage. Voltage and current induced in the center-tapped secondary are in phase with the counter emf of the primary (and $L_1$). Induced current flowing in the resonant secondary circuit will produce reactive emfs of self-induction 90° out of phase with it. Considering the secondary center tap as a reference point, the self-induced voltage in the top half is 180° out of phase with the bottom half, and each is 90° out of phase with the voltage across $L_1$.

When a carrier is received on the frequency to which the secondary is tuned, the vector voltage developed in the top half of the secondary adds at $-90^\circ$ to the voltage across $L_1$. At the same time the vector voltage developed in the bottom half of the secondary is also added at $+90^\circ$ to the voltage across $L_1$. Since the voltages are equal and added at the same phase angle, the current that flows through diode $A$ exactly equals the current that flows through diode $B$, and there is effectively zero volts *difference* across the two resistors in series across the AF output terminals.

When the input signal deviates to a *higher* frequency, the inductive reactance of the secondary increases, while the capacitive reactance of the secondary decreases. When the inductive reactance increases, the current lags behind the *induced* voltage in the secondary. However, the reactive voltage of the coil remains 90° ahead of the current that is flowing in it. (Note that the induced voltage from the primary is not the same as the reactive voltage, which is always 90° ahead of the current in an inductance.) Now the vector sum of the voltage across $L_1$ plus the voltage across the bottom of the coil $L_2$ will not equal the sum of the voltage across $L_1$ plus the voltage across the top of $L_2$. The diode that has the greater vector sum in it will have the greater current flowing through it, and a greater voltage will be developed across its load resistor. The difference between the two voltages appearing across the two resistors is the AF output signal.

When the signal voltage deviates below the carrier frequency, the other diode will have the greater current and an opposite-polarity resultant voltage will be developed across the resistors. In this way an a-c output voltage is developed by the discriminator.

A discriminator circuit such as this finds uses whenever it is desired to produce a voltage variation from a frequency variation.

Although not shown in the diagram (Fig. 18.4), the output of a discriminator in an FM *broadcast* receiver will always have a resistor and capacitor (condenser) similar to $R_1$ and $C_4$ in Fig. 18.5. These form a *de-emphasis* circuit, which is included to decrease the increased high-frequency response always inserted into the modulating voltage at the transmitter. At the transmitter a special *pre-emphasis* circuit in the last audio-amplifier stage increases the high-frequency response according to a prescribed pre-emphasis curve. This produces excessively loud high-frequency signals. When received, these high-amplitude high audio frequencies are considerably above the high-frequency noises normally developed in a receiver. The de-emphasis circuit in the receiver returns the amplitude of the high audio frequencies to their normal lower level, and at the same time decreases the noise in the receiver proportionately. This is another reason why FM reception is more noise-free than the normal AM, since pre-emphasis and de-emphasis are not used with AM transmissions, although they could be.

The discriminator shown in Fig. 18.5 is a variation of the Foster-Seeley and is used in some communication receivers. It center-taps the capacitance of the secondary circuit. An audio gain, or volume control, is shown following the de-emphasis circuit.

Discriminator circuits will demodulate an FM signal, but unfortunately they are susceptible to amplitude variations. They will not prevent amplitude variations due to noise impulses from being detected and fed to the audio amplifiers. It is necessary to use one, or preferably two, *limiter* stages just ahead of the discriminator. These stages must limit the amplitude of the carrier to a given value, regardless of the strength of the input signal. The limiter stages are actually low-gain IF amplifiers, using either grid-circuit limiting, plate-circuit limiting, or both. The limiter in Fig. 18.6 is shown with both.

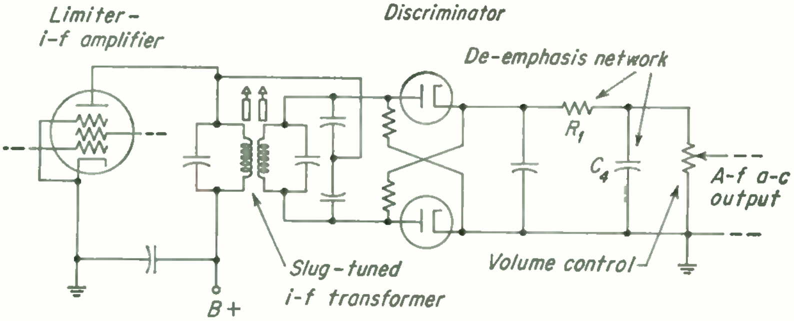


FIG. 18.5. A variation of the Foster-Seeley discriminator circuit.

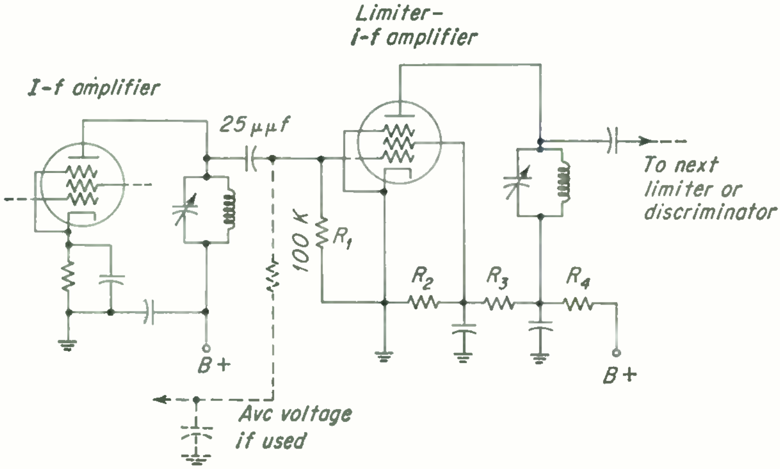


FIG. 18.6. A limiter–IF amplifier stage, employing both grid- and plate-circuit limiting.

It will be noted that the limiter is drawn with impedance coupling. Some are transformer-coupled, and some are resistance-coupled. The grid-leak resistance $R_1$ increases the bias as the signal strength increases, tending to decrease the plate current and hold the output of the limiter to a constant value. The voltage-divider network made up of $R_2$, $R_3$, and $R_4$ lowers the plate and screen voltages on the tube to such an extent that the tube cannot have a very great signal voltage output. In most cases, it is much preferable to have two limiter stages to adequately limit any amplitude signals. If the signal is weak enough, the limiters act as low-gain amplifiers without limiting, and the discriminator will then have noise in its output. This is true of all weak FM signals. They will be accompanied by noise if they are not strong enough to produce sufficient limiting effect.

When tuning from station to station, the receiver operates without any carrier and a high noise level is developed in the discriminator. To prevent this, a squelch circuit similar to the one described in Sec. 17.16 may be used. The automatic-volume-control (AVC) voltage can be taken through a 2- to 4-meg resistor from the top of the grid-leak resistor in the *first* limiter stage. Another squelch circuit is shown in Fig. 18.7. In this circuit, with no signal there is no AVC and no bias on the squelch tube. It draws heavy current through the cathode resistor, biasing the AF amplifier tube well past cutoff. When a signal is received, the AVC biases the squelch tube to cutoff, allowing normal current to flow through the cathode resistor, and the AF amplifier operates normally.

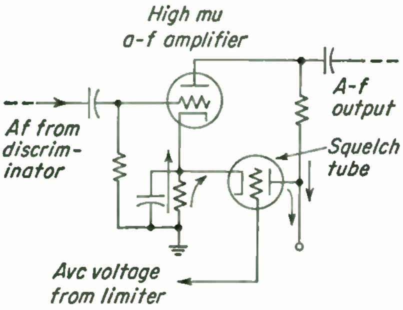


FIG. 18.7. A squelch tube operating from the AVC voltage.

Simple squelch circuits such as this may be satisfactory for FM broadcast receivers, but a much improved *differential* squelch circuit is used in mobile and fixed station communication receivers. It takes amplitude noise appearing at the discriminator, amplifies it, rectifies it, amplifies the d-c produced, and uses this to squelch the audio stage. With this system it is possible to have the squelch automatically ride just above the noise level. This is particularly important in mobile receivers where the car is continuously moving into areas of different noise level. While AVC or AGC (automatic-gain-control) circuits may be used in FM receivers, they are not necessary for satisfactory operation of the receivers.

**18.6 The Ratio Detector.** The ratio detector was designed to demodulate FM signals and suppress amplitude noise impulses without any limiter stages. It follows the last IF stage in a superheterodyne. A diagram of the basic ratio detector is shown in Fig. 18.8.

In the ratio detector, the tuned circuit, the two diodes, and the resistor $R_1$ are all in *series*. The top diode is reversed from the Foster-Seeley discriminator circuit. This allows the voltages that are built up across

$C_1$ and $C_2$, by the half-wave rectifier circuit, to be in series, instead of opposing as in the discriminator. The current through $R_1$ produces a voltage drop across it proportional to the average carrier strength. The large capacitor, $C_3$, has sufficient capacitance (8 $\mu$f) to hold the voltage across $R_1$ essentially constant even if there are instantaneous amplitude variations. $R_1$ and $C_3$ act to produce a constant d-c voltage across themselves. Furthermore, the sum of the voltages across the smaller capacitors, $C_1$ and $C_2$, will always have to add up to the value of the d-c across $C_3$.

When the input signal is on the center frequency of the tuned secondary, the d-c voltages across $C_1$ and $C_2$ are equal and unchanging. When the carrier is frequency-modulated, the voltage across $C_1$ will decrease when the voltage across $C_2$ increases and audio output could be taken off across either $C_1$ or $C_2$. In the circuit shown, an AVC voltage is taken off at the upper end of $R_1$ or $C_3$. The AVC applied to the IF and RF stages of the receiver is expected to maintain a relatively constant amplitude carrier being applied to the ratio detector. The detector itself prevents instantaneous impulses from becoming audible, but if the signal fades up and down, the audible output amplitude will also change in level. For this reason a limiter is often used in front of ratio detectors, and the AVC is taken from the limiter grid. Ratio detectors find use in FM broadcast or TV receivers. Communication receivers use discriminators generally.

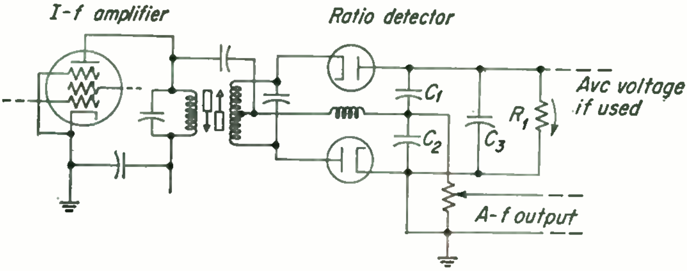


FIG. 18.8. A basic ratio-detector circuit.

**18.7 FM Receivers.** An FM broadcast-band receiver may be constructed as shown in block form in Fig. 18.9. These receivers tune from 88 to 108 Mc and have an IF bandwidth of 200 kc.

Less expensive receivers may leave out the RF amplifier, an IF amplifier, or a limiter stage.

Although single-tube pentagrid converters or triode-hexode converters may be used as the mixer and local oscillator, in VHF receivers it is usually preferable to use a separate oscillator tube to reduce frequency pulling and detuning of the oscillator when the mixer is tuned during alignment. Note that the local oscillator is operated on a lower frequency than the mixer to take advantage of better oscillator-frequency stability at lower frequencies.

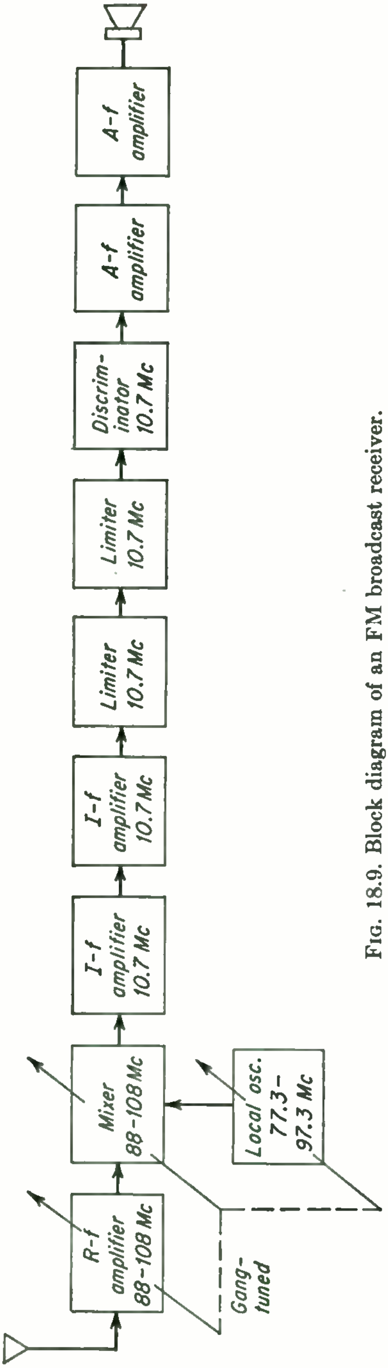


FIG. 18.9. Block diagram of an FM broadcast receiver.

An FM communication receiver suitable for VHF or UHF mobile or fixed station operation is shown in block form in Fig. 18.10.

Although FM is authorized in the amateur bands, it has never been too popular. It is relatively simple to modulate an amateur CW transmitter by direct FM or by PM (phase modulation). However, there are few amateurs who have a satisfactory narrow-band FM receiver to receive such signals properly. In most cases, slope detection must be resorted to on receivers engineered to operate on AM signals. Converters consisting of one or two limiting stages and a discriminator coupled to the output of the last IF amplifier will give satisfactory results.

Two amplitude-modulated stations transmitting on the same frequency both produce sideband signals in an AM detector and can be heard, even if one signal is 10 times the strength of the other. In FM, if one signal is *twice* as strong as another, on the same frequency, it will take control of the oscillation frequency of the discriminator circuit and the weaker signal will not be able to produce appreciable output in the receiver. This blanketing effect in amateur bands is a tremendous disadvantage.

**18.8 Alignment of FM Receivers.** FM broadcast receivers usually use single conversion and have a high intermediate frequency of approximately 10.7 Mc to produce a relatively low-$Q$, broadly tuned, 200-kc bandwidth. On the other hand, FM communication receivers operate in the 30–500-Mc range and use double conversion, with the first IF at a relatively high frequency, 10–30 Mc, to reject image signals. The second IF is usually near 450 kc to produce the 12–30-kc IF bandwidth required for 6–15-kc deviation voice-frequency transmissions.

The alignment of the RF amplifier, mixer, and IF amplifiers in FM receivers is similar to the procedure used in AM receivers. In the FM receiver the discriminator and limiters are aligned first. An unmodulated signal generator is adjusted to the IF and fed to the grid of the last limiter. This feeds a signal to the discriminator transformer. A sensitive d-c voltmeter with an RF choke or a 1-meg resistor in the ungrounded prod or a vacuum-tube voltmeter is connected between ground and the center tap of the two series resistors in the discriminator circuit. The secondary of the discriminator is detuned until an indication of voltage is obtained on the meter. The *primary* of the discriminator transformer is tuned for a *maximum* indication on the meter.

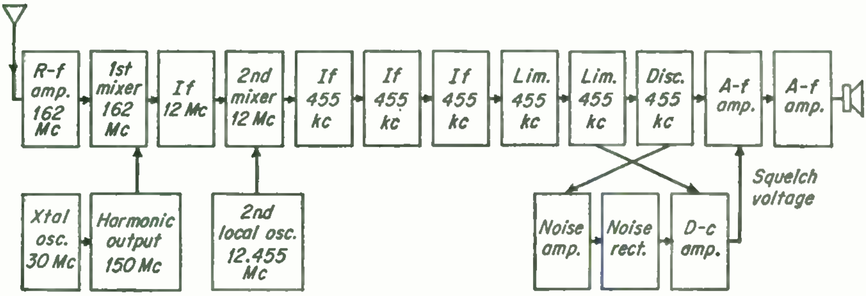


FIG. 18.10. Block diagram of an FM communication receiver.

The meter is next connected to read the voltage across *both* series resistors. The *secondary* of the discriminator is tuned for *zero* voltage indication across the load resistors. The signal generator should be shifted 75 kc above, and then 75 kc below, the IF to check the linearity of the discriminator. The same-amplitude voltage, but of opposite polarity, should appear 75 kc from the carrier in either direction.

The signal generator is next moved to the grid of the *first* limiter. The voltmeter is connected across the grid leak of the second limiter, and the plate circuit of the first limiter is tuned for maximum voltage indication. If transformer coupling is used between limiters, the grid circuit of the second limiter is next tuned, again for maximum voltage indication. The weakest possible signal from the signal generator must be used.

The signal generator is then moved to the grid of the last IF amplifier, the voltmeter to the grid of the first limiter, and the plate circuit of the last IF amplifier tuned for maximum voltage indication. If transformer coupling is used between stages, the grid circuit of the first limiter is tuned next.

The voltmeter can be left in its last position and the remainder of the alignment of the IF, mixer, oscillator, and RF stages will follow the pattern explained for AM receivers.

To align the ratio detector the signal generator is fed to the last IF amplifier grid (or limiter, if any). The primary and secondary of the ratio-detector transformer are both tuned for maximum voltage across the large capacitor in the detector circuit. The voltmeter may be left across the capacitor to tune the IF transformers also. However, if a limiter stage is used, all stages before the limiter should be tuned to produce maximum voltage across the limiter grid-leak resistor, or maximum current flow through it, if a closed-circuit jack is incorporated in this grid-resistor circuit for metering.

**18.9 Direct FM.** Three basic methods of producing FM are in general use. One may be termed *direct FM*, in which the oscillator is made to deviate in frequency. The other methods utilize phase modulation.

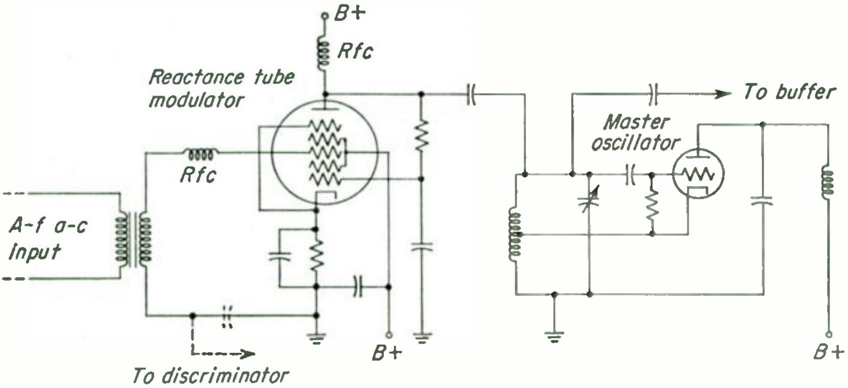


FIG. 18.11. Reactance-tube modulator across the tuned circuit of a self-excited oscillator produces direct FM.

A direct-FM transmitter utilizes a vacuum tube that is made to appear as an inductive or a capacitive reactance across a self-excited oscillator LC circuit (Fig. 18.11).

The arrangement of the resistors and capacitors in the reactance tube is such that the RF a-c voltages developed in the oscillator tank circuit produce current in the modulator circuit, but the current that flows lags the voltage somewhat. How much it lags is determined by the voltage applied to the modulator grid. If the modulator grid is fed an AF alternating current, the reactance tube appears alternately as a greater and a lesser inductive reactance. This is equivalent to varying the inductance in parallel with the oscillator tank circuit, and its frequency of oscillation changes.

Since any voltage change in any part of the oscillator or modulator will shift the center frequency, it is necessary to use some method of assuring that the resting carrier frequency remain constant and on the assigned frequency. This is accomplished electromechanically in some transmitters by using a motor to slowly rotate a variable capacitor connected across the oscillator tank circuit. If the average frequency during modulation, or during no modulation, is not equal to the center frequency, a voltage is fed to the motor to rotate the capacitor slightly. This tunes the oscillator back to the center frequency. When returned, no voltage is fed to the motor and it ceases to rotate.

A discriminator circuit can also be used to return the resting carrier to the center frequency. A block diagram of a simplified frequency-modulated transmitter using this type of frequency control is shown in Fig. 18.12.

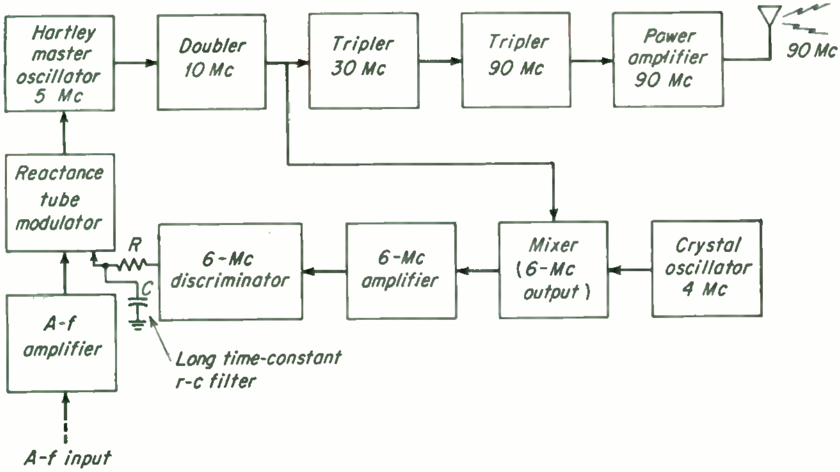


FIG. 18.12. Block diagram of a direct FM transmitter with frequency-controlling circuit.

In this circuit the Hartley oscillator has a center frequency of 5 Mc. The doubler output is 10 Mc. If the oscillator shifts frequency 100 cycles, the output of the doubler will shift 200 cycles. The next stage, a tripler, has a 30-Mc output which is fed to the second tripler. The 90-Mc output of the second tripler drives the power amplifier. Some of the 10-Mc output is fed to a mixer stage. The output of a 4-Mc crystal oscillator is also fed into the mixer. The difference frequency between 10 and 4 Mc is fed to a 6-Mc amplifier and to a discriminator tuned to exactly 6 Mc.

As long as the oscillator remains on 5 Mc, its multiplied output will beat against the 4-Mc crystal and produce 6-Mc a-c, and therefore zero voltage at the discriminator output. If the center frequency drifts upward, the mixer will be fed a frequency higher than 10 Mc, which will beat against the 4-Mc crystal and produce a difference higher than 6-Mc and develop a voltage at the discriminator. This voltage is fed to the grid of the reactance modulator, changing its reactance and shifting the oscillator frequency until no voltage is present at the discriminator, which only occurs when the oscillator is at the center frequency. If the oscillator drifts lower in frequency, an opposite-polarity d-c voltage is developed at the discriminator, shifting the carrier back to the center frequency again.

Under normal FM, the discriminator is alternately developing positive and negative voltages, which, if fed directly back to the reactance tube, would cancel the modulation. A long-time-constant RC circuit is connected between the discriminator output voltage and the modulator grid. Normally, the average of this voltage should be zero if the deviation of the carrier is as great in both higher and lower directions.

A multiplication of 18, 20, or 24 times the oscillator frequency is usually adequate to produce an undistorted 75-kc swing. A multiplication of 18 can be attained with a doubler and two triplers. Thus, a transmitter with a center frequency of 88.1 Mc requires an oscillator with a center frequency of 4,894.3 kc.

With an oscillator frequency of 4,905 kc, a transmitter using a frequency multiplier tuned to the fifth harmonic, with two doubler stages following that, operates on the twentieth harmonic, or on a center frequency of 98.1 Mc. To produce 100 per cent modulation (a 75-kc swing at 98.1 Mc), the oscillator need swing only 3.75 kc.

An FM transmitter employing a doubler, a tripler, and a quadrupler will swing its assigned carrier frequency 48 kc when the oscillator swings 2 kc.

When the output frequency is not a whole-number multiple of the oscillator frequency, a heterodyne-multiplier system, rather than only a series of multipliers, can be used. For example: The oscillator is on 4 Mc, the center frequency is to be 99 Mc. (No series of multipliers will produce 99 from 4 Mc.) If 4 Mc is tripled twice, its frequency is 36 Mc. If this is fed into a mixer stage with a 3-Mc oscillator, the difference-frequency output is 33 Mc. This can be tripled for an output of 99 Mc.

**18.10 A Phase-modulated Transmitter.** Holding a self-excited oscillator on an assigned center frequency requires that many factors remain constant. It might be imagined that the use of a temperature-controlled crystal oscillator would assure a proper center frequency. If the crystal itself is reactance-tube-modulated, any changes in the reactance-tube circuit voltages or components will affect the crystal frequency slightly and the center frequency may drift. The frequency deviation produced by reactance-tube-modulating a crystal circuit is quite small and will require more than the usual 18-times multiplication of the oscillator frequency.

If the crystal oscillator stage itself is not modulated but modulation is applied to following stages, the frequency of the emission cannot be directly varied. However, the modulating voltage can shift the phase of the carrier voltage or current, which results in an instantaneous or indirect form of FM. If a d-c voltage is applied to the grid of a reactance-tube modulator, the frequency of the associated oscillator will shift and stay at the new frequency until the d-c controlling voltage is changed. In phase modulation (PM), the result of shifting the phase will cause the carrier to swing up or down in frequency from one instant to the next, but it cannot be *held* at anything other than the center frequency.

An early system of PM utilized a temperature-controlled crystal oscillator transmitter to develop center-frequency stability and phase-modulated a buffer or amplifier stage. This method uses a balanced modulator stage to cancel out the carrier frequency and produce *amplitude*-modulated sidebands only. These RF a-c sidebands are developed in a circuit that changes their phase by 90°, and then feeds them back to the output of the stage from which the carrier was taken. Figure 18.13 illustrates this in block form.

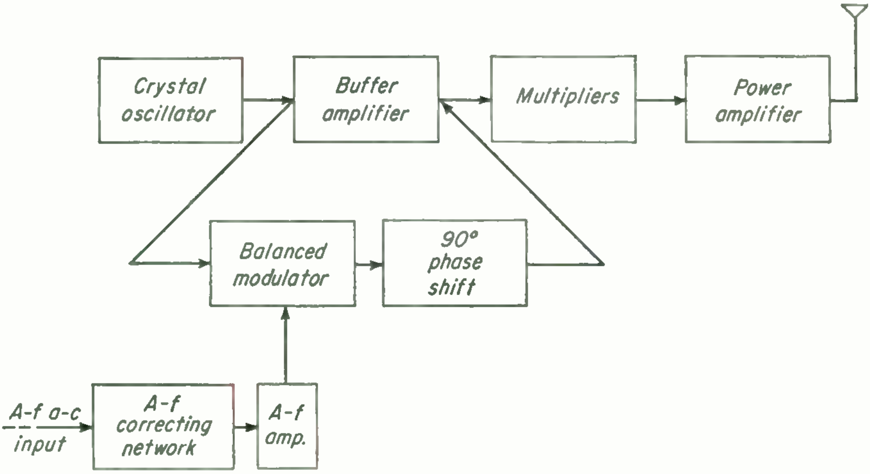


Fig. 18.13. Block diagram of an early form of phase-modulated, or indirect, FM transmitter.

With no audio applied to the balanced modulator, there are no sidebands and therefore no 90°-phase-shifted sideband energy, and the buffer frequency remains on the crystal frequency. When audio is applied, the amplitude of the audio determines the amount of 90°-phase-shift energy that is fed into the output of the first buffer. The grid of the next stage is fed a carrier frequency that is shifting its phase up to a maximum of about 30° instantaneously. With a weak audio signal there is little sideband energy fed to the first buffer and little phase shift, and the indirect FM is small. With more audio there is greater sideband energy, greater phase shift, and greater indirect FM. Any AM produced in this system is flattened out by the limiting action of the class C buffer and multiplier stages operating into the plate-current saturation part of their curves.

The frequency deviation that can be developed with this system is usually about 25 cycles for a 50-cycle tone and about 7,500 cycles of deviation for a 15,000-cycle tone. Unfortunately, a constant-amplitude variable-frequency tone producing only 25 cycles of frequency deviation of the carrier with an AF of 50 cycles will produce 7,500 cycles deviation with an AF of 15,000 cycles. To produce an equal deviation for all modulating AF of similar amplitude, it is necessary to use a low-pass RC network in one of the AF amplifier stages, which makes the audio output amplitude inversely proportional to output frequency. Such a network may consist of a 500,000-ohm resistor in series with the grid circuit in a resistance-coupled audio amplifier with a 0.1-$\mu$f capacitor from grid to cathode. If pre-emphasis is desired, another network is required to raise the higher-frequency response to the desired level.

Since the maximum deviation is only about 25 cycles with this system at the modulated stage, it is necessary to multiply the output frequency by about 3,000 times to produce 75,000-cycle deviation. For a carrier frequency of 90 Mc, this would require an oscillator frequency of 30 kc. In actual practice an oscillator frequency of about 200 kc is used. It is fed through a series of multipliers until the frequency is in the 30-Mc region. It is then heterodyned against a second crystal oscillator and picked up at about 5 Mc (without losing any frequency deviation) and multiplied up to the 90-Mc region. It requires about 20 tubes and circuits from crystal oscillator to the input of the final amplifier.

**18.11 PM from the Phasitron.** Another method of producing PM is by the use of a specially designed *phasitron* tube. Essentially, this tube develops a thin wheel, or disk, of electrons that radiates outward from the cathode toward the eventual plate. Before striking this plate the electrons must pass through holes punched in an inner plate. The flat wheel of electrons is ruffled by three-phase RF a-c voltages applied to a series of grids placed between the cathode and the first plate. The ruffled edges of the electron wheel are made to sweep around, sometimes striking the holes in the first plate and allowing current to flow to the second plate, and sometimes striking the first plate and stopping all current to the second plate. The on-off current flow to the second plate is the current that excites the output RF LC circuit into oscillation.

A crystal oscillator is used to develop the three-phase a-c that rotates the ruffled wheel of electrons. As a result, the output plate-current pulses are directly proportional to the crystal frequency, assuring constant center frequency of the transmitter. A simplified block diagram of a phasitron circuit is shown in Fig. 18.14.

A coil of wire, wrapped around the tube and excited by an AF a-c, produces a magnetic field in the tube that tends to deflect, and thereby either increase the speed of the ruffles in their sweep around the tube or slow them slightly, depending on the magnetic polarity developed in the coil by the AF a-c modulating signal. This produces the PM of the plate-current pulses that flow to the second plate. A deviation of about 175 cycles is possible with this system, requiring a multiplication of 424 times to produce a 75-kc deviation.

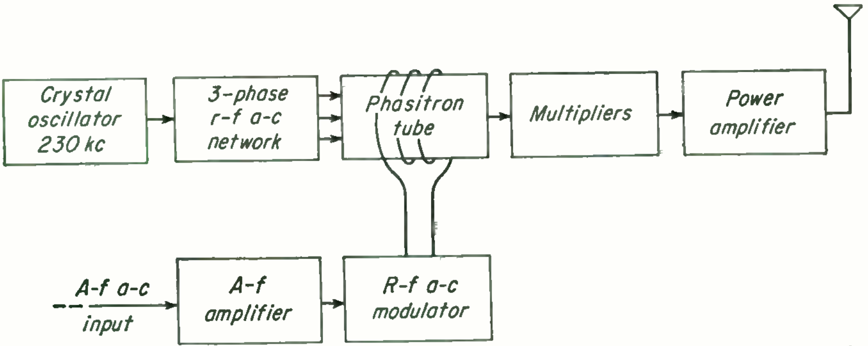


FIG. 18.14. Block diagram of the essentials of a phasitron-tube transmitter circuit.

**18.12 Voice-modulated PM Transmitters.** While the Crosby reactance-tube system, the Armstrong phase system, and the phasitron system represent some of the FM methods used in broadcast stations, by far the greatest number of frequency-modulated transmitters in use today are found in the thousands of taxicabs, police and fire cars, and in other small communication services. These systems are interested only in voice transmissions. As a result, the requirement is to transmit only audio frequencies in the range of 200 cycles to about 3,000 cycles.

If PM can produce only 25 cycles of deviation at 50 cycles, it can produce a deviation of about 100 cycles with a 200-cycle audio signal. This means that only a quarter as much frequency multiplication will be required. Since the highest desired AF is 3,000 cycles, or one-fifth of 15,000 cycles, for a deviation ratio of 5, the carrier will have to be swung only 15 kc instead of 75 kc. This requires only one-fifth as much multiplication. The total, one-fifth times one-quarter, is one-twentieth as much multiplication required for a voice communications FM system as for a broadcast FM system. By reducing the deviation ratio and using phase modulators that will give increased frequency deviation without materially increasing distortion, multiplications of about 24 times are required for 15-kc deviation. The reduction of the deviation ratio results in a lessened audio output from the receivers, but this is partially made up by the lessening of noise with weak signals when the receiver bandwidth is narrowed. For some commercial work a 10-kc deviation is used. Narrow-band FM in amateur work is limited to 3-kc deviation. On some amateur bands, above 26 Mc, wideband FM (75-kc deviation) is permitted in certain portions of the bands.

A PM circuit used in many mobile transmitters is shown in Fig. 18.15. The RF a-c signal is fed across the $C_1R_1C_2$ network, and at the same time, across the $C_3L_2$ network. The frequency of the a-c across $R_1$ and across $L_2$ will be the same, but because one circuit is an RC circuit and the other an LC circuit, the voltage between the top of $L_2$ and ground will be leading the voltage across $R_1$. If the phase-modulator tube is pulled out, the phase of the voltage developed across $L_2$ is solely dependent upon $C_3L_2$. When the tube is in the circuit, the out-of-phase voltage on the grid of the modulator produces an out-of-phase current in the plate circuit through $L_2$. The current that flows through $L_2$ has two out-of-phase components, one due to the voltage fed to the grid, and one due to the voltage from the oscillator. The *resultant* voltage drop across $R_2$ is therefore not in phase with either voltage, but is at some intermediate phase. When an AF a-c is added to the grid circuit of the phase modulator, the plate current still retains the steady oscillator component but the grid-circuit component varies in amplitude, producing a resultant phase shift that varies in accordance with the AF a-c. In this way, PM is developed across $L_2$ and is fed to $R_2$ and the multiplier stages.

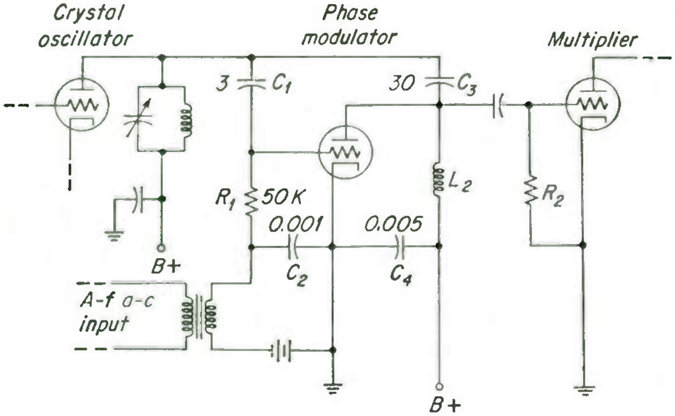


FIG. 18.15. A PM circuit for mobile FM transmitters.

Communications transmitters are required to have a means of limiting the percentage of modulation, if amplitude-modulated, or a means of limiting the frequency deviation, if frequency-modulated. A limiter used in some mobile FM transmitters is shown in Fig. 18.16.

Current flows through $R_2$ and $R$ all the time. Current also flows through $R_1$ and $R$. When a positive audio signal is applied across $R_1$, the cathode of this half of the tube approaches the plate potential, and current flow decreases. This decreases the current through $R$, and less voltage drop is developed across it, while more is developed across $R_2$. Thus, AF a-c from $V_1$ is passed to the filter network. When the cathode of the first half of the diode tube reaches or exceeds its plate potential (because of high-amplitude audio peak voltages), the diode ceases to conduct and any audio signals above this value do not affect the current through $R$, and therefore through $R_2$. The signal is limited, or the peak is clipped off.

On the negative half cycle of audio, the cathode of the first diode is made more negative (plate relatively more positive), increasing the current through $R$, developing a greater voltage drop across it, and decreasing the voltage drop across $R_2$. When the negative signal reaches a certain value, the current through the diode approaches the maximum. Any further increase in the negative signal produces almost no increase in current in the first diode, nearly full voltage drop across $R$, and therefore almost no signal variation across $R_2$. In this way, both the positive and negative halves of high-amplitude audio signals are limited.

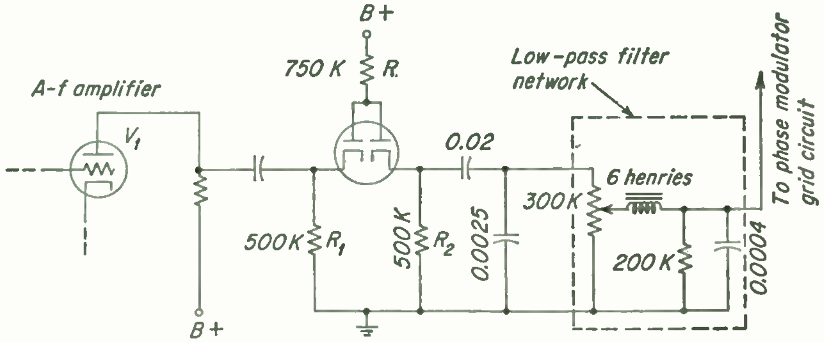


Fig. 18.16. An audio-limiter, or clipper, circuit.

The audio that is developed across $R_2$ is fed through a low-pass filter network that does two things. It tends to round off or filter any square-wave-shaped signals developed in the clipping process, thereby reducing higher-frequency audio harmonics that might otherwise be transmitted. It also acts to make the audio output inversely proportional to frequency (high frequencies attenuated more than lows), as is required in all PM systems to change them and make them act as direct FM.

The setting of the potentiometer arm determines the deviation ratio that the transmitter will produce.

Crystal-controlled transmitters of this type, when adjusted to the proper center frequency, may gradually drift lower in frequency with age. In a few months they may need to be readjusted to the proper center frequency because oxidation of the silver plating on the crystal increases in weight. To allow the crystal to be *warped* into the desired frequency of oscillation, capacitors and inductors may be included in the crystal circuit, by which the crystal frequency can be warped several hundred cycles on its fundamental frequency. This produces several kilocycles of control at the assigned carrier frequency.

**18.13 FM Broadcast Stations.** The block diagram of an FM transmitter and station shown in Fig. 18.17 represents one of the less complicated stations, operating with almost a minimum of facilities. Most stations have more studios, turntables, and control positions.

The control room houses the FM transmitter, a frequency and modulation monitor, and the *master* audio-control console, with which the operator can connect the audio output of the studios, turntables, tape recorders, or his own local microphone into the transmitter.

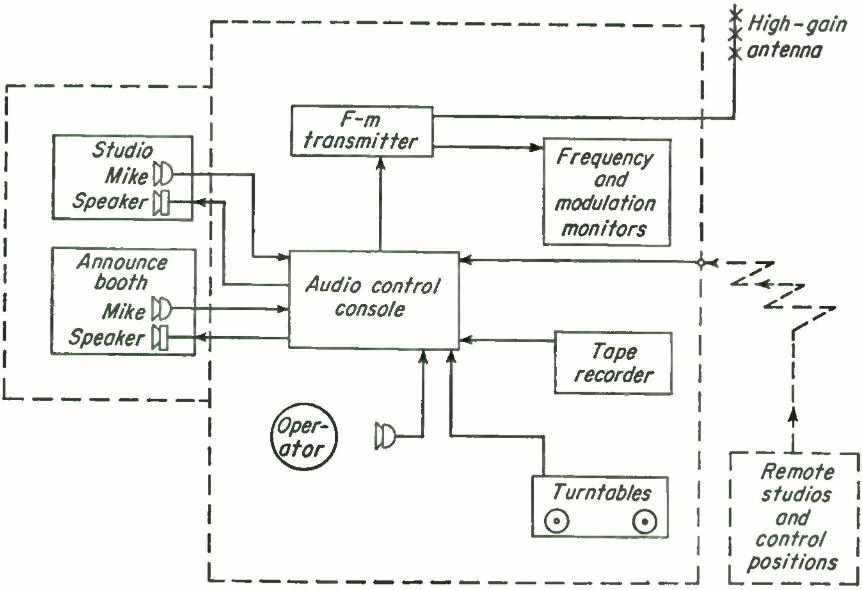


FIG. 18.17. Block diagram of the components of a simple FM transmitting station.

Since most FM transmitters are located on top of a hill, programs may originate in remote downtown studios and may be controlled at that point. The program may be fed to the transmitter station by telephone lines or by a microwave radio link.

Studios or announce booths contain one or more microphones and a monitoring loudspeaker. When the studio is activated, the output of the microphone is fed to the console and the monitor speaker in the studio is automatically cut off to prevent an audio feedback, or howl. As soon as the studio microphone is switched off by the control operator, the monitor speaker in the studio goes on, and the program now *on the air* is fed into the studio, notifying the studio personnel that their microphone is no longer alive.

The transmitting antenna is usually a high-gain, multielement, horizontally polarized, omnidirectional, vertical type, 100 to 500 ft high, installed on top of a tall building or atop some hill near the populated area it is desired to cover. The higher the gain (the more elements in the antenna), the more the transmitted signal is radiated downward, toward the horizon, and the stronger the received signals at a given distance from the transmitter.

Except for the transmitter and the type of antenna used, an FM broadcast system may be identical with a standard AM broadcast station. In fact, the same program may be fed to an AM and an FM broadcast station simultaneously, the only difference being the AF response fed to the two transmitters. The FM station uses an AF response of 50 to 15,000 cycles, whereas the AM station usually attenuates frequencies above 7,500 cycles.

The operating power of FM broadcast stations is determined by the *indirect* method. This is the product of the plate voltage, $E_p$ times the plate current, $I_p$, of the final RF amplifier stage times an efficiency factor, $F$. The formula is

$$\text{Operating power} = E_pI_pF$$

The efficiency factor is established by the manufacturer of the equipment and must be approved by the FCC. It will usually be between 0.65 and 0.8 for class C amplifier stages.

The operating power is maintained as near the authorized power as possible and must not exceed the limits of 5 per cent above and 10 per cent below the authorized power, except in emergencies.

Accurate meters must be provided to measure the final-amplifier plate voltage and plate current, and in addition one must be provided to measure the RF current or voltage of the main transmission line to the antenna. The accuracy of these meters must be at least 2 per cent of the full-scale reading.

Commercial, as well as noncommercial, educational FM broadcast stations are required to keep their center frequency within ±2,000 cycles of the assigned frequency. This is a *frequency tolerance* of 2,000 cycles. It requires a *frequency monitor* with a frequency-indicating range of 4 kc to give a continual visual indication of the transmitter frequency in relation to the assigned frequency. Figure 18.18 is a block diagram of a possible frequency monitor for an FM transmitter operating with a carrier frequency of 100 Mc.

The frequency monitor is first calibrated by switching in the 10-Mc calibration crystal oscillator. The 10-Mc signal passes through the mixer stage, the 10-Mc IF amplifier and limiter, and to the 10-Mc discriminator. The discriminator is adjusted until zero output signal is shown. This indicates the discriminator is accurately tuned. The

30-Mc running crystal, fed through a frequency tripler, is switched into the mixer, and the transmitter is turned on. The 90-Mc and the 100-Mc signals mix and produce a 10-Mc output in the IF stage. If the transmitter and the running crystal are both on the correct frequencies, their difference frequency is exactly 10 Mc and the center-frequency indicator reads 0, or center scale. If the transmitter frequency is slightly high, the discriminator is fed a signal slightly higher than 10 Mc, and an output voltage is produced at the discriminator, moving the indicator needle. It is assumed that the temperature-controlled running crystal operates on the proper frequency. Its frequency can be checked with external frequency-measuring equipment, as can the calibrating crystal.

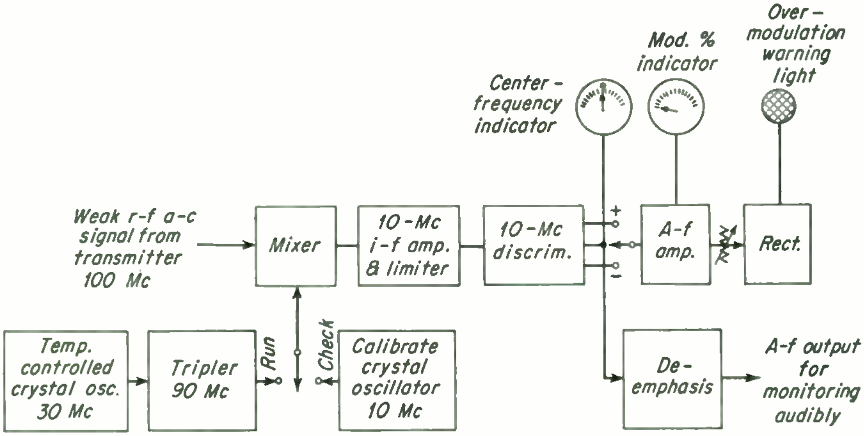


FIG. 18.18. Block diagram of the circuits in an FM station center-frequency and percentage-of-modulation monitor.

The output of the discriminator can be fed through a de-emphasis circuit and used to audibly monitor the transmitted signal. The discriminator output can be selected by a switch and used to indicate the percentage of deviation of the carrier either above or below the carrier frequency. An overmodulation warning light, bell, or other warning device can be operated from the amplified discriminator output.

Operators at the transmitter of commercial FM transmitters must have Radiotelephone First Class licenses. Except with transmitter power outputs of 10 kw or less, any commercial radio license holder, telegraph or telephone (except aircraft-radiotelephone-operator authorization), may operate the station equipment within the following limitations: (1) He may turn the transmitter on and off. (2) He may make power-line voltage adjustments if the line voltage varies. (3) He may control the gain of the audio input to produce the proper modulation percentage. For all other adjustments such operators must be under the immediate supervision of a Radiotelephone First Class operator.

For noncommercial educational FM stations having a transmitter power output in excess of 10 watts and not more than 10 kw, a Radiotelephone Second Class operator may perform the duties of a Radiotelephone First Class operator. When the power is less than 10 watts, a Radiotelephone Second Class or Radiotelegraph First or Second Class operator can perform the duties of a Radiotelephone First Class operator.

One or more spare tubes of every type used in the transmitter and in frequency and modulation monitors must be kept on hand at the equipment location, as given in Table 18.1.

**Table 18.1**

| *Number of each type employed* | *Spares required* |
|---|---|
| 1 or 2 | 1 |
| 3 to 5 | 2 |
| 6 to 8 | 3 |
| 9 or more | 4 |

**18.14 FM Communication Stations.** Most mobile-to-mobile and mobile-to-fixed station communications now use FM in the VHF band. Some police and other base stations transmit in the 1,600–2,900-kc medium frequency (MF) range to their mobiles, and the mobiles answer on VHF bands.

If the fixed station operates on medium frequencies, it transmits AM signals and is very similar to a simple low-powered broadcast station without studios and recording equipment. It usually consists of a crystal-oscillator power-amplifier transmitter of 50 to 1,000 watts output power, either plate- or grid-modulated. The transmitting antenna is usually vertically polarized. The mobile receivers are similar to good AM broadcast receivers, but are fixed-tuned in most cases, with crystal-controlled local oscillator stages. They use either differential or simpler squelch systems to silence the noise when the fixed station is not transmitting. Receiving antennas on mobiles for MF signals are usually 3- to 5-ft vertical whips, similar to those used by motorists to receive broadcast-band stations.

Both fixed and mobile VHF equipment uses vertically polarized antennas. In the 25–54-Mc band the antenna is usually mounted on the rear bumper or fender of the mobile unit and ranges from about 4 to 9 ft long. In the 144–174-Mc bands, the antenna is usually a thin, 20- to 25-in. vertical wire mounted on the top of the car.

All such voice-communication equipment is operated *push-to-talk*. At the fixed station the microphone is usually mounted on the operating desk, while in the cars the microphones are hand-held types, with a switch on one side of them. When this push-to-talk switch is depressed, the receiver is usually muted or silenced and the transmitter is turned on. When the switch is released, the transmitter goes off and the receiver operates again.

To allow more usable spectrum space, FM voice communications are limited to a 60-kc channel width, with a 15-kc carrier swing above and below the center frequency. This will be decreased, possibly cut in half, in the near future, to allow more systems to operate. It only requires a lowering of the gain control in the present transmitters, to limit their frequency swing. New receivers will have to be engineered to have a narrower bandpass in their IF systems if other nearby systems interfere with them. Since noise in an amplifying system is directly proportional to bandwidth, narrowing the bandpass helps to decrease noise when receiving weak signals.

Very-high-frequency reception is subject to much man-made impulse-noise interference from automobile ignition systems, motors, and from electric circuits being made and broken. For a given signal strength, the limiter stages in an FM receiver are more effective in eliminating such interference than audio peak limiters in AM receivers. Probably of more importance, in the VHF region, signals are subject to multipath transmission. Signals transmitted from a car may reach the fixed station receiver from two or more different directions because of the susceptibility of such frequency signals to be reflected by wires and large metal objects. If the multipath signals arrive in phase, the signal is strong. If out of phase, the signal is weakened. If the car is moving, the signals may fade up and down rapidly, producing a fluttering effect in the receiver. The AVC circuits in AM receivers may not follow such a rapid fade, and the reception suffers. Since the FM receiver may use no AVC, depending instead on its limiter stages to keep the signal to the discriminator at a constant level, the FM reception is not subject to the flutter until the signal becomes so weak as not to operate the limiters. As a result, most communications at frequencies over 100 Mc are FM; between 30 and 100 Mc they may be FM or AM; and below 30 Mc most are AM. Aircraft transmissions are always AM, to take advantage of the fact that an interfering signal must be many times stronger than the desired AM signal before suppressing the desired frequency. In FM, a 2:1 signal ratio is all that is needed to prevent the weaker signal from being heard at all.

Mobile transmitters range in power from about 5 watts to about 60 watts output.

**18.15 Noise in Motor Vehicles.** Most communication receivers will satisfactorily amplify and demodulate a 1-$\mu$v received signal, whether AM or FM. However, if the noise being received at the same time has an average value of 1-$\mu$v or more, neither AM nor FM will reproduce the signal satisfactorily. As a result, it is important to reduce local noise as much as possible.

There are some general methods of reducing noise generated in land-based electrical equipment. One is to ground the equipment with as short a ground wire as possible. Another is to bypass the input and output electrical lines to ground with 0.001- to 0.01-μf capacitors, using series RF chokes in the lines if necessary. Another aid is to shield the equipment and lines with metallic housings or braid and ground the shield. Still another aid is to connect a bypass capacitor across any opening and closing electric contact or switch.

In motor vehicles there are several possible sources of impulse interference. The major source of noise is the ignition system. The popping noise developed by the spark plugs increases in frequency with increased engine speed. It can usually be decreased by using resistor spark plugs, making sure all ignition leads are tight, connecting suppressor resistors in the lead from the distributor to the ignition coil, and bypassing the primary of the ignition coil to ground. Resistance ignition cable may also help, although an excessive resistance is detrimental to engine operation. Ignition cables may require shielding.

Another frequent source of noise in mobile receivers is the battery charging generator. When the engine changes speed, a whining noise is heard to change. This noise can be reduced by bypassing the armature terminal of the generator (*not* the field terminal) with a 0.1- to 1-μf capacitor. It may also help to bypass the battery terminal and the armature terminal of the voltage regulator to ground.

Gasoline, temperature, and oil gages can produce clicking or crackling noises. The leads to these gages can be bypassed with 0.25 μf at their source as well as at the dashboard.

An irregular clicking noise that disappears when the brakes are applied is known as *wheel static*. The front wheels riding on an insulating layer of grease may build up a static charge which sparks across when the voltage increases sufficiently. This can be stopped by using wiping-type front-wheel static eliminators. The use of antistatic powder in tire tubes themselves will decrease tire static.

If the metal parts of the chassis of a vehicle become loose, a voltage difference may be developed between the two parts and sparking may occur when the parts work together. Adequate bonding of the major parts of the car, hood, body, chassis, motor, cables, rear axles, brake and speedometer cables, rear-axle assembly, doors, and fenders, with flexible-braid conductors, is often necessary.

All electric leads coming through the fire wall may have to be bypassed at the point where they leave the engine compartment.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

1. What types of radio receivers do not respond to static interference? (18.1) **[3]**
2. Explain what is meant by the following types of emissions: F0, F1, F2, F3, F4. (18.3) **[3]**

**3.** What effect, if any, does modulation have on the amplitude of the antenna current of a frequency-modulated transmitter? (18.3) **[3]**

**4.** In an FM radio communication system, what is the meaning of modulation index? Of deviation ratio? What values of deviation ratio are used in an FM radio communication system? (18.3) **[3]**

**5.** What are the merits of an FM communication system compared with an AM communication system? (18.3, 18.14) **[3]**

**6.** Draw a block diagram of an FM receiver and explain its principle of operation. (18.7) **[3]**

**7.** Draw a block diagram of a frequency-modulated transmitter and indicate the center frequency of the master oscillator and the center frequency radiated by the antenna. (18.9) **[3]**

**8.** Why is narrow-band FM rather than wideband FM used in radio communication systems? (18.14) **[3]**

**9.** How wide is an FM broadcast channel? (18.3) **[4]**

**10.** What is the AF range that an FM broadcast station is required to be capable of transmitting? (18.3, 18.13) **[4]**

**11.** What characteristic of an audio tone determines the percentage of modulation of an FM broadcast transmitter? (18.3) **[4]**

**12.** What is center frequency in reference to FM broadcasting? (18.3) **[4]**

**13.** What is the meaning of the term *frequency swing* in reference to FM broadcast stations? (18.3) **[4]**

**14.** What frequency swing is defined as 100 per cent modulation for an FM broadcast station? (18.3) **[4]**

**15.** An FM broadcast transmitter is modulated 40 per cent by a 5,000-cycle test tone. When the percentage of modulation is doubled, what is the frequency swing of the transmitter? (18.3) **[4]**

**16.** What is the frequency swing of an FM broadcast transmitter when modulated 60 per cent? (18.3) **[4]**

**17.** An FM broadcast transmitter is modulated 50 per cent by a 7,000-cycle test tone. When the frequency of the test tone is changed to 5,000 cycles and the percentage of modulation is unchanged, what is the transmitter frequency swing? (18.3) **[4]**

**18.** How does the amount of audio power required to modulate a 1,000-watt FM broadcast transmitter compare with the amount of audio power required to modulate a 1,000-watt standard broadcast transmitter to the same percentage of modulation? (18.3) **[4]**

**19.** If the transmission-line current of an FM broadcast transmitter is 8.5 amp without modulation, what is the transmission-line current when the percentage of modulation is 90 per cent? (18.3) **[4]**

**20.** What is the purpose of a discriminator in an FM broadcast receiver? (18.4, 18.5) **[4]**

**21.** Draw a diagram of a limiter stage in an FM broadcast receiver. (18.5) **[4]**

**22.** What is meant by pre-emphasis in an FM broadcast transmitter? (18.5) **[4]**

**23.** What is the purpose of a de-emphasis circuit in an FM broadcast receiver? (18.5) **[4]**

**24.** What is the purpose of a limiter stage in an FM broadcast receiver? (18.5) **[4]**

**25.** Draw a diagram of an FM-broadcast-receiver detector circuit. (18.5, 18.6) **[4]**

**26.** What is a ratio detector? (18.6) **[4]**

**27.** How wide a frequency band must the IF amplifier of an FM broadcast receiver pass? (18.7) **[4]**

**28.** If an FM transmitter uses a doubler, a tripler, and a quadrupler, what is the carrier frequency swing when the oscillator frequency swing is 2 kc? (18.9) **[4]**

**29.** An FM broadcast transmitter operating on 98.1 Mc has a reactance tube-modulated oscillator operating on a frequency of 4,905 kc. What is the oscillator frequency swing if the transmitter is modulated 100 per cent by a 2.5-kc signal? (18.9) [4]

**30.** What is the purpose of a reactance tube in an FM transmitter? (18.9) [4]

**31.** Draw a diagram of a means of modulation of an FM station. (18.9) [4]

**32.** What is a common method of obtaining FM in an FM broadcast transmitter? (18.9–18.11) [4]

**33.** What is the frequency tolerance of an FM broadcast station? (18.13) [4]

**34.** What is the frequency tolerance for a noncommercial educational FM broadcast station? (18.13) [4]

**35.** What is the tolerance in operating power of FM broadcast stations? (18.13) [4]

**36.** How is the operating power of an FM station determined? (18.13) [4]

**37.** What is the required frequency range of the indicating device on the frequency monitor at an FM broadcast station? (18.13) [4]

**38.** What is the required accuracy of instruments indicating the plate current and plate voltage of the last radio stage or the transmission-line current or voltage at an FM broadcast station? (18.13) [4]

**39.** Exclusive of monitors, what indicating instruments are required in the transmitting system at an FM broadcast station? (18.13) [4]

**40.** Explain why high-gain antennas are used at FM broadcast stations. (18.13) [4]

**41.** What are the licensed-operator requirements for an FM broadcast station? (18.13) [4]

**42.** If an FM broadcast station uses a total of five tubes of a given type at the transmitter, what is the minimum number of spare tubes of this type required at the transmitter? (18.13) [4]

**43.** What types of radio receivers do not respond to static interference? (18.1) [6]

**44.** Draw a simple schematic circuit diagram of an FM receiver discriminator. (18.5) [6]

**45.** Draw a block diagram of a superheterodyne receiver designed for reception of FM signals. (18.7) [6]

**46.** Draw a block diagram of an FM transmitter. (18.9–18.11) [6]

**47.** What is the meaning of frequency tolerance? (18.13) [6]

## AMATEUR LICENSE INFORMATION

All applicants for Amateur licenses should be able to answer the following question:

★ 1. What is the recognized abbreviation for frequency modulation? (18.1)

## CHAPTER 19

# TRANSISTORS

**19.1 Use of Transistors.** One of the most significant developments in radio and electronics has been the transistor, first announced in 1948. Since that time it has found applications in an untold number of circuits. Its basic use, as far as radio is concerned, is amplification, detection, and rectification, similar to the vacuum tube. The transistor is far more efficient than the vacuum tube, using no power to heat a filament and requiring less voltage for normal operation. It is smaller, lighter, and more rugged, but is quite sensitive to heat. If allowed to become overly warm it may change its characteristics or become defective. For low-power and low-voltage applications the transistor is making a bid to take over many of the jobs of the vacuum tube, particularly in light-weight portable or emergency equipment.

**19.2 Current Flow in Solids.** As explained previously, atoms are considered to be tiny, ball-like structures, composed of a nucleus of protons and neutrons, with *layers* of electrons whirling around the nucleus. The total number of electrons is exactly equal to the number of protons in the nucleus, resulting in a neutral charge for the atom.

The outer layer of electrons is composed of *valence* electrons. These electrons are not tied as closely to the atom as are the electrons in the layers beneath.

When two or more atoms combine to form a molecule, the valence electrons of the outer rings of the atoms are believed to interchange freely, binding the atoms together by this electron interweaving, or coupling.

Another form of atomic coupling is possible. This is the interlinking of molecules or atoms into crystals. Some molecules may link together to form six-sided, cubelike crystals, others may produce eight-sided crystals, and so on. Under the proper conditions, additional molecules may be added to a small crystal resulting in a growth of the crystal, but the crystal *lattice* retains its basic shape, cubical, eight-sided, etc.

When a conductor, such as copper, is drawn into wire form and an emf applied across its ends, there is a drift of the free electrons in the outer layer of the molecules toward the positive terminal of the source, and electrons are fed into the wire from the negative terminal. Current flows.

A *semiconductor*, such as germanium, in its *intrinsic* (pure) crystal form, has all its valence electrons tightly interlocked with the other atoms forming the crystal and theoretically is a nonconductor. However, at normal room temperatures there is enough thermal agitation in the atoms to kick free an electron from the crystal lattice at times. The *hole* in the lattice represents an electronless, or negativeless, area. This is equivalent to saying that the hole has a positive charge.

The freed electrons and the holes may recombine rapidly in the intrinsic crystalline germanium at normal temperatures, but if an emf is applied across the material, there will be enough free electrons available at all times to produce only a slight drift and the germanium acts as a rather poor conductor—as a *semiconductor.*

The germanium atom has four valence electrons that interlock in a tight bond with the other atoms in its crystals. However, if a small amount of an impurity (one part in one million), such as arsenic with five valence electrons, can be introduced into the germanium during the crystallization process, the resulting crystal will be almost like a germanium crystal, except that there will be one extra negative electron in the crystal lattice. Such a crystal is found to have one electron that may temporarily be dislodged from the crystal lattice by normal thermal activity and float around the lattice. Eventually, the electron may recombine, but until that time the germanium exhibits a negative effect and the material is known as *N germanium.*

By the addition of a small amount of gallium, having only three valence electrons, the germanium-gallium crystals form into a lattice *lacking* one electron. This crystal requires another valence electron to make it appear to conform to an intrinsic germanium crystal. Such a crystal has an *electron hole* and acts as a positive charge. This crystalline material is known as *P germanium.* The holes in the P germanium tend to pull electrons from adjacent crystals, producing a hole in these other crystals. The holes in the P material are constantly forming in a random manner. The holes then steal an electron from another nearby crystal lattice. If an emf is placed across the germanium, there will be a drift of the stolen electrons toward the positive terminal and an apparent movement of the holes toward the negative terminal. This apparent moving of the positive holes toward the negative potential might be considered to be a backward-moving current.

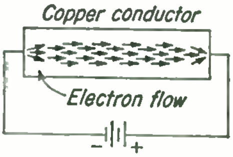


FIG. 19.1. Electrons may be considered to flow directly from negative to positive terminals in a good conductor.

It may be helpful to consider that the electron movement in a good conductor is directly from the negative terminal to the positive terminal through the conductor, as indicated in Fig. 19.1.

In P-type semiconductors the current that flows may be considered as detouring out around the material (Fig. 19.2), trying to find the relatively few usable holes that will support current flow.

**19.3 Germanium Diodes.** When a piece of P germanium and a piece of N germanium are either fused or grown together, they form a *junction* diode. At the junction (Fig. 19.3) there is a continual combining of positive holes and negative free electrons from the two dissimilar types of germanium. This combining effect produces a neutral field at the junction that acts as a barrier for any further electrical combining. The diode is inoperative, but consists of three areas, the P, the junction, or *barrier*, and the N.

When a battery is connected across the diode, with the positive terminal to the P region and the negative to the N region (Fig. 19.4), the positive holes are repelled by the positive potential and move into the junction. The free electrons in the N region are repelled by the negative potential and also move into the junction and combine with the holes. The junction ceases to be a barrier, and current now flows through the semiconductor. The junction is *biased forward.*

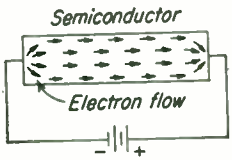


Fig. 19.2. Electrons may be considered as detouring outward—trying to find holes that will support current flow in a semiconductor.

When the battery polarity is reversed, with the positive potential to the N region and the negative potential to the P region, the barrier of the junction is increased and very little current drifts through the semiconductor. The junction is *biased backward,* or reverse-biased.

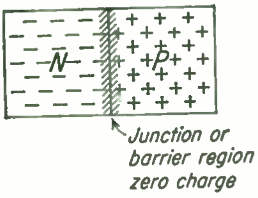


Fig. 19.3. Junction diode.

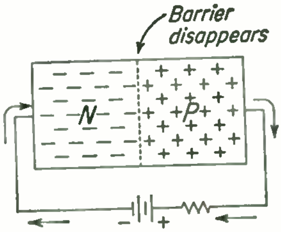


Fig. 19.4. The barrier disappears in the junction diode when biased forward.

Alternating voltages applied across the germanium junction produce a pulsating direct-current flow in the circuit. The junction acts as a diode tube and rectifies the alternating current.

Germanium diodes with designations such as 1N34, 1N306, etc., are used widely as rectifiers when the current through them is small and the inverse voltage applied across them is not great.

It may be wondered how a contact can be made to a P- or N-type piece of germanium without producing a partially rectifying junction. This is possible by using a hot enough solder joint to produce sufficient thermal agitation to break up the P- and N-type crystals and form noncrystalline germanium at the contact point.

**19.4 Principles of a Transistor.** When a PN or NP germanium or silicon junction diode is biased backward, very little current flows through the load resistor in its circuit (Fig. 19.5).

If some holes could be fed into the junction or barrier from an outside source, the barrier would become a better conductor and the current would increase through the junction and therefore through the resistor.

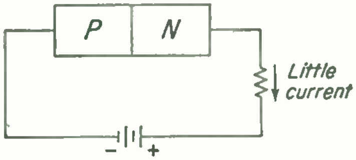


FIG. 19.5. Backward-biased diode. Little current flows.

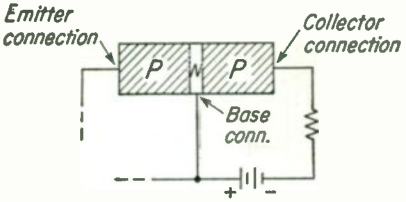


FIG. 19.6. A PNP transistor, with base-collector circuit backward-biased.

By controlling the number of holes fed into the junction, the current through the resistor can be controlled.

One means of accomplishing this is to develop a second junction very close to the first. A very thin slice of N germanium fused between two pieces of P germanium (Fig. 19.6) produces a *junction transistor.*

The connection to the right-hand P-germanium material is called the *collector* connection. The N germanium forms the *base.* The barrier between the base and the collector restricts the flow of electrons in the backward-biased base-collector circuit to a very low value. The voltage drop across the load resistor is therefore quite small.

The connection to the left-hand P material (Fig. 19.7) is called the *emitter* connection. The battery in the base-emitter circuit is connected in a forward-biased manner, producing relatively high current through the base-emitter junction.

The relatively high current through the base-emitter barrier tends to detour or spray holes throughout the base material. Many of these holes move into the collector-base barrier area, giving it more conductivity and increasing the current in the collector-base circuit. In this transistor the emitter emits holes into the base area.

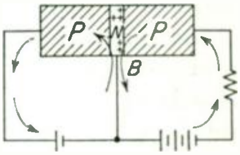


FIG. 19.7. When the base-emitter circuit is forward-biased, increased current flows in the base-collector circuit.

The emitter-base current controls the collector-base current. If the emitter current varies, the collector current will also vary.

A practical transistor amplifier circuit is shown in Fig. 19.8, using the standard transistor symbol.

Since the emitter circuit has a relatively heavy current flow with little voltage applied, it is a low-resistance ($R = E/I$) or low-impedance circuit. To match this low-impedance circuit, the secondary of the coupling transformer must have a low impedance, usually between 50 and 500 ohms. In most cases, the primary of the coupling transformer will have to match a much higher impedance circuit. As a result, the transformer has a step-down turns ratio.

When a signal voltage is applied to the primary of the input transformer, the relatively low secondary voltage adds to the low bias voltage of the emitter battery and produces a varying d-c in the emitter circuit. As this current varies, the number of holes moving into the collector-circuit barrier changes, and the collector current varies. When the current through the high-resistance load in the collector circuit varies, the voltage across it varies. If the signal output across the load resistor is greater than the signal input to the transformer, the whole circuit has produced amplification.

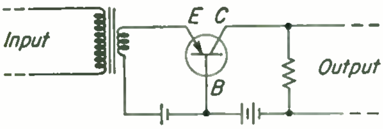


FIG. 19.8. A common-base transistor amplifier circuit.

This is a PNP, junction-type, common-base transistor amplifier-stage circuit.

If all the holes from the emitter could pass through the base and help to produce collector circuit current, the ratio of collector to emitter currents would be 1:1 and the transistor would be said to have an *alpha* (the Greek letter $\alpha$) of 1. Since some of the emitter holes combine with electrons in the N-region base, the alpha, or current amplification, of a junction transistor will always be less than 1, possibly between 0.8 and 0.95.

The common base connection does not have a current gain, but can produce a high voltage gain and an intermediate power gain. Its input impedance is very low, and the output impedance is very high. It is somewhat similar to a grounded-grid vacuum-tube amplifier stage.

**19.5 The Common-emitter Circuit.** It is possible to rearrange the common-base transistor amplifier circuit to a common-emitter circuit (Fig. 19.9).

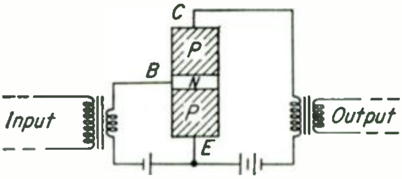


FIG. 19.9. A common-emitter transistor amplifier circuit.

This circuit resembles a triode tube using the emitter as the cathode, the base as the grid, and the collector as the plate, *except* that with a PNP transistor, current flowing in the output circuit is reversed. With no signal input there is a small collector-to-emitter current flowing. The base-emitter bias is forward, producing holes in the barriers and in the base material between the two P regions. This increases the collector current. When a signal is applied between the base and emitter, the collector-to-emitter current varies with the signal.

Since the base-emitter circuit is forward-biased, it is a low-impedance circuit. The collector-emitter circuit without any base-emitter bias represents a high impedance. The greater the base-emitter current, the lower the collector-emitter circuit impedance.

In the common-emitter circuit a small change in base-emitter voltage can produce a relatively large output-signal voltage across the collector-emitter load. A small change in base-emitter current can also produce a greater collector-current change. As a result, the common emitter gives the highest possible power gain of the transistor circuits. It is one of the most used types of transistor amplifier circuits.

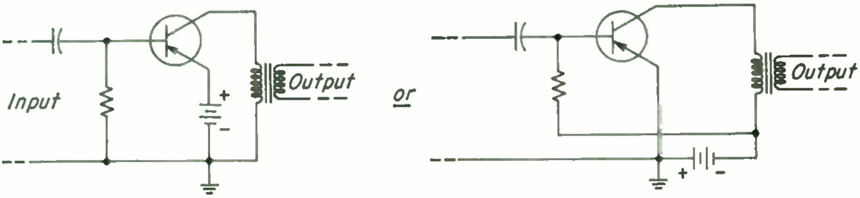


FIG. 19.10. Common-emitter circuits using one battery only.

A common-emitter circuit may use only one higher-voltage battery. The base-emitter current is reduced by including a resistor in series with the base connection, as shown in Fig. 19.10. Note the simplicity of the whole circuit.

**19.6 The Common-collector Circuit.** Another basic configuration of a transistor amplifier is the common-collector circuit (Fig. 19.11). It is not used very frequently. It has high input impedance, low output impedance, the lowest power gain, and no voltage gain. However, it has a large current gain and is useful for converting from a medium-impedance to a low-impedance value.

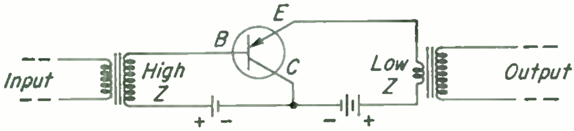


FIG. 19.11. A common-collector transistor amplifier circuit.

**19.7 Transistor Circuits.** The number of possible transistor circuits is apparently as limitless as vacuum-tube circuits. A few of the basic circuits in use with junction-type transistors such as 2N112, 2N63, etc., are included here.

Figure 19.12 illustrates a simple audio amplifier capable of producing sufficient audio to actuate a pair of high-impedance earphones. The base-biasing resistance will vary, depending on the characteristics of the transistors. It is found that transistors of a similar type may have rather widely varying characteristics. Some will operate at much higher frequencies than others.

Figure 19.13 shows an AF amplifier capable of operating a small loudspeaker in a pocket-size radio receiver. Note the low impedances used in the input circuit (4 kilohms) and the large coupling capacitance (2 $\mu$f) needed.

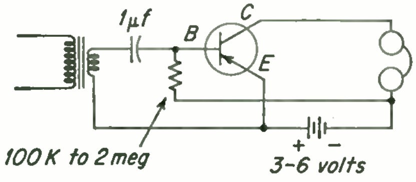


FIG. 19.12. A transistor amplifier to provide earphone volume.

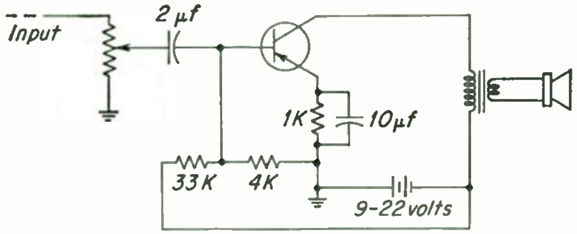


FIG. 19.13. A transistor amplifier capable of low-volume loudspeaker operation.

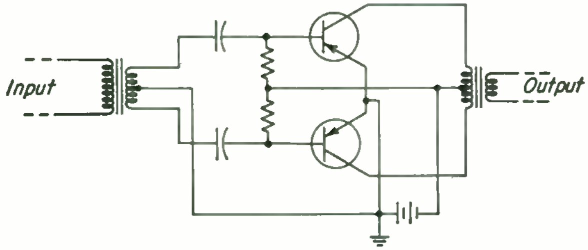


FIG. 19.14. Push-pull transistor audio-power amplifier circuit.

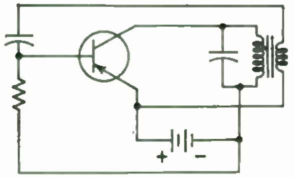


FIG. 19.15. A tuned-collector circuit Armstrong-type AF oscillator.

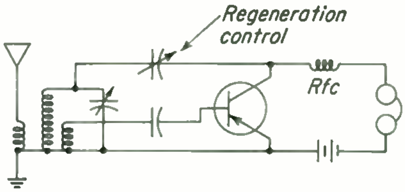


FIG. 19.16. An Armstrong-type oscillator as a regenerative detector.

Figure 19.14 is a diagram of two transistors, such as 2N68s, in push-pull, capable of giving several watts of output audio power.

Figure 19.15 illustrates a tuned-plate circuit type of Armstrong AF oscillator. Either side of the battery can be grounded as desired.

Figure 19.16 shows a variation of the tuned-plate-circuit Armstrong oscillator used as a regenerative detector for a single-transistor receiver. Note that the base circuit has no resistor connected to the negative terminal of the battery. The circuit sometimes operates better with a resistor of 2 to 10 meg between these two points.

Figure 19.17 is a diagram of a Hartley-type oscillator. Note that the transistor Hartley oscillator is similar to the triode vacuum-tube circuit, where the plate and grid (collector and base) connections are at opposite ends of the tuned circuit and the cathode (emitter) is connected to the center tap. The parallel resistor and capacitor form a *grid-leak* biasing circuit.

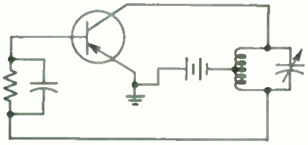


FIG. 19.17. A Hartley-type transistor oscillator.

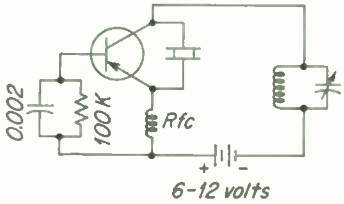


FIG. 19.18. A transistor crystal oscillator circuit.

Figure 19.18 illustrates a transistor crystal oscillator circuit.

Figure 19.19 shows two stages, using resistance coupling between them. Resistor $R_1$ serves a dual purpose. It forms the input impedance of the stage, and with $R_2$ and $R_3$, it forms a voltage divider that biases the base of the first transistor. $R_3$ is the output-load resistance. Because of the relatively low impedances used, a 6-$\mu$f coupling capacitor is required for good low-frequency response. (For voice-frequency amplification only, a 2-$\mu$f capacitor may be satisfactory.) $R_4$ and $R_5$ form a biasing voltage divider for the base, with $R_6$. Note the two methods of connecting the biasing voltage dividers, either to the top or the bottom of the collector-load impedance.

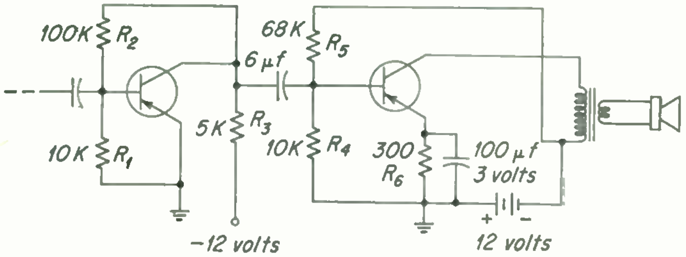


FIG. 19.19. A two-stage transistor amplifier using resistance coupling between stages.

Figure 19.20 shows an IF amplifier circuit used in transistor receivers, coupled to a germanium-diode second-detector–AVC circuit. The input to the IF amplifier is transformer-coupled, with only the primary tuned.

The low-impedance secondary, about 800 ohms, is coupled to the transistor base circuit. The collector is connected to the next IF transformer at the *bottom* of the tuned primary, and the battery lead attaches to a tap on the primary. This sends current through the primary in a direction that will produce the required voltage potential at the top of the coil to neutralize the stage. The 5-$\mu\mu$f capacitor is the neutralizing capacitance. The 4,000-ohm resistor and the 0.01-$\mu$f capacitor form a decoupling network.

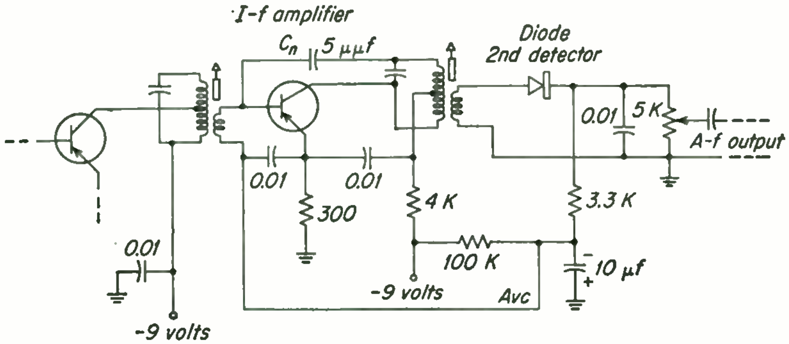


FIG. 19.20. An IF amplifier, second detector, and AVC circuit used in transistor superheterodyne receivers.

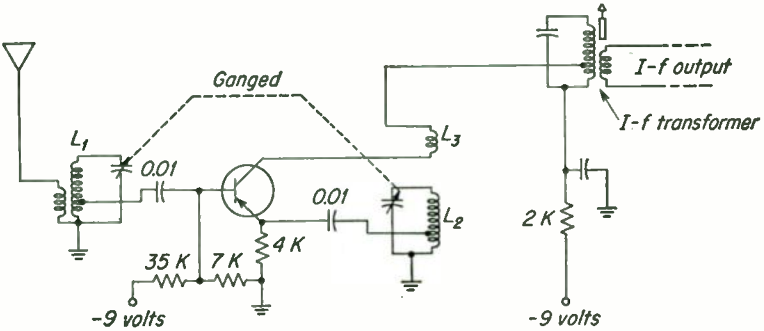


FIG. 19.21. A mixer circuit used in transistor superheterodyne receivers.

The second detector is a germanium diode that rectifies the output of the IF amplifier, producing the AF output and, at the same time, negative AVC biasing voltage. This is applied to the base circuit of the IF transistor through the secondary of the first transformer.

A mixer, or converter, stage similar to those used in many transistor superheterodyne receivers is shown in Fig. 19.21. The signal is coupled to the mixer tuned circuit $L_1$. The low-impedance base is fed from a low-impedance tap on $L_1$. The local oscillator tuned circuit $L_2$ feeds the low-impedance emitter circuit through a 0.01-$\mu$f capacitor and the base through the lower part of $L_1$. The collector has a tickler coil $L_3$ coupled to the emitter circuit. This feeds back amplified energy to $L_2$, producing sustained oscillations in $L_2$. The oscillations and the signal-frequency a-c mix and produce the intermediate frequency. This is fed to the lower part of the first IF transformer through $L_3$.

**19.8 Better High-frequency Operation.** One of the major obstacles in transistor operation has been its inability to function properly at higher radio frequencies. There are three commonly known methods of raising the frequency of operation. One is to use a junction tetrode; the second is to use junction triodes incorporating an intrinsic layer between collector and base; and the third is the use of point-contact transistors.

The relatively high capacitance between emitter and base, and between collector and base, because of their close proximity, may be considered to be a main factor in limiting the frequency response. Making smaller junctions would raise the frequency limits but makes manufacture too difficult. Instead, a second contact can be made to the opposite side of the base, called the base connection No. 2 (Fig. 19.22). When this is biased positively, it tends to restrict the transference of holes across the base to an area near the base connection No. 1. In effect, this makes a smaller transistor, and it operates better on higher frequencies.

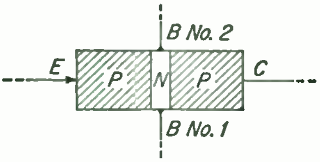


FIG. 19.22. A tetrode transistor, using a second base connection.

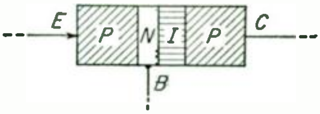


FIG. 19.23. A PNIP junction triode transistor.

Building the transistor with an intrinsic layer of germanium between the collector and the base (Fig. 19.23) reduces the capacitance between these two elements and allows improved high-frequency operation. This is termed a *PNIP junction triode*.

The point-contact transistor, which was the first transistor developed, consists of a piece of N germanium acting as a base. Two sharp contacts are placed near each other on the surface of the base. At the surface of the N germanium where the points touch, a P germanium is produced by an electrical forming process, resulting in a PNP-type transistor, as indicated in Fig. 19.24.

It is also possible to form, in the N-germanium base, under the collector contact, an intrinsic layer, and inside of that a P area, resulting in a PNIP-type transistor with good high-frequency characteristics.

The point-contact transistors, such as the 2N65, 2N132, etc., may have a current gain of 1.2 to over 4 with a common-base circuit, whereas the junction transistors always have an alpha of less than 1.

At present both junction and point-contact transistors are manufactured, with junction types being less expensive, generally.

**19.9 NPN Transistors.** The basic explanations have been made entirely with PNP-type transistors. However, transistors are also made in NPN form. An NPN transistor uses the same circuits as the PNP, except that the battery potentials are all reversed. Whereas the PNP transistor injects holes into the base from the emitter, the NPN transistor injects electrons into the base. The symbol of the NPN transistor reverses the arrowhead on the emitter. A simple two-stage low-voltage ($1\frac{1}{2}$ to 6 volts) audio-amplifier circuit employing NPN transistors is shown in Fig. 19.25.

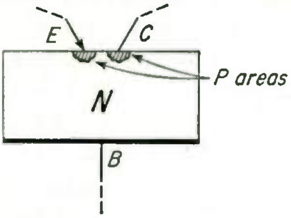


FIG. 19.24. A point-contact transistor.

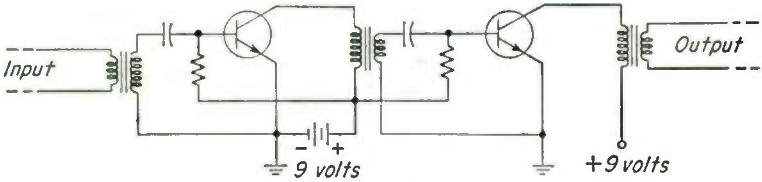


FIG. 19.25. A two-stage amplifier, using NPN transistors, merely reverses the battery polarity and the arrow in the symbol of a PNP circuit.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

1. Describe the physical structure of two types of transistors, and explain how they operate as an amplifier. (19.4, 19.8, 19.9) [3]

2. Draw a simple schematic circuit diagram of a two-stage audio amplifier using transistors. (19.7, 19.9) [3]

## CHAPTER 20

# ANTENNAS

**20.1 The Radio Wave.** An antenna, or aerial, in an accepted form consists of a piece of wire or other conductor, with insulators at both ends, suspended well above the ground, as illustrated in Fig. 20.1.

If the wire is cut to a length equivalent to a half-wavelength, it acts as an oscillating LC circuit. If excited by some source of RF alternating current, the free electrons in it will oscillate back and forth from one end to the other. If the wire were a perfect conductor and had a high $Q$, once shock-excited, the electrons would continue to oscillate back and forth along it indefinitely. In actual operation some of the energy imparted to the electrons is lost in heating whatever resistance is in the wire. A considerably greater amount of the energy is *radiated* into space from the wire. It is this energy lost by the antenna into space that is the *radio wave.*

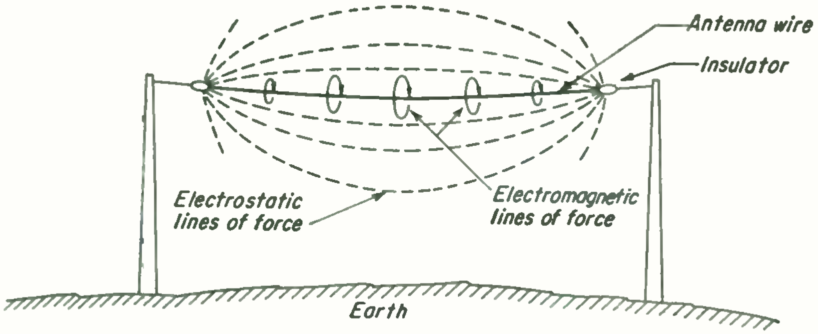


FIG. 20.1. A basic antenna, or aerial, develops electromagnetic fields around it and electrostatic fields between its ends.

If an antenna is shock-excited, free electrons in it will be driven to one end, pile up there, and produce a highly negative charge. At the same time the other end of the wire is left with a deficiency of electrons and is positively charged. An electrostatic strain is developed from one end to the other, and an electrostatic field is developed across the antenna, as shown by the broken lines.

With nothing to hold the electrons at one end, they will reverse their previous motion and start toward the opposite end. As they move they produce a magnetic field, outward around the wire, as shown. The energy that had been stored in the electrostatic field is now transferred to the electromagnetic field. When the potential difference between the ends of the antenna drops to zero, the magnetic field is at a maximum and begins to contract back into the wire, driving electrons toward the once-positive end of the antenna. This end now has an excess number of electrons on it, charging it negative, the other end, having lost electrons, becoming positive. The energy is again stored in the electrostatic field.

This oscillating of electrons and energy in the antenna produces expanding and contracting electrostatic and electromagnetic fields. Part of these fields travel out so far that they cannot return to the antenna when the fields alternate and they are lost to the antenna into space.

If the radio frequency exciting the antenna is low, the antenna must be long to prevent the electric impulse from reaching the end and returning before the driving source potential reverses. As a result, low-frequency antennas are long and high-frequency antennas are short. The following are examples of some half-wavelength antennas. A frequency of 10 kc requires an antenna 46,800 ft long, nearly 9 miles. An antenna for the middle of the standard broadcast band, 1,000 kc, is 468 ft. For a frequency of 10 Mc, 46.8 ft is required; for a frequency of 100 Mc, 4.68 ft; and for 10,000 Mc, 0.0468 ft. By necessity, antennas of less than half-wavelength are used for low-frequency transmissions. They are *loaded* until they will tune properly to the desired frequency.

The radiations of the longer *wavelengths*, or lower-frequency radio waves, tend to travel along the surface of the earth without attenuation. The *ground* wave, that portion of the radiated wave traveling a few yards above the surface of the ground, is usable for hundreds to thousands of miles, day or night.

When higher frequencies are used, the ground wave weakens more rapidly, as energy from it is more effectively absorbed by the surface over which it is moving. As a result, frequencies in the 500–1,000-kc region may have usable ground-wave signals only from 50 to 400 miles.

As the frequency is increased above 5 to 10 Mc, the usable ground-wave signal exists for only a few miles. At these frequencies it is possible to transmit further by using the *direct* wave. When the receiving and transmitting antennas are within sight of each other, the signal is considered a direct wave. At high frequencies where the ground wave is insignificant, aircraft several thousand feet in the air may receive direct waves a hundred miles or more away.

The explanations that follow will consider the antenna as a transmitting device, although if a certain antenna transmits maximum signal east and west, it will receive best east and west. Its radiation resistance for transmitting is the same as when receiving.

**20.2 The Ionosphere.** Near the earth the air is rather dense, but from about 60 to 600 miles above the earth the air is quite thin, and radiated energy from the sun can ionize the widely spaced air molecules. The different degrees of ionization produced form into several recognizable layers. The ionized atmosphere allows the radiated wave to travel faster through it than in the more dense, un-ionized lower air. As a result, the top part of a wave moving into the *ionosphere* speeds up and forges ahead of the lower part of the wave, and eventually may turn, or *refract*, the wave until it is moving downward (Fig. 20.2).

The lower the frequency of the waves, the less penetrating effect they have and the greater the proportion of them that may be turned back toward earth. The higher the frequency, the more penetrating energy the radio wave contains. Signals with frequencies of 10–30 Mc may be deflected, or they may penetrate the ionosphere, depending on the time of day, the angle at which the wave strikes the ionosphere, and the degree of ionization present. With weak ionization they penetrate; with stronger ionization they may be refracted. With still stronger ionization the wave energy may be totally absorbed and dissipated in the ionosphere.

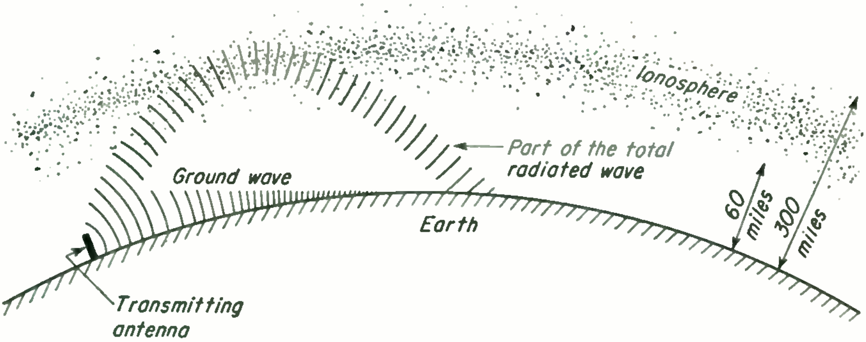


FIG. 20.2. The ionosphere, a layer of ionized gases above the earth, can refract radio waves back to earth.

During times of sunspot activity and while the aurora borealis is active, ionization is considerably increased and long-distance transmission may be interrupted because of almost complete absorption of all waves by the ionosphere.

Besides the frequency factor, the angle at which the radio wave enters the ionosphere determines the penetration or refraction of the wave. While there may be some actual reflection of lower-frequency signals traveling directly upward, almost all that part of higher-frequency waves being transmitted at an angle of nearly 90° above the surface of the earth either penetrate or are absorbed by the ionosphere, as indicated in Fig. 20.3. As the angle becomes less than 90°, there is more chance of refraction. The higher the frequency, the greater the penetration and the lower the angle required to produce refraction. At high frequencies, there may be long distances between the end of the usable ground-wave signal and the reappearance of the reflected wave. At lower frequencies the *sky wave* often returns to earth in the ground-wave region.

If the sky wave returns to earth and strikes a good conducting surface such as salt water, it will be reflected back upward and take a double hop. A double hop may carry a signal a very long distance.

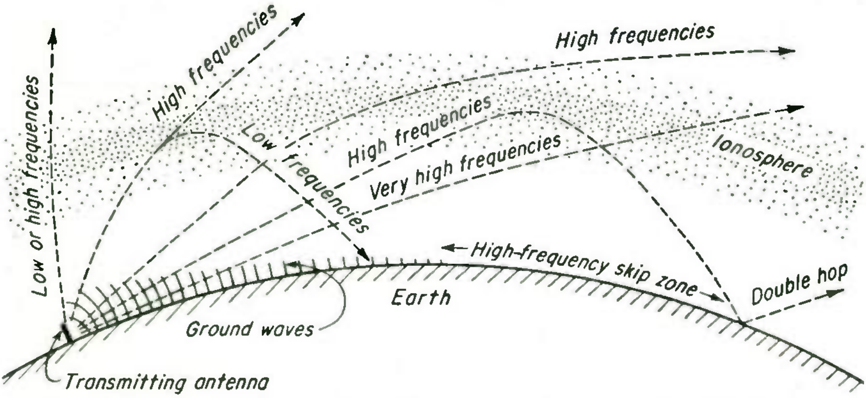


FIG. 20.3. Lower frequencies are affected by the ionosphere more than high frequencies are.

**20.3 Fading.** The fading of signals stems from two major causes. If a sky wave is being received, variations in the ionosphere may refract more or less energy to any given receiving point at different instants, producing a varying amplitude or fading signal.

When the receiving antenna is within both ground- and sky-wave range, the addition of the two waves may be in phase, or it may be out of phase. When arriving in phase they add to each other, producing a strong signal. When out of phase they tend to cancel each other. Variations in the ionosphere can change the sky-wave travel distance, and therefore the phase relationship of the ground and sky waves. In a somewhat similar manner, two sky waves refracted to the same point by two different areas of the ionosphere may arrive in or out of phase and produce fading.

In the VHF or UHF regions, where the direct wave is used, as in television reception, an airplane flying overhead will act as a reflector of the direct wave. A receiving antenna below the plane will receive the direct, or ground, wave from the TV station plus the wave reflected off of the plane. Since the plane is moving, the transmitter-reflector-receiver distance constantly changes and the relationship of the direct and the reflected waves at the receiving point are alternately in and out of phase, producing a continually fading signal.

**20.4 Night and Day Transmissions.** The ground wave remains the same night and day. Only the sky wave changes.

As night approaches, the sun can no longer ionize the atmosphere above the darkened part of the earth, and the ionized layers become thinner. The thinly ionized layers turn the waves back to earth over a wide arc, and the sky wave returns to earth many miles farther away than it does during the daytime.

At low frequencies there is not too much difference between night and day transmissions, although at distances of several thousand miles the nighttime signals will be stronger.

At medium frequencies, out past the ground-wave range, the signals improve materially at night. It is possible to pick up signals several thousand miles away, in comparison with several hundred miles during the daytime.

At high frequencies, from 3 to 10 Mc, the daytime refracted signals may return to earth 20 to 500 miles or more away. At nighttime the refracted signals return to earth 200 to many thousand miles away.

At still higher frequencies, 10 to 30 Mc, the daytime refracted signals may return 500 to 5,000 miles or more away. At nighttime the signals may pierce the ionosphere and may not return to earth at all.

It can be seen that a high-frequency communication system between two points two or three thousand miles apart may have to shift from one frequency to another during the day and night to keep the signals strong enough to be usable.

Frequencies between 30 and 100 Mc may sometimes be refracted during the daytime, but almost never at night. These frequencies are considered unreliable for long-distance communication. They are used for short-distance ground-wave, or direct-wave, communications.

Frequencies above 100 Mc are apparently not subject to refraction by the ionosphere, are similar to light waves, and are used for ground-wave, or direct-wave, transmissions.

Beaming strong UHF or VHF signals toward the horizon causes induction of the signal into conductive areas on the horizon and the signals are reradiated from them. These reradiated signals out past the horizon produce a *scatter*-type transmission which greatly increases the relatively reliable range of such frequencies.

Normally, the greater the altitude, the colder the air. If for any reason a layer of warmer air forms above a colder stratum, a *heat inversion* is present. The two layers have different densities of air and can affect VHF radio waves enough at times to refract them back to earth at distances of a few hundred miles or less. When the layer is thin, it may act as a *duct*, or pipeline, for UHF and SHF (superhigh-frequency) signals. Ducted signals may travel hundreds of miles before leaving the duct and returning to earth. These ducts usually form over water areas.

**20.5 Effect of Lightning on Radio Reception.** A bolt of lightning produces RF energy across almost the whole usable radio spectrum. However, the percentage of energy decreases as the frequency increases. At lower frequencies there is considerable energy, and with good ground-wave transmission, storms within hundreds or thousands of miles can produce considerable interference. The higher frequencies, particularly between 5 and 15 Mc, are subject to local storms, but storms in the skip zones, shown in Fig. 20.3, will not be heard. As a result, the higher frequencies are much less subject to lightning-produced radio noise, called static, and communications will be less subject to interruptions.

**20.6 Polarization.** The polarization of the radiated wave is considered to be in the direction of the electrostatic field of the antenna. Therefore the antenna in Fig. 20.1 transmits a horizontally polarized radio wave. An antenna erected vertically will radiate a vertically polarized wave.

TV and FM broadcasts are made with horizontally polarized antennas. A receiving antenna to pick up a maximum signal voltage from the transmitted wave must have the same polarization. As a result, all TV and FM receiving antennas are erected horizontally. If a TV antenna is erected vertically, almost no signal will be received from the transmitting station.

On lower frequencies, where it is difficult to raise the receiving and transmitting antennas high enough above the surface of the ground, polarization is less important. Standard-broadcast-band transmitters may use either vertically or horizontally polarized antennas with good results. Transmitters on frequencies lower than 500 kc usually have horizontal antennas, although the vertical-radiation component may be greater than the horizontal.

In the frequency ranges from 3 to 30 Mc, under certain conditions, and for a given transmission distance, vertical polarization may operate better than horizontal. Under other conditions, horizontal polarization may produce the better received signal.

For frequencies above 30 Mc, most communication transmissions are vertically polarized, with the exception of TV and FM.

Because of reflection from nonvertical objects, or because of ionosphere contour, the polarization of a ground or sky wave may twist out of its original position. Thus at times a vertically polarized wave may be received best on a horizontal antenna some distance away.

**20.7 The Half-wave Antenna.** The velocity of a radio wave is 300 million meters/sec. This is a little more than 186,000 miles/sec, or about 984 million ft/sec.

If a 1 million-cycle RF a-c is exciting an antenna, the radio wave from it will travel 300 meters in the time it takes the a-c to complete one cycle. A frequency of 1 Mc has a wavelength of 300 meters.

The wavelength of a radio wave, a sound wave, or any other wave varies inversely as the frequency and is determined by the basic formula

$$\lambda = \frac{v}{f}$$

where λ (lambda) is wavelength in whatever unit of length is used; $v$ is velocity of the wave in the unit of length used; and $f$ is the frequency in cycles per second (cps).

From this are derived three formulas often used in radio:

$$\lambda = \frac{300{,}000{,}000}{f} \qquad \lambda = \frac{300{,}000}{f_{kc}} \qquad \lambda = \frac{300}{f_{mc}}$$

where λ is the wavelength in meters; $f$ is the frequency in cycles per second; $f_{kc}$ is the frequency in kilocycles, and $f_{mc}$ is the frequency in megacycles; and 300 million is the velocity of the waves in meters per second.

If an antenna is used with a 1-Mc radio transmitter, the basic length of the antenna wire will be equal to *one-half* of the full 300-meter wavelength, or 150 meters (492 ft). With an antenna of this length excited by a 1-Mc RF a-c, electrons will have just enough time to reach the end of the wire as the source RF a-c reverses polarity. At no time will the natural period of electron oscillation be ahead of, or be behind, the phase of the exciting RF.

While this theory is basically correct, it neglects *end effect.* End effect must be considered with any single half-wave antenna. It may be considered to be a dielectric effect of the air at the end of the antenna that effectively lengthens it. The result of end effect is to make a half-wave antenna wire act as if it were about 5 per cent longer than it actually is. This will produce an interference between the exciting and the oscillating currents and a lessening of the oscillation amplitude, with a corresponding lessening of the radiated field. To overcome end effect it is necessary to cut the antenna to a physical length approximately 95 per cent of the electrically computed half-wavelength to make it resonate properly. For a 1-Mc RF a-c the half-wave antenna will be about 468 ft. The ratio of length in feet, end effect, and frequency holds close enough to set up a general formula to determine the length in feet of any half-wave antenna supported at the end by insulators. The formula is

$$\text{Length in feet} = \frac{468}{f_{mc}}$$

where the length in feet is for a half-wavelength antenna; and $f_{mc}$ is frequency in megacycles.

The length of a 7-Mc antenna is

$$\text{Length} = \frac{468}{f_{mc}} = \frac{468}{7} = 66.9 \text{ ft}$$

If the half-wave-antenna element is self-supporting at the middle and is without end insulators, the end effect is less. The factor 478 may be used in the formula above.

When an antenna is a full wave in length, it is composed of two half-waves, but there is still only one pair of end effects to consider. The total length of such an antenna is equal to one half-wave with end effect plus one half-wave without end effect. The number 492 is used in the formula to compute the half-wave *without* end effect.

To determine the length of a half-wave antenna for 1,100 kc:

$$\text{Length} = \frac{468}{f_{mc}} = \frac{468}{1.1} = 425 \text{ ft}$$

If the answer is desired in meters instead of feet, the wavelength formula can be used. The wavelength multiplied by 0.5 gives the half-wavelength. This multiplied by 0.95 gives the half-wave with end-effect correction.

$$\lambda = \frac{300}{f_{mc}} = \frac{300}{1.1} = 272.7 \text{ meters}$$
$$272.7(0.5)0.95 = 129.5 \text{ meters}$$

as the half-wavelength with end-effect correction

It is sometimes necessary to compute the length, in wavelengths, of an antenna to determine how to feed it.

*Example:* A 405-ft antenna is to be operated at 1,250 kc. What is its wavelength at this frequency? If one meter equals 3.28 ft, the length of the antenna in meters is 405/3.28, or 123.4 meters. The wavelength of 1.25 Mc is 300/1.25, or 240 meters. The ratio of 240 to 123.4 meters gives the decimal fraction of the wavelength of the antenna, or 123.4/240 equals 0.514 wavelength.

**20.8 The Quarter-wave Antenna.** The shortest antenna that will resonate by itself to any frequency is a half-wavelength at that frequency. If a quarter-wavelength wire is connected to a large conducting surface, such as the earth, the conducting surface will operate as the missing quarter-wavelength (or as a great many odd multiples of a quarter-wavelength), and current can oscillate in the antenna as if it were a half-wavelength long.

The end-effect correction for a quarter-wavelength antenna is also equal to 95 per cent of the electrically computed *quarter*-wavelength. However, since quarter-wavelength antennas usually are self-supporting and have no insulators at their tops, a more accurate end-effect correction is usually 97 per cent of the electrically computed quarter-wavelength.

**20.9 Hertz and Marconi Antennas.** Any antenna complete in itself and capable of self-oscillation, such as a half-wavelength or full wavelength, is known as a *Hertz*, or Hertzian, antenna.

When an antenna utilizes the ground (earth) as part of its resonant circuit, it is a Marconi antenna. An example of a Marconi antenna is a quarter-wavelength antenna, where the ground operates as the missing quarter-wavelength. Most long-wavelength, or low-frequency, antennas are Marconi types.

**20.10 Current and Voltage in a Half-wave Antenna.** A half-wavelength antenna excited by an RF a-c source produces an oscillation of the free electrons in the wire, at one instant charging one-half of the wire negative and the other positive. When the cycle reverses, the electrons move to the other end of the antenna, reversing the charges at the ends. Since the maximum number of electrons pile up at the ends, the maximum charge (voltage) always occurs at the far ends of the antenna.

When electrons move from one half of a half-wavelength antenna to the other, the greatest number must move past the mid-point of the wire. Therefore the center has the maximum current through it. Because the electrons that pile up at the end of the antenna do not move past the end, there is zero current at (through) the far end. Figure 20.4 illustrates the voltage and current relationships that exist on a half-wavelength antenna.

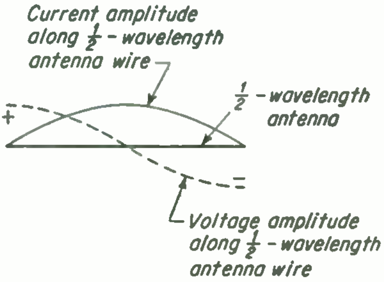


FIG. 20.4. Voltage and current distribution on a half-wavelength antenna.

The current distribution in a half-wavelength wire, if measured by inserting an ammeter at different points in the antenna, would be very nearly sinusoidal. If the voltage at different points could be conveniently measured, it would also vary in a sine-wave manner.

When the electrons pile up at the far ends, the voltage at the ends is at a maximum and the current is zero. When the current at the center reaches a maximum, the voltage difference between the ends is zero. This is the same $E$ and $I$ phase relationship that exists in any freely oscillating LC circuit.

Although shown on the same graph, the current and voltage maximums do not occur at the same time.

**20.11 The Radiation Resistance.** When an antenna is excited into oscillation, it radiates energy in the form of electrostatic and electromagnetic waves. As far as space is concerned, the antenna is acting as a source of power. Any source must have an internal resistance or impedance. If the radiated power is known, and the current maximum at the center of the antenna is known, the power formula $P = I^2R$ can be rearranged to read $R = P/I^2$. The resistance value computed is known as the *radiation resistance* of the antenna. The radiation resistance is the ratio of the radiated power to the square of the current flowing in the antenna.

$R_R$ $\frac{P}{I^2}$

There will always be some heat and dielectric losses in an antenna. The total of the resistance effect that causes these losses plus the radiation resistance is the *impedance* of the antenna.

The theoretical radiation resistance of a resonant half-wavelength antenna several wavelengths above a perfectly conducting ground is approximately 73 ohms. As the antenna is lowered toward the ground, the radiation resistance will vary up and down, but returns to 73 ohms at any multiple of a quarter-wavelength of height. It rises as high as 95 ohms when one-third-wavelength above ground, and drops as low as 58 ohms when about two-thirds-wavelength high. Below a quarter-wavelength in height the radiation resistance decreases down to zero when the antenna is on the ground.

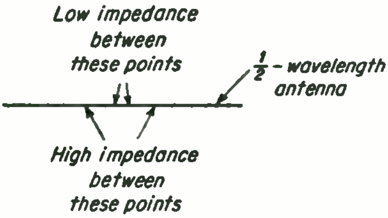


FIG. 20.5. The farther from the center of a half-wavelength antenna, the higher the impedance.

If a half-wavelength antenna is cut in two at the exact center, the two severed points of the antenna will act as a resistance load of 73 ohms (if a multiple of a quarter-wavelength in height). Connecting to the two severed points is a common means of coupling power to a transmitting antenna.

If the antenna is not cut, but two points equally spaced from the center are selected, there will be a resistive impedance value between the two points. If the points are close together, the impedance is low; if far apart, the impedance is high. The ends of a half-wavelength antenna are the points of maximum impedance, as illustrated in Fig. 20.5.

**20.12 Tuning the Half-wave Antenna.** To produce optimum operation of an antenna, it should be tuned to resonate at the frequency on which it is to operate. This tuning is accomplished, basically, by cutting the wire to the proper length, usually a half-wavelength. The shorter the wire, the higher its frequency of resonance.

If an antenna is shorter than desired, it can be cut apart and a *loading coil* inserted in series with it. The wire of the coil can be considered as being part of the required length of the antenna but coiled into a confined space. A short antenna may also be thought of as having too little inductance, and as a result too little inductive reactance. Since $X_L = X_C$ at resonance, the short antenna must have some capacitive reactance uncanceled by inductive reactance. To cancel out the capacitive reactance and attain resonance, inductive reactance in the form of a coil is needed.

When the antenna is longer than desired, the antenna can be cut apart and a capacitor inserted in series with it. An antenna longer than a half-wavelength appears as an inductive reactance to the frequency of operation. The addition of the proper-value capacitor in series with it cancels the excess inductive reactance, making the antenna resonant, and it acts as a pure resistance to the source.

If both the inductance and the capacitance inserted in the antenna are variable, it is possible to tune the antenna to resonance over a reasonably wide band of frequencies. Figure 20.6 shows three possible methods of tuning an antenna.

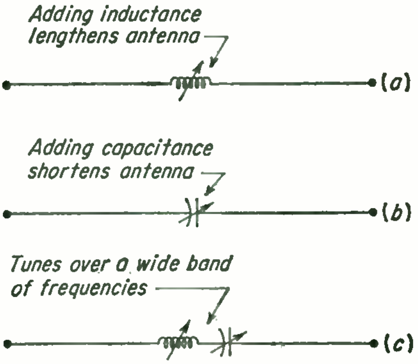


FIG. 20.6. (*a*) Adding inductance to an antenna lowers the resonant frequency. (*b*) Adding capacitance in series raises the resonant frequency. (*c*) Variable coil and capacitor allow the antenna to be tuned over a wide band of frequencies.

**20.13 Transmission Lines.** As in all phases of electricity, to produce maximum transference of energy from one circuit to another the impedance of the two circuits must match. An example of the impedance matching to produce maximum antenna current and radiation is illustrated in Fig. 20.7.

The impedance of the antenna $Z_a$ (73 ohms) must be matched by the *surge* impedance of the two-wire transmission line $Z_{TL}$, which must be matched by the impedance of the secondary of the output transformer $Z_s$, which must couple tight enough to reflect an impedance across the primary $Z_L$ that will equal the plate impedance of the tube $Z_p$. A variation of any part in this chain will prevent maximum output.

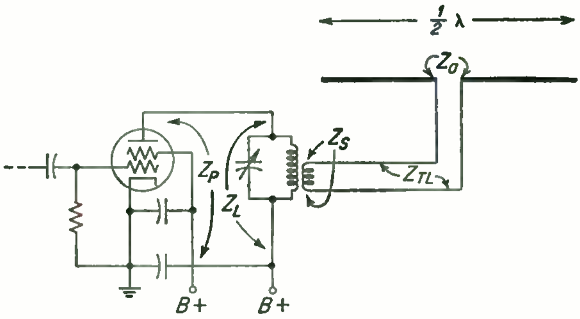


FIG. 20.7. Impedances that must be matched for maximum energy transfer to the antenna.

The two parallel wires are indicated as having a *surge* impedance. Any two parallel wires held apart a constant distance will have a *characteristic*, or surge, impedance value. This impedance is a function of the inductance and capacitance of the parallel wires. It may also be determined by the diameter of the wires and the distance of separation. It can be computed by the formula

$$Z = 276 \log \frac{d}{r}$$

where $Z$ is the impedance in ohms; $d$ is the center-to-center distance of separation of the conductors; and $r$ is the radius of the conductors (using the same unit of measurement as with $d$).

Two No. 14 wires, held 2 in. apart, center to center, form a transmission line with an impedance of 500 ohms. If the wires are thicker, the impedance is lower. If the distance of separation is increased, the impedance increases as the log of the ratio of $d/r$.

If a 500-ohm line is *infinitely* long and is connected across a source of a-c having 500 ohms impedance, maximum power will be taken from the source and dissipated along the line in the form of heat. No energy will return. If the line is a few yards long and is terminated with a 500-ohm resistor, essentially all the power from the source will be delivered to the resistor. Such a transmission line is an efficient method of carrying or transmitting energy from the source to a remote load, provided the transmission line has the proper impedance. A 300-ohm transmission line connected between a 500-ohm source and a 500-ohm load is a mismatch. The load will not draw the maximum power from the source.

When the transmission line does not match the load impedance, all the energy fed down the line does not flow into the load. Some is reflected back, forming *standing waves* on the line. Every half-wave along the line, high-voltage and low-current points appear. Halfway between the high-voltage points will be high-current low-voltage points. The ratio of *voltage* across the line at the high-voltage points to that at the low-voltage points is known as the *standing-wave ratio* (SWR). The SWR is also the ratio of the *current* values at the high and low points on the line. The standing-wave formula is

$$\text{SWR} = \frac{E_{\max}}{E_{\min}} \qquad \text{or} \qquad \text{SWR} = \frac{I_{\max}}{I_{\min}}$$

When the impedances at both ends match the line impedance, there are no standing waves. The current at all points in the line is the same, the SWR is 1:1, and the line is said to be *flat*.

If standing waves appear on a line that should be flat, it is necessary to either change the transmission-line impedance until it matches the antenna and/or change the input circuit until it matches the line. This is important if optimum transmission and reception are desired from an antenna.

Open-wire lines, spaced with insulators every few inches or feet, can be constructed to have impedances from about 150 to 800 ohms.

Some transmission lines for low-power transmitters and receivers use two spaced wires held apart by a ribbon of plastic material. An example of this is the 300-ohm twin lead used in most TV receiving antennas.

When lower impedances are required, coaxial, or "concentric," cables can be used. These may consist of a copper tube, as the outer conductor, and a copper wire, centered inside the tube with insulating beads, as the other conductor. A coaxial cable may consist of a copper wire covered with a plastic insulator, which in turn is covered with a braided copper outer conductor. Coaxial cables are manufactured with various impedances, usually ranging between 50 and 100 ohms.

Hollow coaxial cables have the advantage of having their working surfaces, the inner surface of the outer conductor and the outer surface of the inner conductor, protected from the weather. This prevents oxidation of the surfaces, which would change the skin resistance as well as the dielectric constant between them and alter the impedance of the line. To further prevent oxidation as well as keep a constant atmospheric pressure in the cable, it may be kept full of an inert gas, such as nitrogen, by a pressure tank. If the outer tubing of the cable springs a leak, the pressure forces gas out through the leak, preventing moisture-laden outside air from entering the cable. The loss of gas shows on the pressure gage and indicates trouble.

All discontinuities such as kinks, irregularities, or sharp bends in transmission lines produce slight changes in the impedance at these points and should be avoided.

Although not readily apparent with short, flat lines, when transmission of RF a-c over long lines is required, an attenuation of energy due to skin effect, radiation, and dielectric losses occurs. As a result, the value of current flowing into a long, flat transmission line at the transmitter end may be significantly more than at the antenna end.

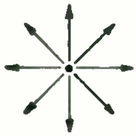


FIG. 20.8. Amplitude of radiation from a horizontal half-wavelength antenna in free space. End view of the wire.

FIG. 20.9. When near the ground, energy is reflected, changing the radiation pattern of the antenna.

**20.14 Directivity of Antennas.** The half-wavelength antenna radiates energy in a direction at right angles to the wire itself. As an example, a horizontal antenna running north and south radiates maximum energy east and west, as well as up into the sky and down toward the earth. If the antenna is suspended in free space, well above the earth, the radiation can be illustrated with vector arrows as in Fig. 20.8.

As the antenna is brought closer to ground, the wave striking the ground reflects back upward and outward, as shown in Fig. 20.9.

When the antenna is a half-wavelength above ground, the reflected wave travels to ground, reverses phase, is reflected upward, and reaches the antenna the equivalent of one wave later, but 180° out of phase. As a result the upward radiation is almost entirely canceled by the reflected wave. When all the vectors of all the angles from such an antenna are combined, the vertical radiation pattern of this antenna is as shown in Fig. 20.10.

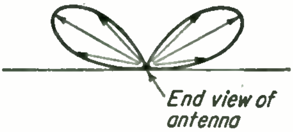


FIG. 20.10. Vertical radiation pattern of a horizontal antenna one half-wavelength above ground. End view of the wire.

The angle of *maximum* radiation is about 30° above the horizon for such an antenna. There is still a relatively strong wave being transmitted a few degrees above the horizon and up to more than 50°.

With the antenna only a quarter-wavelength above ground, the reflected wave returns in time and phase to add to the upward radiation. The result is a raising of the angle of maximum radiation as shown in Fig. 20.11.

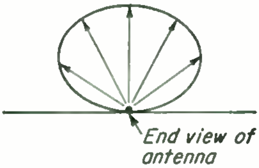


FIG. 20.11. Vertical radiation pattern of a horizontal antenna a quarter-wavelength above ground.

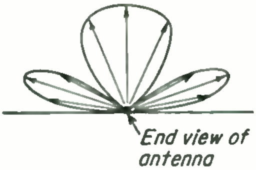


FIG. 20.12. Vertical radiation pattern of a horizontal antenna a three-quarter-wavelength above ground.

With the antenna three-quarters of a wavelength above ground, the reflected waves return in time and phase to add to the upward radiation and also to the outward radiation. The radiation pattern is then made up of three *lobes*, as shown in Fig. 20.12.

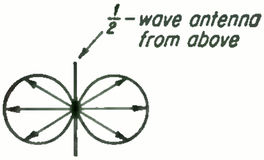


FIG. 20.13. Radiation from a half-wavelength antenna, as seen from above, or radiation from a vertical antenna in free space.

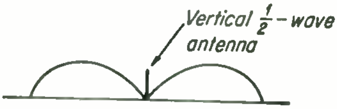


FIG. 20.14. Vertical radiation pattern of a half-wavelength vertical antenna near the ground.

In general, the higher the antenna, the more lobes will be developed.

When looking down on the horizontal half-wavelength antenna from above, the radiation pattern in the *horizontal* direction forms a *figure eight*, as shown in Fig. 20.13.

This shows maximum radiation at right angles to the wire and no radiation in the direction of the wire. The radiated-energy vectors form a *doughnut* around the wire if the antenna is suspended in free space. When the antenna is brought near a reflecting surface, the contour of the doughnut shape is flattened and changed into lobes in the horizontal direction.

A *vertical* half-wavelength will radiate equally well in all horizontal directions (Fig. 20.13) if there are no nearby objects to alter its field. The effect of bringing the antenna near ground is to raise the angle of maximum radiation, as indicated in Fig. 20.14, but has no effect on the circular horizontal radiation pattern (maximum in all directions). A vertical antenna is known as an *omnidirectional* (all-directional) antenna.

It will be noted that directly above the vertical antenna there is always a *cone of silence.* An airplane flying above a vertical transmitting antenna does not hear the station when directly over it. While there is a theoretical cone of silence at the ends of a horizontal half-wavelength antenna, in actual practice the reflected wave from the earth or nearby surfaces closes up the cone and some signal is received directly off the ends.

Summarizing, the radiation from a half-wavelength horizontal antenna, regardless of height, is maximum at right angles to the wire, with little or none off of the ends. The radiation from a vertical antenna is equal in all horizontal directions, but varies in the vertical direction.

**20.15 The Full-wave Antenna.** When the half-wavelength antenna is fed an a-c to which it is resonant, electrons oscillate back and forth along it. If the antenna is a full wavelength, electrons will move from both ends toward the middle during one-half of the excitation cycle, as indicated in Fig. 20.15. When the cycle reverses, the electrons travel from the middle toward the ends. In this way the maximum-voltage points appear at the middle and at the ends of the full-wavelength wire.

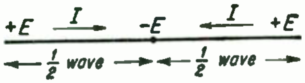


FIG. 20.15. The current flows in opposite directions in the two halves of a full-wavelength antenna at a given instant.

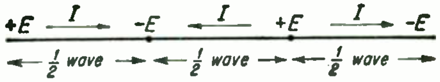


FIG. 20.16. Current and voltages in an antenna three half-wavelengths long, at a given instant.

A ½-, 1-, 1½-, 2-, 2½-, etc., wavelength wire will have maximum voltage points every half-wavelength. The electrons in adjacent half-waves are always traveling in *opposite* directions at any one instant, as indicated in Fig. 20.16.

The development of voltage maximums every half-wave is actually the development of standing waves on the antenna wire. This produces maximum current and maximum energy radiation. If the wires are not an exact multiple of a half-wavelength, lower-amplitude standing waves will be present and the antenna may be a less efficient radiator.

Since the full-wavelength antenna has equal current flowing in opposite directions at any one instant, the radiation from one of the half-waves exactly equals the radiation from the other. With the polarity of the two being 180° out of phase, the result is zero effective radiation at right angles to the wire. The horizontal-radiation pattern of a horizontal full-wavelength antenna is shown in Fig. 20.17. The angle of maximum radiation is approximately 45° from the direction of the wire.

With a 1½-wavelength antenna, two of the half-waves cancel the radiation of each other at right angles to the wire, leaving the third half-wave to radiate in this direction. As a result, the major lobes are depressed toward the wire, and the direction of maximum radiation tends to follow the wire, although there is a lobe at right angles to it. The more half-waves used, the more the maximum-radiation lobes are formed in the direction of the wire. When about four wavelengths long, an antenna is quite directional *in line with the wire* (Fig. 20.18). If the same antenna wire is used for different frequencies of operation, it will appear as having a different number of wavelengths, and therefore different directional characteristics on each frequency.

FIG. 20.17. Radiation pattern of a full-wavelength antenna, as seen from above it.

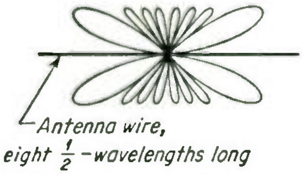


FIG. 20.18. Radiation pattern of an antenna four wavelengths long, as seen from above it.

**20.16 Feeding the Antenna.** There are many methods of feeding energy to an antenna from a transmitter. As previously mentioned, cutting a half-wavelength antenna in the middle and feeding it with a 73-ohm transmission line is a satisfactory method. This is known as *center-feeding*, or *current-feeding*, the antenna, since maximum current is present at the center of such a half-wave *dipole*.

If the antenna is a *full wave* in length and is cut in the middle, two points of high impedance are developed, usually having between 2,000 and 3,000 ohms impedance. Since a two-wire transmission line of more than 700 or 800 ohms is not too practical, such an antenna cannot be fed by matching it with a *flat* transmission line. Instead, a high impedance is developed on a transmission line by deliberately producing standing waves, and thereby high- and low-impedance points on it. Maximum standing waves are obtained when the transmission line is some multiple of a quarter-wavelength. If the transmission line feeding the center of a full-wave antenna is a multiple of a half-wavelength, it may be fed as shown in Fig. 20.19.

If cut to a multiple of a half-wavelength, a transmission line repeats its terminal impedance. In Fig. 20.19, starting at the far end of one of the half-wave radiators (a high-impedance point) and progressing toward the feed point, a point of low impedance appears at the center of each half-wave wire, and another high impedance appears at the feed point. Progressing down the transmission line a half-wavelength, another point of high impedance is reached. By connecting this high-impedance end of the transmission line across the relatively high impedance of a tuned antenna LC circuit, a satisfactory impedance match is produced and maximum current flows in the tuned transmission line and in the two half-wavelength antenna wires.

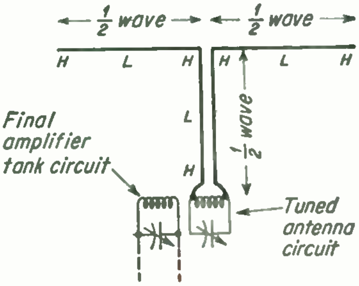


FIG. 20.19. Two half-wavelength antenna wires fed with a half-wavelength tuned feeder.

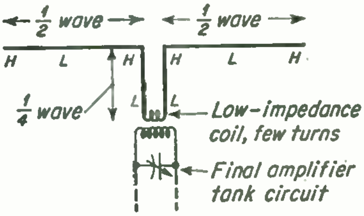


FIG. 20.20. Two half-wavelength antenna wires fed with a half-wavelength tuned feeder.

Starting at the center of the two half-wavelength radiators, but progressing down the transmission line only a quarter-wavelength (or any odd multiple of a quarter-wavelength), a point of *low* impedance is reached. The transmission line can be terminated at such a point. The low-impedance point can be connected to a few turns of wire (a low-impedance coil) inductively coupled to the tuned LC circuit of a transmitter, as shown in Fig. 20.20. The addition of the few turns to the transmission line adds inductive reactance to the circuit. A variable capacitor, not shown, may be added in series with the coil to balance out this inductive reactance.

A half-wavelength antenna may be end-fed by using a tuned feeder system as above, leaving one end of the feed line unconnected, as illustrated in Fig. 20.21. This is known as a *Zepp antenna.*

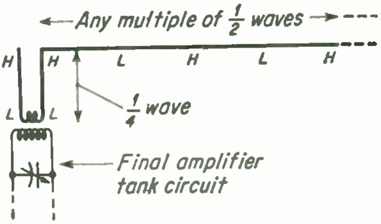


FIG. 20.21. Zepp antenna using a quarter-wavelength tuned feeder.

Another method used to feed an antenna is known as the *delta match* (Δ match). A flat transmission line, usually of 600 ohms impedance, is brought up to the center of a half-wavelength wire. To match the feed line to two points representing 600 ohms on the antenna, it is necessary to spread out the feeders at the antenna end, as shown in Fig. 20.22. The approximate ratio of lengths to match a 600-ohm line to a half-wave antenna is also shown.

Somewhat similar to the Δ match, a low-impedance coaxial line, 73 ohms, for example, will couple to an antenna by connecting the outer sheath of the cable to the center of the antenna and extending the inner conductor out to a point on the antenna equivalent to 73 ohms. This results in a slightly unbalanced *gamma-match* (Γ match) feed system. A better-balanced system can be produced by using two parallel coaxial lines, or a special coaxial cable having two inner conductors parallel to each other. This type of coupling is commonly termed a T match (Fig. 20.23). Capacitors should be added in series with the extended inner conductors to cancel their inductive reactance.

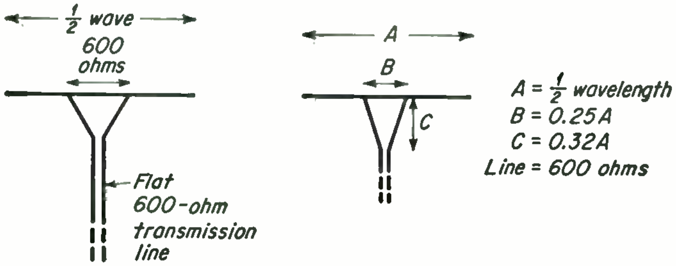


FIG. 20.22. Δ-fed half-wavelength antenna and ratio of dimensions to match a 600-ohm transmission line.

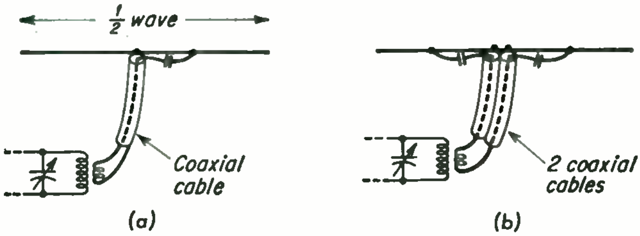
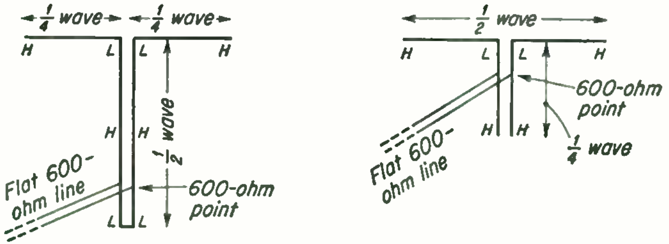


FIG. 20.23. (*a*) Coaxial transmission line forming a gamma match. (*b*) Two coaxial lines forming a T match.

A *shorted stub* or an *open stub* can be inserted in the middle of a half-wavelength antenna to act as an impedance-matching device for a flat transmission line. Figure 20.24 shows a half-wavelength shorted stub connected to a half-wavelength antenna. The low impedance of the center of the antenna is repeated as a low-impedance point at the shorted end of the half-wavelength stub. By connecting a 600-ohm flat transmission line at two points on the stub at which an impedance of 600 ohms appears, an excellent impedance match between transmission line and antenna system can be produced. A quarter-wavelength *open* stub can be utilized in a similar manner, as illustrated.

A flat transmission line can be tapped across two points on a half-wavelength open stub or a quarter-wavelength shorted stub that is connected to the *end* of an antenna. While a stub might be any multiple of quarter-wavelengths, the fewer quarter-wavelengths used, the less radiation from the feeder system.

The quarter-wavelength transmission line has another useful property. It can act as an impedance-matching device between a high- and low-impedance circuit if the line has the proper intermediate impedance.



(a) (b)

FIG. 20.24. Half-wavelength dipoles, center-fed with (a) a shorted half-wavelength shorted stub and (b) quarter-wavelength open stub, with flat lines coupled to the stubs.

This is illustrated in Fig. 20.25 where the 70-ohm center impedance of a half-wave antenna is coupled to a flat 600-ohm transmission line through a quarter-wave *transformer*. The required impedance of the quarter-wave section is found by the formula

$$Z_o = \sqrt{Z_1 Z_2} = \sqrt{70(600)} = \sqrt{42{,}000} = 205 \text{ ohms}$$

where $Z_o$ is the quarter-wavelength line impedance; $Z_1$ is the impedance connected across one end of the transformer; and $Z_2$ is the impedance at the other end of the line.

If a quarter-wave matching transformer is inserted between two *equal* impedances, it must have the same impedance and it becomes a flat transmission line with a 1:1 SWR.

Since there are no free ends on a quarter-wave matching transformer, there is no end effect and the length of the line is computed by the formula

$$L = \frac{246V}{F}$$

where $L$ is the length in feet; $F$ is the frequency in megacycles; and $V$ is the velocity factor of the transmission line.

When transmission lines are constructed of parallel wires with polyethylene insulation, or any other types of dielectric material between the conductors, the velocity of the wave traveling down the line is less than in free air. As a result, tuned transmission lines as well as matching transformer lengths must be multiplied

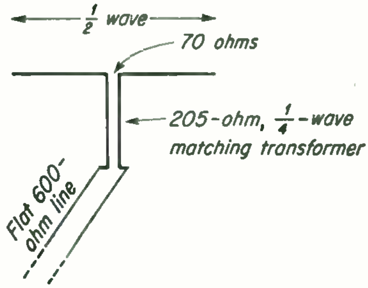


FIG. 20.25. A quarter-wavelength matching transformer.

by a *velocity factor* to produce the proper working lengths. Examples of some velocity factors are given in Table 20.1.

**Table 20.1**

| *Dielectric material between wires* | *Velocity factor* |
|---|---|
| Air-insulated parallel line | 0.975 |
| Air-insulated coaxial cable | 0.85 |
| Polyethylene parallel line (twin lead) | 0.82 |
| Polyethylene coaxial cable | 0.66 |

**20.17 Collinear Beam Antennas.** A shorted quarter-wavelength stub requires a half-wavelength of wire. The voltages at the open ends of a properly excited stub will be 180° out of phase. If the open ends of the stub are connected to two half-wave horizontal radiators (Fig. 20.26), the array is *not* a full-wave antenna but is *two half-waves in phase*, with the currents in both *radiating* half-wave elements in the same direction at any given instant. This forms a two-element beam antenna. It has a maximum radiation in the horizontal direction at right angles to the wire, as does a half-wave dipole, but the lobes are narrower and longer. A gain of a little more than twice the power, about 4 db, is produced in the direction of maximum radiation with the same power input to the antenna.

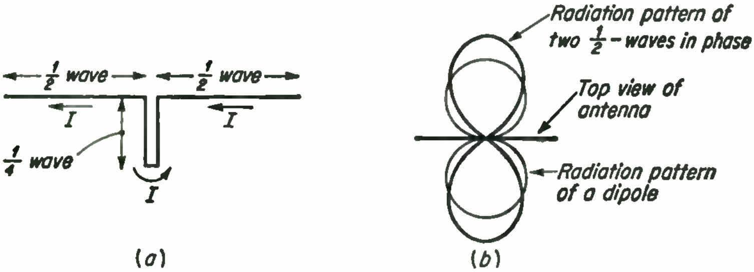


FIG. 20.26. (*a*) Collinear array, composed of two half-wavelengths in phase, and (*b*) comparison of its radiation pattern with that of a simple dipole.

This does not mean that more than twice the power is radiated. In practically all directions except at right angles to the antenna, the energy radiation is less than with a single half-wave radiator.

Two half-waves in phase can be fed with a flat transmission line tapped up on the stub, or tuned quarter- or half-wavelength feeders can be used, or the stub can act as a matching transformer.

Greater energy radiation in the desired direction can be obtained by adding more half-wave elements, each separated from adjacent elements by either a quarter-wave shorted stub, by half-wave open stubs, or any other means of changing the phase 180°, such as an LC circuit tuned to the frequency of operation. This makes up a *collinear*, or *Franklin*, antenna. It gives a gain whether used horizontally or vertically. When used vertically, its main advantage is in holding the radiation down, toward the horizon.

If collinear elements are connected in phase and it is desired to center-feed one of the half-wave elements, the center impedance is greater than 73 ohms, increasing to several hundred ohms with four or more elements.

**20.18 Driven Arrays.** The narrowing, or beaming, of the radiation lobe of a multielement array plus the increased energy radiated at right angles to an antenna are highly effective in producing strong signals at long distances. For reliable point-to-point communication, a beam antenna is highly desirable. For broadcast communication the omnidirectional vertical antenna may be more advantageous if it is desired to reach listeners in all directions. On the other hand, many broadcast stations are located on one side of a population concentration and require an antenna that will beam its signals toward the nearby city, and possibly put a minimum signal in some other direction.

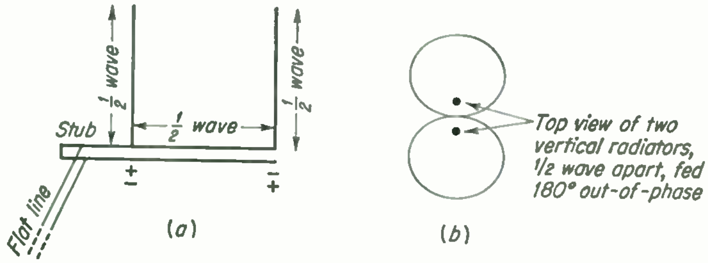


FIG. 20.27. (*a*) Two driven dipoles, fed 180° out of phase, and (*b*) radiation pattern.

There are several types of beam antennas used in broadcasting. Most of them consist of two or three vertical antennas so placed and fed, or *driven*, that their radiated signals reinforce each other in certain directions and cancel each other in others. An example of a two-element vertical beam is shown in Fig. 20.27.

The two half-wavelength vertical radiators are fed by a flat transmission line tapped into a shorted quarter-wave stub, with a half-wave open-wire tuned line between the bases of the two radiators. With the two radiators being fed 180° out of phase, the signal approaching you, the reader, from one antenna would cancel the signal from the other, resulting in zero radiation at right angles to the plane of the page. The radiated wave from the first antenna expands and follows the wave along the transmission line. As a result, the wave from the first antenna arrives in phase with the driven wave in the second antenna, and maximum signal is radiated in a line running through the two radiators. The radiation pattern, looking down on the vertical elements, is shown next to the array.

When the same two antennas are fed by a *transposed* feed line, as shown in Fig. 20.28, they are being fed in-phase signals. The signal approaching the reader is the sum of the two, or a stronger signal than would be radiated by a single antenna element. By the time the radiated wave from the first antenna reaches the second, it finds that the second antenna is being driven out of phase and there is zero signal transmitted in the plane of the page. The radiation pattern, looking down on the vertical elements, is shown next to the array.

It is also possible to feed quarter-wavelength or other length radiators in a somewhat similar manner. The more radiators fed in phase, the greater the gain of the system in the maximum signal directions and the less radiation in all other directions.

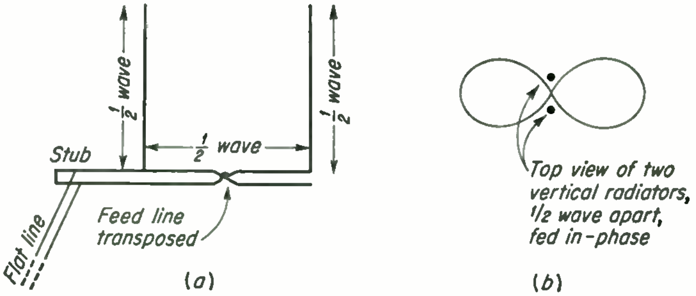


FIG. 20.28. (*a*) Two driven radiators, fed in phase, and (*b*) radiation pattern.

It is common to speak of the separation of two antennas in *degrees*. Two antennas separated by a full wavelength are said to be 360° apart. If separated by a half-wavelength they are 180° apart. Thus, two 950-kc antenna towers separated by 120° are a third-wavelength apart. The wavelength of 950 kc is $\lambda = v/f_{kc}$ or 300,000/950, or 316 meters. One-third of 316 meters is 105.3 meters. Since a meter is equal to 3.28 ft, the two towers are separated by approximately 345 ft.

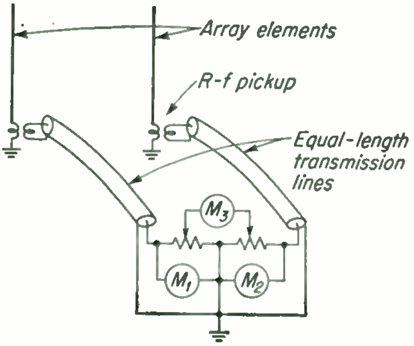


FIG. 20.29. Basic circuit of a phase monitor.

**20.19 Phase Monitors.** When there are two or more elements in a broadcast antenna array, it is necessary that the currents in the elements be maintained within 5 per cent of their licensed values. Two RF a-c sampling pickups may be installed in the base of the antennas with leads brought to meters at the operating position to provide a constant indication of the relative current amplitudes.

To determine the phase of the currents in the elements, a *phase monitor* is used. Basically, a phase monitor consists of coaxial lines of equal length bringing in a sampling of the voltages developed in the RF pickups in the elements, as indicated in Fig. 20.29.

If the *amplitude* of the two voltages fed to RF voltmeters $M_1$ and $M_2$ are adjusted to be equal, meter $M_3$ will read zero when the voltages from the antennas are in phase. The further the voltages are out of phase, the greater the difference of voltage across $M_3$ and the greater its deflection. This results in a direct indication of the phase difference between the two antennas.

It is also possible to utilize these sampling voltages to determine whether the antenna currents are being held within the licensed limits.

**20.20 Parasitic Arrays.** If a driven half-wavelength element is half-wavelength from another similar *undriven* element, as in Fig. 20.30, the second element has a voltage induced in it by the radiated field from the first and is said to be *parasitically excited.* The current that is induced in the parasitically excited element is out of phase with the wave from the first element that produces it (Lenz's law). The parasitic-element current produces a radiated wave that tends to cancel the originating wave, reducing the radiation in the plane of the page, but is in phase with the wave from the first antenna as far as the reader is concerned. Such an array will radiate at right angles to the plane of the page. Since the reradiated wave cannot be as strong as the driven wave, there is no complete null in any direction.

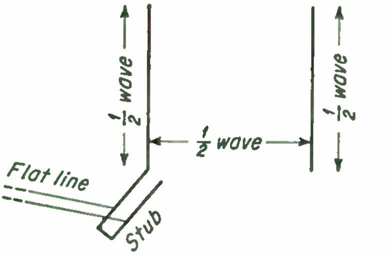


Fig. 20.30. A half-wavelength parasitic element spaced half-wavelength from a driven element.

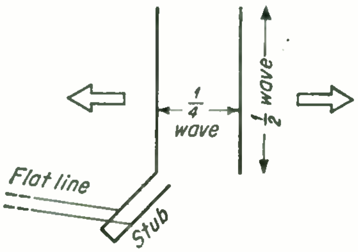


Fig. 20.31. A half-wavelength parasitic element spaced quarter-wavelength from a driven element. Maximum radiation as shown by arrows.

As the parasitically excited element is brought up to within a quarter-wavelength (90°) of the driven element (Fig. 20.31), it intercepts more energy and reradiates a stronger wave of its own. With a quarter-wave separation, the radiated wave travels 90° to the parasitic element, reverses phase 180°, and returns 90° to the driven element, arriving exactly in phase, and maximum signal is produced toward the left and right, as indicated by the arrows in the illustration.

The parasitic element is acting as a *reflector* and *director*, and the array has a gain of nearly 5 db in both *forward* and *backward* direction. The radiation to the sides (toward the reader) is materially reduced.

A parasitic reflector of one half-wavelength gives greatest forward gain when spaced about 0.2-wavelength from the driven element. The radiation resistance at the center of the driven element drops to about 40 ohms. The more elements used in parasitic arrays, the lower the center impedance falls.

If a parasitic element is half-wavelength long and is placed within about 0.1-wavelength of the driven element, the induced voltage and current relationship is such that it acts as a director more than as a reflector and produces nearly 6 db gain in the forward direction.

When the reflector is *tuned* for maximum forward gain (made about 5 per cent longer than a half-wavelength) and a director is also tuned for maximum forward gain (made about 5 per cent shorter than a half-wavelength), a *three-element Yagi* beam is produced. Such a beam antenna can have more than 8-db gain in the forward direction, with a 20-db difference between the forward and backward radiation strength. A delta-fed antenna of this type may be recognized as a popular TV receiving antenna (Fig. 20.32). When more forward gain is required, additional *director* elements may be added.

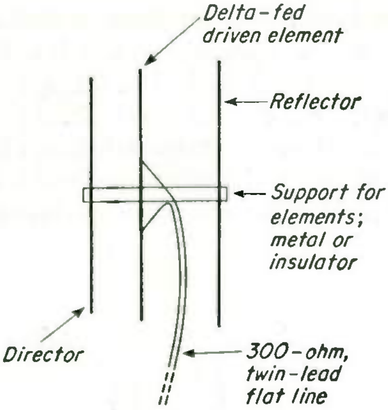


FIG. 20.32. A three-element Yagi, consisting of a driven element, a reflector, and a director.

The radiation resistance of close-spaced three-element Yagi antennas is approximately 10 ohms. This is somewhat difficult to center-feed, although it can be fed with a quarter-wave matching transformer, or with the delta-feed system shown. The driven element may be made into a *folded dipole*, which will raise its radiation resistance. Figure 20.33 illustrates a dipole and a folded dipole. The impedance at the open point of the folded dipole is four times what it would be if the upper wire were not added. With three wires, of if the second wire has twice the *surface area* of the first, the impedance will be nine times the impedance of the dipole.

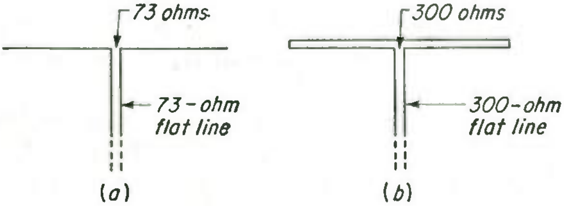


FIG. 20.33. (*a*) Center-fed dipole and (*b*) center-fed folded dipole.

By using two wires and by controlling the size of the upper one, almost any reasonable center impedance can be produced with a folded dipole.

**20.21 Long-wire Beams.** There are several types of long-wire-beam antennas. It has been pointed out that a wire several wavelengths long exhibits marked directional properties in the line of the wire. It is possible to utilize the lobes of such an antenna and form a *V beam*, as shown in Fig. 20.34.

Simplified lobes have been indicated on the two legs of the antenna. It can be seen that lobes 1 and *A* are in the same direction, as are 4 and *D*, resulting in a maximum radiation to the right and left on the page. Lobes 2 and *B* tend to cancel each other, as do lobes 3 and *C*, resulting in little radiation upward and downward on the page. Such a V beam has high gain in the forward *and* backward directions. The longer the legs, in number of wavelengths, the greater the gain. With twice the number of wavelengths there is roughly twice the power, or 3 db gain, in the direction of maximum radiation. This same rough approximation holds fairly true for the number of elements in a tuned array also.

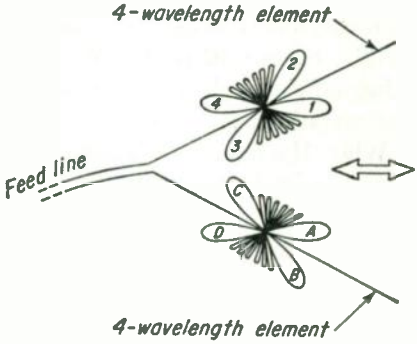


FIG. 20.34. Unterminated V-beam antenna, four wavelengths on a leg.

If desired, the backward radiation of a V beam can be effectively reduced without affecting the forward radiation by terminating the ends of the antenna with noninductive resistors to ground. These resistors must have approximately the impedance of the far end of the antenna, usually about 800 ohms. When terminated with resistance, the antenna becomes nonresonant and therefore not frequency-selective.

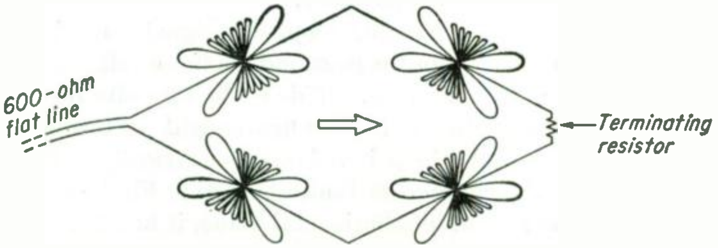


FIG. 20.35. Terminated rhombic-beam antenna, four wavelengths on a leg.

Another long-wire beam, called the *rhombic* (Fig. 20.35), is composed of four legs instead of the two of the V beam, but operates on the same general theory of addition and cancellation of lobes. It usually has more gain and cancels side radiation more effectively, and the resistance termination at the far ends tends to balance more evenly. As much as 15 or more db gain can be obtained with rhombic antennas. They are not resonant to one particular frequency when terminated, as are driven or parasitic arrays. One rhombic antenna may operate satisfactorily in one direction over a frequency range from 6 to 30 Mc, although the gain will vary at different frequencies.

Rhombic antennas are used extensively in high-frequency point-to-point communication systems throughout the world.

**20.22 Loop Antennas.** When speaking of *loop antennas*, the loop is usually considered as being a 1- to 3-ft vertically wound coil of wire, having a few closely wound turns. It may be round or square in shape. The loop coil forms the inductance of a resonant LC circuit, as shown in Fig. 20.36. Such a loop antenna is rarely used for transmitting, as its radiating efficiency is rather low, but it finds use as a receiving antenna because of the sharp *nulls* (zero signals) produced.

When the capacitor is adjusted to resonate the loop circuit to the frequency of a local station, radio waves passing across the loop induce a voltage in it. If the loop is rotated 360°, there will be two points where little or no voltage is induced in it and intermediate points where a maximum signal voltage is produced. The horizontal-plane reception pattern for a loop antenna is shown in Fig. 20.37.

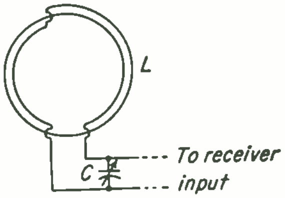


FIG. 20.36. A small loop antenna forms the inductance of a tuned circuit.

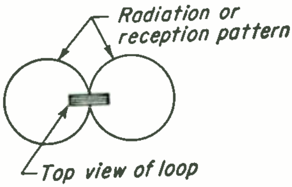


FIG. 20.37. Radiation or reception pattern of a small loop antenna as seen from above.

As we look down on the top of this loop, zero signal is received from a station at the top and bottom of the page and maximum signal from a station at the left or right of the loop. This is the opposite field-strength pattern of a half-wavelength wire. The figure-eight pattern of the loop can be nearly perfect if the loop is balanced electrically. This is discussed more fully in the chapter on Radio Direction Finders.

If the loop antenna is held in a horizontal plane, it becomes omnidirectional, receiving equally well in all directions.

When a loop antenna is used for transmitting, its circumference should be a major portion of a wavelength of the frequency used. As the diameter approaches one wavelength, the maximum lobes are no longer in the line of the loop but break up into four lobes (Fig. 20.38), each falling toward the null direction. As the diameter is further increased, the loop becomes many-lobed, with maximum response at nearly right angles to the loop. This is quite different from the reception pattern of a small-diameter resonant loop.

When the sides of a square loop are quarter-wavelength each, as shown in Fig. 20.39, the loop acts as two quarter-waves in phase, radiating and receiving maximum at right angles to the wires of the loop, with the vertical currents canceling each other. The loop is shown as center-fed with a low-impedance line. If fed with a high-impedance line and opened at the top, it will result in a vertically polarized radiation with the horizontal currents canceling. Such a loop is bidirectional (two-directional) but may be made more unidirectional (one-directional) by using parasitic reflectors behind it or directors in front of it.

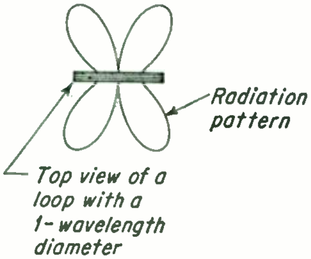


Fig. 20.38. Radiation pattern of loop antenna having a diameter of approximately one wavelength.

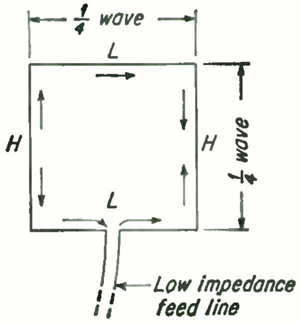


Fig. 20.39. Current flow in a center-fed loop having quarter-wavelength sides, at a given instant.

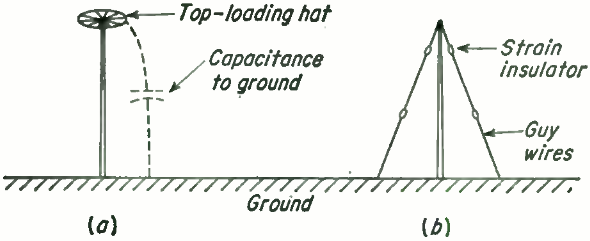


Fig. 20.40. Top-loading a vertical antenna by (a) using a hat and (b) using the top of the guy wires.

**20.23 Lower-frequency Antennas.** Low-frequency (30–300-kc) antennas are usually quarter-wave Marconi types because of their required length.

In the medium-frequency range (300–3,000 kc) it becomes practical to use quarter- to half-wavelength vertical antennas. At the low-frequency end of the broadcast band, approximately 600 kc, the antennas become quite long, and it is often desirable to *top-load* them. Top loading may take the form of a light, wire, wheellike *hat* structure attached to the top of the antenna. This hat increases the length of the antenna out to the edge of the hat and materially increases the capacitance between the top end of the antenna and ground. As a result of the increased length, or inductance, and the increased capacitance, a short antenna can be made to resonate at a relatively low frequency.

Top loading may also be produced by using the top portion of the antenna guy wires as the top hat, as shown in Fig. 20.40. The antenna strain insulators used in this type of work are preferably a glazed-surface porcelain. A hard glossy surface tends to discourage the accumulation of dirt, and thereby reduce losses across the insulators. In areas near salt water, any encrustation may have relatively high conductance and produce unwanted leakage as well as corona effect on any insulators.

In all these antennas, a good ground is important. The best ground system consists of copper-wire radials buried in the ground and radiating from the base of the antenna.

**20.24 Feeding Lower-frequency Antennas.** Most lower-frequency antennas are cut to resonate as quarter-wave antennas and are grounded at the base. If they are approximately half-wavelength, they are insulated from the ground at the base.

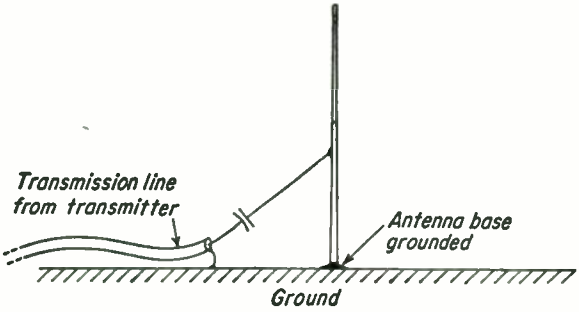


FIG. 20.41. A half-Δ-fed quarter-wavelength vertical antenna.

If the vertical antenna is grounded at the bottom, it can be fed by a half-delta-type system (shunt-fed) to match the impedance of the transmission line to the antenna, as shown in Fig. 20.41.

Between the bottom of any single conductor-type antenna and ground there will be some impedance value. (There may or may not be a reactive component present.) It is necessary to match whatever impedance is developed with a similar impedance transmission line. If the transmission line is not of the proper impedance, a quarter-wave matching transformer or some other impedance-matching device must be used. Figure 20.42 illustrates a $\pi$ (*pi*) *network* that may be used to couple unmatched impedances. The inductance of $L$ and the capacitances of $C_1$ and $C_2$ plus the circuit constants of the antenna and transmission line form a resonant circuit at the transmitting frequency. The lower the capacitance of $C_1$ or $C_2$, the higher the impedance developed across them. By proper adjustment of $L$, $C_1$, and $C_2$, the required impedance match may be produced and maximum current will flow in the antenna.

The $\pi$ network is a low-pass filter and tends to discriminate against the transference of harmonic energy to the antenna when properly tuned.

However, if it is found that harmonic energy is being radiated and interfering with other services, several steps may be taken. If a single harmonic is causing trouble, a series-resonant wavetrap tuned to the undesired harmonic can be connected between antenna and ground. A shorted stub cut to quarter-wavelength of the transmitting frequency represents a very high impedance across its open ends to its resonant frequency and all odd harmonics, but a very low impedance to all *even*-order harmonic frequencies. The shorted stub can be connected across the output of the transmission line or from the bottom of the antenna to ground. It also serves as a low-resistance path to ground for any atmospheric static charges collected by the antenna. Another means of decreasing harmonic radiation is a low-pass filter in the transmission line as discussed in the chapter on Basic Transmitters.

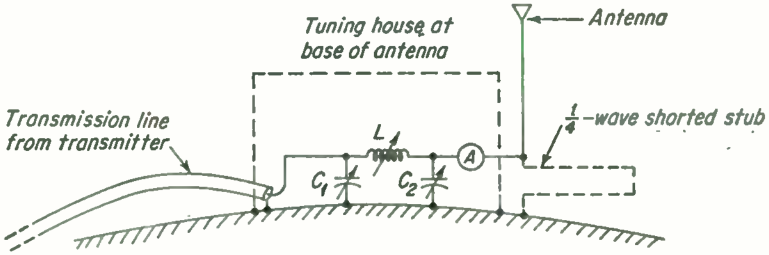


FIG. 20.42. π-network coupling (tuning) device to match the feed line to the bottom end of the antenna. A quarter-wavelength shorted stub tuned to the fundamental frequency is shown in broken lines.

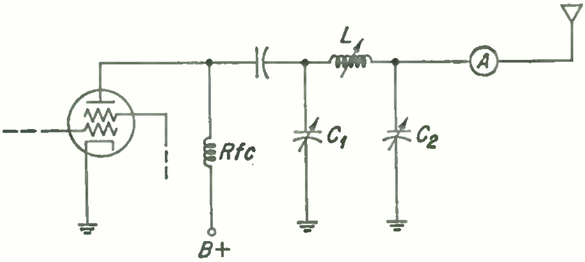


FIG. 20.43. π-network coupling circuit to match tube and antenna impedances.

The π network is often used as the plate-circuit tuning device of an RF amplifier and is connected as shown in Fig. 20.43. $L$, $C_1$, and $C_2$ resonate at the frequency of transmission. The base impedance of the antenna must match the impedance across $C_2$. The impedance of the plate circuit of the amplifier tube must match the impedance across $C_1$. $L$ must be the correct inductance to produce resonance in the circuit when $C_1$ and $C_2$ are adjusted to the proper capacitances. This adjustment will produce maximum output from the stage. If $C_2$ has more capacitance than the optimum value, the impedance across it will be smaller, resulting in a lower voltage drop across it, the antenna will have less excitation, less current will flow in it, and it will radiate less. $C_1$ and $L$ may be readjusted, but less output will still result. The degree of coupling to the antenna is effectively lessened by increasing $C_2$.

On the other hand, if $C_2$ is decreased in capacitance, the circuit can be brought back to resonance by adjusting $L$ and $C_1$, but the impedance across $C_1$ is now lower than the tube impedance and less power will be fed to the antenna, although the internal loss in the tube (plate dissipation) and the minimum plate current will increase. The coupling has been increased past the optimum value.

A *T network* can also be used as a coupling method from a transmission line to an antenna, as shown in Fig. 20.44. This is also a low-pass type of filter circuit and will discriminate against harmonic transmission.

In this circuit the capacitor $C$ is a common coupling factor between the transmission line and the antenna. When properly adjusted, the impedance across $L_1$ and $C$ equals the impedance of the transmission line, and the impedance across $L_2$ and $C$ equals the base impedance of the antenna.

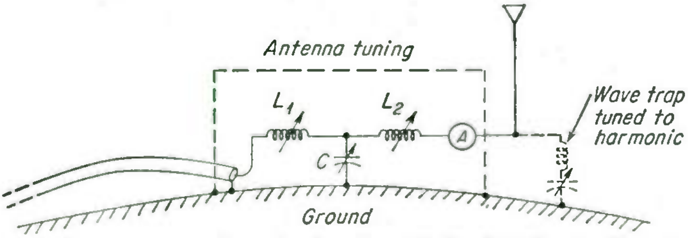


FIG. 20.44. A T-network coupling circuit to match the feed line to the antenna. A wavetrap tuned to a harmonic frequency is shown in broken lines.

Increasing the capacitance of $C$ decreases the coupling between transmission line and antenna. This same circuit may be used to couple the plate circuit of a tube to an antenna. A series wavetrap from antenna to ground, shown in broken lines, can be used to decrease radiation of any harmonic to which it is tuned. A parallel-tuned wavetrap in series with the antenna wire may also be used.

**20.25 Lightning and the Antenna.** An antenna extending high into the air is susceptible to lightning. If it is grounded at the base, the electricity drains to ground and the transmitter is not damaged. If the base of the antenna is ungrounded, lightning may travel to ground through the antenna coils and the transmission line. Between the base and ground, a lightning gap may be installed. This gap is sufficiently wide not to arc with the voltages built up by the transmitter, but will break down and arc with the high voltage of a lightning bolt, protecting the transmission line and antenna coils from excessive current flow. To prevent the antenna ammeter from burning out, a shorting switch may be connected across it.

If an antenna has no d-c connection to ground, a static charge of many thousands of volts may build up on it during certain types of weather and it will arc over intermittently. This is particularly undesirable in a receiver, as such arcing will produce intolerable interference. To relieve this potential, a resistance of a few thousand ohms can be connected between a low-impedance point on the transmission line and ground, through which the static charge can leak off but through which little RF a-c will flow.

When a shorted quarter-wave stub is connected from the base of an ungrounded antenna to ground, it forms a protection for lightning without affecting the signal for which the antenna is tuned.

An antenna-grounding switch may be used. This grounds the antenna, interrupting communications during the storm, but protects the equipment and station personnel.

**20.26 Field Intensity.** To measure the received strength of a radio signal at a certain point in space, the voltage developed in a 1-meter-long wire is considered as the standard. *Field intensity* is therefore measured in received *volts per meter*. Since only a small fraction of a volt will be induced in a remote wire, it is more usual to express the field intensity in either millivolts or microvolts per meter. Thus, if a wire 3 meters long has 0.001 volt induced in it by a certain signal, the field intensity is 0.001/3, or 0.000333 volt/meter, or 0.333 mv/meter, or 333 $\mu$v/meter.

The *effective height* of an antenna can be expressed in meters if the voltage induced in it is known and if the field intensity in which it is erected is known. If the field intensity is known to be 25 mv/meter and 2.7 volts is induced in it, the effective height is 2.7/0.025, or 108 meters.

The field strength of a transmitted signal is dependent on ground, direct, and reflected signals, refracted sky waves, and the directivity of the transmitting antenna. As a result it will vary at different times of the day unless the path is very short.

The ground wave over sea water decreases almost inversely as the distance from the station, particularly in the low- and medium-frequency ranges. If the field strength at 10 miles is 50 mv/meter, at 20 miles the field strength will be only slightly less than 25 mv/meter. As the distance from the station increases to more than 100 miles, the signal decreases more than in a simple inverse proportion. At higher frequencies the signal decreases still more than in the simple inverse proportion.

Because power is proportional to both current squared and to voltage squared ($P = I^2R$ and also $= E^2/R$), twice the current in an antenna represents *four* times the power. Similarly, twice the voltage represents four times the power. If 1,000 watts in an antenna produces 10 mv/meter in a remote antenna, 4,000 watts will produce 20 mv/meter, or twice the field intensity. If the field strength is found to double at a remote point, it indicates that the power in the transmitting antenna has quadrupled (increased 6 db). This is produced by doubling both the antenna current and the antenna voltage. (No fading is assumed.)

When the power in an antenna is doubled, the voltage in it (and therefore the field intensity produced by it) is increased by the square root of 2, or by 1.414. If 1,000 watts in a transmitting antenna can produce 3 mv/meter in an antenna, 2,000 watts in the same antenna will produce 3(1.414), or 4.24 mv/meter. If twice the power represents 3 db, 1.414 times the voltage (or current) also represents 3 db. If the antenna power is lowered to 1,000 watts again, the field intensity will decrease to 0.707 (reciprocal of 1.414) of 4.24, or to 70.7 per cent.

**20.27 Field Intensity of Harmonics.** The field intensity of a harmonic radiation from a transmitter is usually measured in microvolts per meter. The difference between the field intensity of the fundamental and the harmonic is usually expressed in logarithmic relationships, called *decibels* (Sec. 8.6). A ratio of either 10 times, or 1/10, the voltage = 20 db. Twice, or 1/2, the voltage is a ratio represented by 6 db. If the harmonic-field intensity is 1/10 the intensity of the fundamental, it is *20 db down.* If the harmonic is 1/200 of the fundamental, how many db down is it? One-tenth of 200, or 20, equals −20 db. One-tenth of 20, or 2, equals another −20 db. One-half of 2 equals 1 (or unity), which equals −6 db (approximately). Therefore, the harmonic is −20, −20, and −6 db, or −46 db below the fundamental.

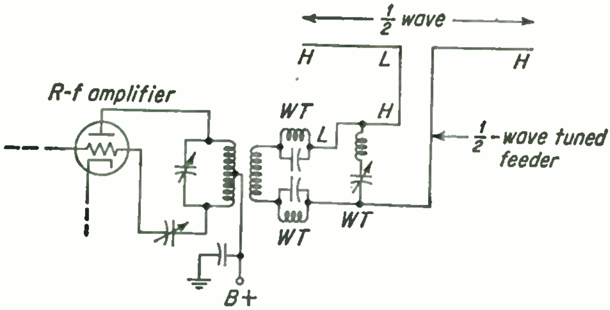


FIG. 20.45. Coupling of a Hertzian antenna to a final amplifier with wavetraps to attenuate harmonic radiation.

If the fundamental is 147 mv/meter and the harmonic is measured as 405 μv/meter, the *voltage* ratio between the two is 0.147/0.000405, or 363:1. One-tenth of this is 36.3 and represents a loss of −20 db. One-tenth of 36.3 is 3.63, which represents another loss of −20 db. One-half of 3.63 is 1.815, which represents −6 db. One-half of 1.815 is 0.908 and another −6 db. However, this has brought the ratio below unity, or 1:1. The total loss represented is −20, −20, −6, and −6, or −52 db. Since this has gone down too far, the approximate loss must be about −51 db. The exact number of decibels can be computed from the formula

$$\text{db} = 20 \log 363 = 20(2.56) = 51.2 \text{ db}$$

Because of the characteristics of transmission of different frequencies at the same time of day, a harmonic signal from a transmitter, if not sufficiently attenuated, may have a greater field intensity at a distant location than does the fundamental and may interfere with other radio services when the fundamental cannot be heard at all by these other services. Thus, a 5-Mc transmitter may not be heard 1,000 miles away during the daytime, but an unattenuated harmonic of 10 Mc may be quite appreciable at that distance.

There are many methods of decreasing harmonic radiation, discussed in Sec. 15.25. Figure 20.45 illustrates how parallel wavetraps can be connected in an antenna transmission line to attenuate any harmonics to which they are tuned. A series wavetrap connected across the transmission line at any point will effectively decrease radiation of the frequency to which it is tuned.

**20.28 Field Gain.** Multielement transmitting antennas may be rated in *field gain*. If a multielement transmitting antenna produces a 500 mv/meter signal in a remote receiving antenna, whereas a simple dipole transmitting antenna will only produce a 250 mv/meter signal, the field gain of the multielement antenna is 2. (A field gain of 2 indicates a voltage gain of 2, power gain of 4, or a 6-db gain.)

The *effective radiated power*, abbreviated erp, of an FM or TV transmitter considers the field gain of the antenna.

*Example:* A transmitter has a 370-watt input to a class C final amplifier operating at 65 per cent efficiency. Therefore the output power fed to the antenna feed line is 240.5 watts. If the transmission line delivering the RF power to the antenna radiating elements is 75 per cent efficient, there are 240.5 × 75 per cent, or 180.4 watts being radiated. Since the field gain is expressed in voltage, and power is proportional to voltage *squared*, with an antenna having a field gain of 1.3, the erp is $180.4 \times 1.3^2$, or 304.9 watts.

A beam antenna may be rated in *power gain*.

*Example:* The output of a transmitter is 1,000 watts. The antenna transmission-line loss is 50 watts. With a power gain of 3, the antenna has an erp of 3(950), or 2,850 watts.

**20.29 The Ground.** The surface of the earth directly below and surrounding an antenna is known as the *ground*. With Marconi antennas the ground is used as one-half of the antenna and is obviously important. With self-resonant Hertzian antennas operated high above the earth, the ground may play a slightly less important role. However, for both types of antennas the ground acts as a reflector of both transmitted and received waves and is responsible for some portion of the total transmitted and received wave amplitude.

The best ground would be a silver sheet extending out several wavelengths in all directions under the antenna. While this is not practical, it is possible to lay metallic screens on or just below the surface of the earth and form an excellent ground. In many cases, a network of copper wires is laid on or under the ground, fanning outward. Each wire is separated from the next by 5 to 15° of arc and is at least a quarter-wavelength long. If some of these ground radials are broken off, the tuning of the antenna will change, as will the radiation resistance and the directivity of the radiation pattern.

Without such an artificial ground, the actual or virtual ground may vary from a few inches below the surface of a moist salt marsh to several feet below the surface of a dry sandy soil. Because an antenna is erected a quarter-wave above ground physically does not mean that it is operating effectively at that height.

**20.30 Computing the Power in an Antenna.** When an antenna is tuned properly, it may be considered to be a resistance. It does not exhibit either capacitive or inductive reactance to the feed line. As a result, the power, voltage, current, and resistance in a tuned antenna can be computed by the Ohm's-law and power formulas. For example, if the resistance and the current at the base of a Marconi antenna are known, the power in, and assumably radiated by, the antenna can be found by using the power formula

$$P = I^2R$$

where $P$ is in watts; $R$ is the radiation resistance; and $I$ is the current in amperes *in the antenna where radiation or feed point resistance is measured.* Actually some of this power is lost in heat in the antenna conductor itself.

This and other power formulas can be rearranged to find the unknown as in the following examples.

The surge impedance of a flat transmission line is 500 ohms and has a current of 3 amp flowing in it. The power being fed to the antenna is

$$P = I^2R = 3^2 \times 500 = 4{,}500 \text{ watts}$$

If the daytime power in a broadcast-station antenna is 2,000 watts and the antenna has a resistance of 20 ohms, the current is

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{2{,}000}{20}} = 10 \text{ amp}$$

If the antenna current of this antenna is cut in half for nighttime operation, the transmitter has an antenna power of

$$P = I^2R = 5^2 \times 20 = 500 \text{ watts}$$

A 72-ohm concentric line with an input of 5,000 watts has a current flowing in it equal to

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{5{,}000}{72}} = \sqrt{69.4} = 8.34 \text{ amp}$$

The antenna current when a transmitter is delivering 900 watts into an antenna having a resistance of 16 ohms is

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{900}{16}} = \sqrt{56.3} = 7.5 \text{ amp}$$

If the antenna current of a station is 9.7 amp for 5,000 watts, the antenna resistance is

$$R = \frac{P}{I^2} = \frac{5{,}000}{94.1} = 53.1 \text{ ohms}$$

If this same station wishes to transmit only 1,000 watts, the antenna current should read

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{1{,}000}{53.1}} = \sqrt{18.8} = 4.34 \text{ amp}$$

If the daytime transmission-line current of a 10,000-watt transmitter is 12 amp, the line impedance is

$$R = \frac{P}{I^2} = \frac{10{,}000}{144} = 69.4 \text{ ohms}$$

If it is required to reduce to 5,000 watts at sunset, the new value of transmission-line current is

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{5{,}000}{69.4}} = 8.5 \text{ amp}$$

A 72-ohm concentric transmission line is carrying 5,000 watts. The rms voltage between the inner conductor and the sheath is

$$E = \sqrt{PR} = \sqrt{5{,}000(72)} = \sqrt{360{,}000} = 600 \text{ volts}$$

Since the radiated power of an antenna is directly proportional to the antenna current *squared*, if the antenna current is doubled, the power is increased $2^2$, or 4 times. If the current is increased 2.77 times, the power increases $(2.77)^2$, or 7.67 times.

A long flat transmission line delivers 10,000 watts at 4.8 amp. The impedance of the line is

$$R = \frac{P}{I^2} = \frac{10{,}000}{(4.8)^2} = 435 \text{ ohms}$$

If the current fed into this transmission line is 5 amp, the power fed into it is

$$P = I^2R = 5^2(435) = 10{,}875 \text{ watts}$$

With 10,875 watts delivered into the transmission line and 10,000 watts output, there must be 875 watts lost in the line itself.

When the antenna resistance and current are known, the output power of a transmitter can be determined. If the plate current and voltage are known, the input power can be determined. From these two values the percentage of efficiency of the amplifier (and antenna-coupling circuit) can be determined.

*Example:* If the d-c input is 1,500 volts and 0.7 amp, the power input to the final amplifier is 1,050 watts. If the antenna current is 9 amp and the antenna resistance is 8.2 ohms, the antenna power is

$$P = I^2R = 9^2(8.2) = 664 \text{ watts}$$

The efficiency is determined by output/input, or 664/1,050, or 0.632. Multiplying by 100, the coefficient is changed to percentage, or 63.2 per cent.

**20.31 Omnidirectional Antennas.** It has been mentioned that the vertical antenna is omnidirectional (all-directional) in the horizontal plane, with vertical polarization.

TV and FM transmissions are required to be horizontally polarized. Transmitting antennas for these services should transmit equally well in all directions and have a *horizontal* polarization.

The horizontal half-wave dipole transmits a two-lobed horizontal pattern, with nulls off the ends of the antenna. By bending a dipole into a horizontal circle, the antenna exhibits less directional properties but is not a true omnidirectional antenna.

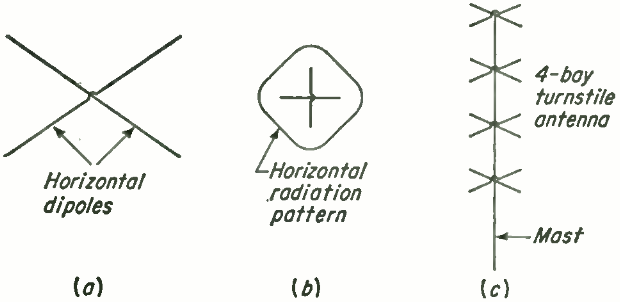


FIG. 20.46. (a) Single-bay turnstile antenna. (b) Horizontal radiation pattern of a turnstile antenna. (c) A four-bay turnstile, feed lines not shown.

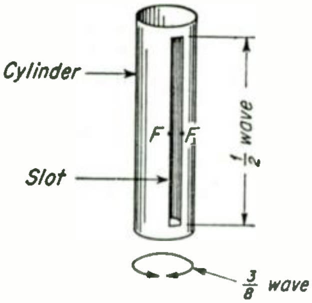


FIG. 20.47. A slotted-cylinder antenna produces horizontally polarized radiation.

If two half-wave dipoles are arranged to form a horizontal X, as shown in Fig. 20.46, and the two antennas are fed 90° out of phase, the resultant horizontally polarized radiation pattern roughly approximates a circle. The two antennas can be fed 90° out of phase by using a transmission line 90° (quarter-wave) longer for one than is used for the other. This forms a basic *turnstile*-type antenna. For greater gain, turnstile antennas are usually stacked with two or more *bays*, one above the other, as shown.

Another omnidirectional antenna is the slotted cylinder. It consists of a metal cylinder longer than a half-wavelength, with a vertical half-wave slot cut out of it. The slot is fed with a coaxial transmission line at the points marked *F* in Fig. 20.47. When a cylinder about ⅜-wavelength in circumference is used, current flows from one side of the slot to the other, around the outside of the cylinder, producing an omnidirectional pattern. If the circumference is greater than a half-wave, the antenna becomes directional with maximum radiation from the slotted side of the cylinder.

Other omnidirectional antennas are forms of horizontal loop antennas, in which the loop is broken up into three or four segments. Each segment is formed from a major portion of a dipole. Each dipole is fed so that the current flow is in the same direction in all segments at the same time.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** What is horizontal and vertical polarization of a radio wave? (20.6) **[3]**

**2.** How should a transmitting antenna be designed if a vertically polarized wave is to be radiated, and how should the receiving antenna be designed for best performance in receiving the ground wave from this transmitting antenna? (20.6) **[3]**

**3.** What is the formula for determining the wavelength when the frequency, in kilocycles, is known? (20.7) **[3]**

**4.** What is meant by the term radiation resistance? (20.11) **[3]**

**5.** Draw a simple schematic diagram of a system of coupling a single electron tube employed as an RF amplifier to a Hertz-type antenna. (20.13) **[3]**

**6.** Show by a diagram how a two-wire RF transmission line may be connected to feed a Hertz antenna. (20.16) **[3]**

**7.** A ship radiotelephone transmitter operates on 2,738 kc. At a certain point distant from the transmitter the 2,738-kc signal has a measured field of 147 mv/meter. The second harmonic field at the same point is measured as 405 $\mu$v meter. To the nearest whole unit in decibels, how much has the harmonic emission been attenuated below the 2,738-kc fundamental? (20.27) **[3]**

**8.** What are the lowest frequencies useful in radio communication? (20.1) **[3 & 6]**

**9.** What effect do sunspots and the aurora borealis have on radio communications? (20.2) **[3 & 6]**

**10.** What radio frequencies are useful for long-distance communications requiring continuous operation? (20.4) **[3 & 6]**

**11.** What frequencies have substantially straight-line propagation characteristics analogous to that of light waves and are unaffected by the ionosphere? (20.4) **[3 & 6]**

**12.** In general, what advantages may be expected from the use of high frequencies in radio communication? (20.4, 20.5) **[3 & 6]**

**13.** Describe the various directional characteristics of a horizontal Hertz antenna. (20.14) **[3 & 6]**

**14.** Describe the various directional characteristics of a vertical Hertz antenna. (20.14) **[3 & 6]**

**15.** Describe the various directional characteristics of a vertical Marconi antenna. (20.14) **[3 & 6]**

**16.** Describe the various directional characteristics of a vertical loop antenna. (20.22) **[3 & 6]**

**17.** Describe the various directional characteristics of a horizontal loop antenna. (20.22) **[3 & 6]**

**18.** Draw a simple schematic diagram showing a method of coupling the RF output of the final power-amplifier stage of a transmitter to a two-wire transmission line, with a method of suppression of second- and third-harmonic energy. (20.2) [4]

**19.** What must be the height of a vertical radiator half-wave length high if the operating frequency is 1,100 kc? (20.27) [4]

**20.** If a vertical antenna is 405 ft high and is operated at 1,250 kc, what is its physical height, expressed in wavelengths? (One meter equals 3.28 ft.) (20.7) [4]

**21.** What is the ratio between the currents at the opposite ends of a transmission line a quarter-wavelength long and terminated in an impedance equal to its surge impedance? (20.13) [4]

**22.** What is the primary reason for terminating a transmission line in an impedance equal to the characteristic impedance of the line? (20.13) [4]

**23.** If the conductors in a two-wire RF transmission line are replaced by larger conductors, how is the surge impedance affected, assuming no change in the center-to-center spacing of the conductor? (20.13) [4]

**24.** Why is an inert gas sometimes placed within concentric RF transmission cables? (20.13) [4]

**25.** If the spacing of the conductors in a two-wire RF transmission line is doubled, what change takes place in the surge impedance of the line? (20.13) [4]

**26.** Explain the properties of a quarter-wave section of an RF transmission line. (20.16) [4]

**27.** What is the direction of maximum radiation from two vertical antennas spaced 180° and having equal currents in phase? (20.18) [4]

**28.** If the two towers of a 950-kc directional antenna are separated by 120 electrical degrees, what is the tower separation in feet? (20.18) [4]

**29.** The currents in the elements of a directive broadcast antenna must be held to what percentage of their licensed value? (20.19) [4]

**30.** In what part of a broadcast-station system is a *phase monitor* sometimes found? What is the function of this instrument? (20.19) [4]

**31.** Why do some broadcast stations use top-loaded antennas? (20.23) [4]

**32.** Draw a simple schematic diagram of a T-type coupling network suitable for coupling a coaxial line to a standard broadcast antenna. Include means for harmonic attenuation. (20.24) [4]

**33.** How may a standard broadcast antenna ammeter be protected from lightning? (20.25) [4]

**34.** If the power output of a broadcast station has been increased so that the field intensity at a given point is doubled, what increase has taken place in antenna current? (20.26) [4]

**35.** How does the field strength of a standard broadcast station vary with distance from the antenna? (20.26) [4]

**36.** In what units is the field intensity of a broadcast station normally measured? (20.26) [4]

**37.** If the field intensity of 25 mv/meter develops 2.7 volts in a certain antenna, what is its effective height? (20.26) [4]

**38.** If the power output of a broadcast station is quadrupled, what effect will this have upon the field intensity at a given point? (20.26) [4]

**39.** What is the effective radiated power of a station if the output of the transmitter is 1,000 watts, antenna transmission-line loss is 50 watts, and the antenna power gain is 3? (20.28) [4]

**40.** What effect do broken ground conductors have on a standard broadcast station? (20.29) [4]

**41.** An antenna is being fed by a properly terminated two-wire transmission line. The current in the line at the input end is 3 amp. The surge impedance of the line is 500 ohms. How much power is being supplied to the line? (20.30) [4]

**42.** If the day input power to a certain broadcast-station antenna having a resistance of 20 ohms is 2,000 watts, what would be the night input power if the antenna current were cut in half? (20.30) **[4]**

**43.** The power input to a 72-ohm concentric line is 5,000 watts. What is the current flowing in it? (20.30) **[4]**

**44.** What is the antenna current when a transmitter is delivering 900 watts into an antenna having a resistance of 16 ohms? (20.30) **[4]**

**45.** If the antenna current of a station is 9.7 amp for 5 kw, what is the current necessary for a power of 1 kw? (20.30) **[4]**

**46.** If the daytime transmission-line current of a 10-kw transmitter is 12 amp and the transmitter is required to reduce to 5 kw at sunset, what is the new value of transmission-line current? (20.30) **[4]**

**47.** The power input to a 72-ohm concentric transmission line is 5,000 watts. What is the rms voltage between the inner conductor and sheath? (20.30) **[4]**

**48.** The ammeter connected at the base of a Marconi antenna has a certain reading. If it is increased 2.77 times, what is the increase in output power? (20.30) **[4]**

**49.** A long transmission line delivers 10 kw into an antenna; at the transmitter end the line current is 5 amp, and at the coupling house it is 4.8 amp. Assuming the line to be properly terminated and the losses in the coupling system negligible, what is the power lost in the line? (20.30) **[4]**

**50.** The d-c input power to the final-amplifier stage is exactly 1,500 volts and 700 ma. The antenna resistance is 8.2 ohms, and the antenna current is 9 amp. What is the plate efficiency of the final amplifier? (20.30) **[4]**

**51.** What is meant by polarization of a radio wave? How does polarization affect the transmission and reception of a radio wave? (20.6) **[6]**

**52.** What is the velocity of propagation of RF waves in space? (20.7) **[6]**

**53.** What is the relationship between the electrical and physical length of a Hertzian antenna? (20.7) **[6]**

**54.** What is the difference between a Hertz and a Marconi antenna? (20.9) **[6]**

**55.** Draw a diagram showing how current varies along a half-wavelength Hertz antenna. (20.10) **[6]**

**56.** At what point on a shipboard antenna system will the maximum potential be found? (20.10) **[6]**

**57.** What will be the effect upon the resonant frequency if the physical length of a Hertzian antenna is reduced? (20.12) **[6]**

**58.** If you desire to operate on a frequency lower than the resonant frequency of an available Marconi antenna, how may this be accomplished? (20.12) **[6]**

**59.** What is the effect on the resonant frequency of connecting a capacitor in series with an antenna? An inductor in series with an antenna? (20.12) **[6]**

**60.** What determines the surge impedance of a two-wire nonresonant RF transmission line? (20.13) **[6]**

**61.** Which type of antenna has a minimum of directional characteristics in the horizontal plane? (20.14) **[6]**

**62.** What is the reception pattern of a vertical antenna? (20.14) **[6]**

**63.** What should be the approximate surge impedance of a quarter-wavelength matching line used to match a 600-ohm feeder to a 70-ohm antenna? (20.16) **[6]**

**64.** What is the directional reception pattern of a loop antenna? (20.22) **[6]**

**65.** What material is best suited for use as an antenna strain insulator which is exposed to the elements? (20.23) **[6]**

**66.** What is the effect upon a transmitter of dirty or salt-encrusted antenna insulation? (20.23) **[6]**

**67.** How is the degree of coupling varied in a pi network used to transfer energy from a vacuum-tube plate circuit to an antenna? (20.24) **[6]**

**68.** What is the relationship between the antenna current and radiated power of an antenna? (20.26) **[6]**

**69.** If a 500-kc transmitter of constant power produces a field strength of 100 mv/meter at a distance of 100 miles from the transmitter, what would be the theoretical field strength at a distance of 200 miles from the transmitter? (20.26) **[6]**

**70.** If the power of a 500-kc transmitter is increased from 150 to 300 watts, what would be the percentage change in field intensity at a given distance from the transmitter? What would be the decibel change in field intensity? (20.26) **[6]**

**71.** If the antenna current at a 500-kc transmitter is reduced 50 per cent, what would be the percentage change in the field intensity at the receiving point? (20.26) **[6]**

**72.** Why does harmonic radiation from a transmitter sometimes cause interference at distances from a transmitter where the fundamental signal cannot be heard? (20.27) **[6]**

**73.** What is the primary reason for the suppression of RF harmonics in the output of a transmitter? (20.27) **[6]**

**74.** What is meant by harmonic radiation? (20.27) **[6]**

**75.** If the resistance and the current at the base of a Marconi antenna are known, what formula could be used to determine the power in the antenna? (20.30) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer the question prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**★1.** What is the relationship between the frequency and wavelength of a radio wave if its velocity in space is 300 million meters/sec? (20.7)

**2.** How does the wavelength vary in respect to frequency? (20.7)

**3.** How is the approximate length of a half-wave dipole antenna for a given frequency determined? (20.7)

**4.** What is the length of a 7-Mc dipole in feet? (20.7)

**5.** What is the formula used for determining the wavelength of radio waves? (20.7)

**6.** What is the formula used for determining the characteristic impedance of an air-insulated parallel-conductor transmission line? (20.13)

**7.** What is the formula used for determining the SWR in a transmission line? (20.13)

**8.** How may a transmitter or receiver be protected against damage due to high values of induced atmospheric electricity collected by the antenna system? (20.25)

# CHAPTER 21

# MEASURING FREQUENCY

**21.1 Means of Measuring Frequencies.** One of the duties of a radio operator is to make sure that the transmitters under his control are always operating on the required frequency. Some of the methods used to measure the output of a transmitter are outlined in this chapter. There are seven general categories into which radio-frequency measuring devices fall: (1) absorption wavemeters, (2) grid-dip meters, (3) primary frequency standards, (4) secondary frequency standards, (5) heterodyne frequency standards, (6) lecher wires, and (7) electronic counters.

The last, electronic counters, can count the cycles per second of an RF alternating current and indicate the exact number of cycles. However, these are not in use in radio stations as yet and will not be discussed.

**21.2 Frequency Tolerance.** The continual and rapid increase in the number of services utilizing radio transmitters makes necessary more and more rigid rules regarding the holding of RF emissions to the frequency assigned to them. There is always some leeway allowed by the FCC and the international frequency-allocation bodies. Transmitters in some services must maintain their assigned frequency within a *tolerance* of 0.02, 0.01, and 0.005 per cent, others within ±2,000 cycles, and standard broadcast stations within ±20 cycles.

If a station is assigned a frequency of 2,738 kc and the maximum frequency tolerance is 0.02 per cent (0.02 per cent = 0.0002), the carrier frequency must always be within 2,738,000(0.0002), or 547.6 cycles of the assigned frequency. The station may transmit on any frequency between 2,738,547 and 2,737,452 cycles. Another station with a tolerance of 0.01 per cent and assigned to 3,117.5 kc must transmit within 3,117,500(0.0001), or 311.7 cycles, of the assigned frequency. Its limits of legal operation are from 3,117.811 to 3,117.188 kc.

The oscillator frequency is subject to the same frequency tolerance as the assigned frequency; that is, a 1-Mc oscillator in a transmitter having an 8-Mc output with a tolerance of 0.04 per cent must maintain its oscillator frequency within 1,000,000(0.0004), or 400 cycles. The tolerance at the assigned 8-Mc output is 3.2 kc, plus or minus. Because of the technical advances made, such a large tolerance is no longer used in this frequency range.

**21.3 Absorption Wavemeters.** The simplest, and least accurate, of the RF measuring devices is the absorption wavemeter. It consists of a coil and a variable capacitor (condenser) in parallel, as shown in Fig. 21.1. The variable capacitor has a calibrated dial, or scale, attached to it.

When a wavemeter is held close to the LC tank circuit of an oscillator or amplifier, energy is absorbed by the meter when it is tuned to the same frequency as the tank. The plate current of the stage will increase when the wavemeter absorbs energy. The wavemeter should be held as far from the tank circuit as possible and still obtain an indication of resonance by the rise in plate current. The looser the coupling, the more accurate the indication given and the less the meter loads or detunes the circuit being measured. When a self-excited oscillator is being measured, the detuning may be considerable if the coupling is tight.

FIG. 21.1. Simple wavemeter circuit.

With the wavemeter adjusted to the resonant point, indicated by the peak plate current, the frequency of the transmitter and the wavemeter are indicated on the dial. Figure 21.2 illustrates a possible wavemeter dial calibrated to read from 3 to 5 Mc. The dial indicates a frequency of 3,575 kc.

When taking absorption wavemeter measurements it is important to remember that the tank coil may have dangerously high d-c or RF a-c voltages in it.

It will be found that less hand capacitance (detuning due to the hand changing the dielectric constant of the space surrounding the capacitor or inductor used in the wavemeter) and less detuning of the circuit being measured is produced if the meter is coupled to the *cold*, or ground, end of the tank circuit rather than to the *hot*, or plate, end.

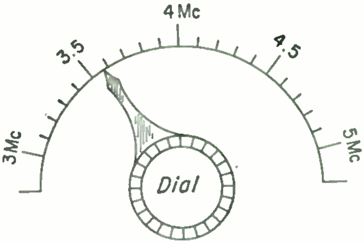


FIG. 21.2. Dial and scale directly calibrated in frequency.

The simple coil and capacitor wavemeter is the most accurate of several similar types, since its $Q$ can be rather high, giving relatively sharp frequency indications. Figure 21.3 illustrates four possible methods of obtaining a visual indication. The first includes a sensitive thermogalvanometer in the resonant circuit, the second a flashlight globe. The third inductively couples a flashlight globe (or other indicator) to the resonant circuit. The fourth uses a neon globe, which will ionize and light when the voltage across it exceeds about 80 volts.

Absorption wavemeters seldom have a frequency accuracy of more than

0.05 per cent. Because of their relatively poor accuracy, they find most application in determining the approximate fundamental frequency, being relatively unresponsive to harmonic output.

Often the wavemeter will have several plug-in coils in order to cover a wide band of frequencies. In this case an arbitrary scale from 0 to 100° is used on the dial. A *calibration chart*, or graph, is used with each plug-in coil. With the graph, arbitrary dial indications can be converted to frequency indications. Figure 21.4 shows an arbitrarily marked dial scale and a frequency-versus-dial division calibration chart. The curve on the chart is used to convert the dial-division reading to the frequency indication.

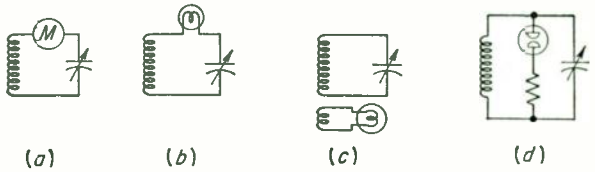


FIG. 21.3. Indicators used with wavemeters. (*a*) Sensitive thermogalvanometer. (*b*) Flashlight globe. (*c*) Inductively coupled globe. (*d*) Neon lamp ($R = 100{,}000$ ohms).

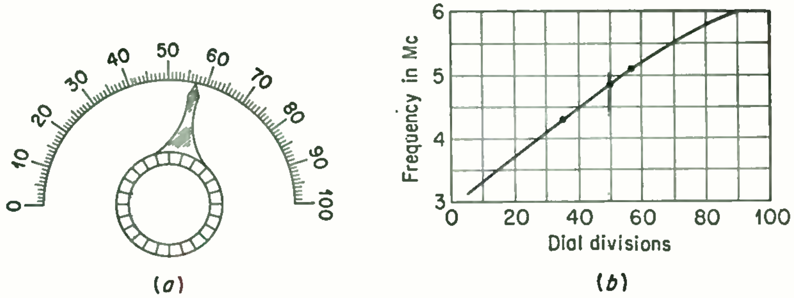


FIG. 21.4. (*a*) Uncalibrated dial and scale. (*b*) Calibration chart that might be used with it.

According to the indication shown on the dial (fifty-seventh division) the frequency of resonance of the wavemeter from the graph is approximately 5.1 Mc. A dial reading of 50 indicates a frequency of approximately 4.85 Mc. A dial reading of 35 indicates a frequency of approximately 4.3 Mc.

Note that the line on this graph is not linear. By the use of special straight-line-frequency capacitors, a nearly straight curve can be produced. This will result in more accurate readings. Another means of increasing the accuracy is to use a larger graph paper.

If a wavemeter has an error *proportional to the frequency* and is accurate within 200 cycles at a frequency of 1,000 kc, it will be accurate within 400 cycles at a frequency of 2,000 kc. If such a frequency-measuring device is accurate to 20 cycles when set at 1,000 kc, its error when set at 1,250 kc can be determined by setting up the ratio, or proportion, of 1,250 is to 1,000 as $X$ is to 20 cycles. In mathematical form,

$$\frac{1{,}250}{1{,}000} = \frac{X}{20}$$
$$1{,}000X = 25{,}000$$
$$X = 25 \text{ cycles possible error}$$

Another more accurate meter has an error proportional to frequency and is accurate to 10 cycles when set at 600 kc. When the meter is set to 1,100 kc its error is

$$\frac{1{,}110}{600} = \frac{X}{10}$$
$$600X = 11{,}100$$
$$X = 18.5 \text{ cycles possible error}$$

**21.4 Lecher Wires.** A parallel-conductor transmission line can be used to determine the frequency of a transmitter operating in the 50–500-Mc region by taking measurements of the standing waves developed on it. One end of a 1- to 3-wavelength transmission line is formed into a loop, which is loosely coupled to the tuned circuit of the amplifier or oscillator being measured, as shown in Fig. 21.5. Linear tank wavemeters of this type are known as *lecher wires*.

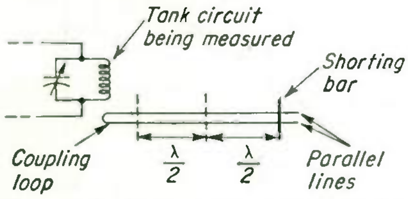


FIG. 21.5. Lecher wires, inductively coupled.

The lecher wires can be constructed of two No. 12 bare copper wires, or ⅛-in. copper tubing, held apart about an inch, stretched tightly to prevent movement, and supported by insulators at the far ends only. A knife-edged metal shorting bar is held at exact right angles across the two parallel lines. Starting near the coupling loop and slowly moving the shorting bar along the line, a point will be reached where the plate current of the transmitter will rise to a sharply defined peak (sometimes a dip for an oscillator). This point is marked on the lecher wires. The shorting bar is moved farther down the lines until a second point of plate-current peak is found. The distance between the two points represents a half-wavelength. Moving farther down the line, the next peak represents another half-wavelength, or a full wavelength from the first. By measuring the full-wavelength distance with a meter stick (similar to a yardstick except that it is marked in centimeters and millimeters instead of inches), the operating *wavelength* is determined. The frequency can be found by using the basic frequency formula (Sec. 20.7),

$$F = \frac{300{,}000{,}000}{\text{wavelength in meters}}$$

If a meter stick is not available, the length of the full wave can be measured in inches and the frequency in megacycles can be determined by the formula

$$F_{mc} = \frac{11{,}810}{\text{length in inches}}$$

If the lecher wires are not long enough to obtain a full-wavelength measurement, a half-wavelength can be used with little loss of accuracy. The formula is then

$$F_{mc} = \frac{5{,}905}{\text{length in inches}}$$

With loose coupling and considerable care, measurements of frequency to about 0.1 per cent can be made with lecher wires.

An alternate method of coupling to lecher wires is by capacitance, in which the two wires at one end of the transmission line are spread slightly and held near the two ends of the tuned circuit being measured, as shown in Fig. 21.6.

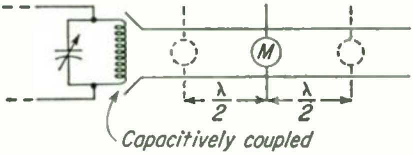


FIG. 21.6. Lecher wires, capacitively coupled.

A sensitive thermogalvanometer with extended contact bars can be moved along lecher wires instead of a shorting bar, and visual indications of current loops (high values) and nodes (low values) will be discernible.

**21.5 Grid-dip Meters.** When it is desired to measure the frequency of a resonant circuit when not in operation, a *grid-dip meter* can be coupled to it.

A grid-dip meter consists of a vacuum-tube oscillator, usually a Hartley or Colpitts circuit. A sensitive milliammeter is connected in series with the grid leak of the oscillator, as shown in Fig. 21.7. When the stage is oscillating, grid current flows. When the oscillating-tank probe coil is coupled to any other external LC circuit tuned to the same frequency, the external circuit will absorb energy from the oscillating tank, weaken its amplitude of oscillation, and lessen the grid current. When the grid-dip oscillator is coupled to a circuit having an unknown frequency of resonance, the grid current dips as the oscillator is tuned past the resonant frequency of the LC circuit being tested.

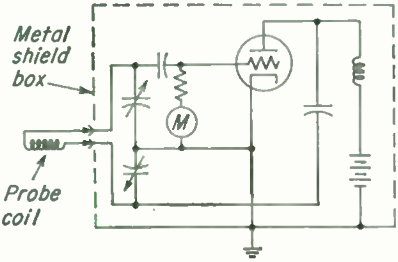


FIG. 21.7. Grid-dip meter circuit.

The lower the degree of coupling between the grid-dip meter and the circuit being tested, the more accurate the results. When accurately calibrated and loosely coupled to an external circuit, its indications are fairly reliable, but it is not designed to have the accuracy of true frequency meters. To cover a wide band of frequencies, grid-dip meters usually have plug-in probe coils. There is a separate calibration scale for each plug-in coil used. The scales are often calibrated directly in frequency.

**21.6 Primary Frequency Standards.** There are few true primary frequency standards. A primary frequency standard checks its frequency of oscillation against astronomical measurements, the most accurate known means of determining time.

The nationally (and internationally) recognized primary frequency standard is at the National Bureau of Standards, Washington, D.C. This bureau has as part of its equipment an elaborate system of checking time by measuring the rotation of the earth against the position of stars. Part of the equipment is a temperature-controlled crystal oscillator in constant operation. A submultiple of the crystal frequency is selected, amplified, and used to operate an a-c clock. As long as the crystal oscillator keeps a constant frequency, the clock will keep correct time. As long as the clock maintains correct time according to celestial observations, it is known that the standard oscillator is on frequency. Therefore all harmonics of the standard oscillator will also be correct. The National Bureau of Standards picks out the 2.5-, 5-, 10-, 15-, 20-, 25-, and 30-Mc harmonics of the standard oscillator frequency, amplifies them, and transmits them under the call of WWV. These frequency transmissions are correct to 1 cycle in 50 million.

The transmitted carrier frequencies are modulated part of the time by a 440-cycle tone and ticks, part of the time by a 600-cycle tone and ticks, and part of the time by only ticks. The 440-cycle-tone modulation commences exactly on the hour and continues for exactly 3 min. At the same time the carrier is modulated by 0.005-sec pulses, transmitted every second, except the fifty-ninth of each minute. These short-duration pulses sound to the listener as a *tick*. The accuracy of the beginning of the tick is 1 part in 1 million. When the tone modulation ceases, the ticks continue. During the 2-min period of no-tone modulation, the call letters of the station are transmitted in MCW (A2), and a short-voice transmission is made indicating the time when the tone will be resumed. The time when the tone will resume in Eastern Standard Time is also transmitted in MCW.

Exactly 5 min after the hour the carrier is again modulated as before, except that the tone of the modulation is now 600 cycles. The alternation of tone-modulated and unmodulated periods continues throughout the hour and the day.

A simultaneous broadcast is made on some of these frequencies by the Bureau of Standards station in the Hawaiian Islands, WWVH.

By means of WWV or WWVH signals it is quite possible to measure a frequency of 10,000,000 cycles within 1-cycle accuracy.

**21.7 Secondary Frequency Standards.** A secondary frequency standard is a relatively simple device in comparison with a primary standard, with many being in use in radio communication. A secondary frequency standard consists of two oscillators; one produces a saw-tooth, or square-wave, output, and the second, a stable low-frequency synchronizing crystal oscillator. The harmonics of the first are the signals that are used.

A secondary standard may consist of the following circuits, shown in Fig. 21.8:

1. A multivibrator oscillator to generate a low-frequency fundamental with a multitude of harmonics
2. One or more resistance-coupled amplifier stages to amplify the multivibrator-oscillator output harmonics

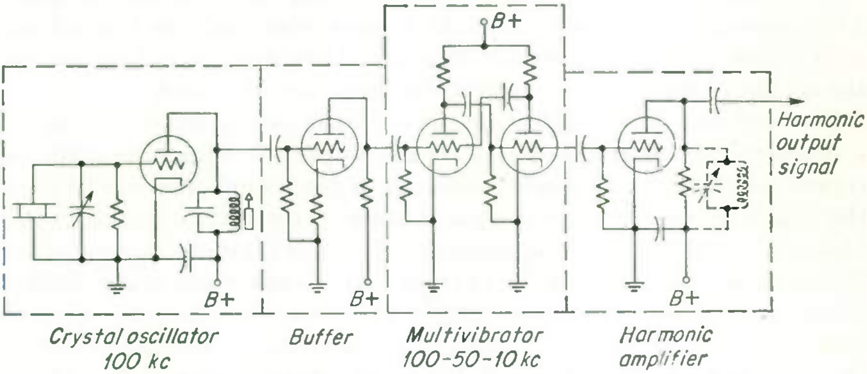


FIG. 21.8. Essential circuits of a secondary frequency standard.

3. A 100-kc crystal oscillator to synchronize or lock the multivibrator into a desired frequency of oscillation
4. A resistance-coupled buffer stage to isolate the crystal oscillator stage from the multivibrator
5. A voltage-regulated power supply (not shown in the illustration)

The source of usable oscillations of the secondary frequency standard is the multivibrator oscillator, *not* the crystal oscillator, as is sometimes believed. The multivibrator oscillator, a two-tube RC-type oscillator, generates a steep-sided a-c waveform, rich in harmonics. In actual practice its harmonics are usable up to the 3,000th or higher.

Basically, the multivibrator oscillator of the secondary standard can be made to produce a harmonic signal every 100 kc throughout the radio spectrum. By comparing the relative position of any signal between two known 100-kc harmonics, it is possible to determine the frequency of the signal. Thus, if a station is tuned in on a receiver and is exactly halfway between the sixth and seventh 100-kc harmonics, the station must be transmitting on 650 kc. A calibrated receiver is necessary in order to correctly identify which harmonics are being heard.

The calibration of a receiver can be checked by feeding the signal from a 100-kc oscillating secondary standard to it. A signal from the standard should appear on the receiver dial at every point where a mark representing a multiple of 100 kc is shown. For example, a signal should be received on such points on the dial as are marked 600 kc, 900 kc, 1.5 Mc, 2.7 Mc, etc.

By incorporating multiple-contact switches in a secondary standard multivibrator circuit, it is possible to change the plate-load resistors and coupling capacitors that determine the frequency of oscillation from 100 to 50 kc or to 10 kc.

To increase the output strength of the multivibrator-oscillator harmonics, a tuned circuit may be incorporated in the plate circuit of the stage amplifying the multivibrator output and shown in broken lines. The harmonics falling on or near the frequency of this tuned circuit are amplified considerably more than they would be otherwise. This extends the usable high-frequency range of the secondary standard.

The stability of the multivibrator oscillator is improved by feeding a synchronizing signal into one of its grid or plate circuits from a 100-kc crystal oscillator. The sine-wave output of the crystal oscillator triggers the multivibrator circuit, forcing it to start its oscillations at the proper instant, thereby assuring proper output frequency from the multivibrator. The sinusoidal crystal output can trigger off the saw-tooth multivibrator to the fundamental or any *submultiple* of the crystal frequency. Thus, a 100-kc crystal can hold a multivibrator oscillator at 100, 50, 33.3, 25, 20 kc, and so on, down to about the tenth submultiple, which is 10 kc. If the multivibrator normally oscillates at 49.9 kc by itself, a 100-kc synchronizing oscillator will shift it into exactly 50-kc oscillations. Regardless of the natural frequency of the multivibrator, it will be synchronized to the closest exact submultiple of the 100-kc frequency.

To check the frequency of oscillation of the crystal oscillator, the secondary frequency standard should be turned on and allowed a ½- to 4-hr warm-up period to allow the circuits to stabilize. A short-wave receiver is then tuned to WWV, and the secondary standard set to 100-kc harmonic output. If the harmonics of the multivibrator produce a zero beat (no audible difference of frequency between the unmodulated WWV signal and the harmonic of the multivibrator), the crystal must be oscillating on 100 kc exactly. If there is a difference frequency heard, the trimmer capacitor across the crystal can be varied until a zero beat is produced. When the 100-kc harmonics are correctly adjusted, there should be no need to readjust the crystal when the multivibrator is switched to 50- or 10-kc harmonic output.

**21.8 Frequency Measurements with a Secondary Standard.** It is possible to determine the approximate frequency of any transmitter by tuning it in on a receiver and noting the two 10-kc multivibrator harmonics between which the signal is received.

It will be assumed that a signal of 4,673 kc is going to be measured. After an adequate warm-up period, the secondary standard is switched to 100-kc harmonic output and fed into a 6–10-kc-bandwidth communication receiver with the BFO (beat-frequency oscillator) turned on. The signal to be measured is tuned in. From the calibration of the receiver dial it is found that the signal falls between the 4,600- and 4,700-kc harmonics, as shown in Fig. 21.9.

The secondary standard is next switched to 50-kc harmonic output, and the signal is now observed to be between the 4,650- and 4,700-kc markers. The receiver is set to 4,650 (or 4,700) kc, and the standard is switched to 10-kc harmonic generation. The receiver is carefully tuned toward the signal, and each time the receiver zero-beats against a 10-kc harmonic, another 10 kc is added to the 4,650-kc starting frequency (or subtracted from the 4,700-kc starting frequency). In the example being used, when the receiver comes to zero beat with the 4,670-kc marker, a 3-kc difference frequency will also be heard. This is produced by the beating of the 4,670-kc harmonic and the received signal (4,673 kc). It is impossible to tell by ear that the difference is 3 kc. Some means must be used to determine accurately how far above 4,670 kc the signal frequency is. There are two methods by which this difference can be found: (1) by interpolation, and (2) by audio comparison.

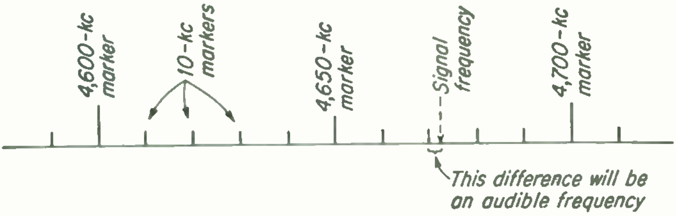


Fig. 21.9. Marker signals on a receiver dial, and the signal to be measured.

The *interpolation* method of determining the displacement of the signal from a marker signal requires a variable RF oscillator of good stability, incorporating a straight-line frequency capacitor to produce a linear frequency-versus-dial relationship. This oscillator is not calibrated for frequency, but in arbitrary units only.

The receiver is left tuned to the 4,670-kc marker, and the BFO in the receiver turned off. The variable oscillator is fed into the receiver and tuned until a zero beat is produced against the 4,670-kc marker. (A beat signal of maximum strength is produced when the amplitudes of the two signal voltages are equal. If one is much greater than the other, the beat may be weak and difficult to hear.)

The dial reading of the variable oscillator, when in zero beat with 4,670 kc, is noted on a piece of paper. The receiver is tuned to the received signal, and the oscillator is tuned to a zero beat with this, and the oscillator dial reading noted again. The receiver is finally tuned to the next higher, or 4,680-kc, marker, and the variable oscillator is brought to a zero beat again. The oscillator dial reading is again noted. The ratio of the received signal to the 4,670-kc marker in comparison with the separation between markers will indicate the received frequency.

*Example:*

Let 4,670 kc = 40° on the oscillator dial
Signal = 49° on the oscillator dial
4,680 kc = 70° on the oscillator dial

Then

Difference between 4,670 kc and the signal can be called $a$.
Difference between 4,670 and 4,680 kc can be called $b$
Difference between 40 and 49° can be called $c$
Difference between 40 and 70° can be called $d$

Using these factors, it is possible to set up the ratio needed to solve for the unknown, the difference between 4,670 kc and the signal:

$$\frac{a}{b} = \frac{c}{d}$$

Substituting known values, the ratio becomes

$$\frac{a}{10\text{ kc}} = \frac{9^\circ}{30^\circ}$$

Solving for $a$

$$a = \frac{9(10)}{30} = 3\text{ kc}$$

The signal has now been computed to be 3 kc above 4,670 kc, making it 4,673 kc.

The accuracy of this method depends on the accuracy of the three zero-beat dial readings and the linearity of the dial on the oscillator. To improve the accuracy of the results, it is possible to zero-beat the oscillator against the marker or signal frequency and then switch on the BFO of the receiver. The BFO is adjusted until a tone of about 1,000 cycles is heard. The tone produced by the BFO beating against the marker and oscillator zero beat will be heard to waver in *amplitude*. As the oscillator is brought closer to true zero beat, the waver of the audible signal will become slower. When the wavering is down to a fraction of a cycle per second, the oscillator can be assumed to be zero beat with the marker or signal frequency.

When the signal being measured is within a few kilocycles of a marker signal, the audio comparison method can be used. With the receiver tuned to 4,670 kc and with the BFO off, a beat tone between the 4,670-kc marker and the signal frequency will be produced in the receiver. A loudspeaker may now be connected to the output of an accurately calibrated audio signal generator. The signal generator is tuned back and forth until the audio signal from it has exactly the same pitch as the beat signal present in the receiver. If the two tones have the same pitch with the audio signal generator set to 3,000 cycles, the frequency of the received signal must be 3 kc from the nearest marker.

When the signal is found to be closer to the higher marker frequency, 4,680 kc in the example, the audible difference between 4,680 kc and the signal is found and is *subtracted* from 4,680 kc to give the correct frequency.

Use of a broad receiver, having a bandpass of more than 10 kc, makes it somewhat difficult to determine from which 10-kc marker the difference is being obtained. In any case, the accuracy of the audio-signal-generator calibrations becomes less as the audible difference frequency approaches 5 kc.

If the operator does not have a sufficiently musical ear to determine the equality of the pitch of the two tones, it is possible to feed the audible-tone output from the receiver to the horizontal plates of an oscilloscope and the tone from the audio signal generator to the vertical plates. When the two tones are equal, the pattern on the oscilloscope screen will be either a circle or a stationary elipse.

The accuracy of the audio comparison method depends on the accuracy of calibration of the audio signal generator.

**21.9 Heterodyne Frequency Meters.** While the use of a secondary standard to measure a frequency utilizes a heterodyne, or beat-frequency, signal to determine the unknown frequency, the name *heterodyne frequency meter* is reserved for the type of meter employing a variable oscillator with an accurately calibrated dial.

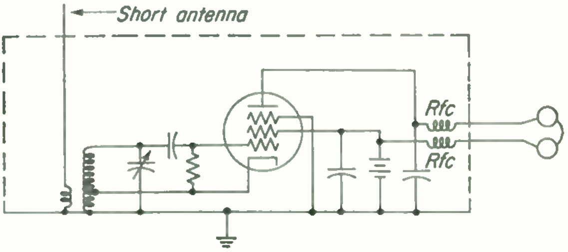


FIG. 21.10. Simple heterodyne-frequency-meter circuit subject to frequency pulling.

A heterodyne frequency meter may be used as an accurately calibrated oscillating receiver when measuring the frequency of a transmitter. It may also be used to transmit a weak but accurately calibrated signal to a local receiver in order to zero-beat against a received signal to determine the received-signal frequency.

A heterodyne frequency meter in one of its simpler forms is shown in Fig. 21.10. It is a Hartley-type electron-coupled oscillator, with earphones in the output circuit. It might be operated from self-contained batteries or from a power supply. Note the RF chokes in the earphone leads to prevent the earphones from acting as a relatively long antenna. The antenna coupled to the oscillator is usually only a few inches long to limit the signal input to a low value, since a strong input signal will pull the frequency of oscillation toward the incoming frequency, resulting in a broad and inaccurate zero beat. This tendency of two oscillations of slightly different frequency to synchronize must be guarded against in frequency measurements with this type of equipment.

An improved heterodyne frequency meter is shown in Fig. 21.11, which isolates the oscillator completely. Incoming signals cannot pull the frequency of oscillation. The signal is received by the short antenna and fed to one grid of a mixer tube. When the oscillator, which is fed into another grid of the mixer tube, is tuned to a frequency near the received signal, a heterodyne, or beat, tone is heard in the earphones. When the tone is brought to a zero beat, the frequency of the oscillator is the same as the frequency of the incoming signal.

The *harmonic* of a *local* transmitter will produce a beat tone in such a meter. Furthermore, the *harmonics* of the heterodyne frequency-meter

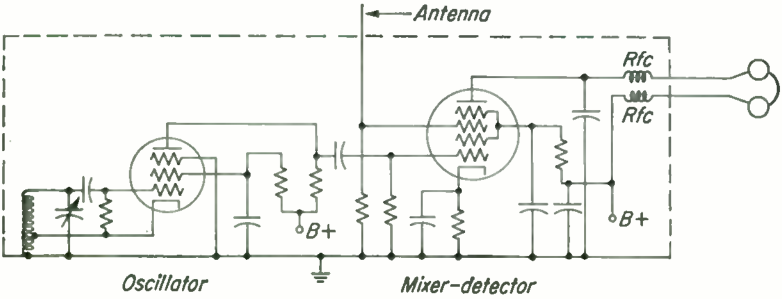


FIG. 21.11. Heterodyne-frequency-meter circuit not subject to frequency pulling.

*oscillator* will beat against any signal picked up by the short antenna to produce a heterodyne tone.

When the frequency of a local transmitter is measured, it may be necessary to use an absorption wavemeter to determine the approximate frequency, and then use the frequency meter to obtain a more exact frequency indication.

In many cases, the harmonic of a local transmitter is the signal measured. For example, if a heterodyne frequency meter has a calibrated range or dial from 1,000 to 2,000 kc and it is used to measure the frequency of a transmitter operating on approximately 500 kc, a zero beat should be found on the scale when it reads 1,000 kc (second harmonic of 500 kc), when it reads 1,500 kc (third harmonic of 500 kc), and when it reads 2,000 kc (fourth harmonic of 500 kc). If the meter indicates a zero beat at 1,008 kc, the actual frequency of the transmitter must be 1,008 divided by 2, or 504 kc.

The accuracy of this type of a heterodyne frequency meter can be checked by beating one of its harmonics against WWV. For example, the frequency meter has a band spread from 1,000 to 2,000 kc. When set to 1,000 kc, the fifth harmonic should fall on 5 Mc. With a receiver receiving WWV on 5 Mc, the output of the frequency meter should zero-beat when its dial frequency indicates oscillation on 1,000 kc. Similarly, when set to 1,250 kc, its fourth harmonic will fall on 5 Mc. When set to 1,666.666 kc, its third harmonic will also fall on 5 Mc. Thus, the frequencies of 1,000, 1,250, and 1,666.666 kc are *check points* when used in conjunction with WWV on 5 Mc. If these check-point frequencies agree with the dial calibration of the frequency meter, it is assumed that all intermediate frequencies on the dial are also accurate.

Many heterodyne frequency meters have built-in check-point oscillators. A 100-kc crystal oscillator can be used as such a calibration oscillator. It is used only when checking the accuracy of the dial readings of the frequency meter. Prior to measuring the frequency of a signal, the meter is allowed sufficient warm-up time, and then the 100-kc oscillator is turned on and a point on the dial near where the received signal will be heard is checked. Suppose the signal is known to be at about 1,425 kc. The frequency-meter oscillator is tuned to 1,400 kc. The fourteenth harmonic of the 100-kc oscillator should produce a zero beat. If the zero beat is a little low or high, a trimmer capacitor connected across the oscillator tuned circuit can be adjusted to bring the dial into calibration. The 100-kc crystal oscillator is then turned off, and the signal is measured.

If it is desired to measure the frequency of a signal on 2,850 kc (twice the frequency of 1,425 kc used above), the same procedure is used. When measuring the 2,850-kc signal, it is the second harmonic of the *frequency-meter* oscillator that is brought to a zero beat with the signal. For the correct frequency it is necessary to double the frequency shown on the calibrated dial.

Rather than rely on the operator doubling or tripling the frequency readings, special calibration charts are usually provided with such meters. With these calibration charts the frequency-meter dial is marked off in arbitrary units, possibly ranging from 0 to 100°, with a vernier, or slow-moving, dial that makes it possible to read 10 or even 100 parts of each basic unit on the scale. In effect, this results in a dial with 1,000, or even 10,000, measurable units from one end to the other for more accurate frequency measurements.

The following is an example of the use of such equipment:

An absorption-type wavemeter indicates that the approximate frequency of a transmitter is 500 kc. At the same time the transmitter signal produces a zero beat on an accurately calibrated heterodyne frequency meter at a dial reading of 374.1. The frequency-meter calibration chart indicates the following dial readings versus frequencies:

*Dial* *Frequencies*

367.0° = 499.4–998.8 kc
371.5° = 499.6–999.2 kc
376.0° = 499.8–999.6 kc

Since the absorption wavemeter indicates the approximate frequency to be 500 kc, the dial reading of 374.1 must indicate a frequency between 499.6 and 499.8 kc, rather than one between two of the 999-kc harmonic frequencies. To find the exact frequency from the given information, it is necessary to interpolate as explained in reference to secondary-frequency standard measurements. Thus:

$$\begin{array}{c} \textit{Dial} \qquad \textit{Frequency} \\ b\left\{\begin{matrix} a\left\{\begin{matrix}371.5^\circ = 499.6\text{ kc}\\ 374.1^\circ = \text{the signal}\end{matrix}\right\}c \\ 376.0^\circ = 499.8\text{ kc}\end{matrix}\right\}d \end{array}$$

$a$ = difference between 371.5 and 374.1 = 2.6°
$b$ = difference between 371.5 and 376.0 = 4.5°
$c$ = difference between 499.6 and signal = unknown
$d$ = difference between 499.6 and 499.8 = 0.2 kc

Setting up the ratio and solving for the unknown difference:

$$\begin{aligned} \frac{a}{b} &= \frac{c}{d} \\ \frac{2.6}{4.5} &= \frac{c}{0.2} \\ 4.5c &= 0.2(2.6) \\ c &= \frac{0.52}{4.5} = 0.1156\text{ kc} \end{aligned}$$

Therefore the unknown frequency is 0.1156 kc greater than 499.6 kc, or 449.7156 kc.

The following is a somewhat similar problem:

A heterodyne frequency meter has a dial reading of 31.7 for a frequency of 1,390 kc and a dial reading of 44.5 for a frequency of 1,400 kc. What is the frequency of the ninth harmonic of the frequency corresponding to a scale reading of 41.2?

By interpolation, the frequency corresponding to the scale reading of 41.2 is

$$b\left\{\begin{matrix} a\left\{\begin{matrix}31.7^\circ = 1{,}390\text{ kc}\\ 41.2^\circ = \text{unknown signal}\end{matrix}\right\}c \\ 44.5^\circ = 1{,}400\text{ kc}\end{matrix}\right\}d$$

$$\begin{aligned} \frac{a}{b} &= \frac{c}{d} \\ \frac{9.5}{12.8} &= \frac{c}{10\text{ kc}} \\ 12.8c &= 9.5(10) \\ c &= \frac{95}{12.8} = 7.422\text{ kc} \end{aligned}$$

The unknown frequency is 7.422 kc above 1,390, or 1,397.422 kc. The ninth harmonic of this frequency is 9 × 1,397,422 cycles, or 12,576.798 kc.

Frequency meters are delicate instruments and must be handled with considerable care. Should a tuning capacitor or coil become damaged, it usually means many tedious hours of work to recalibrate the equipment. When it becomes necessary to replace an oscillator tube, the equipment should be allowed several hours warm-up, and then the meter should be tested at several points on the dial to see if it is indicating accurately. In some cases more than one tube should be tried until one having approximately the same characteristics as the original is found.

**21.10 A Constant Frequency Indicator.** When a constant indication of the frequency of a transmitter is required, as in a broadcast station, other types of meters are used. A type used in FM broadcast stations is discussed in Sec. 18.13.

In standard AM broadcast stations, the transmitter must maintain its assigned frequency at all times within 20 cycles, plus or minus. This rigid frequency tolerance is required to prevent two stations on the same frequency but in different parts of the country from producing an audible beat tone in a receiver. With a 20-cycle tolerance, the maximum difference of frequency between any two stations is 40 cycles. A 40-cycle tone is normally inaudible in modern receivers. In most cases the stations actually maintain their assigned frequency within about 5 cycles, resulting in a maximum beat tone of only about 10 cycles.

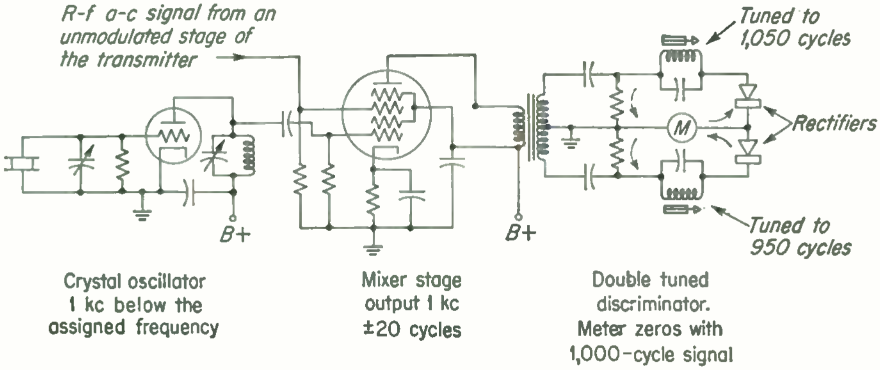


FIG. 21.12. Simplified broadcast-station frequency monitor to give a constant frequency indication.

Maintaining this degree of frequency stability is possible by use of temperature-controlled crystals in the transmitters. A *frequency monitor* for such a station also uses a temperature-controlled crystal oscillator. A monitor might use a crystal oscillator on the assigned frequency of the transmitter and indicate the number of cycles difference between the transmitter and the monitor. However, producing a frequency-indicating device that will read a 1- or 2-cycle difference is difficult. Instead, the monitor crystal is usually a few hundred cycles above or below the assigned frequency, and this difference frequency is read. Figure 21.12 is a simplified diagram of a possible frequency-monitoring circuit.

In this circuit, an RF signal of constant amplitude from one of the *unmodulated* stages in the transmitter is fed to one of the grids of the mixer tube. (The sideband frequencies developed in a modulated stage during modulation might produce erroneous readings in the monitor.) The output of the monitor crystal oscillating at a frequency 1,000 *cycles* lower than the assigned frequency of the transmitter is fed into another grid of the mixer tube. In the plate circuit of this tube an audible frequency difference of 1,000 cycles appears. This is fed to a discriminator type of circuit utilizing two tuned circuits, one tuned to 1,050 cycles and the other to 950 cycles. With the transmitter on frequency and the monitor 1,000 cycles lower in frequency, the two resonant circuits are tuned until an equal voltage is developed across each. This results in equal and opposite rectified d-c voltages across the meter $M$ and a resultant of zero current through it. The meter reads center scale with no current flowing through it. With the transmitter on frequency, the meter will read center scale, a point marked 0 cycles.

If the transmitter shifts up in frequency by 10 cycles, the beat tone becomes 1,010 cycles and the circuit tuned to the higher frequency develops more voltage across it, and current will flow through the meter in the diagram from left to right. The needle moves up to a point on the meter scale marked 10 cycles high.

If the transmitter shifts down in frequency 5 cycles, the beat tone becomes 995 cycles, more voltage is developed across the circuit tuned to 950 cycles, and current from this circuit, flowing from right to left through the meter, moves the indicating needle to a point indicating 5 cycles low. Thus a constant indication of the frequency of the transmitter is available.

Frequency monitors in broadcast stations may drift and give erroneous readings and must be checked periodically for accuracy. Commercial radio companies with primary standards can check the frequency of the transmitter at a specified time. From the frequency check of the transmitter by the commercial company and the indication of the frequency monitor at the same time, it is possible to determine the accuracy of the frequency monitor at the station.

For example, a station makes arrangements for a frequency check at 1 A.M. on a certain day. At that time the operator notes the frequency monitor reading—4 cycles high. The commercial radio company reports the frequency of the station to be 2 cycles low. The difference between the two readings, 6 cycles, is the error in the monitor. In this case the monitor is 6 cycles high. The monitor can be adjusted to indicate a frequency 6 cycles lower, and its readings can be assumed to be correct. The transmitter frequency may also be trimmed, although it is expected that the carrier will drift back and forth a few cycles under normal operation.

**21.11 Frequency Considerations for Amateurs.** Commercial radio systems are assigned one or more specific frequencies of operation. Frequency measurements are made to determine if the transmitting equipment is on frequency within the tolerances allowed by the FCC.

Amateur transmitting stations are not assigned any specific frequencies, but bands of frequencies. For example, any *general-class* licensed amateur station can operate on *any* desired frequency in the 7,000-

7,300-kc band. As a result, it is only necessary that the amateur be assured that his transmitter is not outside these frequencies. When operating near the band limits, accurate frequency determination becomes necessary and frequency tolerance of equipment being used must be considered.

If an amateur has a frequency meter (wavemeter) that has a possible error of 1 per cent and he wishes to operate as close to 7,000 kc as possible, on what frequency, according to his meter, can he operate and know that he is in the band? The problem can be stated:

$$F_x = 7{,}000 \text{ kc} + 1\% \, (F_x)$$

where $F_x$ is the unknown frequency. This can be rearranged to solve for $F_x$:

$$\begin{aligned} F_x &= 7{,}000 + 0.01(F_x) \\ F_x - 0.01(F_x) &= 7{,}000 \\ F_x(1 - 0.01) &= 7{,}000 \\ F_x &= \frac{7{,}000}{1 - 0.01} = \frac{7{,}000}{0.99} = 7{,}070.7 \text{ kc} \end{aligned}$$

To *assure* operation *inside* the band, the amateur must set his transmitter to a frequency not lower than 7,071 kc according to his frequency meter.

An amateur is to purchase a crystal guaranteed to be within 0.05 per cent of the frequency shown on its holder to operate as close to the 3,500-kc end of the 3,500–4,000-kc amateur band as possible. What is the lowest safe crystal frequency that should be ordered? This is computed as above:

$$\begin{aligned} F_x &= 3{,}500 + 0.0005(F_x) \\ F_x - 0.0005(F_x) &= 3{,}500 \\ F_x(1 - 0.0005) &= 3{,}500 \\ F_x &= \frac{3{,}500}{1 - 0.0005} = \frac{3{,}500}{0.9995} = 3{,}501.7 \text{ kc} \end{aligned}$$

To assure operation inside the band, the lowest frequency to order would be 3,502 kc. However, the same crystal may operate on one frequency in one circuit, but several hundred cycles higher or lower in another type of circuit. To allow for this possibility, an extra kilocycle might well be added, making 3,503 kc the crystal frequency to order.

Rather than go through the mathematical steps to determine the frequency, the formula for the above problems is

$$F_x = \frac{\text{lower frequency limit}}{1 - \text{the percentage}} + \text{any additional safety allowances}$$

When computing the same type of problem to find what frequency crystal to order close to the *high* frequency end of the band, the formula is

$$F_x = \frac{\text{upper frequency limit}}{1 + \text{the percentage}} - \text{any additional safety allowances}$$

When an amateur transmitter is amplitude-modulated, allowance must be made for the sideband frequencies developed on both sides of the carrier during modulation as well as the frequency tolerance of the carrier.

*Example:* If an amateur transmitter has a frequency tolerance of 0.1 per cent and a maximum AF in the modulation system of 3,000 cycles (3 kc), what is the closest frequency to the upper end of the 3,500–4,000-kc band to which the carrier can be safely set without any sidebands appearing outside the band limits? This may be computed by the last formula above, using the 3 kc of the sidebands as the additional safety allowance. Thus

$$F_x = \frac{4{,}000}{1 + 0.001} - 3 = \frac{4{,}000}{1.001} - 3 = 3{,}996 - 3 = 3{,}993 \text{ kc}$$

It might still be advisable to add another kilocycle for safety and operate on 3,992 kc.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** If an aircraft station is assigned the frequency of 3,117.5 kc and the maximum tolerance is 0.01 per cent, what are the highest and lowest frequencies within the tolerance limits? (21.2) **[3]**

**2.** If a ship telephone station is assigned the frequency of 2,738 kc and the maximum frequency tolerance is 0.02 per cent, what are the highest and lowest frequencies within the tolerance limits? (21.2) **[3]**

**3.** If a frequency meter having an over-all error proportional to the frequency is accurate to 10 cycles when set at 600 kc, what is its error in cycles when set at 1,110 kc? (21.3) **[3]**

**4.** Discuss lecher wires, properties, and uses. (21.4) **[3]**

**5.** In accordance with the commission's Rules and Regulations, what is the primary standard for RF measurements of radio stations in the various services? (21.6) **[3]**

**6.** If a heterodyne frequency meter having a calibrated range of 1,000–5,000 kc is used to measure the frequency of a transmitter operating on approximately 500 kc by measurement of the second harmonic of this transmitter, and the indicated measurement was 1,008 kc, what is the actual frequency of transmitter output? (21.9) **[3]**

**7.** What precautions should be observed in using an absorption-type frequency meter to measure the frequency of a self-excited oscillator? Explain. (21.3) **[3 & 6]**

**8.** Draw a diagram of an absorption-type-wavemeter and explain its principles of operation. (21.3) **[3 & 6]**

**9.** With measuring equipment that is widely available, is it possible to measure a frequency of 10 million cycles to within 1 cycle of the exact frequency? (21.6) **[3 & 6]**

**10.** What is a multivibrator, and what are its uses? (21.7) **[3 & 6]**

**11.** What is the meaning of zero beat as used in connection with frequency-measuring equipment? (21.7, 21.8) **[3 & 6]**

**12.** What precautions should be taken before using a heterodyne type of frequency meter? (21.9) **[3 & 6]**

**13.** What is the device called which is used to derive a standard frequency of 10 kc from a standard-frequency oscillator operating on 100 kc? (21.7) **[4]**

**14.** What determines the fundamental operating frequency range of a multivibrator oscillator? (21.7) **[4]**

**15.** In frequency measurements using the heterodyne zero-beat method, what is the best ratio of signal emf to calibrated heterodyne oscillator emf? (21.8) **[4]**

**16.** Describe the technique used in frequency measurements employing a 100-kc oscillator, a 10-kc multivibrator, a heterodyne frequency meter of known accuracy, a suitable receiver, and a standard frequency transmission. (21.8) **[4]**

**17.** What procedure should be adopted if it is found necessary to replace a tube in a heterodyne frequency meter? (21.9) **[4]**

**18.** If a heterodyne frequency meter having a straight-line relation between frequency and dial reading has a dial reading of 31.7 for a frequency of 1,390 kc and a dial reading of 44.5 for a frequency of 1,400 kc, what is the frequency of the ninth harmonic of the frequency corresponding to a scale reading of 41.2? (21.9) **[4]**

**19.** What is the reason why certain broadcast-station frequency monitors must receive their energy from an unmodulated stage of the transmitter? (21.10) **[4]**

**20.** What is the purpose of using a frequency standard or service independent of the transmitter frequency monitor or control? (21.10) **[4]**

**21.** A station has an assigned frequency of 8,000 kc and a frequency tolerance of plus or minus 0.04 per cent. The oscillator operates at one-eighth of the output frequency. What is the maximum permitted deviation of the oscillator frequency, in cycles, which will not exceed the tolerance? (21.2) **[6]**

**22.** What are the advantages and disadvantages of using an absorption-type wavemeter in comparison with other types of frequency meters? (21.3) **[6]**

**23.** If a wavemeter having an error proportional to the frequency is accurate to 20 cycles when set at 1,000 kc, what is its error when set at 1,250 kc? (21.3) **[6]**

**24.** Do oscillators operating on adjacent frequencies have a tendency to synchronize oscillation or drift apart in frequency? (21.9) **[6]**

**25.** An absorption-type wavemeter indicates that the approximate frequency of a ship transmitter is 500 kc and at the same time the transmitter signal produces a zero beat on an accurately calibrated heterodyne frequency meter at a dial reading of 374.1. The frequency-meter calibration book indicates dial readings of 367.0, 371.5, and 376 for frequencies of 499.4, 499.6, and 499.8 kc, respectively. What is the frequency of the ship transmitter? (21.9) **[6]**

**26.** A certain frequency meter contains a crystal oscillator, a variable oscillator, and a detector. What is the purpose of each of these stages in the frequency meter? (2.19) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**1.** Draw a simple schematic diagram of a wavemeter with an indicating device. (21.3)

**2.** Given a transmitter frequency tolerance of $\pm X$ kc and a maximum audio frequency in the modulation system of $Y$ cycles, how close to the edge of an amateur band may one operate an amplitude-modulated radiotelephone transmitter? (21.11)

**3.** With a frequency meter having a possible error of 1 per cent, to what frequency could you safely set your radiotelegraph transmitter and still be as near the lower edge of the 7–7.3-Mc band as possible? (21.11)

**4.** A crystal manufacturer supplies crystals calibrated to within 0.05 per cent of the frequency specified on them. If it is desired to operate as near the 3,500-kc end of the 3,500–4,000-kc amateur band as possible, what frequency, to the nearest kilocycle, may you order and still be sure to be within the band, assuming circuit constants and temperatures may vary the frequency of the crystal no more than 1 kc? (21.11)

# CHAPTER 22

# BATTERIES

**22.1 A, B, and C Batteries.** An electric *battery* is a combination of two or more electrochemical *cells*. A cell is either not rechargeable, and called a *primary* cell, or is rechargeable and called a *secondary* cell. Cells and batteries store energy in chemical form in such a way that they can produce electric energy when required to.

Whenever a direct current or voltage is required, a cell or battery can be used as the power supply. In radio, batteries used to heat a tube filament are called A batteries; when used to supply plate potential they are called B batteries; and when they supply grid-bias voltage they are called C batteries. Either primary or secondary cells may be used as A, B, or C batteries. In general, an A battery delivers a relatively high current at a low voltage. A B battery has a high voltage but delivers a low current. C batteries may provide a low voltage with little or no current drain.

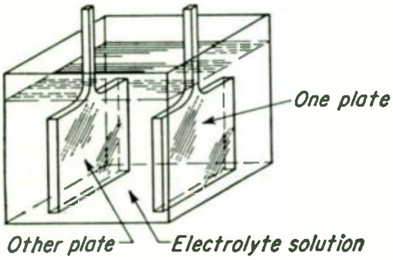


FIG. 22.1. Basic electric cell, consisting of two dissimilar plates and an acidic or basic electrolyte.

**22.2 Primary Cells.** Almost any two *dissimilar* metals or conductors immersed in a dilute acid or alkaline solution will produce a difference of potential between them (Fig. 22.1). The chemical action that will take place in such a cell produces a negative charge on one of the plates and a positive charge on the other. The solution into which the plates are immersed is known as an *electrolyte*. Such a cell may produce a few tenths of a volt to nearly 3 volts, depending upon the metals and chemicals used. Unless the materials employed are selected properly, a continuous chemical action will take place and the cell will wear itself out in a short time.

When carbon is selected as the positive plate or pole, zinc as the negative plate or pole, and a solution of sal ammoniac and zinc chloride as the electrolyte, a cell known as a *Leclanché* cell is produced that gives 1.5 volts when new. This cell will slow or reduce its chemical action during periods when not in use to such an extent that it may retain a nearly full charge from one to about three years if not operated.

When the Leclanché cell is under load and in use, the chemical action produces hydrogen atoms at the positive plate. This forms a nonconductive hydrogen-gas sheath around the surface of the plate, and the current flow of the cell is hindered. The cell is said to be *polarized* by the gas.

The hydrogen gas can be made to combine with oxygen to form water by adding manganese dioxide, which is rich in oxygen, to the electrolyte. In this way, the cell is depolarized and a relatively heavier current can flow through it. This is the basic theory of operation of the common *dry cell*, which is actually only dry when seen from the outside (similar to the "dry" electrolytic capacitors that have a damp electrolyte in them but by careful packaging present a dry appearance to the viewer).

Dry cells are made in three basic forms, illustrated in Fig. 22.2.

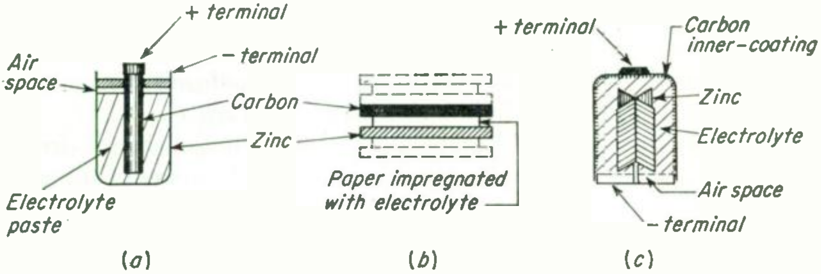


FIG. 22.2. Different dry-cell constructions. (*a*) Older, carbon-rod cell. (*b*) Layer-built type. (*c*) Inside-out cell.

The first and oldest form uses a cylindrical zinc can as the negative pole. A mixture of ground carbon, manganese dioxide, sal ammoniac, and zinc chloride forms the thick black paste electrolyte nearly filling the can. A carbon rod is used as the positive pole and is held in the center of the electrolyte. A layer of sealing wax seals the top of the cell. A small air space is left between the sealing wax and the electrolyte. The cell is usually covered with cardboard or other protective and insulating covering.

When packaging several cylindrical cells of this type to form a battery, the space between cylinders is wasted. To reduce this, the cells may be constructed in layers, as indicated.

The latest form is the *inside-out* dry cell. It uses an outer cylinder with a coating of carbon on its inner surface. A connection from the carbon coating is brought up to the top of the cell as the positive connection. The same type of thick-paste electrolyte is used as in other cells. The negative plate consists of a sheet-zinc structure extending up into the electrolyte. A lead from the zinc is connected to the metal base of the cell to form the negative pole.

As the chemical action of any dry cell continues, the zinc is eaten away by chemical action with the electrolyte. In zinc-can-type cells this produces holes in the can and electrolyte oozes out, or the side of the cell may swell. The inside-out cell has the carbon, which is not affected by the chemical reaction, on the outside and the chemically active zinc inside. Thus, the cell does not puncture and leak.

The condition of charge of a dry cell is determined by measuring the voltage across it, preferably with a load on the cell. A new cell has a voltage of slightly more than 1.5 volts. A 30-cell battery should read at least 45 volts. As a cell ages, the voltage across it decreases. When the voltage without load drops approximately 15 per cent, or to about 1.27 volts, it is usually considered as being near the end of its chemical life. Under load the cell voltage drops more, and a cell may not be considered as nearing the end of its chemical life until it drops below 0.9 volt. When it reaches the end of its chemical life, a primary cell is discarded. *Recharging* such a cell by forcing a current backward through it may depolarize it somewhat but does not actually recharge it by returning the chemicals to their original form. (This cell must not be confused with a newer, completely sealed nickel-cadmium *rechargeable dry cell.*)

A B battery in a receiver may begin to produce noise when it drops in potential, because of small instantaneous variations in current through the cell. As a result, a 45-volt B battery may be near the end of its useful life when it reads 38 to 40 volts under normal load.

The *shelf life* of a dry cell (period it may be stored before using) is increased by storing it in a cool place. In the normal room this is either on or near the floor. If the cell is allowed to heat, the internal chemical reactions increase and the cell life decreases. Although dry cells are not damaged if exposed to low temperatures, they will not produce their normal current while extremely cold. A large type-G dry cell, 1¼ by 4 in., has a short-circuit current of about 30 amp. The largest-size flashlight cell, type D, has a short-circuit current of about 6 amp. The smaller sizes have proportionately less. A short-circuit test is not a true indication of the life expectancy of a dry cell and is not recommended.

Another type of primary cell, developed during the Second World War, is known as the *Ruben cell*, or the *alkaline mercuric oxide* cell. The main ingredients are zinc, mercuric oxide, and potassium hydroxide. The cell has a no-load voltage of 1.34 volts. Under normal loads the voltage will range from 1.25 to 1.31 volts. Whereas the Leclanché-type-cell voltage drops off more or less constantly with use, the Ruben cell holds its output voltage relatively constant over most of its full life, and then drops off sharply. The cell has a good shelf life and is highly efficient, utilizing 80 to 90 per cent of the possible chemical energy in it. It has four to seven times the current capacity of other dry cells for an equal volume, making it suitable for small hearing aids and transistorized portable equipment.

**22.3 The Lead-Acid Battery.** The secondary cell in most general use has a lead dioxide (sometimes called lead peroxide) positive plate, a pure, spongy lead negative plate, and an electrolyte of dilute sulfuric acid (Fig. 22.3). A group of these cells in series forms a *lead-acid* battery. These batteries are used in automobiles and as emergency power supplies for receivers and radio equipment of many types on land and at sea.

In practice, several positive plates are attached together, as are several negative plates, with the two sets interleaved as indicated in Fig. 22.4. Since a slightly greater negative plate area than positive is required, there is always one more negative plate. Thus the outer plates are always negative.

To prevent the positive and negative plates from rubbing against each other and shorting the cell, thin wooden, glass, rubber, or plastic *separator* sheets (not shown in the illustration) are inserted between each positive and negative plate. The separators are vertically grooved to allow the gas bubbles that form on the plates during the charging process to float to the surface and escape from the cell.

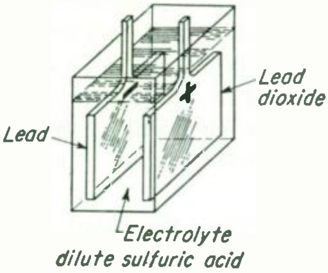


FIG. 22.3. Basic lead-acid cell, consisting of a negative and positive plate and electrolyte.

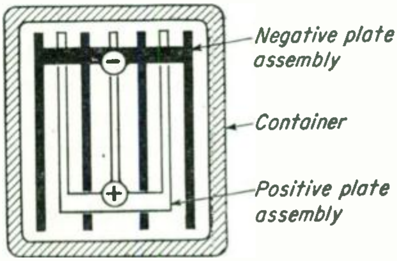


FIG. 22.4. Interleaved lead-acid cell plates in a container, top view. Separators not shown.

The plates and electrolyte are enclosed in a hard rubber container or, in some stationary applications, in glass containers. A screw-type cap in the top cover of each cell allows access to the electrolyte, which must be maintained at a depth of ¼ to ½ in. above the plates at all times.

When a load is connected across a charged lead-acid cell, the chemical action that takes place internally can be represented by

| | | | |
|---|---|---|---|
| (+ plate) | lead dioxide | → | lead sulfate |
| (Electrolyte) | sulfuric acid | → | water |
| (− plate) | lead | → | lead sulfate |

During the time the cell is discharging, the sulfuric acid is combining chemically with both the lead dioxide and the pure lead plates, changing them to lead sulfate. When both have been changed to lead sulfate, the plates are no longer different materials, no potential difference is produced between them, and the battery is completely *dead*. The sulfuric acid, having combined with the plates, leaves only water as the electrolyte.

In actual practice, a lead-acid cell should never be allowed to become completely discharged, because it will become irreparably damaged. During discharge, lead sulfate forms as crystals on the plates, causing them to swell. This swelling will bend, or *buckle*, the plates, possibly splitting the separators or even the battery case itself. When the amount of sulfuric acid in the electrolyte drops to a certain percentage, the battery must be recharged.

To recharge a lead-acid cell, a source of d-c emf greater than that of the battery must be used. This will force a current in a backward direction through the battery, reversing the chemical action of discharging, explained above. The sulfate in both plates is chemically changed back to sulfuric acid in the electrolyte, leaving the positive-plate lead dioxide and the negative-plate pure lead. When this occurs, the battery is again fully charged.

This type of battery must be recharged as soon as possible after being discharged. The lead sulfate first forms what may be thought of as *soft* crystals on the plates. If allowed to age, the crystals grow and turn *hard*. The soft crystals respond to recharging and easily change back into the sulfuric acid, lead, and lead dioxide. If allowed to harden, the crystals require a long slow recharging to complete the chemical reversal. It becomes impossible to recharge completely a battery that has become *sulfated* in this manner.

Jarring a discharged battery, particularly while in the sulfated state, knocks some of the crystals off of the plates and they fall to the bottom of the cell. This active material is lost forever to the plates. An old battery will be found to have a thick layer of this sludge in the pockets built into the case beneath the plates. When the sludge builds up to the point that it covers the bottom surfaces of any two positive and negative plates, the cell becomes shorted and useless. The cell also becomes shorted if a separator cracks and the sludge can form a conducting path through the separator. It can be understood why automobile or emergency batteries that are allowed to remain in a semicharged or discharged state for long periods may have short lives and lose their capacity.

A battery becomes warm if charged or discharged rapidly. This heat is caused by the internal chemical action and the $I^2R$ loss of the current that flows through the lead and antimony *grids* that hold the active materials of the plates. Some batteries add silver and nickel to the grids to decrease the resistance in them and allow a greater current flow and less heat loss. A battery should not be discharged or recharged at a rate that will heat it to more than 110°F.

**22.4 Specific Gravity of a Lead-Acid Cell.** A voltage reading of a lead-acid cell under a heavy load gives a fair indication of its state of charge, but the measurement of the *specific gravity* of the electrolyte is more reliable.

The specific gravity of any liquid or substance is a comparison of its weight to the weight of a similar volume of water. Water has 1.000 sp gr. Chemically pure sulfuric acid has 1.835 sp gr, since it weighs 1.835 times as much as water by volume. The specific gravity of the electrolyte solution in a lead-acid cell ranges from 1.210 to 1.300 for new, fully charged batteries. This is about 20 per cent acid and 80 per cent water. The higher the specific gravity, the less internal resistance of the cell and the higher the possible output current. To start an automobile motor, 150 to 250 amp may be needed. As a result, automobile batteries have a fully charged specific gravity of 1.280 to 1.300. However, the higher the specific gravity, the more active the chemical action and the faster the battery will tend to discharge itself and eventually shorten its life.

When used in stationary services, as standby or emergency power supplies, or in any service where a relatively low-current drain over a long period of time is required, lead-acid batteries usually have a full charge of only 1.210 to 1.220 sp gr. The lower specific gravity results in longer life, but the internal resistance is greater and less instantaneous current drain is possible.

The voltage of a lead-acid cell varies somewhat with the specific gravity. With a 1.300 sp gr a cell has approximately 2.2 volts. A 1.280 sp gr produces about 2.1 volts. A 1.220 sp gr produces about 2.05 volts.

In most cases, a battery should be recharged before its specific gravity drops 100 points, unless the battery is discharging rapidly, when 125 points may be a safe value. Usually, a 1.280-sp gr battery should be recharged when it reaches a 1.180 sp gr.

The electrolyte in a lead-acid cell can freeze, but if the battery is fully charged and the specific gravity is 1.280, the freezing temperature of the electrolyte is approximately −90°F. With a 1.180 sp gr the freezing point is approximately −6°F. With a 1.100 sp gr the electrolyte will freeze at about 18°F. If the cell does freeze, it may split its case and be ruined. A trickle-charging battery will not freeze, because of the internal heat developed by the charging process.

Cold prevents the chemical action of a battery from occurring rapidly, but does not necessarily damage it. A semicharged battery may not be able to develop enough current to start an automobile on a cold winter day, whereas it might have started it on a warm summer day.

**22.5 The Hydrometer.** Specific gravity is measured with a *hydrometer*. Hydrometers in general use are of the syringe type (Fig. 22.5), with a compressible rubber bulb at the top, a glass barrel, and a rubber hose at the bottom of the barrel. A bottom-weighted, calibrated, thin, hollow glass float is inside the barrel.

To measure the specific gravity, the screw cap is removed from the top of the cell and the hydrometer hose is dipped into the electrolyte above the plates. The bulb is compressed *slowly* and then released, so that some of the electrolyte is drawn into the barrel. The calibrated float rides in the solution as shown. The heavier the electrolyte, the higher the float rides. The specific gravity is indicated by the highest calibration that is visible below the surface of the electrolyte, about 1.280 in the illustration.

Many hydrometers have a thermometer included in the base of the barrel that indicates the temperature of the electrolyte being measured. Since heating the electrolyte causes it to expand, warm electrolyte is lighter per unit volume. Therefore the warmer the solution (above 70°), the greater the correction to *add* to the specific-gravity reading to express what it will be at the standard reference temperature of 70°F (3°F = Sp gr change of 0.001).

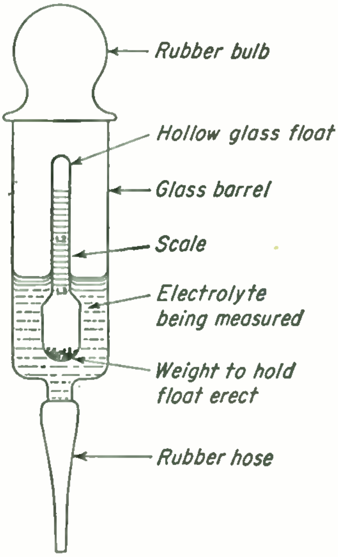


FIG. 22.5. Hydrometer, used to measure specific gravity of a solution.

If the temperature of the electrolyte is less than 70°, the solution is more dense and the correction must be subtracted from the hydrometer indication. The proper corrections are marked on the thermometer scale.

When taking hydrometer readings, care must be taken to prevent drops of the electrolyte from spilling on the top of the cells or touching clothing or hands. The sulfuric acid is very corrosive and will eat holes in fabrics, particularly cottons, and will burn human skin. When an acid solution is spilled on flesh or clothing, immediate flushing with water is recommended. The acid can then be counteracted by applying a weak base or alkali solution, such as dilute ammonia or baking soda.

Batteries that are frequently tested for specific gravity may lose enough electrolyte by the drop or two taken out in the hydrometer each time the battery is measured to require additional sulfuric acid after a period of time. When the fully charged specific-gravity reading drops 20 or 30 points, it may be necessary to add sulfuric acid to the electrolyte. (CAUTION: When mixing electrolyte always pour the acid into the water. Never pour water into concentrated acid or the heat produced by ionization will cause a corrosive steam and acid explosion.) Actually, it is rarely necessary to replace electrolyte in batteries.

**22.6 Water for Batteries.** The caps on the tops of storage cells usually have a tiny hole in them to relieve any internal gas pressure that may be developed but still prevent dirt and foreign objects from falling into the electrolyte. There is little evaporation of water from a battery unless it is allowed to become overheated. However, whenever a battery is charging, the chemical action that occurs produces hydrogen gas on one plate and oxygen gas on the other. These gases bubble to the surface and then out through the vent hole in the cap. Thus, water ($H_2O$) is lost to the cell when the gases leave.

The water that escapes must be replaced to maintain the electrolyte level at the desired depth above the plates. While there are many arguments as to the purity of the water used to replace that lost during charging, the fact remains that almost any impurity in the added water will chemically combine with the sulfuric acid, or the plates, and form a stable compound that will not enter into the charge or discharge action of the battery. The presence of impurities on a cell plate, either placed there during manufacture or added later, produces a *local action* at that point. The part of the plate involved in the local action is effectively lost, and the cell has decreased its capacity to some extent. To be safe, only distilled water should be added to a cell. Distilled water should be stored or carried in either glass or rubber containers, not metal containers (excepting lead). Boiling water has no chemical purifying action, but the steam that rises can be condensed in a glass tube, and the resulting distilled water is pure enough to use in batteries.

**22.7 Capacity of a Battery.** The *capacity* of a battery is rated in ampere-hours. The number of ampere-hours produced in an 8-hr period to bring a lead-acid cell down to 1.75 volts is one standard of measurement used. If the battery is forced to discharge faster than this, the number of ampere-hours produced will be somewhat less. If allowed to discharge slower, the number of ampere-hours obtainable from the battery will be considerably greater.

The capacity of a storage battery determines how long it will operate at a given discharge rate. An 80-amp-hr battery must be recharged after 8 hr of an average 10-amp discharge. When fully charged such a battery may be capable of 1,000-amp discharge for a short period without damaging it. When the heat of the cell rises to more than 110°F, the discharge must be stopped.

The capacity required of a storage battery to operate an emergency radiotelegraph transmitter for 6 hr, assuming a continuous transmitter load of 70 per cent of the key-locked demand of 40-amp (current required with the telegraph key held down) plus a continuous emergency-light load of 1.5 amp, can be computed:

$$\begin{aligned}\text{Capacity} &= \text{amperes} \times \text{hours}\\ &= 70\% \times 40 \text{ amp} \times 6 \text{ hr plus } (1.5 \text{ amp} \times 6 \text{ hr})\\ &= 0.7 \times 40 \times 6 + (1.5 \times 6) = 168 + 9 = 177 \text{ amp-hr}\end{aligned}$$

When a lead-acid cell is constructed, pink lead oxide is molded into the grids of the positive plates. The battery must then be *formed* by *cycling*, which is alternately charging and discharging the cells until the lead oxide is changed to brown lead dioxide. After each cycle the ampere-hour output of the battery increases. After the battery is bought by the user, its capacity may increase for a few discharge-charge cycles. With sufficient cycling, all the lead oxide is finally converted to lead dioxide and the battery reaches its maximum capacity.

**22.8 Charging Batteries.** When a current is forced backward through a lead-acid battery, the discharge chemical action is reversed and the battery is recharged. There are several methods used to obtain the charging current. Figure 22.6 illustrates a *constant-voltage* charging circuit. Note the positive-to-positive and negative-to-negative connection of the battery and charging source.

In this circuit, the d-c generator has an output voltage between 5 and 25 per cent greater than the full-charge voltage of the battery, depending on the rate of charge desired. When the battery is discharged, the voltage differential between battery and charging source is great, and relatively high current flows. As the battery becomes charged, the differential between battery and charging source is less, and less charging current is produced.

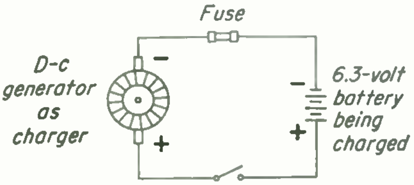


FIG. 22.6. Constant-voltage battery-charging circuit.

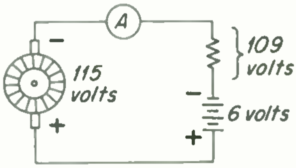


FIG. 22.7. Constant-current battery-charging circuit.

*Example:* This type of charging circuit can be used with a discharged storage battery of three cells having an open-circuit voltage of 1.8 volts per cell and an internal resistance of 0.1 ohm per cell. The potential needed to produce an initial charging rate of 10 amp for this 5.4-volt 0.3-ohm internal-resistance battery will be the voltage in excess of 5.4 that will produce 10 amp through the 0.3 ohm, or

$$\begin{aligned} E_r = IR = 10(0.3) &= 3 \text{ volts} \\ E_{bat} &= 5.4 \text{ volts} \\ E_{chg} = 3 + 5.4 &= 8.4 \text{ volts} \end{aligned}$$

A *constant-current* circuit is shown in Fig. 22.7. In this circuit the charging source has a potential several times that of the battery. The charging resistor limits the value of current that will flow. With low resistance the charging current will be high. With high resistance the charging current will be low. Since the difference of battery voltage between full charge and discharge is relatively small in comparison with the charging voltage, the charging current will decrease very little as the battery nears full charge. If the current is 2 amp or less, it may be known as a *trickle* charge. Batteries used only intermittently may be given a constant, low trickle charge.

*Example:* If a 3-amp charging rate is required, the value of the required charging resistance is computed by Ohm's law. If the battery has approximately 6 volts and the source 115 volts, the charging resistance must produce 115 volts less 6 volts, or a 109-volt drop across it when 3 amp flows:

$$R = \frac{E}{I} = \frac{109}{3} = 36.3 \text{ ohms}$$

The minimum power rating of the charging resistor will be

$$P = EI = 109(3) = 327 \text{ watts}$$

A 500-watt resistor would probably be used to allow a margin of safety for the resistance.

*Example:* A 12.5-volt battery requires a 0.5-amp trickle charge. If the source voltage is 110 volts, what is the value of the charging resistor?

$$110 - 12.5 = 97.5 \text{ volts across the resistor}$$
$$R = \frac{E}{I} = \frac{97.5}{0.5} = 195 \text{ ohms}$$

In an emergency, a 100-watt 120-volt light in series with a 6-volt battery and a 100- to 120-volt d-c line will produce approximately a 1-amp charging rate; a 200-watt light will result in approximately a 2-amp rate; and so on.

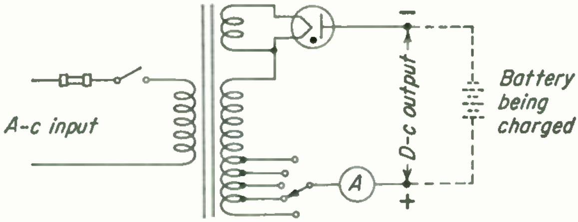


FIG. 22.8. Electronic-tube battery-charging circuit.

An electronic battery charger is shown in Fig. 22.8. It consists of a half-wave rectifier circuit using a multitapped transformer and a round, glass-enveloped, argon-gas, tungsten-filament, carbon-plate diode tube. When the voltage differential between the a-c voltage of the transformer secondary and the voltage of the battery exceeds the ionization potential of the tube, current flows through the circuit, charging the battery. Two tubes can be used in a full-wave center-tap circuit, similar to the circuits shown in the chapter on Power Supplies. Two tubes in full wave will give twice the average charging current of the half-wave circuit with the same a-c voltage per tube. Capacitive filter must not be used with gaseous tubes. Diode rectifiers used as battery chargers cannot discharge the battery if the output voltage falls below the battery voltage since current cannot flow backward through a diode. A d-c generator used to charge a battery will operate as a motor if its output voltage drops below the battery voltage and will discharge the battery.

Quick-charge automobile-battery chargers may use a starting current of 60 amp or more. These chargers can use high-current d-c generators, or copper-oxide or selenium-type dry rectifiers, in a full-wave center-tap or bridge-rectifier circuit.

There are different values of charging current used with lead-acid batteries. A trickle charge is usually about one hundredth of the ampere-hour rating. Thus, a 120-amp-hr battery may use a 1.2-amp trickle charge.

A low starting charge may be about one-eighth of the ampere-hour rating of the battery, while a high starting charge may be as much as one-half of the ampere-hour rating.

As charging progresses, the charging rate must be tapered off to prevent excessive heat and electrolysis (loss of water due to electrolytic action).

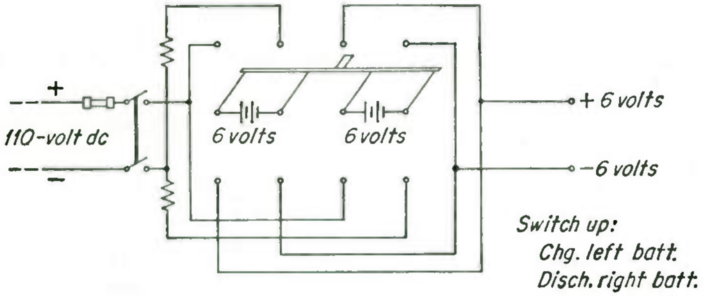


FIG. 22.9. Circuit to charge one battery while the other is being discharged.

When the battery becomes fully charged, there is no further chemical action between the plates and electrolyte but the water of the electrolyte continues to be driven off in the form of hydrogen and oxygen gas. A constant watch should be maintained to determine the amount of gassing produced. If no hydrometer is available, an indication of probable full charge is given by rapid gassing with a low charging rate. A trickle charge of several hours is usually beneficial at the end of a rapid charging period.

Frequently, it is possible to operate a receiver or transmitter from a storage battery and charge the battery at the same time. In this case, the battery acts as a voltage-regulating device. The energy to operate the equipment is coming from the charging source, but if the charging source drops off, the battery feeds energy to the equipment. This is essentially what happens in automobile radio equipment.

When a constant radio watch is maintained, using batteries to heat the receiver filaments, as at sea, it is possible to use one battery and charge another at the same time. When one becomes discharged, the other is switched in and the first is placed on charge again. Figure 22.9 shows a charging circuit of this type.

In the charging circuit of Fig. 22.7, if the polarity of the charging source is inadvertently reversed, the battery voltage and the charging source will be in series and a higher current will flow. In this *constant-current* charger the current may not increase sufficiently to burn out the fuse or actuate an overload relay, but the battery will rapidly discharge. In this case, the voltage across the battery will read less than normal, whereas the voltage across a charging battery will always be higher than the full-charge voltage.

With a *constant-voltage* charger, incorrect polarity across the battery will produce an extremely high current and the overload relay will refuse to stay closed, or the fuse in the circuit will burn out.

If one of the cells of a battery becomes faulty, shorts out, and discharges itself, the cell then acts as a series resistance. When the battery is under a load, the voltage drop across this cell will be found to be the reverse of its original polarity. This can be explained by reference to Fig. 22.10. The dead cell is represented by a resistor. If it is remembered that current flows through a resistor from its negative terminal to its positive, the polarity will be understood as shown. The battery will produce very little output current with one dead cell. The dead cell may even charge and hold a reversed polarity for a time.

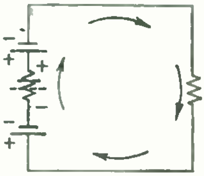


FIG. 22.10. A discharging circuit with one cell dead.

Another test for a dead cell is gas produced in it by electrolysis when the battery is under a heavy load. When a copper bar is held across the terminals of a 6-volt storage battery and one of the cells gases profusely, that cell is dead.

There are several simple methods of determining the polarity of a d-c line. The line can be checked with a voltmeter. When the voltmeter reads correctly, the terminal of the meter marked positive will be connected to the line with the positive potential. When a wire from the positive terminal and a wire from the negative terminal of a source of direct current are held in a glass of salt water, the wire having the greater number of bubbles developed around it by electrolysis is the negative terminal. If two *copper* wires are stuck into a raw potato, a blue color will develop around the positively charged wire.

**22.9 Maintaining Lead-Acid Cells.** There are several important points regarding the maintenance of lead-acid batteries:

1. Keep flames and sparks away from a charging or recently charged battery. The mixture of hydrogen and oxygen gases given off during charge is highly explosive.
2. Be careful when using a hydrometer. Avoid spilling drops of acid electrolyte.
3. Keep the tops of the cells clean and free from moisture to prevent leakage across the surface of the cell top and to prevent dust and dirt from falling into the electrolyte.
4. Keep the terminals of cells coated with petroleum jelly (Vaseline) to prevent the formation of corrosion.
5. Keep cell tops on while charging to prevent electrolyte droplets from spraying out of the cell.
6. Maintain the proper electrolyte level.
7. Use only distilled water to replace lost water.
8. Take a hydrometer reading at least once a week.
9. Test-operate the battery at least once a month if possible.
10. Trickle-charge unused batteries at least one full day a month.
11. Always bring batteries up to full charge after a discharge.
12. Use only *chemically pure* sulfuric acid (diluted) if it should become necessary to add new electrolyte.
13. Provide adequate ventilation while charging, since the gas given off is highly explosive and contains some acid vapor.
14. If a battery box is used, clean the inside surfaces once a year to remove sulfuric acid droplets that may form during charging.
15. Do not overcharge a battery, since overcharging affects the grids.
16. Batteries may be stored several months if first fully charged and then kept refrigerated (not frozen).
17. If necessary to store for a year or more, batteries should be fully charged, the electrolyte removed, the cells flushed with clear water, and then filled with distilled water.
18. The plates and separators must never be allowed to dry.
19. When removing caps, do not turn them over or place them on an unclean surface. This will prevent the transportation of foreign materials into the cells when the caps are replaced.

**22.10 Edison Batteries.** A lighter, more rugged cell than the lead-acid is the *Edison*, also known as the *nickel-iron-alkaline* cell. When fully charged, it has a positive plate made up of nickel and nickel hydrate, in small perforated nickel-plated steel tubes. It has a negative plate with iron as the active material, in small pockets in a nickel-plated steel plate. The electrolyte is composed of potassium hydroxide, a little lithium hydrate, and distilled water.

While discharging, the electrolyte transfers oxygen, chemically, from the nickel-oxide positive plate to the iron negative plate, producing iron

nickel +
iron —

oxide (rust). When recharged, the iron oxide is reduced to iron, and the oxygen appears in the positive plate as a higher oxide of nickel.

The electrolyte has about 1.220 sp gr, but does not change during charge and discharge. Therefore a hydrometer is useless in determining the state of charge. Instead, the voltage of the cell, measured under load, gives the best indication of state of charge An ampere-hour meter may also be used.

The Edison cell has a fully charged voltage of approximately 1.4 volts with no load. When a load is applied, the voltage decreases rapidly to about 1.3 volts. As the discharge progresses, the voltage drops off more or less linearly until a voltage of approximately 1.1 volts is reached. After this, the voltage drops rapidly. When the voltage reaches 1.0 or 0.9 volt the cell should be recharged.

The Edison cell can be completely discharged without damaging it. In fact, it can be recharged to the opposite polarity and will return to normal operation when charged properly. It may be stored for any length of time in a completely discharged condition without damage.

Whereas the lead-acid battery uses a highly corrosive acid electrolyte, the Edison cell has a somewhat less corrosive alkaline electrolyte. The lead-acid battery can produce high current with its low internal resistance. The Edison cell has approximately three times the internal resistance of a lead-acid cell of the same capacity, and therefore produces less current under load.

While charging, the Edison cell also produces hydrogen and oxygen gases, and as a result the electrolyte requires replenishing with distilled water after charging. The electrolyte should not be allowed to drop below the level of the plates.

The capacity of an Edison cell, or battery, is measured in ampere-hours. Loss of capacity of this cell will result if an excessively high discharge rate is used. If the battery is trickle-charged, it will not reach full charge. If the electrolyte becomes contaminated, the capacity will be lowered. If the battery becomes excessively hot, the *capacity* will be less, although the current output will be greater.

To prevent absorption of carbon dioxide by the electrolyte from the air, Edison cells have capped vents that prevent entrance of outside air into the cell.

**22.11 Nickel-Cadmium Cells.** A cell similar to the Edison, using cadmium instead of iron, is known as a *nickel-cadmium-alkaline* cell. It has approximately the same characteristics as the Edison cell.

Lately, nickel-cadmium cells have been developed that can be produced in a sealed container, since there is no gassing during their charge periods. They have relatively low internal resistance and cannot be overcharged. Small units are known as *rechargeable dry cells.* Larger units are also manufactured.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** What will be the result of discharging a lead-acid storage cell at an excessively high current rate? (22.3) [3]

**2.** What value of resistance should be connected in series with a 6-volt battery that is to be charged at a 3-amp rate from a 115-volt d-c line? (22.8) [3]

**3.** Describe the construction and characteristics of a battery-charging rectifier tube. (22.8) [3]

**4.** How does a primary cell differ from a secondary cell? (22.1–22.3) [3 & 6]

**5.** What form of energy is stored in lead-type storage batteries? (22.1) [3 & 6]

**6.** Describe an electrolyte. (22.2–22.4, 22.10) [3 & 6]

**7.** What material is used in the electrodes of a common dry cell? (22.2) [3 & 6]

**8.** What is polarization as applied to a primary cell, and how may its effect be counteracted? (22.2) $H_2$ bubbles on + plate [3 & 6]

**9.** How may a dry cell be tested to determine its condition? (22.2) [illegible] [3 & 6]

**10.** What is the chemical composition of the positive plate of a lead-acid cell? The negative plate? The electrolyte? (22.3, 22.4) [3 & 6]

**11.** What may cause sulfation of a lead-acid storage cell? (22.3) [3 & 6]

**12.** What are the effects of sulfation? (22.3) [3 & 6]

**13.** What may cause the plates of a lead-acid cell to buckle? over discharge (22.3) [3 & 6]

**14.** What is the cause of the heat developed within a storage cell under charge or discharge conditions? (22.3) [3 & 6]

**15.** What is the approximate voltage of a lead-acid cell when fully charged? (22.4) [3 & 6]

**16.** Why is low internal resistance desirable in a storage cell? (22.4) [3 & 6]

**17.** Explain how the state of charge of a lead-acid storage cell is determined. (22.5) [3 & 6]

**18.** What chemical will neutralize a storage-cell acid electrolyte? baking soda (22.5) [3 & 6]

**19.** What is the effect of local action in a lead-acid storage cell and how may it be compensated? (22.6) reduces capacity of cell, use only distilled water [3 & 6]

**20.** Why should distilled water be added to a lead-acid storage cell and for what purpose? (22.6) [3 & 6]

**21.** If the charging current through a storage battery is maintained at the normal rate but its polarity is reversed, what will result? (22.8) voltage will drop [3 & 6]

rapid gassing at low charge

**22.** How may the polarity of the charging source to be used with a storage battery be determined? (22.8) [3 & 6]

**23.** Describe the care which should be given a group of storage cells to maintain them in good operating condition. (22.9) [3 & 6]

**24.** Why should adequate ventilation be provided in the room housing a large group of storage cells? (22.9) [3 & 6]

**25.** What steps may be taken to prevent corrosion of lead-acid storage-cell terminals? (22.9) [3 & 6]

volt meter

**26.** Explain how the condition of charge of an Edison cell is best determined. (22.10) [3 & 6]

+ nickel hydroxide

− iron

potassium hydroxide

**27.** What is the chemical composition of the active material composing the positive plate of the Edison cell? The negative plate? The electrolyte? (22.10) [3 & 6]

**28.** Describe three causes of a decrease in capacity of an Edison-type storage cell. (22.10) [3 & 6]

**29.** What is an A, a B, and a C battery? (22.1) [6]

**30.** How can the condition of charge of dry B batteries be determined? (22.2) [6] keep cool

**31.** What precaution should be observed in storing spare B batteries? (22.2) [6]

**32.** What is the meaning of electrolyte? List two types of radio equipment in which it may be used. (22.2) [6]

**33.** Draw a sketch showing the construction of a storage cell. (22.3) [6]

**34.** Define specific gravity as used in reference to storage batteries. (22.4) [6]

**35.** Your emergency lead-acid storage battery has 1.120 sp gr. What should be done? (22.4) charge it [6]

**36.** What is the effect of low temperatures upon the operation of a lead-acid storage battery? (22.4) lower capac [6]

**37.** What special precautions should be taken when lead-acid storage cells are subject to low temperatures? (22.5) prevent freezing [6]

**38.** Why should care be taken in the selection of water to be added to a storage cell to replace that lost by evaporation? (22.6) to prevent local action [6]

**39.** What should be done if the electrolyte in a lead-acid storage cell becomes low because of evaporation? (22.6, 22.9) [6]

**40.** If you found that it was impossible to keep the receiver-storage A battery charged and at the same time maintain the required watch period, what remedy might be found? (22.8) [6]

**41.** What capacity storage battery is required to operate a 50-watt emergency radiotelegraph transmitter for 6 hr, assuming a continuous transmitter load of 70 per cent of the key-locked demand of 40 amp? The emergency light load is 1.5 amp. (22.7) [6]

**42.** Lacking a hydrometer, how may the state of charge of a storage battery be determined? (22.8) [6]

**43.** If you place the emergency batteries on charge and the overload circuit breakers refuse to stay closed, what is the trouble? (22.8) reverse polarity [6]

**44.** Why does the charging rate to a storage cell, being charged from a fixed voltage source, decrease as charging progresses? (22.8) voltage increases [6]

**45.** What is indicated if, in testing a storage battery, the voltage polarity of some of the cells in the battery is found reversed? (22.8) [6]

**46.** Draw a diagram of the charging circuits of two batteries using a four-pole double-throw switch such that while one battery is on charge the other is on discharge. Indicate the d-c power source, voltage-dropping resistors, and connections to the battery load. (22.8) [6]

**47.** Describe the construction and operation of rectifier tubes that are used for charging batteries. Draw a diagram of a battery-charging circuit employing such a tube. (22.8) [6]

**48.** A storage battery with a terminal voltage of 12.5 is to be trickle-charged at a 0.5-amp rate. What value of resistance should be connected in series with the battery if the trickle charge is to be made from a 110-volt d-c line? (22.8) [6]

**49.** A discharged storage battery of three cells has an open-circuit voltage of 1.8 volts per cell and an internal resistance of 0.1 ohm per cell. What potential is necessary to produce an initial charging rate of 10 amp? (22.8) ? V [6]

**50.** If an auxiliary storage battery has a voltage of 12.4 volts on open circuit and 12.2 volts when the charging switch is closed, what is the difficulty? (22.8) [6]

**51.** Why should the tops of lead-acid storage batteries be kept clean and free from moisture? (22.9) [6]

**52.** Why should an Edison storage battery not be charged at less than the normal rate specified by the manufacturer? Explain. (22.10) it will not become fully charged [6]

**53.** What are the main differences between Edison and lead-acid types of storage batteries? (22.3, 22.10) lasts longer than [illegible] [6]

not as corrosive, lower volta [illegible], up hour

# CHAPTER 23

# MOTORS AND GENERATORS

**23.1 Electrical Machines.** A motor is a *prime mover*, a device that converts energy of one form into mechanical rotational power, or *torque* (pronounced **tork**). Examples of motors are gasoline or diesel engines, which convert the expansion of gas by heating into torque; a steam engine, which converts the expansion of hot steam into torque; an electric motor, which converts electricity into twisting effort by the interaction of magnetic fields.

A generator, on the other hand, converts mechanical rotational power into electric energy and may be called a *prime source* of emf. The two basic forms are the d-c generator and the a-c generator, the latter being more correctly termed an *alternator*. All generators require a prime mover (motor) of some type to produce the rotational effort by which a conductor can be made to cut through magnetic lines of force and produce an emf. The simplest machine of the motors and generators is the alternator.

**23.2 Alternators.** An alternator consists basically of three parts: (1) a magnetic field, (2) one or more rotating conductors, (3) a mechanical means of making a continuous connection to the conductors as they rotate. A simplified alternator is pictured in Fig. 23.1.

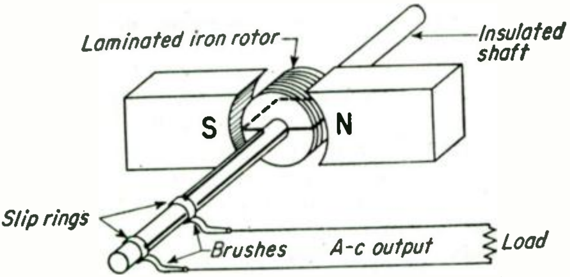


FIG. 23.1. Essential parts of a simple alternator.

The magnets, called the *field poles*, produce lines of force from north to south. The laminated soft-iron rotor presents a highly permeable path for the lines of force, resulting in fewer leakage lines and a greater magnetic-field strength in the gaps between the field-pole faces and the rotor. A conductor is wound onto the soft-iron rotor. One end of the conductor terminates at a brass *slip ring* on the insulated shaft to which the rotor is fixed. The other end of the conductor terminates at a second slip ring. Held against the slip rings by spring tension are two *brushes*, made of copper, brass, or carbon.

When the shaft is rotated by a prime mover, the iron rotor and conductor turn. The conductor moving past the field pole has an emf induced in it. As a wire rotates down past the north pole, an emf across the brushes will be in one direction (toward the reader, in the illustration). As the conductor continues on and passes upward across the face of the south pole, the same lines of force are being cut, but in the opposite direction, resulting in an opposite-polarity emf appearing at the brushes. Continuous rotation of the conductor produces continually alternating emf at the brushes.

To produce a greater emf, the rotor may be wound with a many-turn coil instead of the single-turn shown. The emf induced in each turn adds to that of all the other turns, and a much higher amplitude a-c emf is produced. The number of magnetic lines of force produced by a permanent magnet is rather limited. A much more intense field can be produced by making the field poles of iron and wrapping them with several hundred turns of wire. When the field coils are excited by a direct current, they form strong electromagnets. The greater the current flowing through the externally excited field poles, the greater the number of lines of force produced and the higher the output voltage of the rotor coil. Thus, a practical means of controlling the output emf of an alternator is to vary the d-c excitation to the field coils.

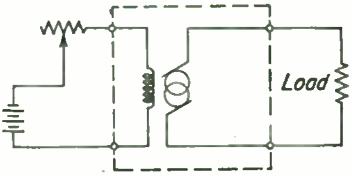


FIG. 23.2. An externally excited alternator.

Another means of varying the output voltage is to vary the speed of rotation. However, varying the speed of the rotor varies the output *frequency* as well as the amplitude, which is usually undesirable.

A diagram of a separately, or externally, excited field alternator is shown in Fig. 23.2. The two interlocked circles represent the slip rings with their brushes pressing against them. The coil represents the field windings. The rheostat is used to vary the excitation current to the field and control the output voltage. The prime mover is not indicated, but must exist.

Another form of alternator excites a pair of rotating field coils with d-c (Fig. 23.3). When excited, the rotor part becomes a strong electromagnet. In the position shown, a strong magnetic field is induced in the *stator* poles. The magnetic-field path is completed through the frame of the alternator. As the rotor moves to a point 90° from that shown, the stator poles are left without any magnetic field. Continued rotation of the rotor alternately produces and stops magnetic flux in the stator poles. The changing magnetic fields in the stator poles induce an alternating current into the turns wound around them. It is from the stator coils that the a-c emf is taken.

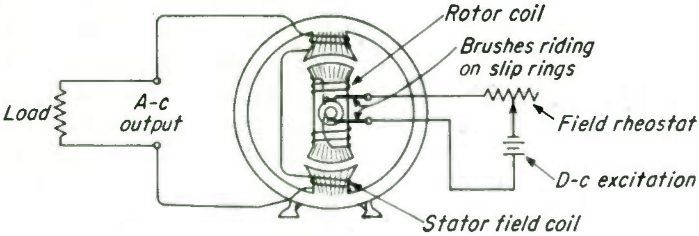


Fig. 23.3. Elementary rotating-field alternator.

In actual practice, the rotor is usually made into four-pole form, with opposite poles in parallel. Only one pair of slip rings is required. The stationary part of the machine also has four poles, with all stationary armature windings in series for maximum voltage output.

A third type of alternator is known as an *inductor alternator*, illustrated in simplified form in Fig. 23.4. With the toothed soft-iron rotor in the position shown, the d-c excitation on the stator-pole piece produces a magnetic flux that takes the path from pole 1 into tooth *A* and out of teeth *B* and *D* back to pole 1. In this condition, a maximum number of lines of force are in the iron-pole piece. When the toothed rotor moves 45°, the magnetic path between pole 1 and the rotor teeth lengthens, greatly lessening the number of lines of force in the field pole. As the rotor continues to rotate, the alternately stronger and weaker magnetism in the pole induces an a-c into the secondary winding.

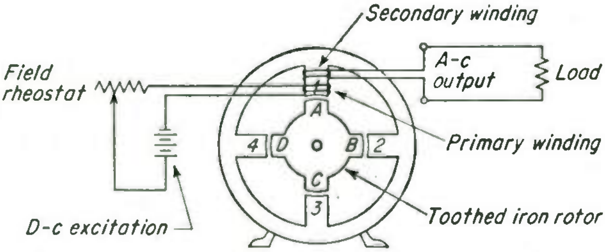


Fig. 23.4. Simplified inductor alternator.

Present in all practical machines, but not shown in the illustration, are the primary and secondary windings on the other three pole pieces. These windings are interconnected in such a manner as to add to the effect of the one pole shown.

In practical applications, inductor alternators may vary in construction from the type shown. They usually have many pairs of pole pieces, with a tooth on the rotor for each pole piece. They are generally employed when 500-cycle or higher-frequency a-c is required. Lower-frequency a-c, 50 to 60 cycles, is normally produced by rotary *field* alternators.

The iron portions of all motors and generators, both a-c and d-c, are laminated (made up in thin sheets of iron) when they carry expanding and contracting magnetic fields. This reduces the eddy-current losses, explained in the chapter on Inductance and Transformers.

**23.3 Voltage Output of an Alternator.** The alternator itself operates as an inductance. When a purely resistive load is connected across it, the output voltage will be somewhat less than the no-load output. If the load has an inductance value also, its inductive reactance adds to the reactance of the alternator and the output voltage sags even more. However, if the load is capacitive, the capacitive reactance will counteract the inductive reactance inherent in the alternator, and an increased voltage output of nearly the no-load value will be produced.

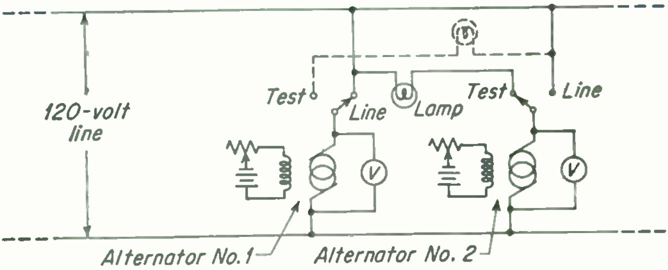


FIG. 23.5. Circuit to determine when two alternators are in phase.

**23.4 Field Excitation of an Alternator.** All alternators require a d-c field-excitation current. This can take the form of a battery or a rectified a-c that is filtered, as explained in the chapter on Power Supplies. In many cases, the excitation is produced by a d-c generator attached to the same prime mover that rotates the alternator. As soon as the prime mover rotates, the generator (*exciter*) produces d-c, which excites the field coils of the alternator, allowing a-c to be generated.

**23.5 Paralleling Alternators.** When it is necessary to connect a second alternator across a line already being fed by one alternator either to aid the first in carrying the load or to allow the first to be removed from the line without interruption of service, it is necessary to cut in the second machine at an instant when the *voltage* and *phase* of the two are equal.

The voltage of the second can be controlled by the field rheostat and the voltage phase compared with the present line voltage. There are several methods by which the phase can be compared. One of the simplest is by using an electric light connected as shown in Fig. 23.5.

Alternator No. 1 is supplying the line. Alternator No. 2 is to be fed to the line also. Alternator 2 is adjusted to 120 volts output. With the switch of alternator No. 2 as shown in the diagram, the voltage across the light will be something between 240 volts, if the two alternators are 180° out of phase, and zero, if the emfs of the two machines are in phase. The speed of the prime mover of alternator No. 2 must be adjusted until the light varies in intensity *very slowly*. This indicates a slow shift of phase between the two machines. The switch is thrown to the "line" position while the lamp is dark (indicating that the two a-c voltages are in phase). A 240-volt lamp, or two similar 120-volt lamps in series, must be used as the indicator in this operation.

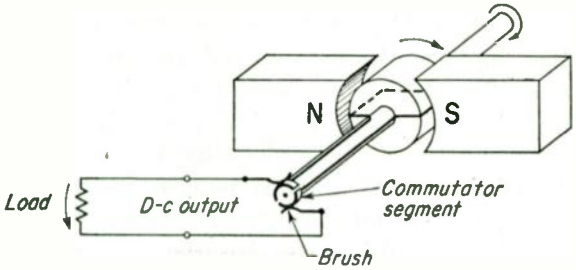


FIG. 23.6. Essential parts of a simple d-c generator.

**23.6 D-C Generators.** The basic d-c generator is similar to the basic alternator except for the substitution of a *commutator* for the slip rings (Fig. 23.6).

As in the alternator, when the shaft is rotated, the rotor and conductor turn and an a-c is induced in the *armature*, as the coil and laminated soft-iron core are called.

With the conductors rotating clockwise as indicated, and in the position shown, a maximum emf will be produced, in a direction outward from the top brush and inward to the bottom brush.

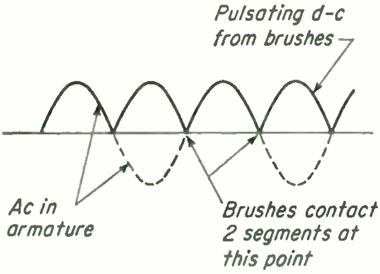


FIG. 23.7. Output pulses of a two-pole d-c generator.

As the armature rotates to a point 90° from that shown, the conductors will be moving *with* the magnetic lines of force, not across them, and no voltage will be induced in the conductors. At this instant, the commutator segments have rotated and each brush is making contact with *both* segments. The brushes are now shorting the segments together, but at a time when zero voltage is being induced in the armature. If the armature windings and the commutator segments are not properly oriented, the brushes may short the segments when there is a slight emf between them, and sparking at the brushes will occur. Such sparking is one of the difficulties experienced with d-c motors and generators, particularly in radio applications.

As the armature rotates another 90°, the emf induced in the conductors is again at a maximum, and again in a direction out of the top segment and brush and into the bottom brush and segment.

With continual rotation of the armature, the a-c emf induced in the armature conductors is made to enter and leave the brushes in the same direction at all times. This action of the commutator and coil results in a full-wave-rectified output (Fig. 23.7). This is a form of mechanical rectification of the armature a-c.

When a four-segment commutator with two armature coils wound at right angles to each other is used, the d-c produced does not drop to zero at any time, as shown in Fig. 23.8. The more pairs of commutator segments and armature coils, the less variation in the output d-c.

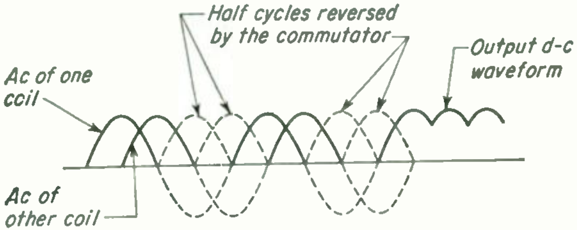


FIG. 23.8. Output pulses of a four-pole d-c generator.

**23.7 The Externally Excited D-C Generator.** As with the alternator, the magnetic field of a d-c generator is normally supplied by an electromagnet rather than by the permanent magnet shown in the simplified illustration. The diagrammatic symbol of a d-c generator with a separately excited field is shown in Fig. 23.9.

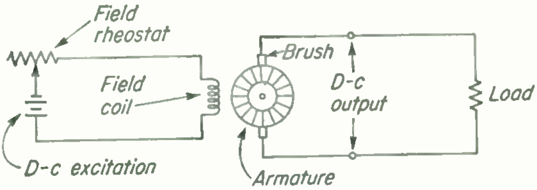


FIG. 23.9. An externally excited d-c generator.

The external excitation is represented as coming from a battery and controlled by a *field rheostat.* The brushes and the multisegment commutator of the armature are indicated in symbol form. The prime mover is not shown.

The voltage output is dependent upon the speed of armature rotation and the magnetic field produced by the field coils. The greater the field-coil current, the greater the output voltage of the generator, assuming constant speed of armature rotation—up to the point of field-pole saturation. Any increase in field-coil current past field-pole saturation will not increase the output voltage.

The output voltage of this type of generator is also subject to an internal voltage drop because of resistance in the windings of the armature. As the output current increases, the internal voltage drop increases. As a result, the separately excited generator has a constantly sagging voltage output with increase of load, although the percentage of voltage drop may not be great.

**23.8 The Series D-C Generator.** When the field coils are made with a few turns of heavy wire and are connected in series with the armature, a *series generator* results. This is shown in diagrammatic form in Fig. 23.10.

A series generator with no load has almost no voltage output. In the diagram, with the load resistor disconnected, there is no current flowing through the field coil and therefore the rotating conductors are cutting only the residual lines of force that may still remain in the field poles from their last magnetization. This results in a very low output-voltage value.

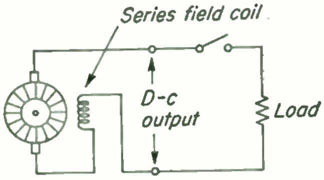


FIG. 23.10. A series-field d-c generator.

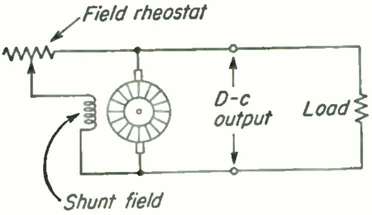


FIG. 23.11. A shunt-field d-c generator.

When a load is connected across the output, current begins to flow in the circuit. The field poles build up a stronger magnetism, and the voltage output of the generator increases. The heavier the load, the greater the field current and the higher the output voltage of a series generator, up to the point where saturation of the field poles occurs. Because of its varying voltage output with a varying load, such a generator finds little application unless an unvarying load can be used. This rules out the series generator in practically all radio applications.

**23.9 The Shunt D-C Generator.** A more practical d-c generator is produced by connecting the field coil across the armature. This forms a *shunt generator* (Fig. 23.11). The shunt field coil has many turns of fine wire to produce a maximum number of ampere-turns of magnetic force with as little drain on the output current as possible.

The rheostat in the field of the shunt generator controls the current flow through the field coil, thereby determining the magnetic-field strength and controlling the voltage output for a given rotation speed of the armature. Increased field current produces increased voltage output.

The shunt-type generator has a voltage characteristic similar to an externally excited generator, although its output voltage drops more as the load is increased.

**23.10 The Compound D-C Generator.** In many radio applications the load varies over a relatively wide range. For example, a radiotelegraph transmitter requires little power when the key is up and full power each time the key is pressed. To maintain a constant-voltage output from the source, neither the series generator with its increasing output voltage under load nor the shunt generator with its decreasing output voltage under load is suitable. However, it is possible to use both series and shunt windings on each field pole. By selection of the proper proportions of each winding, a *flat-compounded* generator can be produced. If the series field coils have too many turns, an *overcompounded* machine results which has a rising voltage with increase of the load. If the series field coils have too few turns, an *undercompounded* machine results. If the power lines carrying the current to a distant load are long, a slightly overcompounded generator may be desirable to compensate for voltage losses due to the resistance in the line. A compound d-c generator is shown in diagrammatic form in Fig. 23.12.

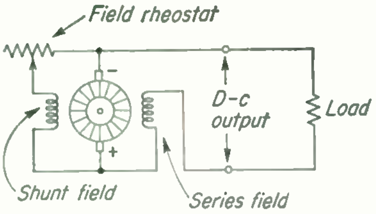


FIG. 23.12. A compound-field d-c generator.

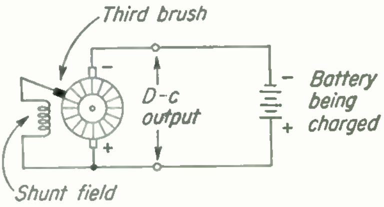


FIG. 23.13. A third-brush generator.

When the series and shunt fields are additive, the machine is said to be *cumulatively compounded.* If the fields are connected in opposition, a *differentially compounded* machine results, which has a very sharply decreasing output voltage under load, making it unsuitable in normal applications.

The voltage output of a compound generator is controlled by the shunt-field excitation current—by the rheostat shown.

**23.11 The Third-brush Generator.** The d-c generator in automobiles is used to charge the battery. If a shunt- or compound-wound generator is used, the output voltage, and therefore charging current, will vary with the speed of the engine. To prevent overcharging and over-current flow in the generator, the shunt field may be connected to a third brush on the commutator (Fig. 23.13). The position of this brush may be adjusted to fix the maximum output current. The farther down the commutator the third brush is placed, the lower the maximum current output from the generator. The charging current may be a few amperes at 20 miles per hour (mph), 20 amp at 25 mph, 30 amp at 30 mph, and remain at or near 30 amp at all speeds above 30 mph.

The placement of the brush actually controls the *voltage* output of the generator, which in turn determines the charging-current rate. These generators are rarely used any more.

**23.12 Commutating Poles, or Interpoles.** In the description of the simple d-c generator it was mentioned that the brushes must move from one segment of the commutator to the next during a time when no voltage difference is being produced between them. If not, sparking will be produced at the brushes.

For any given armature-rotation speed and output current, the brushes can be adjusted to a *neutral* point and there will be negligible sparking. The neutral point is determined by the interaction of the magnetism of the field poles and the magnetism produced around the armature. If either the output current or the rotation speed of the generator changes, the magnetic fields of the field poles and the armature shift the neutral position. To reduce sparking, the brushes must be rotated forward or backward slightly around the commutator. When the load is changing rapidly, a physical shifting of the brushes is not feasible.

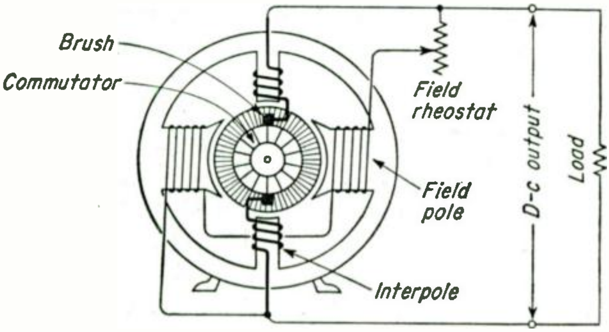


FIG. 23.14. Commutating-pole connections on a shunt-wound d-c generator (or motor).

With no load, the mechanical neutral (position of the brushes) and the magnetic neutral are exactly halfway between field poles. With a load, the magnetic neutral shifts a few degrees in the direction of armature rotation in a generator (backward in a motor). An electromagnet *commutating pole*, or *interpole*, can be placed between field poles at the mechanical neutral. Its winding is connected in series with the *armature.* When the armature current increases, the interpole current increases, producing an opposite field to that of the armature. This cancels the effect of the armature field and holds the magnetic neutral at the mechanical-neutral point. The brushes can now be set at the mechanical neutral, and minimum sparking will occur at all load values.

Interpoles are used in almost all larger d-c generators and motors. Figure 23.14 illustrates the placement and connection of the interpoles on a two-pole d-c generator.

**23.13 Brush Sparking.** In radio, any nearby electric sparking can produce interference to received signals or modulation of transmitted signals. Sparking at the commutator or slip rings pits them and wears out the brushes at an abnormal rate. It is necessary to lessen all sparking as much as possible.

When the brushes of a generator or motor are not set to the neutral position, excessive sparking may occur. Other causes of sparking at the brushes are worn or dirty commutators, worn or improper-size brushes, overloading the machine, an open armature coil, and a shorted interpole coil.

To prevent interference to local reception, bypass capacitors (condensers) are usually connected from each brush of a generator or motor to ground. In some cases, a low-pass-filter circuit composed of an RF choke is used in series with the ungrounded line with a bypass capacitor from each side of the choke to ground. A similar low-pass filter may be used in the field-coil lines. This will also filter out any RF a-c from a transmitter that might otherwise find its way into the generator or motor and possibly break down insulation in the machine.

**23.14 D-C Motors.** A d-c motor is the same machine as a d-c generator. A series d-c generator will operate as a series d-c motor. A shunt generator will operate as a shunt motor, and a compound generator will operate as a compound motor.

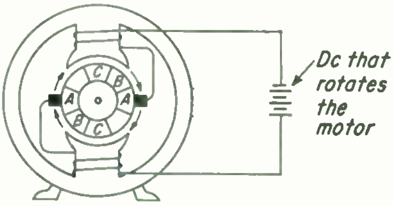


FIG. 23.15. Series motor. As the armature rotates, the brushes slide from one pair of commutator segments to the next.

**23.15 Series D-C Motors.** Whereas series-wound *generators* are rarely used, there are many series-wound motors in use.

When current is fed to the series motor (Fig. 23.15), the low resistance of the field coils and the armature allows a high current to flow through them and strong magnetic fields to form around them. The armature and the stator fields oppose each other and produce a pushing effort on the armature conductors, forcing them to move away from the stator-field poles. The twisting effort experienced by the armature is torque.

In the figure, the brushes are contacting the two commutator segments marked *A*. When current flows, the armature coil connected to these segments (not shown) is pushed away from the field poles, perhaps in a clockwise direction, and segments marked *B* are moved into position under the brushes. Now the current flows through the *B* segments and coil, producing further clockwise torque, moving the *C* segments under the brushes, and so on. Continuous rotation of the armature results.

If the current direction through the motor is reversed, the polarities of the field poles *and* the armature conductors are both reversed, resulting in a pushing effort between them in the *same* direction as before. Because of this, a series motor will rotate when excited by an *alternating* current, its direction of rotation being the same for both halves of each cycle. The lower the frequency of the a-c, the greater the torque that can be produced. If the frequency is high, the inductive reactance of the coils in the machine limits the current that can flow and the power of the motor.

When d-c is applied to the series motor, the current flowing has nothing to oppose it except the resistance in the circuit. This results in a high starting current and also a very strong starting torque.

As soon as the armature starts to rotate, the movement of the armature conductors through the stationary magnetic field of the field poles produces a counter emf in the armature wires. If the counter emf could rise to the value of the source emf, the motor would no longer increase in speed. However, in the series machine the counter emf can never equal the source emf, so that a series motor may continually accelerate until it flies apart because of the centrifugal force *if it is operated without a load.*

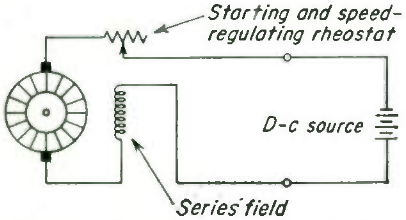


FIG. 23.16. A series d-c motor with a rheostat for speed regulation and starting.

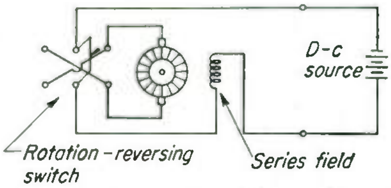


FIG. 23.17. To reverse the direction of rotation of a motor, the armature connections are reversed.

When starting a series motor, a rheostat may be included in series with it (Fig. 23.16). This adds resistance to the circuit and reduces the starting current. As the motor picks up speed, counter emf is developed and the rheostat resistance can be lessened. The rheostat can also be used to adjust the speed of the motor to a certain extent. Small motors may require no starting resistors, but larger motors always do.

Small series motors are used in fans, blowers, in some less expensive electric drills, or in any application where high-speed rotation is required but in which good speed regulation is not important. The high starting torque makes larger series-type motors useful for such heavy duties as starting street cars. The poor speed regulation of the series motor makes it undesirable for use in a motor-generator set in radio applications.

The direction of rotation of a series motor can be reversed by reversing the direction of the current through *either* the armature or through the field coil, but not through both. Figure 23.17 illustrates a double-pole double-throw switch used as a rotation-reversing switch. Reversing the armature connections is also the method of reversing shunt and compound motors.

**23.16 Shunt D-C Motors.** The shunt-type motor has good speed regulation and is used in many applications. A shunt-type motor with a three-connection *starter* device is shown in Fig. 23.18.

To start the motor the field rheostat is first adjusted to zero resistance (low running speed) to produce maximum counter emf in the armature. The line switch is then closed, and the starter-rheostat arm is moved to the second contact. Current begins to flow through the armature and field, through the starter resistor and the holding magnet. Without the starting resistance the current through the armature would be excessive. The two magnetic fields of the armature and the shunt field repel each other, and the armature starts to turn. As the armature conductors move, a counter emf is induced in them. As the speed increases, the counter emf increases and the current through the armature begins to decrease. The starter-control arm is moved from contact to contact, slowly enough to allow the counter emf at each point to build up as the resistance of the starter is being decreased. One or two seconds on each starting contact will prevent excessive current flow through the machine and starter resistor at any time.

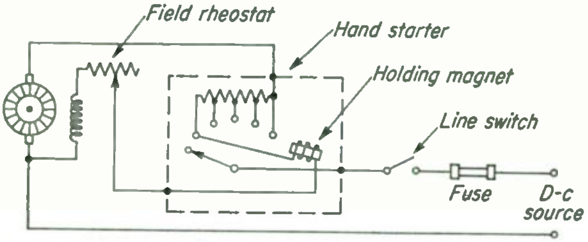


FIG. 23.18. A three-point hand starter connected to a shunt motor.

If the starter rheostat is moved too fast, the counter emf will not develop fast enough and the current through the machine may be excessive, and the starter rheostat, the armature, or fuses in the line may burn out. If the starter rheostat is moved too slowly, it may become overly heated, particularly if there is any load on the motor. In general, a motor should be started with as little load on it as possible.

When the iron rheostat arm is brought up to the full "on" position, it is attracted to the holding magnet and is magnetically held in the running position against a spring tension in the arm.

When the line switch is opened and the motor is disconnected from the source, the motor becomes a d-c generator, with the same polarity as when it was operating as a motor. As a generator, it supplies current to the holding magnet until it slows down to the point where its emf will not produce enough current to energize the magnet coil. The rheostat arm then snaps back to the "off" position by the action of the arm spring. If the motor is running unloaded, it may take several seconds before the arm disengages. If the motor is loaded, it will come to a rapid halt and the arm will drop back almost immediately.

The shunt motor does not have as great a starting torque as the series ~~motor but~~ builds up a counter emf equal to the source voltage, minus the voltage losses in the armature. This limits the speed to a definite value. To increase the speed of a shunt motor, the generation of the counter emf in the armature must be reduced. This can be done by *decreasing* the field-coil current. When the resistance in series with the shunt field is increased, the field current is less and the counter emf decreases. With less counter emf, more current flows through the armature and it picks up speed until it can again produce a counter emf almost equal to the source voltage.

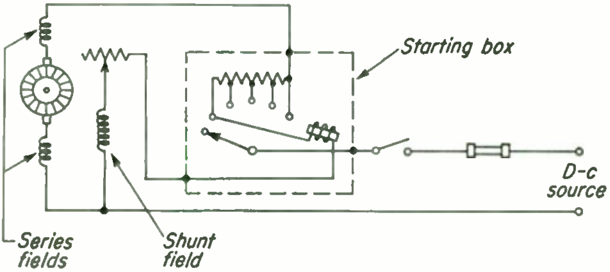


FIG. 23.19. A hand starter connected to a compound motor.

If a shunt motor, running without load, has its shunt field suddenly opened or burned out, the counter emf will fall to nearly zero and the armature will continually increase its speed of rotation until the machine flies apart. If the motor were loaded, loss of the shunt-field current would result in a stopping of the motor and a burnout of the armature, fuse, or overload relay in the line. With the starter shown, an open field circuit would de-energize the holding magnet and the starter arm would immediately snap to the off position.

In most motors of any size, interpoles, or commutation poles, are used to assure a constant neutral position for the brushes, as described in Sec. 23.12. These are not shown in the simplified diagrams here.

The shunt motor is usually reversed by reversing the current through the armature (and interpoles, if any).

The inductive reactance in the shunt winding limits current through this field to such an extent that the shunt motor is not usable as an a-c motor.

**23.17 Compound D-C Motors.** The compound d-c motor has a series and a shunt field, and usually interpoles. A simple schematic diagram is shown in Fig. 23.19.

The control of the speed of a compound motor is similar to the method employed in the shunt motor, where the resistance in series with the shunt field controls the counter emf generated in the armature, and therefore the speed of the machine. Maximum resistance results in maximum speed. Starting is also similar to the shunt motor.

To reverse the direction of rotation of a compound motor, the armature leads (and interpoles, if any) are usually reversed, as shown in Fig. 23.17, with a series motor. It is also possible to reverse the rotation by reversing *both* the shunt and series fields at the same time.

It was mentioned that the differentially compounded machine produced a generator with a badly sagging voltage output under load. However, a differentially compounded machine operated as a motor has a very good speed regulation, superior to the shunt types, and may be found in radio applications.

**23.18 A-C Motors.** Most modern motors operate from an a-c source. In a relatively few cases, such as in ships where d-c is the primary source of available power or where a wide range of speed control is desired, d-c motors may be employed.

While there are many different types of a-c motors, only three basic types will be discussed here, the *universal*, the *synchronous*, and the *squirrel-cage* motors.

**23.19 Universal Motors.** The series-type d-c motor will rotate when either d-c or low-frequency a-c is applied to it, as explained previously. Such a *universal* motor is used in fans, blowers, food mixers, portable electric drills, and other applications where a high speed under light load or slow speed with high torque is required.

One of the difficulties with universal motors as far as radio is concerned is the commutator sparking and the accompanying radio interference, or noise. This may be reduced by bypassing the two brushes to the frame of the motor with 0.01- to 1-$\mu$f capacitors and grounding the frame.

**23.20 Synchronous Motors.** An alternator can be used as a motor under certain circumstances. If the field is excited by d-c and a-c is fed to the slip rings and rotor coil, the machine will *not* start rotating. The field around the rotor coil is alternating in magnetic polarity, but during one-half of the cycle it may try to move in one direction and during the other half cycle it will try to move in the opposite. The net result is no movement at all. The machine will merely heat and possibly burn out.

The rotor of a two-pole *alternator* must make one complete rotation to produce one cycle of a-c. It must rotate 60 times a second or 3,600 revolutions per minute (rpm), to produce 60-cycle a-c. If such an alternator can be rotated at 3,600 rpm by some outside mechanical device, such as a d-c motor, and *then* excite the armature with a 60-cycle a-c, it will continue to rotate as a *synchronous* motor. Its synchronous speed is 3,600 rpm. If it is to operate on 50-cycle a-c, its synchronous speed will be 3,000 rpm. As long as the load is not too heavy, a synchronous motor will run at its synchronous speed, and at this speed only. If the load becomes too great, the motor will slow down, lose synchronism, and come to a halt. Synchronous motors of this type all require a constant d-c field (or rotor) excitation, as well as the a-c rotor (or field) excitation.

It is possible to produce an essentially synchronous motor by constructing the normally round rotor of a squirrel-cage-type motor with two flat sides.

An example of a synchronous motor is the electric clock that must be started by hand when it stops. As long as the a-c is maintained at the correct *frequency*, the clock will keep correct time. A precise voltage amplitude is not important.

**23.21 Squirrel-cage Motors.** Most of the motors that operate from single-phase a-c have a *squirrel-cage* type of rotor. A simple form is illustrated in Fig. 23.20. Practical squirrel-cage rotors are considerably more massive than the one pictured and have a laminated iron core.

The conductors running the length of the squirrel cage are copper and are welded to the metal end pieces. Each conductor forms a shorted turn with the conductor on the opposite side of the cage. When this cage is between two electromagnetic field poles that are being magnetized by an alternating current, an alternating emf is induced in the shorted turns, a heavy current flows in them, and a strong counter field is produced which bucks the field that produced the current (Lenz's law). Although the rotor may buck the field of the stationary poles, there is no reason for it to move in either one direction or the other, and so it remains stationary. This is similar to the synchronous motor which is not self-starting either. What is needed is a *rotating* field rather than an alternating one.

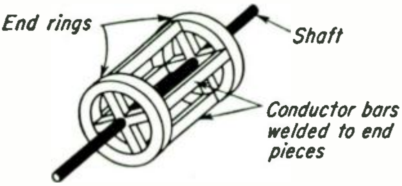


Fig. 23.20. A basic form of rotor for a squirrel-cage motor.

How the field is made to have a rotary effect names the type of squirrel-cage motor. A *split-phase* motor uses additional field poles that are fed out-of-phase currents, allowing the two sets of poles to develop maximum current and magnetic fields at slightly different times. The out-of-phase windings on the out-of-phase field poles could be fed by two-phase a-c and produce a rotating magnetic field, but for single-phase operation the second phase is usually developed by connecting a capacitor (or resistor) in series with the out-of-phase winding. This can shift the phase by more than 20° and produces a maximum magnetic field in the phased winding that leads the magnetic field in the main winding. The effectively moving maximum strength of the magnetic field from one pole to the next one attracts the squirrel-cage rotor with its induced currents and fields, rotating it. This makes the motor self-starting. The split-phase winding can be left in the circuit, or it can be cut out by use of a centrifugal switch that disconnects it when the motor reaches a predetermined speed. Once the motor starts rotating, it operates better without the split-phase winding. Not being a synchronous motor, it does not have to maintain a particular synchronous speed. In fact, the rotor of a split-phase induction motor always slips behind in speed by a small percentage of what would be the synchronous speed. If the synchronous speed would be 1,800 rpm, the squirrel-cage rotor with a certain load may rotate at 1,750 rpm. The heavier the load on the motor, the more the rotor slips. Under optimum operating conditions a split-phase motor with the phased poles disconnected may operate at approximately 75 per cent efficiency.

Another method of producing a rotary field in a motor is to *shade* the field poles. This is accomplished by slotting the field poles and connecting a copper ring around one part of the slotted pole, as illustrated in Fig. 23.21.

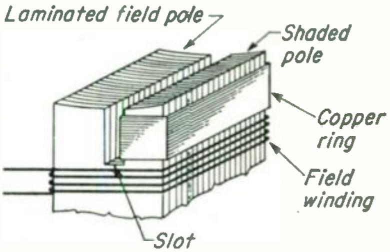


FIG. 23.21. Details of the field pole of a shaded-field a-c motor.

As an alternation is increasing in amplitude in the field coil, the magnetic field expands and induces an emf and current in the copper ring. This produces a magnetic field around the ring that bucks the magnetism in the part of the pole surrounded by the ring. Maximum magnetic field is developed at this time in the *unshaded* part of the pole, and minimum in the shaded part. As the field-current cycle reaches a maximum, the magnetic field no longer moves and the copper ring has no current induced in it and it has no effect. Maximum magnetic field is now developed across the whole pole face. As the alternation decreases in amplitude, the field collapses, induces an emf and a current in the ring in the opposite direction, and produces a maximum field in the shaded part of the pole face. Thus the maximum magnetic field moves from the unshaded over to the shaded part of the field pole as the cycle progresses. This maximum-field movement produces the necessary rotating field in the motor to make the squirrel-cage rotor self-starting. The efficiency of shaded-pole induction motors is not high, ranging from 30 to 50 per cent.

One of the main advantages of all squirrel-cage motors, particularly in radio applications, is the lack of commutator and brushes, or slip rings and brushes. This assures interference-free operation when such motors are used.

**23.22 Polyphase Motors.** When three-phase a-c (Sec. 10.30) is available, a three-phase motor is usually desirable. Each of the three phases is fed to separate field coils wound around separate field poles in the motor. Since each phase is 120° from the other phases, current maximums appear in one field pole, then 120° later in the next pole, 120° later in the third pole, and so on. The action of the three-phase a-c on the field poles produces a true revolving field. All such motors are self-starting and quite efficient (are usually of the squirrel-cage rotor type) and operate at a nearly constant speed, although they have a percentage of *slip*.

At the instant of starting, a very high current flows. Either series resistances must be used in two of the three power lines feeding the motor to limit the starting current or the line voltage must be stepped down to a lower value until the machine approaches running speed.

When the machine is rotating at normal speed, the induced currents and fields in the rotor occur at such a time and in such a phase that they do not cancel the field-coil inductance. With effective inductance in the field coils, their reactance limits the line current to a low value. When a load is applied, it tends to slow down the rotor, causing the induced fields in it to partially cancel the inductance of the fields. More current flows through the machine, and it develops more torque and horsepower and tries to maintain its speed.

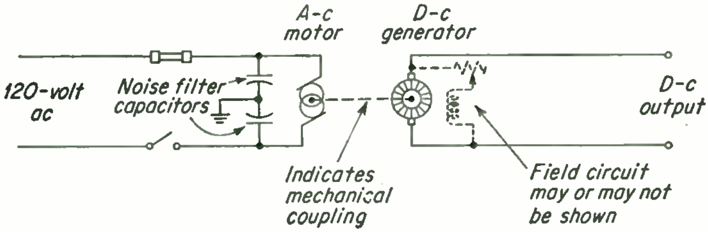


FIG. 23.22. An a-c motor–d-c generator system.

A "two-pole" three-phase motor (two-poles per phase) operating on 60-cycle a-c will rotate at a speed of 3,600 rpm, a four-pole motor will rotate at 1,800 rpm, and so on.

**23.23 Motor-Generators.** When it is desired to convert one form of electricity to another, a motor and generator are often coupled together. The motor may be either a-c or d-c, and the generator may be either a-c or d-c. For example, 1,500 volts d-c is required for a transmitter, but the power lines carry 120 volts a-c. A 120-volt a-c motor coupled to a 1,500-volt d-c generator will provide the necessary high-voltage d-c. A diagram of such a motor-generator set is shown schematically in Fig. 23.22.

A motor-generator set is quite heavy and bulky and makes a certain amount of audible noise. It is rather costly to purchase, although maintenance thereafter is not great. Being partly mechanical, it requires lubrication, commutator or slip rings need cleaning, and brushes must be replaced periodically. It has fairly good voltage regulation, although the output voltage may be somewhat limited because of difficulty of insulating the armature and commutator components in d-c machines. Sparking at brushes may cause radio interference. In comparison, a vacuum-tube rectifier is lighter, less expensive, has almost unlimited voltage possibilities, operates without noise or vibration, is more efficient, produces no radio interference, but may have poorer voltage regulation, requires new tubes periodically, and is possibly less rugged, although in some cases it may be operated in any position.

**23.24 Dynamotors.** A *dynamotor* is a form of a d-c motor-generator but has one common field coil for both motor and generator. Dynamotors are normally used for low-power radio equipment, as in mobile stations. The motor part normally operates from a 6- to a 28-volt battery. The output d-c voltage ranges from about 225 volts when used for a receiver to 1,000 volts or more when used for transmitters.

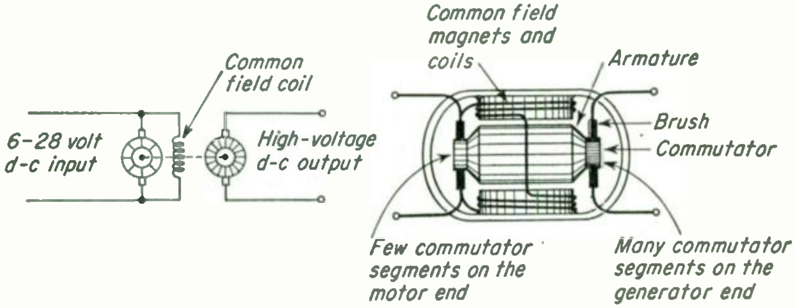


FIG. 23.23. Schematic diagram and picture of the components of a dynamotor.

An advantage of a dynamotor is its relative light weight and compactness when compared with a motor-generator, made possible by the common field winding. One end of the common armature core carries the commutator segments for the motor. The other end carries the commutator segments for the generator. The motor and generator armature coils are separate coils, but are wound into the same slots in the armature. Figure 23.23 shows the schematic diagram of a dynamotor and a pictorial diagram.

The output voltage of a dynamotor cannot be changed efficiently, which is probably its greatest disadvantage. If the primary-source voltage is changed, the output will change, but its best efficiency and voltage regulation is produced with a specific input voltage. The over-all efficiency ranges from 50 to 60 per cent, somewhat less than the efficiency of a motor-generator. The voltage regulation of most dynamotors is fair, but does not compare with a properly designed motor-generator. The relatively high output power for its weight is produced by its high-speed-of-rotation characteristic.

**23.25 Rating Generators and Motors.** Direct-current generators can be rated by the number of watts output they can deliver. However, when an alternator feeds power to a circuit it is not known what power factor the load will exhibit. If the load is completely resistive ($E$ and $I$ are in phase), the power output will be equal to the volts times the amperes and will be the true power. On the other hand, if the load is completely reactive ($E$ and $I$ out of phase by 90°), the current drawn from the machine may be the maximum that the wires of the alternator can stand without overheating, but the true power delivered to and *used* by the load is zero ($E \times I \times \cos\theta = E \times I \times 0$) watts. Current is flowing and producing a field, but the field collapses and returns current to the circuit again. The wires are carrying current, but no power is being lost. In such a case, an alternator normally thought of as capable of 2 kw output when used on electric lights alone will be delivering no true power to a reactive load but may still be running at maximum current output. For this reason, alternators are always rated by *apparent* power, designated as *volt-amperes*, or VA. Large alternators are rated in kilovolt-amperes (kva).

It is customary to rate motors in output *horsepower* (746 watts equals 1 hp). Motors may range from fractions of a horsepower to hundreds or thousands of horsepower. A 3-hp d-c motor *delivers* the equivalent of 2,238 watts of turning power. However, the machine is not 100 per cent efficient and therefore must be drawing more than this number of watts from the line. If the machine is to be 85 per cent efficient, 2,238 watts is 85 per cent of the input power, or

$$0.85(P_i) = 2{,}238 \text{ watts}$$

$$P_i = \frac{2{,}238}{0.85} = 2{,}573 \text{ watts}$$

From this, the formula to determine input power is

$$P_i = \frac{P_o}{\%}$$

where $P_i$ is the input power in watts; $P_o$ is the output power in watts; and $\%$ is the percentage of efficiency expressed as a decimal.

If the motor above is operating from a 110-volt d-c line, from the power formula $P = EI$, the line current would be

$$I = \frac{P}{E} = \frac{2{,}573}{110} = 23.4 \text{ amp}$$

Alternating-current motors are also rated in horsepower, but besides their efficiency, the power factor must also be considered.

A 7-hp a-c motor operating at full load, with a power factor of 0.8 and 95 per cent efficiency, will have what power input? Power factor can be considered as a type of a-c efficiency rating. The power output developed is equivalent to 7(746), or 5,222 watts. The input power is 5,222/0.8(0.95), or 6,871 watts. If the motor is operating from a 120-volt line, the line current is $I = P/E$, or 6,871/120, or 57.3 amp.

**23.26 Maintenance of Motors and Generators.** It is usually an assignment of an operator at a radio installation to see that the motors and generators are in proper operating condition at all times. The following are some suggestions regarding such maintenance.

Oil on rubber insulation causes the insulation to soften and weaken. Care must be exercised when oiling motors and generators that no oil is splashed or allowed to drip onto electrical wiring.

The bearings of rotary machines must be oiled periodically to prevent overheating and freezing. If a bearing overheats, it should be flushed with light oil until cool. The machine should not be stopped during the flushing operation.

Sparking at the brushes indicates trouble. The brushes may be worn down and be making poor contact. The slip rings or commutator may be dirty. An armature coil may be shorted or open. The machine may be running with too heavy a load. The interpoles may be inoperative or incorrectly wired.

If slip rings or commutators become dirty, they can be cleaned with a piece of heavy canvas and carbon tetrachloride, or they may be sanded smooth with a very fine grade of sandpaper. (WARNING: carbon tetrachloride is poisonous. Do not touch the liquid or breathe the fumes. Also, emery paper and steel wool must *never* be used to smooth the commutator since metal particles may lodge between segments and cause a short circuit when the machine is operated.) The mica insulation between commutator segments may wear more slowly than the copper or brass segments, leaving the brushes to ride on insulated ridges instead of on the segments. The mica insulation should be *undercut* below the level of the surface of the commutator segments.

Motors and generators should be cleaned and dusted regularly and given a close visual examination by the operator. The length of the brushes should be checked. Care should be taken to replace those worn out with the correct-size brushes. In an emergency, a larger brush may be sanded down to the proper size to fit the machine. The spring tension holding the brush against the commutator should produce the proper pressure.

When the commutator segments show signs of excessive wear, the armature may have to be taken out of the machine and the commutator turned down on a lathe. After turning down a commutator, remove all metal particles that may be deposited in the mica insulation between segments. The mica insulation must be undercut. If an armature coil should become shorted, the armature will heat and the brushes will spark excessively.

If a motor or motor-generator switch is closed but the machine does not start, the operator should check the line voltage, the fuses, or the overload relay. If the overload relay will not hold in when the motor is switched on, the bearings of the machine may be frozen or the armature shaft may be locked. The armature may have a shorted turn, or the field-coil circuit may be open or burned out. If the fuses or overload relays are not open and the line voltage is normal, a brush may not be making contact with the commutator or slip ring because of dirt under the brush, or there may be a poor electrical connection leading into the motor.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element numbers at right.)

**1.** How may the output voltage of a separately excited a-c generator, at constant output frequency, be varied? (23.2) **[3]**

**2.** State the principal advantage of a third-brush generator for radio power supply in automobiles. (23.11) **[3]**

**3.** Why is it sometimes necessary to use a starting resistance when starting a d-c motor? (23.15) **[3]**

**4.** What might be the result of starting a motor too slowly using a hand starter? (23.16) **[3]**

**5.** Why are RF chokes sometimes placed in the power leads between a motor-generator power supply and a high-powered radio transmitter? (23.18, 23.23) **[3]**

**6.** What determines the speed of a synchronous motor? (23.20) **[3]**

**7.** List the comparative advantages and disadvantages of motor-generator and transformer-rectifier power supplies. (23.23) **[3]**

**8.** What materials should be used to clean the commutator of a motor or generator? (23.26) **[3]**

**9.** List three causes of sparking at the commutator of a d-c motor. (23.26) **[3]**

**10.** Why is laminated iron or steel generally used in the construction of the field and armature cores of motors and generators instead of solid metal? (23.2) **[3 & 6]**

**11.** What is the purpose of a commutator on a d-c generator? On a d-c motor? (23.6, 23.15) **[3 & 6]**

**12.** Describe the action and list the main characteristics of a series d-c generator. (23.8) **[3 & 6]**

**13.** What is the purpose of commutating poles, or interpoles, in a d-c motor? (23.12) **[3 & 6]**

**14.** Why are bypass capacitors often connected across the brushes of a high-voltage d-c generator? (23.13) **[3 & 6]**

**15.** How may the RF interference, often caused by sparking at the brushes of a high-voltage generator, be minimized? (23.13) **[3 & 6]**

**16.** Name four causes of excessive sparking at the brushes of a d-c motor or generator. (23.13) **[3 & 6]**

**17.** What determines the speed of a d-c series motor? Of a synchronous motor? Of an induction motor? (23.15, 23.20, 23.21) **[3 & 6]**

**18.** Describe the action and list the main characteristics of a series-wound d-c generator. (23.15) **[3 & 6]**

**19.** What is meant by counter emf in a d-c motor? (23.15, 23.16) **[3 & 6]**

**20.** If the field of a shunt-wound d-c motor were opened while the machine was running under no load, what would be the probable result(s)? (23.16) **[3 & 6]**

**21.** Describe the action and list the main characteristics of a shunt-wound d-c motor. (23.16) **[3 & 6]**

**22.** What may cause a motor-generator bearing to overheat? (23.26) **[3 & 6]**

**23.** Draw a diagram of a shunt-wound d-c motor. (23.16) **[4]**

**24.** What is the approximate speed of a 220-volt 60-cycle four-pole three-phase induction motor? (23.22) **[4]**

**25.** What conditions must be met before two a-c generators can be operated in parallel? (23.5) **[6]**

**26.** Explain the principle of operation and list the main operating characteristics of a d-c shunt generator and a d-c compound generator. Explain how the voltage of a d-c generator can be controlled. Draw a simple schematic circuit diagram of each of these types of generators. (23.9, 23.10) **[6]**

**27.** Draw a simple schematic circuit diagram of three kinds of d-c motors, including a starting device. (23.15–23.17) **[6]**

**28.** What is the danger of operating a d-c series motor without a load? (23.15) **[6]**

**29.** Why is a series motor not used in radio power-supply motor generators? (23.15) **[6]**

**30.** When starting a large d-c motor-generator set, what adjustment should be made to the motor field rheostat? (23.16) **[6]**

**31.** Explain the principle of operation and list the main characteristics of a compound-wound d-c motor and explain how the speed is regulated. (23.17) **[6]**

**32.** Explain the principle of operation of an induction motor and how such motors are started. (23.21) **[6]**

**33.** When increased output voltage is desired from a motor-generator set, what is the usual procedure? (23.23) **[6]**

**34.** Describe the construction of a dynamotor. What are its operating characteristics? (23.24) **[6]**

**35.** How may the output voltage of a dynamotor be regulated? (23.24) **[6]**

**36.** What is the principal advantage in the use of a dynamotor, rather than a motor generator, to furnish plate power to a small mobile transmitter? Principal disadvantage? (23.24) **[6]**

**37.** What is the effect of an inductive load on the output voltage of an alternator? (23.25) **[6]**

**38.** In what units is an alternator output ordinarily rated? (23.25) **[6]**

**39.** If a 3-hp 110-volt d-c motor is 85 per cent efficient when developing its rated output, what will be the line current? (23.25) **[6]**

**40.** What is the line current of a single-phase 7-hp a-c motor when operating from a 120-volt line at full rated load and at a power factor of 0.8 and 95 per cent efficiency? (23.25) **[6]**

**41.** What will be the effect(s) of a short circuit in an armature coil of a d-c motor? (23.26) **[6]**

**42.** What may be the trouble if a motor-generator fails to start when the start button is depressed? (23.26) **[6]**

**43.** Why should emery cloth never be used to clean the commutator of a motor or generator? (23.26) **[6]**

## CHAPTER 24

# THE BROADCAST STATION

**24.1 Standard Broadcast Stations.** "Standard" broadcast stations operate in the band of frequencies between 535 and 1,605 kc. This band is broken up into 106 *channels* of 10 kc each. The center frequency of each channel, beginning at 540 kc, is assigned to one or more stations in the country as its carrier frequency. Broadcast transmitters must operate on the assigned carrier frequency with a tolerance of ±20 cycles. The type of emission is always amplitude modulation, with an assigned operating *unmodulated* carrier power of 100 to 50,000 watts, depending on the geographical area the station is expected to serve. Since the channels are only 10 kc wide, transmission of audio frequencies in excess of 5 kc will produce sidebands in adjacent channels and may interfere with reception of stations assigned to these channels.

The service area of a broadcast station is described as *primary* if there is no fading of the signal; *secondary* if there is fading but no objectionable interference; and *intermittent* if the signal is subject to some interference and fading.

Standard broadcast stations may be located in the central portion of cities, but the tendency is to locate the transmitter and antenna adjacent to populated areas in order that reception may be good, but not so strong that local receivers are overdriven. The transmitters are often located on marshy land to take advantage of the excellent ground conditions such an area provides or on a slight rise overlooking a populated area. Whereas FM broadcast stations (88 to 108 Mc) and TV stations (54–890 Mc) are located on the highest nearby peak, standard broadcast stations are generally located at lower altitudes.

When the broadcast station is located in the city, the studios in which "live" programs are produced may be in the transmitter building. When the station is erected at a remote location, the studios may be maintained in the city and the program fed to the transmitter on telephone wires or by an ultrahigh-frequency *STL* (studio-to-transmitter link) FM transmitter.

**24.2 Components of a Broadcast System.** Many of the circuits of equipment found in a standard broadcast station have been previously discussed or are similar to the circuits mentioned in chapters on Basic

Transmitters, Amplitude Modulation, Frequency Modulation, Antennas, and others. A block diagram of a possible transmitter and associated equipment is shown in Fig. 24.1. This composite station incorporates much of the currently used equipment necessary for the operation of a radio transmitting system with remote studios.

The complete system includes the main transmitter with small local studios and facilities, a radio link (STL) from remote downtown main studio facilities, and leased lines from transmitter and main studios, for either telephone communication or for transmission of programs if the STL equipment is not used. A remote STL transmitter capable of transmitting an athletic event or other program may also be used from a remote location to an STL receiver at the main transmitter.

The main transmitter consists of a crystal-controlled oscillator, one or more RF buffer amplifiers, a driver amplifier, and a radio-frequency final or power amplifier feeding the antenna. The program to be transmitted may originate in the local studios or be played from the local magnetic tape recorders or from the local turntables (TT). Announcements may be made in the local studio, the announce booth, or from the operator's microphone. The operator sitting at the *console*, or control board, can switch in any of these circuits as desired, and with the *gain controls*, also known as *attenuators*, *faders*, or *pots* (potentiometers), he can vary the amplitude of the program to keep the highest peaks of modulation above the required 85 per cent and below 100 per cent. He is aided in this by the limiter (Sec. 24.8).

A monitor receiver audibly indicates the operation of the transmitter. The modulation monitor, and possibly an oscilloscope, give a constant visual indication of the transmitted signal. A frequency monitor indicates the deviation of the carrier from the assigned frequency in cycles per second.

This particular station has an *auxiliary* transmitter that is maintained only for transmitting the regular programs of the station in case of failure of the main transmitter. There may also be auxiliary power equipment, such as a gasoline engine driving an alternator to supply power in case the public-utility lines fail. Such an auxiliary transmitter may operate with the same power as the main transmitter, or less, but on the same frequency with the same technical requirements of operation. It must be tested at least once a week. This is not the same as an *alternate transmitter*, which is a duplicate of the main transmitter, often used by stations operating on 24-hr broadcast schedules to allow servicing and maintenance without interruption of programs.

Most stations have a workshop or equipment-repair room where microphones, amplifiers, and other gear can be serviced by the operators.

If the program is originating at the main, downtown studios, it may be fed to the transmitter control board on leased telephone lines or by an

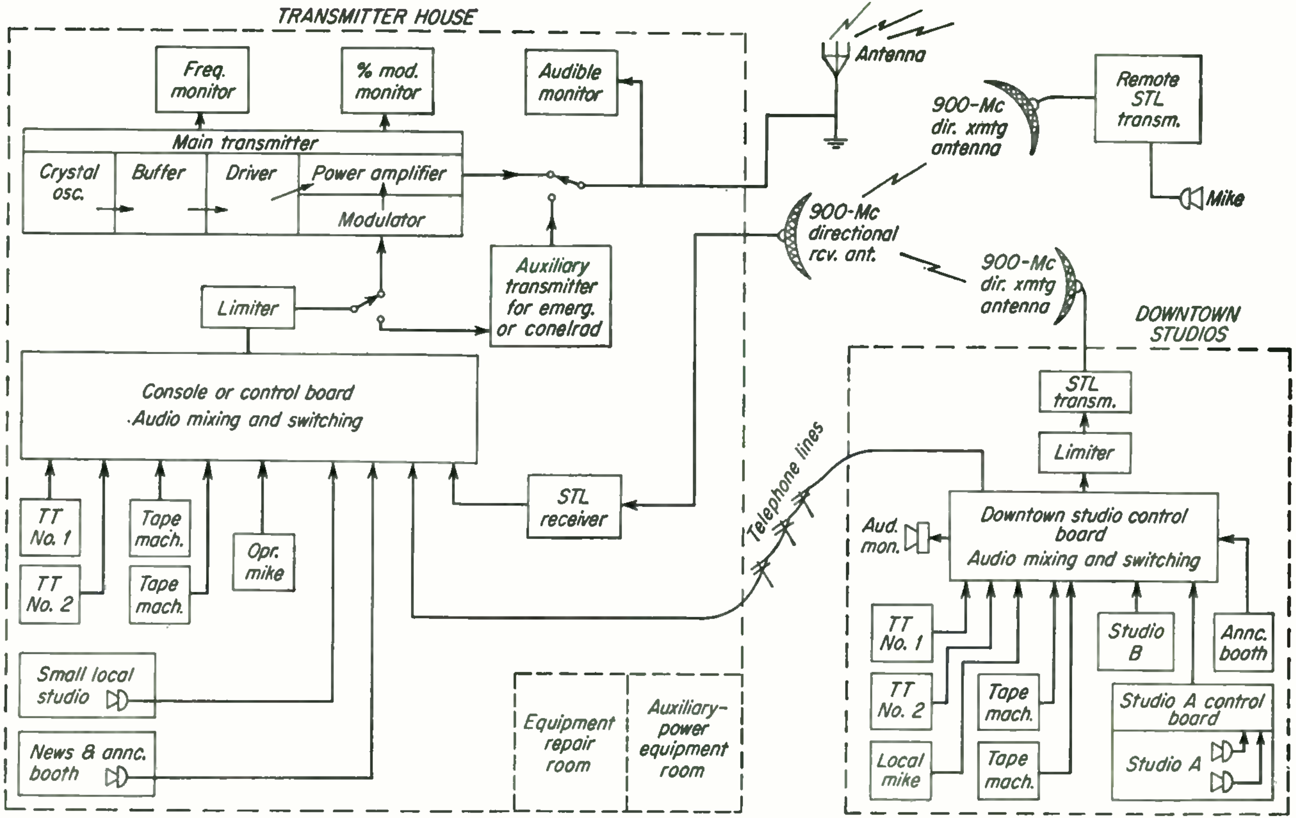


FIG. 24.1. Block diagram of a transmitting station, including remote studios and a remote STL.

STL system. The main studios are usually considerably more elaborate than those at the transmitter. The largest studio may have a special control board of its own, at which an operator mixes several studio microphones into the line feeding the program to the studio control board. The operator at the studio control board may do the major mixing and program switching, while the operator at the transmitter makes sure that the output of the STL receiver or telephone line is producing the desired percentage of modulation of the transmitter.

To properly produce a *disc-jockey* record program it is necessary to have three turntables and a microphone. One or more tape machines may also be used or may be used instead of turntables.

It is not unusual to have a program originating in studio A being broadcast while another program in studio B is being tape- or disc-recorded for replay at a later time. Perhaps a program originating at some other city is also being fed into the downtown studio or to the transmitter control board and is also being taped for later use. The control-board operators must be familiar with their equipment in order not to switch the wrong program into the on-the-air program channel at any time. In smaller stations the radio operator may also spin the records and make announcements. He is known as a combination, or "combo," operator.

When remote programs, such as football or baseball games, are broadcast, leased lines may be used, or an STL transmitter-receiver circuit may be established directly to the transmitter station. STL transmitters for standard broadcast stations operate in the frequency range between 925.5 and 939.5 Mc (940.5–951.5 Mc for FM broadcast station STL systems) and use wideband (200-kc channel) frequency modulation to relay speech or music from a remote location to the main transmitter. STL transmitters have a power output of only a fraction to a few watts, but use high-gain directional antennas to beam the signal to the directional receiving antenna at the main station. Being licensed transmitters, they require a licensed operator to set them up and tune them. They must maintain a frequency tolerance of 0.005 per cent.

**24.3 Conelrad.** Broadcast stations participating in *conelrad*, the CONtrol of ELectromagnetic RADiation system that goes into effect when an enemy air attack is imminent or under way, have additional lines and equipment. The main transmitter, or a second transmitter, must be capable of transmitting on 640 or 1,240 kc at intervals, in sequence with other broadcast stations in the same *cluster*, or area. Conelrad sequential control lines as well as a special telephone line to carry the conelrad messages terminate in the main transmitter building and must be tested at frequent intervals. When a conelrad alert occurs, the main transmitter carrier will be shut off for 5 sec, on for 5 sec, off for 5 sec, and then return to the air. A 1,000-cycle steady tone will be broadcast for 15 sec, followed by the conelrad "radio alert message," advising listeners to listen on 640 or 1,240 kc. The transmitter is then shifted to one o these frequencies and is connected into the sequential keying system tha turns one station of the cluster on and all others off. Then a second station is keyed on and the others off, and so on. The order and duration o the transmissions follow no conceivable pattern. In this way enem aircraft are unable to take direction-finder bearings on any *known* station at any known location.

**24.4 The Broadcast Console.** The nerve center of the broadcas station is its console, or control board. It is a complicated series of audi amplifiers, switches, relays, and gain controls. The operator switches th

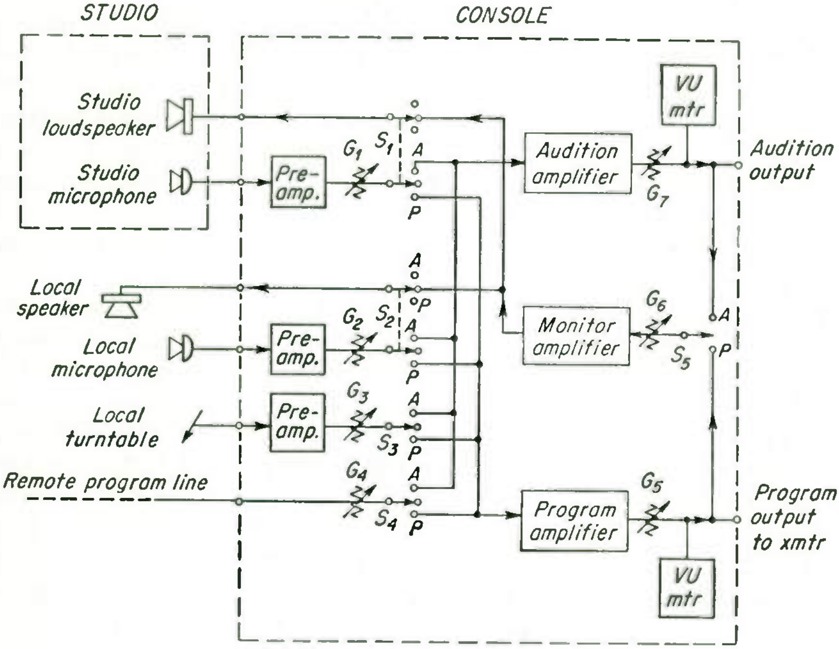


FIG. 24.2. Functional block diagram of a simple broadcast console and studio.

desired studio, turntable, microphone, or remote program through the console into the limiter and modulator stage of the transmitter.

The block diagram of Fig. 24.2 illustrates a simplified console circuit that will serve to demonstrate some of the requirements that must be met in broadcast work. Included are the console itself, the microphone, turntable, and speaker for the console operator, and a studio with a microphone and loudspeaker.

For a program originating in the nearby studio, the studio microphone switch $S_1$ is thrown to the program, or "P," position. The output of the microphone, through its preamplifier and gain control $G_1$, is connected to the input of the *program amplifier*. The output of the program amplifier is fed through the master gain control to the transmitter. At the same time the console operator is fed the signal output from the program amplifier, via the monitor amplifier, if the monitor input switch is in the P position, and if the operator's local microphone switch $S_2$ is in the "central" or "off" position. Thus, the operator hears the program originating in the studio and also has a visual indication of the signal strength by the volume-unit (VU) meter in the output line of the program amplifier. Note that when $S_1$ is thrown to the P position, the studio speaker is automatically disconnected from the monitor amplifier output, preventing an audio feedback howl from being produced in the studio.

While the studio is on the air (being fed into the program line), the operator can be recording an announcement or program to be used later by switching his microphone, local turntable, or the remote-line switches to the audition, or "A," position. This feeds his program into the audition amplifier, the output of which can be fed to a tape- or disc-recording machine. The local speaker and microphone are interconnected by $S_2$ so that the speaker is disconnected at any time the microphone is in use, preventing a feedback howl.

When the studio program is completed, the operator switches off the studio circuit $S_1$ and, by throwing his local microphone switch $S_2$ to P, can make a *station break* (station identification) or any other desired announcement. In many stations there is a second smaller studio, called an *announce booth* (not shown in this simplified system), in which a staff announcer may make the station break.

If the next program is coming in from a distant network station, the operator usually checks the remote-line signal strength a few minutes before the program is scheduled to start by throwing $S_4$ and $S_5$ to the A position. This feeds the remote signal through the audition and monitor amplifier and to his local speaker. When it is time for the remote program to start, $S_4$ is connected to its program position, and the program is fed through the program amplifier to the transmitter.

On many occasions it is necessary to provide *talk-back* facilities between the console operator and the announcers or actors in the studio before they go on the air. This can be done with the audition channel of this console. The operator first switches $S_5$ to the audition position. When he throws his local microphone switch to audition, he can be heard in the studio. When he throws his microphone switch to the central or off position and the studio microphone to the audition position, he can hear anyone speaking in the studio. Talk-back may be used to notify a studio that it is about to be switched on the air.

When the program is originating at the console, as in a disc-jockey show, the turntable that is playing the announced record is in the program position. The next record is set up on another turntable, not shown, and its output is fed into the audition channel. By switching the monitor amplifier switch $S_5$ to the A position, the operator can hear the output of the second turntable. He sets the pickup needle in the outer groove of the record and then spins the turntable by hand until he hears the modulation on the record. By backing the turntable past the first sign of modulation he has *cued* the record, and it is ready to be played. This turntable is switched to the program line. A fraction of a second after the motor switch for this turntable is turned on, the music of the record will begin. In this way there are no long pauses after the announcement of the record as the needle moves over the first few unmodulated grooves.

The console described here is far simpler than those in actual use, although its basic functions are similar. With this console, the studio is fed the output of the program amplifier, allowing those in the studio to hear what is being broadcast at all times when their studio is not on the air. However, when the operator is cuing a record, the studio is fed the sounds of the cuing rather than the program being broadcast. This is not desirable, and a separate cuing amplifier might be used in connection with the turntables.

The attenuators $G_1$, $G_2$, $G_3$, and $G_4$ may be termed *channel* gain controls. The attenuator $G_5$ is known as the *master program* gain control since it can control any console signal. The *audition* master control is $G_7$. The monitor gain is $G_6$.

**24.5 Audio Levels.** There are three important requirements during a broadcast. One is timing. The programs must start and stop when they should. Announcements and station breaks must be squeezed into the time allotted for them. A second requirement is fidelity. All amplifiers must be operating in such a manner that they do not add distortion to the program. This means constant maintenance and testing of the console and associated circuits. The input and output impedance of the lines of all equipment must be properly matched and terminated. A third requirement is maintaining the proper audio signal amplitude, or *level.*

Audio levels are usually expressed in *decibels*, *volume units*, or dbm, which are all logarithmic *ratios* of one power to another or one voltage to another (Sec. 8.6). In broadcast work, zero db or VU (volume unit) represents a reference level of 0.001 watt in a 600-ohm line. The abbreviation *dbm* indicates *decibels* (db) *using a reference of 1 milliwatt*, which is, for most purposes, the same as VU. In any of these, a gain of 10 db, VU, or dbm equals a gain of 10 times the power, or 3.16 times the voltage. A gain of 20 db equals 100 times the power, or 10 times the voltage.

With these two facts in mind,

$$\begin{aligned} 10 \text{ db} &= \text{a power change of 10 times} \\ 20 \text{ db} &= \text{a voltage change of 10 times} \end{aligned}$$

the following types of examples can be computed without paper and pencil:

1. If the power output of a modulator is decreased from 1,000 to 10 watts, how is the power reduction expressed in decibels? A loss of 10 db reduces the power to 100 watts; another 10 db (−20 db) reduces the power to 10 watts. Therefore the reduction from 1,000 to 10 watts equals a 20-db loss of power.

2. An AF amplifier has an over-all gain of 40 db, and the output is 6 watts. What is the input power? Starting with the output of 6 watts and working back 10 db gives a power of 0.6 watt. Another 10-db loss (−20 db) gives a power of 0.06 watt. Another 10-db loss (−30 db) gives a power of 0.006 watt. Another 10-db loss (−40 db) gives a power of 0.0006 watt. If 0.0006 watt is fed into the amplifier, the output will be 6 watts (assuming that the input and output impedances are equal).

3. The output of a voltage amplifier is −40 db. This is fed into a mixer with a loss of 10 db. How much voltage amplification is required to produce a +10-db output power? The total decibel loss is −40 and −10, or −50 db. The total number of decibels between −50 and +10 is 60 db. Since 20 db equals a gain of 10 times the voltage, 40 db equals a gain of 10 × 10, or 100 times the voltage, and 60 db equals a gain of 10 × 10 × 10, or 1,000 times the voltage.

A microphone feeding into the console may have a rating of −85 dbm with a given value of sound striking it. Therefore the console must be capable of amplifying the signal at least 85 db (or VU) to produce a zero-VU-level output. Weaker signals striking the microphone will require more gain in the amplifiers, possibly 100 db. There is usually a loss of at least 6 to 10 db in the gain control in the microphone channel amplifier.

Another input, a turntable, feeds in a signal of −45 dbm and requires an amplifier of only 45 db to bring its output up to the required zero VU used to feed the transmitter. Between these two inputs there is a difference of about 40 db, or a voltage difference of about 100 times.

A third input signal, a remote program, may be coming in at a zero-VU level on telephone lines. (The nominal signal level on commercial telephone lines is zero dbm, to prevent *cross talk* between lines running in the same cable.)

To bring up very low levels to a value that can be adjusted with a gain control without introducing excessive amounts of noise, a preamplifier, a one- or two-stage amplifier before the gain control, is used. If the mixing (switching and gain controlling) is accomplished at a −10 dbm level, the amplifier that follows the mixing must be capable of a gain of at least 10 db, and preferably 20 to 30 db. The preamplifier must be capable of 75 to 95 db for the microphone. The preamplifier for the turntable must be capable of 35 or more db gain. The remote program must *lose* 10 db before being fed into the mixer.

To produce approximately the same signal at the mixer point, more amplifier stages can be used for the microphone than for the turntable. For the remote-line signal, a resistance pad between the line and console will *reduce* the signal.

**24.6 Attenuator Pads.** It is possible to use the same type of high-gain preamplifiers for all inputs but intentionally lose signal level by inserting *H-* or *T-pad* attenuators between inputs and preamplifiers.

These pads are groups of resistors that act as voltage dividers, at the same time holding the output and input impedances of the circuits being coupled at a constant value, usually 600 ohms.

The T pad is used with *unbalanced* lines, which have one of the lines grounded, as shown in Fig. 24.3.

If it is desired to drop the voltage to one-half, which is a loss of 6 db, and maintain an impedance match at both transformers, the values shown can be used. The 600-ohm secondary of the left-hand transformer looks at a 200-ohm resistance in series with two parallel 800-ohm impedances ($R_2$ plus the 600-ohm primary in parallel with the 800-ohm resistance), or approximately 400 ohms. It sees an impedance of 600 ohms. The other transformer sees the same thing. If there is 1 volt delivered by the input transformer, the ratio of 200:400 ohms in series produces a voltage drop across the 400-ohm resistance of $\frac{2}{3}$ volt. Since the 200-ohm $R_2$ and the 600-ohm primary are in series across $\frac{2}{3}$ volt, the primary sees $\frac{600}{800}$ of $\frac{2}{3}$, or $\frac{6}{12}$, or $\frac{1}{2}$ volt.

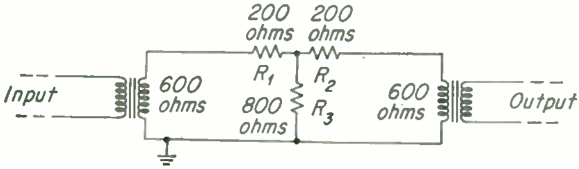


FIG. 24.3. A T-type attenuator pad for a 600-ohm line.

If a loss of approximately 10 db is desired, $R_1$ and $R_2$ may be 300 ohms each and $R_3$ 400 ohms. For a 20-db loss, $R_1$ and $R_2$ may be 500 ohms and $R_3$ 120 ohms. (These are approximate values.)

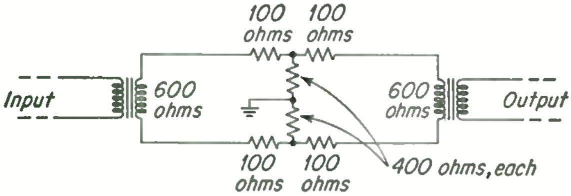


FIG. 24.4. An H-type attenuator pad.

In most long lines, a balanced transmission line is used. The H pad is used in this case. The series resistors are one-half the value of those in the T pad above. The resistance across the line is the same as in the T pad, except that it is center-tapped (Fig. 24.4). The H pad shown will give a 6-db loss.

Pads are also used to terminate amplifiers from remote studios that are feeding a long transmission line to the transmitter equipment. Such *lines* have differing transmission characteristics for different frequencies. If terminated by a −6- to −10-db pad, the characteristics of the line have little effect on the amplifier and less distortion will be produced by it.

The matching of impedances in all audio equipment is important to reduce distortion.

Another application of a T pad is in the variable attenuator, or gain control, of a mixer system (Fig. 24.5). The arms of all three resistors vary at the same time, holding the input and output impedance essentially constant regardless of the setting of the control arm. This is superior to a simple potentiometer-type gain control which always changes both input and output impedance values as the moving arm is varied.

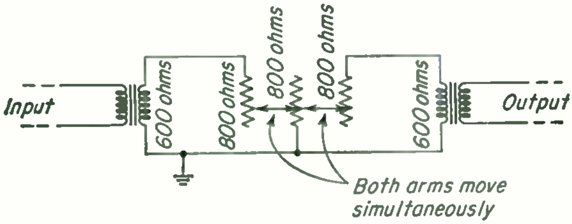


FIG. 24.5. A variable T-type attenuator, or gain control.

It will be noted that if 800-ohm resistors are used on the three arms, at full gain the 600-ohm transformer winding sees an 800-ohm resistance and a 600-ohm impedance in parallel, which is lower than its own impedance. At minimum gain the transformer sees an 800-ohm resistance which is higher than its own impedance. Near mid-gain the impedances match satisfactorily, although at high and low settings they are not greatly mismatched.

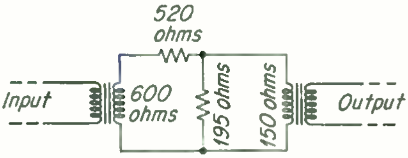


FIG. 24.6. An L-type pad to match a 600-ohm output to a 150-ohm input circuit.

When coupling two audio circuits having unequal impedances, either a coupling transformer or an L or U pad may be used. The L pad shown in Fig. 24.6 matches a 600-ohm output to a 150-ohm input. There is no selection of loss in these pads. To match these two impedances only the two resistors shown can be used. The loss happens to be a little more than 10 db.

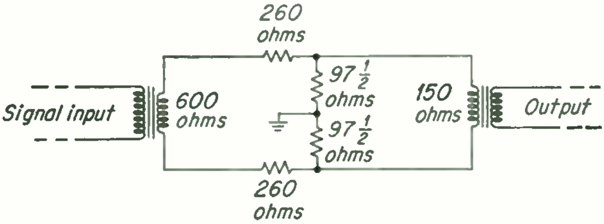


FIG. 24.7. A U-type balanced pad to match dissimilar impedances.

For a balanced line, a U pad is used, shown in Fig. 24.7. As in the H pad, the series resistance value of the unbalanced L pad is halved and the shunt resistor is center-tapped.

At the receiving end of a transmission line a center-tapped primary transformer is usually used. The center tap is grounded. This tends to balance out hum or noises picked up by the lines. The shunt or center-tapped resistor of an H or U pad may be a potentiometer to allow a more accurate balance of the lines. With such pads at the receiving end, a center-tapped transformer may not be required.

To reduce capacitive coupling of noise impulses picked up by transmission lines the transformer used at the receiving end often has an electrostatic shield between primary and secondary windings. This shield is connected to the core, which is grounded.

**24.7 Line Equalizers.** A short pair of wires carrying an audio signal at a nominal impedance of 600 ohms of both input and output transformers produces very little attenuation of any of the audio frequencies. However, when a line exceeds a few hundred yards in length, the inductance of the lines and the capacitance between the two wires do affect the transmission of the signal, attenuating the high frequencies more than the low. If the line is terminated at both ends with lower-impedance transformers, 150 ohms, for example, the high-frequency loss is less.

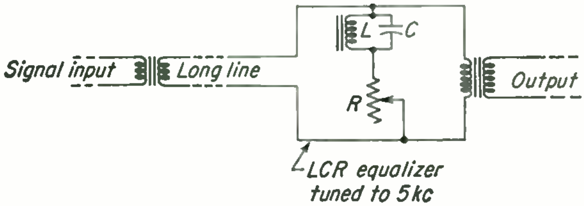
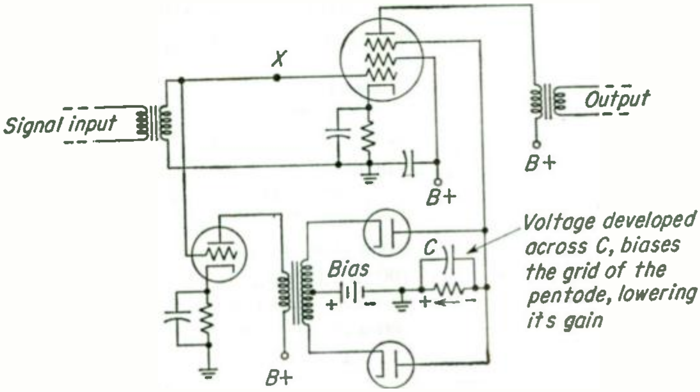


FIG. 24.8. A parallel-resonant-circuit line equalizer.

The use of a line pad at the output of the amplifier feeding the line helps to flatten the frequency response of the final-amplifier stage, but for high-fidelity transmissions, the lines should transmit all audio frequencies equally well. For standard broadcast, this is usually considered to be from 50 cycles up to a minimum of 7,500 cycles. For FM and TV, the lines must be substantially flat up to approximately 15,000 cycles.

If a line is found to attenuate the higher frequencies, a *line equalizer* can be placed across the receiving end of the line to decrease the amplitude of all lower frequencies. This can be accomplished by using a parallel-resonant circuit in series with a variable resistance across the line (Fig. 24.8). The circuit is made resonant at some high frequency to be used, 5,000 cycles, for example. The high impedance of the circuit to frequencies near 5,000 cycles allows these frequencies to pass without attenuation. Lower frequencies (as well as higher) find that the equalizer presents a lower impedance, and they are attenuated somewhat. By adjustment of the resistance, it is possible to control the attenuation of the lower frequencies and equalize the frequency characteristics of the line from 50 to 5,000 cycles.

**24.8 Peak Limiter Amplifiers.** Speech and music produce relatively high peaks of audio voltage at times. If the operator adjusts the gain controls to allow the average signal level of a musical program to produce 75 to 85 per cent modulation, the peaks that occur may produce more than 100 per cent modulation, distortion, and excessive sidebands, may actuate overload relays, or may damage tubes or associated equipment. In speech communication systems, peak limiters, or clippers, are usually used (Sec. 18.12). The distortion that is produced with this type of limiting is too great for broadcast standards and special higher-fidelity *limiting amplifiers* are used. The basic idea of a limiting amplifier is shown in simplified form in Fig. 24.9.



Voltage developed across C, biases the grid of the pentode, lowering its gain

FIG. 24.9. Basic principle of a limiter amplifier.

The program signal is fed to the grid of an amplifier stage, and at the same time is fed to a second amplifier coupled to a biased, full-wave diode rectifier. When the signal level exceeds the positive bias on the diode cathodes, current flows through the tubes and produces a negative voltage across the capacitor (condenser) $C$. This negative voltage is used as a bias on one of the grids in the amplifier tube, decreasing its amplification and reducing the amplitude of the output peak signal. The value of the bias voltage on the diodes determines the value at which limiting will occur.

Once charged, capacitor $C$ discharges relatively slowly. If music rises in volume slowly, the bias voltage across $C$ tends to rise also, attenuating the signal, acting as an automatic gain control. However, if a sharp, single peak of sound occurs, capacitor $C$ charges and biases the tube for a period of time. All signals that follow the short peak are held for a time at a low level by the bias voltage of $C$. This results in an unpleasant *hole* punched in the program following high-amplitude sounds.

A steep-sided audio wave tends to beat the building up of the bias voltage and may produce an instantaneous overmodulation peak before gain reduction occurs. To reduce this, a limiting amplifier may incorporate an inductance-capacitance *delay line* in the circuit at point $X$ in the diagram. This results in the bias voltage being developed before the signal is applied to the limiting-amplifier grid.

The limiting amplifier operates at a low level, usually about 0 VU. It normally is fed the output of the console. The output of the limiter is attenuated to a level of about zero VU so that it may be cut in or out of the circuit if desired without materially changing the audio level of the system. It feeds the audio amplifiers that drive the modulator stage. Limiters allow a higher average percentage of modulation of the transmitter.

**24.9 Classifications of Powers.** When a broadcast station is licensed for operation, the instrument of authorization will specify a certain *licensed power*, or *authorized operating power*. The operating power is the actual output power of the transmitter. The tolerance of the operating power of the station must not exceed the licensed power by more than 5 per cent, nor fall more than 10 per cent below the licensed power, except in emergencies, when lower power may be used for a limited time. The operating power may also be known as the *carrier power* and is always the *unmodulated* value.

Table 24.1

| Factor ($F$) | Method of modulation | Maximum rated carrier power of the final amplifier | Class of final amplifier |
|---|---|---|---|
| 0.80 | Plate | 5,000 watts and over | C |
| 0.70 | Plate | 100 to 1,000 watts | C |
| 0.65 | Low level | 100 watts and over | BC |
| 0.35 | Low level | 100 watts and over | B |
| 0.35 | Grid | 100 watts and over | C |

The *maximum rated carrier power* of a broadcast-station transmitter is the maximum power at which this make of transmitter can be operated satisfactorily. It is determined primarily by the tubes and plate voltages used in the final amplifier. The maximum-rated-carrier-power capabilities of a transmitter must always be equal to, or exceed, the licensed power. For example, a station licensed for 500 watts may use 500 watts from a transmitter that has a capability of 1,000 watts.

The *plate input power* of a broadcast-station transmitter is determined by the product of the plate voltage and the plate current ($P = E_pI_p$) of the final amplifier tube(s) during a time when no modulation is being applied.

The operating power of a standard broadcast station is determined by the *direct method.* This is the power determined by using the formula $P = I^2R$, where $I$ is the antenna current with no modulation and $R$ is the resistance of the antenna at the point where the current is measured. The *indirect method,* which is used to determine the output power of FM broadcast stations and TV aural transmitters, is used in standard broadcasting only in an emergency, or when authorized installation changes, changes of equipment, or antenna changes are being made. The indirect power is determined by the formula

$$P = E_pI_pF$$

where $F$ is a factor between 0.35 and 0.80 (depending on the type of modulation used) as determined by the FCC (see Table 24.1).

**24.10 Broadcast-station Tests.** Before a broadcast station is constructed, it is first necessary to obtain a *construction permit* from the FCC. During the construction period, after the transmitter has been installed, it is permissible to test the transmitting equipment for short periods between midnight and local sunrise. These are known as *equipment tests.*

After construction is completed, and until the station license has been issued by the FCC, application can be made to test the station on the air. These are known as *service,* or *program,* tests.

The period of the day between midnight and local sunrise is known as the *experimental period.* During this time, broadcast stations may transmit for testing and maintaining equipment, provided that such tests do not interfere with other stations broadcasting on the frequency at that time.

All broadcast stations must be capable of transmitting between 85 and 95 per cent modulation with a total AF harmonic distortion not to exceed 7.5 per cent. For all percentages of modulation of 84 per cent or less the total harmonic distortion must not exceed 5 per cent. The distortion is measured using modulating frequencies of 50, 100, 400, 1,000, 5,000, and 7,500 cycles, plus any intermediate or higher frequencies found necessary.

Broadcast stations operating in a conelrad cluster must test the functioning of the conelrad air-raid warning signal by turning off the transmitter for 5 sec, on for 5 sec, off for another 5 sec, and must then return to the air and transmit a 15-sec 1,000-cycle tone signal.

**24.11 Broadcast-station Meters.** The meters involved in the determination of the power input and power output of a transmitter must have a required degree of accuracy. These meters are the final-amplifier plate voltmeter and ammeter, an RF ammeter to measure the base current of the antenna, and, for directional antenna systems, an RF ammeter at the point of common input to the directional antenna.

The ammeters and voltmeters associated with the final radio amplifier-stage plate circuit must have an accuracy of at least 2 per cent of the full-scale reading. A 1,000-ma meter must be accurate to within 20 ma or less at any point on its scale. The full-scale reading of these meters shall not be greater than five times the minimum indication when the transmitter is in normal operation.

Antenna current meters are usually thermocouple types and have essentially square-law scales. No scale division above one-third full-scale reading of such meters shall be greater than one-thirtieth of the full-scale reading. For example, an ammeter with a full-scale reading of 6 amp is acceptable for reading currents from 2 to 6 amp, provided no scale division between 2 and 6 amp is greater than $\frac{1}{30}$ of 6 amp, or 0.2 amp. When remote-reading antenna ammeters are employed and their indications are included in the station log, the calibration of these meters shall be checked against the regular meter at least once a week.

When directive antennas are used, the currents in the elements must be held within 5 per cent of the authorized values.

If a required plate circuit or antenna meter burns out and no substitute conforming to required specifications is available, an appropriate entry must be made in the operating log indicating when the meter was removed from and restored to service. The FCC Engineer in Charge of the radio district must be notified immediately after the meter is found to be defective and as soon as it is replaced. The meter must be repaired or replaced within 60 days; if not, a special request must be filed for an extension of time. (This does not apply to remote-reading antenna ammeters, since they are not required.)

**24.12 Broadcast-operator Requirements.** It would be desirable to have all operators in a broadcast station hold Radiotelephone First Class licenses. This would allow any operator to adjust any piece of equipment at any time. However, stations have found it difficult to find a sufficient number of such qualified operators. Recently, the requirements have been relaxed to allow holders of lesser licenses, Radiotelephone Second Class licenses and radiotelephone permits, to operate certain types of broadcast equipment as long as the work entails only the turning on or off of the station, adjustment of the primary-power-line voltage and of the gain of the transmitter, and transfer of operation to the conelrad condition, provided the operator has been instructed how to properly change the equipment by a First Class license holder.

A First Class license holder must be on call at all times in case the transmitter or other equipment should fail and require adjustment.

Operators of transmitters having directional antennas should have Radiotelephone First Class licenses, as should operators of transmitters having 10,000 watts licensed power (which includes short-wave International Broadcast Stations).

**24.13 Remote Control.** A standard broadcast station may be operated by remote control if: (1) It has an output power of 10,000 watts or less. (2) It does not have a directional antenna. (3) The transmitter is protected against operation by unauthorized persons. (4) The transmitter automatically shuts itself off if trouble occurs in it. (5) The control and monitoring equipment allows the licensed operator to perform all the necessary functions of turning the station on, monitoring it properly, and turning it off from the remote position.

Remote control is also allowed with directional antennas and over 10,000 watts if a First Class licensed operator is available and the transmitter is properly protected.

**24.14 Frequency Monitoring.** Modern broadcast transmitters use low-temperature-coefficient-type crystals in the oscillator circuit. In many cases a station will also have a second stand-by oscillator stage ready to switch into service if the first one fails. The variation of the temperature inside the temperature-controlled crystal chamber (Sec. 12.14) must not exceed ±1.0° centigrade for such crystals. If either *X*- or *Y*-cut crystals are used in the oscillator circuit, the temperature tolerance is ±0.1°C, to assure compliance with the ±20-cycle frequency tolerance of the standard broadcast station.

A frequency monitor operating independently of the frequency-control circuit of the transmitter and of a type approved by the FCC must be in operation at all times that the transmitter is on the air, at either the transmitting station or at the remote-control point. Such a frequency monitor must give a constant visual indication of the operating frequency in cycles per second, similar to the frequency monitor explained in Sec. 21.10.

The correctness of the frequency-monitor indications can be checked by comparing a frequency report from a commercial measuring service with the indication of the monitor. If the frequency-measuring report indicates the station is 15 cycles low and the monitor shows the frequency to be 5 cycles high at the same time, the monitor must be indicating 20 cycles too high and should be serviced and recalibrated.

**24.15 Modulation Monitors.** Each station is required to have in operation at the transmitter, or at the place the transmitter is controlled, a modulation monitor that will give a visual indication of the percentage of modulation at all times.

The modulation monitor must have (1) a d-c meter to read the average rectified carrier value, which will also read carrier shift during modulation; (2) a rapidly moving type of meter to indicate the percentage of the negative and positive peaks of modulation, selected by a switch; (3) a peak-indicating light or alarm that can be set at any value from 50 to 120 per cent modulation of positive peaks and/or from 50 to 100 per cent of negative peaks.

Standard-broadcast-station modulation monitors operate on a principle somewhat similar to the simplified diagram in Fig. 24.10.

A small amount of modulated RF alternating current is coupled into the tuned circuit from the transmitter. Across this tuned circuit is a shunt-type half-wave diode carrier-detector circuit, with the meter, $M_1$, and its resistor as a load. The RF choke and $C_2$ remove the RF a-c component, leaving only a steady current flowing through $M_1$ when there is no modulation, and a varying direct current when the carrier is modulated. The input circuit is tuned to a peak indication on the carrier meter, and the input coupling is adjusted until the carrier meter indicates *half* scale. When no modulation is applied to the transmitter, the carrier meter, which is acting as a carrier-shift indicator, does not move. When it does, carrier-shift distortion is present in the emission. Carrier shift should not exceed 5 per cent in standard broadcast stations in either a positive or negative direction. The resistor $R_1$ shunts the tuned circuit, lowering its $Q$ and preventing it from peaking too sharply and not responding adequately to higher-frequency sidebands.

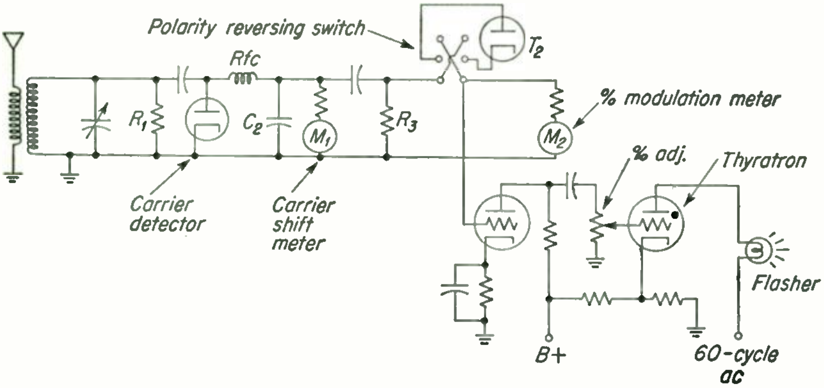


FIG. 24.10. A percentage of modulation indicator, including a carrier-shift meter and an overmodulation flasher.

The output of the carrier detector is capacitively coupled to the resistor $R_3$. With no modulation, no current flows through $R_3$, but when modulation occurs, an AF a-c flows through it. A sensitive d-c meter and a diode tube $T_2$ are in series across $R_3$. With the polarity-reversing switch in the downward position, whenever the top of $R_3$ becomes positive, current flows through the meter $M_2$. On the negative half cycle of modulation, no current flows through the meter. However, when the diode switch is reversed, the negative half cycles produce current flow through the meter. Depending on the position of the switch, either the extent of the positive peaks of modulation or the extent of the negative peaks can be made to register current and cause deflection of meter $M_2$. $M_2$ is calibrated in percentage of modulation. It is always necessary to readjust the $M_1$ carrier level to the same value as when calibration was accomplished, usually to a center-scale reading.

The overmodulation-indicator flasher circuit can utilize the polarized signal voltage fed to the percentage-of-modulation meter circuit. These half-wave pulses are amplified and actuate a thyratron-tube circuit with 60-cycle a-c as its plate voltage supply. The thyratron-tube cathode is connected across a voltage-divider circuit, making it positive in respect to ground. The grid of the thyratron is returned to ground and is thereby more negative than the cathode. When the amplified signal voltage fed to the thyratron grid exceeds the bias sufficiently, the thyratron ionizes and conducts current, flashing the lamp in its plate circuit. The tube de-ionizes on the negative half cycle of the 60-cycle a-c. The potentiometer dial is calibrated in percentage of modulation required to produce a flash of the lamp.

In practice, more amplifiers may be used in both the percentage-of-modulation circuit and in the flasher circuit. For greater linearity of indications, other refinements are incorporated in the commercial equipment available.

Many stations also use an oscilloscope, displaying either an envelope or a trapezoidal indication of the percentage of modulation of the transmitter. This gives a more accurate check on the peaks of modulation than any modulation monitor can.

**24.16 International Broadcast Stations.** There are a few licensed broadcast stations in the United States that beam their transmissions to the general public in foreign countries. These are *short-wave* stations and operate in one or more of seven short-wave bands, commonly known as:

Band A, or the 6-Mc band
Band B, or the 9.5-Mc band
Band C, or the 11.7-Mc band
Band D, or the 15.1-Mc band
Band E, or the 17.7-Mc band
Band F, or the 21.5-Mc band
Band G, or the 25.6-Mc band

These stations must maintain a carrier-frequency tolerance of ±0.003 per cent on all frequencies of operation and have a licensed power output of not less than 50,000 watts. Because of the variations of transmission paths during different times of the day and year, these stations shift from one band to the other during the day, to operate on the band that will have the best chance of reaching the audience desired. Directional antennas having a minimum power gain of 10 (10 db) in the desired direction are required for these stations. Frequency monitors, modulation monitors, auxiliary or alternate transmitters, and other technical items are similar to standard broadcast stations. Radiotelephone First Class licenses are required of all operators at the transmitters of these stations.

**24.17 Spare Tubes.** The requirement of all broadcast stations, standard, FM, TV, and International, regarding spare tubes is given in Table 18.1.

**24.18 Logs.** There are two types of logs required in standard broadcast stations, a program log and an operating log.

A *program log* contains:

1. An entry of the time each station-identification announcement (call letters and location) is made
2. An entry briefly describing each program (music, drama, speech), the program name, sponsor, beginning and ending times, if any mechanical record is used, time announced as a mechanical record, and political affiliation of political-candidate speakers
3. An entry showing that each sponsored-program broadcast has been announced as sponsored, paid for, or furnished by the sponsor
4. An entry showing, for each program of network origin, the name of the network originating the program

An *operating log* contains:

1. An entry of the time the station begins to supply power to the antenna and the time it stops
2. An entry of the time each program begins and ends
3. An entry of each interruption to the carrier wave, its cause and duration
4. If required, an entry regarding antenna-structure illumination
5. An entry of the following, every 30 min: (*a*) plate-circuit voltage and current of the final RF amplifier stage, (*b*) antenna current, (*c*) frequency monitor reading

Logs are retained for a period of two years, unless they contain information that might be required (information regarding claims or complaints or distress communications).

Logs are kept by persons competent to do so (licensed operators for the operating logs), who have actual knowledge of the facts required and who shall sign the log when starting duty and again when going off duty. There is no prescribed form of a log other than that it be suitable and orderly.

No log or portion thereof shall be erased, obliterated, or willfully destroyed within the period of retention provided by the rules. Any necessary correction may be made only by the person originating the entry, who shall strike out the erroneous portion, initial the correction made, and indicate the date of correction.

**24.19 Recording Equipment.** Program material to be broadcast may be recorded on disc recordings (records), magnetic tape, or magnetic wire.

The recording of audible sounds on a disc involves the cutting of a continuous, spiral groove inward from the outside of the record blank, or outward from near the center of the record blank.

The cutting instrument, a *needle*, or *stylus*, is sharpened to an 89° angle to cut a 2.5-mil (0.0025 in.) to 3-mil groove, or to a 76° angle to cut a 1-mil groove.

The 2.5- or 3-mil grooves are used on the older-type 78-rpm 8-, 10-, or 12-in.-diameter records, and for the 33-rpm 16-in.-diameter transcriptions.

The 1-mil grooves are used on 45-rpm, 33-rpm LP (long-play) records, and the 16-rpm book records.

The advantage of the narrow grooves is the increased number of usable grooves for a given-diameter record. Whereas a 78-rpm 3-mil-groove record may have approximately 100 grooves to the inch, a 45-rpm 1-mil-groove LP has approximately 250 grooves to the inch. One inch of groove diameter of a 78-rpm record gives about 1⅓ min of playing time. One inch of a 45-rpm record requires about 5 min to play.

The grooves are *modulated* by vibrating the cutting stylus sideways by magnetic means as it cuts along the grooves. A 500-cycle modulation produces 500 lateral wavers in the groove in one second. When a playback needle rides along the groove, it is made to waver back and forth 500 times a second, which produces a 500-cycle a-c in the playback *pickup head.*

The uncut area between the grooves is known as the *land area.* When recording, the operator must check the land and groove areas and keep them approximately equal. If the stylus and the recording head exert too much downward pressure, the cut becomes too deep, the groove too wide, and the land area too narrow.

If the stylus is not modulated sufficiently, it does not cut a wide enough waver in the grooves and the playback mechanism reproduces a weak signal. If the stylus is modulated too much, one groove may waver over into, or too close to, adjacent grooves and distortion will be produced. The extent of the groove modulation is checked by making a test cut and observing it through a microscope.

A cutting stylus that is not properly sharpened, that becomes dull, or that has a chip in it produces a rough-surfaced groove that results in noise on playback. Old recording blanks become dry, and the groove tends to chip out instead of cutting out smoothly, again resulting in noise on playback.

When the stylus has the proper pressure and angle and when the record blanks have a live surface, a thread of recording material is produced as the stylus cuts the groove. This thread must be pushed in toward the center of the record by the operator during outside-in recordings, or may be left to accumulate near the center of the record with inside-out recordings. Usually a vacuum device with its opening riding along with the stylus point sucks up the recording thread and deposits it in a container of water. (The thread cut from acetate-surfaced record blanks is usually quite explosive if ignited.)

The recording mechanism requires about 1 watt of undistorted audio to produce the required modulation of the stylus and grooves. This is usually obtained from a 5- to 10-watt amplifier.

While slower-turning records provide longer playback time, the reduced groove speed gives less satisfactory high-frequency modulation of the grooves. This can be overcome by using larger-diameter records, which result in longer grooves per second.

Cutting styluses are made with diamond, sapphire, stellite, or other steel points. The steel points have a limited life, 3 to 10 min of cutting; sapphire considerably longer, 30 min or more; and diamond, many hours.

The same is true of playback needles. Steel needles last only a few records, sapphire several thousand playings, and diamond needles more than 20,000 playings. The weight of the playback head determines the pressure of the needle on the groove (sometimes tons of pressure per square inch). The lighter the head, the less wear on the records; yet the head must be heavy enough to hold the needle in the groove to reproduce all the modulation.

Each time a record is played, the playback needle polishes off some of the high-frequency modulation in the grooves. After several playings the fidelity suffers. Old records require the use of *needle-scratch* filters, which are low-pass filters that start cutting off frequencies above 3,000 to 5,000 cycles. This eliminates much of the scratch noise, which is usually in the 5,000- to 12,000-cycle range.

While the 2.5-mil playback needle will reproduce much of the modulation in a 1-mil groove, a separate needle should be used for the two different-diameter grooves. Some playback heads have both types of needles. The desired one can be swung into position and played. In other cases, two playback arms, each with its own head and needle, may be used.

**24.20 Wire Recorders.** In the 1930s the wire recorder came into commercial use. It employs a spool of thin steel wire having a high retentivity. The wire is pulled past a recording head and then wound onto a large-diameter spool that rotates at a constant speed to produce a relatively constant wire speed past the recording point (Fig. 24.11).

When an AF a-c is fed to the recording-head coil, a strong magnetic field appears at the slot in the core of this electromagnet. The rapidly moving wire becomes magnetized according to the frequency and the amplitude of the modulating AF a-c.

After recording, the wire is rewound on the original spool. To reproduce the recorded material, the wire is wound back on the take-up spool at the same speed as when the recording was made. The magnetized sections of the wire crossing the gap in the head change the flux in the electromagnet core and induce an a-c into the attached coil that is proportional in frequency and amplitude to the AF a-c that originally magnetized the wire.

The magnetization of the wire remains fixed on the wire for long periods of time with little change. The wire can be cleaned of magnetization by running it over a strong permanent magnet, but this method leaves a recorded noise on the wire. In practice, a high-frequency a-c, in the region of 30 kc, will re-record the wire at this frequency deep enough to wipe off any audio modulation on the wire. The 30-kc signal is not audible, resulting in an apparently clean wire.

In practice, the wire is first fed over a wiping head before it passes over the recording head. Thus, the wire may be wiped clean and re-recorded at the same time. On playback and rewind, the erase head is automatically disconnected from the circuit.

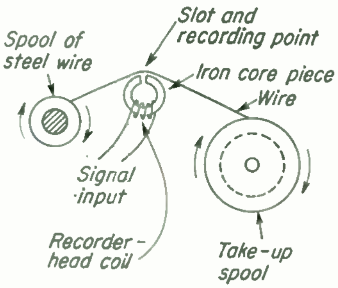


FIG. 24.11. Essential parts of a wire recorder.

The recording head moves up and down slowly, during recording, rewinding, and playback. This winds the wire in even layers on the two spools.

If the wire turns to any extent during playback, the portion of the wire that was recorded does not pass over the pickup slot and the amplitude of the playback signal is lessened.

When the wire breaks, it often becomes wound into the mechanism or tangles. A broken wire can be tied, but some of the modulation is lost, and a click is produced each time the knot passes the playback head.

Vest-pocket recorders used for on-the-spot interviews are usually tiny battery-operated portable wire recorders.

**24.21 Tape Recorders.** The broadcasting industry uses a great many tape recorders today. It is standard practice for network stations to record programs on tape and hold them for a few minutes to several hours before transmitting them. Both the picture and the sound of a TV program can be tape-recorded and transmitted when desired.

Audio-frequency recording tape is made of plastic (or paper) a few thousandths of an inch thick and approximately $\frac{1}{4}$ in. wide. On one surface it is painted with a finely ground material having a high retentivity. The tape is wound onto thin spools made of plastic or metal. The basic operation is indicated in Fig. 24.12.

When the constant-speed rotating drive wheel is forced up against the tape and the idler wheel, the tape is pulled along toward the take-up reel. The take-up reel has a light torque that allows it to reel in the tape that is fed to it. The other reel has a very slight drag to keep the tape taut and tight against the heads. As in the wire recorder, an AF a-c fed to the recorder-head electromagnet produces magnetic flux at the gap, magnetizing the passing tape. During recording, the erase head is fed a supersonic frequency a-c that erases the tape before it is recorded.

To rewind the tape, the drive-wheel pressure is released, the take-up reel has a slight drag placed on it, and the other reel is driven backward at high speed.

During playback, the drive wheel is engaged and the wiping head is disconnected electrically. The AF a-c produced in the playback coil as the tape passes over the gap is amplified and corresponds to the original AF a-c that magnetized the tape during the recording process.

For high fidelity and best high-frequency response, the speed of the tape moving over the gap is 15 in./sec. For slightly less fidelity, a speed of 7½ in./sec is used, allowing twice the playing time for the same reel of tape. For speech only, a speed of 3¾ in./sec may be considered adequate. This speed may be halved for a low-fidelity system that will operate for a relatively long period of time with a given length of tape. It is used for recording stories or books.

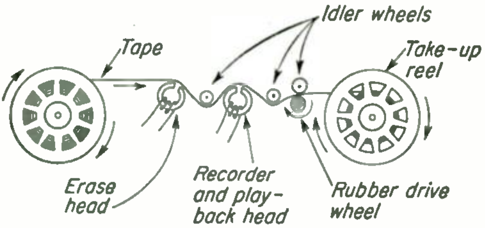


FIG. 24.12. Essential parts of a tape recorder.

Some recorders record on one half of the tape. The reel can be turned over or the direction of pull reversed, and the other half of the tape can be recorded. This results in twice as much recording time on the same-length reel of tape.

**24.22 Broadcast Microphones.** Microphones used in broadcast studios may be of the dynamic, velocity, or condenser types. These are discussed in Secs. 16.29 to 16.33. In practically all broadcast applications the microphones are coupled to the amplifiers through transformers that change the impedance of the microphone to either a 150- or a 600-ohm impedance value, allowing easy interchange of microphones without the necessity of matching impedances.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

1. What is the frequency tolerance for a standard broadcast station? (24.1) [4]
2. What is the effect of 10,000-cycle modulation of a standard broadcast station on adjacent channel reception? (24.1) [4]
3. What is the frequency tolerance for a broadcast STL station? (24.2) [4]

**4.** What type of antenna is required at a broadcast STL station? (24.2) **[4]**

**5.** Define an auxiliary broadcast transmitter, and state the conditions under which it may be used. (24.2) **[4]**

**6.** For what purpose is an auxiliary transmitter maintained? (24.2) **[4]**

**7.** How frequently must the auxiliary transmitter of a standard broadcast station be tested? (24.2) **[4]**

**8.** If a preamplifier having a 600-ohm output is connected to a microphone so that the power output is −40 db, assuming the mixer system to have a loss of 10 db, what must be the voltage amplification necessary in the line amplifier in order to feed +10 db into the transmitter line? (24.5) **[4]**

**9.** If a certain AF amplifier has an over-all gain of 40 db and the output is 6 watts, what is the input? (24.5) **[4]**

**10.** If the power output of a modulator is decreased from 1,000 to 10 watts, how is the power reduction expressed in decibels? (24.5) **[4]**

**11.** Why are preamplifiers sometimes used ahead of mixing systems? (24.5) **[4]**

**12.** Why should impedances be matched in speech-input equipment? (24.6) **[4]**

**13.** What is the purpose of a line pad? (24.6) **[4]**

**14.** Why are grounded center-tap transformers frequently used to terminate program wire lines? (24.6) **[4]**

**15.** Why are electrostatic shields used between windings in coupling transformers? (24.6) **[4]**

**16.** Why is a high-level amplifier, feeding a program transmission line, generally isolated from the line by means of a pad? (24.6) **[4]**

**17.** What are the purposes of H- or T-pad attenuators? (24.6) **[4]**

**18.** Why is a variable attenuator used in a speech input system? (24.6) **[4]**

**19.** Draw a diagram of an equalizer circuit most commonly used for equalizing wire-line circuits. (24.7) **[4]**

**20.** What is the purpose of a line equalizer? (24.7) **[4]**

**21.** In what part of a broadcast station system are limiting devices usually employed? What are their functions? (24.8) **[4]**

**22.** What are the permissible tolerances of power of a standard broadcast station? (24.9) **[4]**

**23.** Define the plate input power of a broadcast-station transmitter. (24.9) **[4]**

**24.** Define the maximum rated carrier power of a broadcast station transmitter. (24.9) **[4]**

**25.** What is the power that is actually transmitted by a standard broadcast station termed? (24.9) **[4]**

**26.** Under what conditions may a standard broadcast station be operated at a power lower than specified in the station license? (24.9) **[4]**

**27.** What is the power specified in the instrument of authorization for a standard broadcast station called? (24.9) **[4]**

**28.** Describe the various methods by which a standard broadcast station may compute its operating power, and state the conditions under which each method may be employed. (24.9) **[4]**

**29.** Are the antenna current, plate current, etc., as used in the Rules and Regulations of the Commission with reference to radio telephone transmitters, modulated or unmodulated values? (24.9) **[4]**

**30.** At broadcast stations using the direct method of computing output power, at what point in the antenna system must antenna current be measured? (24.9) **[4]**

**31.** What factors enter into the determination of power of a broadcast station which employs the indirect method of measurement? (24.9) **[4]**

**32.** When the operating power is determined by the indirect method, which of the efficiency factors established by FCC rules is used? (24.9) **[4]**

**33.** When the transmitter of a standard broadcast station is operated at 85 per cent modulation, what is the maximum permissible combined audio harmonic output? (24.10) **[4]**

**34.** What percentage of modulation capability is required of a standard broadcast station? (24.10) **[4]**

**35.** For what purpose may a standard broadcast station licensed to operate daytime or specified hours operate during the experimental period without specific authorization? (24.10) **[4]**

**36.** With reference to broadcast stations, what is meant by the experimental period? (24.10) **[4]**

**37.** What are meant by equipment, program, and service tests where these are mentioned in the Rules and Regulations of the Commission? (24.10) **[4]**

**38.** What is the required full-scale accuracy of the plate ammeter and plate voltmeter of the final radio stage of a standard broadcast transmitter? (24.11) **[4]**

**39.** How frequently must a remote-reading ammeter be checked against a regular antenna ammeter? (24.11) **[4]**

**40.** If the plate ammeter in the last stage of a broadcast transmitter burns out, what should be done? (24.11) **[4]**

**41.** What portion of the scale of an antenna ammeter having a square-law scale is considered as having acceptable accuracy for use at a broadcast station? (24.11) **[4]**

**42.** In accordance with the Commission's Standards of Good Engineering Practice, what determines the maximum permissible full-scale reading of indicating instruments required in the last radio stage of a standard-broadcast transmitter? (24.11) **[4]**

**43.** What is the required full-scale accuracy of the ammeters and voltmeters associated with the final radio stage of a broadcast transmitter? (24.11) **[4]**

**44.** What are the licensed-operator requirements for a 5-kw nighttime directional standard broadcast station? (24.12) **[4]**

**45.** Under what conditions may a standard broadcast station be operated by remote control? (24.13) **[4]**

**46.** If a broadcast station receives a frequency-measurement report indicating that the station frequency was 45 cycles low at a certain time, and the transmitter log for the same time shows the measured frequency to be 5 cycles high, what is the error in the station frequency monitor? (24.14) **[4]**

**47.** When an *X*- or a *Y*-cut crystal is employed in the automatic frequency-control equipment at a standard broadcast station, what is the maximum permitted temperature variation at the crystal from the normal operating temperature? (24.14) **[4]**

**48.** What is the maximum carrier shift permissible at a standard broadcast station? (24.15) **[4]**

**49.** What is the frequency tolerance allowed an International Broadcast Station? (24.16) **[4]**

**50.** If a broadcast transmitter employs seven tubes of a particular type, how many spare tubes of the same type are required to be kept on hand in accordance with FCC regulations? (24.17) **[4]**

# CHAPTER 25

# TELEVISION

**25.1 The Television System.** The discussion of TV systems involves many of the basic radio circuits mentioned previously. A TV signal is composed of two separate emissions, an aural and a visual. The aural, or sound, is an FM (F3) signal, very similar to that of an FM broadcast station discussed in the chapter on Frequency Modulation, except that 100 per cent modulation is represented by 25-kc deviation instead of 75-kc. The audible frequencies that the transmitter must be capable of transmitting are from 30 to 15,000 cycles. This audio signal is developed in a completely separate transmitter from the visual, or *video*, signal. The two emissions use the same transmitting antenna but are otherwise independent. The visual signal is a radio-frequency carrier that is amplitude-modulated with picture information (A5), blanking pulses, and both horizontal and vertical synchronizing pulses, which all work together to produce the picture on the cathode-ray, or *picture*, tube in the receiver. At the transmitter, amplitude modulation (AM) is applied to the control grid of a class C RF amplifier, which may be followed by one or more linear amplifiers to increase the output power of the station.

It will be assumed that you have observed a TV receiver and noted that the picture is composed of many horizontal lines across the face of the picture tube and that the illumination of the different parts of each of these lines changes in intensity as the televised scene changes.

It is the duty of the TV transmitter to cut the scene to be televised into about 495 separate lines, each with varying intensities, transmitting a stronger signal where the lines are dark and a weaker signal where the lines are light.

The TV receiver must lay down the lines in their correct order and with light and dark portions in their proper places to reproduce the picture.

A block diagram of a TV transmitter, including both aural and visual transmitters, is indicated in Fig. 25.1. The program to be televised is being produced in the studio. A camera and microphone are in this room.

The output of the microphone is amplified, fed through the audio mixer or console, and monitored by the control-room personnel. The audible signal is then fed to the aural FM transmitter, monitored by the transmitter-room operators, and fed to the antenna *diplexer* and to the transmitting antenna.

The signals picked up by the studio camera are fed to the control room, to the camera control, and to the visual mixer, called a *switcher*, monitored and fed to the transmitter, where they are used to amplitude-modulate the grid of an RF amplifier. The RF a-c output of this stage is amplified by a linear amplifier. Some of the low-frequency sidebands are attenuated by the vestigial sideband filter. The carrier, the high-frequency sidebands, and the remaining low-frequency sidebands are fed to the antenna diplexer and to the transmitting antenna. A sample of the visual signal is fed to a visual monitor to enable the transmitter operators to keep a check on the output signal.

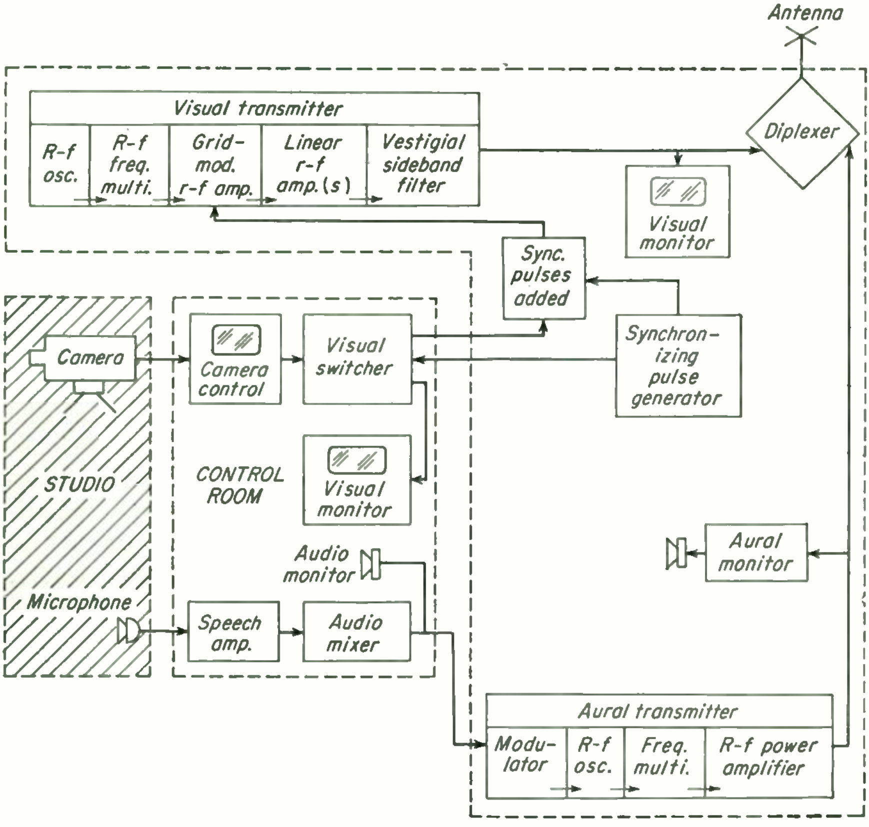


FIG. 25.1. Block diagram of a TV transmitting station.

A *synchronizing pulse generator* is also in the transmitter room. It generates the necessary pulses to hold the transmitted and received signals in proper synchronization.

The radiated signals from the two transmitters are received by viewers on a wideband TV superheterodyne receiver, in which the aural and the visual signals are amplified and separated. The block diagram of Fig. 25.2 indicates the elements of a TV receiver.

The aural portion of the composite signal from the intermediate-frequency (IF) amplifiers is fed to a special circuit tuned to pass these frequency-modulated signals only. They are fed to a discriminator, detected, are amplified by an audio amplifier, and actuate a loudspeaker.

The visual portion of the signal from the IF amplifiers passes to the visual signal amplifiers and to the grid-cathode circuit of the cathode-ray picture tube. The vertical and horizontal pulses added to the signal at the transmitter are separated from the picture signals and are used to hold vertical and horizontal saw-tooth oscillators in proper synchronization. These oscillators generate the voltages that produce the visually modulated lines on the face of the picture tube.

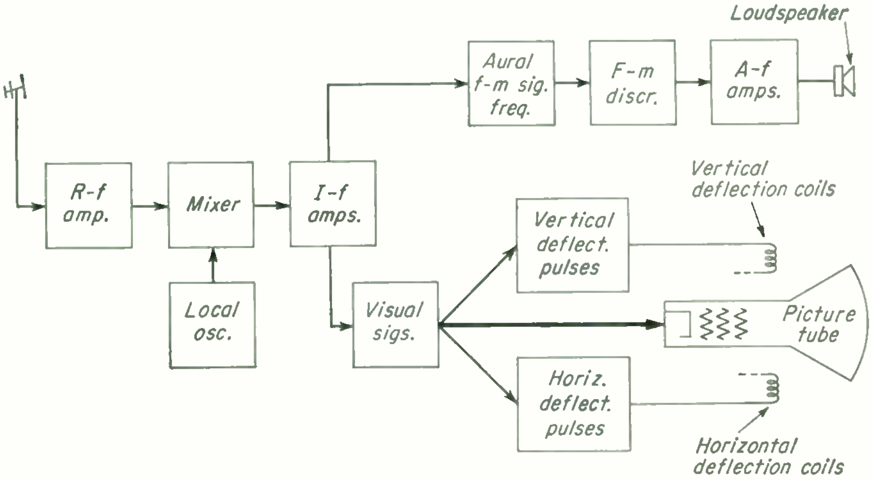


FIG. 25.2. Block diagram of a TV receiver.

**25.2 Camera Tubes.** At the present writing, an *image-orthicon* type of camera tube is usually used in studio or out-of-door cameras. Motion pictures or still slides may be projected onto the *mosaic* screen of an *iconoscope* tube or onto the screen of a *vidicon* tube, or a photoelectric device known as a *flying-spot scanner* may be used.

**25.3 The Image Orthicon.** The most practical of present-day monochrome (black-and-white) camera tubes for scenes having normal or little illumination is the image orthicon. It is used in most studio and field cameras. Figure 25.3 illustrates the fundamental components of such a vacuum tube.

The scene to be televised is focused on the front of a negatively charged, thin, semitransparent *photocathode* through a series of glass optical lenses. Lighter portions of the scene liberate many electrons from the *back* of the photosensitive cathode, whereas dark portions liberate none. The freed electrons are attracted toward the less negatively charged *target plate* made of a thin sheet of glass having a carefully controlled conductivity from one flat surface to the opposite. To strike the glass plate the electrons must pass through the spaces of a very fine wire screen. If each electron hitting the target glass produces a secondary emission of two electrons from the front face, the glass becomes *positive* at any point where electrons strike it. The secondary electrons bounce back toward the slightly positive metal target screen and are led from the tube to the power supply. This leaves the glass target plate with positive charges corresponding to the light areas focused on the photocathode and with no charge where dark areas fall. The visible scene has now been transferred to the target plate as a scene composed of areas of various degrees of electric charge instead of areas of light and dark as on the photocathode.

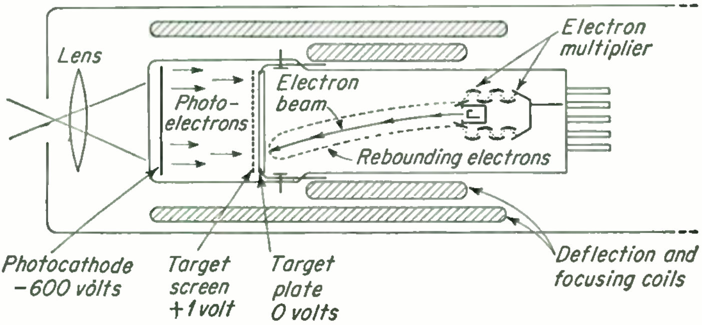


FIG. 25.3. Essential components of an image-orthicon camera tube.

An electron gun at the far end of the tube emits a thin beam of electrons that is allowed to strike the back of the conductive glass target plate. Wherever this beam strikes the back of a positively charged area on the target, it loses some of its electrons. When the beam electrons hit an area of zero charge, they rebound from the glass and all of them travel back down the tube toward a positively charged signal-collecting plate surrounding the outlet of the cathode-ray beam. The outer surface of this plate is coated with a substance that produces considerable secondary emission. Such a plate may be called a *dynode*, meaning a dynatron-type anode.

As the electron beam sweeps across the electrical scene and moves from light to dark areas, the returning electrons will vary in number. In this way, it is possible to produce an electron current back down the tube that varies in accordance with the illumination on different parts of a visible scene. To reproduce the whole visible scene in its counterpart of electric impulses, it is necessary to *scan* the scene. The beam is made to sweep across the top of the picture from left to right, blank out, move down the width of the beam, retrace to the left, unblank, and sweep a second line across the scene, and so on until the whole scene has been scanned top to bottom and electric impulses have been collected from all parts of the scene. These electric video impulses may be amplified and used to amplitude-modulate the TV transmitter. At the receiver the amplitude of these impulses determines the illumination produced by the scanning beam in the cathode-ray picture tube.

The returning beam in the image orthicon is a relatively weak current of electrons. To increase the output current, a series of dynodes are used to form an *electron multiplier*. As returning electrons strike the first dynode plate, each electron may liberate two secondary electrons. These liberated electrons are attracted to the next dynode plate, which has a higher positive potential. Each of these electrons liberates two or more electrons, and so on. By the use of five dynode elements it is possible to produce a current amplification of more than one hundred times. This is the reason for the high sensitivity of the image-orthicon camera tube.

One of the difficulties experienced in image-orthicon operation is the requirement of maintaining the target plate at a temperature between 95 and 140°F and at approximately the same temperature as the outer glass envelope of the tube. This requires a rather long warm-up period of 30 min or more before the tube can be used. Normally, heat from the amplifier tubes and the deflection coils wrapped around the tube will keep the tube at an operating temperature. During cold weather, a special internal heating system may be required if the camera is used out of doors.

If a bright scene is focused on the tube for more than a few minutes, the scene will continue to be observed for several minutes after the camera is focused on another scene. The operator must be careful not to allow a bright scene to remain stationary on such an orthicon screen. A system has been developed whereby the passage of photoelectrons is interrupted during blanking times, reducing the average time the scene is applied to the target plate and decreasing burning in.

**25.4 Magnetic Deflection.** In the chapter on Measuring Devices, a cathode-ray tube was discussed that used an electrostatic (positive and negative) means of deflecting the electron beam. Electrostatic deflection has also been used in TV cathode-ray tubes, but it has been found that electromagnetic deflection is usually more economical and trouble-free. As a result, practically all types of cathode-ray devices used in a TV system are magnetically deflected. The theory of electromagnetic deflection is explained briefly here.

A beam of moving electrons represents a current of electricity. From basic magnetic theory it is assumed that the direction of lines of magnetic force around a current is shown by the left-hand rule, where the thumb points to the current direction and the fingers point in the direction of the lines of force. In Fig. 25.4 an electron beam is moving toward the reader through a magnetic field.

The part of the line of force surrounding the beam at the top has a direction similar to that of the lines of force of the stationary field. Since like lines of force repel, the beam tends to deflect downward. Similarly, the line of force of the beam that is below it is found to be in the opposite direction to the stationary lines. Since unlike lines attract, the beam is attracted downward still more. Note that the electron-beam deflection is at *right angles* to the magnetic field through which it is moving, not toward either magnetic pole. By sending a beam of electrons through the area between two poles of an electromagnet, it is possible to control the *amount* of deflection of the beam by controlling the strength of the magnetic field, and the *direction* of deflection (up or down) by controlling the direction of the current flow through the electromagnets. Figure 25.5 illustrates vertical deflection of a beam in a cathode-ray tube (CRT).

When current flows through the vertical-deflection coils, a horizontal magnetic field is produced across the neck of the CRT. The amount of vertical deflection will depend on the strength of the magnetic field, and the direction of deflection (up or down in this case) will depend on the polarity of the magnetic field.

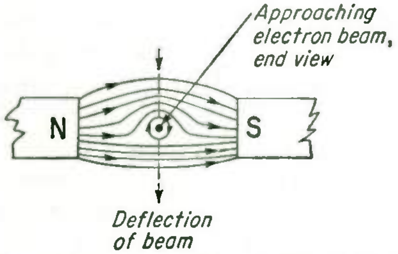


FIG. 25.4. An electron beam moving across a magnetic field is deflected at right angles to the field.

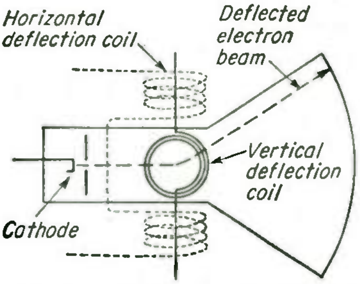


FIG. 25.5. Horizontal- and vertical-deflection coils around the neck of a TV picture tube.

When current flows through the horizontal-deflection coils, a vertical magnetic field is produced across the tube. The amount of horizontal deflection again depends on the strength of the field, and direction of deflection depends on polarity of the field.

By use of both horizontal- and vertical-deflection coils, the beam can be moved to any place in the tube by applying the proper polarity and strength current to the two sets of coils. Two horizontal and two vertical coils form a *deflection yoke*.

**25.5 Magnetic Focusing.** The electron beam in a CRT may be focused by electrostatic means (Sec. 11.29) or by electromagnetic means. If a coil of wire carrying a steady current is wrapped around the neck of a CRT, as shown in Fig. 25.6, the lines of force of the magnetic field produced are parallel to the axis of the CRT neck. Electrons in the beam tend to converge as they pass through this field of parallel magnetic lines. The current in the coil, and therefore the strength of the field, determines where the electrons of the beam will come to a point of focus. Television picture tubes usually have magnetic deflection yokes and magnetic focusing coils, although magnetic deflection and electrostatic focusing is also possible.

**25.6 Interlaced Scanning.** If a motion-picture film is projected with a *frame* (single-picture) frequency of about 15 a second, an illusion of movement is created, but the motions seem jerky and flicker of bright areas is apparent. Increasing the frame frequency to 24 or 30 a second makes motion appear smooth, but a slight flicker can still be noted on more brilliantly lit areas of the picture. Doubling the frame frequency will eliminate the flicker, but too much film would be required. Instead, it is possible to flash each picture on the screen twice by the use of a shutter that opens and closes 48 or 60 times a second, and the flicker disappears. *Interlaced scanning* of the TV picture has a similar effect.

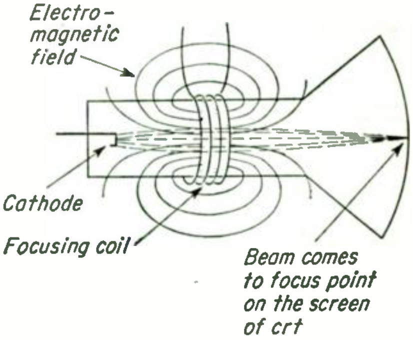


FIG. 25.6. An electromagnetic focusing coil around a CRT.

The TV picture always has an *aspect ratio* of 4:3; that is, the picture is always four units wide to three units high. Thus a round 10-in. picture tube can produce an 8- by 6-in. picture, an oblong 17-in. tube can produce a 16- by 12-in. picture, and an oblong 21-in. tube can produce a 20- by 15-in. picture. The size of the tube has no effect on the number of lines received. On the larger tubes each line is merely wider and longer.

It has been found that satisfactory vertical definition can be produced by breaking a picture into about 485 horizontal lines. (Actually, any number of lines between 482 and 495 can be employed at the discretion of the transmitting station.) Allowing time for 525 lines per picture includes an allowance of about 40 lines, during which the scanning circuits can be brought into proper synchronism to assure that the receiver starts scanning at the same time that the transmitter does.

To produce an equal *horizontal* picture definition for a *square* picture (aspect ratio of 1:1), 485 dark and light units per line would be required. This represents a positive and negative alternating current of $^{485}\!/_{2}$, or 242.5 cycles. However, the TV picture is not square, but is one-third longer than it is high. As a result, the horizontal line should have the equivalent of approximately 323 cycles per line. With each line requiring

323 cycles, 525 lines would require a bandwidth of roughly 180,000 cycles and, using 30 frames per second, a frequency of about 5.4 Mc. However, it is found that adequate definition can be produced by using a bandwidth of about 4.2 Mc.

To prevent flicker and still not show the *complete* picture more than 30 times a second, interlaced scanning is used (Fig. 25.7). The first time the picture is scanned, only the even-numbered lines are used. This presents a picture with only 262.5 lines, known as a *field*. The field in itself would be a rather poorly defined picture vertically, although the horizontal definition would be satisfactory. However, the picture is immediately scanned again, this time using the odd lines only. This second field is interlaced between the lines of the first field, but since the two are presented within 1/30 sec, the eye accepts them as one frame, having satisfactory vertical and horizontal definition, and showing no flicker on brightly lit areas. Since no more lines have been added, the bandwidth (4.2 Mc) required to transmit the picture signal has not been increased. In a TV transmission the frame frequency is 30 per second and the field frequency is 60. The requirement of having half lines (262.5) in each field complicates the scanning problem. Accurately timed synchronizing pulses must be utilized to enable all horizontal lines to start at the correct time to produce straight vertical edges of the picture, as well as to start the half line at the top of the picture properly.

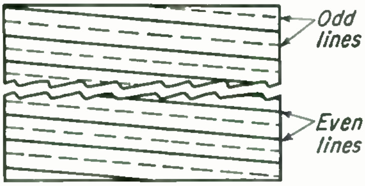


FIG. 25.7. Interlaced scanning. One field is shown by solid lines and the other by broken lines.

Since each horizontal line is below the previous one, a gradually increasing current must be fed to the *vertical*-deflection coils to continually move successive lines farther down the picture. This is known as the *vertical sweep* current. The sweep current must return rapidly to the starting value as soon as a field is scanned all the way to the bottom. A saw-tooth waveform can produce the required relatively slow vertical movement downward, as well as the rapid return upward at the end of the cycle. This saw-tooth wave must have a frequency of 60 cps (cycles per second), the same as the field frequency, and preferably be synchronized to the public-utility-power frequency.

A saw-tooth current is also applied to the horizontal-deflection coils to produce the horizontal scanning motion of the electron beam in the camera and picture tubes. With 525 lines required per frame and 30 frames per second, the horizontal saw-tooth a-c must have a frequency of 15,750 cps.

**25.7 The Synchronizing-pulse Generator.** The brain of the TV transmitter is the *synchronizing-pulse generator* (sync-pulse generator).

This complex piece of equipment may require up to 60 or 70 tubes to generate the following pulses, shown in Fig. 25.8:

1. 31,500-cycle equalizing pulses having a duration of approximately 2.7 μsec (microseconds) each, the leading edges of each separated by 31.75 μsec
2. 15,750-cycle horizontal sync pulses, having a duration of about 5.4 μsec, the leading edges of each separated by 63.5 μsec
3. 15,750-cycle horizontal blanking pulses, having a duration of about 10 μsec each
4. 60-cycle vertical sync pulses, having a total duration of 190 μsec but slotted, or *serrated*, by 4.4-μsec spacings every 27.3 μsec

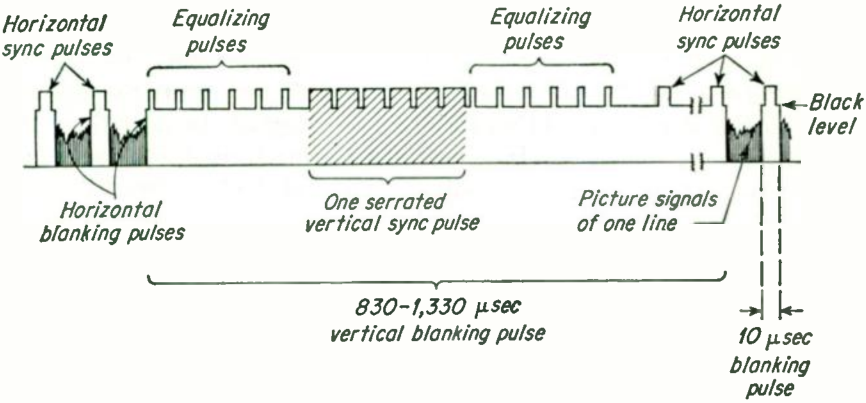


FIG. 25.8. Blanking, synchronizing, and equalizing pulses of a television transmission.

5. 60-cycle vertical blanking pulses, having a duration of between 830 and 1,330 μsec, depending on how many lines are used in the complete picture
6. Horizontal and vertical *driving pulses* similar to the sync pulses that are transmitted to receivers, but out of time slightly to properly synchronize studio cameras and equipment

Note that the horizontal sync pulses ride on top of the horizontal blanking pulses, except for a few (determined by how many lines are used in the picture) that ride on top of the vertical blanking pulse along with the equalizing pulses. The visual modulation is inserted between the horizontal sync pulses, described later.

The vertical blanking pulse carries the one serrated vertical sync pulse in addition to the equalizing and horizontal sync pulses.

Basically, the sync generator consists of an oscillator having a frequency of twice the horizontal sweep, or 31,500 cycles. Each of these cycles synchronizes a circuit to generate a narrow pulse at this frequency. When shaped properly, they appear as the equalizing pulses that are used before and after the vertical sync pulse (Fig. 25.8). These equalizing pulses are also used to serrate, or slot, the vertical sync pulse into six parts. Serrations keep the horizontal sweep oscillators in receivers in synchronism during the long-duration vertical sync pulse. The vertical sync pulse triggers vertical sweep oscillators and the equalizing and horizontal sync pulses trigger horizontal sweep oscillators in TV receivers. The equalizing pulses allow the receivers to hold sync during the periods between the end of the last line of a field and the beginning of the serrated vertical pulse, and between the end of the vertical pulse and the beginning of the next line. The equalizing-pulse rate is used to produce the horizontal sync pulses by dropping out every other one, giving the required frequency of 15,750 to these pulses.

Just before the horizontal sync pulse is produced between lines, a blanking pulse appears that cuts off the electron beam in the camera tube in the transmitter and in the picture tube in the receivers. During the interval of the blanking pulse, the horizontal oscillators return the electron beam to the starting condition for the beginning of the next line. In receivers the sweep current is generated by a local saw-tooth oscillator, and the sync pulses that are transmitted as part of the complete TV signal are used to make any correction to this oscillator frequency that is necessary to assure the proper starting time of each line after the blanking pulse drops off. Thus, technically, the equalizing, the horizontal, and the vertical sync pulses are only added to the TV signal as an aid to receiver operation, not being used in the transmitter itself.

At the transmitter each piece of equipment has its own local saw-tooth sweep oscillator. The *driving pulses* of the sync generator are used to keep the oscillators in proper synchronism. These pulses are similar to the transmitted horizontal and vertical sync pulses except that they are timed to produce the required time difference for the transmitting equipment.

It is desirable to lock the sync generator into synchronism with the local public-utility 60-cycle source. This prevents a creeping waver up or down the face of the picture tube if receivers have any 60- or 120-cycle ripple in their power-supply voltage.

The sync generator also has a crystal oscillator capable of producing an accurate 60-cycle frequency if local power is not available, as is often the case when the equipment is operating out in the field. With field equipment in operation, the remote sync generator develops the pulses for the main transmitter. The sync generator at the main station has an input circuit to allow it to lock in on signals originating from remote sync generators, from network programs, or from field equipment.

Transmission to the main transmitter from the field pickup is usually made by a superhigh-frequency FM-klystron transmitter (6,500–7,050 Mc), using high-gain directional transmitting antennas to beam the signals.

**25.8 Modulation Percentages of the Visual Carrier.** There is never a constant-amplitude carrier in a visual transmission. The only parts of the emission that remain constant are the peaks of the sync pulses and the blanking level (Fig. 25.9).

The top of any sync pulse is the maximum value of the emitted carrier and may be considered the 100 per cent level.

The *blanking*, or *pedestal*, level, on which is found the *front porch* and the *back porch*, is 75 per cent of the peak value (±2.5 per cent).

The *reference black level*, which will produce the *darkest* black in the transmitted picture, is about 70 per cent of the peak level.

The reference white level, which will produce the whitest white in the picture, is 15 per cent of the peak value. It is undesirable to transmit a whiter white than this, as the power of the emission is then so low that noise at the receiving location may interfere with picture quality, and more important, there will be insufficient carrier to beat against the aural FM signal to produce a beat frequency and audible signals in the receiver (in intercarrier receiving systems).

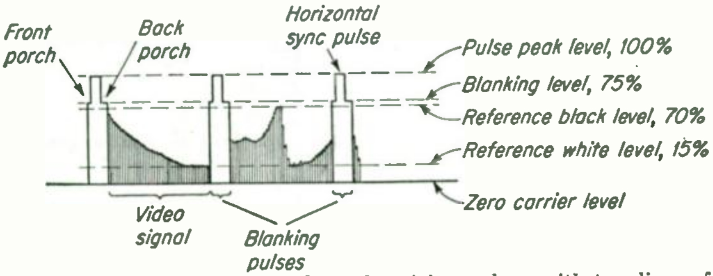


FIG. 25.9. Details of the blanking and synchronizing pulses, with two lines of picture modulation between them.

The illustration shows two complete lines of video (picture) and three blanking pulses with front and back porches, with three horizontal sync pulses on top of the blanking pedestals. The first line illustrates one line of a scene that is black at the left-hand side and white at the extreme right-hand side. The second line is gray at the left-hand side, changes to black at the center, abruptly changes to white, and fades off to a light gray.

**25.9 Camera Chains.** A TV camera with its associated equipment, an electronic view finder, and a camera control unit with the necessary power supplies make up a *camera chain*. A block diagram of two camera chains and other video equipment necessary for the pickup of a live studio program is shown in Fig. 25.10.

The camera usually has an electronic view finder and a 5- or 7-in. picture tube, mounted directly above the camera itself, appearing to be part of the camera. The view finder operates much the same as a TV-receiver picture tube except that it receives its picture information directly from the output of the video frequency amplifiers in the camera and its blanking and driving pulses from the sync generator. The output of the camera is also fed to a nearby control position by low-impedance coaxial lines and to a camera-control unit. This unit has two cathode-ray tubes, one a 7- to 10-in. monitor tube similar to the view finder in the camera, and the other a 3- to 5-in. oscilloscope with a horizontal sweep frequency of 30 cps, which synchronizes the video and blanking signals in such a manner that a composite display of two complete lines is continually shown on the screen. The operator watches the video-signal amplitude on the oscilloscope, controlling it to prevent video modulation peaks from exceeding the reference black and white levels.

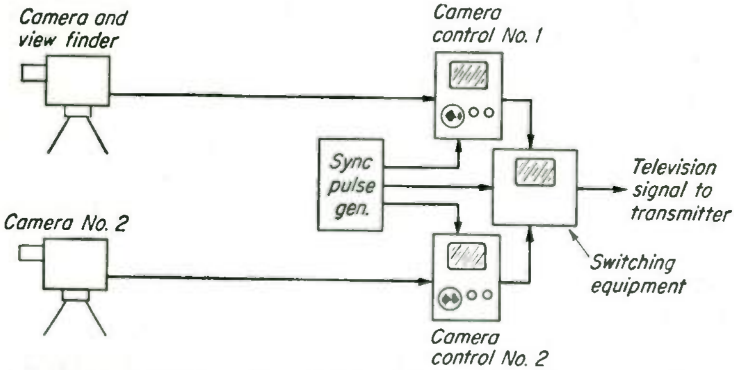


FIG. 25.10. Block diagram of two camera chains, synchronizing pulse generator, and switching equipment.

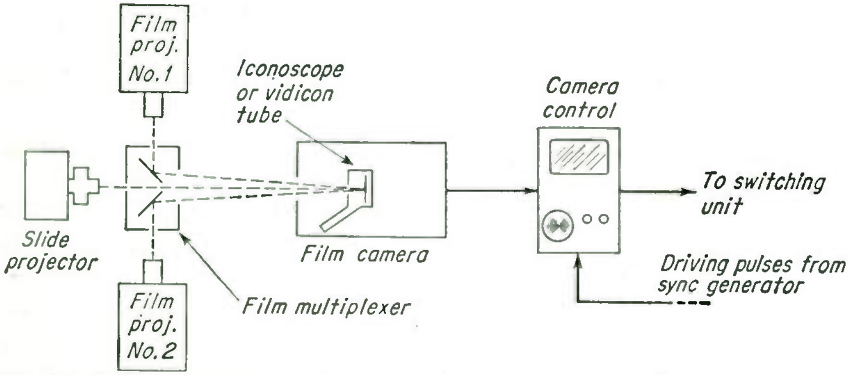


FIG. 25.11. Block diagram of a film-camera chain, including a multiplexer to allow one camera tube to pick up pictures from three projectors.

A camera chain may also be composed of one or two film projectors and a slide projector, all aimed at the mosaic plate of an iconoscope-type camera tube or at the photosensitive screen of a vidicon tube, and a camera control unit, as indicated in Fig. 25.11.

The mirrors and slide projector form a physical unit called a *film multiplexer*.

**25.10 Personnel Required.** Several men are involved in the production of a live studio TV program. On the studio floor is a boom-microphone operator who keeps the microphone near the actors but out of sight of the cameras, one or more camera operators, and a floor director.

At an operational console in the control room are one or more camera-control operators continually watching the technical condition of the camera signals. A program director watches the camera pictures and advises a technical director which camera to use for the program. Seated in this same room is an audio operator, controlling the microphone output that is fed to the aural FM transmitter. There is a telephone intercommunication system between the control-room personnel and the phone sets worn by the operating personnel in the studio.

The motion-picture and slide-projection operator and equipment are located in a separate room. The output of the film camera also terminates at the switching position in the control room and has a separate monitor screen of its own.

From the switching position at the visual console the TV signal is fed to the TV transmitter in another room, while the aural signal is fed to the FM transmitter. In the transmitter room an operator or two monitor both the visual and the aural signals that are being transmitted, as well as keep a constant check on the operation of the transmitter itself. These operators keep an *operating log*, including the time the station begins and stops supplying power to the antenna, when programs begin and end, entries of any interruptions to the carrier waves, and, every 30 min, plate current and voltage of the last RF amplifier stages of both transmitters, transmission-line readings for both transmitters, frequency monitor readings, and antenna structure-illumination entries. Unless detailed to other personnel, these operators may keep the program log, which requires entries pertaining to station identification, type of program, whether live or mechanically reproduced, sponsor, and network originating the program.

All camera units of the TV station are fed the sync-pulse-generator signals through the master switching position.

**25.11 The Iconoscope.** The first successful camera tube developed was the iconoscope. It does not have the sensitivity of the image orthicon, but it is still in use as the pickup tube for motion pictures and for slide films in some stations. The tube consists of an electron gun with deflection coils, a *mosaic* picture screen, an insulator sheet, a plate, and a collector anode. A simple illustration of an iconoscope is shown in Fig. 25.12.

Microscopic islands of photoelectric silver globules are deposited on one side of a thin mica or plastic sheet. Each globule is electrically insulated from all globules adjacent to it. The other side of the insulating sheet is coated with a conductive material. Thus, each globule forms a tiny capacitor (condenser) between itself and the back plate, with the insulator sheet as the dielectric. When a scene is focused on the mosaic screen, electrons are liberated from the photoelectric globules, leaving the light areas positive and the darker areas less positive. The photoelectrons that are released from the globules are drawn to the collector anode. This leaves the mosaic screen with areas of electric charge that conform to the light and dark areas of the scene focused on it, with each tiny capacitor charged in proportion to the light striking it. The attraction due to all the positively charged capacitor plates pulls a charging current of electrons upward through the load resistor *R*.

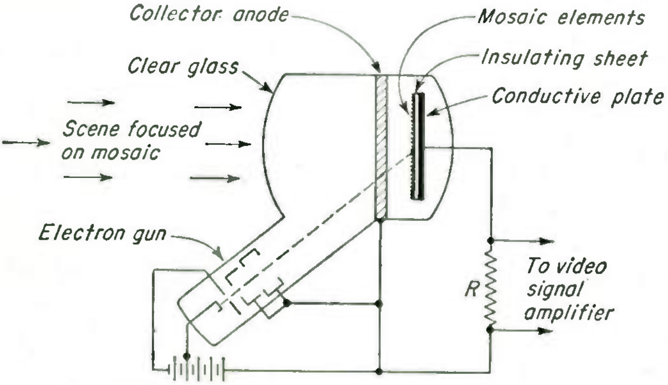


FIG. 25.12. Iconoscope camera tube and basic circuit.

When the electron beam is made to scan across the mosaic, it feeds electrons to the positive globules, discharging them. As they are discharged, they no longer tend to hold electrons in the circuit connected to the top of the resistor, and a discharging electron current flows down through the resistor. As scanning continues, a signal current flows up and down the resistor in accordance with the light striking the part of the scene being scanned and discharged at the time. These currents produce voltage drops across the load resistor, forming the video signal that is amplified and transmitted.

**25.12 Motion-picture Projection for TV.** The TV frame frequency was selected as 30 per second to allow transmitters and receivers to lock into synchronization and prevent waver of the received picture. Unfortunately, both 35- and 16-mm motion pictures have a frame frequency of only 24 per second. To reduce flicker, each frame must be produced as two or more fields for both motion pictures and TV. A standard 16-mm projector can be used for TV projection by using either a xenon-gas, electronically flashed light or an incandescent projection lamp with a special shutter to allow the following sequence of operations with an iconoscope pickup tube:

1. The film is pulled down into position in the projector. No flashed or shuttered light shines through the film as yet.
2. During the TV blanking-pulse interval, the scanning beam of the iconoscope is blanked out and is returning to the starting point. At this time a flash of light is allowed to shine through the film, projecting the picture on the mosaic.
3. The mosaic retains the electrically charged image of the picture.
4. The mosaic is scanned for one field, and the video signals obtained are transmitted.
5. At the end of the *field*, during the next blanking pulse and scanning retrace period, the projector light is again flashed, once again projecting the same picture on the mosaic.
6. The second (interlaced) field is scanned, and the video signals obtained are transmitted.
7. During the scanning time of the second field the next frame of the film is pulled down into position. Because of the difference between 24 and 30 frames per second, during this frame there is enough time to flash the projector light *three* times during blanking pulses before the next frame is pulled down.

In this way, the first film frame is scanned twice, producing two fields for the TV picture, but the second frame is scanned as three fields. This allows the correction that is necessary to change 48 fields per second for the film to 60 fields per second for the TV picture.

Standard 16-mm projectors have a short pulldown time between pictures and can be converted rather simply to TV use. The longer pulldown time of 35-mm projectors makes them less desirable.

Accurate synchronization is required between blanking pulses and the operation of the shutter, or the flashing of the xenon light. This necessitates synchronous motors for the shutters, or a multivibrator-keyed light source synchronized by driving pulses from the sync-pulse generator.

**25.13 Television Transmission Requirements.** A TV station has one antenna, usually a turnstile or similar horizontally polarized array, common to two transmitters, one the frequency-modulated audio signal and the other the amplitude-modulated picture signal. These two transmitters always operate with the center frequency of the aural, or sound, transmitter 4.5 Mc higher than the carrier frequency of the picture transmitter. The whole TV transmission for one station must be contained in a 6-Mc-wide *channel*, as shown in Fig. 25.13. The visual carrier is always 1.25 Mc above the lower channel limit.

The higher-frequency sidebands exist for more than 4 Mc before they are made to drop to zero as the sound carrier frequency is approached. The lower-frequency sidebands are allowed to exist for only about 0.75 Mc before they are attenuated by a *vestigial sideband filter* in the output circuit of the transmitter, or by other means. Since only a vestige of the lower-frequency sidebands are transmitted, the emission is termed *vestigial sideband.* It has the advantage of requiring considerably less bandwidth than the more common double-sideband amplitude-modulated type of emission.

The operating power of the *aural* transmitter is determined by the *indirect method* (Sec. 24.9), where

$$\text{Operating power} = E_pI_pF$$

As with FM and AM broadcast stations, the operating power is measured with no modulation applied to the carrier.

The operating power of the *visual* transmitter is determined at the output of the vestigial sideband filter if one is used, otherwise at the transmitter output terminal. The *average* power is measured while operating the transmitter into a dummy load of substantially zero reactance, with a resistance equal to the transmission-line surge impedance, and while transmitting a standard *black* picture. The average power is determined by multiplying the d-c plate voltage by the plate current of the last RF amplifier stage. When the antenna is coupled to the transmitter the average-power indications must be substantially the same as with the dummy antenna.

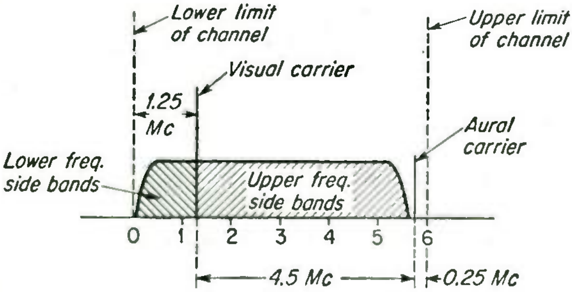


FIG. 25.13. Location of carriers and sidebands in a 6-Mc television channel.

Television transmitters are rated in peak power output, which is determined by multiplying the average power above by the factor 1.68. (Note that the factor $F$ used in the indirect method of power-output determination is not used.)

The effective radiated power (erp) of a TV transmitter is the *peak* power times the antenna field gain (voltage gain over a simple dipole) squared (Sec. 20.28). Thus, if a transmitter has a peak power of 10 kw and an antenna has a field gain of 3 the erp is $10{,}000 \times 3^2$, or 90,000 watts.

Since the peaks of the transmitted sync pulses always remain at the same amplitude, the peak power of the transmitter is monitored to determine whether the transmitter output is within licensed limits. The peak power must be held within 10 per cent above and 20 per cent below the authorized power, except in emergencies. The same limits are required of the FM transmitter of the aural signal, although the carrier power of the aural transmitter is usually held to a value approximately *one-half* the *peak* power rating of the visual transmitter. This produces nearly equally effective visual and aural signals at receivers.

The frequency of the visual transmitter is maintained within ±1,000 cycles of the authorized carrier frequency. The center frequency of the aural transmitter must be maintained 4.5 Mc, ±1,000 cycles above the visual carrier frequency.

Whenever a TV station is in operation, one or more radio operators holding Radiotelephone First Class licenses must be on duty at the transmitter. In an experimental TV broadcast station, the requirements for the operator(s) is either a Radiotelephone First or Second Class license.

**25.14 The Visual Transmitter.** The visual transmitter is required to pass the carrier plus about 4.2 Mc of upper sidebands and about 0.75 Mc of lower sidebands. This is a total bandwidth of about 4.95 Mc. Furthermore, out past these limits the sidebands must be attenuated sharply: at the high-frequency end to prevent visual sidebands from occurring at the aural carrier frequency; at the low-frequency end to prevent sidebands from appearing in the adjacent channel.

One means of developing the desired bandpass is to grid-modulate a low-level RF amplifier. This amplifier must have a flat tuning characteristic over at least 8 Mc to produce acceptably the proper carrier and video sidebands 4 Mc on each side of the carrier. The several class B linear amplifiers that follow the modulated stage can be overcoupled and stagger-tuned to produce the required 4.95-Mc transmission band. Series-circuit wavetraps are also used in the amplifiers to assure proper attenuation of both sidebands.

Another means of producing the desired transmitted band configuration is to grid-modulate the final amplifier and add a vestigial sideband filter between the output circuit and the antenna diplexer. This filter consists of series-tuned wavetraps with added LC circuits to present a constant impedance to the amplifier for all frequencies but still attenuate the sideband signals that are fed to the antenna.

To tune a TV transmitter properly, a *sideband analyzer* must be used. This consists essentially of a narrow-band receiver that is swept (tuned) across the 6-Mc channel of the transmitter while a complex signal that consists of the carrier and all the video sidebands is being transmitted. The received signal amplitude is displayed on an oscilloscope CRT. The oscilloscope has a horizontal sweep in step with the receiver tuning sweep. The output of the receiver is fed to the vertical-deflection plates of the oscilloscope. The amplitude of the received signal as the receiver sweeps across the channel is displayed on the scope tube. Figure 25.14 illustrates two sideband-analyzer displays, one of a properly tuned amplifier producing both upper and lower sidebands properly, and the other of an improperly tuned amplifier in which the upper sidebands are attenuated improperly.

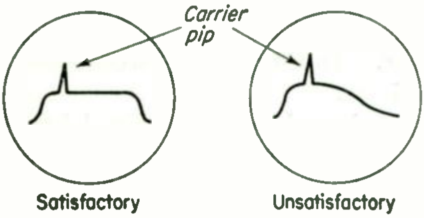


FIG. 25.14. Examples of a satisfactory and unsatisfactory presentation on a sideband analyzer of a television-transmitter test transmission.

**25.15 TV Receivers.** It has been indicated previously that the duty of the TV superheterodyne receiver is to amplify the received TV signal, separating it into an aural component and a video component. From the video, a picture signal is applied to the grid-cathode circuit of the picture tube. Horizontal and vertical sync pulses are separated from the visual signal and are used to synchronize the frequency of oscillation of horizontal and vertical saw-tooth oscillators that produce the sweep currents for the picture tube.

The frequency of operation of commercial TV is between 54 and 890 Mc. Receiver circuits that operate effectively in this range must be used. Actually, these are basically similar to lower-frequency circuits in many respects, except for the requirement of extremely short connecting leads.

Table 25.1

| Lower VHF band | | Upper VHF band | | UHF band | |
|---|---|---|---|---|---|
| Channel | Lowest frequency, Mc | Channel | Lowest frequency, Mc | Channel | Lowest frequency, Mc |
| 2 | 54 | 7 | 174 | 14 | 470 |
| 3 | 60 | 8 | 180 | 24 | 530 |
| 4 | 66 | 9 | 186 | 34 | 590 |
| | (4 Mc skipped) | 10 | 192 | 44 | 650 |
| 5 | 76 | 11 | 198 | 54 | 710 |
| 6 | 82 | 12 | 204 | 64 | 770 |
| | | 13 | 210 | 74 | 830 |
| | | | | 83 (highest) | 884 |

The frequency allocations for commercial TV are in Table 25.1. Each channel is 6 Mc wide. Only the lowest frequency of each channel is given. Only every tenth UHF channel is listed, since these channels are all contiguous. (Note that channel 1 has been deleted. The frequencies originally allotted to this channel are now being used for other services.)

**25.16 The Front End.** The *front end* of a superheterodyne receiver includes the antenna input, the RF amplifier stage(s), the local oscillator circuit, and the mixer stage.

Most VHF TV receiving antennas consist of three or more elements operating as a parasitically excited Yagi beam. For reception in areas of strong signals, one antenna, tuned near the lowest-frequency TV channel, may be used to pick up all the adjacent-channel local stations. Thus, a channel 3 antenna may produce satisfactory pickup of channels 2 to 6, the lower VHF band. A channel 8 antenna will operate fairly well over channels 7 to 13, the upper VHF band. Broad-banding techniques, such as the use of large-diameter antenna elements or the use of a folded-dipole main element, may be used. In the UHF band, broad-band *bow-tie*, or conical antennas with sheet reflectors, are commonly used because of their ability to accept all frequencies above their fundamental with almost equal response. In weak-signal areas it may be necessary to have a special beam antenna for each frequency to be received. Actually, this is necessary at any time that optimum reception is desired. Practically all receivers have a 300-ohm antenna input-impedance circuit. This allows use of 300-ohm twin lead as the transmission line, which is relatively inexpensive and simple to install.

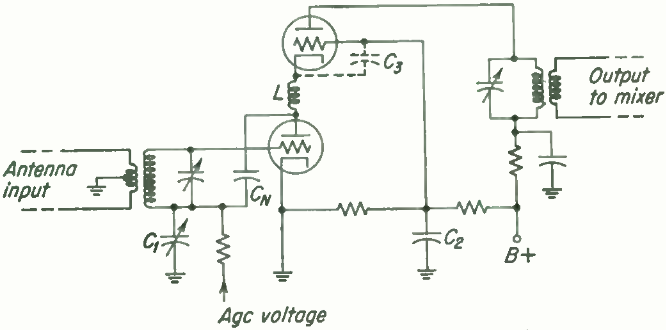


FIG. 25.15. Cascode RF amplifier circuit.

The RF amplifier in a TV receiver must be capable of producing amplification and have low inherent noise. Any noise generated in this stage develops white dots, commonly termed "snow," on the face of the picture tube. A pentode tube may be used as the RF amplifier, but a triode has a lower noise figure, although a single triode does not amplify as much and requires neutralization unless used in a grounded-grid circuit. A popular, low-noise RF amplifier circuit for VHF and UHF receivers is the *cascode* (cascaded stages, cathode-coupled). It consists of two triodes in series, the first stage directly coupled to a grounded-grid second stage (Fig. 25.15).

To neutralize the first tube, capacitor $C_n$ forms a grid-neutralizing type of circuit. Capacitor $C_1$ acts as a means of controlling the neutralization and to bypass the grid coil to ground.

The amplified signal is fed directly to the cathode of the second tube through the small inductance $L$. The grid of this tube is bypassed to ground with $C_2$ and biased with a voltage divider. Being a grounded-grid amplifier, the tube requires no neutralization.

The inductance $L$ is in series with the grid-cathode interelectrode capacitance of the second tube, $C_3$, and $C_2$ and is made series-resonant to the middle of the high-frequency TV band. Signals near the resonant frequency produce relatively heavy current flow, and therefore relatively high voltage across $C_3$ (between cathode and grid). This provides added gain at these frequencies, which normally are subject to considerable loss.

Twin triodes, such as the 6BZ7 and 6BQ7, having gold-plated grids to prevent the grid from emitting electrons when the tube ages, are particularly adaptable to the cascode circuit. They have low noise and relatively high gain. The cascode amplifier also acts as a satisfactory isolation stage to prevent radiation of local oscillator signals.

The diagram shows standard coil and capacitor tuning. In practice each channel may have its own separate slug-tuned coil, utilizing distributed capacitance to complete the tuned circuit. When the channel selector in the receiver is changed from one channel to the next, a separate set of coils is connected into the RF amplifier-grid circuit, into the mixer-grid circuit, and into the oscillator circuit. Each of these coils can be separately peaked to give optimum signal for its own channel.

The mixer stage is similar to the mixer stage of any superheterodyne, except that the local oscillator is almost always a separate triode circuit coupled into the mixer. It is unusual to use a converter tube, such as a hexode or heptode, for frequency conversion with signals over 100 Mc.

The local oscillator is usually a triode in a Colpitts or ultraudion circuit, capacitively coupled to the mixer grid. It is possible to incorporate automatic frequency control in the local oscillator circuit, operated by a reactance-tube modulator circuit from the voltage developed at the discriminator of the audio section of the receiver. This AFC circuit makes a *fine tuning*, or trimmer, adjustment unnecessary.

**25.17 The IF Section.** The output of the mixer stage is an intermediate frequency, or IF (Sec. 17.13). There are two standard frequencies being used as the IF: the newer is 41–47 Mc; the older is 21–27 Mc. In earlier sets even lower frequencies were used. Experience has shown that the higher frequencies give greater freedom from interference developed in nearby receivers, from nearby amateur transmitters, and beats from two or more local RF signals.

At present, a sound IF of 41.25 Mc and a video carrier IF of 45.75 Mc are recommended. Note that the mixing process inverts the positions of the sound- and video-carrier frequencies. Whereas the sound carrier is transmitted at a frequency 4.5 Mc *higher* than the video carrier, in the IF amplifiers the sound appears as 4.5 Mc *lower* than the video carrier. This has no effect on the detected signal, however.

A sound IF of 21.25 Mc and a video carrier IF of 25.75 Mc were previously recommended.

Most modern TV receivers amplify both the video carrier and its sidebands, as well as the sound carrier and its sidebands, with the same IF amplifiers. This is known as an *intercarrier* receiver. The transmitted signal and the desirable bandpass characteristics of the TV-receiver IF section are shown in Fig. 25.16.

In older so-called "conventional" TV receivers, the sound IF was taken from the mixer stage separately. Slight variations of the local oscillator frequency due to drift, detuning, etc., detuned the sound noticeably. This does not occur with the intercarrier receiver, because the 4.5-Mc IF is produced by the beating of the video and aural carriers, which are always transmitted 4.5 Mc apart by the TV transmitting station.

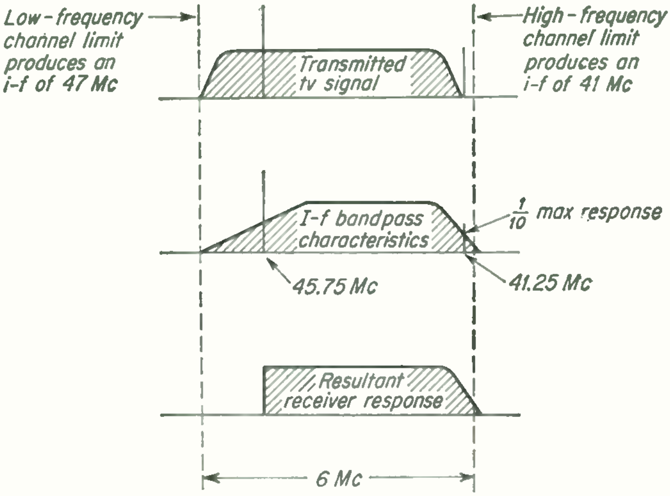


FIG. 25.16. Carriers and sidebands of a transmitted TV signal, ideal IF response curve in a receiver, and idealized resultant receiver response.

At the transmitter it would be too difficult to cut off all the lower-frequency sidebands and leave just the carrier and the higher-frequency sidebands. As a result, the vestigial lower sideband, shown in the first characteristic curve, is transmitted. To utilize the lower-frequency sideband, it is desirable to slope the receiver bandpass characteristics, as illustrated in the second curve. In this way the addition of the upper and lower sidebands near the carrier, those carrying the low video *modulating frequencies*, produces a sum equal to the maximum of the higher-modulating-frequency sidebands. The result is an idealized response to the transmitted signal, as shown by the third characteristic curve. The output from the IF amplifiers contains all the sidebands starting at the carrier out to more than 4 Mc with equal amplitude. Signals displaced farther than this are attenuated.

The slope of the bandpass curve must drop off in such a way that *only*

*10 per cent* of the maximum amplification is being given to the *sound carrier*. This drop prevents the sound signal from forcing its way through to the picture tube and producing dark and light bars across the screen. It also makes the sound-carrier amplitude similar to the whitest white value, which will allow these two signals, sound- and video-carrier, to beat together and produce a 4.5-Mc signal, to form the sound signal in the receiver.

There have been many different types of coupling used in TV IF stages to produce the required bandpass characteristics needed. Some of these are impedance-coupling single-tuned transformers, double-tuned transformers, autotransformers, and more lately the *bifilar* (pronounced by-fi-lar) transformer. A bifilar transformer has the primary and secondary turns interwound, a form of unity coupling (Fig. 25.17). The lumped plate-ground and grid-ground distributed capacitance of the two tubes involved acts as the capacitance of the tuned circuit. A single powdered-iron-core slug broadly tunes the bifilar-transformer circuits to the desired frequency.

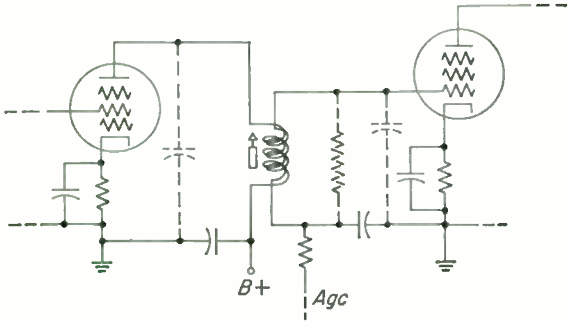


Fig. 25.17. A bifilar-transformer interstage-coupling circuit.

The resistance shown in broken lines in Fig. 25.17 is sometimes used to lower the $Q$, broaden the tuning, and decrease the possibility of oscillation in the stages. Bifilar-transformer coupling, besides being more economical to manufacture, has the advantage of reducing noise impulses on the picture-tube screen that result when capacitive-coupling circuits are employed. A high-amplitude noise pulse charges the coupling capacitor of an impedance coupling circuit. The discharge of the capacitor through the coupling resistors represents a relatively long-duration signal that produces white tails on the black noise spots on the screen, making the noise much more noticeable.

The IF amplifier strip in a TV receiver has three or four stages of sharp-cutoff pentodes, with automatic gain control (AGC) applied to the control-grid circuits. (AGC is similar to AVC, automatic volume control.)

To produce the desired bandpass characteristics the stages are stagger-tuned. With the sound IF at 41.25 Mc and the video carrier IF at

45.75 Mc, the first transformer may be tuned to 43.1 Mc, the second to 45.3 Mc, and the third to 43.1 Mc. This arrangement should result in a bandpass characteristic similar to the second curve in Fig. 25.16.

There are several frequencies other than the desired TV channel signals that may be able to force their way through the front end and the IF strip and cause visual or audible interference. To prevent this interference, wavetraps are used in most TV receivers. To prevent blanketing or overpowering of the front end by local amateur or commercial radio signals, a high-pass filter is often incorporated in the antenna input circuit. This is a sharp-cutoff filter designed to attenuate all frequencies lower than about 54 Mc but pass all higher frequencies without loss.

Because of the broadness of the IF strip, one source of interference may be the sound carrier of a station operating on the adjacent lower channel. Another source of interference may be the visual carrier of a station operating on the adjacent higher channel. Either series-resonant or parallel-resonant traps tuned to the IF frequencies produced by such interfering signals, namely, 47.25 and 39.75 Mc, may be included in the IF amplifiers. Such traps not only attenuate the undesired responses but tend to narrow the skirts of the IF bandpass out past the channel limits. A sound-carrier IF trap (4.5 Mc below the video carrier) follows the detector circuit to which the IF amplifier is coupled (Fig. 25.18).

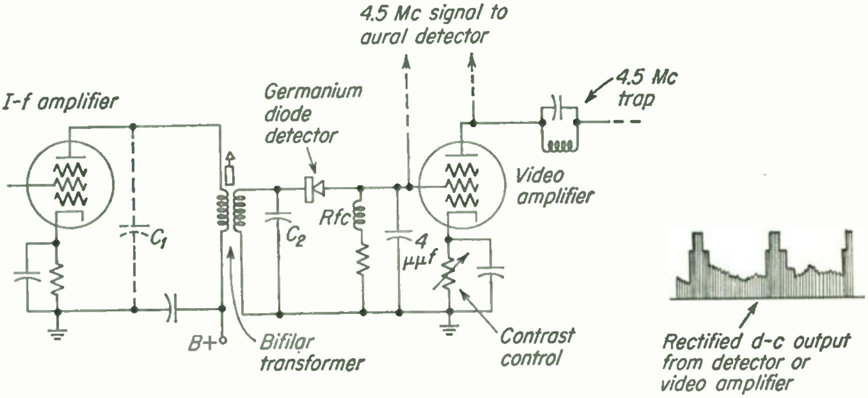


FIG. 25.18. Video detector directly coupled to a video amplifier, and a graph of the detector or video amplifier plate current.

**25.18 The Second Detector.** The second detector of a TV receiver is similar to the half-wave-rectifying diode detector used in AM receivers. The signal from the IF amplifiers, containing the visual and aural information as well as blanking and sync pulses, is fed to a vacuum tube or germanium diode, by which it is rectified or detected, producing a varying d-c output (Fig. 25.18), which may be directly coupled to the video amplifier tube.

When the frequency-modulated sound carrier (at 41.25 Mc in the IF strip) and the amplitude-modulated video carrier and sidebands (45.75 Mc in the IF strip) arrive at the second detector, they mix to produce a 4.5-Mc signal across the detector-load resistor. This 4.5-Mc beat frequency will be modulated in accordance with the FM produced at the aural transmitter and will also be amplitude-modulated by the variation of the visual carrier amplitude. The frequency-modulated 4.5-Mc signal may be taken from the second detector or from the plate circuit of the video amplifier that follows, as indicated by the broken lines in the figure.

Capacitor $C_2$ is approximately equal to the plate-to-ground capacitance of the last IF tube. The required filter capacitance across the diode load is very small because of the high-frequency video signals it is to filter.

**25.19 The Sound System.** The 4.5-Mc FM signal is fed to a 4.5-Mc sound IF amplifier and to one or more limiter stages. The limiter output is fed to either a discriminator or a ratio detector, by which the sound is detected. This is followed by a resistance-coupled triode audio amplifier and a beam-power audio output tube that operates the loudspeaker. The sound system is similar to the IF, detector, and audio circuits of receivers discussed in the chapter on Frequency Modulation.

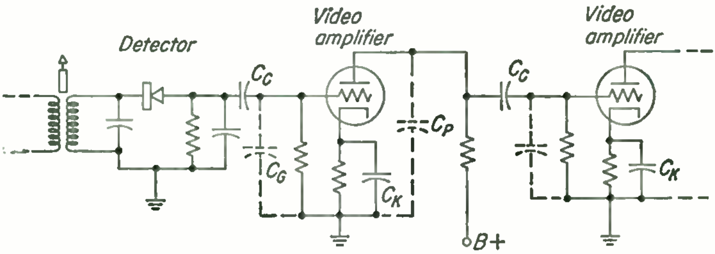


FIG. 25.19. Video detector with resistance-coupled video amplifiers.

**25.20 The Video Amplifier.** The output from the diode visual detector is an amplitude-modulated d-c. The variations in the current will range from approximately zero frequency when the camera tube is scanning a scene that has no change of illumination to variations having a frequency component of as much as 4 Mc when the camera tube is scanning along a dark object and suddenly strikes a light area, or vice versa. Thus, the amplifier that must amplify the video signal must have a nearly flat response from a few cycles to more than 4 Mc.

Consider the more or less standard resistance-coupled amplifier shown in Fig. 25.19, coupled to a diode detector. If the detector is used in an AM receiver, the amplifier would be expected to pass only frequencies between about 30 and 10,000 cps and with carefully chosen components would give a flat response for this range of frequencies.

When frequencies less than 30 cycles are to be passed, the reactance of the coupling capacitors $C_c$ is found to increase. When the reactance of the coupling capacitor begins to approach the grid-to-ground resistance value, the capacitor and resistor form a voltage divider, and less signal is across the grid-cathode circuit at lower frequencies. The bypass, or filter, capacitor $C_K$ across the cathode resistor filters less effectively at low frequencies, allowing more degeneration to occur at lower frequencies than at higher. This all results in a dropping off of the response of the amplifier as the frequency approaches zero.

To extend the low-frequency capabilities of the amplifier further, larger coupling and bypass capacitors can be used. Direct-coupling the detector to the video amplifier lessens the difficulty of coupling low frequencies. The same is true when coupling the video amplifier to the grid-cathode circuit of the picture tube. As a result, it is fairly common practice to use a direct-coupled video amplifier between the visual detector and the picture-tube grid.

When frequencies higher than 10,000 cps are to be passed, the grid-to-ground and the plate-to-ground capacitances ($C_g$ and $C_p$) become important. As the frequency increases, the reactance of these capacitances decreases. They act as bypass capacitors, effectively shunting the higher frequencies to ground. This can be overcome materially by using low values of plate- and grid-circuit resistances. However, the lower these resistances, the less gain possible. By using load resistances of 2,000 to 5,000 ohms and tubes with low interelectrode capacitances, it is possible to extend the high-frequency response up to well over 1 Mc before it begins to drop off.

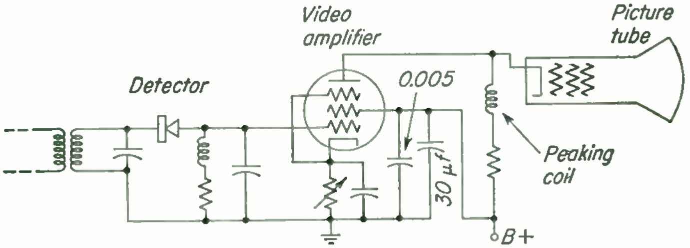


FIG. 25.20. Video amplifier directly coupled to the picture tube.

To extend the high-frequency capabilities of the video amplifier past 1 Mc, special resonant, or *peaking,* circuits are used. Figure 25.20 illustrates a direct-coupled video amplifier using a small peaking coil, selected to form a parallel-resonant circuit with distributed capacitance at a frequency of approximately 3 Mc. This results in a nearly flat response out to the required frequency limits.

Note that the screen grid is bypassed with two capacitors, one a 0.005-μf, and the other a 30-μf. This is a common practice in cases where low- and high-frequency bypassing is required. For the low frequencies, an electrolytic capacitor can be used. The 0.005-μf paper or mica capacitor is effective for the higher frequencies, for which an electrolytic may be ineffective.

Not all video amplifiers are directly coupled. When capacitively coupled, another difficulty appears. Either capacitive or transformer coupling produces an a-c in the grid circuit, even if the plate-circuit current is varying d-c. If the detected visual signal with its pulses were converted into an equivalent-shaped a-c, the blanking pulses would not have sufficient amplitude to cut off the tube during retrace periods and unsatisfactory picture reproduction would be produced. Figure 25.21 illustrates how the d-c video signal would be changed to an a-c signal if capacitively coupled to the grid of the picture tube.

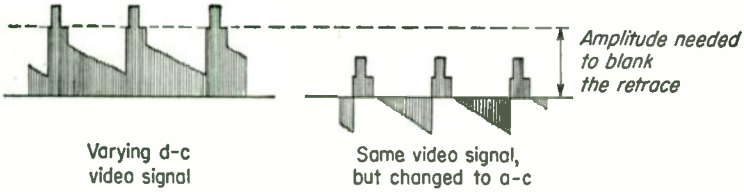


FIG. 25.21. Video signal when directly fed and when fed through a capacitance.

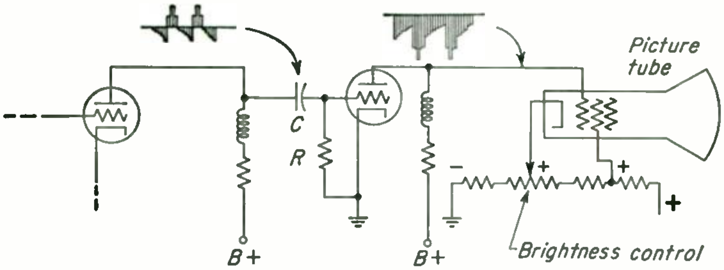


FIG. 25.22. Grid-leak-type d-c reinsertion circuit.

When capacitively coupled video amplifiers are used, it is necessary to use a *d-c-restorer*, or *d-c-reinsertion*, circuit so that the a-c signal can be added to a d-c voltage to produce the required negative amplitude to cut off the picture tube during blanking periods.

Direct-current reinsertion can be accomplished by using a grid leak in the grid circuit of the video amplifier before the picture tube, or by using a diode in the grid circuit of the picture tube itself. A diagram of a simplified grid-leak d-c reinsertion circuit in the video amplifier is shown in Fig. 25.22.

During the positive half cycles of the incoming signal, the grid draws electrons, charging the capacitor $C$. If the resistance $R$ is sufficiently high in value, a bias is developed across it that cannot leak off in the 1/15,750 sec between two sync pulses. When the picture is nearly black, the voltage *difference* between sync-pulse peaks and black signal level is small and the bias developed is small. This establishes a high value of average plate current and a high blanking current and voltage applied to the picture-tube grid. If the picture becomes nearly white, the variation between sync-pulse peaks and the visual signal increases, producing greater bias and lowering the average plate current, but leaving the blanking level essentially constant regardless of the average picture illumination.

The grid-cathode circuit of the triode is acting as a diode as far as producing bias is concerned.

It is possible to reinsert the d-c in the grid of the picture tube by using a diode in a way somewhat equivalent to the grid-leak circuit above. A simplified circuit is shown in Fig. 25.23.

The video signal produces a positive bias at the top of resistor *R*, which is stored there by the charging action of capacitor *C*. To make the picture-tube grid more negative than the cathode, it is necessary to feed the cathode a more positive voltage than is developed across the diode and *R* by the video signal. The potentiometer forms the brightness control.

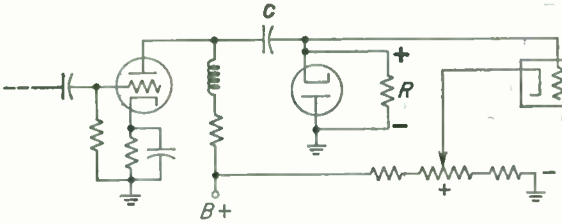


FIG. 25.23. Diode-type d-c reinsertion circuit.

If the cathode is made a great deal more positive than the grid, the grid can be cut off entirely and no beam or picture signal can reach the picture-tube screen.

**25.21 Sync-pulse Separation.** So far, the TV signal has been received, converted to an IF, amplified, and detected, and the aural signal has been separated, amplified, detected, and fed to a loudspeaker. The video signal, consisting of the blanking and sync pulses, and the modulation of each line of the picture have been amplified and fed to the *brightness* grid of the cathode-ray picture tube. The electron beam is modulated in intensity by the video signal. The amplitude of the blanking pulse is sufficiently negative to cut off the electron beam entirely during retrace periods. The picture signals being less negative than the blanking pulses allow the beam to strike the fluorescent coating on the inside of the picture tube. The less negative the picture information, the stronger the beam and the more illumination produced on the screen.

Note that the sync pulses, perched on top of the blanking pulses, are also fed to the brightness grid of the CRT, but since they are even more negative than the blanking pulse, they represent a "blacker than black" voltage and have no effect on the picture. Therefore there is no reason to eliminate them from the CRT grid.

The same video signal fed to the CRT grid may also be fed to a circuit which will respond to the sync pulses only. Such a circuit is known as a *synchronizing-pulse separator*, or more simply, a *sync separator*. Diode, triode, or pentode tubes may be used to separate the sync pulses from the video signal. The pulses are then applied to the vertical and the horizontal oscillator circuits that produce the sweep currents in the picture tube.

The basic idea of a sync separator can be explained by the circuit in Fig. 25.24. The composite video signal is fed to the sync-separator diode from the last IF amplifier through capacitor $C$. The positive halves of the signal draw electrons through the diode and through $R_2$, charging capacitor $C$ negatively on the diode side. This applies a negative potential to the diode plate that decreases slowly as the charge leaks off through $R_1$. Only peak voltages can now overcome this negative biasing voltage and produce current flow through the cathode resistor $R_2$. Thus, the only voltage drops to occur across $R_2$ are the result of the sync pulses. The pulses are fed to the triode amplifier stage (which is also operating as a phase inverter), and from there to both the vertical sweep oscillator and to the horizontal sweep automatic-frequency-control (AFC) circuit. The resistors $R_3$ and $R_4$ form a voltage divider and are selected to give the desired bias for the triode amplifier stage.

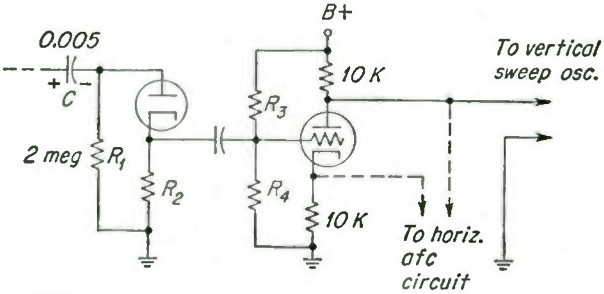


FIG. 25.24. A diode sync-separator circuit feeding sync pulses to a triode phase inverter.

**25.22 Vertical Deflection.** The relatively wide 60-cycle serrated vertical pulses can be isolated from the narrow 15,750-cycle horizontal and equalizing pulses by the use of a low-pass RC filter, known as an *integrator* circuit. To produce a steeper waveform than would appear at the output of the integrator circuit, a *blocking oscillator* may be used. This is a more or less standard sine-wave oscillator circuit, but operating in such a way that the duration of the plate-current pulse is very short. An example of an integrator circuit coupled to a 60-cycle blocking oscillator which uses an RC circuit to develop a saw-tooth waveform, and to a vertical sweep amplifier is shown in Fig. 25.25.

The phase of the sync pulses must be such that the vertical pulse coming from the integrator circuit produces a positive voltage on the grid of the blocking oscillator. The grid then draws electrons from the cathode, charging the integrator capacitors negatively and allowing a pulse of plate current to flow. Because of the regeneration of the circuit the plate current rapidly builds to a peak and cuts off. Before the pulse arrived at the grid, capacitor *C* had been charged positive on its top plate by the B+. When the grid is driven positive, electrons flowing through the tube flow into the positive plate of the capacitor, rapidly discharging it. When the plate current ceases to flow, the capacitor slowly regains its positive charge, losing electrons to B+ through the high-resistance *R*. Thus a saw-tooth waveform is developed across *C*. This in turn is fed to the amplifier, and then to the vertical-deflection coils.

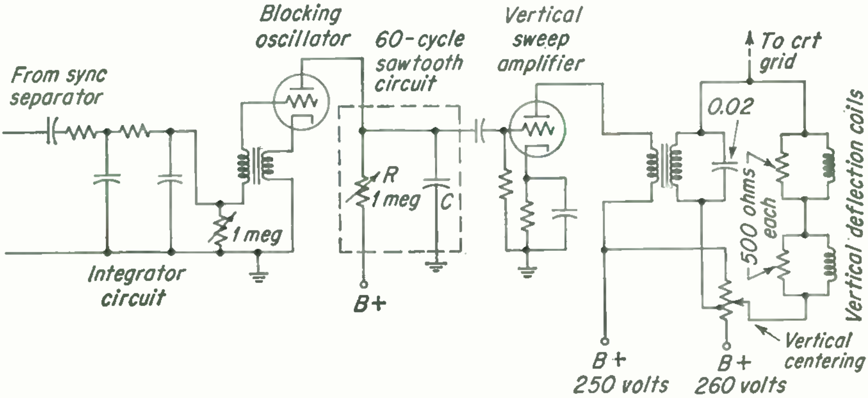


FIG. 25.25. A simple vertical-deflection circuit, employing a blocking oscillator.

By necessity, this description has been highly simplified. Not included are the rather complex waveform corrections that must be made to the simple nonlinear RC saw-tooth oscillator signal to produce the desired linear sweep of the electron beam downward across the face of the picture tube.

To overcome the inductive effects exhibited by the vertical-deflection coils, each is shunted by a resistor of about 500 ohms. Some of the voltage developed across the vertical-deflection coils may be fed to the brightness grid of the picture tube to aid in blanking the beam during retrace periods.

Vertical centering is produced by introducing direct current in one direction or the other through the vertical-deflection coils. Such a circuit is shown in the diagram above by the center-tapped potentiometer between two different positive power-supply potentials.

A multivibrator-type saw-tooth-wave vertical oscillator is used in many TV receivers. It can receive its synchronization from the integrator circuit directly.

**25.23 Horizontal Deflection.** The horizontal-deflection system often consists of a 15,750-cycle multivibrator oscillator and an amplifier that feeds the horizontal-deflection coils. Such a multivibrator circuit can be synchronized simply by feeding the output of the sync separator through a high-pass RC filter, called a *differentiator* circuit. (If the sync-pulse circuit is termed a *clipper*, the integrator and differentiator circuits may be called *sync-separator* circuits.) The differentiator develops a sharp *pip* for the leading edge and an opposite-polarity pip for the trailing edge of each pulse. A multivibrator can be synchronized by feeding either a positive or negative pip to one of its grid circuits. The only difficulty with this simple system of synchronization is the tendency of noise pulses to upset the proper synchronization and tear out portions of the picture.

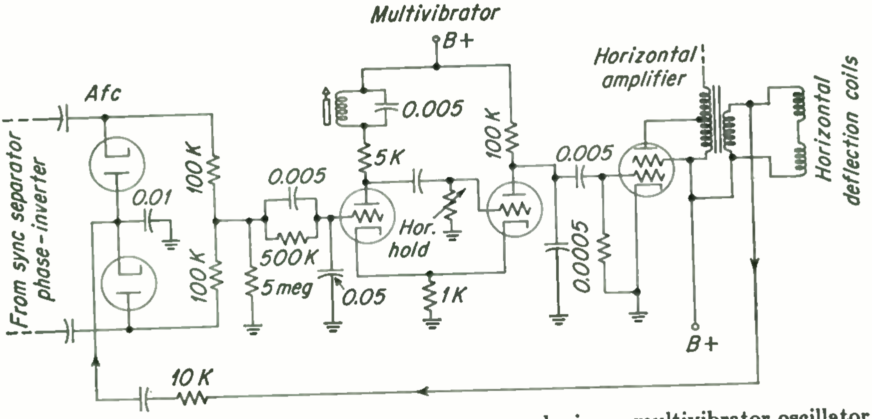


FIG. 25.26. A basic horizontal-deflection system employing a multivibrator oscillator and an AFC circuit.

A better system uses some of the horizontal-deflection-coil signal and feeds it back to a horizontal AFC circuit, sometimes called a *phase detector*, where it is compared with the horizontal sync pulses from the sync separator. If the multivibrator is operating at the proper frequency and phase, the AFC circuit has no effect on its oscillation. If the multivibrator is not in step with the sync pulses, the AFC develops a voltage that tunes the multivibrator until it is in proper synchronism. The diagram in Fig. 25.26 illustrates, in simplified form, a horizontal-deflection system.

The 15,750-cycle saw-tooth a-c that is to produce the horizontal sweep is generated by the two-tube multivibrator circuit and appears across the 0.0005-$\mu$f capacitor. The basic frequency of oscillation can be controlled by adjusting the grid-leak resistor in the second tube. This is called the *horizontal-hold* control. The parallel coil and capacitor in the plate circuit of one of the multivibrator tubes are resonant to 15,750 cycles and stabilize oscillations. The frequency of multivibrator oscillation can be varied slightly by variation of any grid or plate component of this cathode-coupled-type circuit.

The saw-tooth a-c output is fed to a grid-leak-biased class C beam-power-tetrode amplifier, such as a 6BG6, 6BQ6, 6CD6, etc., which is transformer-coupled to the horizontal-deflection coils. The build-up of current in these coils deflects the electron beam across the face of the picture tube 15,750 times a second.

A sample of this saw-tooth wave is fed back to the AFC circuit to be compared with the sync pulses from the sync-separator phase-inverter circuit.

The AFC circuit is fed sync pulses (both horizontal and vertical) from the sync separator and phase inverter. Each pulse is fed to one diode tube as a positive voltage and to the other tube at the same time as an equal-value negative voltage. Thus, both tubes try to charge the 0.01-μf capacitor, but since the charging currents are 180° out of phase and equal, the capacitor is not affected. The center tap between the two 100-kilohm resistors is also at zero potential as far as the pulses are concerned. However, if the saw-tooth a-c fed back to the AFC circuit from the deflection circuit has either a negative or positive polarity at the time the pulses arrive, this polarity will be added to one of the tubes and subtracted from the other, and the capacitor will charge either positively or negatively. This will result in the center tap of the 100-kilohm resistors having either a positive or negative potential. Changing the potential of the multivibrator grid circuit will change the time of charge and discharge of the oscillator circuit and change its frequency. As a result, the multivibrator will shift frequency or phase until the saw-tooth feedback voltage arrives with a zero voltage at the time the pulses arrive. The RC network between the AFC and multivibrator circuits has a long time constant and prevents rapid changes in the frequency of oscillation, thereby preventing random strong noise impulses from throwing the horizontal circuit out of synchronism.

**25.24 Horizontal-output Circuit.** Basically, the horizontal amplifier output feeds the deflection current to the horizontal-deflection coils. It also produces the high voltage for the picture tube and a *B+ boost* voltage for the horizontal amplifier and for the first anode of the picture tube. Such a circuit is illustrated in Fig. 25.27.

When the saw-tooth a-c builds up slowly on the grid of the horizontal amplifier, the plate current builds up slowly but evenly through the transformer primary and through the damper tube. This produces a practically constant secondary voltage in the output transformer and a constantly increasing deflection-coil current and magnetic-field strength, resulting in the electron beam being deflected slowly but evenly across the picture-tube screen. The current flows in a downward direction through the coils during the build-up of the magnetic field.

When the saw-tooth a-c on the grid drops suddenly to a high negative value, plate current in the amplifier drops to zero. The magnetic field around the deflection coils collapses rapidly, inducing a high-amplitude *flyback* emf across the transformer secondary. This produces a sharp pulse of high-amplitude flyback current flow upward in the secondary of the transformer, and a high induced flyback emf downward in the *primary* winding, making the top of the primary positive. The several thousand volts induced into the primary is rectified by the high-voltage rectifier, filtered with an RC network, and connected to the high-voltage anode of the cathode-ray picture tube.

During the discharge period, the energy stored in the magnetic field around the deflection coils would tend to produce damped oscillations in the LC circuit consisting of these coils and any distributed capacitance that existed. This would interfere with the production of the next saw-tooth wave. However, when the collapsing magnetic field induces a current flow downward in the coils, the damper tube passes current, charging the capacitor $C$. The energy that would have produced oscillations is now contained in the capacitor. The polarity of this charge is such that it is in series with the plate supply voltage. This results in a source of available voltage and energy for the horizontal-amplifier plate circuit and for the first anode of the CRT of nearly twice the power-supply voltage.

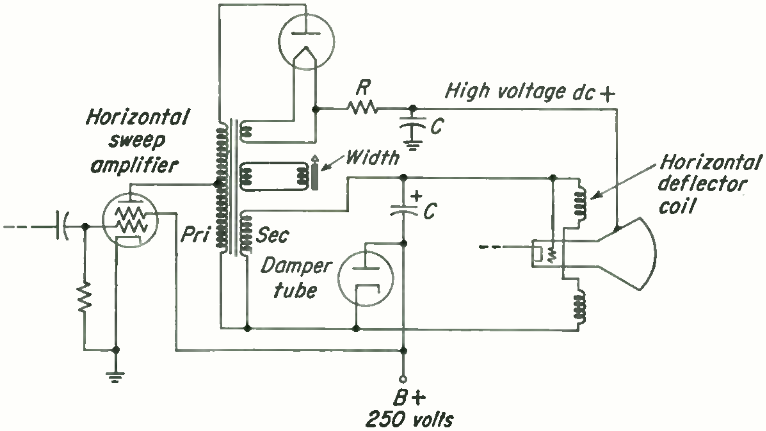


FIG. 25.27. The high-voltage circuit, damper tube, and horizontal-deflection coils driven by the horizontal sweep amplifier.

The high voltage developed by the horizontal flyback and connected to the final anode of the picture tube may exceed 10,000 volts. Care must be exercised to discharge this circuit to ground after the TV receiver has been turned off before attempting to make any internal adjustments to the set. Care must also be taken not to strike or jar the picture tube, since it can implode violently, throwing broken glass and parts many feet.

The width of the picture can be controlled by shunting a small variable inductance across a few secondary turns of the output transformer, as shown.

**25.25 Automatic Gain Control.** Automatic gain control, or AGC, in a TV receiver is similar in action to automatic volume control, or AVC, in AM receivers. A received AM carrier is rectified, filtered with a long-time-constant RC filter, and fed as a negative bias to the grid circuits of the RF and IF amplifier tubes to produce nearly constant average signal at the second detector regardless of the strength of the signal received. Automatic volume control is possible in an AM receiver because the average voltage of the carrier is constant, with or without modulation.

An AVC circuit operating in a similar manner from the second detector of a TV receiver would develop a low bias voltage for light scenes and high bias voltage for dark scenes, which would not produce the desired pictures. However, if the AGC voltage is developed from the amplitude of the sync pulses, which do not change, a satisfactory bias voltage will result. One AGC system, previously used, employed a sync-separator circuit and a long-time-constant RC filter. The long time constant was required to filter the 60-cycle and the 15,750-cycle ripple that appeared when the vertical and horizontal pulses were rectified. However, airplanes flying overhead reflected rapidly changing in-phase and out-of-phase signals to the receiver and produced wildly changing AGC amplitudes that sometimes threw the receiver completely out of synchronization. This was overcome by the use of *keyed AGC*.

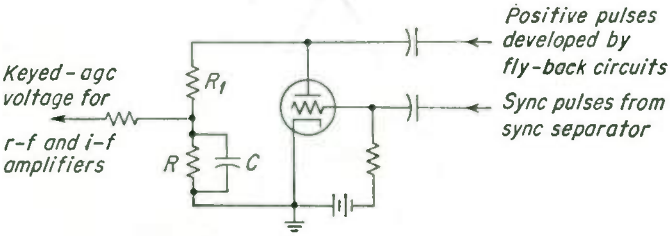


FIG. 25.28. A method of producing keyed AGC voltage.

The basic theory of a keyed-AGC system can be explained by the simplified diagram of Fig. 25.28. Two sets of pulses are fed to the AGC tube. Positive pulses developed in the horizontal output transformer by the flyback operation are fed to the plate. These pulses last for only a few microseconds. Positive pulses are fed to the negatively biased grid from the sync separator stage. If both grid and plate are keyed positively at the same instant, the tube conducts and electrons flow through it, and eventually down through resistors $R_1$ and $R$, charging capacitor $C$ negative at the top. This negative voltage is fed to the RF and IF grid circuits as the AGC voltage. If noise pulses are fed to the grid through the sync separator, they cannot produce plate current unless the plate is also positive. Thus, the keyed AGC discriminates against noise impulses that occur during the reception of the visual signals. These cannot affect the AGC voltage, even if of extremely high amplitude. The RC time constant can be relatively short, allowing the AGC voltage to follow reasonably rapid fading, such as produced by airplanes, making such fading only slightly noticeable.

It must be pointed out that this and many of the other circuit diagrams shown may not be exact duplicates of those found in modern TV receivers. For each basic circuit described here, there are dozens of variations in practical use. (For more detailed explanations of TV circuits, refer to TV-receiver texts.)

**25.26 Color.** Radio waves are a form of radiant energy that will travel through space. Light differs from radio waves in frequency or wavelength only. Red light has a wavelength of about 700 millimicrons (billionths of an inch, abbreviated m$\mu$), green light about 520 m$\mu$, and blue light about 400 m$\mu$. If the correct proportions of pure ("saturated") colors ("hues") of these three are added together, any desired color can be produced. For example, a blue, a green, and no red will produce a blue-green, called *cyan*. A green, a red, and no blue results in yellow. With proper levels of green, blue, and red, all color perception in the eye is canceled and "white" is seen. Thus, to transmit a picture in full color it will only be necessary to scan the picture for its blue content, again for its green content, and for its red content. When the same percentage of each color is projected on a screen at the same time and in the correct places, the picture appears as the original. Bright white areas in the picture will be projected as strong pure green, strong pure red, and strong pure blue colors. Gray areas will be projected as weak green, weak red, and weak blue colors. Black areas will be projected with no green, no red, and no blue. By proper combinations of hues and intensities, any desired color could be reproduced as well as white, grays, and black.

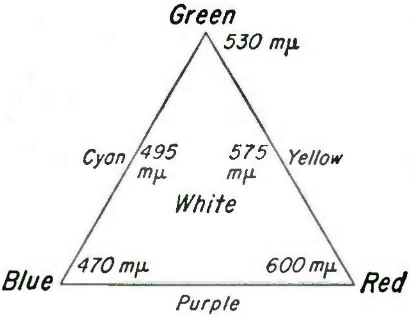


FIG. 25.29. A simplified color triangle.

The color triangle in Fig. 25.29 represents a rough approximation of the distribution of colors it is possible to reproduce by striking picture-tube phosphors with an electron beam. None of the colors shown can actually be reproduced in a 100 per cent saturated form, but the possible percentage is equal to, or better than, the percentage that can be obtained with printing inks. From this it can be expected that color TV will reproduce very lifelike colors if the transmitting and receiving systems are operating properly.

**25.27 Transmitting Color Signals.** The TV color camera may consist of one lens system focusing the picture to be televised onto and through special *dichroic* glass mirrors. A dichroic mirror will reflect the color for which it is made and pass all other colors through it. The three reflected color scenes are picked up by three separate camera tubes (image orthicon for studio and field pickup and vidicon for motion-picture pickup), as shown in Fig. 25.30. In this way the red, green, and blue color content of a picture is separated into three separate signals. The three camera tubes scan their respective color scenes in unison, developing modulated-line information similar to a black-and-white camera tube. Eventually, these three electrical signals will be made to illuminate red, green, and blue phosphor dots or lines on the face of a color-picture tube and the original scene will be reproduced in color.

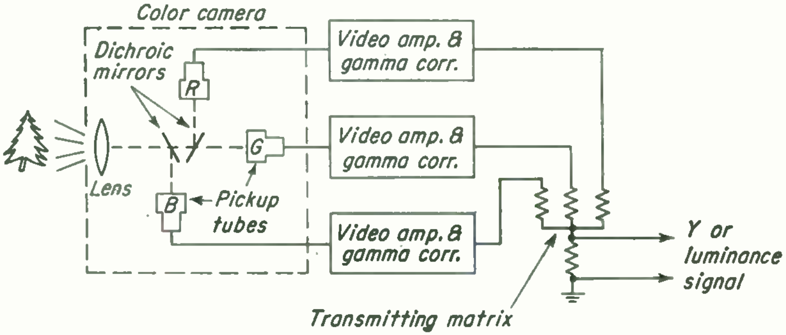


FIG. 25.30. Block diagram of a color camera and circuits to produce the $Y$, or luminance, signal.

At the transmitter, the output of the camera tubes is amplified by a series of video amplifiers and is *gamma*-corrected. Gamma (a measurement of contrast) correction is required because the camera tubes produce a brightness output that does not correspond to the brightness recognition of the human eye. The three gamma-corrected video signals are then fed to a *transmitter matrix*. In the matrix the three color signals are combined into one composite signal with a ratio of 59 per cent green, 30 per cent red, and 11 per cent blue. This is done to produce a signal that will better discriminate against noise during passage through the transmitting and receiving systems. Such noises would show as a flicker in the final picture. These percentages of color information also produce a good rendition of white, grays, and black when the signal is viewed on a monochrome receiver. The output from this part of the matrix is known as the $Y$, or *luminance*, signal. This luminance signal is the only one used to amplitude-modulate the TV transmitter carrier directly. It contains video frequencies up to 4.2 Mc and produces a black-and-white picture on any monochrome TV receiver. Thus, the color transmission will be *compatible* (receivable on either a color or monochrome receiver).

Besides the $Y$, or luminance, signal, in the matrix the three color signals are again combined as 28 parts green, 60 parts red, and 32 parts blue. The resulting signal containing these components is known as the $B - Y$ ($B$ minus $Y$), the *blue chrominance*, or the $I$ (in-phase) signal.

The third output signal from the matrix is the $R - Y$ ($R$ minus $Y$), or *red chrominance*, or the $Q$ (quadrature) signal. It has components in the proportions of 52 parts green, 21 parts red, and 31 parts blue.

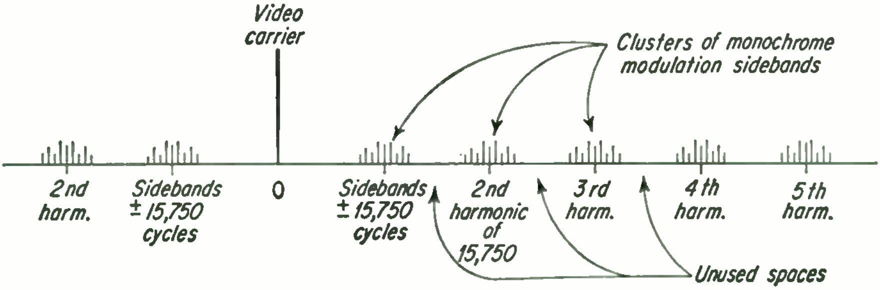


FIG. 25.31. A monochrome emission groups its sidebands around harmonics of 15,750 cycles, leaving room for color information in between.

The first matrix signal ($Y$) is used to control the brightness of the color signal in the receiver. The amplitude of the other two signals will determine the saturation (purity) of the colors, and the *phase* difference between the $I$ and $Q$ signals will determine the hue (actual color) of the parts of the received picture.

The problem of transmitting the regular black-and-white luminance signal, requiring 4.2 Mc of sidebands, as well as the chrominance information, without increasing the required bandwidth, has been ingeniously solved. The key to the answer lies in the fact that the sidebands that are produced by monochrome modulation of the transmitter cluster around frequencies that are harmonics of the line frequency of 15,750. As a result, there are spaces between these clusters that are not used, as shown in Fig. 25.31.

By careful selection of available frequencies, it was found that a *subcarrier* with a frequency of 3,579,545 cycles above the video carrier could be used. In determining the desired subcarrier frequency it was found necessary to change the line frequency slightly. A monochrome transmitter uses a line frequency of 15,750 per second and a field frequency of 60 per second. A color transmitter uses a line frequency of 15,734.26 per second and a field frequency of 59.94 per second. The difference between these frequencies is so slight that the average TV receiver will hold synchronism on either without adjustment of the sync controls.

If the subcarrier frequency is amplitude-modulated by the $R - Y$ signal, the sidebands that are produced will fall in the spaces between the sideband clusters produced by the luminance modulation. In this way the luminance and the chrominance modulation can be transmitted within the same 4.2-Mc bandwidth. The positions of the video carrier and its sidebands, the red-chrominance subcarrier and its sidebands, and the aural-carrier center frequency are shown in Fig. 25.32.

A significant difference between the luminance and the chrominance bandwidth is apparent. It has been found that the fine detail presented by the higher-frequency sidebands of a TV signal is not necessary in transmission or color. The human eye sees color in large areas, and to a certain extent in moderately small areas, but color is not apparent in fine detail. Therefore the fine detail in a color transmission can be carried by the $Y$ signal alone, and a narrow chrominance bandwidth may be used. When the chrominance information is inserted where it appears to be high-frequency sidebands to the video carrier, it shows on the screen as very-small-detail patterns. If the interlaced color fields are transmitted properly, a near cancellation of the chrominance signals occurs on the picture-tube screen, making these black-and-white renditions of the color signals hardly noticeable. (In this respect the chrominance signals act as undesirable interference signals to the luminance carrier and information.)

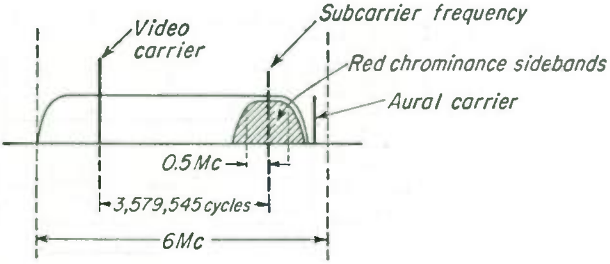


FIG. 25.32. Placement of the color subcarrier and the red chrominance sidebands in a 6-Mc TV channel.

The subcarrier frequency is shown by a broken line because it is suppressed and is not actually transmitted. If it were, it would produce an undesired pattern on the receiving picture-tube screen.

In the following discussion explaining how the chrominance information is applied to the emitted signal, the $R - Y$, or red chrominance, signal will be investigated first. The $R - Y$ signal from the matrix is first fed through a 0–0.5-Mc low-pass filter to remove all higher frequencies. (It is still a video frequency signal, not sideband, because it has not yet been used to modulate a carrier.) The filtered signal is fed to a balanced modulator that is being fed the 3,579,545-cycle subcarrier (3.58 Mc for simplicity) at the same time. This stage balances out the carrier itself, but leaves the upper and lower sidebands produced by the $R - Y$ signal. These sidebands are a-c signals ranging in frequency from 3.18 Mc (3.58 − 0.5) to 4.18 Mc (3.58 + 0.5). They are fed through a 3–4.2-Mc bandpass filter to remove any spurious products of modulation and are added to the $Y$ signal before it modulates the video carrier of the transmitter (Fig. 25.33).

The $B - Y$ signal is also used to modulate the 3.58-Mc subcarrier in a balanced modulator. It is first passed through a 0–1.5-Mc low-pass filter to remove any higher (finer-detail) frequencies. The carrier that the $B - Y$ signal modulates is also 3,579,545 cycles, but has been shifted in phase by 90° and is said to be in *quadrature* with the carrier modulated by the $R - Y$ signal. When the $B - Y$ and $R - Y$ signals are added to the $Y$ signal, the two sets of sidebands are 90° out of phase. They form a resultant which acts as phase modulation. The phase angle is determined by the relative amplitude of the two signals. In the receiver the resultant of these out-of-phase signals will represent the hue, or color, of the signal to be displayed, while the amplitudes of the signals will represent the saturation of the color.

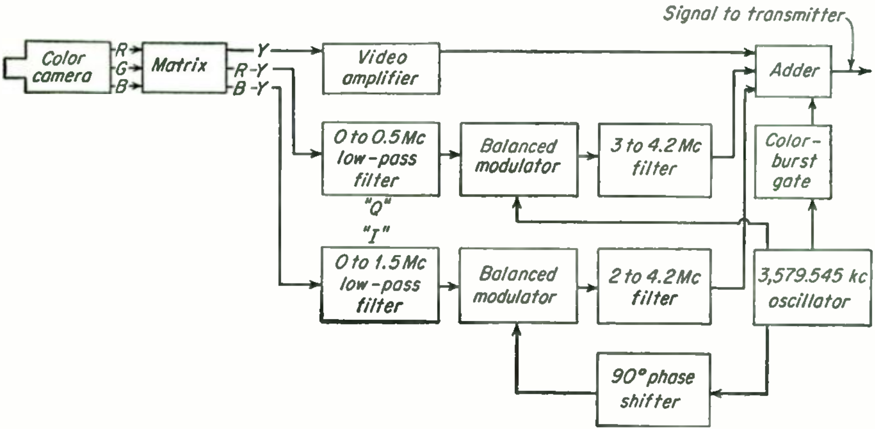


FIG. 25.33. Block diagram of the video circuits from color camera to the modulating signal applied to the TV transmitter.

The only other added information required in the transmission of color TV signals is a short burst of the subcarrier frequency. Eight cycles or more of this frequency are added to the back porch of the horizontal blanking signal, as shown in Fig. 25.34. This *color burst* is used in the receiver to synchronize an oscillator and hold it on the frequency of the missing subcarrier. The received sidebands must be mixed with this carrier frequency in order that they may be detected properly in the receiver.

It will be noted that the $B - Y$ signal has a bandpass of 1.5 Mc. This would produce sidebands 1.5 Mc above and below the subcarrier frequency, or sidebands past the aural carrier and out of the channel. To prevent this the filter following the $B - Y$ balanced modulator is a 2–4.2-Mc bandpass circuit, producing a vestigial-sideband-type of $B - Y$ signal.

It would appear that the green signal has been forgotten entirely. However, all signals, $Y$, $R - Y$, and $B - Y$, contain components of all three colors. In the receiver it is possible to separate the components and produce a $G - Y$ (green chrominance) signal, even though none is transmitted as such.

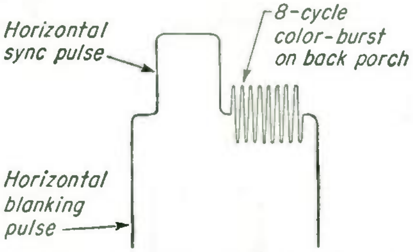


FIG. 25.34. Placement of the color burst on the back porch of the blanking pulse.

**25.28 Color-TV Receivers.** The transmitted VHF or UHF color-TV signal contains three separate systems of sidebands all within a band of 4.2 Mc. The luminance signal extends for the full 4.2 Mc. The two separate sets of chrominance sidebands occupy the spaces between the luminance sideband clusters in the upper 2.2 Mc of the luminance band. A color burst of about eight cycles of the suppressed subcarrier frequency of 3.58 Mc modulates the back porch of the blanking pulses.

The requirement for the receiver is first to reproduce signals equal to the three original color signals picked up in the camera tube. Then it must reassemble these signals in their own component colors and intensities in corresponding points on the screen of the color picture tube.

The antenna, front end, IF amplifiers, AGC, and sound systems are very similar to corresponding systems in monochrome receivers except that the color receiver requires more accurate alignment of RF and IF channels to produce the required response curve. A falling off of response of the higher-frequency sidebands in a monochrome receiver will produce a slightly less defined picture. Since all the chrominance information is in the higher-frequency end of the IF bandpass, a loss of response will mean loss of proper color rendition on the picture tube.

The block diagram in Fig. 25.35 shows the section of the color-TV receiver that separates the three color signals. It starts with the composite detected signal from the video (second) detector.

The whole composite signal, including all video frequencies that lie

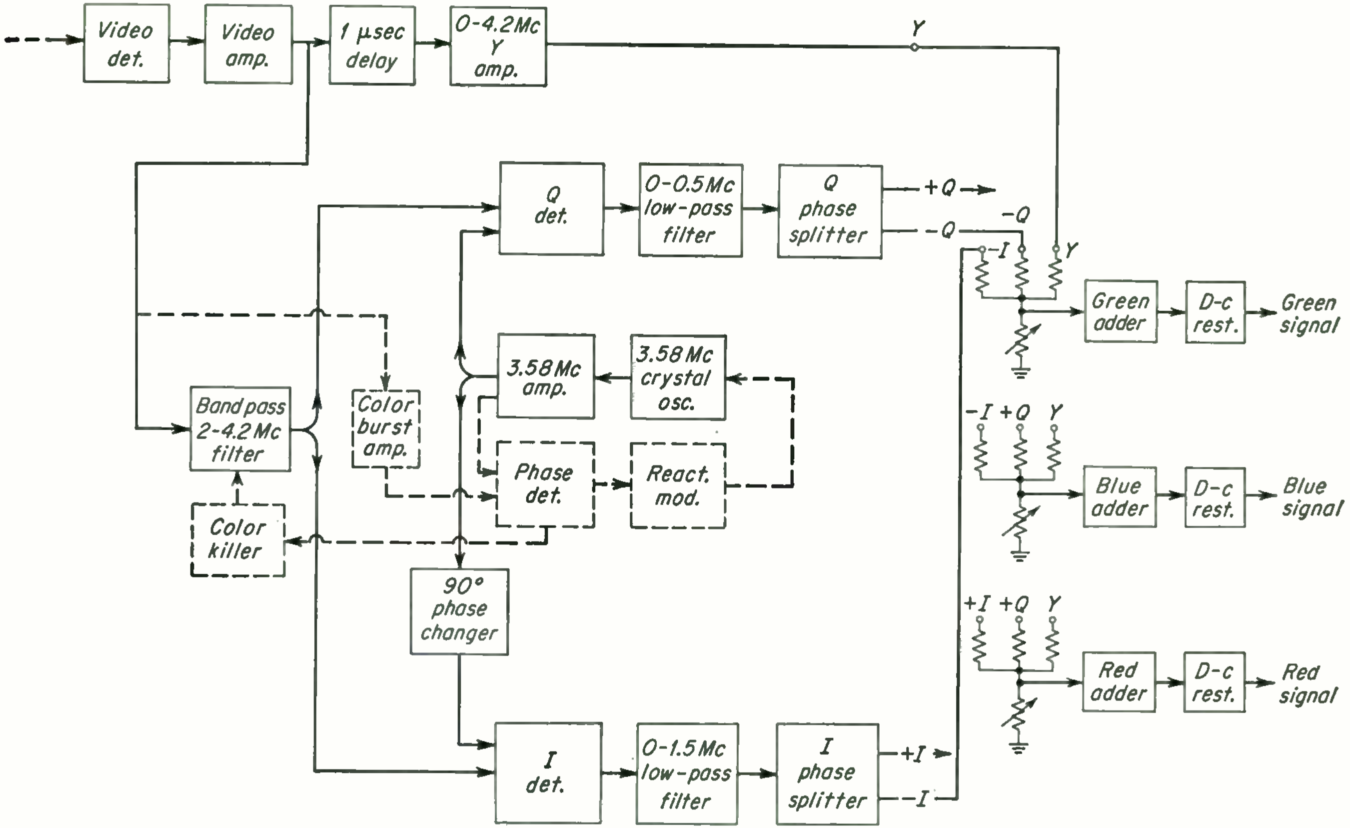


FIG. 25.35. Block diagram of the color signals from the receiver detector to the three signals that produce the colors in the color tube.

between zero and 4.2 Mc, is passed through a 1-μsec delay circuit and is then fed to the luminance amplifier. (The delay circuit is required because of the wider passband of the luminance circuits. The chrominance signals pass through a narrower passband which will not pass them as rapidly.)

When the receiver is adjusted to receive only monochrome transmissions, the $Y$ signal forms the black-and-white signal.

The chrominance signals in the composite signal do produce black-and-white signals on the picture-tube screen but are hardly noticeable. The whole $Y$ signal is fed to the three sections of the receiving matrix.

The whole composite signal is also fed to a 2–4.2-Mc bandpass amplifier circuit. This passes those frequencies which were developed by the sidebands of the subcarrier, the $R - Y$ and the $B - Y$ modulation.

A 3.58-Mc crystal oscillator is made to fall into exact synchronization with the color-burst signal through the use of the phase detector and the reactance modulator. The amplified 3.58-Mc signal is fed directly to the $Q$ (called $R - Y$ in the transmitter) detector or demodulator. Since this injected carrier is the same frequency and in the same phase as the subcarrier that originally produced the $Q$ sidebands in the balanced modulator, the output of the $Q$ detector or mixer reproduces only the $Q$ signals. Any $I$ signals, since they are 90° out of phase, are canceled in the $Q$ detector output. The signal from the $Q$ detector is now in the form of video frequencies of 0 to 0.5 Mc. The 3.58-Mc carrier frequency is also present. These signals are passed through a 0–0.5-Mc low-pass filter to eliminate the 3.58-Mc frequency and any other frequencies developed above 0.5 Mc. The $Q$ signal is fed to a phase splitter or inverter which delivers a positive and a negative $Q$ signal of the same amplitude to the three sections of the receiving matrix, as indicated in the block diagram.

The $Q$, the $I$, and the $Y$ detected signals (the $Y$ signal was detected in the video detector circuit) are mixed in the top section of the matrix in proper proportions to produce a resultant which is equivalent to the *green* signal in the transmitter. In the center section, the proportions of the $I$, $Q$, and $Y$ signals are such as to produce the *blue* signal. In the lower section of the matrix, the *red* signal is developed. Three signals have now been separated that are relatively the same as the three color signals that were produced in the color camera tube at the transmitter. It is now necessary to use these three signals to key a scanning beam in such a manner that the proper color proportions will be laid down where they belong on the color picture-tube screen.

When the signal being received is in monochrome, there are no color bursts. This means that there are no color-burst signals being fed to the phase detector by the color-burst amplifier. As a result, the *color-killer* circuit receives no bias from the phase-detector circuit, and a positive flyback pulse from the horizontal yoke produces current flow in the color-killer tube. This current in turn is made to bias the bandpass filter amplifier past cutoff, and no signals are fed through it to the $I$ and $Q$ systems.

The scanning circuits of the color receiver are basically the same as for monochrome receivers. For example, the vertical-deflection system consists of a 59.95-cycle oscillator, an amplifier, and the deflection coils or yoke. If a three-electron-gun color tube is used, a vertical parabolic voltage is developed in the vertical output and used in the *convergence* system. Convergence is necessary to make the three separate electron beams converge to a point at the shadow mask in back of the picture screen, to be explained later.

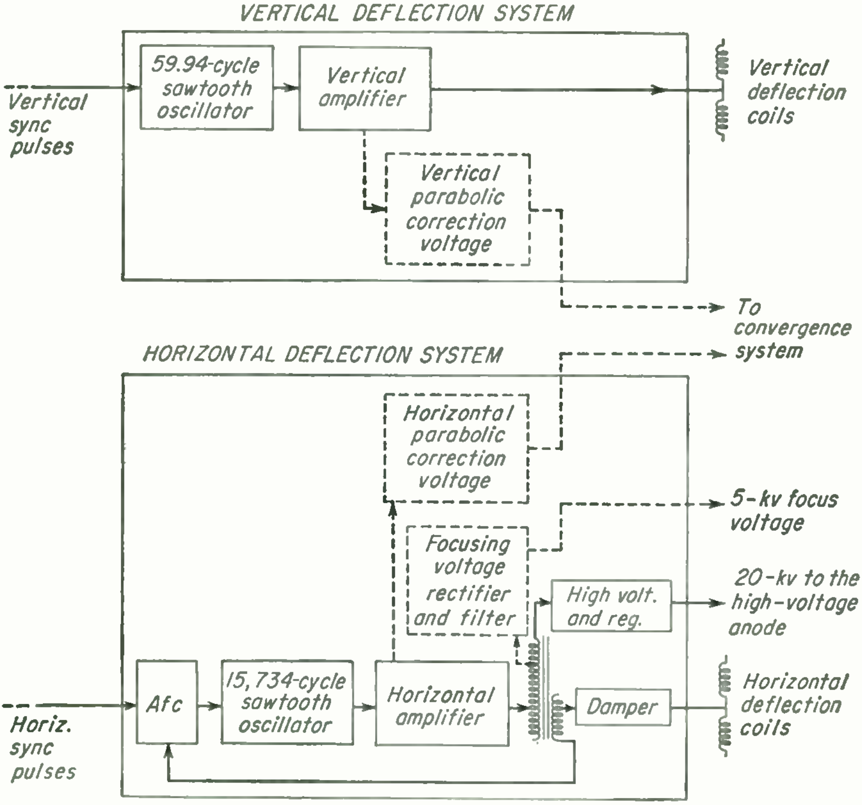


FIG. 25.36. Block diagrams of vertical- and horizontal-deflection systems for single-gun and three-gun (shown in broken lines) color tubes.

The horizontal-deflection system consists of an AFC circuit, a horizontal oscillator, amplifier, damper, flyback high-voltage rectifier circuit, plus a high-voltage regulator. When a three-gun tube is used, a horizontal parabolic convergence voltage is developed from the horizontal-amplifier stage, and a 5,000-volt *focusing* voltage is required. A block diagram of the vertical and horizontal systems is shown in Fig. 25.36. The circuits shown in broken lines are used in three-gun tubes.

**25.29 Color-picture Tubes.** With the three color signals and the deflection systems, the color picture can be displayed on a color tube. There are two basic types of tubes in use. The first type to be produced was the shadow-mask tricolor tube. A tube of this general type is illustrated in Fig. 25.37.

The three electron guns shown are actually placed equidistant and 120° from each other. Each projects an electron beam toward the screen end of the tube. The focusing electrode potential (+5,000 volts) on each electron gun focuses its own beam to a tiny spot on the screen. The convergence electrode voltage (+11,000 volts) forces the three beams to converge at the surface of the shadow mask to allow all three beams to squeeze through the same hole in the mask. The beams cross and deconverge after they pass through the hole in the shadow mask, each striking its own phosphor spot. Tubes with screens larger than 19 in. usually use magnetic convergence instead of electrostatic, although they are extremely sensitive to external magnetic fields.

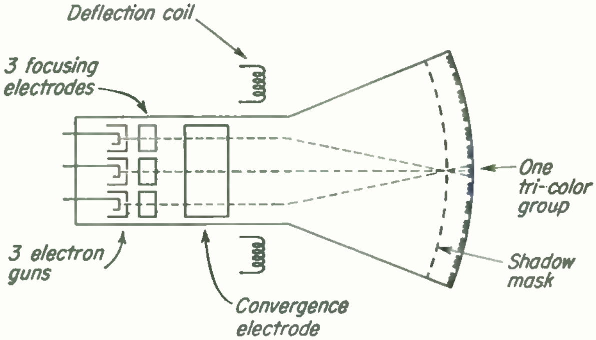


Fig. 25.37. Components of a three-gun color tube.

The metallic shadow mask has about 250,000 tiny holes in it. For each hole there is a green, a red, and a blue phosphor dot on the screen, or a total of 750,000 color dots. When three beams are all passing through one hole, the red-signal beam strikes a red phosphor, the blue-signal beam a blue phosphor, and the green-signal beam a green phosphor. If all are of equal intensity, the tricolor spot appears white to the viewer. When only the green-signal and the red-signal electron-gun grids are receiving color signals, only these two phosphors are illuminated and the viewer sees a yellow color. By scanning the picture in synchronism with the camera-tube scanning, the original scene can be reproduced in full color on the tricolor picture tube.

The other type of color tube uses only one electron gun and therefore requires no convergence system. This tube, known as a *chromatron*, instead of dots has thin horizontal red, green, and blue phosphor lines on the screen. A simplified illustration of such a tube is shown in Fig. 25.38. The electron gun, the focusing coil, and the deflection yoke are all similar to those in monochrome picture tubes. A gridwork of wires is mounted near and parallel to the phosphor lines on the screen, as indicated.

A set of grid wires is between each red line and the electron gun, and another set of grid wires is between each blue line and the electron gun. All the wires in front of the red lines are connected together. All wires in front of blue lines are connected together. When the two systems of grids have the same electric potential, the electron beam is attracted to neither and passes midway between them, striking the green phosphor. If the red grid is more positive, the beam is deflected toward the red phosphor. When the blue grid is more positive, the beam strikes the blue phosphor, as shown in the illustration. The simplified drawing indicates only about a dozen phosphor lines, whereas in practice there are 720 or more such lines.

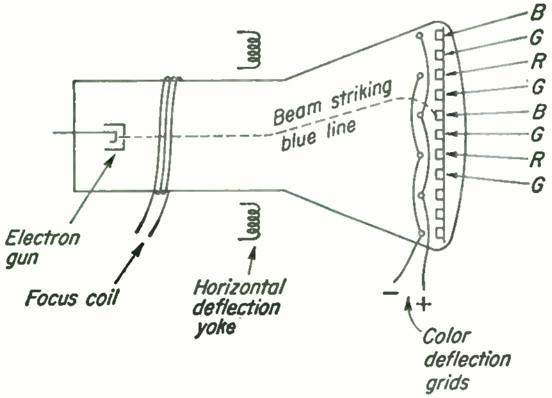


FIG. 25.38. Simplified single-gun color tube.

Back at the transmitter, the camera tube is producing *simultaneous* red, blue, and green color signals. A single gun, and therefore single beam tube, must use red, blue, and green signals in rapid succession to produce a small three-color spot. This is accomplished by modulating the electron-beam position with a high-frequency sine-wave a-c to deflect the beam up and down across the red, green, and blue phosphors as the beam travels along a horizontal line. The 3.68-Mc a-c generated in the receiver is amplified and used for this purpose. The red, green, and blue signals are *gated* on to the electron-gun grid at a rate equal to three times 3.68 Mc. In this way the electron-gun grid is receiving a green signal when the electron beam is moving past the green phosphor, a red signal when the electron beam is striking the red phosphor, and a blue signal as the beam is deflected to the blue line. When all three phosphors are illuminated with equal signals, the three spots produced on the three lines are so close that the eye sees a single white area. The color display and the definition of this type of tube are quite good.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

**1.** What safety precautions should a person observe to avoid personal injury when making internal adjustments to a television receiver? (25.24) **[3]**

**2.** Does the video transmitter at a television broadcast station employ frequency or amplitude modulation? (25.1) **[4]**

**3.** Does the sound transmitter at a television broadcast station employ frequency or amplitude modulation? (25.1) **[4]**

**4.** If standard broadcast emissions are classified as A3 emissions, what is the classification of TV broadcast video emissions? (25.1) **[4]**

**5.** What is the range of audio frequencies that the aural transmitter of a TV broadcast station is required to be capable of transmitting? (25.1) **[4]**

**6.** Besides the camera signal, what other signals and pulses are included in a complete TV broadcast signal? (25.1) **[4]**

**7.** What is meant by vestigial sideband transmission of a TV broadcast station? (25.1, 25.13) **[4]**

**8.** Draw a block diagram of a typical monochrome TV transmitter, indicating the function of each part. (25.1) **[4]**

**9.** Describe scanning as used by TV broadcast stations. Describe the manner in which the scanning beam moves across the picture in the receiver. (25.6) **[4]**

**10.** Why is a scanning technique known as *interlacing* used in TV broadcasting? (25.6) **[4]**

**11.** If the CRT in a TV receiver is replaced by a larger tube such that the size of the picture is changed from 8 by 6 to 16 by 12 in., what change if any is made in the number of scanning lines per frame? (25.6) **[4]**

**12.** In TV broadcasting, what is the meaning of the term *aspect ratio*? (25.6) **[4]**

**13.** Numerically, what is the aspect ratio of a picture as transmitted by a TV broadcasting station? (25.6) **[4]**

**14.** How many frames per second do TV broadcast stations transmit? (25.6) **[4]**

**15.** What is the field frequency of a TV broadcast transmitter? (25.6) **[4]**

**16.** What are blanking pulses in a TV broadcasting and receiving system? (25.7, 25.8, 25.21) **[4]**

**17.** What are synchronizing pulses in a TV broadcasting and receiving system? (25.7, 25.21) **[4]**

**18.** In TV broadcasting, why is the field frequency made equal to the frequency of the commercial power supply? (25.7) **[4]**

**19.** What is meant by 100 per cent modulation of the aural transmitter at a TV broadcasting station? (25.8) **[4]**

**20.** In a transmitted monochrome TV signal, what is the relationship between peak carrier level and the blanking level? (25.8) **[4]**

**21.** What is a monitor picture tube at a TV broadcast station? (25.9) **[4]**

**22.** What is a mosaic plate in a TV camera? (25.11) **[4]**

**23.** How wide is a TV broadcast channel? (25.13) **[4]**

**24.** If a TV broadcast station transmits the video signals in channel 6 (82–88 Mc), what is the center frequency of the aural transmitter? (25.13) **[4]**

**25.** What is the frequency tolerance for TV broadcast transmitters? (25.13) **[4]**

**26.** How is the operating power of the aural transmitter of a TV broadcast station determined? (25.13) **[4]**

**27.** Under what conditions should the indicating instruments of a TV visual transmitter be read in order to determine the operating power? (25.13) **[4]**

**28.** Within what limits is the operating power of a TV aural or visual transmitter required to be maintained? (25.13) **[4]**

**29.** What is meant by antenna field gain of a TV broadcast antenna? (25.13) **[4]**

**30.** What are the licensed-operator requirements for a TV broadcast station? (25.13) **[4]**

**31.** What are the radio-operator license requirements for the person on duty at an experimental TV broadcast station? (25.13) **[4]**

**32.** Describe the procedure and adjustments necessary to couple properly a typical VHF visual transmitter to its load circuits. (25.14) **[4]**

**33.** For what purpose is a voltage of saw-tooth waveform used in a TV broadcast receiver? (25.22, 25.23) **[4]**

**34.** Describe the composition of the chrominance subcarrier used in the authorized system of color TV. (25.27) **[4]**

**35.** Describe the scanning process employed in connection with color-TV broadcast transmissions. (25.27) **[4]**

# CHAPTER 26

# SHIPBOARD RADIO EQUIPMENT

**26.1 Radio aboard Ship.** Small vessels may not carry radio equipment, but ships carrying passengers, or those over certain tonnage ratings, may be required to have radio equipment aboard for the safety of life at sea. Determining which ships must carry radio equipment is rather complex and is set by international agreement. Usually, however, ships of more than 500 gross tons or those carrying more than 12 passengers on deep-sea voyages are compulsorily equipped.

This chapter outlines the types of equipment that may be found aboard larger ships, carrying one, two, or three radio operators. (Smaller vessels, commercial fishing boats, tugs, boats on inland waters, etc., may carry a low-powered radiotelephone transmitter and receiver for communication with other ships, nearby coast stations, or the Coast Guard. This equipment operates in the 2,000–3,000-kc band, is fixed-tuned, and requires no radio operator but only a radiotelephone permittee to operate it.)

Older ships may have 110 volts d-c, some newer ships may have both 110 volts d-c and 115 volts 60-cycle a-c, and some may have only 115 volts a-c generated aboard. As a result, shipboard radio equipment may be manufactured to operate on 110 volts d-c or 115 volts a-c, or in some cases from either 12- or 24-volt batteries. Direct-current equipment can be used on a-c ships by using an a-c motor driving a d-c generator.

Unlike land-type power systems, in which one line is at ground potential, neither of the d-c power lines aboard ship is connected to ground (the metal hull of the vessel). This requires that all motors have both brushes insulated from ground, and to bypass them with capacitors (condensers) it is necessary to use a separate capacitor from the positive and from the negative terminal to ground. If a voltmeter between ground and either line reads the full line voltage, it indicates that the other line has become grounded at some place on the ship.

As in other radio services which require the sharing of frequencies, the minimum transmitting power for satisfactory communication should be used at sea. For most distress communications the maximum power output may be desirable, except when conservation of batteries may be a factor.

**26.2 Compulsory Radiotelegraph Installations.** When a ship is required to be radio-equipped, the minimum radio requirements are usually (1) a main radio transmitter and associated main radio receiver, (2) a separate emergency transmitter and an associated separate emergency receiver, (3) an emergency power supply, separate from the ship's electrical supply, to operate the main equipment, (4) emergency lights that operate from the emergency power supply, (5) a main antenna and either an emergency antenna or a spare main antenna, including insulators, and (6) a reliable intercommunication system between the radio room and the navigation bridge.

**26.3 The Main Transmitter.** A *main* radiotelegraph transmitter aboard a compulsorily equipped ship must be capable of (1) a minimum of 160 watts of A1 radio-frequency power output to the main antenna, (2) a minimum of 200 watts of A2 RF output to the main antenna, (3) break-in operation.

The A2 emission required when transmitting an SOS on 500 kc must be at least 70 per cent, but not over 100 per cent, modulated. The frequency of the modulating tone must be between 450 and 1,250 cycles.

The transmitter must be capable of transmitting on at least three frequencies in the medium-frequency range. One is the international calling and distress frequency of 500 kc; another is the direction-finding frequency of 410 kc; and at least one other "working" frequency between these two. The frequency tolerance in per cent of either emission is 0.1. [0.1 per cent is 0.001. For 500 kc, 500(0.001) = 0.5 kc.]

The transmitter must have the following meters: (1) an antenna ammeter, (2) a final-amplifier plate voltmeter, (3) a final-amplifier plate milliammeter.

The transmitter must have some means of reducing the plate input power to 200 watts or less for tuning and short-range operation.

The antenna power is determined by the formula $P = I^2R$, where $P$ is the power in watts; $I$ is the antenna current in amperes; and $R$ is the resistive component of the impedance of the antenna at the point where the antenna current is measured.

A commercial marine radiotelegraph main transmitter (Mackay Radio type 2009-A) in simplified schematic form is shown in Fig. 26.1.

The oscillator stage is a type-6AU6 tube in a Pierce crystal circuit. The operating frequency is selected from one of eight crystals by adjusting a rotary switch (shown with only three positions in the simplified diagram). The output of the oscillator drives a type-6146 buffer amplifier stage. A pi-network circuit (Sec. 20.24) is used as the tuned coupling device between the buffer stage and the grid of the 813 power amplifier. The frequency of this coupling circuit is selected by a switch connected to taps on the coil. This switch is ganged with the oscillator crystal switch. The coupling circuit between the power amplifier and the antenna is also

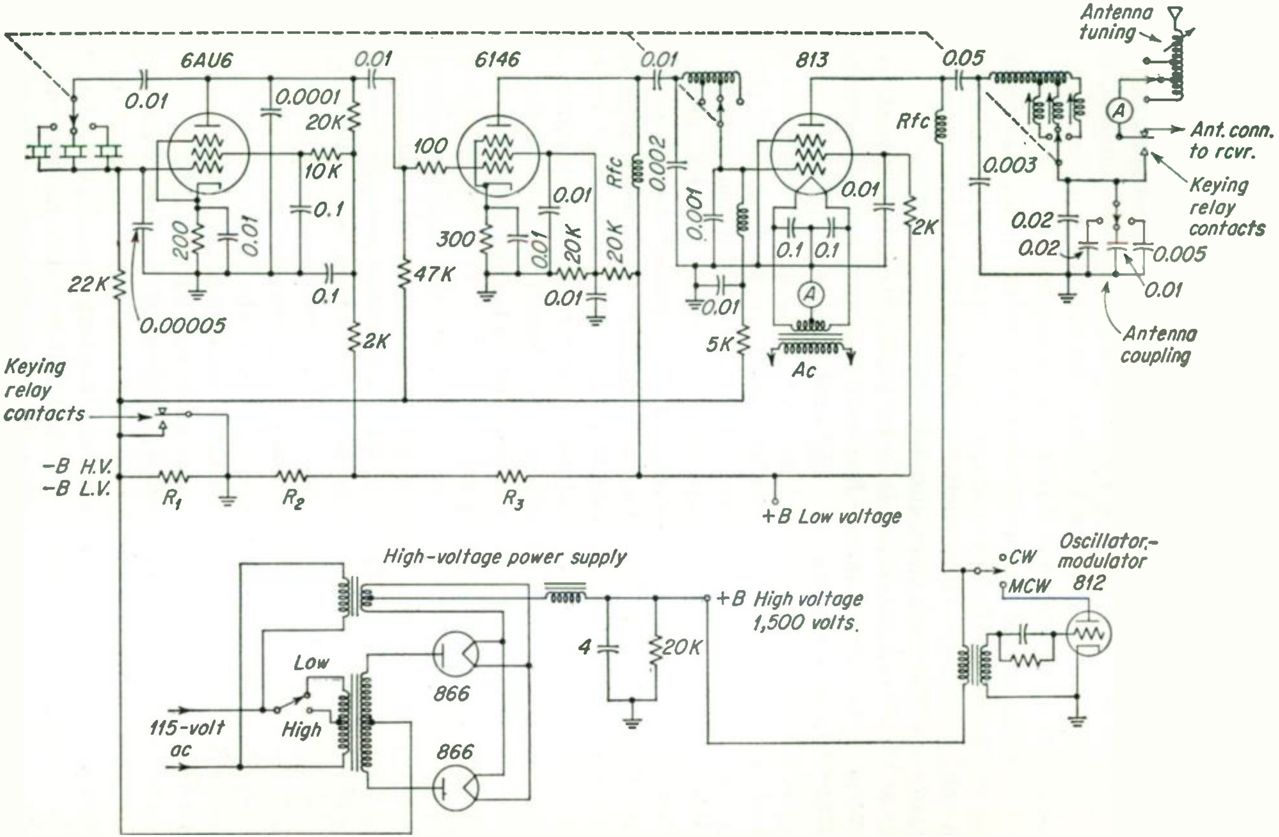


FIG. 26.1. Simplified schematic diagram of a Mackay Radio type 2009-A crystal-controlled 410–500-kc 200–250-watt radiotelegraph transmitter used on board ships.

a pi network and is also gang-switched to resonance with each frequency pretuned by slug-tuned inductances. The degree of antenna coupling is determined by the capacitance selected by the antenna coupling switch. (The greater the capacitance, the lower the degree of coupling.) Resonance of the antenna circuit is produced by adjusting an antenna variometer. Resonance is indicated by a peaking of the antenna ammeter reading. While a single 813 type is shown for simplicity of circuitry, the transmitter actually employs a pair of 813s in parallel.

Low- or high-power output is selected by using all the power-supply transformer primary for low-voltage output, or half of the primary for high-voltage output. (Using only half of the primary turns increases the voltage step-up ratio of the transformer.)

A2 or MCW emission is available by setting the A1–A2 switch to the MCW position, turning on the filaments of a pair of parallel-connected type-812 triodes operating as a high-power audio-frequency oscillator. (Only one tube is shown in the diagram.) This also connects the high-voltage output of the oscillator modulator to the plate circuit of the 813 power-amplifier stage, producing a tone-modulated output signal.

With the key up, the voltage-divider resistors $R_1$, $R_2$, and $R_3$, across the low-voltage power supply, develop a high enough negative voltage between ground and $-B$ to bias all stages to cutoff, preventing them from operating. When the key is pressed, the keying-relay contacts between ground and $-B$ are closed, shorting the biasing voltage and allowing the stages to function. A second set of contacts on the relay switches the antenna from the receiver position to the output of the transmitter, allowing break-in operation.

To change from one frequency to another, the operator selects the desired crystal with the eight-position ganged switch. This sets all stages to pretuned conditions for this frequency. The high-low power switch is turned to LOW for tune-up, the key is pressed, and the antenna variometer is adjusted to maximum antenna current. The transmitter is ready for operation. If more power is required, the power switch may be turned to HIGH. The antenna coupling may also be increased, although changing the coupling may necessitate repeaking of the antenna current.

**26.4 The Main Receiver.** The main receiver must be capable of tuning over the international calling and distress frequency of 500 kc and the adjacent working frequencies, and also of tuning to the marine calling frequency of 143 kc and its adjacent working frequencies. The two bands required are 405–515 kc and 100–200 kc. The receiver must be capable of detecting A1, A2, and type B (spark) emissions and be capable of detecting a signal with as low an input as 100 $\mu$v and make it clearly audible on earphones or loudspeaker.

Note that there is no great selectivity requirement for the main receiver. If this receiver is used to stand a watch on 500 kc, it is actually desirable that the receiver *not* be too selective, or signals not exactly on the frequency to which it is adjusted may pass unheard.

The circuit used for this type of receiver in the past has consisted of one or two tuned RF amplifiers, a regenerative detector, and two audio amplifiers (see TRF circuit, Sec. 17.9). Such a circuit is relatively simple and can be quickly and easily repaired. Superheterodynes may also be used. A combination intermediate- and high-frequency "superhet" is often used as the main receiver.

RF amplifier stages are required in marine receivers. This prevents radiation of a signal by a regenerative detector when in an oscillating condition, or radiation of the local oscillator of a superheterodyne. Radiation must be held to less than 400 $\mu\mu$w (micromicrowatts) on all frequencies below 30 Mc.

Commercially manufactured receivers for marine use may tune from 15 to 650 kc in two to four overlapping bands and may be operated from 110 volts d-c, 115 volts a-c, or from a 6- or 12-volt storage-battery filament supply and a 90-volt B battery for plate supply.

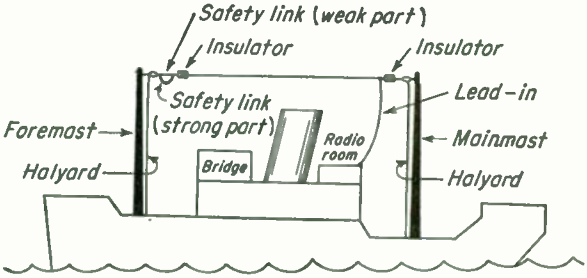


FIG. 26.2. Essentials of a shipboard main-antenna installation.

Sometimes, when approaching coastal cities in which high-powered broadcast stations are located, two strong local signals may mix in the first RF-amplifier grid circuit and a *beat*, or *difference*, frequency may be heard on 500 kc. Installation of a wavetrap in the antenna circuit of the receiver, tuned to the frequency of one of the interfering stations, will eliminate or greatly reduce such interference to the 500-kc watch. If the signal received is due to inability of the receiver-tuned circuits to discriminate against it, loosening the antenna coupling or reduction of the gain control of the RF amplifier stage may help.

**26.5 The Main Antenna.** The main antenna must be as efficient as practicable under the prevailing physical limitations on board ship. It usually consists of a single wire hung from the peak of the foremast to the peak of the mainmast, with a lead-in to the radio station (Fig. 26.2). On smaller vessels it is made as long and kept as high as possible.

A *safety link* must be incorporated in the antenna. It is a planned weak section in the halyard at one end of the antenna. A short weak wire and a longer heavy wire are fastened across one another and are inserted in the halyard as illustrated. If the ship is subjected to a sudden stress, because of collision, grounding, torpedoing, etc., the weak part of the link breaks as the masts are forced apart and the antenna takes up the slack in the longer, stronger part of the link. This causes the antenna to sag, but prevents its falling, and it remains usable. The sag can be corrected by tightening one of the halyards.

Unless care is taken in hoisting an antenna, the insulators may fracture should they strike any metal objects. The wire must not be allowed to kink, since it becomes weakened at such a point and may break under sudden strain.

When the main antenna is used on the 410–515-kc band it is operating as a base-loaded quarter-wavelength wire. The far end is the maximum voltage point, and the part leading into the transmitter is the high-current part. When used on high-frequency bands, the far end is always a high-voltage point, with other high-voltage points every half-wave along the wire and high-current points halfway between the voltage points. Ships using high frequencies may use short-wave dipole antennas for receiving and the main antenna for transmitting.

**26.6 The Emergency Equipment.** For safety of life at sea, compulsorily equipped ships must carry an emergency transmitter and receiver, have an emergency power source independent of the propelling power of the ship, and be fitted with an emergency antenna. Such emergency equipment must be capable of being put into operation within one minute after the need for it arises.

The emergency transmitter must be capable of operating on 500 kc, 410 kc, and one other working frequency between 415 and 490 kc. It must be capable of feeding at least 25 watts to the main antenna when energized from the emergency power supply. The type of emission is A2, using a modulating tone between 300 and 1,250 cycles, with a percentage of modulation 70 per cent or more but not over 100 per cent. The transmitter frequency tolerance in per cent is 0.1 if it is ever to be used for nonemergency operation and 0.3 if used only for emergency work. The transmitter must be equipped with an antenna ammeter and a means of indicating the filament voltage. Such transmitters are usually MOPA (Sec. 15.10) circuits.

The requirements for the emergency receiver are the same as for the main receiver except that it need tune only from 405 to 515 kc and must be powered by the emergency power supply or by batteries.

The emergency power supply shall be located as near to the emergency transmitter and receiver as is practicable and may only be used to energize the emergency transmitter, receiver, emergency lights in the radio room, the automatic-alarm-signal keying device, and the autoalarm receiver. Emergency power may be produced from batteries or from a motor-generator set, such as a gasoline engine rotating a d-c generator. It must be capable of operating the emergency equipment for a period of 6 hr.

The emergency equipment must be tested before leaving port and at least once a day while the vessel is outside a harbor or port, and entries to this effect made in the radio log. Emergency equipment may be used for communication if not for more than one hour a day. This may serve as the daily test. The emergency receiver may be used to stand a watch provided that this does not reduce the ability of the emergency power supply to energize the emergency installation. When wet batteries are used as part or all of the emergency power supply, daily hydrometer readings of a pilot cell must be taken, if the batteries are lead-acid types. Other types, such as Edison cells, require daily voltage readings to determine their state of charge. If a gasoline- or diesel-driven generator is used for emergency power, it must be tested, and the quantity of fuel and oil checked daily.

**26.7 Medium- versus High-frequency Communications.** During daylight hours the medium frequencies between 405 and 515 kc provide reliable communication for a 200-watt transmitter over a range of 300 to possibly 600 miles under normal conditions. During nighttime the range may extend out to more than 2,000 miles. However, these frequencies are subject to high-amplitude static, making long-range communication difficult at times. Ships on long voyages find that frequencies between 4 and 24 Mc provide more satisfactory operation over long distances. As a result, many ships engaged in international trade are fitted with high-frequency transmitters.

**26.8 High-frequency Calling and Working Frequencies.** Segments of the RF spectrum called *bands* of frequencies are allotted to the marine radiotelegraph service. Each band is divided into three separate sections. The lower frequencies are used as the working frequencies for passenger vessels, indicated as P1, P2, etc., in Fig. 26.3. The higher frequencies are used as working frequencies for freighters or cargo ships and are indicated as F1, F2, etc. The mid-frequencies are reserved for calling, C1, C2, etc. The calling frequency C5 is the only one used by aircraft, lifeboats, and other survival craft for communication with stations of the maritime mobile service. The C5 frequency of 8,364 is the only one used for lifeboats and survival craft that are compulsorily equipped with radio apparatus.

Note the harmonic relationship between the 2-, 4-, 6-, 8-, 12-, and 16-Mc bands (2,067.5 × 2 = 4,135, etc.). Also note that the 22-Mc band is not related harmonically. Because of the harmonic relationship, a passenger vessel with an assigned fundamental frequency P2 can operate on 4,137.5, 6,206.25, 8,275, 12,412.5, and 16,550 kc with only one 2,068.75-kc crystal in a transmitter having frequency-multiplier stages.

A passenger vessel will normally be assigned a calling frequency and two or more working frequencies (C2, P4, and P8, for example). If it has lifeboat or survival-craft radio equipment, it will also apply for C5 as a calling frequency. Freighters will be assigned one 2-Mc frequency and both of the frequencies shown together in the 4-, 6-, 8-, 12-, 16-, and 22-Mc bands.

The most popular marine bands are 8, 12, and 16 Mc, although the others may be used also.

A ship with a message for a high-frequency coastal station listens on the coastal station's frequency until it is determined that the station is not working anyone else. The ship station then calls the coast station on the ships assigned calling frequency. The coast-station operator is constantly tuning across all the calling frequencies in the band adjacent to its own calling frequency (8,356–8,372 kc, for example). When the coast station hears a ship calling, he stops tuning, waits to the end of the ship's call, and then answers the ship. The ship then advises its working frequency, shifts to that frequency, and calls the coast station again until contact is once more established. Then the message is sent.

Passenger ship working frequencies

| P1 | P2 | P15 |
|---|---|---|
| 2067.5 | 2068.75 | 2087.5 |
| 4135 | 4137.5 | 4175 |
| 6202.5 | 6206.25 | 6262.5 |
| 8270 | 8275 | 8350 |
| 12405 | 12412.5 | 12525 |
| 16540 | 16550 | 16700 |
| 22075 | 22085 | 22215 |

Calling frequencies

| C1 | C2 | C5 | C9 |
|---|---|---|---|
| 2089 | 2089.5 | 2091 | 2093 |
| 4178 | 4179 | 4182 | 4186 |
| 6267 | 6268.5 | 6273 | 6279 |
| 8356 | 8358 | 8364 | 8372 |
| 12534 | 12537 | 12546 | 12558 |
| 16712 | 16716 | 16728 | 16744 |
| 22225 | 22230 | 22245 | 22265 |

Freighter working frequencies

| F1 | F2 | F49 |
|---|---|---|
| 2094<br>(2106.25) | 2094.25<br>(2106.5) | 2106<br>(2118.25) |
| 4188<br>4212.5 | 4188.5<br>4213 | 4212<br>4236.5 |
| 6282<br>6318 | 6282.75<br>6319.5 | 6318<br>6354.75 |
| 8376<br>8425 | 8377<br>8426 | 8424<br>8473 |
| 12564<br>12637.5 | 12565.5<br>12639 | 12636<br>12709.5 |
| 16752<br>16850 | 16754<br>16852 | 16848<br>16946 |
| 22272.5<br>22335 | 22272.5<br>22335 | 22332.5<br>22395 |

*(Frequencies in parentheses are not assigned but are the fundamentals of the frequencies listed below them)*

FIG. 26.3. Chart of some of the high-frequency passenger-ship working and calling and freighter working frequencies available to merchant-marine ships.

When a coast station has a message for a ship, it places the call letters of the ship in the traffic list that it transmits either frequently or continually when it is not working any ships. A ship operator listening to the traffic list calls the coast station on the ship-calling frequency if he hears his call letters. Since the ship will only have to acknowledge receipt of the message, it may not be necessary for the ship to shift to a working frequency.

**26.9 High-frequency Transmitters.** High-frequency marine transmitters usually have a power output of 200 to 500 watts, although passenger vessels of more than 5,000 gross tons may operate with as much as 8,000 watts and other vessels with as much as 2,000 watts input. The type of radiotelegraph emission used on high-frequency bands is A1.

Since the frequency tolerance of marine radiotelegraph transmitters is 0.02, the transmitters are usually crystal-controlled, with a selection of 10 or 12 different fundamental frequencies. These transmitters may also have a self-excited master oscillator that can be used in place of crystals to allow the transmitter to operate on any crystal frequency should such crystals become faulty or if operation is required on any frequency not available by crystal. The crystal-oscillator tube may be switched to operate as a self-excited Colpitts oscillator, or a separate master-oscillator stage may be used.

Figure 26.4 is a simplified schematic diagram of the RCA (Radio Corp. of America) type ET-8052 300-watt high-frequency transmitter covering 4 to 24 Mc. The fundamental frequency is selected by the crystal switch in the oscillator grid circuit. The band of operation is selected by a second ganged switch that automatically chooses the correct inductance settings of the third buffer, the power-amplifier plate circuit, and the two antenna-coil tap connections. After selecting the fundamental frequency and the band desired, it is only necessary to adjust the antenna coupling value, then tune the third buffer, the power amplifier, and the antenna.

With the oscillator cathode connected to the center tap of the two series capacitors $C_1$ and $C_2$, the crystal between grid and ground forms a Colpitts-like crystal oscillator using the screen grid as the oscillator anode. This results in an electron-coupled output to the grid of the first-buffer stage. The output of the first buffer is broadly tuned to about 4 Mc and fed to the second buffer. The second-buffer output is broadly tuned to about 8 Mc, resulting in sufficient harmonic output from 4 to 12 Mc. This is fed to the third-buffer amplifier, which is used as a multiplier for operation on the 16- and 22-Mc bands. The output of the buffer doubler drives the 813 final-power-amplifier stage. The power-amplifier plate circuit is tuned with a pi-network circuit to match the impedance of the tube to the impedance of the antenna feed point. The setting of the *differential* variable capacitor between the antenna circuit and the power amplifier determines the degree of coupling. The greater the capacitance between its rotor and the upper stator plates, the greater the coupling. The ET-8052 actually uses two parallel 807 buffer-doubler tubes and two parallel 813 tubes, not included in this simplified diagram.

The RCA ET-8039 is a similar transmitter but uses three parallel 813 tubes, resulting in a 500-watt output transmitter. The power-amplifier plate circuit of the ET-8039 is different, being shunt-fed, parallel-tuned, and capacitively coupled to the antenna or to an antenna tuner composed

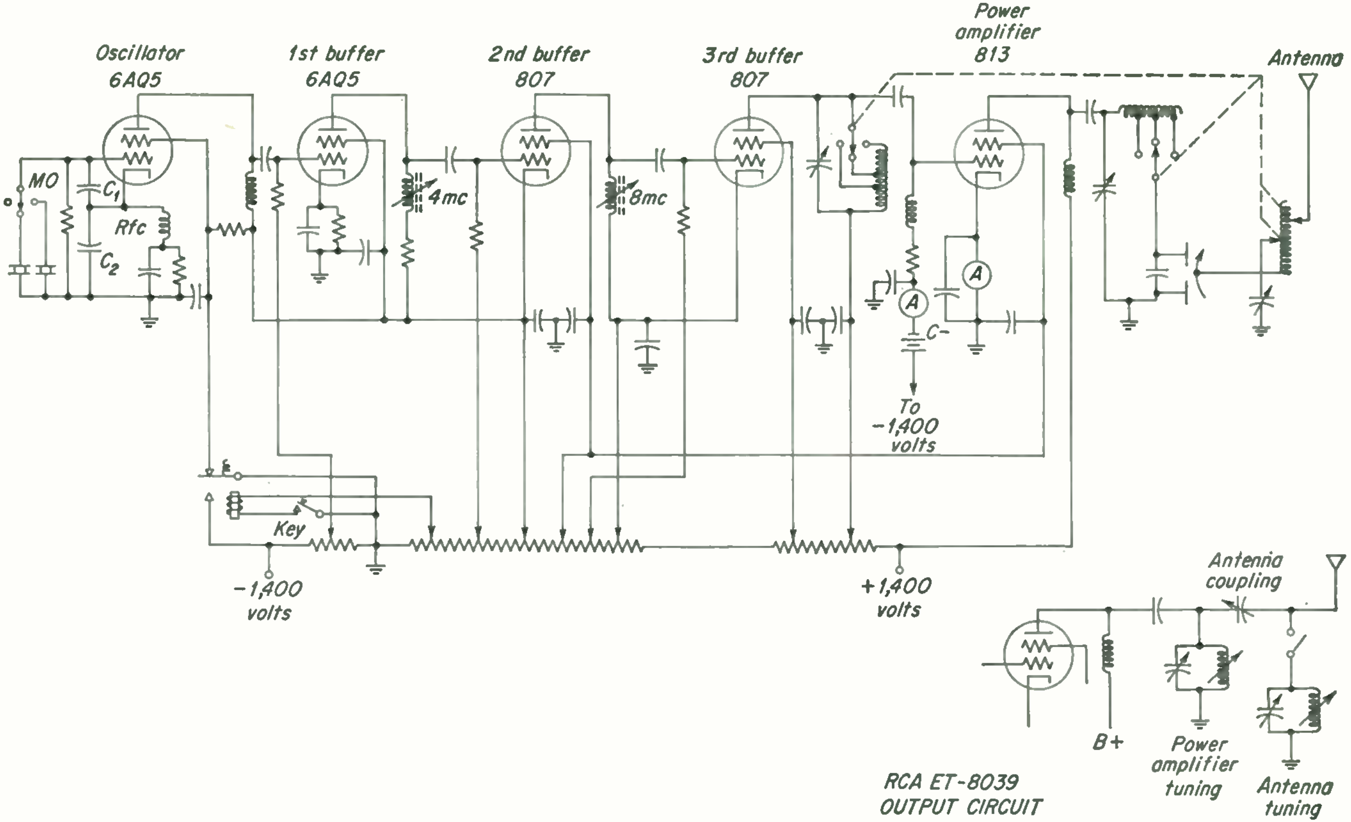


FIG. 26.4. Simplified schematic diagram of an RCA-type ET-8052 marine high-frequency ship transmitter. The insert illustrates an alternate antenna coupling circuit used in the ET-8039.

of a variable capacitor and a tapped variable inductance, as indicated in Fig. 26.4.

With the key up in either of these transmitters, the oscillator screen grid is grounded, preventing oscillation. All the buffers and the 813 are biased past cutoff, being across portions of the 1,400-volt voltage-divider resistor. When the key is pressed, the screen grid of the oscillator is ungrounded and the stage starts to oscillate. At the same time the left-hand portion of the voltage divider is grounded out, reducing the bias on the 813 and the first buffer, and the transmitter operates.

**26.10 High-frequency Receivers.** Most modern marine high-frequency receivers cover 2 to 24 or 30 Mc in 4 to 14 separate bands and also include 100–500-kc coverage to enable them to qualify as main receivers. They are always superheterodynes and may be of the double-conversion type with the first intermediate frequency in the 1–2-Mc region and the second conversion IF in the 50–70-kc region. Signals taken from the higher-frequency first-IF strip have a rather broad bandpass, 5 to 10 kc, while signals taken from the second IF strip may have a narrow bandpass, possibly 0.1 to 1.5 kc. This greater selectivity is required to allow proper separation of stations operating on closely adjacent frequencies on the high-frequency bands. Older marine receivers have a bandpass of 12 kc or more.

To allow break-in operation the high-frequency receiver is often operated with a doublet antenna, while the transmitter uses the main transmitting antenna. The keying relay in the transmitter may have separate contact points to either short out or open the receiving-antenna leads when the transmitter is keyed to prevent excessive RF from appearing in the receiver antenna coil. When the receiver is switched to a medium-frequency band, one lead of the doublet is disconnected from the receiver antenna coil, and the doublet acts as a single-wire antenna on these lower frequencies. The bottom of the antenna coil is connected to ground to complete the antenna circuit for the receiver.

A modern receiver may include such features as AVC, BFO, noise clipper, audio limiter, S meter, AF gain control, RF gain control (see chapter on AM Receivers), and a crystal calibrator. The crystal calibrator may be a 100-kc crystal oscillator which, when turned on, produces harmonics every 100 kc across the whole radio spectrum. Comparison of the dial markings with received calibrator signals can determine if the dial of the receiver is accurately calibrated.

**26.11 Lifeboat Radio Equipment.** One type of lifeboat radio equipment that may be required by law is the portable type, consisting of a radiotelegraph transmitter with an attached telegraph key, capable of emitting not less than 1.7 watts of A2-type emission on 500 kc and 4 watts of A2 on 8,364 kc to a self-contained antenna rod (or wire) and ground connector. It must operate manually on 500 and 8,364 kc and be capable of automatically transmitting the autoalarm signal followed by SOS three times on 500 kc, as well as three SOS signals followed by a long dash of 30 sec or more on 8,364 kc. The power supply is a manually operated electric generator, operated by crank handles rotated at 70 rpm or less.

To insure operation within the frequency tolerance of 0.5 per cent, such equipment is usually a master-oscillator-power-amplifier (MOPA) transmitter, modulated with either a chopper or some other type of single-tone modulation. The frequency of operation is selected by switch, but is not adjustable from outside the case.

The receiver is fixed-tuned on 500 kc and is broad enough to receive A2 signals on any frequency from 492 to 508 kc. The receiver must tune from 8,266 to 8,745 kc and be capable of receiving A1 and A2 signals. The equipment must be capable of floating in sea water and of withstanding a drop of at least 20 ft into the water.

*Nonportable* lifeboat equipment is permanently installed aboard a lifeboat in a housing large enough to hold the equipment and the operator. The transmitter must have not less than 30 watts output on 500 kc and 40 watts on 8,364 kc. It is powered by batteries (6- or 12-volt) of sufficient capacity to operate the equipment for at least 6 hr. It must be capable of manual operation on either frequency and have the same automatic transmissions as the portable types. The battery-charging line to the battery in the lifeboat must run through the main radio station to enable the operators on watch to keep the charging current under surveillance.

A lifeboat transmitter usually consists of a 500-kc crystal oscillator stage, an 8,364-kc oscillator stage, a power-amplifier stage, and an audio oscillator to produce the modulation for the A2 emission.

A simplified diagram of a possible 500–8,364-kc receiver is shown in Fig. 26.5. To receive 500 kc the switch is adjusted to the A position, connecting the 500-kc tuned circuit to the first grid of the first tube and grounding its cathode through a biasing resistor. This tube operates as an RF amplifier for 500 kc. The following stage is a second RF amplifier tuned to 500 kc which feeds the signal to a germanium diode detector and to a triode audio amplifier with shunt-fed earphones. A triode beat-frequency oscillator (BFO) is used when receiving A1 or A2 emission signals. The receiver for 500 kc operates as a tuned radio frequency (TRF).

To receive 8,266–8,745-kc signals the switch is set to the B position, connecting the antenna to a broad-bandwidth tuned circuit peaked at 8,500 kc. This feeds any signals between 8,266 and 8,745 kc to the third grid of the first tube. The first grid and cathode are now connected to the tunable local oscillator circuit. The local oscillator signal and the input signals mix in the first tube, and the 500-kc difference appears in the tuned transformer between the first and second tube. The second tube operates as a 500-kc IF amplifier, feeding signals to the detector as

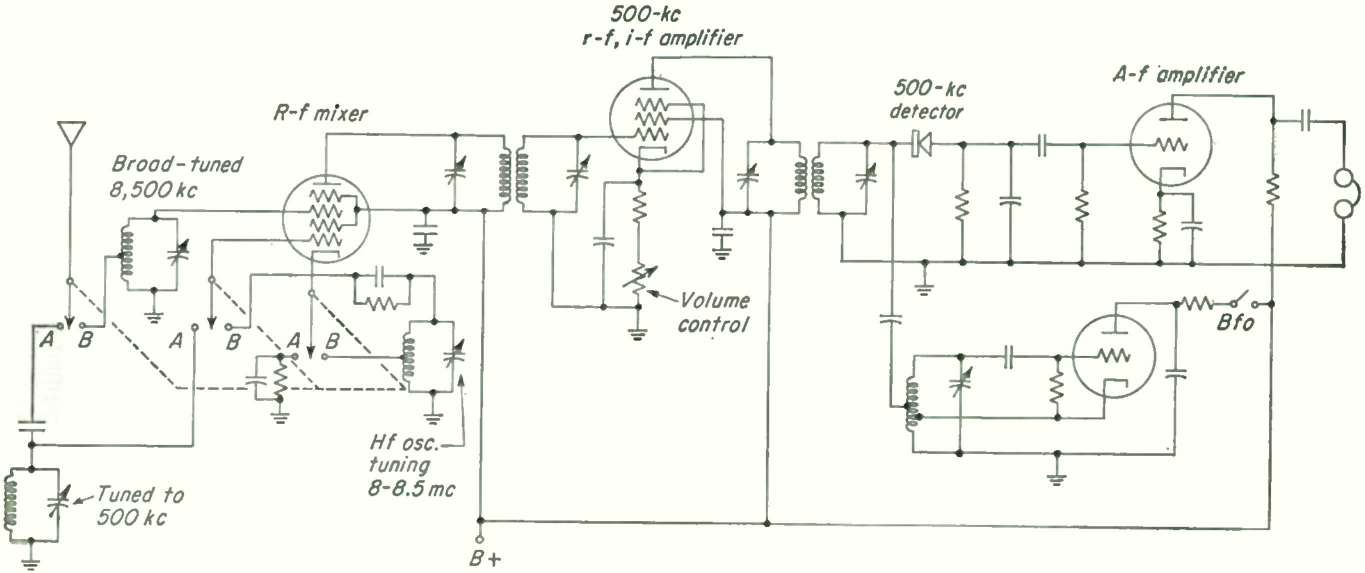


FIG. 26.5. Schematic diagram of a lifeboat receiver to receive either 500-kc or 8,000–8,500-kc signals. The circuit operates as a TRF on 500 kc and as a superheterodyne on 8,000–8,500 kc.

before. The receiver operates as a superheterodyne for 8,266–8,745-kc signals.

Both transmitter and receiver, as well as the dynamotor or vibrator power supply, are fused to prevent a short circuit in one of these pieces of equipment from drawing excessive power from the battery and decreasing its operating life. Abnormally low voltage at the input-power terminals of the transmitter while it is in operation might be due to a low battery, a faulty dynamotor, a partial short circuit in the transmitter, by not having the final-amplifier stage tuned to resonance, or a high-resistance connection in the line between the power supply and the transmitter.

**26.12 Radiotelephone.** Coastal radiotelephone equipment usually operates in the 2,000–3,500-kc range with power outputs ranging from about 20 to possibly 100 watts. Equipment for this service is produced by many manufacturers.

Inland waterway communications operate in the 2,000–9,000-kc range and may operate satisfactorily with power outputs of 50 to 150 watts.

Ships on the high seas may have radiotelephone equipment operating in the range of 2,000–22,000 kc, with power outputs of 85 to 1,000 watts. An example of an 85-watt station is the RCA ET-8050-HF, with a crystal oscillator, an 807 buffer stage, and four 807s in parallel as the power amplifier. The microphone is a telephone hand set fed to a preamplifier stage coupled to an audio clipper and filter, a phase inverter, a driver stage, and four 807s in push-pull-parallel as the modulators. The accompanying receiver is a superheterodyne featuring an RF amplifier, noise limiter, and squelch circuits (see chapter on AM Receivers).

A high-frequency radiotelegraph transmitter can be converted for radiotelephone operation by the addition of a special modulator system. The modulator usually consists of the microphone, speech amplifiers, and an AF power output sufficient to modulate the power amplifier to at least 70 per cent. It may also include a circuit known as a *vodas*. Vodas operation with radiotelephone is equivalent to break-in operation with radiotelegraph. When the microphone is spoken into, some of the audio power is rectified and made to operate a sensitive relay that switches the transmitter on and the receiver off. As soon as the person ceases talking, the audio power drops to zero and the relay falls out, turning the transmitter off and the receiver on. This allows a more or less normal back-and-forth type of conversation, in comparison with the more usual radiotelephone *press-to-talk* type of operation, where the speaker holds down a button as long as he wishes to transmit and releases when he wishes to receive.

**26.13 Autoalarms.** During times when no radio operator is standing watch on a compulsorily equipped ship at sea, a device known as an autoalarm must be in operation.

By international agreement, prior to sending an SOS on 500 kc, all ships will transmit (if time allows) an autoalarm signal, consisting of alternate 4-sec dashes and 1-sec spaces for a period of 1 min (12 dashes and 11 spaces). Whenever possible, the autoalarm signal will be followed by a 2-min silence before the SOS message is transmitted.

An autoalarm receiver is designed to register the dash-space autoalarm transmissions, rejecting them if they are not timed correctly but accepting them if they are reasonably close to the required lengths. After registering *four* successive, properly made dashes and spaces, the autoalarm rings a bell in the radio station, on the navigation bridge, and in the radio operator's living quarters. (Note that the autoalarm does not stand watch for an SOS but for the autoalarm signal that should precede the SOS message.)

Autoalarms offered for type approval after January, 1951, must conform to the following specifications: To allow for imperfectly made manually transmitted dashes between 3.5 and 4.5 sec in length and spaces between 0.5 and 1.5 sec, the autoalarm should be capable of operating when dashes of 3.5 to 6 sec in length and spaces between 0.01 and 1.5 sec in length are received. These tolerances tend to prevent static or interference bursts of short duration from interfering with the reception of a properly made alarm signal. The autoalarm must respond to A2- or B-type emissions, provided the tone modulation has a frequency between 300 and 1,350 cps. The receiver must not overload on strong signals and must automatically and rapidly adjust to a condition in which it can most readily distinguish an alarm signal. The receiver is fixed-tuned to 500 kc and must have a 16-kc bandwidth (492–508 kc). On the reception of a properly made autoalarm signal, the burnout of the filament of any of the tubes, or failure of the power supply, it will sound an alarm by bell in the three required locations. A device that will generate a weak local signal on a frequency of 500 kc for testing purposes must be included in the equipment. Once set into operation, the audible alarm must continue to function until switched off by a control located in the radio station. Autoalarm equipment must be capable of withstanding vibration and damp atmospheric conditions at sea.

Autoalarms approved before 1951 have somewhat similar, but less stringent, requirements and may continue to be used aboard ships.

When the main antenna switch is moved to the AA (autoalarm) position, the equipment is turned on. Activating a push button on the front panel transmits a local test signal. A second push button, when held down, disconnects the bell circuits on the bridge and in the radio operator's cabin and is only used when testing the autoalarm. An earphone jack allows audible monitoring of received signals. One or more meters capable of being switched to different circuits are used to check the tubes, receiver sensitivity, and power-supply voltages. The Mackay 5002-A uses neon globes as operational indicators and contains a separate tube tester. Both receiver and selector (timing circuits) operate from the line voltage of the ship, but the bells are energized by the 12-volt emergency or other battery, allowing them to sound a warning if the ship's power fails. The filaments of the tubes are connected in series. A relay coil in series with the filaments falls out if one of the filaments open-circuits, and the alarm bells ring continuously until the trouble is corrected or until the antenna switch is thrown to some position other than AA, thereby disconnecting the autoalarm.

Prior to signing off watch, a radio operator turns on the autoalarm, tests it to see that it is operating properly, and enters this fact in the radio log. While the ship is at sea, at least one test of the autoalarm is required each day.

**26.14 RCA Autoalarms.** RCA autoalarm receivers constructed prior to 1951, such as the type AR-8602, consist of a superheterodyne circuit having an RF amplifier and converter tuned to 500 kc, a 600-kc Pierce crystal circuit as the local oscillator, and an 1,100-kc IF strip with a bandpass of 16 kc. A manual RF-amplifier gain control, called a *sensitivity* control, permits the operator to adjust the receiver to operate properly with the noise level that prevails at the time. A long-time-constant automatic-volume-control (AVC) circuit feeds a negative voltage to the RF-amplifier grid circuit, which helps to lower the sensitivity of the receiver during periods of strong signals or static.

The second detector is a more or less normal linear diode detector, developing a negative voltage across its load resistor when either a modulated or unmodulated signal is received. This negative voltage is fed directly to the grid of an unbiased *signal-relay tube.* With no signal this tube has no bias and a relatively heavy plate current flows through the relay coil in its plate circuit. When the negative voltage due to the rectification of a received signal is applied to the grid of the signal-relay tube, the plate current decreases sharply and the relay arm falls. This applies, through a long-time-constant resistance-capacitance network, a positive voltage to the grid of the *selector tube.* Because the timing and selecting are accomplished electronically, this unit is known as an electronic-selector-type autoalarm.

After 3.5 sec the capacitor charges to a potential sufficiently positive to produce enough plate-current flow in the selector tube to advance a *stepping relay* to its first position. By the use of three other relays and two other selector tubes, the proper timing of the dash lengths and space lengths is accomplished. At the end of the fourth correctly made dash the *bell-ringing relay* is energized and the alarm sounds.

As the stepping relay advances to the first step, it energizes a red warning light in the radio room and on the bridge. The presence of a high noise level acts as a constant signal and may also actuate the warning light. If such a condition persists for a period of about 5 min or more, the officer on the bridge notifies the operator, who then lowers the sensitivity setting to allow the equipment to operate properly, and logs the fact.

When the bell sounds a warning, the operator immediately goes to the radio room and pushes the "reset" button on the panel of the autoalarm. If the bells stop, the indication is that either a true alarm signal has been received, or by chance, static and/or received signals have combined to produce a false alarm. After listening for a reasonable period on 500 kc and not hearing any SOS, the operator logs the fact that a false alarm was received and returns the equipment to operation.

If the warning bell does not cease when the reset button is pressed, the indication is that either a filament of a tube is burned out or the power-supply voltage is too low or too high. The meters are used to determine the source of the trouble.

Intermittent ringing of the alarm bell indicates that the line voltage is varying past acceptable limits periodically, and the engine room officer should be notified.

The new type ET-8603 uses a TRF receiver, limits the detected signal, and then feeds it to a signal-relay tube. The signal relay actuates RC timing circuits, making these circuits completely independent of any variations in signal amplitude. It also produces an automatic gain control (AGC) voltage that is dependent upon the duration of the received signals, rather than on their amplitude as in the normal AVC circuit. This AGC voltage increases during times of high noise level, making manual gain-control adjustments unnecessary.

**26.15 Mackay Autoalarms.** Prior to 1951 the Mackay Radio Company manufactured a mechanical-selector-type autoalarm, of which the 5001-A is the latest model. It employs a fixed-tuned TRF receiver and a grid-leak, or *square-law*, detector. Audio amplifiers following the detector require modulated signals; therefore this type of autoalarm does not respond to type-A1 emissions. However, inasmuch as all autoalarm signals and distress calls are required to be transmitted with types A2 or B emission, this is not a disadvantage. A potentiometer in the screen-grid circuit of an RF amplifier controls the gain or sensitivity of the receiver.

The audio output from the detector is fed to audio amplifiers and then to the grid of a zero-biased high-$\mu$ triode. Because of the high $\mu$, even without bias the tube allows almost no plate current to flow through it. When an audio a-c signal drives the grid more positive during half of the input cycle, the average plate current of the tube increases materially and activates a relay in series with the plate circuit.

A d-c motor with a centrifugal governor to produce constant speed is geared down to rotate a shaft at a speed of 6 rpm. On this shaft are two electromagnetic drums which, when energized, attract nearby cams and clutch them against the drums. This causes the cams to begin to rotate slowly with the drums. When de-energized, the cams disengage and spring back to their nonoperating positions.

A received dash activates the relay in the plate circuit of the high-$\mu$ triode, in turn engaging two cams, one on each side of the first drum. After 3.5 sec the first cam rotates to a position where it strikes a contactor and activates a system of relays that act as a counter. If the dash is less than 3.5 sec long, the cam drops away from the drum and returns to a starting condition. If the dash is longer than 4.5 sec in length (the older timing requirement for length of dashes in autoalarms), the second cam is rotated far enough to make a contact to return the equipment to the starting condition again. If the dash is of proper length, the first step of the counter is energized. The spaces are timed through the action of the second drum, a third cam, and relays. When the fourth proper-length dash ends, the bell-ringing relay is activated and the alarm is sounded.

As with other autoalarms, pressing the reset button will stop the bells for either a true or a false alarm. If the bells do not stop, either a filament is burned out, a fuse is blown, the line voltage has dropped, or the motor is running too slowly. Warning lights in the radio room and on the bridge indicate the beginning of the reception of an alarm signal or interference locking up the receiver, requiring a readjustment of the sensitivity control. Earlier models automatically shifted the receiver to a battery supply if the line voltage failed and the warning light was activated.

The newest Mackay autoalarm is the type 5002-A, a radical change from earlier types. It uses printed circuits and electronic computer and counting techniques to time the dashes and spaces and to count the number of properly made alarm signal dashes. Basically, it consists of two parts, a TRF receiver and a selector, both housed in the same cabinet.

A received dash gates into operation a constant-amplitude 1,000-cycle tone. The tone starts a 2.3-cycle square-wave oscillator into operation. A flip-flop counter system counts the number of cycles of this oscillator, thus timing the length of the received dash. The same square wave is used to produce an AGC voltage that rides along with the duration of received signals, rather than being affected by their amplitude, making a manual gain control unnecessary.

At the conclusion of any correct-duration dash, a 15-cycle square wave is set into operation, and the number of cycles before the next dash is counted. If there are too many 15-cycle pulses, an erase impulse resets all timing circuits to a starting condition.

**26.16 Autoalarm-signal Keyer.** While the autoalarm signal may be transmitted manually by an operator watching the sweep second hand of a clock, a more accurate alarm can be transmitted by automatic means. Such a device is the RCA Alarm Signal Keyer, AR-8651, shown schematically in Fig. 26.6.

The keyer is operated from the emergency battery. When the switch is turned on, a reed-type 60-cycle vibrator is set into vibration. When the reed is in the "up" position, current flows downward through the motor; when it is in the "down" position, current flows upward through the motor. Thus, the motor is fed an alternating current. The 20-$\mu$f power-factor-correcting capacitor aids in producing a better a-c waveform.

The synchronous-type motor rotates at 3,600 rpm, which is reduced through a series of gears to a speed of 12 rpm (5 seconds per revolution) to rotate a circular cam. One-fifth of the outer rim of the cam is raised, as indicated. When the raised portion strikes the microswitch (light-pressure switch), the keying-relay circuit is opened and the relay contacts open. Thus for 4 sec the keying-relay circuit remains closed, followed by a 1-sec open period. One of the two sets of contacts on the keying relay is permanently connected across the key leads of the main transmitter, the other across the key leads of the emergency transmitter.

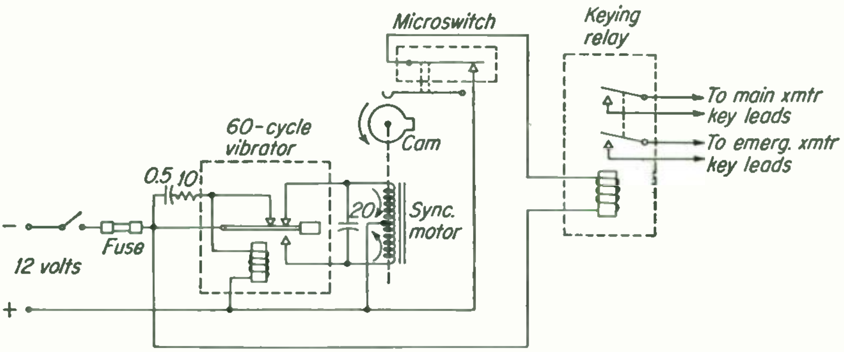


FIG. 26.6. An autoalarm-signal keyer, RCA-type AR-8651, used to transmit automatically an autoalarm signal.

Any battery voltage between 10 and 14.5 volts will produce satisfactory operation of the device. The 0.5-$\mu$f and 10-ohm resistor across the vibrator contacts decreases contact sparking.

Other signal keyers are used that employ 12-volt d-c motors and require no vibrator. They utilize a somewhat similar cam-keying device.

**26.17 The Main-antenna Switch.** Besides the main antenna, a ship may have an auxiliary antenna. Either of these antennas may be connected to the main-antenna switch, which will have several different positions, as follows:

*Ground.* The main antenna is switched to ground when the radio watch is secured or when the ship is in an electrical storm.

*Main Transmitter.* When moved to this position the main antenna is connected to the main receiver and to the main transmitter through a break-in relay.

*Emergency Transmitter.* The main antenna is connected to the emergency receiver and to the emergency transmitter through a break-in relay.

*AA.* The main antenna is connected to the autoalarm receiver, and the transmitters are disabled by interconnecting circuits.

*DF.* The main antenna is open-circuited or an auxiliary antenna is connected to the main receiver, depending on the antenna conditions when the radio direction finder was calibrated, and the transmitters are disabled.

*AA-DF* (May be labeled AA only.) Main or auxiliary antenna is connected to the autoalarm, as when the radio direction finder was calibrated.

*HF Transmitter.* Main antenna is connected to the high-frequency transmitter. (May be connected to the high-frequency receiver and to the high-frequency transmitter through a break-in relay if a high-frequency doublet antenna is not used on the high-frequency receiver.) The auxiliary antenna may be connected to the main receiver when the main antenna is used on the high-frequency transmitter.

**26.18 Shipboard Radio Operators.** Freighters and tankers usually employ one radio operator who stands 8-hr watch daily, using the autoalarm for the other 16 hr. The operator is a ship's officer and eats with the other ship's officers. A Radiotelegraph First Class license or a Second Class license with an endorsement of 6 months' satisfactory service is required. The minimum age is twenty-one years.

Passenger vessels usually employ three watch-standing operators. The chief operator usually has passenger privileges. On larger ships there may be a chief and three watch-standing operators. When radar is used aboard the ship, one or more of the operators must have radar endorsements (FCC Element 8) on their licenses to allow them to service the equipment.

The minimum age for any radiotelegraph operator license is eighteen years. The minimum age for a Radiotelegraph First Class license is twenty-one. One year of experience aboard ship is required of any applicant for a Radiotelegraph First Class license. The Radiotelegraph First and Second Class licenses authorize the holder to operate any radiotelephone equipment aboard the vessel.

**26.19 Standing Watch.** The radio operator is carried aboard ship to enable the ship to signal its plight in case of emergency, to receive distress messages from other ships, to transmit weather reports, to handle messages pertaining to shipping business, and to send and receive routine messages for passengers or crew members.

The main duty of the operator is to keep an efficient watch by earphones or loudspeaker on the international calling and distress frequency, 500 kc. He must log any signals heard on this frequency during the two 3-min silence periods from 15 to 18 min and from 45 to 48 min after each hour, and also log at least one other call heard on this frequency every 15 min.

If no signals are heard, he makes a log entry to this effect. All log entries are in 24-hr Greenwich Mean Time (GMT).

The radio-room clock is an 8-day wind-up type, marked with 12 hours and with additional markings up to 24 hours (Fig. 26.7). It has a sweep second hand to allow reading time accurately and to aid the operator if he must transmit an autoalarm signal by hand. It has the two 3-min silence periods marked off in red, and around the minute or second scale it has twelve 4-sec red arcs separated by 1-sec spaces representing the autoalarm signal. On compulsorily equipped vessels this clock is compared daily with a standard time transmission from such stations as WWV, Bureau of Standards station, Washington, D.C., which transmits constant time signals on 2.5, 5, 10, 15, 20, and 25 Mc, similar transmissions from WWVH in Honolulu, or *time ticks* from NSS in Washington, D.C., or NPG in San Francisco.

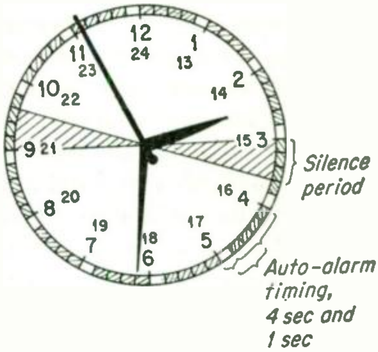


FIG. 26.7. Shipboard radio-room clock marked in 24 hr, showing the two 3-min silence periods of each hour and the correct timing for an autoalarm signal. The time shown would be either 0.230:56, or 1430:56 GMT.

The operator must abide by all Federal as well as international telecommunication laws, rules, and regulations, as applicable. If he observes a ship station flagrantly violating international radio regulations, he may make a report of it on a form supplied by the radio company servicing his ship and submit the report to the FCC, Washington, D.C.

On single-operator ships the operator stands an aggregate of 8 hr daily, possibly 2 hr on and 2 hr off, using the autoalarm for the off hours. Ship stations whose service is not continuous should not close before finishing all operations resulting from a distress call, or urgency or safety signal, or exchanging, as far as possible, all traffic for the ship to or from any coastal station within its range.

A ship station which has no fixed working hours normally advises the nearest coastal station with which it is in communication the hours of its closing and reopening, unless the ship is in foreign waters, in which such transmissions are prohibited.

New York City and San Francisco are the principal Atlantic and Pacific Coast ports or shipping terminals as well as the major centers of telecommunication for communication with Europe or the far Pacific, although the greatest traffic is handled out of New York, both shipping and by radio. The greatest number of telecommunication channels are between New York and Europe.

**26.20 Positions and Time.** A shipboard radio operator is expected to know a reasonable amount of world geography, approximate locations of the continents and well-known ports, and the meaning of latitude, longitude, international date line, and GMT.

The earth being a nearly round sphere rather than having a flat, plane surface presents some difficulties to a navigator who must sail his vessel from one point on the sphere to another. To help him, the earth is divided into the Northern Hemisphere, with the North Pole at the "top," and a Southern Hemisphere with the South Pole at the "bottom." An imaginary line running from the North to the South Pole is known as a *line of longitude*, or a *meridian*. The sphere is divided into 360°, with a starting point of zero degrees being the imaginary longitudinal line running through Greenwich (pronounced grin-itch), a borough of London, England. Progressing *westward* from 0°, the meridians are termed *west*. New York is located on a meridian about 75° west of Greenwich, the Panama Canal about 80°W, Los Angeles 120°W, and Honolulu about 157°W. Moving to the eastward of the 0° meridian, Cairo is 30° east, Bombay 73°E, Shanghai and Manila 120°E, and Tokyo about 142°E. At the 180th, the east and west meridians meet in the *international date line*. Here, halfway around the world from Greenwich, the day begins. When it is noon tomorrow in Greenwich, it is midnight on the date line, and today is considered to be starting. (The date line runs through no populated areas, being mostly over the ocean.) When a ship passes over this line from west to east, it skips a day, possibly going from 6 P.M. Wednesday to 6 P.M. Thursday. When traveling in the opposite direction, it will have two identical days—perhaps two Fridays.

Since there are 360° of longitude and there are 24 hr in a complete rotation of the earth, one twenty-fourth of the total rotation, or 15°, represents how far the sun travels in one hour. Therefore, each 15° of longitude represents one hour that the traveler must turn his clock back if going westward, or forward if progressing eastward. A ship keeps its clocks on *local*, or sun, time. The local time of a ship traveling east or west may change a few minutes per day near the equator to more than half an hour in the high-latitude regions where the lines of longitude are closer together.

Since Shanghai is 120°, or 8 hr east of Greenwich, when it is 1700 GMT (12 hours plus 5 hours, or 5 P.M.) Monday in London, it is 17 hours plus 8 hours, which would be 25 o'clock, or 1 A.M., in Shanghai on the next day, Tuesday. Since New York is 75°W, or 5 hr behind GMT, when it is 1 A.M. Tuesday in Shanghai, it is 12 noon Monday in New York (and 9 A.M. in San Francisco).

All radio-room clocks are kept on GMT. One-operator ships usually have the operator standing watch according to GMT for the area of the world in which the ship is traveling. Three-operator ships usually have the operators standing watch by local time to prevent confusion at meal times, but the log is still kept in GMT.

The *equator* is an imaginary line girdling the world in the middle. From the equator to either pole is one-fourth of a circle, or 90°. Imaginary lines parallel to the equator are known as lines of *latitude*, or *parallels*. Since lines of latitude do not converge, the distance between 5° of latitude anywhere in the world may be considered the same. A degree is often considered to be composed of 60 equal parts called *minutes*. A minute of latitude is equal to one *nautical mile*, approximately 1⅛ land miles. Latitude lines above or below the equator are said to be so many degrees north or south. The position of a point on the earth, Colon, Panama, for example, can be indicated accurately by its longitude and latitude. Thus, "Colon is at 80°W and 9°N" specifies only one place in the world where it can be found. The island of Guam, located in the Pacific Ocean, is at approximately 14°N and 146°E; Sydney, Australia, is at 33°S and 151°E; and so on.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

**1.** What is indicated if a voltmeter connected between the negative side of a ship's d-c line and ground reads the full-line voltage? (26.1) **[6]**

**2.** In all cases other than those in which the transmitter output must be maintained at a fixed value, what amount of power should be employed for routine communication? (26.1) **[6]**

**3.** Between what points on a ship, compulsorily equipped with a radiotelegraph installation, is a reliable intercommunication system required? (26.2) **[6]**

**4.** With what type(s) of emission and upon what frequency should a radiotelegraph transmitter be adjusted to transmit a distress call? (26.3) **[6]**

**5.** How is the power output of a marine vacuum-tube radiotelegraph transmitter ordinarily adjusted? (26.3, 26.9) **[6]**

**6.** Upon what band, in addition to the 350–515-kc band, must a main receiver on a U.S. ship be capable of operation? What is the purpose of this additional band? (26.4) **[6]**

**7.** If broadcast signals interfered with your reception of signals on 500 kc while aboard ship, how would you reduce or eliminate such interference? (26.4) **[6]**

**8.** What care should be taken in hoisting the antenna of a shipboard radiotelegraph station to avoid damage to the antenna wire and insulators? (26.5) **[6]**

**9.** Draw a sketch of a typical shipboard antenna for transmitting on 500 kc, showing the supporting insulators, the safety link, and the lead-in wire. How does voltage vary along the length of the lead-in and along the antenna? (26.5) **[6]**

**10.** For how long a period of continuous operation should the emergency power supply of a compulsorily equipped ship station be capable of energizing the emergency radiotelegraph installation? (26.6) **[6]**

**11.** While a vessel is in port, how frequently should the emergency equipment be tested? (26.6) **[6]**

**12.** How frequently must the quantity of fuel in the supply tank for use with an oil- or gas-driven emergency generator be checked while the vessel is in the open sea? (26.6) **[6]**

**13.** While the vessel is in the open sea, how frequently must the specific gravity of the emergency battery be taken? (26.6) **[6**

**14.** While the vessel is in the open sea, how frequently must the emergency equipment be tested? (26.6) **[6]**

**15.** What could cause abnormally low voltage at the input power terminals of a lifeboat radiotelegraph transmitter while it is in operation? (26.11) **[6]**

**16.** During the time that a vessel is at sea, how frequently must the autoalarm be tested? (26.13) **[6]**

**17.** What signal will cause an approved autoalarm receiver to ring the warning bell? (26.13) **[6]**

**18.** If a vacuum-tube heater burns out in an approved autoalarm, what causes the warning bells to ring? (26.13) **[6]**

**19.** Describe the number of dashes, or dots, and spaces which compose the international autoalarm signal and indicate the time intervals involved. (26.13) **[6]**

**20.** To what frequency, or band of frequencies, is an approved autoalarm receiver tuned? (26.13) **[6]**

**21.** On a vessel of the United States equipped with an approved type of autoalarm which employs a linear detector and an electronic selector, what factors cause the bell to sound? The warning light to operate? (26.14) **[6]**

**22.** With an autoalarm of the type which employs a linear detector and an electronic selector, what is the most probable cause of the intermittent ringing of the bells? (26.14) **[6]**

**23.** If an autoalarm bell rings and upon pressing the release button it stops, what could be the cause(s)? (26.14) **[6]**

**24.** If you were a radio operator on a vessel of the United States equipped with an approved type of autoalarm which employs a linear detector and an electronic selector, describe what would happen upon failure of a vacuum-tube filament. (26.14) **[6]**

**25.** If an autoalarm bell rings, and upon pressing the release button it does not stop, what could be the cause(s)? (26.14) **[6]**

**26.** On a vessel of the United States equipped with an approved autoalarm, where is the control button which silences the warning bells located? (26.14) **[6]**

**27.** When the autoalarm bell rings, what should the operator do? (26.14) **[6]**

**28.** What factor(s) determine the setting of the sensitivity control of an autoalarm receiver approved for installation on a vessel of the United States? (26.14) **[6]**

**29.** With an autoalarm of the type which employs a square-law detector and a mechanical selector, what factors cause the bell to sound? The warning light to operate? (26.15) **[6]**

**30.** With an autoalarm of the type which employs a square-law detector and a mechanical selector, why does this alarm receiver not respond to type-A1 emission? (26.15) **[6]**

**31.** What is the purpose of an autoalarm-signal keying device on a compulsorily equipped ship? (26.17) **[6]**

**32.** What means usually are provided to prevent the operation of the ship's transmitter when the autoalarm receiver is in use? (26.18) **[6]**

**33.** What is the purpose of an auxiliary receiving antenna installed on a vessel which is also fitted with a direction finder? (26.18) **[6]**

**34.** What experience is the holder of a First or Second Class Radiotelegraph operator license required to have before he is permitted to act as chief or sole operator on a compulsorily radio-equipped cargo ship? (26.19) **[6]**

**35.** Are there any age requirements that a person must meet before he can be issued a radiotelegraph operator license? (26.19) **[6]**

**36.** How frequently should an entry be made in a ship radiotelegraph log while a radio watch is being maintained? (26.20) **[6]**

**37.** Upon compulsorily equipped vessels, which are required to have an accurate clock in the radio room, how frequently must this clock be adjusted and compared with standard time? (26.20) **[6]**

**38.** Why is the clock in a compulsorily equipped ship radiotelegraph station required to have a sweep second hand? (26.20) **[6]**

**39.** What action, if any, may a radio operator take when he observes a ship station flagrantly violating the international radio regulations and causing harmful interference to other stations? (26.20) **[6]**

**40.** Under what conditions may a ship station close if its service is not required to be continuous? (26.20) **[6]**

**41.** What exceptions are permitted to the regulation which states that a ship station, which has no fixed working hours, must advise the coast station with which it is in communication of the closing and reopening time of its service? (26.20) **[6]**

**42.** What is the principal port of the United States on the Pacific Coast at which navigation lines terminate? (26.20) **[6]**

**43.** In what city is the major telecommunication center of the United States located? (26.20) **[6]**

**44.** What is the principal Atlantic Coast port of the United States at which navigation lines terminate? (26.20) **[6]**

**45.** To what continent do the greatest number of telecommunication channels from the United States extend? (26.20) **[6]**

**46.** What is the GMT time and the day of the week in Shanghai when it is Wednesday noon in New York City? (26.20) **[6]**

**47.** What is the approximate latitude of Colon, Republic of Panama? (26.21) **[6]**

**48.** In what ocean is the island of Guam located? (26.20) **[6]**

## CHAPTER 27

# RADIO DIRECTION FINDERS

**27.1 Basic Radio Direction Finder.** A simple horizontal dipole antenna capable of being rotated, coupled to a radio receiver, forms a rudimentary *radio direction finder* (abbreviated RDF or DF). According to basic antenna theory, when the antenna wire is pointing toward a transmitting station, a *minimum* signal is received. When the antenna wire is parallel to the wavefront of an approaching radio wave from the station, a maximum signal is produced in it. The indication of the maximum signal is very broad—the antenna can be swung many degrees before any change in signal amplitude is discernible. On the other hand, the signal will drop to a *minimum* and back up again in a very few degrees of rotation. For this reason the minimum signal gives a more definite *line of position*, or bearing, and is the one normally used in DF work.

A short rotatable dipole has a poor signal-reception capability. For a given size, a loop antenna is more efficient, although its pickup response is somewhat different from that of the dipole.

**27.2 The DF Loop.** The usual DF antenna is a loop, constructed in either circular or square form, although either responds similarly. Figure 27.1 can be used to illustrate the basic properties of a loop.

A vertically polarized signal striking the loop wires induces currents in the vertical sides, $S_1$ and $S_2$. These currents are equal in amplitude and polarity if the transmitter is an equal distance from the two sides, as when the radio waves are traveling toward the loop from the position of the reader, or striking it from behind the page. Two equal induced currents flowing upward, as shown, would cancel at the top of the loop and in the receiver, leaving a zero resultant received signal. On the opposite half cycle a cancellation still occurs. Rotating the loop 180° places the wires in a similar relative position, and again there is zero signal received.

With a transmitter at either position $T_1$ or $T_2$, the currents induced in $S_1$ and $S_2$ will not be of equal amplitude during the major portion of any cycle because they are different distances from the transmitter, and a current equal to the difference between the two induced currents will flow in the receiver. While this difference current is quite weak, multiturn loops with a diameter of about 3 ft produce satisfactory pickup for sensitive receivers for shipboard operation.

When a loop is rotated 360°, it should form the figure-eight reception pattern shown. As we look down on the loop, signals approaching at a 90° angle from the plane of the loop will be received as nulls. Signals approaching in the direction of the plane of the loop will be maximums. Signals from other directions will be intermediate in amplitude. The loop is said to have a *bilateral*, or *bidirectional* (two-way), response, giving a good null in two directions 180° apart and two maximums 180° apart.

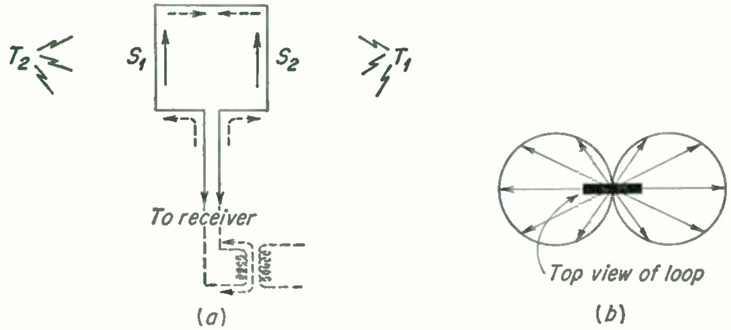


FIG. 27.1. (*a*) Basic balanced RDF loop circuit. (*b*) Reception pattern of the loop.

Note that the horizontal portions of the loop are considered to be picking up no signal at all from approaching radio waves. Any signal induced in the top portion is canceled by that induced in the bottom portion, by any wave traveling parallel to the earth, regardless of how the loop is positioned. However, if the signal is approaching the loop from above, there will be a horizontal difference current induced in these portions of the loop. This appears as a residual signal, either shifting the null, making a complete null impossible, or both. This occurs with signals reflected from the ionosphere (sky waves), but is nonexistent for ground wave signals alone.

Practical loop antennas are 10 to 15 turn coils of 3-ft diameter, encased in a hollow brass or aluminum case. This shield is broken only at the top, at which point an insulating segment is inserted (Fig. 27.2). Without the insulating segment no signal would be able to penetrate to the pickup wires inside. The insulation allows oscillating currents to be induced in the metallic shield, inducing voltages into the internal pickup wires.

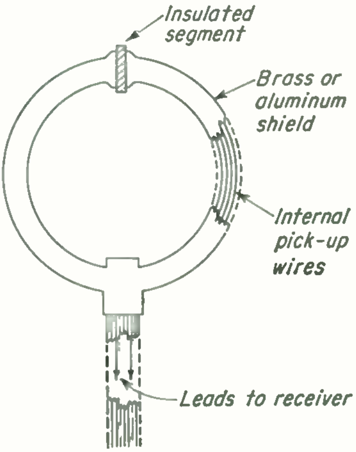


FIG. 27.2. A shielded RDF loop antenna.

The loop is rotated by hand. The loop shaft terminates below deck at the operating position and is coupled mechanically to a wheel. Rotating the wheel 360° rotates the loop 360°.

**27.3 An Unbalanced Loop.** A loop antenna that is properly balanced electrically produces a perfect figure-eight reception pattern. Small differences in length of wire between the two sides, or differences of distributed capacitance between the two sides and ground (or shield), will unbalance the loop. Unbalance results in one of the reception lobes being greater than the other, in the lack of complete nulls, and in a shifting of the nulls from their normal 180° relative positions. Figure 27.3 illustrates $S_1$ as being shorter electrically and picking up less signal than $S_2$, resulting in noncancellation. A possible reception pattern is shown. Note the lack of complete nulls, and also that the best nulls are no longer 180° apart. In the unbalanced condition neither minimum is suitable for determining direction. The lack of a deep, sharp null on stations within 50 or 100 miles usually indicates loop unbalance and erroneous bearings.

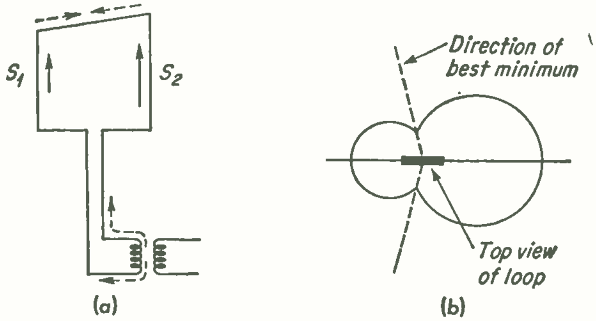


FIG. 27.3. (a) Unbalanced loop results in a difference current in the receiver. (b) Reception pattern of the unbalanced loop.

**27.4 Methods of Balancing a Loop.** By proper manufacturing precautions a loop can be constructed that has little electrical unbalance. If such a loop is placed in a clear space, or in the central portion of an airplane where nearby portions of the body on both sides are symmetrical, errors tend to balance out and no electrical balancing may be required.

On a ship there may be no place where such a physically symmetrical condition is available. As a result, a means of electrical balance must be used. There are three basic methods.

The first loop in Fig. 27.4*a* uses a differential variable capacitor (condenser) to balance both sides of the loop to ground. Rotating this capacitor increases the capacitance to ground from the left side as the capacitance to the right side is decreased and vice versa. This can make up for electrical unbalance due to greater capacitance to ground from one side of the loop than from the other. Note that the center of the loop coil is always connected to the shield (ground) to aid in balancing both sides of the loop.

The second loop (Fig. 27.4*b*) uses a differential capacitor and a short vertical antenna. The reception pattern of the vertical antenna is circular (equal reception in all horizontal directions). Signals from this "sense" antenna can be fed by the differential capacitor to the side of the loop that is not picking up sufficient signal because of improper electrical balance.

The third loop (Fig. 27.4*c*) employs a rotatable coil to inductively induce the required amplitude and phase signal voltage into the loop to produce balance.

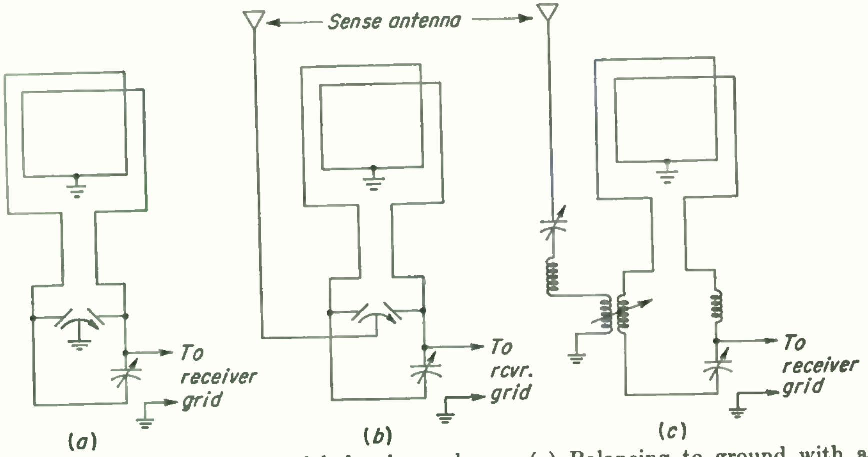


FIG. 27-4. Three methods of balancing a loop. (*a*) Balancing to ground with a differential capacitor. (*b*) Balancing with a vertical antenna and a differential capacitor. (*c*) Inductive balancing with a vertical antenna.

In all these methods it is necessary to balance the loop on each bearing taken, as a single balance adjustment may not hold for more than a few degrees of loop rotation.

The usual procedure for balancing a loop is to tune in the signal, rotate the loop for the best minimum obtainable, and then rotate the balancing control to the weakest response possible. If the null is not to zero signal, the loop must be rotated to a still greater minimum and the balancing control adjusted until a sharp null results. If the DF has been compensated correctly, the sharp null should indicate reliably the bearing or direction of the station being received.

**27.5 Unidirectional Bearings.** The loop alone gives bidirectional or bilateral bearings (two nulls for 360° rotation). If the loop is intentionally unbalanced, a distorted figure-eight pattern results, and if the distortion is sufficient, the amplitudes of the two maximums are noticeably different. The stronger maximum is normally used as the indication of the direction of the station. This is known as a unidirectional, or unilateral, bearing. Since it is a maximum-signal indication it is not accurate by itself. It is necessary either to sense the direction of the signal (take a unidirectional bearing) and then take a balanced (bidirectional) null bearing on the station or to reverse this procedure.

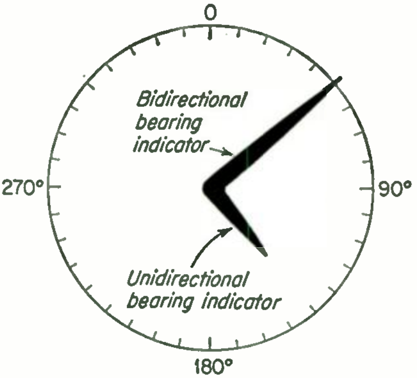


FIG. 27.5. An RDF bearing indicator rotates with the loop.

The indicator on a DF is directly coupled (mechanically) to the rotator wheel and normally has two pointers. One is long and points out the bearing of the null on a compass card marked in degrees. The other is the unidirectional indicator, is short, and points at right angles to the bearing indicator (Fig. 27.5).

The unbalancing of the loop is accomplished by pressing a sense switch that resonates and couples the sense antenna to one side of the loop.

The sense antenna is usually about 20 to 30 ft long, is erected as close to the loop as practical, and is made as nearly vertical as possible.

The amount of sense-antenna signal, determined by the antenna length, tuning, and degree of coupling to the loop, affects the shape of the reception pattern. A small value of sense signal decreases one maximum a little and increases the other. With the correct value of signal, one of the maximums can be canceled entirely and the other increased materially.

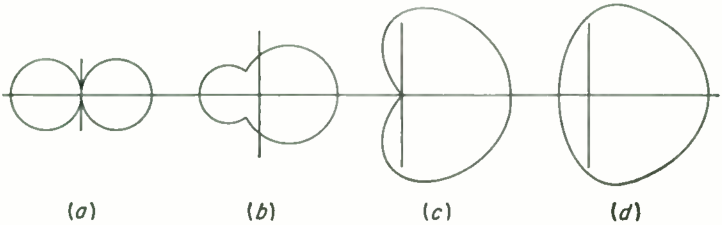


FIG. 27.6. Reception patterns with four values of sense signal. (*a*) Balanced loop. (*b*) With a small value of sense signal. (*c*) A cardioid with still more sense signal. (*d*) Excessive value of sense signal.

This results in a *cardioid,* or heart-shaped, reception pattern. Still greater sense signal produces a signal with no minimums at all (Fig. 27.6).

While the cardioid would seem to be a good general-purpose bearing indicator, its null is not sharply enough defined to make it practical. Furthermore, if the received frequency is changed, the cardioid shape is altered. A little less than that required to produce a cardioid pattern is the value normally used in a DF.

**27.6 DF Errors.** There are several errors to which a DF is subject. All may cause significant changes in bearings.

*Coast-line Refraction.* This is also known as *land effect.* Radio waves crossing from a land to a water area at any angle other than a right angle will refract, or bend, toward the coast line. The resulting error may not be appreciable if the transmitter is within a few hundred yards of the coast, but may be significant if the station is situated inland several miles.

*Nonopposite Minimums.* This is also known as *antenna effect.* It is a form of loop unbalance due to stray signal pickup through earphone cords or power lines or improper shielding or grounding of the loop. To lessen this, earphones are bypassed and low-pass filters are installed in any power lines feeding the DF. The shield constructed around the loop coil materially decreases this effect, reducing nonopposite minimums to less than a degree.

*Reradiation.* Signals striking the loop may also strike nearby metal objects, inducing currents in them that produce reradiated signals. In this case, the loop receives the same signal from two directions at two different amplitudes and displaced in phase. The loop responds to the vector sum of the two signals, which represents a deviation error when compared with the true direction of the approaching signal and the transmitting station. Such signals also require an adjustment of the balancing control to feed in an opposite phase signal to the loop circuit to attain a sharp null. Bearings taken within ½ mile of large bridges, ships, or other metal objects may be subject to considerable error because of reradiation and should be used with caution.

*Great-circle Error.* Radio signals approach the receiver on a *great-circle track.* Since Tokyo and San Francisco are both at approximately 37° north, it would be assumed by looking at the usual map that the shortest route between the two would be to travel directly east or west along the 37th parallel. However, since the world is a sphere, the shortest track between the two cities takes a route northward up to almost the 50th parallel. Thus, for all normally used maps or charts (except great-circle charts), radio waves, which always travel the most direct route, appear to travel a curved course rather than a straight line. The only time they conform to the usual maps is when they are traveling either north or south or along the equator. When the transmission distance is only a few miles, great-circle curvature can be ignored, but for distances in excess of 100 miles it may have to be considered in navigation.

*Polarization Errors.* As mentioned previously, ground-wave signals striking the loop induce currents in the vertical portions, with any induced currents in the horizontal portions balancing out. However, signals approaching the loop from above induce nonbalancing currents in the horizontal portions that add vectorially with the vertical signals and result in loss of null as well as a deviation. With medium frequencies used in marine DF work (285–500 kc), the ground wave is so much stronger than the sky wave for 50 miles or more that any downward-approaching sky waves are too weak to be significant. Furthermore, during the daytime the sky wave tends to be attenuated. During nighttime hours the sky wave refracts from the ionosphere and is receivable for long distances. When the sky-wave amplitude approaches the ground-wave amplitude, the null of a loop antenna is no longer reliable. This is known as *night effect.* Loop reception is always considered unreliable for navigation with sky-wave signals alone.

The variation of the ionosphere at night produces a fading sky-wave condition that may make the null appear to vary back and forth over several degrees in a short period of time.

During the periods of ½ hr before and ½ hr after sunrise and sunset the ionosphere is varying so wildly that bearings at even 50 miles may be affected.

**27.7 Calibrating a DF.** A shipboard DF will normally be quite accurate for signals approaching from dead ahead, from directly behind, or from either beam. However, between these points it may deviate several degrees. These are known as *quadrantal* errors. By running the vessel in a circle within sight of a radio transmitting antenna, it is possible to take simultaneous visual and radio bearings every 5° or 10° as the ship turns. Comparison of the two bearings will indicate how far the DF bearings are in error. This is known as *calibrating* the DF. By building into the DF indicator system a mechanical means of producing opposite errors at desired points, it is possible to produce a resultant DF indicator with no appreciable error. Adding the mechanical opposite errors is known as *compensating.*

Another form of compensation is sometimes used. The masts, deck, and smokestack, plus guy and other wires aboard ship, form a semiresonant circuit that may introduce considerable quadrantal error in the DF if it is located in this area. This error can often be reduced by closing the mast-deck-stack circuit with a wire connected between the top of the mast and the top of the stack. (Sometimes this increases the error.)

Because the DF is sensitive to signals reflected from nearby objects, it is important that the calibration be carried on when the ship is in its seagoing condition as far as halyards, guy wires, masts, and booms are concerned. Since the main radio antenna usually is installed over the top of the loop, the calibration of the DF may shift if the resonant frequency of the radio antenna is changed. To prevent this, the DF is interlocked with the main antenna switch in the radio station. When the bridge officers turn on the DF (located on the bridge) a red light is turned on in the radio room. The operator throws his main antenna switch to the "DF" position. This disconnects his main antenna, closes a circuit that allows the DF to start operating on the bridge, and connects his watch-standing receiver to an auxiliary antenna that has no effect on the DF. (It is in this condition that the DF is calibrated.)

**27.8 Frequencies Used for Marine DF.** Marine radio direction finders must be capable of operating on 500 kc to take bearings on ships in distress, on the international DF frequency of 410 kc, used when requesting DF bearings of other stations, and to the marine radio-beacon stations operating between 285 and 320 kc. Most DF bearings are taken on radio-beacon stations. As a result the DF is usually calibrated at a frequency near 315 kc. The further from the frequency at which it is calibrated, the greater the quadrantal error that may be present in it.

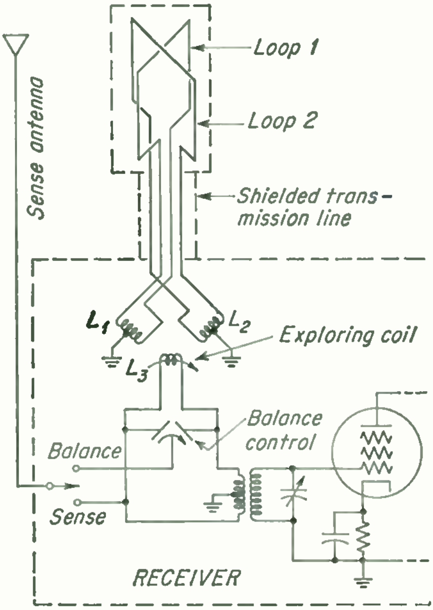


FIG. 27.7. Goniometer loops coupled to a receiver.

**27.9 Goniometer-type Direction Finders.** Rotating loop-type direction finders have been used aboard ships for many years. Such equipment has some disadvantages. The loop and receiver must be relatively close together, with a mechanical connection between the loop and the operating position in the cabin below the loop. The moving parts of such equipment require maintenance to keep them in proper working condition.

A nonrotating, double-loop *goniometer* type of DF is now being used on American ships. The nonrotating loop can be as far as 100 ft from the operating position and coupled to the receiver by only an electrical transmission line. The theory of operation of a goniometer can be explained by reference to a simplified diagram (Fig. 27.7).

Two separate fixed loops are set at right angles to each other, usually on top of a mast, and centered above the navigation bridge. Such a centered position eliminates some of the quadrantal errors to which the rotating-loop installations were subject. Each loop has its own transmission line that terminates in a fixed coil in the receiver. The two fixed coils $L_1$ and $L_2$ are connected to loops 1 and 2. The two coils are installed at right angles to each other, as are the loops. A rotary *exploring* coil $L_3$ can be adjusted to pick up signals from either $L_1$ or $L_2$ or from both simultaneously.

If loop 1 happens to be receiving a null from a station, then loop 2, at right angles, will be receiving a maximum. If the exploring coil is rotated for maximum coupling to $L_1$, with no signal in loop 1, no signal is picked up by the exploring coil. Since $L_3$ is 90° from coil $L_2$, it is completely decoupled and can pick up no signal from this coil either. Therefore no signal is heard in the receiver. When the exploring coil is rotated in either direction, the coupling between it and $L_2$ increases, and signals are received.

If the transmitted wave approaches at an angle of 45° from both loops, the exploring coil will receive equal-amplitude and *opposite-phase* signals from $L_1$ and $L_2$ when it is midway between them. This results in a zero signal output when the exploring coil is at 45° from $L_1$ and $L_2$. Thus, the exploring coil is pointing in the direction of the approaching signal whenever a null is being received. An indicator arrow is attached to the shaft of the exploring coil and sweeps over a circular scale calibrated in 360°.

The goniometer-type DF may be balanced and sensed by methods similar to those used with rotating-loop direction finders. The two types of direction finders are also operated in a similar manner when taking bearings.

**27.10 RDF Receivers.** The receiver used in conjunction with the DF antenna is usually a sensitive superheterodyne, although TRF receivers have also been used. To enable the receiver to operate successfully on weak signals, or signals having no modulation, a BFO is used. Since an aural null is the indication of direction, an AVC circuit is not desirable. An RF gain control is included in the circuit, but no audio-volume control.

To attain a better balance, earlier direction finders employed a push-pull input stage in the receiver. Later models use a single-ended input stage fed by a balanced transmission line similar to that shown in Fig. 27.7. Both receiver and transmission line must be well shielded to prevent stray-signal pickup.

Some receivers use a form of tuning-eye tube as a visual indicator of the amplitude of the received signal, although earphone or loudspeaker operation is generally considered most suitable. More elaborate land-based or aircraft-type direction finders may utilize a cathode-ray-tube display as a bearing indicator.

On ships having only 110 volts d-c, a 6-volt storage battery may be used for the filament supply and either dry batteries or a dynamotor operating from the storage battery as the plate voltage supply. On a-c-powered ships the filaments operate from a-c and the plate supply is a rectifier and filter circuit.

**27.11 Maintenance of Direction Finders.** Besides the usual electrical maintenance of vacuum tubes, batteries, etc., a DF of the rotating-loop type requires periodic checks for freedom of rotation and noisy slip rings. The rotating-loop mechanism requires greasing or oiling once or twice a year, and the silver-plated slip rings and brushes that connect the rotating loop to the receiver require cleaning with a dry cloth from time to time. The insulating segment between the two tubular sections at the top of the loop must not be painted, or loss of signals will result.

**27.12 Adcock Antennas.** The loop-type direction finders are satisfactory for shipboard work because the frequencies used are low and a strong ground wave exists for a considerable distance. At higher frequencies the ground-wave range decreases and a loop becomes inaccurate at distances over 10 to 30 miles because of loss of ground wave, which means that a preponderance of the sky-wave signal is being received.

For short-wave use, or for long-distance low-frequency use, an *Adcock* antenna can be used with a DF receiver. It consists of two vertical antennas separated by perhaps 10 to 20 ft. From the centers of the two verticals the signal is coupled to a two-wire horizontal transmission line that is coupled in turn to the receiver (Fig. 27.8). The transmission line balances out any signals striking it, leaving the vertical portions of the antenna as the only signal-accepting elements. Waves approaching the antenna, either in a direction parallel to the earth or downward from the ionosphere, induce currents in the vertical elements. The sky and ground waves can be out of phase, but accurate bearings can be taken as long as the sky wave has not been changed in travel direction by the ionosphere. By the use of sky waves alone, past the ground-wave range, reasonably accurate bearings can be obtained as long as the ionosphere is relatively constant in density. Because of their large size, Adcock direction finders are usually found on shore stations only.

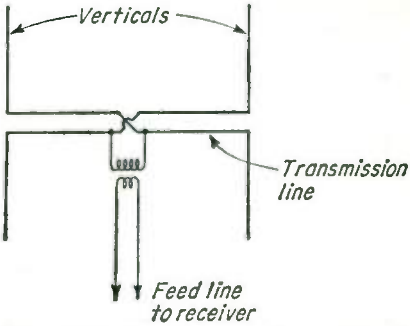


FIG. 27.8. Basic form of an Adcock antenna, used for long-distance direction finding.

Rather than rotate such a large antenna, direction finders may be constructed using two pairs of Adcock verticals installed at right angles and fed to a set of fixed coils similar to a goniometer. The exploring coil is the only part that rotates.

**27.13 Determining a Position by RDF.** A vessel can determine its position by taking a bearing on two shore transmitters whose locations are known and plotting the two bearings on a map, or *chart*, of the local area. The point on the chart where the two bearings cross is the position of the vessel. For example, a vessel takes a bearing on two shore-transmitter stations $S_1$ and $S_2$ whose positions are shown on the chart (Fig. 27.9). The bearing of $S_1$ happens to be due east, or 90° (90° from true north). The bearing of $S_2$ happens to be due south, or 180° from true north. On the chart, a pencil line is drawn through the position of $S_1$, at an angle of 90° (east and west). The angle is taken from the *compass rose* on the chart and transferred to the position of $S_1$ by a device known as *parallel rules.* Another line is drawn through $S_2$ at an angle of 180°. The position indicated by the crossing of the two lines of position is known as a *fix.*

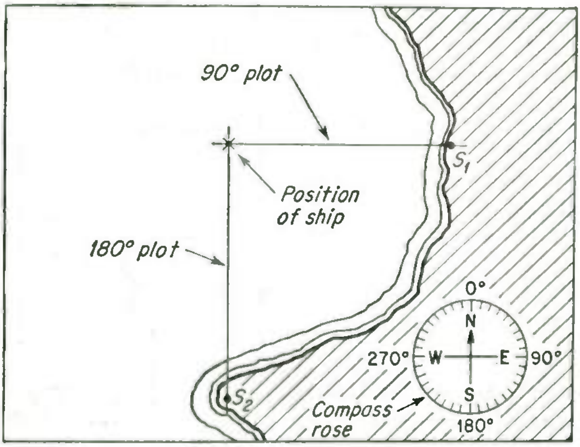


FIG. 27.9. A fix of a ship's position by RDF bearings on two shore stations, or by plotting bearings of the ship from the two stations.

Many lighthouses and light vessels along coast lines have radio-beacon transmitters to allow navigators to take DF bearings on them. During clear weather many of them do not operate, but during foggy weather they are all in operation, allowing navigators continually to check their positions by this means. These beacon stations transmit an identifying signal (listed in the publication "Radio Aids to Navigation," aboard all ships) such as dash-dash-dot, or perhaps dot-dot-dash-dot, to enable the navigator to identify properly the station on which he is taking a bearing.

While a bearing on a station only gives a *line of position,* it is possible to cruise a few minutes and then take a second bearing on the same station. When these two bearings through the position of the beacon station are properly plotted on a chart, since course, speed, and elapsed time are known, the position of the ship at the time of both bearings can be determined.

The position of a ship can be determined by two RDF stations ashore taking bearings on radio transmissions from the ship. Plotting the two bearings on a chart, as in Fig. 27.9, indicates the position of the ship. Such a service was previously available to ships through the U.S. Coast Guard but has been discontinued. Many foreign countries still operate RDF stations, however.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

**1.** Describe the construction and operation of a shielded loop antenna as used with a marine DF. (27.2) **[6]**

**2.** What is the directional reception pattern of a loop antenna? (27.2, 27.5) **[6]**

**3.** Why are loop antennas, associated with radio direction finders, metallically shielded? (27.2, 27.6) **[6]**

**4.** What is the purpose of an auxiliary receiving antenna installed on a vessel which is also fitted with a DF? (27.4) **[6]**

**5.** What is the function of the balancing capacitor in a DF? (27.4) **[6]**

**6.** What is the principal function of a vertical antenna associated with a unilateral RDF? (27.5) **[6]**

**7.** What is the principal function of a vertical antenna associated with a bilateral RDF? (27.5) **[6]**

**8.** What figure represents the reception pattern or a properly adjusted unilateral RDF? (27.5) **[6]**

**9.** From how many simultaneous directions is a DF capable of receiving signals if adjusted to take unilateral bearings through 360°? (27.5) **[6]**

**10.** How is the unilateral effect obtained in a DF? (27.5) **[6]**

**11.** What is indicated by the bearing obtained by the use of a unilateral RDF? (27.5) **[6]**

**12.** What is a *compensator* as used with radio direction finders? What is its purpose? (27.7) **[6]**

**13.** On shipboard, what factors may affect the accuracy of a DF after it has been properly installed, calibrated, and compensated? (27.6, 27.7) **[6]**

**14.** Within what frequency-band limits do all U.S. marine radio-beacon stations operate? (27.8) **[6]**

**15.** What is indicated by the bearing obtained by the use of a bilateral RDF? (27.13) **[6]**

**16.** Draw a sketch showing how a *fix* on a ship station can be obtained by taking DF bearings. (27.13) **[6]**

# CHAPTER 28

# LORAN

**28.1 The Loran System.** Radio direction finders have been in general use as a means of navigating by radio since the early 1920s. During the Second World War, a new, entirely different method of radio navigation was introduced, called *loran* (LOng RAnge Navigation). Whereas the maximum reliable range of RDF is only one or two hundred miles, loran is usable for approximately 700 miles during the daytime and 1,400 miles at night.

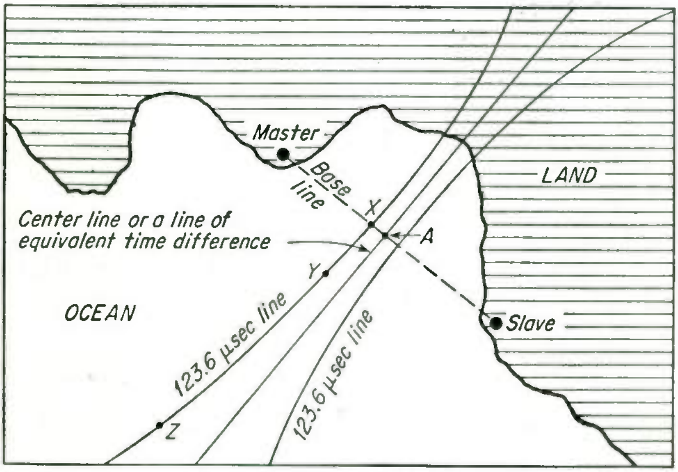


FIG. 28.1. Loran chart, showing center and base lines, and two 123.6-μsec hyperbolic curves *if* the master and slave transmitted at the same time.

The loran system aboard a ship (or airplane) consists of a short vertical antenna, a superheterodyne receiver, a complicated comparing and timing device called an *indicator*, and loran charts. No shipboard transmitter or special rotating antenna is required.

The loran receiver picks up signals from a *pair* of transmitters located on shore, an average of about 300 miles apart. One of these stations is known as the *master* and the other the *slave*. Both transmit 40-μsec (microsecond) pulses of radio-frequency energy, and on the same frequency. Figure 28.1 illustrates a pair of loran transmitters. If both stations transmit their pulses simultaneously, a ship on the *base line*, exactly midway between them, at point $A$, will receive the two pulses at the same time. In fact, anywhere on the *center line*, the pulses will be received simultaneously. Thus, the center line is a line of equal time difference.

Radio waves travel a mile in 6.18 μsec. If the ship were 10 miles closer to the master than to the center line, at point $X$, the pulse of the master would arrive 123.6 μsec (20 × 6.18) ahead of the slave pulse. At points $Y$ and $Z$ the same time difference occurs. If a sufficient number of such similar time-difference points were located and a line drawn intersecting them, a curve known as a *hyperbola* would be developed. The center line and such other hyperbolic curves are known as loran *lines of position*. If a loran receiver indicates a difference in arrival time of 61.8 μsec, the ship would be somewhere on the hyperbola of this time difference, although it might be on another similar hyperbolic curve on the opposite side of the center line. To prevent this last possible ambiguity, the master transmits its pulse first. The slave receives the pulse by the constant-velocity ground wave, delays a fraction of a second, and then transmits its pulse a carefully controlled time later. Each major hyperbolic curve on a loran chart is numbered. This number is the actual number of microseconds time difference between master and slave signals that will be received on the particular curve.

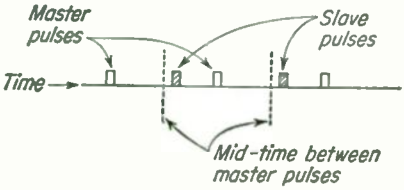


FIG. 28.2. Delaying the slave pulse past the mid-time causes the slave pulse always to appear to the right of the master on the CRT.

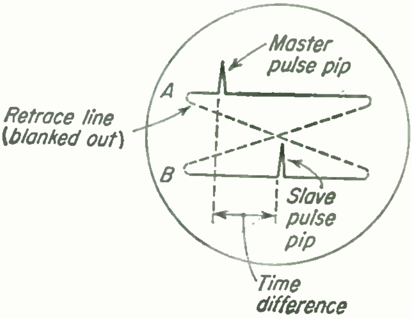


FIG. 28.3. CRT display showing the master pip on the A trace and the slave pip on the B.

The pulses from the master station are transmitted at the basic $H$ (high) rate of 33⅓ pulses per second (pps), or the $L$ (low) rate of 25 pps, although a new $S$ (slow) rate of 20 pps may be used in the future. If the slave is made to transmit its pulse a specific time after the mid-time between the master pulses (Fig. 28.2), it is possible to produce on the loran receiver-indicator a cathode-ray-tube display of two horizontal lines. The master pulse is made to appear as a pip on the top line, and the slave pulse as a pip on the bottom line (Fig. 28.3). A measurement of the horizontal-displacement distance between the leading edges of the two pulses indicates the time difference between the two signals. The difference in time indicates on which hyperbolic line of position the ship is located.

How the master and slave pulses are properly set on the two oscilloscope traces and how the time difference between them is measured are the items that must be determined when finding a loran line of position.

A single line of position may be of little use. It is usually necessary to use another pair of loran transmitters for a second line of position to obtain a *fix*. Where the two hyperbolic lines of position cross on the special loran chart is the location of the receiver.

In many cases the master is double-pulsed and is operated in conjunction with a second slave station. In this way, only three stations are required for two loran pairs. Figure 28.4 illustrates a few hyperbolic curves for the second slave station, $S_2$. If a navigator first locates his ship as being on the curve marked 2H4-3300, for example, and then takes another loran reading on the second slave and master and finds he is on curve 2H3-1600, by reference to his chart he knows that he is at the latitude (marked along the vertical sides of the chart) and longitude (marked along the horizontal sides of the chart) of the point where these curves cross, as at point $Z$. When the received time difference falls between two hyperbolic curves on the chart, the navigator must interpolate to find an accurate point of crossing.

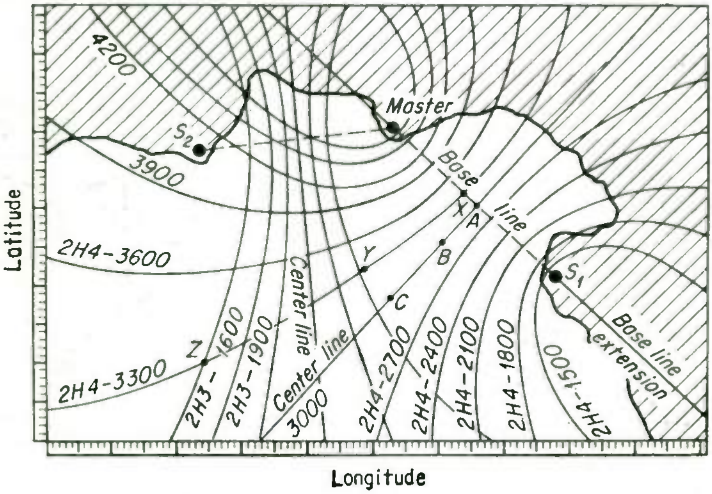


FIG. 28.4. A loran chart, using one master to double-pulse two slave stations, showing station identification and time differences on the curves.

**28.2 Loran Station Designations.** Each pair of loran stations is designated by a three-character identification symbol, such as *2H4*. The first number represents the channel on which the transmitters operate.

Channel 1 = 1,950 kc
Channel 2 = 1,850 kc
Channel 3 = 1,900 kc
Channel 4 = 1,750 kc

The letter indicates the *basic pulse recurrence rate,* such as,

H = $33\frac{1}{3}$ pps
L = 25 pps
S = 20 pps

The last number indicates the *specific pulse recurrence rate* and will be between 0 and 7. When the specific pulse recurrence rate (PRR) is designated as 0, the specific and basic pulse rates are the same. As the numbers increase, the specific rate becomes higher in frequency than the basic rate. For example,

H0 = $33\frac{3}{9}$ pps
H1 = $33\frac{4}{9}$ pps
H2 = $33\frac{5}{9}$ pps
H3 = $33\frac{6}{9}$ pps
H4 = $33\frac{7}{9}$ pps
H5 = $33\frac{8}{9}$ pps
H6 = 34 pps
H7 = $34\frac{1}{9}$ pps

L0 = 25 pps
L1 = $25\frac{1}{16}$ pps
L2 = $25\frac{2}{16}$ pps
L3 = $25\frac{3}{16}$ pps
L4 = $25\frac{4}{16}$ pps
L5 = $25\frac{5}{16}$ pps
L6 = $25\frac{6}{16}$ pps
L7 = $25\frac{7}{16}$ pps

S0 = 20 pps
S1 = $20\frac{1}{25}$ pps
S2 = $20\frac{2}{25}$ pps
S3 = $20\frac{3}{25}$ pps
S4 = $20\frac{4}{25}$ pps
S5 = $20\frac{5}{25}$ pps
S6 = $20\frac{6}{25}$ pps
S7 = $20\frac{7}{25}$ pps

Each curve on a loran chart carries not only the time-difference indication but the master-slave identification symbol as shown in Fig. 28.4.

The identity of any received loran signal can be determined by adjusting the channel, the basic PRR, and the specific PRR switches until the signal synchronizes and stands still on the screen. If the settings of the switches are noted, the identity will be obvious. When the channel switch is set to "1," the basic pulse rate is set to "L," and the specific PRR is 5, the station pair being received is 1L5. This is the only type of identification of such a station. On an ordinary receiver, loran emissions sound like a continuously firing machine gun that changes tone slowly.

**28.3 Determining Time Difference.** Assume that it is desired to determine a line of position when within range of the loran pair 2L3. An example of the front panel of a loran receiver is shown in Fig. 28.5.

The receiver tuning control, a four-position switch, is turned to channel 2. The receiver in this position is fixed-tuned to 1,850 kc.

The basic pulse recurrence rate, or basic PRR, switch of the indicator portion, marked "L-H" in earlier sets, or "H-L-S" in newer models, is set to "L." This selects a sweep frequency of *twice* 25 cps, to produce the two horizontal sweep lines on the cathode-ray tube (CRT). A series of signals will be seen drifting across the two CRT traces.

The seven-position "specific PRR" switch is set to "3." This changes the CRT sweep frequency to twice $25\frac{3}{16}$ cycles, and the two signals from the 2L3 loran pair are in synchronism with the sweep frequency and appear to stand still on the screen. Any other loran station signals received will not be in synchronism and will continue to drift. These are ignored by the operator. (In some equipment the basic and specific PRR controls are combined into one multitapped switch.)

At this point, with the "function," or "operations," switch in the first position, the screen display may appear as shown in Fig. 28.6*a*. On the upper, or "A," trace, one signal is stopped and a fixed rectangular *pedestal* is seen near the left end of the trace. If both signals are on one trace, the "left-right," or "drift," control is pressed until one of the signals is moved to the left-hand end of the A pedestal. If the other signal is now on the B trace, but to the *left* of the signal on the A trace, the master and slave are reversed, and the left-right control must be operated until the other signal, the master, is on the A pedestal. The slave will then be on the B trace, under and to the *right* of the master.

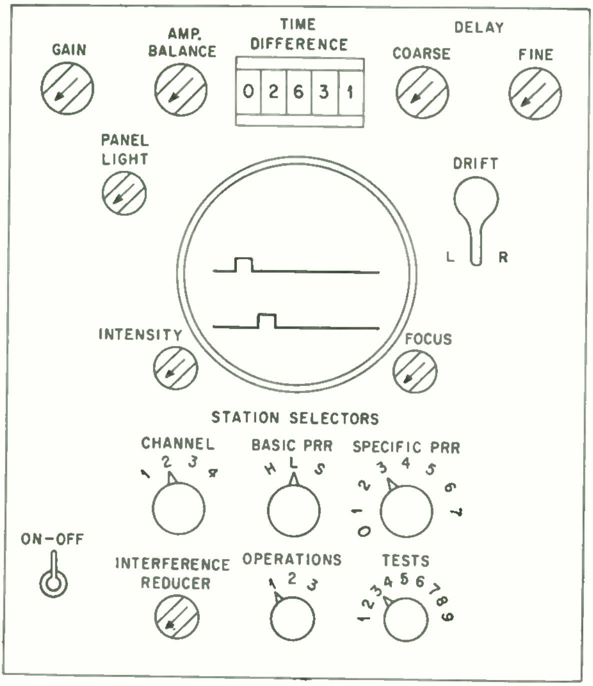


FIG. 28.5. Front-panel controls of a loran receiver-indicator.

The left-right control increases or decreases the sweep rate slightly, depending on the direction in which it is pressed. This shifts the position of the received signal pips along the traces.

The B-trace pedestal must now be moved to a position under the slave signal by operating the coarse "delay" control one way or the other. This should result in a display as in Fig. 28.6*b*, with the slave pip at the left end of the B pedestal. If the signals continue to drift slowly, they can be stopped by adjusting the "drift" control, which slightly changes the basic oscillator frequency from which the sweep voltages are developed. (If automatic frequency control is included in the equipment, the AFC circuit can be switched on to stop the drift.)

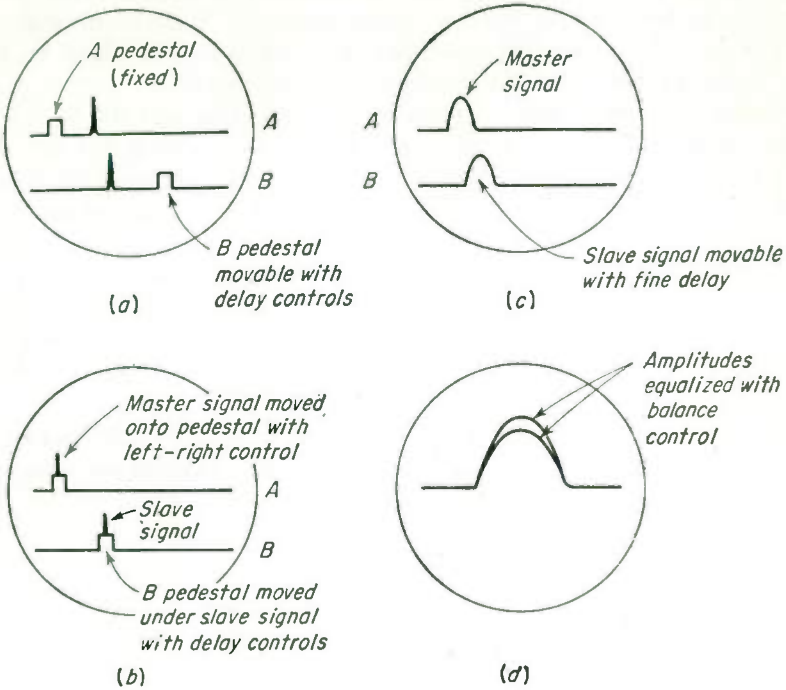


FIG. 28.6. Loran displays. (*a*) When station is first tuned in. (*b*) Master signal moved onto pedestal, and pedestal moved under slave. (*c*) Display of pedestals only. (*d*) Both signals displayed on the same trace.

The function, or operation, switch is now set to position 2. This displays on the screen only the top of the two pedestals with their two signal pips. The remainder of the A and B traces are blanked out with special internal circuits. The pip display now appears magnified, as shown in Fig. 28.6*c*. If the two pulses are not directly above one another, further adjustment of the fine delay control is required. The "balance" and "gain" controls are adjusted until the amplitudes of both signals are as nearly the same height as possible. The RF gain control determines the amplitude of the signals fed to the indicator section. The balance control varies the relative signal strengths fed to the two pedestals.

When the function switch is set to position 3, only one trace is displayed. Both signals now appear on one trace. By careful manipulation of the delay control, the *leading*, or *left-hand*, edges of the two signals can be made to coincide. Again, the balance and gain are adjusted for equal amplitude of both signals. The cranking of the delay control to properly position the two pips has resulted in the operation of a mechanically coupled counting device. How far the delay control has been moved to make the master and slave signals coincide perfectly represents the time difference between the arrival of the two signals. This time difference is shown by the numbers on the counter. If the number shown is 2100, it indicates that the position of the ship is somewhere on the hyperbolic curve marked 2L3-2100 on the loran chart.

In early loran sets, the basic frequency of oscillation was 100 kc. Frequency-divider circuits were used to develop the twice 33⅓- and the twice 25-cycle sweep frequencies, as well as 10-, 50-, 500-, and 2,500-$\mu$sec *marker* signals. After the master and slave signals were brought to coincidence, a fourth function position was switched on, which displayed the A and B traces again. This time, along with the pedestals and signal pips, a series of these marker signals was superimposed on the two sweep lines. It was then necessary to count the number of time-marker signals between master and slave pips to determine the time difference. Some of these models may still be in use.

**28.4 Using Sky-wave Signals.** Whenever possible, ground-wave signals should be used for loran lines of position. Ground-wave signals can be received about 800 miles by day and 600 miles by night. (The noise level increases at night, because of better long-distance reception, while the ground-wave signal remains constant.)

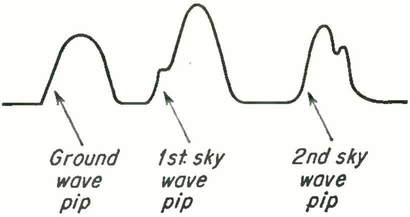


FIG. 28.7. Ground-wave, first sky-wave, and second sky-wave pips, as seen on the CRT.

Sky waves travel upward, are refracted from the ionosphere, and return to earth. Because of the longer travel distance of sky waves, they are received a little later than are the ground-wave signals. Furthermore, the sky-wave signals fade up and down in amplitude, whereas the ground-wave signals remain constant. As another means of identification, sky-wave signals may be the resultant of two or more signals striking the receiving antenna from slightly different points of the ionosphere, and the received pip may vary in shape as it is observed on the screen.

Since the sky wave is received some time after the ground wave, it appears as a separate signal to the right of the ground-wave pip. A third signal, a *two-hop* sky-wave pip, is often seen to the right of the first sky-wave signal (Fig. 28.7). Only the *first* sky-wave signal is usable.

When the first sky wave is used, it is important that only the base of the left edges of the two pips be brought into coincidence. When fading is occurring, it may be necessary to watch for a minute or so to determine whether the true left-hand edges are being compared.

Because the sky-wave signal travels a greater distance than does the ground wave, a correction must be added to any reading taken on sky-wave signals. The required corrections are indicated on the loran charts or tables. Sky-wave signals should not be used when within 250 miles of either station, as the corrections are no longer reliable at this range. However, at this distance the ground wave should be satisfactory.

**28.5 Loran Transmitters.** Loran transmitters emit 40 μsec pulses. For H rate pairs the basic recurrence interval is every 30,000 μsec. For L rate pairs, 40,000 μsec. For S rate pairs, 50,000 μsec. Each pulse may have a power in excess of 200,000 watts, but since the *duty cycle* (time the transmitter is on duty) for an L rate pair, for example, is only 40/40,000, or 0.001, of the time, the transmitter has an *average* power output of only about 200 watts (200,000 × 0.001).

If any trouble occurs at either the master or slave station that might impair the accuracy of the pulse timing, the transmitters will be operated "on" for a period of about 2 sec, and then "off" for a like time. This appears to the receiving operator as a *blinking* signal. Blinking signals must not be used for navigational purposes.

**28.6 Loran Receivers.** The loran receiver may consist of a fixed-tuned superheterodyne with an RF amplifier, a mixer, two or more 50-kc-*bandwidth* IF stages (wide bandwidth is required to accept the sharp-cornered pulse wave plus its many harmonic-frequency sidebands), a detector, and two or more audio or video amplifiers. The output signals from the video amplifiers are coupled to the vertical-deflection plates of a 3-in. CRT, producing the visible pips on the horizontal traces.

The indicator section is quite complicated. It consists of a horizontal sweep generator, a pedestal generator, delay multivibrators to delay the beginning of the pedestal on the trace, a basic oscillator from which the desired sweep rates are developed with frequency-divider circuits or flip-flop counter circuits, sweep speed controls, amplitude-balance circuits, as well as gating, amplifying, clamping, inverting, and other circuits.

The CRT requires an anode potential of 1,500 to 2,200 volts. Caution must be observed by an operator when servicing such equipment to disable the high-voltage circuit, shut off the equipment, then touch a grounded wire or screwdriver to the high-voltage lead. Removal of the type 2X2 high-voltage rectifier will prevent the d-c high voltage from being developed but will not de-energize the high-voltage transformer lead to the rectifier. Without high-voltage direct current, no display will be visible on the screen but the other circuits should operate.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

**1.** In determining a fix, or position, by a marine loran system, what is the minimum number of land transmitters involved? (28.1) **[6]**

**2.** Draw a simple sketch showing relative positions of pairs of master and slave stations of a loran system, and indicate lines of position of each pair of stations. (28.1) **[6]**

**3.** What is the relationship between a master and a slave station in reference to loran systems? (28.1) **[6]**

**4.** Explain why pulse emission rather than continuous waves is used by loran transmitters. Approximately what pulse repetition frequency, pulse duration, and operating frequency are used in loran systems? (28.1, 28.2) **[6]**

**5.** How can the operator of a loran receiver on shipboard identify the transmitting stations that are being received? (28.2) **[6]**

**6.** When several pairs of loran transmitting stations are operating on the same frequency, how does the operator at the loran receiver select the desired pair of transmitting stations? (28.2, 28.3) **[6]**

**7.** During daytime hours approximately what is the maximum distance in nautical miles from loran transmitting stations that loran lines of position can be determined? (28.4) **[6]**

**8.** What is the purpose of blinking in a loran system, and how is blinking recognized at the receiver? (28.5) **[6]**

**9.** What precautions should an operator or serviceman observe when working with cathode-ray tubes and the associated circuits of loran receivers? (28.6) **[6]**

# CHAPTER 29

# RADAR

**29.1 Principles of Radar.** The use of echoes as an aid to navigation is not new. When running in fog near a rugged shoreline ships have sounded a short blast on their whistles, fired a shot, or struck a bell. The time between the origination of the sound and the returning echo indicated how far the ship was from the cliffs of the shore.

Sound is known to travel approximately 1,100 ft/sec. If an echo was heard after 2 sec, it indicated a total sound-travel distance, outward and return, of 2,200 ft. The ship must be half this distance, or 1,100 ft from shore. The direction from which the echo was heard indicated the relative bearing of the shore.

Today, ships transmit a short burst of radio energy, receive the echo produced when the radio wave is reflected from any solid object, and electronically measure the time between transmission and reception. This results in an indication of the range of the reflecting "target." By use of an antenna with a narrow radiation beam, the direction of the reflecting target can be accurately determined. This is *radar*, from RAdio Direction And Range.

Besides its use as a marine navigational aid, radar is also used by aircraft, by landing fields, by the Army and Navy as a means of locating enemy targets, for aiming the guns at the target, and even by the police to determine accurately the speed of an unwise and unsuspecting motorist.

The indicating devices of marine radar sets are usually calibrated in U.S. nautical miles, 6,080 ft (the international nautical mile is 6,076 ft), although the equipment can be calibrated in statute miles, of 5,280 ft. A cathode-ray tube is used as the indicating device.

Radio waves travel 162,000 nautical miles/sec, 186,000 statute miles/sec, or 300,000,000 meters/sec. In one microsecond they travel 0.162 mile. To travel one nautical mile a radio signal requires a little less than 6.2 μsec. A *radar mile* is considered equal to 12.4 μsec, since the wave must travel for this period of time (to and from the target) if the target is one mile away. Thus, if a target is 10 miles away, it takes 124 μsec from the time of transmission for the echo signal to return and be displayed on the radar indicator.

The frequencies used for marine radar are in the SHF (superhigh frequency) part of the radio spectrum, either in the 3,000–3,246-Mc band (also known as the 10-cm, or S, band) or in the 9,320–9,500-Mc band (3-cm, or X, band). A third band, 5,460–5,650-Mc, is also available.

For the 10-cm band, a half-wave antenna is only 5 cm (approximately 2 in.) long. An antenna reflector 5 or 6 ft wide can form a radiated beam with a horizontal width of 2° or 3°. In the 3-cm band, the antenna is only 1½ cm in length, and a similar-sized reflector can form a 1° or 2° beam. At these frequencies the effective range is only slightly more than line of sight.

Marine radar is usually made to operate with a maximum range of 20 to 40 miles and with a minimum range of less than 100 yd from the antenna.

The number of pulses transmitted per second, known as the *pulse repetition rate*, or PRR, varies between about 800 and 2,000 per second. The lower PRR may be used for longer ranges, and the higher for shorter-range work. The pulses on long-range equipment have a somewhat longer duration, representing a greater power output from the transmitter, producing stronger echo signals from distant objects.

The average pulse width is about 0.4 $\mu$sec, with 0.25 $\mu$sec being used on some equipment for better short-range indications. A pulse width of as much as 1.0 $\mu$sec is used for long-distance operation.

**29.2 A Basic Radar System.** Before explaining the operation of one of the more complex radar systems, the functioning of a simple one (Fig. 29.1) will be described.

The heart of the system is in the modulator, keyer, or timer. In this section, a 0.4-$\mu$sec pulse is formed and fed to the single-magnetron-tube oscillator circuit, resulting in the transmission of a 0.4-$\mu$sec pulse of SHF (superhigh frequency) radio energy. At the same time, the timer pulse is also fed to the indicator, starting a dot moving horizontally, tracing from the center of the scope face to one edge. If the maximum range of the radar set is to be 10 miles, the time for the barely visible dot to move to the edge of the scope will be 124 $\mu$sec. The timer pulse is also fed to the grid (or cathode) of the scope tube, producing a bright spot at the center of the tube at the start of the trace.

After each RF pulse has been transmitted, the antenna automatically switches to the receiver. The receiver waits for the return of the echo signal. If a target happens to be 5 miles away, *and in the beam of the antenna*, after 62 $\mu$sec a weak echo signal is received by the antenna, fed to the receiver, amplified, and fed to the grid of the indicator scope. This signal increases the brightness of the moving dot wherever it happens to be on the trace line, and a bright spot appears. The distance from the center spot to the echo dot is an indication of the range of the target. In this case the target *blip* will appear halfway across the 10-mile trace. The direction of the target is indicated by the direction to which the antenna must be rotated to pick up the echo signal.

As soon as the trace travels for 124 μsec, the indicator tube is desensitized, and the dot retraces to the center without producing any trace.

By the use of a PRR of 1,000, every 1,000 μsec a new pulse is produced, and the target signal is registered at the same point on the trace. If the target is approaching the radar set, the distance between blip and center spot on the trace shortens. In this way a constant check can be maintained on the range of the target vessel.

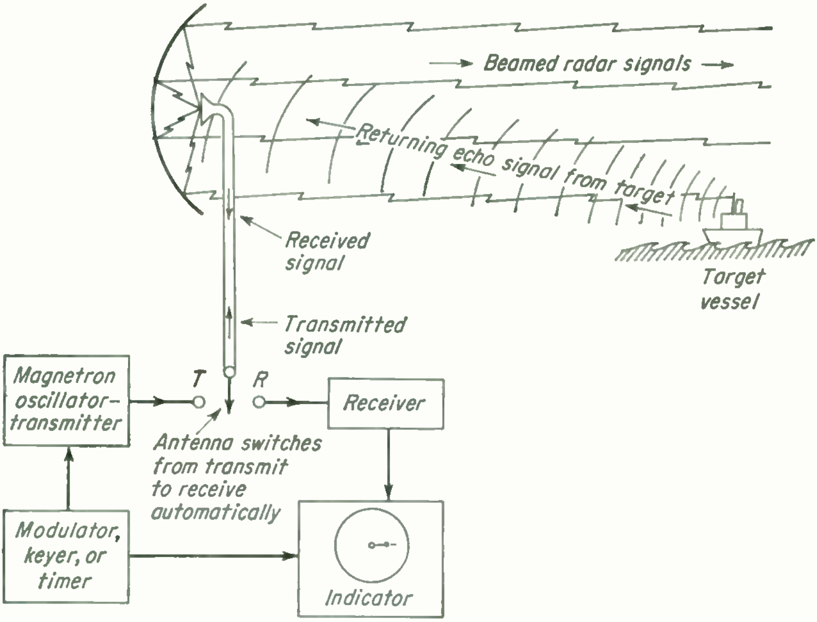


FIG. 29.1. Block diagram of the basic components of a simple radar system.

The parabolic antenna reflector is constructed to produce a beam with about a 2° horizontal width for good *bearing resolution*, with a vertical height of 15° to 20°. Bearing resolution is the ability to separate adjacent targets the same distance away. *Range resolution* is the ability to distinguish two or more targets in the same direction but at different distances.

If the antenna rotation were controlled manually, it would be very difficult to keep the target in the 2° horizontal beam if either the target ship or the radar should move. As a result, it is necessary to improve this basic radar system to make it a practical aid to navigation.

If the antenna is made to rotate horizontally at a constant speed, 10 times a minute, it will make one rotation in 6 sec. With a PRR of 1,000, it will fire 6 × 1,000, or 6,000 pulses per single rotation. This is about 17 pulses per degree of rotation. If the horizontal sweep coils are rotated physically around the neck of the cathode-ray tube in exact synchronism with the rotation of the antenna, targets will be shown on the indicator face in exact relationship with their range and bearing. This is known as a PPI (plan position indication) presentation, and is the type used in marine navigation, in aircraft, and at airports.

The cathode-ray tubes used in radar use electromagnetic deflection and vary in size from 7 to 16 in. in diameter. They differ from television tubes in screen persistence. The radar-tube faces are coated with a little fluorescent and considerable phosphorescent material. The phosphors retain a latent image for a period of 10 sec or more, which is longer than is required to make one antenna rotation. As a result, a PPI presentation forms a constant, well-illuminated plan, map, or chart of the targets in all horizontal directions from the ship. A block diagram of the component parts of the system is shown in Fig. 29.2.

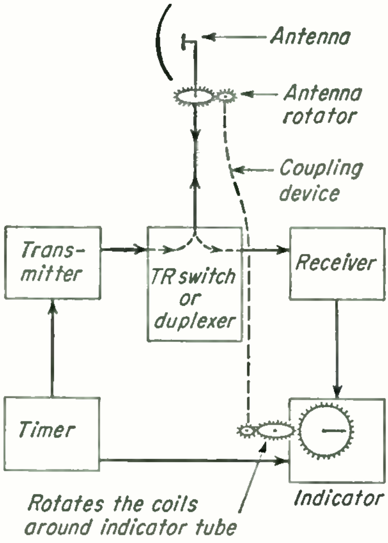


FIG. 29.2. Block diagram of the components of a PPI navigational radar system.

**29.3 A Marine Radar System.** A step-by-step explanation of the important circuits in a marine radar system will be given. Most of the circuits in the receiver and indicator are similar to those found in other types of equipment, explained previously. There are six circuits which are definitely new, and these will be explained at some length. They are the magnetron oscillator, pulse-forming circuits, the antenna circuit, transmit-receive tubes, the klystron oscillator, and the antenna-rotation mechanism. In each, the circuitry has been simplified as much as possible to give a general understanding, since it is impossible to cover all the various types and models of radar.

**29.4 The Transmitter Portion.** The radar transmitter will be considered as the blocking oscillator, a pulse-forming circuit, and the magnetron oscillator (Fig. 29.3).

The blocking-oscillator circuit depends on the $C_g$ and $R_g$ values to determine how many times a second it will operate. The circuit shown resembles an Armstrong oscillator, but any oscillator circuit will block if high values of grid-leak resistance and capacitance are used. As soon as the circuit starts to oscillate, plate current flows for an instant, charging $C_g$ well beyond plate-current cutoff. During the *resting time,* $C_g$ discharges slowly through $R_g$ and the bias voltage decreases until plate current can begin to flow again. This results in short-duration plate-current pulses, which induce high-amplitude peaks in the grid winding of the transformer. The number of peaks of current per second in this stage determines the PRR of the whole radar system.

The grid of the hydrogen thyratron (hydrogen is used in radar thyratrons because it ionizes and de-ionizes more rapidly than argon or mercury) is triggered by the positive pulse, and the tube ionizes. Ionization discharges the capacitors of the pulse-forming network that have charged to a 3,000-volt potential from the power supply through the charging reactor during the nonoperating period of the oscillator. This charge produces a square-wave pulse of current through the primary of the pulse transformer, inducing a high voltage in the two secondaries. These two voltages are of equal value and are in phase, raising the filament and cathode of the magnetron to a negative potential of several thousand volts above the magnetron plate, without changing the potential between the two filament terminals. The plate of a magnetron consists of a series of tuned metal cavities surrounding the cathode. As a safety measure, the plate cavities with their metal cooling fins are always grounded, and the high-voltage pulse is fed to the cathode. The average value of magnetron plate current, 2 to 5 ma, is indicated by the meter between ground and the secondary of the filament transformer. The square-wave pulse of current from the pulse transformer excites electrons into oscillation in the cavities of the magnetron. These oscillations are coupled to the antenna and form the RF output burst.

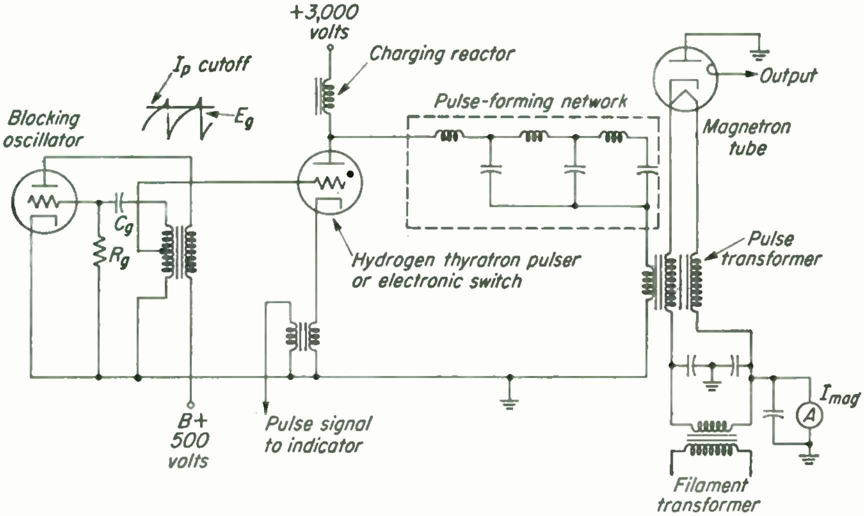


FIG. 29.3. Simplified diagram of a radar transmitter.

A pulse-forming network, as shown, may also be called an *artificial transmission line.* A transmission line has the ability to produce a square-wave output when triggered with a short burst of energy, provided its impedance is matched to the load impedance. The length of the pulse will be a function of the values of inductance and capacitance used in the pulse-forming network. An artificial transmission line may also be called a *delay line* because a pulse voltage fed across the input end will appear a few microseconds later across the output end. If an electric impulse travels 300 meters in one microsecond, a 300-meter line will delay the voltage 1 μsec. An artificial line with similar values of series inductance and shunt capacitance will delay the same time.

The transformer in the cathode of the thyratron pulser tube has a primary of two or three turns, which induces a voltage into the secondary. This voltage is fed to the indicator circuits to start the trace across the CRT screen.

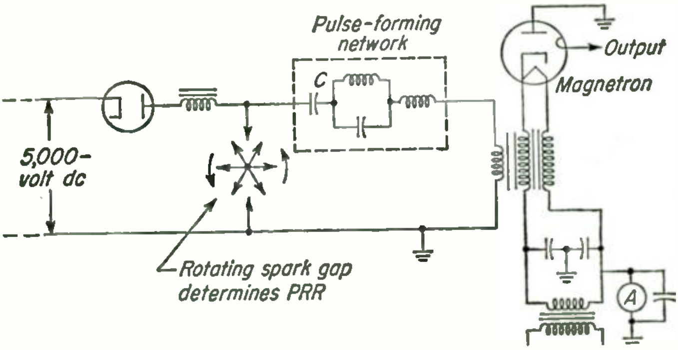


FIG. 29.4. Simplified diagram of a rotating-spark-gap radar transmitter.

One of the earlier radar systems employed a rotating spark gap to produce the pulses (Fig. 29.4). The capacitor (condenser) charges to 5,000 volts during the time the spark gap is open. When it rotates closed, the capacitor discharges through the pulse line and the primary of the pulsing transformer, developing the desired square-wave pulse that fires the magnetron into operation.

**29.5 The Magnetron Tube.** At frequencies used for radar, 3,000 and 9,000 Mc, the lengths of leads and interelectrode capacitances of standard vacuum tubes make their operation impossible. *Klystron* tubes, to be explained later, will efficiently produce relatively low power with small sizes, but magnetron tubes can produce pulse powers in excess of 100 kw without difficulty, using physically small components.

A magnetron may be visualized as being a cylindrical brass block, about 2½ in. in diameter and about 1½ in. long. A large hole is drilled down the center, and eight smaller holes are drilled between the center and outer edges (Fig. 29.5). Slots interconnect the holes.

The smaller holes are known as *cavities*. When the magnetron is operating, electrons take a back-and-forth path along the walls of the cavities, as indicated by vector arrows in one cavity. Actually, a cavity oscillates in a manner similar to a lower-frequency coil and capacitor circuit. The walls of the cavity form the inductance, and the capacitance across the cavity opening forms the capacitor.

A cylindrical cathode, with an internal heater wire, is located in the center of the central hole. One heater lead connects on the near side of the magnetron; the other lead on the far side.

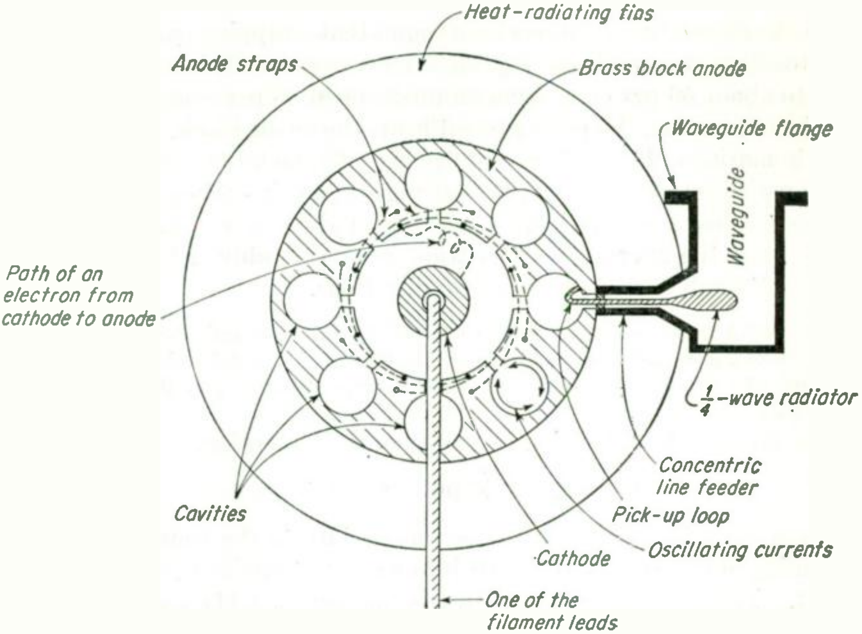


FIG. 29.5. Cross section of a magnetron coupled to a waveguide.

A small hook in one of the cavities acts as a pickup loop, extracting RF energy from the cavity when it is oscillating. Current oscillating along the walls of the cavity induces a voltage into the loop. This is fed to a short concentric transmission line terminated with a quarter-wavelength radiator, which is protruding into the end of a *waveguide*.

The magnetron block acts as the anode or plate and is connected to ground. When the tube is pulsed, the cathode is driven negative by 10 to 20 kv. This makes the plate relatively positive, and electrons from the hot cathode start moving toward it. However, a strong, external, horseshoe-shaped permanent magnet, with its north pole at one end of the cathode and the south pole at the other end, produces an intense magnetic field down the central hole. According to the right-hand motor rule (Sec. 3.17), the electrons will be deflected at right angles to the lines of force through which they are passing. This results in an elliptical path for the electrons as they progress toward the anode areas.

The positive potential of the anode accelerates the electrons toward it. This is the same as saying the electrons pick up energy from the difference of potential. As the electrons whirl past the slots between anode areas, they induce voltages between the slot faces which drive currents into oscillation along the surfaces of the cavity walls. In this way the energy of the cathode electrons is transferred to the oscillating currents in the cavities. All the cavities are the same size and oscillate at the same frequency. However, adjacent cavities have opposite-direction currents in them at any one time. It has been found that strapping *every other* anode face together (broken lines, Fig. 29.5) increases the efficiency of a magnetron to about 50 per cent, from an unstrapped 35 per cent.

When operating, the plate current heats the anode block. Magnetrons used in marine radar have several flat, parallel, metal fins attached to the outer perimeter of the block, permitting simple air cooling to be used.

Magnetrons are sometimes used to produce a constant-amplitude carrier, but the average power output is considerably reduced from the values attainable with pulse-type applications.

*Example:* A radar transmitter has a PRR of 900 pps, each pulse having a duration or length of 2 μsec and a peak pulse power of 15 kw. The total emission duration is 2 × 900, or 1,800 μsec, or 0.0018 sec. The average power is only 0.0018 × 15,000, or 27 watts.

The formula to determine average power is therefore

$$P_{\text{av}} = \text{PRR} \times \text{pulse width} \times P_{\text{peak}}$$

The *duty cycle* is the ratio of the pulse width to the time between the beginning of two pulses, (this last is known as the *pulse repetition time*, or PRT). For a PRR of 900, the PRT is $\frac{1}{900}$ sec, or 1,111 μsec. The duty cycle for the transmitter above is 2/1,111, or 0.0018. The transmitter is actively on duty for 0.0018 of each second. The formulas for duty cycle are

$$\text{Duty cycle} = \frac{\text{pulse width}}{\text{PRT}} \qquad \text{and} \qquad \text{duty cycle} = \frac{\text{average power}}{\text{peak power}}$$

*Example:* What is the peak power and duty cycle of a radar transmitter with a pulse width of 1.0 μsec, PRR of 900, and average power of 18 watts? Solving from the formula,

$$P_{\text{peak}} = \frac{P_{\text{av}}}{\text{PRR} \times \text{pulse width}} = \frac{18}{900(0.000001)} = 20{,}000 \text{ watts}$$

$$\text{Duty cycle} = \frac{P_{\text{av}}}{P_{\text{peak}}} = \frac{18}{20{,}000} = 0.0009$$

**29.6 The Antenna System.** The radar antenna system consists of a coaxial output line from the magnetron, a waveguide leading to the antenna, an antenna, and a *duplexer* in the waveguide near the magnetron, shown in block form in Figs. 29.6 and 29.9. The RF energy extracted from the magnetron by the loop and coaxial line is radiated into a waveguide, as mentioned previously.

A waveguide is a long rectangular (or cylindrical) metal box, the widest inner dimension being more than a half-wavelength at the frequency being used. The end of the center conductor of the magnetron coaxial line acts as a quarter-wavelength antenna, transmitting RF energy down the waveguide. At the far end, the walls of the waveguide may be expanded to form a horn, and the RF energy will radiate from the horn into a nearby parabolic antenna reflector. In some equipment the waveguide carries the signal up to the antenna, where the inner conductor of a coaxial cable projects into the waveguide, acting as a receiving antenna. The signal picked up is transferred a short distance by coaxial cable to a tiny vertical half-wavelength dipole which radiates RF energy into the reflector.

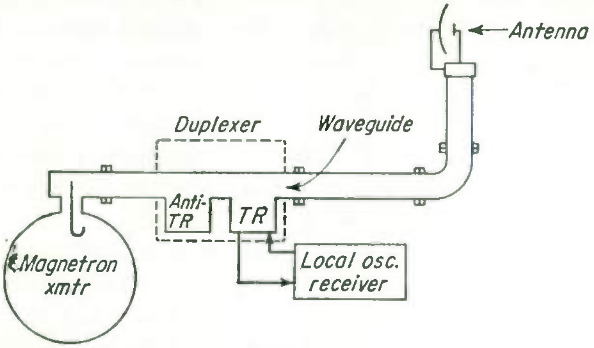


FIG. 29.6. Block diagram of a magnetron transmitter, waveguide, duplexer, receiver, and antenna.

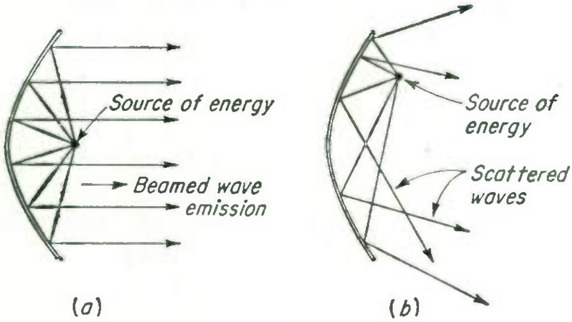


FIG. 29.7. Parabolic reflectors. (a) With the source at the focal point, the reflected waves are all radiated parallel, forming a narrow beam. (b) Waves are scattered when the source is not at the focal point.

Radio waves of 3,000 or 9,000 Mc propagate much the same as light rays. As in a flashlight, these radio waves can be focused into a narrow beam with a metal parabolic reflecting surface by placing the radiator at the focal point (Fig. 29.7). By shaping the reflector properly, the emitted wave can be formed into the desired 2° horizontal width and 15° vertical beam height.

Both radiator and reflector are rotated constantly at about 10 rpm, in synchronism with the sweep coils rotating around the neck of the CRT in the indicator.

The horn, or dipole radiator, is usually covered with polystyrene, or some other plastic, to protect it from weather. This plastic must not be painted. An excessive amount of soot or dirt on either the polystyrene cover or on the active surfaces of the reflector may decrease the transmission and reception to a slight degree. The radiated power is considerable with some radar equipment. There are reports of people standing near the reflector, in line with the beam of high-powered equipment, for a few minutes being cooked internally and dying within a few days. Radar beams have been known to ignite a shipment of photograph flashbulbs and to start fires.

The placement of the radar antenna is important. It should be mounted as high and as much in the clear as possible. The higher the antenna, the farther it can "see" targets. If the radiated beam is above masts, booms, and stacks, these objects will not be able to reflect, re-reflect, and produce false signals on the indicator.

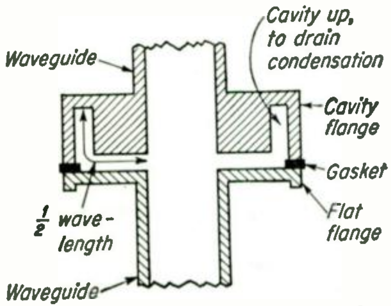


FIG. 29.8. Cross-section details of a choke joint used to couple waveguide sections.

Waveguides must be securely clamped to stationary housings with special hangers and grounded, every few feet in some cases, to prevent unwanted radiation from them and to prevent joints from loosening. Rectangular waveguides are preferable to cylindrical ones since they are less likely to operate in undesirable modes and are simpler to install and maintain.

The waveguide method of conducting RF energy is much more efficient than coaxial or other transmission lines at radar frequencies. At lower frequencies the required dimensions (more than a half-wavelength across) make them undesirable. To prevent reflection of waves and loss of energy, the inner surfaces must be dry and perfectly smooth, preferably silver-plated to present a low-resistance surface or gold-plated to form a nontarnishing surface.

When coupling sections of waveguide together, it is difficult to make a perfect enough bolt-together flat-flange joint to prevent reflections at the irregularities of the joining point. Instead, a *choke joint* is used (Fig. 29.8). When the flat flange is pressed against the hollowed and notched flange, a half-wavelength deep, right-angled cavity is produced, shorted at the far end. This reflects a low impedance a half-wavelength away at the opening between the two waveguides, and energy passes the joint without being reflected. The choke joint must be securely bolted together to make it weatherproof. This is usually accomplished by using a thin rubber gasket between bearing surfaces. Such an electrical separation does not affect the operation of the flange cavity. For this reason choke joints can be made into rotating joints, as between the top of the waveguide and the rotating antenna.

Condensation in the waveguides becomes a problem at sea. On vertical-waveguide runs it is necessary to install choke joints with the cavity in the position shown, to allow any water that may form in it to drain out.

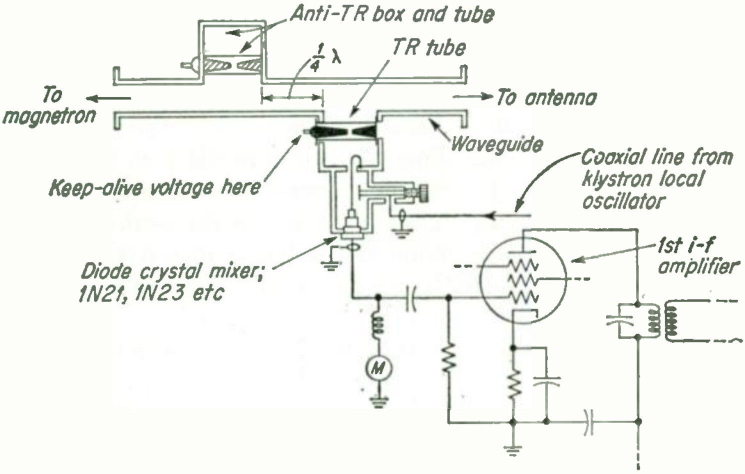


FIG. 29.9. Details of the TR, anti-TR, and crystal-mixer circuits.

Long horizontal runs are undesirable because droplets lying in the waveguide will attenuate the wave. At the bottom of elbows, or bends, in waveguides a small hole is sometimes used as a draining outlet.

**29.7 TR Boxes.** The radar transmitter and receiver use the same antenna system. Some means must be provided to prevent the powerful transmitter signal from feeding directly into the receiver and burning out the input circuit. This is accomplished by using a resonant *transmit-receive* (TR) cavity with a special gas-filled spark-gap TR tube in it. The cavity is coupled to an opening in the antenna waveguide. Signals in the waveguide excite the tuned cavity into oscillation. A coupling loop in the cavity feeds these signals to the crystal-diode mixer and to the receiver (Fig. 29.9).

When the transmitter emits a pulse from the magnetron, the high-powered waves from this signal induce enough voltage across the TR cavity to ionize the TR tube, and it conducts. The tube then effectively shorts out the cavity, detunes it, and prevents high-amplitude signals from forming in it. At the conclusion of the transmitted pulse, the T tube de-ionizes and the cavity is ready to receive any returning echo signals. To make the TR tube more sensitive, a d-c *keep-alive* voltage i applied across it at all times. This voltage is not quite high enough t support ionization. However, a small increase in voltage across the ga will ionize it. When the TR tube ages, it requires a greater signal voltage to produce ionization, and it does not protect the crystal diode i the mixer circuit of the receiver, and the diode burns out.

The distance from the point where the magnetron is coupled to th waveguide and where the TR box is installed is very critical. A les critical means of coupling the TR box to the waveguide is to use a secon tuned cavity, placing it exactly a quarter-wavelength from the TR bo opening. This second cavity is called an *anti-TR box*.

The anti-TR box has a TR tube in it also, but since it does not have t protect any circuits, it has no keep-alive voltage. The anti-TR ionize during the transmitted pulse, presenting a low impedance across its opening in the waveguide. This allows the pulse moving up the waveguid to pass unattenuated. When the pulse ceases, the anti-TR tube de-ionizes and presents a high-impedance point to the waveguide. Now ech signals coming down the waveguide can no longer pass to the magnetron but are reflected at the anti-TR opening, and dispose of their energy i the TR cavity, which is the input circuit of the receiver.

**29.8 The Klystron Tube.** Radar receivers are always superheterodynes, with an intermediate frequency (IF) of approximately 30 Mc. This requires an oscillator operating at a frequency only 30 Mc removed from the transmitting frequency (approximately 3,000 or 9,000 Mc). Normal triode-type tubes will not operate at these frequencies. Small magnetrons could be employed, but they require dangerously high potentials. Therefore a klystron tube is used in the local oscillator circuit.

Some klystrons are constructed with an attached resonant cavity, while others may be fitted into a properly dimensioned cavity in the receiver. The basic klystron oscillator circuit is shown in Fig. 29.10. Although it appears to have two cavities in the cross-section-type illustration, it actually has one doughnut-shaped cavity, with two grids closing the *doughnut hole.*

Electrons are emitted by an indirectly heated cathode and are attracted through the tube by the positive charges on the control grid and the two cavity grids. The electron stream passing through the cavity grids will always have a slight variation (unequal cathode emission, impulses, etc.) and will excite the cavity into weak oscillation. This oscillation makes one of the cavity grids a little more, and the other a little less, positive, which tends to group the electrons into bunches as they pass through. When the electron bunches emerge from the cavity-grid area, they are moving toward a negatively charged *repeller plate.* The negative charge causes the electron bunches to slow down, stop, and then be repelled or cast back toward the positive cavity-grid area. Because of the cast-back effect, these tubes are known as *reflex* klystrons.

If the repeller plate has the proper negative amplitude, the bunches will arrive back at the second cavity grid in time to aid the cavity oscillations that are bunching the electrons. Under this condition the circuit results in better-defined bunches and produces sustained oscillations in the cavity.

Should the repeller voltage be such that the electron bunches return too soon, or too late, the repelled bunches oppose the oscillation of the cavity and the circuit will not produce sustained oscillations. Single-cavity reflex klystrons may be only 1 or 2 per cent efficient, but this is sufficient for the mixer service in a receiver.

The factors that determine frequency of oscillation are the physical size of the cavity and, to a lesser degree, the potential on the repeller plate. Factors determining sustained oscillation or not are the relative potentials on the grids and repeller plate.

The output energy is taken with a loop in the cavity of the klystron and is coupled, by coaxial line, to the duplexer-mixer cavity in the radar set. Here the RF oscillation is capacitively coupled to the output of the TR cavity, which is coupled in turn to the mixer crystal diode. Thus, the crystal diode has both the received signals and the output of the klystron fed to it at the same time. The difference between these is the intermediate frequency fed to the first IF amplifier, (Fig. 29.9).

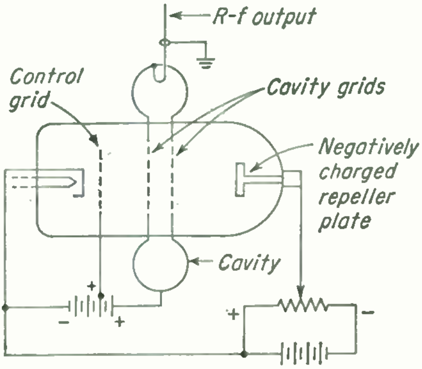


FIG. 29.10. Elements of a reflex klystron, SHF, cavity-oscillator tube.

**29.9 The Radar Receiver.** The radar receiver consists of the crystal-diode mixer stage, a klystron local oscillator, six or more 30-Mc IF amplifiers, a diode-rectifier second detector, and two or more stages of *video* amplification capable of amplifying signals up to several megacycles. This wide range is required because a pulse of 0.5 μsec duration represents a frequency of 1 Mc. The square waveshape of the pulse represents many harmonics of the 1-Mc frequency. To reproduce the waveshape, its fundamental plus many harmonics are needed.

Some radar sets use an automatic-frequency-control (AFC) circuit to keep the klystron circuit oscillating on the correct frequency. In such a case, a second crystal diode is coupled to the duplexer-mixer cavity. The output of this crystal mixer is similar to that of the receiver mixer, feeding an IF amplifier and a 30-Mc discriminator circuit. When the transmitter and klystron are separated by the proper IF difference, no output is delivered by the discriminator circuit. Should either the transmitter or the klystron drift in frequency, a d-c output voltage is produced by the discriminator, is amplified, and is made to vary the repeller voltage of the klystron, forcing it to oscillate at a frequency 30 Mc from the transmitter frequency. A block diagram of a radar receiver with an AFC circuit is shown in Fig. 29.11. When mixer crystals must be replaced, AFC crystals should also be changed at the same time.

The IF stages of a radar receiver are basically similar to other superheterodynes. However, to prevent returning echos from nearby sea waves, known as *sea return*, from being shown on the indicator, it is necessary to desensitize the receiver immediately after the transmitted pulse. The sensitivity of the IF stages must return to maximum in 10 to 15 μsec. Sea-return elimination may be accomplished by using a thyratron tube in a *sensitivity time control* (STC) circuit. A simplified STC circuit is shown in Fig. 29.12

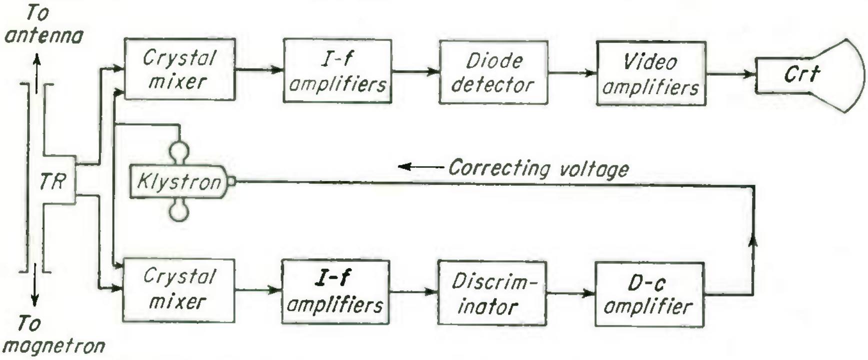


FIG. 29.11. Block diagram of an AFC system in a radar receiver.

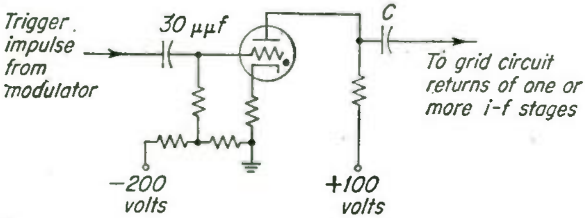


FIG. 29.12. A thyratron STC circuit that develops a decaying bias for the IF amplifiers.

When a positive trigger impulse from the transmitter modulator is applied to the thyratron grid circuit, it overcomes the bias. The tube ionizes, conducts heavily, and discharges capacitor $C$ (Fig. 29.12). This drives electrons from the right-hand plate of the capacitor to the grid circuits of the IF stages, biasing them negatively and desensitizing them. At the completion of the trigger pulse, the thyratron de-ionizes, and capacitor $C$ begins charging, reducing the negative charge on the grids to normal in a few microseconds. Thus, as the transmitted pulse is produced, the IF stages are highly biased and insensitive. As time progresses, the bias falls off, and in 10 to 15 μsec normal sensitivity returns. STC is controlled by a switch on the panel.

The signal from the IF stages is rectified, or detected, by a crystal diode and fed to the video stages, where it is limited to reduce *blooming* (excessively expanding blips on the CRT screen).

The output impulses of the video amplifiers are fed to either the grid or to the cathode of the CRT, producing the visible echo signals on the screen. A manual gain control in the video stages acts as the *brilliance* control for the scope presentation.

A manual gain control on the IF amplifiers acts as the *sensitivity* control. This control is adjusted to produce a just-visible trace on areas of the CRT screen where no targets are displayed.

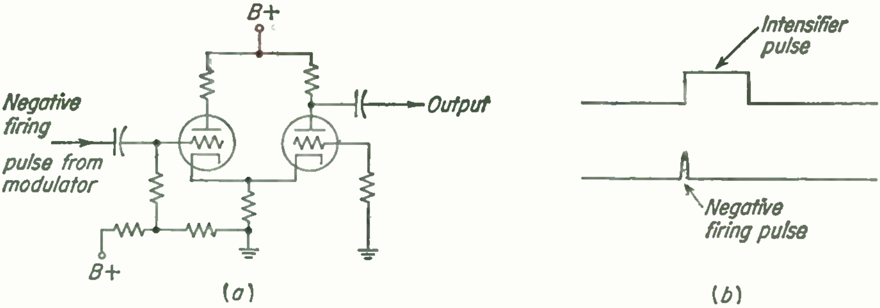


FIG. 29.13. A one-shot multivibrator oscillator (*a*), used to develop the intensifier pulse (*b*).

**29.10 The Indicator.** The indicator section of the radar system will be considered as the CRT, the necessary gating oscillator, sweep signal generator, marker signal generator, and mixer circuit.

To activate the CRT for a period equal only to the maximum range of the radar set, a square-wave voltage, known as an *intensifying pulse* (Fig. 29.13), is generated by a special *one-shot* multivibrator oscillator. When this pulse drops off, received signal voltages past the desired range cannot appear on the scope. To produce this, the positive trigger voltage from the modulator is amplified and inverted to a negative pulse which fires the one-shot multivibrator. The output of this stage is fed to two points. One is to a saw-tooth wave-shaping circuit, where the leading edge of the intensifier pulse discharges a capacitor, which produces a saw-tooth waveform as it recharges. This wave is amplified, fed to a direct-current restorer, to a mixing stage, and then fed across the deflection coils that are rotating around the neck of the CRT, as well as through a circuit that permits accurate centering of the starting trace.

The intensifying pulse is also fed to a second circuit, the *range-marker* generator. This circuit normally has current flowing through it, but when the intensifying pulse appears, it drives the tube into nonconduction. A high-$Q$ coil-capacitor circuit in its cathode is shocked into several cycles of damped oscillation at a frequency dependent upon the $LC$ product. One radar mile is equivalent to 12.4 $\mu$sec. An oscillation frequency of 80.7 kc will produce one cycle in this time. These cycles are shaped or clipped to equal amplitude. The leading edge of each cycle is used to generate a very short impulse. This short pulse is fed to the mixer circuit along with the intensifying pulse. The result is an intensifying pulse with sharp positive spikes every 12.4 $\mu$sec, or every radar mile. This is the composite signal fed to the deflection coils as the sweep voltage. The range-marker signals appear on every outward-moving trace, all around the face of the tube, resulting in a pattern of concentric circles, each separated from the next by the equivalent of a mile. By counting range markers, the range of any observed target blip can be accurately estimated. A gain control on the output of the range-marker circuits controls the intensity of the rings. On longer-range presentations, the markers may be generated every 5 or 10 miles, instead of every 1 mile.

The CRT used in radar has 10-sec persistence instead of the few hundredths of a second of TV tubes. A TV receiver employs both vertical- and horizontal-deflection coils, but in a radar indicator there is only one set of coils. These are gear-driven around the neck of the tube 10 times a minute, in synchronism with the rotation of the antenna. Connections are made to the moving coils by two slip rings and brushes.

With the exception of the synchronizing system between antenna and sweep coils on the CRT, a complete radar system has been outlined.

To summarize the operation, the sequence began with the blocking oscillator generating a series of pulses at approximately 1,000 pps. These pulses were shaped and used to fire a magnetron, as well as being used to trigger the indicator circuits. The magnetron emitted a strong RF burst from the slowly rotating antenna. The TR and anti-TR tubes protected the receiver and allowed only received echo signals to enter the mixer cavity of the receiver. The received impulses were amplified, detected, and fed to the cathode of the CRT. At the same time, the trigger impulse started an intensifying pulse that was fed to the grid of the CRT, enabling received signals to produce indications on the screen. The intensifying pulse also started a saw-tooth wave that produced the sweep trace from the center of the screen out to the edge, 1,000 times a second as the sweep coils were rotating. This resulted in a presentation of all radar targets in their relative position around the ship. The direction of the targets is determined by their angle from the top of the screen; their range is determined by how far they are from the center. As an aid to determining distance, range markers can also be turned on. To reduce sea-return echoes, the sensitivity time control circuit can be adjusted to the lowest value that does not produce blurred light areas near the center of the screen.

**29.11 Antenna Synchronization.** If the antenna were only a few feet above the indicator, it would be possible to use a single vertical drive shaft with gears at both ends and rotate the antenna and the deflection coils, mechanically, in perfect synchronization. In practice this is not feasible.

Some sort of *selsyn* system is usually used. A basic form of selsyn system consists of a selsyn generator and a selsyn motor. Both units are similar, each having a rotor and three stator windings, interconnected as shown in Fig. 29.14.

The connections of the stator windings make this appear to be a three-phase system, but this is not true. There is only the single phase of the 115-volt 60-cycle a-c. This emf is fed to both motor and generator rotors. The magnetic fields from these rotors induce voltages in the stators. As long as the two rotors are resting at the same relative angle between similar field coils, the voltages induced in these stator coils will equal each other, and a condition of balance occurs. If the motor is held in position and the generator rotor is moved by hand in a clockwise direction, the voltages induced in the two sets of stators will no longer be similar. This results in a magnetic pulling, in a counterclockwise direction, by the generator rotor, and clockwise pull by the motor. If both are released at the same time, both rotors will rotate until they reach a median position, where there is no magnetic pull on either. When the generator is turned, the motor will respond to the proportionate magnetic changes produced in its stator fields and will follow the angular rotation of the generator rotor.

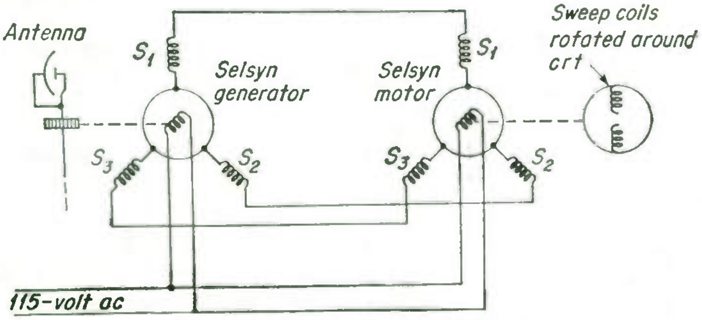


FIG. 29-14. A basic selsyn system.

Mechanically coupling the rotating radar antenna to a selsyn generator and the selsyn motor to the rotating mechanism that drives the deflecting coils around the neck of the CRT provides a means of synchronizing antenna and deflection-coil rotation. However, in operation, rotation of the selsyn motor must always lag that of the generator by some degree. The degree may change with variations of friction, wind pressure against the antenna, etc. The possibility of change of lag angle and an inherent lack of sensitivity make other forms of selsyns more desirable.

The selsyn circuit in Fig. 29.15 uses the emf induced in the unexcited motor rotor as a correcting voltage. If the two rotors are in the same angular position, no voltage will be induced in the motor rotor. As the rotors are varied in angular placement, the motor-rotor-induced voltage will change, but the rotor does not try to turn. A 60-cycle a-c voltage is induced in it, is fed to a vacuum-tube amplifier, is shifted in phase, and is fed to one winding of a two-phase a-c motor. The power-circuit a-c is fed to the other winding of the motor. With both phases applied, the motor rotates, turning the selsyn motor rotor, which is geared to turn the deflection coils of the CRT. If the antenna tends to rotate faster than the deflection coils, a greater voltage is induced in the motor rotor. This correction voltage increases the speed of the two-phase motor, and the deflection coils pick up the necessary speed. Again, the motor must always lag the generator somewhat, but in this system the amplifiers reduce the lag, or variation in lag, to a small value, resulting in satisfactory synchronization for the radar system. The amplifier and driving motor are known as a *servomechanism*. Note that the rotation of the CRT coils is completely dependent on the rotation of the antenna. If the antenna motor stops, the selsyn generator is no longer rotated by the antenna rotation, the correcting voltage is no longer developed, and the CRT coils stop.

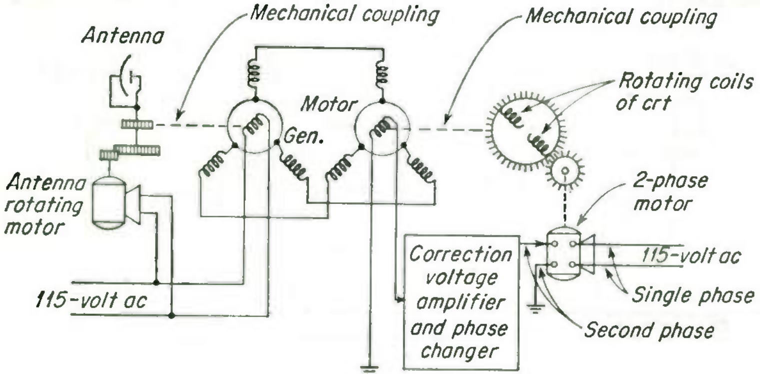


FIG. 29.15. A servomechanism, or synchro system, to synchronize the rotation of the radar antenna and the deflection coils around the cathode-ray display tube.

**29.12 Heading Flash.** As the radar antenna turns toward the bow of the ship, it trips a microswitch, which feeds a short positive pulse of voltage to the grid of the CRT. This results in a trace being made from the center of the screen to the edge. Such a *heading flash* indicates, on the CRT, the direction the ship is taking on the chartlike presentation of the PPI screen. The circuit can be turned on or off by a control on the indicator panel.

**29.13 Echo Box.** When at sea, with no targets available, or whenever it is desired to test the over-all sensitivity and operation of the radar set, an *echo box* can be used. This is a high-$Q$ cavity, resonant to the transmitter frequency. It may be coupled into the waveguide at some convenient place to pick up RF pulses. Each transmitted pulse shock excites the cavity into oscillation, and it responds with a damped-wave output. The coupling to the echo box is usually adjusted to ring for about 12 μsec. As long as it is active, it produces a tapering-off signal for the receiver and will result in illumination of the screen, outward from the center, for a distance equal to about one mile. If tubes or crystals become weakened, or the system is not operating properly, the distance indicated is less, or no echo box signal will be seen at all.

Since the echo box will blot out all targets within a mile radius, it is necessary either to decouple it by some mechanical means or detune it far enough so it will not ring. One method utilizes a plunger that tunes the box through resonance as it is pushed down. This results in a flash on the radial traces that are being presented only during the time that the box is being tuned through resonance.

**29.14 Operating the Radar Set.** The master of the vessel, or any person designated by him, may operate the radar set. No radio license is required. Furthermore, such persons may replace fuses or receiver-type tubes in the set, although this duty usually falls to one of the radio operators. However, whenever the equipment requires maintenance other than this, only persons holding First or Second Class licenses *with radar endorsements*, or persons working under direct supervision of such a license holder, may make adjustments, or service, or install radar equipment.

Each radar installation must have an installation and maintenance record, kept at the radar station. This record will include the date and location of installation and the name and license number of the person installing it. All subsequent maintenance, tubes, fuses, oiling, interference reports, tuning, etc., must be noted, with date and action taken, signed by the person responsible. The station licensee, usually through the master, is jointly responsible with the operator concerned for the faithful and accurate making of such entries.

It is required that at least one set of instructions for the use and operation of the particular type of radar being used, as well as the FCC publication, "Part 8—Stations on Shipboard in the Maritime Services," be on board the vessel.

A radar transmitter is one of the few RF emissions that require no specific identifying emissions or call letters.

**29.15 Radar Interference.** In most cases, the only interfering signals received on a radar set are due to other radar transmitters operating in the same area. This may take the form of curved dotted lines across the screen.

The radar transmitter can produce interference to other radio receiving or electronic devices in its vicinity, however. Such radiation of interfering signals may be caused by improper shielding, bonding, or grounding of radar equipment or connecting cables and waveguides, or by inadequate bypassing of the input power lines.

Interference to a radio receiver by radar is characterized by a harsh tone having a frequency of the PRR, about 1,000 cycles. The noise may increase and decrease as the radar antenna rotates, or be steady if originating at the radar set itself. If grounding and bypassing power lines and other circuits do not help, it may be necessary to change the position of the receiving antenna. Rotation of the RDF loop may indicate nulls on interference produced by a radar transmitter.

Motors or generators in the radar set, with slip rings or armatures and brushes, may cause a constant scratching sound. Such interference may appear to peak at certain frequencies, particularly if caused by re-radiation by random-length wires, but may be picked up on all frequencies used at sea (100 kc to 150 Mc).

On the loran screen, radar interference appears as either *grass* or *spikes.* Sparking noise from motors appears as many vertical pips across the traces of the loran screen and actually looks like grass. Interfering signals due to the constant-rate pulsed emission of the radar transmitter appear as spikes on the loran screen. These spikes may appear to drift in one direction or the other or may appear to synchronize for short periods of time.

On an autoalarm receiver, radar interference will sound the same as on any other receiver if earphones are used. It presents a constant signal which may activate and hold the first dash counter circuit. The red light on the bridge and in the radio station will glow, indicating trouble.

Intercommunication, motion-picture, or public-address systems on the vessel may also pick up radar impulses if they are not properly shielded and grounded, or if they have poor connections at some points in them.

**29.16 Basic Radar Maintenance.** Although cabinet enclosures may be protected by interlocks that remove high voltages when opened, some voltages, up to two or three hundred, may not be disconnected. Interlocks should never be jumpered or shorted to operate the high-voltage systems with the enclosure doors open.

In most cases, faulty operation of a radar set is the result of weak tubes, faulty TR gaps or crystals, or blown fuses. Tubes may be checked with a tube tester, or similar tubes substituted, one by one. When a TR gap weakens, the mixer crystals usually fail also, and the crystal current drops. When mixer crystals are replaced, it may be necessary to replace the TR gap at the same time. The crystals are quite sensitive to mechanical shock, magnetic fields, and electric current. Under certain conditions, the operator may attain a static charge. When he pushes the cartridge-like crystal (about the size of a 22-caliber shell) into its socket, he may discharge through the crystal, burning it out. To prevent this, the operator should always touch the crystal cavity with one hand while inserting the crystal with the other, or ground himself in some other way. When a crystal is handed from one person to another, it should be kept in its metal-foil capsule to prevent static discharge and burnout. Never apply mechanical pressure to the crystal in any way.

The magnetron current should be checked periodically. No plate current may indicate an open filament or no modulator pulses. If the current is abnormally high, it may mean a gassy magnetron or a high PRR. The permanent magnet used in conjunction with the magnetron is quite strong. There is danger, when a magnetron is being removed or installed, that iron and steel tools may be grabbed by the magnet and cause damage to the tube. The filament leads and the output circuit have long glass seals that may be fractured by mechanical jarring.

If the permanent magnet weakens, the magnetron current will increase, the output power will lessen, and the frequency of operation may change so much that the automatic frequency control (AFC) will not hold the receiver in tune.

When the AFC circuit or the magnetron is functioning improperly bright pie sections may appear on the screen.

Remember that the filament leads to the magnetron have several thousand volts on them when the set is in operation.

Most equipment has a series of jacks into which a test meter can be inserted to test the operation of the different circuits. It will be necessary to check the instruction booklets that accompany the equipment to determine what the readings should be.

With the sensitivity control turned to maximum, with little or no grass or signals appearing, and low crystal current indicated, the crystal may be suspected. It may be removed and checked by measuring its resistance with a sensitive ohmmeter (with a 10,000-ohm resistor in series) in both directions. If the front-to-back ratio is less than about 10:1 it should be replaced. No crystal current may also indicate a defective klystron. Turn off the equipment before changing this tube, which may have several hundred volts on the shell of its cavity. When klystrons or TR tubes are replaced, it is usually necessary to retune the associated cavities to bring the set up to optimum performance.

Cathode-ray tubes are dangerous to service because of high voltages applied to them and the possibility of implosion. Heavy gloves and a face mask should be worn when changing them.

Motors and generators should be checked every 200 to 300 hr of operation. They should be cleaned, and the brushes checked and replaced if necessary. Oil or grease should be applied where necessary. Remember that oil left on rubber and other electrical insulations may cause them to deteriorate.

Before leaving the dock, the radar set should be turned on and tested. At this time it should be dusted thoroughly and observed carefully, and any signs of overheating at any place or improper functioning of mechanical parts should be noted.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

1. If the velocity of a radio wave is 186,000 statute miles/sec, how many nautical miles does a radar pulse travel in 1 μsec? (29.1) [6]

2. In what part of the RF spectrum do marine radar systems operate? (29.1) [6]

3. Approximately at what speed does the antenna of a navigational radar rotate? (29.2) [6]

4. Draw a simple block diagram showing the essential components of a radar system. Label the components, such as receiver, indicator, etc. (29.2) [6]

5. What is the average plate power input to a radar transmitter if the peak pulse power is 15 kw, the pulse length is 2 μsec, and the pulse repetition frequency is 900 cycles? (29.5) [6]

6. How is a radar set adjusted by the operator to reduce sea return? (29.9) [6]

7. What is the distance in nautical miles to a target if it takes 123 μsec for a radar pulse to travel from the radar antenna to the target, back to the antenna, and be displayed on the PPI scope? (29.1) [8]

8. Within what frequency bands do ship radar transmitters operate? (29.1) [8]

9. Explain briefly the principle of operation of a radar system. (29.1, 29.2) [8]

10. Draw a block diagram of a radar system, labeling the antenna, duplexer, transmitter, receiver, modulator, timer, and the indicator. (29.2) [8]

11. Explain the principle of operation of the cathode-ray PPI tube, and explain the function of each electrode. What is the purpose of the aquadag coating? (29.2, 11.29, 25.4) [8]

12. Draw a diagram of a CRT as used in radar showing the principal electrodes in the tube and the path of the electron beam. (11.29, 25.4) [8]

13. What circuit element determines the operating frequency of the self-blocking oscillator? (29.4) [8]

14. What component in a radar set determines the PRR? (29.4) [8]

15. What is meant by bearing resolution of a radar set? (29.2) [8]

16. What is the purpose of an artificial transmission line in a radar set? (29.4) [8]

17. What is the purpose of the rotary spark gap used in some radar sets? (29.4) [8]

18. Draw a simple diagram of an artificial transmission line showing inductance and capacitance, source of power, the load, and the electronic switch. (29.4) [8]

19. Why is the anode in a magnetron in a radar transmitter normally maintained at ground potential? (29.5) [8]

20. Explain briefly the principle of operation of the magnetron. (29.5) [8]

21. Draw a simple cross-section diagram of a magnetron showing the anode, cathode, and the direction of electronic movement under the influence of a strong magnetic field. (29.5) [8]

22. What is the peak power of a radar pulse if the pulse width is 1.0 μsec, PRR is 900, and the average power is 18 watts? What is the duty cycle? (29.5) [8]

23. How are waveguides terminated at the radar antenna reflectors? (29.6) [8]

24. Is there any danger in testing or operating radar equipment aboard ship when explosive or inflammable cargo is being handled? (29.6) [8]

**25.** Why are choke joints often used in preference to flange joints to join sections of waveguides together? (29.6) **[8]**

**26.** What precautions should be taken when installing vertical sections of waveguides with choke coupling flanges to prevent moisture from entering the waveguide? (29.6) **[8]**

**27.** Draw a longitudinal section of a waveguide choke joint and explain briefly its principle of operation. (29.6) **[8]**

**28.** Why are rectangular cross-section waveguides generally used in preference to circular cross-section waveguides? (29.6) **[8]**

**29.** Why are waveguides used in preference to coaxial lines for the transmission of microwave energy in most shipboard radar installations? (29.6) **[8]**

**30.** When installing waveguides, why should long perfectly level sections of waveguides be avoided? Why is a small hole about ⅛ in. in diameter sometimes drilled on the underside of an elbow in a waveguide near the point where it enters the radar transmitter? (29.6) **[8]**

**31.** Describe briefly the construction of a waveguide. Why should the interior of the waveguide be clean, smooth, and dry? (29.6) **[8]**

**32.** What effect, if any, does the accumulation of soot or dirt on the antenna reflector have on the operation of a ship radar? (29.6) **[8]**

**33.** What considerations should be taken into account when selecting the location of the radar antenna assembly aboard ship? (29.6) **[8]**

**34.** Describe how a radar beam is formed by a paraboloidal reflector. (29.6) **[8]**

**35.** Describe briefly the construction and operation of radar TR and anti-TR boxes. What is the purpose of a "keep-alive" voltage? (29.7) **[8]**

**36.** Draw a simple block diagram of a radar duplexer system, labeling the waveguide, the TR box, anti-TR box, the receiver, and the transmitter. (29.7) **[8]**

**37.** Draw a simple frequency-converter circuit (mixer) as frequently used in radar superheterodyne receivers, and indicate which is the crystal stage. (29.7) **[8]**

**38.** Explain briefly the purpose of the STC circuit in a radar set. (29.9) **[8]**

**39.** Draw a simple block diagram of a radar receiver, labeling the signal crystal, local oscillator, AFC crystal stage, IF amplifier, and discriminator. (29.9) **[8]**

**40.** What is the purpose of the discriminator stage in a radar superheterodyne? (29.9) **[8]**

**41.** What nominal intermediate frequencies are commonly found in radar receivers? (29.8) **[8]**

**42.** Explain briefly the principle of operation of the reflex klystron. (29.8) **[8]**

**43.** What is the purpose of the klystron tube in a radar set? (29.8) **[8]**

**44.** What type of detector is used frequently in radar receivers? (29.9) **[8]**

**45.** What is sea return on a radar scope? (29.9) **[8]**

**46.** Draw a simple diagram showing how a synchro generator located in the radar antenna assembly is connected to a synchro motor located in the indicator to drive the deflection coils. Show proper designation of all leads, designating where a-c voltages (if needed) are applied. (29.11) **[8]**

**47.** Explain how heading flash and range-marker circles are produced on a radar PPI scope. (29.12) **[8]**

**48.** What is the purpose of an echo box in a radar system? Explain the principle of operation of the echo box. What indications may be expected on a radar scope when using an echo box and the radar set is operating properly? When the radar set is not operating properly? (29.13) **[8]**

**49.** Who may operate a ship radar station? (29.14) **[8]**

**50.** Under what conditions may a person who does not hold a radio operator license operate a ship radar station? (29.14) **[8]**

**51.** May fuses and receiving-type tubes be replaced in ship radar equipment by a person whose operator license does not have a ship radar endorsement? (29.14) **[8]**

**52.** What are the FCC license requirements for the operator who is responsible for the installation, servicing, and maintenance of ship radar equipment? (29.14) **[8]**

**53.** Who has the responsibility for making entries in the installation and maintenance record of a ship radar station? (29.14) **[8]**

**54.** What entries are required in the installation and maintenance record of a ship radar station? (29.14) **[8]**

**55.** Who may make entries in the installation and maintenance record of a ship radar station? (29.14) **[8]**

**56.** Describe how various types of interference from a radar installation may be apparent to a person listening to a radio communications receiver. (29.15) **[8]**

**57.** Explain briefly why radar interference to a radiotelephone receiver is frequently characterized by a steady tone in the radio loudspeaker. (29.15) **[8]**

**58.** Why is it important that all units of a radar installation be thoroughly bonded to the ship's electrical ground? (29.15) **[8]**

**59.** On what frequencies should the radar serviceman look for radar interference to communication receivers on ships equipped with radar? (29.15) **[8]**

**60.** In checking a radio direction finder for interference caused by radar equipment, would it be a good policy to check for interference while the DF loop is being rotated? (29.15) **[8]**

**61.** Is there any likelihood of a radar installation causing interference to radio receivers if long connecting lines are used between the radar transmitter and the radar modulator? (29.15) **[8]**

**62.** What steps might be taken by a radar serviceman to eliminate a steady-tone type of interference to radio communication receivers, or interference to loran receivers evidenced by spikes? (29.15) **[8]**

**63.** List at least two types of indications on a loran scope that signify that a radar installation is causing interference to the loran. (29.15) **[8]**

**64.** How are the various types of radar interference recognized in (*a*) autoalarm equipment, (*b*) DF equipment? (29.15) **[8]**

**65.** What steps might be taken by a radar serviceman to reduce grass on a loran scope or motor-generator noise in communication receivers? (29.15) **[8]**

**66.** Name at least four pieces of radio or electronic equipment aboard ship that might suffer interference from the radar installation. (29.15) **[8]**

**67.** What care should be taken when handling silicon crystal-rectifier cartridges for replacement in radar superhet receivers? (29.16) **[8]**

**68.** What precautions should the service and maintenance operator observe when replacing the CRT in a radar set? (29.16) **[8]**

**69.** What precaution should a radar serviceman observe when making repairs or adjustments to a radar set to prevent personal injury to himself or other persons? (29.16) **[8]**

**70.** What precautions should a radar serviceman take when working with or handling a magnetron to prevent weakening or damage to the magnetron? (29.16) **[8]**

**71.** In a radar set what indicates (*a*) a defective magnetron, (*b*) a weak magnet in the magnetron, (*c*) a defective crystal in the receiver converter stage? (29.16) **[8]**

**72.** What tests may a radar serviceman make to determine whether or not the radar receiver mixer crystal is defective? (29.16) **[8]**

**73.** What symptoms on a radar scope would indicate that the radar receiver mixer crystal is defective? (29.16) **[8]**

**74.** What may cause bright flashing pie sections to appear on a radar PPI scope? (29.16) **[8]**

# CHAPTER 30

# BASIC COMMUNICATION LAWS

1+2 3rd class
1-2-3 2nd class
1-2-3-4 1st class

**30.1 FCC Requirements.** This chapter contains a summary of information needed to pass Element 1, included in *all* FCC commercial license examinations. Any radio-operator examination given by the FCC will be composed of one or more of the following eight elements:

class

1. *Basic law.* Provisions of laws, treaties, and regulations with which every operator should be familiar.

2. *Basic operating practice.* Radio-operating procedures and practices generally followed or required in communicating by means of radiotelephone stations.

2nd

3. *Basic radiotelephone.* Technical, legal, and other matters applicable to the operation of radiotelephone stations other than broadcast.

1st

4. *Advanced radiotelephone.* Advanced technical, legal, and other matters particularly applicable to the operation of the various classes of broadcast stations.

5. *Radiotelegraph operating practice.* Radio-operating procedures and practices generally followed or required in communicating by means of radiotelegraph stations primarily other than in the maritime mobile services of public correspondence.

6. *Advanced radiotelegraph.* Technical, legal, and other matters applicable to the operation of all classes of radiotelegraph stations, including maritime mobile services, radio navigational aids, message traffic routing and accounting, etc.

7. *Aircraft radiotelegraph.* Basic theory and practice in the operation of radio communication and radio navigational systems in general use on aircraft. (Not covered completely in this book.)

8. *Ship radar techniques.* Specialized theory and practice applicable to the proper installation, servicing, and maintenance of ship radar equipment in general use for marine navigational purposes.

The Element 1 part of any of the license examinations will consist of 20 multiple-choice questions selected from subjects similar to those indicated in the FCC questions at the end of this chapter. It will be noted that some information of a general nature from other elements has been added to this section.

**30.2 Radio Laws and Regulations.** To prevent intolerable interference, radio stations throughout the world operate according to agreements set up at international communication meetings.

In 1934, the United States combined laws of many previous acts and agreements into the Communications Act of 1934. The Communications Act set up general laws to be followed in the United States that would coincide with communication agreements with other countries. To execute and enforce the provisions of this Act, the Federal Communications Commission was constituted. The FCC has developed a series of rules and regulations for different types of communications services. Part 1 of these rules and regulations is known as "Practice and Procedure." Part 3 is "Radio Broadcast Services." Part 8 is "Stations on Shipboard in the Maritime Services." Part 12 is "Rules Governing Amateur Radio Services." Part 13 is "Commercial Radio Operators." Each part is subject to change as the art of radio progresses in its particular field. Thus, a rule regarding broadcast-station operation last year may not exist or may be changed this year. It is important that owners and operators of radio systems keep themselves informed about the rules and regulations referring to their particular service. Any person who willfully does anything prohibited by the *Communications Act*, or knowingly omits to do anything required by the Act, is subject, upon conviction, to a fine of not more than $10,000 and/or imprisonment for a period of 1 year on the first offense, and 2 years on the second offense.

Anyone willfully violating any *rule*, *regulation*, *restriction*, or *condition* set up by the FCC by authority of the Communications Act or by international treaty to which the United States is a party is subject, upon conviction, to a fine of not more than $500 for each day during which such offense occurs.

One of the many functions of the FCC is the issuance of operator and station licenses to those qualifying for them. This requires the administration of operator examinations. The FCC also has authority to, and does make inspections of, licensed U.S. radio stations of all types whenever necessary to assure operation in accordance with FCC rules and regulations.

Messages transmitted by radio are subject to secrecy provisions of law. No one receiving such messages (amateur, distress, broadcast, and messages preceded by CQ—"attention all stations"—excepted) may divulge their content to anyone but the legal addressee, nor may they use information so gained to their advantage.

**30.3 Operator Licenses.** All U.S. commercial and amateur stations must be licensed by the FCC and must be operated by FCC-licensed operators or permittees. (Army, Navy, and government stations are excluded.)

Various types of commercial communication systems may require operators with different types of licenses. There are four licenses and three permits issued by the FCC. The operator *licenses* and examination requirements are as follows:

| *Radiotelegraph* | *Radiotelephone* |
|---|---|
| FIRST CLASS | FIRST CLASS |
| Elements 1, 2, 5, 6<br>Code test: 20 code groups/min and 25 wpm plain language | Elements 1, 2, 3, 4 |
| SECOND CLASS | SECOND CLASS |
| Elements 1, 2, 5, 6<br>Code test: 16 code groups/min | Elements 1, 2, 3 |

Two lower-grade operating permits are also issued. The holders of these permits are not allowed to make any adjustments that might result in improper transmitter operation (except in a conelrad alert). Any such actual technical adjustments must be made under the supervision of a *licensed* operator. The operator *permits* and examination requirements are as follows:

| *Radiotelegraph* | *Radiotelephone* |
|---|---|
| THIRD CLASS OPERATOR PERMIT | THIRD CLASS OPERATOR PERMIT |
| Elements 1, 2, 5<br>Code test: 16 code groups/min | Elements 1, 2 |

The lowest-grade permit is the Restricted Radiotelephone Operator Permit, requiring no test, only a certification in writing that the applicant requires the permit, can receive and transmit spoken messages in English, is familiar with rules and regulations, and can keep a log. Such a permit is used by taxi drivers, policemen in radio-equipped patrol cars, etc. An understanding of the material in this chapter and the chapter on Communicating by Voice forms a satisfactory minimum communication knowledge for such operations.

All licenses and permits require an ability to transmit and receive spoken messages in English and are issued to citizens of the United States only. An applicant must be twenty-one years of age to be eligible for a Radiotelegraph First Class license examination, and at least fourteen years old for a Restricted Radiotelephone Operator Permit.

To obtain a commercial license it is necessary to take a test at one of the Field Engineering Offices of the FCC, located in most of the larger cities of the country. An application form must be filled out before the license examination will be given. Most offices set specific days for certain types of license examinations. This information should be obtained by phone or mail before appearing at the nearest office for an examination.

Licenses are normally issued for a period of 5 years. To renew a license, a renewal application may be obtained by mail and filled out. The original license and the renewal application may then be presented to the nearest office in person or by mail, within the last year of the license term, or within a 1-year grace period after the expiration of the license. The renewal application must be supported by documentary evidence describing in detail the service performed and showing that the applicant actually operated in a satisfactory manner. During the period when the license and the renewal application are in the mail or at the FCC office, the operator may continue operating by posting an exact, signed copy of his renewal application in lieu of the original license or permit.

The license of an operator normally must be posted at the place where he is on duty. If he is working at two different stations, he may post his license or permit at one station, and at the other station he may post a duly issued *verified statement* (FCC Form 759).

A license or permit holder may apply for a *verification card* (FCC Form 758-F). This card may be carried on the person of the operator in lieu of the original license or permit when operating any station at which posting of an operator license is not required, provided the license or permit itself is reasonably accessible if needed.

If a license or permit is lost, mutilated, or destroyed, the FCC should be notified and a duplicate license or permit requested. If the license is lost, the application for duplicate should state that reasonable search has been made and that if found, either the original or duplicate will be returned for cancellation. The applicant should also submit documentary evidence of the service (experience) that has been obtained under the original license or permit, or a statement under oath or affirmation embodying that information. A signed copy of the application for duplicate license may be used in lieu of the license until the duplicate is issued.

**30.4 Suspended Licenses.** The FCC has authority to *suspend* the license of any operator upon proof that he has violated a provision of acts, treaties, or FCC rules; failed to carry out a lawful order of the master or person lawfully in charge of the ship or aircraft on which he is employed; willfully damaged or permitted radio apparatus to be damaged; transmitted superfluous radio communications or signals, obscene language, false or deceptive signals, or call signals not assigned by proper authority to the station he is operating; willfully or maliciously interfered with any other radio communications; assisted another or obtained an operator's license by fraudulent means.

Such a suspension becomes effective 15 days after the licensee receives the notice of suspension. In this 15-day period the licensee may make application for a hearing on the suspension order. The suspension will be held in abeyance until the conclusion of the hearing, and the licensee may continue to operate until that time at least.

**30.5 Notices of Violations.** The FCC maintains several monitoring stations throughout the country. The operators at these stations spend their time listening to, and checking, all receivable signals. If a radio station appears to have violated any provision of the Communications Act, or FCC rules and regulations, it will be served with a *notice of violation*, calling the facts to the station's attention and requesting a written statement concerning the matter within 3 days (unless another period is specified). The answer must be addressed to the office of the FCC originating the notice and be a full explanation of what occurred, what steps have been taken to prevent future violations, or what new apparatus has been or will be installed, and the name and license number of the operator in charge if the notice of violation relates to lack of attention or to improper operation of the transmitter. If an answer cannot be sent nor an acknowledgment made within the required period by reason of illness or other unavoidable circumstances, acknowledgment and answer must be made at the earliest practical time with a satisfactory explanation of the delay.

**30.6 Who May Operate Transmitters.** Any transmitter employing radiotelegraph (International Morse Code) must be *operated* by a person having a suitable *radiotelegraph* license or permit.

Transmitters employing a microphone for communication are normally expected to be operated by persons holding a suitable radiotelephone, and in many cases radiotelegraph, license or permit. However, a nonlicensed person may speak over a microphone in some services, provided that a licensed operator is in control of the transmitting equipment. In the public-safety radio service (police, fire, etc.), an unlicensed person, such as a patrolman, may operate a mobile station during the course of normal rendition of service, after being authorized to do so by the station licensee.

Radiotelegraph licenses and permits are used by operators on ship radiotelegraph and radiotelephone stations, coastal radiotelegraph stations communicating with ships, aircraft radiotelegraph stations, aeronautical radiotelegraph stations communicating with aircraft stations, police radiotelegraph zone or interzone point-to-point stations, or any other services employing radiotelegraph.

Radiotelephone First Class licenses are required in broadcast, FM, and TV stations. Almost all other radiotelephone communications, such as experimental TV, police, fire, forestry, highway maintenance, special emergency, aircraft, aeronautical, power, petroleum, forest products, motion picture, relay press, industrial, motor carrier, railroad, taxicab, and automobile radio services, as well as experimental broadcast, require only a Radiotelephone Second Class license to operate, and in most cases only a Third Class operator permit.

**30.7 Who May Service or Adjust Transmitters.** Except for standard broadcast, FM, and TV stations, which require Radiotelephone First Class license holders, radiotelephone transmitters in other services, listed above, may be serviced, tuned, or adjusted by holders of Radiotelephone and, in many cases, of Radiotelegraph Second Class *licenses.* Permit holders are not authorized to make technical adjustments to any transmitters (an exception is in the case of a conelrad alert).

Radiotelegraph transmitters (shipboard, coastal, aircraft, aeronautical, zone, etc.) cannot be serviced, tuned, or adjusted by radiotelephone license holders. Technical adjustments must be made by radiotelegraph license holders.

No person holding only an amateur license is authorized to operate or make technical adjustments to commercial radio transmitting equipment (except limited *operation* of *disaster communication services* stations).

No person holding only a commercial license or permit is authorized to operate or make technical adjustments to any amateur radio transmitting equipment.

**30.8 Classification of Communications.** The normal transmissions from radio stations may be classified as *routine.* Transmissions made during times of emergency or to prevent possible disasters, by reason of their importance, demand a higher priority. The order of high-priority radio transmissions or messages is as follows:

1. *Distress*
2. *Urgency*
3. *Safety*

A mobile station in *distress* is in need of immediate assistance. By radiotelegraphy the distress signal is the transmission of the letters SOS (···———···) sent as one character with no spacing between letters. By radiotelephone the distress signal is the word MAYDAY (from the French *m'aider*), usually transmitted three or more times to attract attention. A distress message should contain the name of the station, particulars of its position, nature of the distress, kind of assistance desired, and any other information which might facilitate rescue. The mobile station in distress is responsible for the control of distress-message traffic. However, if the station in distress is not itself in a position to transmit the distress message, or if the master of a station observing the one in distress believes that further help is necessary, then the observing station can send a distress message. Distress messages are not subject to the secrecy provisions of law as are most other radio communications. Any false or fraudulent signals of distress are prohibited by law and punishable by a fine of not more than $10,000 and not more than one year in prison.

Radio messages with an *urgency* classification refer to a situation that requires immediate attention and might conceivably become distress in nature. By radiotelegraphy the urgency signal is the transmission of the three letters XXX. By radiotelephone the urgency signal is the spoken word PAN repeated three or more times.

Radio communications with a *safety* classification refer to meteorological information, particularly storms, hurricanes, etc., or to other navigational warnings. By radiotelegraphy the safety signal is the three letters TTT. By radiotelephone the safety signal is the word SECURITE (from the French *sécurité*).

The subject of message classifications is discussed at greater length in the chapters on Communicating by Voice and on Communicating by Radiotelegraph.

**30.9 Conelrad Alert.** When a conelrad alert is called, a person holding any class of radio operator license or permit who is authorized to perform limited operation of a standard broadcast station may make any adjustments necessary to effect operation on a conelrad frequency in accordance with the station's conelrad authorization. However, it is necessary that a Radiotelephone First Class operator of the station have previously instructed the person in the required adjustments to the transmitter to accomplish conelrad operation (Sec. 24.3).

**30.10 Logs.** All communication systems are required to keep logs of their transmissions. Log entries normally show the date, time, operator on duty, station with whom the communication was carried on, and an indication of what communications occurred or what traffic was handled. Logs are made out by those legally competent to do so. If an error is made in a log, it may not be erased. The error should be struck out, the correct entry made above the error, and then the correction initialed and dated by the operator who made the original entry. Logs are usually required to be kept for at least 1 year. If they contain information pertaining to distress traffic, they should be kept for at least three years. If they contain information pertaining to an investigation being made by the FCC, they must be kept until authority to destroy them is received in writing. (See also Secs. 24.18, 25.10, 31.11, 31.14, 32.14.)

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right.)

1. What penalty is provided by law for willful and knowing violation of the radio laws? (30.2) [1]
2. What penalty is provided by law for willful and knowing violation of regulations imposed by the FCC and of radio treaties? (30.2) [1]
3. Are radio stations subject to inspection by the FCC? (30.2) [1]
4. Does the government have authority to impose fines for failure to comply with the rules and regulations governing the use of radio on compulsorily equipped ships? (30.2) [1]
5. Should a radio station that is required to be operated by a licensed radio operator be a licensed radio station? (30.3) [1]
6. How soon before expiration of an operator license or permit should application be made for renewal? (30.3) [1]
7. What provision is made for operation without an actual operator license or permit pending receipt of a duplicate? (30.3) [1]

**8.** Is it permissible to operate pending receipt of a duplicate operator license or permit after application has been made for reissue? (30.3) **[1]**

**9.** In applying for a duplicate operator license or permit, what documentary evidence must be submitted along with an application? (30.3) **[1]**

**10.** What must a person do whose operator license or permit has been lost, mutilated, or destroyed? (30.3) **[1]**

**11.** Must a person designated to operate a radiotelephone station post his operator license or permit, and if so, where? (30.3) **[1]**

**12.** Where and how is an operator license or permit obtained? (30.3) **[1]**

**13.** May a person who has received an order of suspension of operator license or permit request a hearing? (30.4) **[1]**

**14.** How soon after receiving notification of suspension of an operator license or permit does a suspension order become effective? (30.4) **[1]**

**15.** Can suspension of an operator license or permit take effect prior to notification? (30.4) **[1]**

**16.** May the FCC suspend an operator license or permit for due cause? (30.4) **[1]**

**17.** Is it prohibited by law to transmit unnecessary and superfluous signals? Is profane and obscene language prohibited? (30.4) **[1]**

**18.** How soon does the FCC require a response to a notice of violation? (30.5) **[1]**

**19.** How must a person who receives a notice of violation from the FCC reply? (30.5) **[1]**

**20.** If a person cannot respond to a notice of violation in the time prescribed by the FCC, is it necessary to explain the reason for any delay? (30.5) **[1]**

**21.** To whom is a response to a notice of violation addressed? (30.5) **[1]**

**22.** Should the answer to each notice of violation be complete, and should reference be made to remedial action, if any specific remedial steps are necessary? (30.5) **[1]**

**23.** Is the holder of a Radiotelephone Third Class operator permit authorized to make technical adjustments to the transmitter he operates? (30.7) **[1]**

**24.** What does the distress call consist of when sent by radiotelephony? (30.8) **[1]**

**25.** What information must be contained in a distress message? (30.8) **[1]**

**26.** Are communications bearing upon distress situations subject to the secrecy provisions of law? (30.8) **[1]**

**27.** Is it prohibited by law to transmit false or fraudulent distress signals from radio stations? (30.8) **[1]**

**28.** Under what conditions may a mobile radio station send a distress message for another mobile station in distress? (30.8) **[1]**

**29.** In the case of a mobile radio station in distress, what station is responsible for the control of distress-message traffic? (30.8) **[1]**

**30.** In radiotelephony, what are the distress, the urgency, and the safety signals? (30.8) **[1]**

**31.** In radio communication, what does the transmission of the distress, urgency, and safety signals signify, respectively? (30.8) **[1]**

**32.** What is the priority of the urgency signal? (30.8) **[1]**

**33.** How may necessary corrections to the log record be made? (30.10) **[1]**

**34.** Is it necessary that the original operator license be posted at an aeronautical station? An aircraft station? An airport station? A broadcast station? A ship station? (30.3) **[3]**

**35.** What is a verification card and under what circumstances may it be used? (30.3) **[3]**

**36.** List four classes of stations which may be operated by a person holding a Radiotelephone Second Class license. (30.6, 30.7) **[3]**

**37.** May the holder of a Radiotelephone Second Class operator license adjust and service or supervise the adjustment and servicing of any class of police radio station? (30.6) [3]

**38.** List four classes of stations, whose equipment may be adjusted and serviced by the holder of a Radiotelephone Second Class operator license. (30.6, 30.7) [3]

**39.** List three classes of stations which may not be serviced or adjusted by the holder of a Radiotelephone Second Class operator license. (30.7) [3]

**40.** If an operator is employed at more than one station, how may he comply with the rule requiring the posting of operator licenses? (30.3) [6]

**41.** Under what circumstances may a station be operated by an unlicensed person? (30.6) [6]

**42.** For what period of time must a station log, which contains entries incident to a disaster, be retained? (30.10) [6]

## CHAPTER 31

# COMMUNICATING BY VOICE

**31.1 Radiotelephone Operation.** This chapter deals with the basic radiotelephone operating practices and procedures included in Element 2 of *all* FCC commercial radiotelephone *and* radiotelegraph licenses or permits. It assumes an understanding of Chap. 30. The 50 questions forming Element 2 in license examinations are subdivided so that a candidate who wishes to do so may, for 10 of the questions, select the subject to be dealt with from one of three fields, namely ship, coastal, or aircraft radiotelephony.

By far the most numerous radio communications are made by radiotelephone. A single, fairly busy police communications system may handle more than 1,500 calls per day on one channel or frequency. There may be 100 to 300 mobile units in contact with the headquarters station during the day. There are several hundred thousand radiotelephone communication circuits in operation in the United States daily, most of them carrying on an informal type of communication. To reduce confusion and interference, some form of logical procedure must be followed. This chapter outlines, in simplified form, a possible procedure and discusses in general terms some of the rules and regulations that pertain to radiotelephonic communications. No attempt has been made to word the explanations in this or other chapters in precise legal language.

Radiotelephone communications take place ship to ship, ship to shore, land station to land station, land station to mobile, mobile to mobile, aircraft to aircraft, aircraft to ground, and so on.

**31.2 Order of Message Priority.** For obvious reasons, it is more important to handle certain more urgent types of messages before other routine types. The order of message priority in any radio communication system follows, whenever applicable, that shown in the list below:

1. Distress calls, messages, and traffic
2. Communications preceded by the urgency signal
3. Communications preceded by the safety signal
4. Communications relative to radio-direction-finding bearings
5. Messages relative to the navigation and movement of aircraft

6. Messages relative to navigation, movements and needs of ships, and official weather-observation messages
7. Government messages for which priority has been claimed
8. "Service" messages relating to previously transmitted messages or to the operation of the communication service
9. All other "routine" communications

**31.3 Distress.** A distress call has absolute priority over other transmissions. Stations hearing it must immediately cease any transmissions capable of interfering with it and must listen on the frequency used for the distress call.

*Preceding the distress call* by radio*telephone* should be the signal ···———··· (SOS in code), produced by a whistle or any other suitable means.

The distress *call* sent by radiotelephony comprises:

1. The distress signal MAYDAY spoken three times
2. The words THIS IS, followed by the identification of the mobile station in distress, the whole repeated three times

The distress *message* must follow the distress call as soon as possible and should contain:

1. The distress call
2. The name of the ship, aircraft, or vehicle in distress
3. Particulars of the position, nature of distress, and kind of assistance desired
4. Any other information which might facilitate rescue

The position is given in either latitude and longitude or by bearing in degrees from true north and distance in miles from a known geographical point.

An operator in the mobile service hearing a distress call must listen on the distress frequency for the distress message and must immediately acknowledge receipt of the distress *message* if the mobile station in distress is in the vicinity. (Acknowledgment is given *after* the distress *message*, never after the distress call.) An acknowledgment by radiotelephone might be:

1. Call of the station in distress three times
2. The words THIS IS, followed by the call of the acknowledging station three times
3. The words ROGER YOUR MAYDAY MESSAGE
4. The word OUT

Every mobile station which acknowledges receipt of a distress message must, on the order of the person responsible for the ship, aircraft, or other vehicle, transmit as soon as possible the following information in the order shown:

1. Its name
2. Its position at the present time
3. The speed at which it is proceeding toward the station in distress

Before sending this message, the station must insure that it will not interfere with emissions of other stations better situated to render immediate assistance to the station in distress.

Any operator in the mobile service who has knowledge of distress traffic must follow such traffic, even if he does not take part in it. For the duration of the distress traffic no station must use the distress frequency for other types of calls or traffic. If a transmitting operator is told that he is interfering with distress traffic, he must cease transmitting immediately and listen for distress signals.

An operator situated in such a position that he cannot assist in a distress message must take all possible steps to attract the attention of stations which might be in a position to render assistance.

Stations not directly involved in distress traffic may continue normal service on frequencies that will not interfere with the distress traffic after the distress traffic is observed to be well established.

Any land station receiving a distress message must, without delay, take the necessary action to advise any authorities that might participate or be participating in rescue operations. Otherwise the land station must maintain silence on the distress frequency unless involved in the distress traffic. If it appears that the distress call and message have not been acknowledged, all steps should be taken to attract the attention of stations in position to render assistance.

If a radio watch is required on a distress frequency, it is desirable that the receiver be tuned to this frequency as soon as traffic is completed on other frequencies to better guard for distress calls.

When distress traffic is ended, an announcement should be made on the distress frequency, such as:

1. The words MAYDAY ALL STATIONS, three times
2. The words THIS IS, followed by the call letters of the station transmitting the message
3. The name of the station in distress
4. The words DISTRESS TRAFFIC ENDED. OUT

**31.4 Urgency Signals.** The urgency signal by radiotelephone is PAN, spoken three times, followed by the words THIS IS and the call of the transmitting station. It indicates an urgent message is to follow. It may be used when the message to follow concerns the safety of a ship or person but is not quite of distress priority.

Mobile stations hearing the urgency signal must continue to listen for at least 3 min. At the end of this period, if no urgency message has been heard, they may resume their normal service.

**31.5 Safety Messages.** The *safety signal* by radiotelephone is SECURITY, spoken three times, followed by the words THIS IS and the call of the transmitting station three times. It is used to indicate that a storm warning, danger to navigation, or other navigational-aid message is to follow as soon as possible.

All stations hearing the safety signal must continue to listen on the frequency on which the safety signal has been transmitted until they are satisfied that the message is of no importance to them. They must, moreover, not make any transmissions likely to interfere with the message.

A *safety communication* is not necessarily the same as a message following the safety signal. A safety communication pertains to any distress, urgency, or safety messages which if delayed in transmission or reception might adversely affect the safety of life or property. Stations handling paid radio messages cannot charge for forwarding any safety-communication messages.

**31.6 Intelligibility.** Communication by radiotelephone may be hampered by static, fading signals, interference due to other stations, noise in the receiving room, noise picked up by the transmitting microphone, unusual voice accents, colloquialisms, improper enunciation or pronunciation of words, and by speaking too fast. To improve intelligibility at the receiving end, the transmitting operator should speak slowly, using well-known words and phrases and simple language. Unusual or important words should be repeated or spelled out if it is known that the receiving operator is experiencing any difficulty in reception.

Speaking too far from the microphone may result in weak, hard-to-understand signals. Shouting into the microphone produces a distorted output signal that may be difficult to understand even with perfect reception. Most communication microphones are constructed for close talking but in a normal tone of voice. If there is considerable talking or local noise in the area of the microphone, it may help intelligibility to cup the hand around the microphone and speak directly into the cupped hand in a moderate voice. Directing the front of the microphone away from noise sources may also help.

Distortion of the voice is also produced by fading signals and by improper functioning of the transmitting circuits. In the latter case, the fault must be found by a licensed operator or serviceman. In many cases, a distorted transmission is readable if the operator speaks very slowly and distinctly.

**31.7 Phonetic Alphabet.** When words are spelled out in a radiotelephone communication, considerable confusion can result because many of the letters of the alphabet sound similar unless clearly heard. For example, the letters B, C, D, E, G, P, T, V, and Z, all have the same *ee* ending sound. The word "get," when spelled out, might be copied as b-e-t, p-e-t, b-e-d, etc. To prevent this confusion, each letter of the alphabet may be represented by a well-known word. Thus, "golf" for G, "echo" for E, and "tango" for T might be used. When the word "get" is spelled out, using this "phonetic alphabet," it is spoken, "golf echo tango." The receiving operator writes down the first letter of each word and receives "get."

There have been many phonetic alphabets in the past, using names, cities, and other words. Unfortunately, non-English-speaking people mispronounced our English words so badly that confusion still resulted. An international phonetic alphabet has been selected using words that are familiar to most languages. It is given in Table 31.1.

Table 31.1 International Phonetic Alphabet

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Alpha | F | Foxtrot | K | Kilo | P | Papa | U | Union | Z | Zulu |
| B | Bravo | G | Golf | L | Lima | Q | Quebec | V | Victor | | |
| C | Coca | H | Hotel | M | Metro | R | Romeo | W | Whiskey | | |
| D | Delta | I | India | N | Nectar | S | Sierra | X | Extra | | |
| E | Echo | J | Juliet | O | Oscar | T | Tango | Y | Yankee | | |

In the interest of consistency it has been recommended that communication systems use this phonetic alphabet.

**31.8 Operational Words.** In the course of radiotelephone operation many special words or phrases have a definite meaning and are desirable to use. A list of some of these follows:

| *Words* | *Meaning* |
|---|---|
| ROGER | I received your message. |
| OVER | I have completed transmitting and await your reply. |
| GO AHEAD | Same as OVER. |
| OUT | I have completed my communication and do not expect to transmit again. |
| CLEAR | I have no further traffic. (Sometimes used in place of OUT.) |
| STAND BY | Wait for another call or further instructions. |
| BREAK | I am changing from one part of the message to another (address to text . . .). (Also used to request the receiving operator to indicate if he has received the portion of the message transmitted so far.) |
| WORDS TWICE | Transmit each word or phrase twice, or, I will transmit each word or phrase twice. |
| READ BACK | Read the message back to me. |
| I SPELL | I will spell (usually phonetically) the word I just said. |
| SAY AGAIN ALL AFTER | Repeat all words transmitted after . . . (give last correctly received word). |
| SAY AGAIN ALL BEFORE | Repeat all words transmitted before . . . (give first correctly received word). |
| SAY AGAIN . . . TO . . . | Repeat all words transmitted from . . . (word before missing portion) to . . . (word after missing portion). |

**31.9 Calling and Working.** A station, call sign KBBB, wishes to communicate with another station, call sign KAAA. KBBB transmits on a frequency known to be monitored by KAAA, saying,

KAAA KAAA KAAA THIS IS KBBB KBBB KBBB OVER

The called station answers, saying,

KBBB THIS IS KAAA OVER (or GO AHEAD)

Note that only on the first call is it usually necessary to call the standard three times and sign three times. The fewer calls *necessary*, the better.

A formal type of message from KBBB to KAAA might be transmitted as follows:

KAAA THIS IS KBBB. MESSAGE NUMBER ONE FROM SAN FRANCISCO FEBRUARY TWELFTH NINETHIRTY AM. BREAK. MACPHERSON UNIT TWENTYTHREE. BREAK. ADVISE EXPECTED ARRIVAL SAN FRANCISCO. BREAK. SIGNED WILLIAMS. BREAK (or END OF MESSAGE). THIS IS KBBB. OUT.

The operator at KAAA would copy the message in a form similar to:

| | |
|---|---|
| KBBB NR 1 SAN FRANCISCO FEBRUARY 12 1958 9:30 AM | (Preamble) |
| MACPHERSON<br>UNIT 23 | (Address) |
| ADVISE EXPECTED ARRIVAL SAN FRANCISCO | (Text) |
| WILLIAMS | (Signature) |
| 9:50A LC | (Service) |

Note the terminology for the different parts of the message. The service indicates the time and operator (initials) receiving the message.

The receiving operator acknowledges the message and also signs out:

KBBB THIS IS KAAA. ROGER YOUR MESSAGE NUMBER ONE. OUT.

After a contact has once been established, continuous two-way communication is usually desirable without identification on each transmission (if no mistake in identity is likely to occur) until termination of the contact, unless the contact is of 15 min or more duration.

A mobile station calling a particular station by radiotelephone must not continue for a period of more than 30 sec in each instance. If the called station is not heard to reply, it should not be called again until after an interval of 1 min (emergencies excepted). A coast station must not call for more than 1 min and must wait 3 minutes between calls.

If it is desired to call a vessel within sight when its identity is not known, such as a yacht in a definable area, an operator may make a radiotelephone call on 2,182 kc, saying, in effect, "Calling the green, twomasted yacht passing Point Conception. (3 times) This is WMBD WMBD WMBD. Over." If the yacht hears, it should answer on the same frequency.

In the 2,000–3000-kc band, in regions of heavy radio traffic, the duration of communications between two stations should not exceed 5 min (excluding distress or emergency communications).

**31.10 Radiotelephone Station Identification.** Both mobile and fixed stations should identify themselves by their FCC assigned call letters in English, or with modulated code, transmitted by a licensed telegraph operator, or with an approved automatic device. Identification should be made slowly and clearly so that listening stations cannot confuse the call sign.

If a mobile station has no assigned call letters, it must use its full name, transmitted in English, as "Yacht Cleopatra". A coast station may identify itself by location, as "Washington marine operator," if this has been approved.

A mobile or coastal station should identify itself at the beginning and end of each communication with another station, as well as at the beginning and end of test or other transmissions. Mobiles must transmit their call letters at intervals not exceeding 15 min whenever transmission is sustained for a period of more than 15 min. Stations in the Public Safety Radio Services (fire, police) transmit identifying calls at the end of each transmission or exchange of transmissions, or at 30-min intervals, as the licensee may prefer.

**31.11 Good Operating Practices.** Before making a call, or testing, an operator should listen on the frequency on which he is going to transmit to insure that interference will not be caused to communications which may be already in progress. Under normal conditions an operator should never transmit on a frequency he cannot monitor with a receiver, as he may interrupt or interfere with important communications on that frequency.

To allow maximum use of a frequency or channel and to prevent possible interference to emergency messages, all communications should be as brief as possible and all unnecessary calls and transmissions should be avoided. To further facilitate movement of traffic, the transmitter and receiver should be capable of changing frequency rapidly and should be in constant readiness to make a call or to answer a call.

With routine-type messages, if receiving and transmitting conditions are poor and difficulty is experienced in communicating because of static, fading, and interference, it may be better to wait for improved conditions rather than tie up the frequency with slow-moving nonemergency traffic.

Tests, when necessary, must be made when the frequency is not in use, and then as briefly as possible. The testing station must identify itself by call sign. A radiotelephone transmitter should be tested at least once a day (except when a ship is tied up in port) to assure proper operation of the equipment. A suitable daily test may consist of turning on the transmitter briefly, saying, "This is (call letters) testing." If all meters indicate normal values, it is assumed the transmitter is operating properly. If it is observed that the transmitter is not functioning properly, the master of the vessel shall be promptly notified, and an attempt made to correct the fault. A test transmission is not required if the transmitter is used to communicate with another station during the day.

When two or more groups of stations are sharing the use of one frequency or channel, it is good practice to leave an interval between calls and communications in case one of the other sharing stations desires to break in and transmit emergency traffic.

It must be remembered that radiotelephone transmissions may be received by many unauthorized persons and are not confidential. It is sometimes necessary to choose the phrasing of messages carefully to attain a desired secrecy of meaning.

Anyone may be authorized (by the master of a ship, for example) to speak over the station microphone, provided that the licensed operator continues to exercise his control so as to insure the proper operation of the station.

An operator must remember that he is responsible for any transmissions made by a station under his control. If anyone uses obscene language, it is his duty to stop such transmission immediately.

Operators must take all steps to prevent unauthorized use of transmitting equipment. Transmitters in a public place must not be left unattended. (Police and other similar mobile services should turn off the transmitter filaments when the operator leaves the car.)

The license of the operator of a radiotelephone station should be posted in plain view in the operating room.

As in other communication services, an accurate log must be kept of all transmissions made, tests or maintenance performed, messages handled, and distress, urgency, and safety messages heard. Each sheet is to be serially numbered and signed by the operator or person authorized to do so. Logs for international voyages are kept in Greenwich Mean Time; others may be in local time, using 24-hr time (1:30 PM being 1330 hours).

**31.12 Calling and Working Frequencies.** In the maritime mobile radiotelephone service *calling* and *working* frequencies are used. The original contact between two stations may be accomplished on a recognized calling frequency, such as the international radiotelephone distress and general calling frequency of 2,182 kc.

For mobile or coast stations this frequency is reserved for short calls and answers, or for distress, urgency, or safety communications. However, it may be used for short tests of equipment or to broadcast lists of stations for which a coastal station has traffic.

Normally, as soon as contact between two stations is accomplished on the calling frequency, operations are shifted to some other nearby assigned correspondence channel (working frequency) on which all routine-type messages must be transmitted. It is good practice to listen first on the working frequency to see if it is in use before making contact with a station on the calling frequency.

The medium-distance ship radiotelephone working and calling frequencies fall in the 2,000–3,000-kc. range. Communications on these frequencies must consist of safety or maritime traffic, never social or personal messages.

Another frequency, 156.8 Mc, is the short-range international radiotelephone frequency for calling, safety, intership, and harbor-control purposes for the maritime mobile service using frequencies within the 156.25–162.05-Mc band. These frequencies are not open to public correspondence or communications.

In some cases it is possible to call and work stations without using the calling frequency at all.

To contact a coast station (KSA) for routine traffic, the operator (of WPNB) would first check the working frequency of the coast station, next the calling frequency, and then call on 2,182 kc, saying,

KSA KSA KSA THIS IS WPNB WPNB WPNB ANSWER ON . . . KC. LISTEN ON . . . KC. OVER.

As soon as KSA acknowledges the call, WPNB shifts his transmitter to the frequency he designated as his working frequency and completes the communication on these frequencies.

The U.S. Coast Guard usually monitors the maritime calling frequencies (2,182 kc for radiotelephone, 500 and 8,364 kc for radiotelegraph). The three letters NCU signify "calling all Coast Guard stations." Thus, the call, "NCU NCU NCU THIS IS WPNB WPNB WPNB OVER," on 2,182 kc, is a general call to any Coast Guard station to answer on that calling frequency. If the call letters of a desired Coast Guard station are known, they may be used instead of NCU. If no answer is obtained, the Coast Guard may be called on the government frequency of 2,670 kc, *for distress traffic only.*

Ship stations licensed for radiotelephone operation (and not licensed for radiotelegraphy) on one or more frequencies in the 1,600–3,500-kc band shall, during their hours of service for telephony, maintain an efficient watch on 2,182 kc whenever it is not in operation on another frequency.

Use of the calling frequencies (2,182 kc and 156.8 Mc) should be as brief as possible, in no case over 3 min duration for one exchange of communication (emergency traffic excepted).

**31.13 Antenna Tower Lights.** Radio transmitting or receiving towers on land, high enough above the surrounding terrain to be considered dangerous to aerial navigation, are required to carry one or more warning lights on them. These lights may burn steadily or be rotating beams.

Such lighted towers require daily observance of the proper operation of the lights, or observance of an automatic indicator designed to register any failure of the lights. An automatic alarm system may be installed which is designed to detect any failure of the lights and to provide an indication if improper operation occurs.

In case of a failure of the antenna tower lights at a radio station, it is necessary that a report be made immediately by telephone or telegraph to the nearest airways communication station or office of the Civil Aeronautics Administration of a failure or of improper beacon rotation, if not corrected within 30 min. When the lights are functioning properly again, the same office must be notified of the correction at once.

Any automatic or mechanical control devices, indicators, and alarm systems associated with the tower lighting must be inspected at intervals not to exceed 3 months, to insure proper operation.

Tower-light information is entered in the station log. It consists of the time the tower lights are turned on and off daily, if manually controlled; the time the daily check is made; nature of any failure; date and time the failure was observed; date, time, and nature of the adjustments, repairs or replacements made; notification times of CAA of failures and of resumption of normal operation; results of the required 3 months' inspection.

**31.14 Coast Stations.** Public coast stations must maintain an accurate log during their hours of service of the following items: an "on duty" and "off duty" entry of the licensed operator(s) on watch; an indication of the call signs of all stations worked and the time in Greenwich Mean Time (GMT) (except on inland waters when a local standard time may be used); any interruptions of the watch, including reasons and when the watch was resumed; all distress, urgency, and safety messages intercepted or transmitted copied in full into the log; all tests made; a daily comparison of the required station clock(s) with standard-time signals; any measurements of transmitter frequency; all service or maintenance work performed on the transmitter; antenna-tower-light (if any) entries. Each sheet of the log is to be numbered in sequence, dated, and is to carry the call sign of the station and the signature(s) of the licensed operator(s) performing operating duties. ("Signature" indicates a minimum of first initial and last name, *written*, not printed.)

Similar logs are also kept by compulsorily radio-equipped ships.

A coast station communicates with ship or aircraft stations. It communicates with other coast stations only to facilitate communications with ship stations. Except for safety communications and short calls on calling frequencies, a coast station operates on its assigned working frequency as much as possible.

**31.15 Aircraft Radiotelephone.** Aircraft radiotelephone follows the basic procedure outlined in Sec. 31.3. However, there are some specific points of general importance that should be noted.

Communications by an aircraft station are normally limited to the necessities of safe aircraft operation. Contact with an airdrome control station is not attempted unless the aircraft is within the area served by that particular airdrome station.

Since many aircraft may be in the same area and be using the same frequencies of operation, to prevent interference of important communications it is required that aircraft stations do not make unnecessary on-the-air tests.

Aircraft may be assigned call letters. However, usually either the official aircraft registration number or the company flight identification is used instead. On the initial call the full registration number must be used. On following calls, if the ground station operator inaugurates the practice, only the last three numbers of the registration may be used.

The ground station will use either its assigned call letters or the name of the city, area, or airdrome which it serves.

The frequency 121.5 Mc is a universal aeronautical radiotelephone channel for emergency and distress communications to provide a means of calling and working between the various services in connection with search and rescue operations, an emergency means for direction finding, and establishing air-ground contact.

Air-carrier (passengers or cargo for hire) aircraft communicate with the airdrome control stations on the following frequencies: 125.7, 125.9, 126.1, 126.3, or 126.5 Mc. For passenger air-ground telephone service, 126.7 Mc is used.

Private aircraft have a calling and working frequency of 3,023.5 kc; for telephone service, 122.1 and 122.3 Mc; to airdrome control stations, 122.5, 122.7, or 122.9 Mc.

The frequencies 375, 457, 500, and 8,364 kc are used by aircraft traveling across the ocean. Normally radiotelegraph is used on these frequencies. There are other frequencies that may be assigned for radiotelephone.

Most of the aircraft communications take place in the 118–132-Mc band. The transmission characteristics of this range of frequencies is *line-of-sight* only. The higher the altitude of the aircraft, the greater the distance it can see, and the greater distance it can transmit and receive.

When an aircraft approaches an airdrome, it adjusts its transmitter to a frequency known to be monitored by the control tower and uses a radiotelephone calling procedure similar to that outlined previously.

The maintenance records of the radio equipment of all classes of stations in the aviation services must be made available for inspection upon request by the FCC.

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses; FCC element number at right; star indicates special group questions mentioned in Sec. 31.1.)

**1.** What is the order of priority for radiotelephone communications? (31.2) [2]

**2.** Should messages bearing upon safety, including weather information, be given priority over business messages? (31.2) [2]

**3.** What is the operator's responsibility upon hearing a distress call in the mobile services? (31.3) [2]

**4.** What is the correct form for transmitting a distress call by radiotelephony? (31.3) [2]

**5.** If a station is required by law to listen on a calling and distress frequency, when may the listening be discontinued? (31.3) [2]

**6.** What must the operator do if he is told that he is interfering with a distress call? (31.3) [2]

**7.** If a station is required to maintain effective listening on a distress frequency, why is it desirable for the equipment to return automatically to reception on the distress frequency immediately after completing use of the equipment on another frequency? (31.3) [2]

**8.** What is the operator's responsibility upon hearing the word "security" repeated three times? (31.5) [2]

**9.** In radiotelephone communications why should the operator use well-known words and phrases and simple language as much as possible? (31.6) [2]

**10.** Under what conditions may it be desirable to repeat important words by radiotelephony? (31.6) [2]

**11.** What would you do as radiotelephone operator if you were told that your voice was distorting? (31.6) [2]

**12.** Is it a good practice to shield the microphone with the hands when speaking into a microphone in a noisy location? (31.6) [2]

**13.** Are there any ill effects to radio communication if the operator shouts into the microphone? (31.6) [2]

**14.** What is the significance of the word "clear" when transmitted at the end of a radiotelephone communication? (31.8) [2]

**15.** What is the significance of the word "over" when transmitted at the end of a radiotelephone communication? (31.8) [2]

**16.** What is indicated by the word "out" when transmitted at the end of a radiotelephone communication? (31.8) [2]

**17.** In calling a station by radiotelephony, how many times does the calling station generally repeat the call sign or name of the calling station in each calling transmission? (31.9) [2]

**18.** In calling a station by radiotelephony should the calling station repeat the call sign or name of the called station in each calling transmission more than three times? (31.9) [2]

**19.** Why is it important to give clearly the station call sign? (31.10) [2]

**20.** Why should you be brief in radiotelephone conversations? (31.11) [2]

**21.** Why is it important to avoid unnecessary calls by radio communication? (31.11) [2]

**22.** Why is it advisable to listen on a channel before transmitting? (31.11) [2]

**23.** Is it required that a person listen on a channel before transmitting? (31.11) [2]

**24.** Why should stations using a shared frequency leave an interval between calls? (31.11) [2]

**25.** Why should a radiotelephone transmitter be kept off the air when voice transmissions are not in progress? (31.11) **[2]**

**26.** When routine radio communications are unreliable because of static or fading, should the operator continue transmitting or wait for more favorable conditions? (31.11) **[2]**

**27.** Can a radio operator always consider his radiotelephone conversation completely confidential and not heard by other persons? (31.11) **[2]**

**28.** Why is it beneficial for the transmitter of a radio station to be in constant readiness for making a call? (31.11) **[2]**

**29.** Why is rapid frequency change of the transmitter and receiver desirable? (31.11) **[2]**

**30.** Under normal conditions would a transmission on a calling frequency be proper if the receiver for that frequency was inoperative? (31.11) **[2]**

**31.** Why should a trial of the radiotelephone installation be made every day? (31.11) **[2]**

**32.** Should a test of the radiotelephone equipment be made each day? (31.11) **[2]**

**33.** Before placing the transmitting apparatus of a radio station in operation for a test, what precautions must be taken? (31.11) **[2]**

**34.** How can the radiotelephone installation be tested? (31.11) **[2]**

**35.** If a radiotelephone operator desires to make a brief test of a transmitter, what would be a good choice of words to use in the test? (31.11) **[2]**

**36.** What is the difference between calling and working frequencies? (31.12) **[2]**

**37.** Under what conditions may a radiotelephone station employ a calling frequency as contrasted to a working frequency? (31.12) **[2]**

**38.** Is it good practice to listen on the working frequency to be later used before making an initial call on the calling frequency? (31.12) **[2]**

**★39.** Is it necessary that the authority of the master or person responsible for the vessel be obtained prior to sending information required following acknowledgment of a distress call? (31.3) **[2]**

**★40.** What information is required to be sent following acknowledgment of a distress message? (31.3) **[2]**

**★41.** What is the proper form to use in acknowledging a distress call? (31.3) **[2]**

**★42.** Is it necessary for all vessels having knowledge of distress traffic to follow the traffic even if they do not take part in it? (31.3) **[2]**

**★43.** Is it desirable that care be taken to insure that an acknowledgment to a distress message will not interfere with other acknowledgments from vessels better able to assist? (31.3) **[2]**

**★44.** Is a vessel which hears a distress message but is not in a position to assist required to take all possible steps to attract the attention of stations which might be in a position to assist? (31.3) **[2]**

**★45.** If a coast station hears a distress call from a mobile station, what action, if any, should the operator on duty take? (31.3) **[2]**

**★46.** Under what conditions may a coast station intervene in a distress situation? (31.3) **[2]**

**★47.** What is meant by the term "safety communication" in the maritime mobile service? (31.5) **[2]**

**★48.** Do public coast stations normally charge for forwarding messages reporting dangers to navigation? (31.5) **[2]**

**★49.** What type of radiotelephone communications must be handled free by a public coast station which normally charges for its service? (31.5) **[2]**

**★50.** What is meant by a phonetic alphabet in radiotelephone communication? (31.7) **[2]**

★51. What is indicated by the use of the word "roger" as a reply to a radiotelephone communication? (31.8) [2]

★52. What is indicated by the use of the word "break" in a radiotelephone conversation? (31.8) [2]

★53. What is indicated by the expression "words twice" when transmitted by radiotelephone? (31.8) [2]

★54. What is indicated by the use of the words "read back" in a radiotelephone communication? (31.8) [2]

★55. In making a ship-to-ship contact, except in an emergency involving safety, how long may a ship radiotelephone station continue calling in each instance? (31.9) [2]

★56. How would you contact another vessel prior to actually communicating with it for routine communication purposes? (31.9) [2]

★57. Give a typical procedure you might use to call a vessel when its identity is not known. (31.9) [2]

★58. Except in an emergency involving safety, if a ship radiotelephone station does not receive a reply after calling, how long must the station wait before calling again? (31.9) [2]

★59. When calling a mobile radiotelephone station but receiving no immediate reply, how often may a coast station using radiotelephony repeat the call? (31.9) [2]

★60. How often should station identification be made at a base or land radiotelephone station? (31.10) [2]

★61. How is a ship radiotelephone station required to be identified in connection with its operation? (31.10) [2]

★62. How should station identification be made at a coast station using radiotelephony? (31.10) [2]

★63. If a licensed radio operator at the controls of a radio station hears obscene language being spoken by another person and transmitted through the facilities of the station, what action should he take? (31.11) [2]

★64. Who signs the radio log of a ship radiotelephone station certifying to entries made therein? (31.11) [2]

★65. How can the radiotelephone installation be tested each day? (31.11) [2]

★66. If the radiotelephone ship installation is normally used during the day, is it necessary to make any special test communication for the purpose of trying the radio? (31.11) [2]

★67. Is it necessary to make a trial of the ship radiotelephone installation every day? (31.11) [2]

★68. If a radiotelephone installation provided on board ship for safety purposes, in accordance with treaty, becomes defective, what action must the licensed operator take? (31.11) [2]

★69. How does the licensed operator of ship radiotelephone stations exhibit his authority to operate the station? (31.11) [2]

★70. Who may operate the radiotelephone set aboard a vessel? (31.11) [2]

★71. What precautions should be taken when a radio station is left unattended in a public place? (31.11) [2]

★72. Under what circumstances should a public coast station employing radiotelephony use a calling frequency in establishing a communication circuit with a ship or aircraft? (31.12) [2]

★73. Is it permissible to communicate with coast stations or any other station on 2,182 kc, except for safety purposes? (31.12) [2]

★74. Is it permissible to use 2,182 kc for establishing contact prior to communicating on an appropriate public-correspondence channel? (31.12) [2]

★75. What procedure would you use in contacting a coast station on 2,182 kc, and what would you say over the air? (31.12, 31.9) [2]

**★76.** Is it general practice for a ship to use 2,182 kc for establishing contact prior to communicating with a coast station on an appropriate public-correspondence channel? (31.12) **[2]**

**★77.** What radio channel or channels are used by ships for communicating by radiotelephone with the U.S. Coast Guard? (13.12) **[2]**

**★78.** What procedure would you use to get in touch with the U.S. Coast Guard? (31.12) **[2]**

**★79.** What types of communications may be transmitted by ship stations on the ship-to-ship frequencies between 2,000 and 3,000 kc? (31.12) **[2]**

**★80.** What are the requirements with respect to a listening watch in a ship radiotelephone station during its hours of service in the 2,000–3,000-kc band? (31.12) **[2]**

**★81.** In regions of heavy traffic how long may the ship-to-ship radiotelephone frequencies between 2,000 and 3,000 kc be used for any one exchange of communications (other than distress and emergency communication)? (31.12) **[2]**

**★82.** What should be done in case of failure of the antenna tower lights at a radio station? (31.13) **[2]**

**★83.** What entries must be made in the logs or records of radio stations required to have antenna tower lights? (31.13) **[2]**

**★84.** What attention should be given periodically to the antenna tower lights and associated apparatus at a radio station? (31.13) **[2]**

**★85.** What daily attention should be given to the antenna tower lights at a radio station? (31.13) **[2]**

**★86.** To what extent may a coast station using radiotelephony communicate with stations other than ship stations? (31.14) **[2]**

**★87.** What are the requirements with respect to log keeping at a coast station using radiotelephony? (31.14) **[2]**

**★88.** When must an aircraft radio station and maintenance records be made available for inspection? (31.15) **[2]**

**★89.** How is the communication range of an aircraft radio station on a very high frequency dependent on the altitude of the aircraft? (31.15) **[2]**

**★90.** What is the normal calling procedure of a private aircraft for contacting a control tower? (31.15) **[2]**

**★91.** For what purpose is the frequency 121.5 Mc authorized to be used by an aircraft radio station? (31.15) **[2]**

**★92.** What is the national calling and working frequency for air-carrier aircraft? (31.15) **[2]**

**★93.** How should an air-carrier aircraft radiotelephone station normally be identified in operation in lieu of using the call sign? (31.15) **[2]**

**★94.** In lieu of using a call sign, how may a private-aircraft telephone station be identified in the course of operation? (31.15) **[2]**

**★95.** Why should an aircraft station avoid making unnecessary on-the-air tests? (31.15) **[2]**

**★96.** What types of communications or messages is an aircraft radiotelephone station authorized to transmit? (31.15) **[2]**

## CHAPTER 32

# COMMUNICATING BY RADIOTELEGRAPH

**32.1 Basic Operation.** Most of the Element 5 license test questions, except a few covered in the chapters on Basic Transmitters and AM Receivers, are answered in this chapter. Besides basic radiotelegraph operating procedure, information has been included here regarding radiotelegraph messages for stations open to public correspondence (handling paid messages), message construction, charges, etc., of particular interest to prospective marine operators. (Amateur messages are similar to commercial in many respects, except that the number of words in the address may not be counted.)

There is a basic similarity of radiotelephone and radiotelegraph regulations. For instance, the list of message priorities is the same for both (Sec. 31.2); radiotelegraph stations must not be operated by unlicensed persons; operator licenses should be posted at the operating position; and so on.

It will be found that when an operator exercises good common sense in communications he will usually be conforming with regulations. Such regulations have been developed to enable the most stations to handle the most traffic, in the least amount of time possible, with the least confusion. Long calls, failure to listen on a frequency before transmitting, transmitting on a frequency already in use, employing either more or less transmitting power than necessary (the minimum necessary should always be used), sending faster than the receiving operator can copy, sending faster than the transmitting operator can legibly telegraph, using improperly functioning equipment, and using abbreviated procedures with stations not understanding them are common operating faults that can needlessly delay the communications of all stations concerned.

**32.2 Radiotelegraph Licenses.** There are three types of radiotelegraph licenses or permits: First Class license, Second Class license, and Third Class permit, as explained in the chapter on Basic Radio Laws. All require passing at least Elements 1, 2, and 5, plus code tests. Holders of the First and Second Class licenses are authorized to make any technical adjustments to any radiotelegraph transmitters, as well as any radiotelephone transmitters in the mobile service. Radiotelegraph permit holders are not authorized to make technical adjustments, but can operate any equipment that can be operated by a Radiotelephone Third Class permit holder, plus operate radiotelegraph stations, or transmit radiotelegraph call signs at certain stations having a power output of 250 watts or less. Radiotelegraph permit holders cannot operate any broadcast, TV, or FM stations (except noncommercial educational FM of 10 watts or less), ship stations required to have a radiotelegraph installation, coastal radiotelephone stations of more than 250 watts, or aircraft stations employing radiotelegraphy.

Unlike radiotelephone, there is no time that an unlicensed person can transmit with a telegraph key, with the exception of a dire emergency, such as in a lifeboat, with no operator aboard, and adrift at sea. With radiotelephone transmitters, anyone may operate provided he is authorized by the person in charge or is under the direct supervision of a licensed operator.

**32.3 The Morse Code.** The telegraphic code used for normal commercial and amateur radiotelegraphic communication is the *International,* or *Continental, Morse Code,* consisting of dots and dashes. (This

*The International, or Continental, Morse Code*

| | | | | | |
|---|---|---|---|---|---|
| A | ·— | N | —· | 1 | ·———— |
| B | —··· | O | ——— | 2 | ··——— |
| C | —·—· | P | ·——· | 3 | ···—— |
| D | —·· | Q | ——·— | 4 | ····— |
| E | · | R | ·—· | 5 | ····· |
| F | ··—· | S | ··· | 6 | —···· |
| G | ——· | T | — | 7 | ——··· |
| H | ···· | U | ··— | 8 | ———·· |
| I | ·· | V | ···— | 9 | ————· |
| J | ·——— | W | ·—— | 0 | ————— |
| K | —·— | X | —··— | | |
| L | ·—·· | Y | —·—— | | |
| M | —— | Z | ——·· | | |

| | | |
|---|---|---|
| . | (period) | ·—·—·— |
| , | (comma) | ——··—— |
| ? | (question mark)($\overline{\text{IMI}}$) | ··——·· |
| / | (fraction bar) | —··—· |
| : | (colon) | ———··· |
| ; | (semicolon) | —·—·—· |
| ( or ) | (parentheses) | —·——·— |
| ’ | (apostrophe) | ·————· |
| - | (hyphen or dash) | —····— |
| $ | (dollar sign)* | ···—··— |
| “ | (quotation marks) | ·—··— |
| | or, | ·—··—·* |

| | |
|---|---|
| Error sign (8 dots) | ········ |
| Separation indicator also known as $\overline{\text{BT}}$ | —···— |
| End of transmission of a message ($\overline{\text{AR}}$) | ·—·—· |
| Invitation to transmit | —·— |
| Wait ($\overline{\text{AS}}$) | ·—··· |
| End of work ($\overline{\text{SK}}$ or $\overline{\text{VA}}$) | ···—·— |
| Starting signal | —·—·— |

* These characters are not listed internationally but may be heard in domestic communications.

differs from the *American Morse Code*, consisting of dots, dashes, and spaces.) In International Morse Code a *dot* is made by pressing the telegraph key down and allowing it to spring back up again rapidly. The length of dot duration is the basic time unit of code. A *dash* is made by pressing the key down and holding it for a period of three basic time units. The spacing between two dots or between a dot and dash in the same letter is equal to one time unit. The spacing between two letters in one word is equal to three units. The spacing between two words is equal to seven units.

A number and a fraction is transmitted: Number, hyphen, and fraction. For example, 45½ is transmitted: 45-1/2.

Four dashes (— — — —) may be used as the two letters *ch*, or as an "end of paragraph" indicator.

Two question marks (··— —·· ··— —··) are sometimes used instead of the eight-dot error signal.

There are several other codes used in communications. One is the American Morse Code used on telegraph lines (*landlines*). Another code is used in teletype circuits. It is a five-character code, in which the length of time of each letter, number, or function is the same. It is an on-off, or *mark-space*, code. The Japanese and Russians have special radiotelegraph codes also.

**32.4 Frequencies Used.** Radiotelegraph-equipped ships on the high seas maintain either a constant or a specified number of hours watch on the international calling and distress frequency of 500 kc (previously known as "600 meters") in the "405–535-kc band." All coastal radiotelegraph stations maintain a constant watch on 500 kc. Most of these stations also keep watch on one or more high-frequency ship calling frequencies, the 4-, 6-, 8-, 12-, 16-, and 22-Mc bands (Sec. 26.8).

There is a less used international maritime mobile band between 90 and 160 kc, having a calling frequency on 143 kc (previously known as "2,100 meters").

The calling frequency of 8,364 kc is reserved for aircraft, lifeboats, and other survival craft for communication with stations of the Maritime Mobile Service. This frequency is monitored by the U.S. Coast Guard and Navy and, being the center of the ship calling frequency band, is constantly scanned by coastal stations listening for calls by ships.

**32.5 Calling by Radiotelegraph.** An original call is made by radiotelegraph by transmitting the call sign of the station called not more than three times, followed by the letters DE (meaning "from"), the call sign of the calling station, and the letter K (meaning "go ahead"). For example, an American ship KBBB calls a station with call letters KAAA:

KAAA KAAA KAAA DE KBBB KBBB KBBB K

In the bands between 4 and 23 Mc, when the conditions of establishing contact are difficult, the call signs may be transmitted more than three times but not more than eight times.

Calls are made on a frequency that is known to be monitored by the station to be called. If within a few hundred miles, the frequency of 500 kc is used for ship-to-ship or ship-to-shore traffic. If farther away, other assigned HF calling frequencies are used.

Except for distress traffic, all stations handle traffic on working frequencies, not on calling frequencies. A ship station calling a coastal station listens for the coastal station on its assigned working frequency and notifies the coast station to listen for the ship station on one of its assigned working frequencies. Thus, "KFS DE KDMW QSW 463" means "KFS from KDMW, I am going to send on 463 kc. Listen for me there." If KFS hears the call, it acknowledges on its working frequency and no other transmission may be made on the calling frequency.

In the 405–535-kc band, coastal stations may shift to the calling frequency to call a ship station or to advise all stations after sending the call CQ ("attention all stations") that it is going to transmit a list of traffic on hand using its working frequency. In the high-frequency bands the coastal stations always remain on their working frequencies.

The general call to all ships is CQ. If a coast station has traffic for one or two ships, it may transmit their call signs on the calling frequency. If the list of traffic is for three or more ships, the coast station must send a traffic list on its working frequency. It will first send CQ on the calling frequency and the indicator to listen on its working frequency (or wavelength). For example,

CQ CQ CQ DE WSV WSV WSV TFC QSY 735 $\overline{\text{AS}}$

This indicates a traffic list will be transmitted by WSV on a *wavelength* of 735 meters (408 kc) as soon as the station can switch to that wave. However, new regulations state that the *frequency* be indicated rather than the wavelength.

The letters CP followed by two or more call signs on a calling frequency is a general call to those stations only and indicates that no reply is expected from them. It precedes a general broadcast to these stations on a working frequency.

**32.6 Answering by Radiotelegraph.** When the operator of a ship station hears another ship or a coast station calling him on a calling frequency, he should answer on the same frequency (or on any frequency designated by the calling station) as soon as possible. As an example, KAAA hears KBBB calling on 500 kc and responds with

KBBB DE KAAA QSY 468 K

This notifies KBBB to change to a transmission on 468 kc and assumes that KAAA will also shift to the same frequency. (See Q signals, Sec.

32.23.) KBBB usually responds with an R, indicating "I received your message" and concur with its meaning.

A ship operator responding to a call of a coastal station would normally respond with Q signals. However, the word UP is sometimes used to notify the other station to move up to its working frequency (or *wave*) or that both stations are to shift up to their usual working frequencies. (This is a historically founded procedure and is not recognized internationally.)

If a station hears another station calling it but cannot make out the call sign, it should transmit the Q signal meaning "By whom am I being called?" followed by its call sign, "QRZ? QRZ? QRZ? DE ·· (call sign) ·· K."

If a station hears another calling, but is busy at the time, if possible it should answer the calling station and transmit $\overline{\text{AS}}$ (·—···), followed by a number indicating how many minutes to wait. It may also use the Q signal QRX, followed by the number of minutes to wait.

**32.7 Tuning and Testing.** When it becomes necessary to test or tune a transmitter, a time should be chosen when the frequency to be used is idle. The tuning should be accomplished as rapidly as possible. At the conclusion the call sign of the station must be transmitted. A radiotelegraph station usually transmits a series of VVV as a test signal, followed by DE and its call sign.

**32.8 Station Identification.** Besides the normal station identification that occurs during calling and answering, radiotelegraph stations usually transmit a station identification by their call signs in Morse Code at the completion of each transmission, or at the conclusion of an exchange of transmissions, or every 15 min if a transmission is sustained for a period exceeding 15 min. In the Public Safety Radio Services a station may sign after each transmission, or after each exchange, or every 30 min, as the licensee desires.

**32.9 Autoalarm Signal.** A signal of 1-min duration, composed of twelve 4-sec dashes with 1-sec spacing between them, is known as an *autoalarm signal.* Any four consecutive alarm dashes will activate an autoalarm receiver and sound an alarm aboard any ship on which an operator is off watch. The autoalarm signal is used only before distress calls from ships or aircraft, or before urgent cyclone warnings transmitted by coastal stations. A period of 2 min should elapse before a message follows an autoalarm signal to allow time for operators who have been summoned by the alarm to get to the radio room to stand watch (see autoalarms, Sec. 26.13).

**32.10 Silence Periods.** All ships and coastal stations operating on 500 kc must listen on, but not transmit on, 500 kc during the fifteenth to the eighteenth and the forty-fifth to the forty-eighth minutes of every hour of their operation. These 3-min periods are known as *silence periods.*

Ships in distress should repeat their distress messages during these periods to assure reception (see also Sec. 26.19).

During silence periods (also during distress, urgency, and safety traffic on 500 kc) routine transmissions are forbidden in the bands 485–515 kc.

**32.11 Distress.** One of the main reasons why a ship carries radio equipment is to enable it to signal its condition and position in case of emergencies or distress.

The distress *signal* by radiotelegraph is ···———··· transmitted three times. This is usually referred to as an SOS but is actually a single character selected for its easy identification. It is sent only on the authority of the master or person responsible for the ship, aircraft, or other vehicle and only when the distressed station is in grave and imminent danger and requests immediate assistance.

When the international mobile distress frequency of 500 kc is used, if time allows, the autoalarm signal should be transmitted for 1 min before the distress signal is transmitted three times. After a 2-min interval, to allow operators summoned by the autoalarm signal to assume a watch, the distress *call* is transmitted. This consists of the distress signal three times, DE, and the call sign of the station three times.

The distress call must be followed as soon as possible by the distress message transmitted at no more than 16 words per minute. The distress *message* consists of (1) the distress call again, (2) the name of the ship, aircraft, or vehicle in distress, (3) particulars of its position, the nature of the distress, the kind of assistance desired, plus speed and course if underway, and (4) any other information which might facilitate the rescue.

After the distress message, the mobile station should transmit two 10-sec dashes, followed by its call sign, to permit direction-finding stations to determine its position.

The distress message should be repeated again on the next silence period.

All subsequent distress messages must contain the SOS indicator in their preamble.

Distress signals, calls, and messages should be transmitted using type-A2 or type-B emissions (modulated-code signals) if possible.

Stations that cannot use 500 kc should use their normal calling frequency for distress transmissions.

The station in distress is in complete control of distress traffic unless it delegates control to another station.

An operator hearing a distress call must cease transmitting and listen on the frequency of the distress call. If the station in distress is without doubt in the vicinity, after the completion of the distress message, the operator must acknowledge receipt of the message by transmitting (1) call of the distressed station (three times), (2) DE followed by the call of the receipting station (three times), and (3) R R R $\overline{\text{SOS}}$.

Stations receiving a distress message without a doubt *not* in their vicinity must allow a short interval of time before acknowledging receipt to permit closer stations to acknowledge.

When distress traffic is well established, stations not involved and in no position to help may continue normal service on other frequencies provided they do not interfere with any distress traffic.

When all distress traffic has ceased, or when silence is no longer necessary, a station which has controlled the distress traffic must send a message to terminate the distress condition. Such a message will take the form (1) $\overline{\mathrm{SOS}}$ CQ CQ CQ DE followed by the call of the station sending, (2) time of the message, (3) name and call of distressed station, and (4) QUM (meaning, "The distress traffic is ended") $\overline{\mathrm{SK}}$.

**32.12 The Urgency Signal.** In radiotelegraph the urgency signal is the group XXX sent slowly three times, usually on 500 kc or another calling frequency. It indicates that the calling station has a very urgent message to transmit concerning the safety of a ship, aircraft, or other vehicle or of some person on board or within sight. It must be authorized by the person responsible for the transmitting ship.

The urgency signal transmitted by a ship is usually addressed to a specific station. The urgency signal, with the approval of the responsible authority, may be transmitted from a coast station and addressed to all ships.

Mobile stations hearing the urgency signal must continue to listen for at least 3 min. If no urgency message has been heard by then, they may resume their normal service.

An autoalarm signal may be transmitted before an urgent cyclone warning by a coastal station authorized to do so by its government. A period of 2 min must elapse between transmission of the autoalarm signal and the cyclone-warning message.

**32.13 The Safety Signal.** In radiotelegraphy, the safety signal consists of three repetitions of the group TTT sent slowly. It indicates that the station is about to transmit a message concerning the safety of navigation or important meteorological warnings and is sent on the distress frequency. The safety *signal* is usually transmitted during the last minute of the first available silence period. The safety *message* is then transmitted at the conclusion of the silence period.

Operators hearing a safety signal must continue to listen to the message until they are satisfied that it is of no importance to them. They may then resume normal service on frequencies that will not interfere with the safety transmission.

**32.14 Radiotelegraph Logs.** All ship stations authorized to use telegraphy on frequencies between 90 and 535 kc must maintain an accurate radiotelegraph log. The first page is a *title page*. At the completion of the voyage the following information is placed on it: the name of the ship, the call letters, the period of time covered by the log, the number of pages, a statement whether any distress-message entries are contained in it and on what pages, as well as the operator's signature and mailing address, his license number, its class, and its date of issuance.

Each page is numbered serially for the voyage, contains the name of the ship, call letters, and name of the operator on watch. The entry "on watch" must be made by the operator beginning a watch, followed by his signature. The entry "off watch" must be made by the operator being relieved or terminating a watch, followed by his signature.

The log is kept in Greenwich Mean Time (or Eastern Standard Time for ships in the Great Lakes) and must contain all calls or tests transmitted by the ship, stations contacted, and serial numbers of messages handled, stating times and frequencies. A positive entry with respect to reception on 500 kc should be made at least once in each 15 min. Entries shall be made twice per hour stating whether or not the international silence period was observed, noting any signals heard during these periods. All distress, urgency, and safety signals heard must be entered, with complete text of distress messages if possible. Any harmful interference noted should be logged. Once a day the position of the ship and a comparison of the radio-station clock with standard time, including errors noted, must be entered. Times of arrival and departure from ports are logged. Failures of equipment and corrections taken should be noted. Results of emergency-equipment tests, battery specific gravity, when placed on and taken off charge, and the quantity of fuel for emergency generators must be entered. On cargo vessels, the time the autoalarm was placed in service and when out of service, as well as the setting of the "sensitivity" control, results of tests, alarms, and false alarms must be logged.

Logs are kept by the licensee of the station for a period of 1 year. If the logs contain distress or disaster traffic they must be kept 3 years. Station logs which include entries of communications incident to or involved in an investigation by the FCC and concerning which the station licensee has been notified are retained until authorization to destroy them is received in writing.

Stations in other services keep logs, but include only the above information applicable to their service.

**32.15 Commercial Radiotelegraph Messages.** Radiotelegraph messages from ship to ship or from ship to shore are composed of a preamble, address, text, and signature, as explained in the chapter on Communicating by Voice. An example of a standard, paid, ship-to-ship message, as transmitted from KBBB to KAAA, might be as follows:

P 1 KBBB CK 13 SS GOLDEN ARROW 12 2145 $\overline{\text{BT}}$
FRED MANGELSDORF
SS GOLDENSPEAR (or SS KAAA) $\overline{\text{BT}}$
MAKING ARRANGEMENTS MEET YOU HAVANA TWENTYFIRST $\overline{\text{BT}}$
STEVE AND FREDA $\overline{\text{AR}}$
1 KAAA ES 2213 12

In the preamble, P 1 KBBB indicates a paid message number 1 from the station of origin, KBBB, the SS GOLDEN ARROW. The check (CK) is the number of words paid for in the address, text, and signature. The 12 indicates the twelfth day of the month. The 2145 indicates the filing time of 2145 GMT. The serial numbering of messages begins at midnight (0000 hours) GMT and continues up to the next midnight (2400 hours). (Stations on inland waters may use local time.) The date and time may be sent as a date-time group, in this case, 122145Z (Z indicating GMT). The word DATE may be sent to indicate the filing date is the same as the sending date. The arrangement of the preamble may vary considerably. The same preamble might be transmitted in one of the following forms:

P 1 SS GOLDEN ARROW CK 13 12TH 2145
P 1 13 SS GOLDEN ARROW DATE 2145 GMT
NR 1 KBBB CK 13 RDO SS GOLDEN ARROW 2145 GMT 12

(RDO meaning the same as the service indicator P).

The address includes the name of the person to which the message is being sent, and sufficient address to deliver it.

The text is the body of the message.

The signature, if any, is the person sending the message. If no signature is to be sent, the words NO SIG are transmitted in place of the signature. The sign $\overline{\text{AR}}$ indicates "end of message."

The servicing is on the line below the signature, placed on the message by the transmitting operator. It indicates the message was sent as NR 1 to KAAA by operator ES at 2213 on the 12th. Somewhere on every message the full date, month, day, and year must be shown. If it is not in the preamble, it must be in the servicing.

The receiving operator should copy the message in a form similar to the following:

P 1 KBBB CK 13 SS GOLDEN ARROW FEBRUARY 12 1958 2145 GMT
FRED MANGELSDORF
SS GOLDENSPEAR
MAKING ARRANGEMENTS MEET YOU HAVANA TWENTYFIRST
STEVE AND FREDA
12 2213 BW

Note that the operating signals $\overline{\text{BT}}$ and $\overline{\text{AR}}$ are not shown on the received message. Also, the receiving operator has typed in the complete date in the preamble. He may use the full date in the servicing instead, however.

A ship-to-shore message is addressed to some destination on land. It is transmitted to a coastal station and has a form similar to the ship-to-ship message.

A message filed at a telegraph station ashore for a ship is relayed by telegraph to a coastal station and transmitted to the ship as soon as it can be contacted. An example of a shore-to-ship message as received by a ship operator might be as follows:

P 1 RENO NEVADA CK 14 FEBRUARY 12 1957 8:45 AM
SASSER
SS GOLDENARROW
BOLINASRADIOKPH
MEETING  YOU ON ARRIVAL SANFRANCISCO TUESDAY
AFTERNOON WITH RONADLO
JANE
2301 12 BW

Note that the name of the coastal station transmitting the message is counted as one word. Actually, the call letters of the coastal station are all that are normally transmitted, the receiving operator filling in the complete name of the station. Also note that the receiving operator double-spaces after the fifth word (meeting) and drops to the next line after the tenth word (and after every multiple of 10 words in long messages) to facilitate counting check while he is copying the message.

The punctuation in the filing time is usually transmitted as a period, although the code letter R may sometimes be used. It may be copied as a period or as a colon.

When a message contains a word that appears to the receiving (or transmitting) operator as possibly improperly spelled or copied, he should *confirm* (or *collate*) any such odd words, figures, or symbols. For example, the last word in the text of the shore-to-ship message above appears suspicious. At the completion of the transmission of the message the receiving (or transmitting) operator may transmit CFM RONADLO K, meaning "Confirm the spelling of the word Ronadlo." If the questioned spelling is correct, the transmitting operator responds with R, or preferably C, meaning "yes," or "correct." If the receiving operator confirms a word incorrectly, the transmitting operator must correct him, as N RONALDO (if this happens to be the corrected spelling). The N indicates negation, or "no."

**32.16 Counting Words in Messages.** In any of the acceptable languages, English, French, German, etc., any word or name in the *text* up to 15 letters long counts as only one word. If it has 16 or more letters, it is charged for as two words (31 letters as three words).

When pronounceable but meaningless code or cipher words are used in the text in such a manner as to hide the meaning of the message, the same number of letters per word is counted as in plain-language texts.

When unpronounceable, or code, words are used, made up of letters, numbers, or letters and numbers, one word is counted for each five letters. CBS3 is one word. RCBS3 is one word. RCBX32 is two words. RCBX321465L is three words. Since 45-1/2 has six transmitted characters, it is two words. The number 5-1/2 is 1 word.

In the *address* names may be longer than 15 letters and still be counted as 1 word. The words "street," "avenue," "boulevard," etc., may be added to the street name and counted as one word if the total of all letters does not exceed 15, as ELMSTREET. If transmitted as two words, it is counted as two words. The name of a ship is always 1 word in the address, as PRESIDENTHOOVER. If used, the SS (steamship) always counts as a word. The state, and country if necessary, may be sent attached to the city name, as SANFRANCISCOCALIFORNIA, or the state may be enclosed in parentheses and may not be counted, as SANFRANCISCO (CALIFORNIA).

When requested to be transmitted, punctuation marks such as period, comma, colon, question mark, parentheses, and quotation marks are counted as separate words. Parentheses and quotation marks require two characters for each single word count, however.

**32.17 Message Charges.** Each word in the address, text, and signature of a radiogram is charged for. (This differs from the domestic or landline telegraph messages which charge for the text only.) Between U.S. ships and shore stations the rates are charged for in dollars and cents. When a U.S. ship has traffic with a foreign station, the rates (other than its own ship charges) are charged for in *gold francs*, with 3 gf equaling 1 dollar.

For a regular, full-rate radiogram (*P*), 8 cents goes to the transmitting ship for each word, and 8 cents (or 0.40 gf) to the receiving ship, 12½ cents to the coastal station (varying rates in gold francs to foreign-country coastal stations), and 5½ cents landline charge to any place in the United States. Thus, a ship-to-ship message between U.S. ships costs 16 cents per word, and a ship-to-shore message costs 26 cents per word.

**32.18 Types of Messages.** *SVC*, or *A*. *Service* messages refer to previous messages that have been handled, to the operation of the communication system, or to notify of nondelivery of messages. Since SVC messages refer to previous traffic, they have priority over any other routine messages. They carry no charges. They may or may not carry a serial number. An example of a service message might be:

```
SVC 3 (or A 3)
      KAAA
RE OUR NR 1 12 CORRECT FIRST WD TXT READ MAILING
                                       KBBB 13
```

This message advises the operator at KAAA to change the NR 1 message of KBBB of Feb. 12 to make the first word of the text read "mailing" instead of the way it was originally transmitted. The signature of the SVC is the call letters and date of the service.

*ST*. *Paid service* messages are made out in the more formal preamble, address, text, and signature form. This type of service adds words to or corrects a message because of errors made by the originator of the message. The sender must pay standard rates for only the words in the text that are required to make the correction.

*NRT. Night radio telegrams* (minimum of 20 words charged) must be filed before midnight (ship time), are transmitted to coastal stations, telegraphed to destination city, and delivered sometime the next morning. Ship charge 8 cents, coast 6¼ cents, landline 2¾ cents.

*SLT. Ship letter telegrams* are mailed to destination by the receiving coastal station. First 20 words or less, ship 83 cents, coast $1.25. Additional words, ship 4 cents, coast 6¼ cents.

*GOVT. Government* radiograms by accredited officials of the U.S. government on official government business. Full rates.

*RP. Reply prepaid* messages carry the amount prepaid as the *first word of the address*, as RP$2.60 (transmitted RP DOLS 2.60). Any message in reply to an RP is known as an *ANSTORP* (answer to RP) and is prepaid, in this case, up to $2.60. If the charges of the answering message are greater than this, the sender must pay the excess. Full rates are charged for the RP message, plus the prepaid amount.

*OBS. Observer* messages are meteorological reports from ships at sea to the U.S. Weather Bureau, addressed OBSERVER in the city where the report is to be sent. No charges as far as the ship operator is concerned.

*HYDRO. Hydrographic* messages report menaces to navigation and are addressed to HYDRO WASHINGTON. No charges as far as the ship operator is concerned.

*DH MEDICO. Deadhead medical* messages are free (deadhead) messages pertaining to medical or surgical advice for persons aboard a ship and are normally addressed to MARINE HOSPITAL in a city served by the coastal station receiving them.

*DH or PDH.* These complimentary franked messages may require payment of only the landline charges, the ship and coastal charges being franked (transmitted free). The sender must possess a frank card.

*TC. Collated* messages are transmitted back to the transmitting operator by each receiving operator as a confirmation of correct copy. Charges 50 per cent higher than standard radiogram rates. TC is sent before the first word in the address and charged for as one word.

*PRESSE, or PX. Press* messages transmitted by authorized members of the press when addressed to newspapers, magazines, or broadcast stations are charged for at a rate 50 per cent of the standard radiogram rates. The word PRESSE is also transmitted as the first word of the address and is charged for.

*CODH, or DHCO. Company deadhead* messages refer to traffic, licenses, repairs, supplies, etc., exchanged by radio between ships and offices of the same radio service. No charges.

*DH OPR. Operator deadhead* messages are personal messages of radio officers and may be forwarded through the coast stations of the same radio service, subject only to landline charges.

*MSG. Masters' messages* are free messages between masters of vessels when pertaining to ship's business.

*PTR, or TR. Position reports* may be requested by land stations of mobile stations. The answering message indicates approximate distance in nautical miles and bearing in relation to the land station, position in latitude and longitude, course, speed, and next place of call, when furnished by the master of the ship or vehicle.

*CDE. Code* messages consisting of a text having five-letter coded words only. Previously having reduced rates, now are classed as P.

*PR. Deliver by registered mail* messages.

*PC. Acknowledged delivery of message.* Coastal station notifies sender via telegraph of time and date message was delivered to the ship destination.

**32.19 Transmitting Speed.** The average speed of radiotelegraphic communications is probably about 20 words per minute (wpm). This is a comfortable telegraphic hand-key speed. By exerting himself a little, an operator can send 25 to 30 wpm with a hand key. However, with a mechanical key, called a *bug*, good operators may work easily at speeds of 35 to 40 wpm under fair to good conditions. The same operators may not be able to average 15 wpm when static, fading, and interference are bad. The limiting factor is always how well the *receiving* operator can read the transmitted signal. The transmitting operator must gage his sending speed to that which the receiving operator can copy without breaking too often. When receiving conditions are poor, an operator should not hesitate to send QRS (send more slowly) in order to attain accuracy, the most important factor in communications.

In the cases of distress, urgency, and safety traffic, the speed should not exceed 16 wpm to assure a maximum number of operators copying correctly.

**32.20 Transmitting Radiotelegraph.** There are two basic types of mechanisms by which Morse Code is transmitted by hand. The first is the *telegraph key* (Fig. 32.1). The operator places his first finger on the top of the knob, his thumb at the side of the knob, and with a downward pressure of his first finger closes the contacts. A quick make and break produce a *dot.* A *dash* is produced by holding the contacts closed for three times as long as for a dot. For speeds over about 18 wpm, two fingers are used on the top of the knob. The contacts are adjusted for a maximum opening of about 1/16 in. The spring is adjusted to the desired, comfortable upward pressure. For higher speeds a slightly lighter spring tension and less contact spacing are usually more desirable.

The second mechanism is a semiautomatic key, called a *bug* (Fig. 32.2). When the knob is pressed to the left with the first finger, the contacts close, as with a telegraph key. When the paddle is pressed to the right with the tip of the thumb, the vibrating arm makes a series of dots. The speed of the dots is controlled by the placement of the weights on the arm of the bug. The dots are made automatically, but the operator must make each dash separately. The dot contact moves about 1/8 in. before making contact, the dash contact only about 1/32 in., although these adjustments are made at the pleasure of the operator. (An *electronic bug* not only makes the dots automatically but makes a series of dashes when the dash knob is pressed. This can result in very precise sending.)

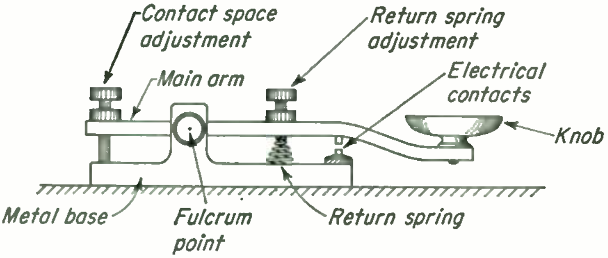


FIG. 32.1. Telegraph, or hand, key. Electrical connections are made to the bottom contact and to the top contact through the metal base.

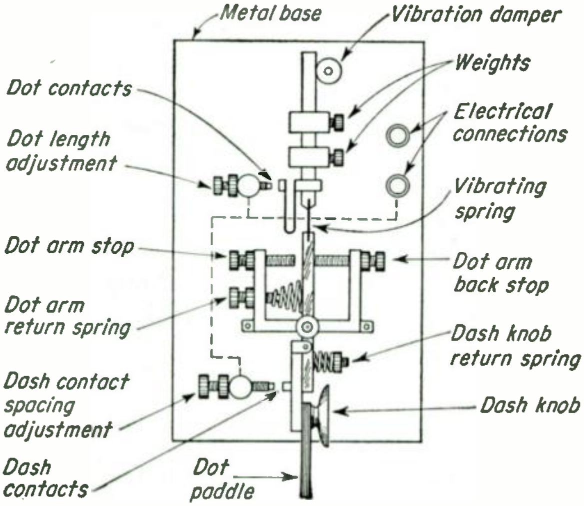


FIG. 32.2. Semiautomatic telegraph key, or bug. Pushing the dot paddle causes the weighted bar to vibrate and make a series of dots.

When an error in sending has been made, the transmitting operator should immediately send a series of eight dots, stop, and start at the beginning of the word in which the error was made. If the error occurs on the first letter of a word, he should transmit the eight-dot error signal and start at the beginning of the word *before* the word in which the error was made.

Table 32.1 Operating Signals

| *Signal* | *Meaning* |
|---|---|
| AA (?AA) | All after . . . |
| AB (?AB) | All before . . . |
| ABV | Repeat figures in abbreviated form |
| ADS | Address |
| $\overline{\text{AS}}$ | Wait |
| BK | Used to interrupt a transmission in progress |
| BN | All between . . . and . . . |
| BQ | A reply to an RQ |
| C | Yes |
| CFM | Confirm |
| CL | I am closing my station |
| COL | Collate, or I collate |
| CP | Call to two or more stations |
| CQ | General call to all stations |
| CS? | Call sign? |
| ER or HR | Here |
| ETA | Estimated time of arrival |
| ITP | The punctuation counts |
| JM | Make a series of dashes if I may transmit, dots if not to transmit |
| K | Invitation to transmit |
| MN or MIN | Minute(s) |
| N | No |
| NIL | I have nothing for you |
| NW | Now |
| OK | We agree |
| PBL | Preamble |
| R | Received |
| REF | Reference to . . . |
| RPT | Repeat |
| RQ | Indication of a request |
| SIG | Signature |
| SYS | See your service message |
| TFC | Traffic |
| TU | Thank you |
| TXT | Text |
| $\overline{\text{VA}}$ or $\overline{\text{SK}}$ | End of work |
| W or WD | Word |
| WA | Word after . . . |
| WB | Word before . . . |

**32.21 Call Letters.** The nationality of a station is indicated by the first or the first two letters (or number and letter) of its call sign. All calls beginning with *K*, *W*, *N*, and *AA* to *AL* are U.S. stations.

*G* and *2A* calls are assigned to Great Britain; *F* calls to France and its Colonies and Protectorates; *R* and *U* calls to the Union of Soviet Socialist Republics; *V* calls to British Colonies; *4U* to United Nations; and so on.

In general, three-letter calls indicate coastal stations in the maritime service or land stations in other services. Four-letter calls are ship stations, or land stations. Five-letter calls are aeronautical mobile stations. Many of the services are now assigned three letters and one to three numbers. For example KMD92 is a police radiotelegraph station call. KMA539 is a police radiotelephone station call.

**32.22 Operating Signals.** To facilitate communication between operators speaking the same or different languages, operating signals have been developed which have the same meanings in all languages. Some of these and their meanings are given in Table 32.1.

**32.23 Q Signals.** To facilitate communication between operators speaking the same or different languages a group of Q signals have been developed which have the same meanings internationally. Those referring to marine radiotelegraph and operating in general are given in Table 32.2.

Table 32.2

| *Signal* | *Meaning* | *Signal* | *Meaning* |
|---|---|---|---|
| QRA? | What is the name of your station? | QRA | The name of my station is . . . . |
| QRB? | How far approximately are you from my station? | QRB | The approximate distance between our stations is . . . nautical miles. |
| QRC? | By what private enterprise (or state administration) are the accounts for charges for your station settled? | QRC | The accounts for charges of my station are settled by . . . . |
| QRD? | Where are you bound and where are your from? | QRD | I am bound for . . . from . . . . |
| QRE? | What is your estimated time of arrival at . . . ? | QRE | ETA at . . . is . . . hours. |
| QRF? | Are you returning to . . . ? | QRF | I am returning to . . . ; or return to . . . . |
| QRG? | Will you tell me my exact frequency (or that of . . .)? | QRG | Your exact frequency (or that of . . .) is . . . kc/s (or mc/s). |
| QRH? | Does my frequency vary? | QRH | Your frequency varies. |
| QRI? | How is the tone of my transmission? | QRI | The tone of your transmission is: (1) Good. (2) Variable. (3) Bad. |
| QRK? | What is the readability of my signals (or those of . . .)? | QRK | The readability of your signals (or those of . . .) is: (1) Unreadable. (2) Readable now and then. (3) Readable, but with difficulty. (4) Readable. (5) Perfectly readable. |
| QRL? | Are you busy? | QRL | I am busy (or busy with . . .). Please do not interfere. |
| QRM? | Are you being interfered with? | QRM | I am being interfered with. |
| QRN? | Are you troubled by static? | QRN | I am troubled by static. |
| QRO? | Shall I increase power? | QRO | Increase power. |
| QRP? | Shall I decrease power? | QRP | Decrease power. |
| QRQ? | Shall I send faster? | QRQ | Send faster (. . . wpm). |

Table 32.2 (*Continued*)

| *Signal* | *Meaning* | *Signal* | *Meaning* |
|---|---|---|---|
| QRR? | Are you ready for automatic operation? | QRR | I am ready for automatic operation. Send at . . . wpm. |
| QRS? | Shall I send more slowly? | QRS | Send more slowly. |
| QRT? | Shall I stop sending? | QRT | Stop sending. |
| QRU? | Have you anything for me? | QRU | I have nothing for you. |
| QRV? | Are you ready? | QRV | I am ready. |
| QRW? | Shall I inform . . . that you are calling him on . . . kc? | QRW | Please inform . . . that I am calling him on . . . kc. |
| QRX? | When will you call me again? | QRX | I will call you again at . . . hours (on . . . kc). |
| QRY? | What is my turn? | QRY | Your turn is number . . . . |
| QRZ? | Who is calling me? | QRZ | You are being called by . . . (on . . . kc). |
| QSA? | What is the strength of my signals (or those of . . .)? | QSA | The strength of your signals (or those of . . .) is: (1) Scarcely perceptible. (2) Weak. (3) Fairly good. (4) Good. (5) Very good. |
| QSB? | Are my signals fading? | QSB | Your signals are fading. |
| QSC? | Are you a cargo vessel? | QSC | I am a cargo vessel. |
| QSD? | Is my keying defective? | QSD | Your keying is defective. |
| QSG? | Shall I send . . . telegrams at a time? | QSG | Send . . . telegrams at a time. |
| QSI? | . . . . . . . . . . . | QSI | I have been unable to break in on your transmission; or will you inform . . . that I have been unable to break in on his transmission on . . . kc. |
| QSJ? | What is the charge to be collected per word to . . . including your internal telegraph charge? | QSJ | The charge to be collected per word to . . . including my internal telegraph charge is . . . francs. |
| QSK? | Can you hear me between your signals? | QSK | I can hear you between my signals. |
| QSL? | Can you acknowledge receipt? | QSL | I am acknowledging receipt. |
| QSM? | Shall I repeat the last telegram which I sent you, or some previous telegram? | QSM | Repeat the last telegram which you sent me [or, telegram (s) number(s) . . .]. |
| QSN? | Did you hear me (or on . . . kc)? | QSN | I did hear you (or, on . . . kc). |
| QSO? | Can you communicate with . . . direct or by relay? | QSO | I can communicate with . . . direct or by relay through . . . . |
| QSP? | Will you relay to . . . free of charge? | QSP | I will relay to . . . free of charge. |
| QSQ? | Have you a doctor on board [or, is . . . (name of person) on board]? | QSQ | I have a doctor on board [or, . . . (name of person) is on board]. |
| QSU? | Shall I send or reply on this frequency (or, on . . . kc) (with emissions of class . . .)? | QSU | Send or reply on this frequency (or, on . . . kc) (with emissions of class . . .). |

Table 32.2 (*Continued*)

| *Signal* | *Meaning* | *Signal* | *Meaning* |
|---|---|---|---|
| QSV? | Shall I send a series of V's on this frequency (or . . . kc)? | QSV | Send a series of V's on this frequency (or . . . kc). |
| QSW? | Will you send on this frequency (or, . . . kc) (with emissions of class . . .)? | QSW | I am going to send on this frequency (or, on . . . kc) (with emissions of class . . .). |
| QSX? | Will you listen to . . . (call sign) on . . . kc? | QSX | I am listening to . . . (call sign) on . . . kc. |
| QSY? | Shall I change to transmission on another frequency? | QSY | Change to transmission on another frequency (or, on . . . kc). |
| QSZ? | Shall I send each word or group more than once? | QSZ | Send each word or group twice (or, . . . times). |
| QTA? | Shall I cancel telegram number . . . as if it had not been sent? | QTA | Cancel telegram number . . . as if it had not been sent. |
| QTB? | Do you agree with my counting of words? | QTB | I do not agree with your counting of words; I will repeat the first letter or digit of each word or group. |
| QTC? | How many telegrams have you to send? | QTC | I have . . . telegrams for you (or, for . . .). |
| QTE? | What is my TRUE bearing from you (or, What is my TRUE bearing from . . . ; or, What is the TRUE bearing of . . . from . . .)? | QTE | Your TRUE bearing from me is . . . degrees (at . . . hours) (or, Your TRUE bearing from . . . was . . . degrees at . . . hours; or, The TRUE bearing of . . . from . . . was . . . degrees at . . . hours). |
| QTF? | Will you give me the position of my station according to the bearings taken by the direction-finding stations which you control? | QTF | The position of your station according to the bearings taken by the direction-finding stations which I control was . . . latitude . . . longitude. |
| QTG? | Will you send two dashes of 10 sec each followed by your call sign (repeated . . . times) (on . . . kc)? | QTG | I am going to send two dashes of 10 sec each followed by my call sign (repeated . . . times) (on . . . kc). |
| QTH? | What is your position in latitude and longitude (or according to any other indication)? | QTH | My position is . . . latitude . . . longitude (or according to any other indication). |
| QTI? | What is your TRUE track? | QTI | My TRUE track is . . . degrees. |
| QTJ? | What is your speed? | QTJ | My speed is . . . knots. |
| QTK? | What is the speed of your aircraft in relation to the surface of the earth? | QTK | The speed of my aircraft in relation to the surface of the earth is . . . knots. |
| QTL? | What is your TRUE heading (TRUE course with no wind)? | QTL | My TRUE heading is . . . degrees. |
| QTN? | At what time did you depart from . . . (place)? | QTN | I departed from . . . (place) at . . . hours. |
| QTO? | Have you left dock (or, Are you airborne)? | QTO | I have left dock (or, I am airborne). |

Table 32.2 (*Continued*)

| *Signal* | *Meaning* | *Signal* | *Meaning* |
|---|---|---|---|
| QTP? | Are you going to enter dock (or, Are you going to alight)? | QTP | I am going to enter dock (or, I am going to alight). |
| QTQ? | Can you communicate with my station by means of the International Code of Signals? | QTQ | I am going to communicate with your station by means of the International Code of Signals. |
| QTR? | What is the correct time? | QTR | The correct time is . . . hours. |
| QTS? | Will you send your call sign for . . . minute(s) now (or, at . . . hours) (on . . . kc) so that your frequency may be measured? | QTS | I will send my call sign for . . . minute(s) now (or at . . . hours) (on . . . kc) so that my frequency may be measured. |
| QTU? | What are the hours during which your station is open? | QTU | My station is open from . . . to . . . hours. |
| QTV? | Shall I stand guard for you on the frequency of . . . kc (from . . . to . . . hours)? | QTV | Stand guard for me on the frequency of . . . kc (from . . . to . . . hours). |
| QTX? | Will you keep your station open for further communication with me until further notice (or, until . . . hours)? | QTX | I will keep my station open for further communication with you until further notice (or, until . . . hours). |
| QUA? | Have you news of . . . (call)? | QUA | Here is news of . . . (call sign). |
| QUB? | Can you give me, in the following order, information concerning visibility, height of clouds, direction and velocity of ground wind at . . . (place)? | QUB | Here is the information requested . . . . |
| QUC? | What is the number (or other indication) of the last message you received from me (or, from . . . call sign)? | QUC | The number (or other indication) of the last message I received from you [or, from . . . (call sign)] is . . . . |
| QUD? | Have you received the urgency signal sent by . . . (call sign)? | QUD | I have received the urgency signal sent by . . . (call sign). |
| QUF? | Have you received the distress signal sent by . . . (call sign)? | QUF | I have received the distress signal sent by . . . (call sign). |
| QUG? | Will you be forced to alight (or land)? | QUG | I am forced to alight (or land) immediately [or, I shall be forced to alight (or, land) at . . . (position or place)]. |
| QUH? | Will you give me the present barometric pressure at sea level? | QUH | The present barometric pressure at sea level is . . . (units). |
| QUI? | Are your navigation lights working? | QUI | My navigation lights are working. |
| QUJ? | Will you indicate the TRUE course for me to steer toward you (or) . . . with no wind? | QUJ | The TRUE course for you to steer toward me (or . . . with no wind) is . . . degrees at . . . hours. |
| QUK? | Can you tell me the condition of the sea observed at . . . (place)? | QUK | The sea at . . . (place) is . . . . |
| QUL? | Can you tell me the swell observed at . . . (place)? | QUL | The swell at . . . (place) is . . . . |
| QUM? | Is the distress traffic ended? | QUM | The distress traffic is ended. |

Table 32.2 (*Continued*)

| *Signal* | *Meaning* | *Signal* | *Meaning* |
|---|---|---|---|
| QUN? | Will vessels in my immediate vicinity (or in the vicinity of . . . latitude . . . longitude) (or, of . . .) please indicate their position, TRUE course, and speed? | QUN | My position, TRUE course, and speed are . . . . |
| QUO? | Shall I search for . . . [(1) aircraft, (2) ship, (3) survival craft] in the vicinity of . . . latitude . . . longitude (or according to any other indication)? | QUO | Please search for . . . [(1) aircraft, (2) ship, (3) survival craft] in the vicinity of . . . latitude . . . longitude (or according to any other indication). |
| QUP? | Will you indicate your position by . . . [(1) searchlight, (2) black-smoke trail, (3) pyrotechnic lights]? | QUP | My position is indicated by . . . [(1) searchlight, (2) black-smoke trail, (3) pyrotechnic lights]. |
| QUQ? | Shall I train my searchlight nearly vertical on a cloud, occulting if possible and, if your aircraft is seen, deflect the beam up wind and on the water (or land) to facilitate your landing? | QUQ | Please train your searchlight on a cloud, occulting if possible, and, if my aircraft is seen or heard, deflect the beam up wind and on the water (or land) to facilitate my landing. |
| QUR? | Have survivors . . . [(1) received survival equipment, (2) been picked up by rescue vessel, (3) been reached by ground rescue party]? | QUR | Survivors . . . [(1) are in possession of survival equipment dropped by . . . , (2) have been picked up by rescue vessel, (3) have been reached by ground rescue party]. |
| QUS? | Have you sighted survivors or wreckage? If so, in what position? | QUS | Have sighted . . . [(1) survivors in water, (2) survivors on rafts, (3) wreckage] in position . . . latitude . . . longitude (or, according to any other indication). |
| QUT? | Is position of incident marked? | QUT | Position of incident is marked (by . . .). |
| QUU? | Shall I home ship or aircraft to my position? | QUU | Home ship or aircraft [(1) . . . (call sign) to your position by transmitting your call sign and long dashes on . . . kc, (2) . . . (call sign) by transmitting on . . . kc] courses to steer to reach you. |

## COMMERCIAL LICENSE INFORMATION

(Section where answered in parentheses. FCC element number at right.)

**1.** What is meant by the statement, "A station is open to public correspondence"? (32.1) **[5]**

**2.** Where should the operator on duty at a manually operated radiotelegraph station normally post his operator license or permit? (32.1) **[5]**

**3.** Is the holder of a Radiotelegraph Third Class operator permit authorized to make technical adjustments to a radiotelephone transmitter? To a radiotelegraph transmitter? (32.2) [5]

**4.** List three classes of stations which may not be operated by the holder of a Radiotelegraph Third Class operator permit. (32.2) [5]

**5.** In order to avoid confusion in transmitting numbers involving a fraction, how should such numbers be transmitted? Give an example of such a number showing how it should be transmitted. (32.3) [5]

**6.** If a radiotelegraph operator makes an error in transmitting message text, how does he indicate that an error has been made? (32.3, 32.20) [5]

**7.** What radiotelegraph signal is generally employed in a call "to all stations"? (32.5) [5]

**8.** Describe a procedure of radiotelegraph transmission in which one station calls another. Give an example. (32.5) [5]

**9.** Describe a procedure of radiotelegraph transmission in which one station answers the call of another. Give an example. (32.6) [5]

**10.** If, upon being called by another station, a called station is busy with other traffic, what should the operator of the called station do? (32.6) [5]

**11.** When testing a radiotelegraph transmitter, what signals are generally transmitted? (32.7) [5]

**12.** What are the requirements for station identification at radiotelegraph stations in the Public Safety Radio Services? (32.8) [5]

**13.** The speed of radiotelegraph code transmission in cases of distress, urgency, or safety must not in general exceed what speed? (32.11, 32.19) [5]

**14.** What is the radiotelegraph distress signal? Urgency signal? Safety signal? (32.11–32.13) [5]

**15.** What is meant by the preamble in a radiotelegraph message? What information is usually given in the preamble? (32.15) [5]

**16.** In addition to the preamble, what parts does a radiotelegraph message contain? (32.15) [5]

**17.** What is meant by a service prefix or indicator in a radiotelegraph message? (32.15) [5]

**18.** What is the meaning of word count, or check, in a radiotelegraph message? (32.15) [5]

**19.** At what time, or times, does the serial numbering of radio messages begin? Does the period of numbering vary in some services? (32.15) [5]

**20.** Immediately following the transmission of a radiotelegraph message containing figures or odd symbols, why are such figures sometimes collated? (32.15, 32.18) [5]

**21.** Code or cipher groups are often used in radiotelegraph messages for what purpose? (32.16) [5]

**22.** In general, what is the purpose of a service message in radiotelegraph communication? (32.18) [5]

**23.** Should the speed of transmission of radiotelegraph signals be in accordance with the desire of the transmitting or receiving operator? (32.19) [5]

**24.** How should a manual radiotelegraph transmitting key be adjusted for good operation? Is the adjustment always the same for slow as it is for high speed? (32.20) [5]

**25.** Describe how an automatic key, or bug, should be properly adjusted to send good readable radiotelegraph signals. (32.20) [5]

**26.** What is meant by the following radiotelegraph operating signals: R, $\overline{\mathrm{AS}}$, $\overline{\mathrm{IMI}}$, C, $\overline{\mathrm{BT}}$, K, $\overline{\mathrm{AR}}$, $\overline{\mathrm{VA}}$, DE? (32.22) [5]

**27.** Why are Q signals or other arbitrarily selected procedure signals used in radiotelegraph communications? (32.23) [5]

**28.** What is meant by the following signals: QRA, QRM, QRN, QRT, QRZ, QSA, QSV, QUM, QRL? (32.23) **[5]**

**29.** If receiving conditions are bad and you desire that the transmitting station send each word or group twice to facilitate reception, what operating signal would be appropriate to use? (32.23) **[5]**

**30.** If the signal strength of a radiotelegraph signal is reported on a scale of 1, 2, 3, 4, 5, what scale number would indicate a very strong signal? What scale number would indicate a very weak signal? (32.23, see QSA) **[5]**

**31.** In all cases other than those in which the transmitter output must be maintained at a fixed value, what amount of power should be employed for routine communication? (32.1) **[6]**

**32.** Indicate the order of priority of the various types of radio communications. (32.1, 31.2) **[6]**

**33.** Under what circumstances may a station be operated by an unlicensed person? (32.2) **[6]**

**34.** In the transmission of the International Morse Code, what are the relative time lengths of dashes, dots, and spaces? (32.3) **[6]**

**35.** You intercept CQ CQ WSV TFC QSY 735 $\overline{\text{AS}}$. What does this message mean? (32.5) **[6]**

**36.** If, upon being called by another station, a called station is unable to proceed with the acceptance of traffic, what should the operator of the called station do? (32.6) **[6]**

**37.** At what time(s) must the international silent period be observed? (32.10) **[6]**

**38.** At what time(s) are routine transmissions forbidden in the band 485–515 kc? (32.10) **[6]**

**39.** Under what circumstances must log entries be made regarding observance of the international silence period? (32.14) **[6]**

**40.** Describe how a distress call should be made. (32.11) **[6]**

**41.** What station shall be in control of distress traffic? (32.11) **[6]**

**42.** What is the international radiotelegraph distress frequency for stations in the mobile service? (32.11) **[6]**

**43.** With what type(s) of emission and upon what frequency should a radiotelegraph transmitter be adjusted to transmit a distress call? (32.11) **[6]**

**44.** What transmission should precede the sending of a the distress call? (32.11) **[6]**

**45.** What space of time should elapse between the transmission of the international autoalarm signal and the distress call? (32.11) **[6]**

**46.** Upon hearing an SOS, what should an operator do? (32.11) **[6]**

**47.** After a distress call has been transmitted, every distress traffic radiotelegram shall contain what symbol in the preamble? (32.11) **[6]**

**48.** Under what circumstances is a station in the mobile service not required to listen to distress traffic? (32.11) **[6]**

**49.** During what periods must a distress message be repeated following the initial transmission? (32.11) **[6]**

**50.** How long must mobile stations listen after they have heard an urgency signal? (32.12) **[6]**

**51.** What interval of time must elapse between the end of the autoalarm signal and an urgent cyclone warning? (32.12) **[6]**

**52.** Under what circumstances and by whom may the international autoalarm signal be transmitted to announce an urgent cyclone warning? (32.12) **[6]**

**53.** During what periods must the safety signal be transmitted? (32.13) **[6]**

**54.** Upon hearing a safety signal, what should the operator at the receiving station do? (32.13) **[6]**

**55.** What time system shall be used in making log entries with respect to the observance of the international silence period? (32.14) **[6]**

**56.** For what period of time must a station log, which contains entries incident to a disaster, be retained? (32.14) **[6]**

**57.** Explain cable count and the use of standard service abbreviations and show the difference between cable count and domestic word count. (32.15–32.17) **[6]**

**58.** Construct a plain-language radiotelegram and indicate what portions comprise (*a*) the preamble, (*b*) the address, (*c*) the text, and (*d*) the signature. (32.15) **[6]**

**59.** Explain the use and meaning of the following indicators, or prefixes, on radiotelegrams and describe the difference in handling of the various types of radiotelegrams: RP, TC, PC, PR, TR, MSG, CDE, OBS, PDH, CODH. (32.18) **[6]**

**60.** If you received a distress call signed by a call signal composed of five letters, could you determine the type of craft which transmitted the signal? (32.21) **[6]**

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

★**1.** What are the recognized abbreviations for Eastern Standard Time and Greenwich Mean Time? (32.14)

**2.** What are the meanings of the following Q signals: QRT, QSZ, QSY, QSA, QRK, QRM, QRX? (32.23)

**3.** What type of transmissions or messages have absolute priority or precedence over all other types of communications? (32.11)

## CHAPTER 33

# AMATEUR RULES AND REGULATIONS

**33.1 The Amateur Radio Service.** The information in this chapter explains briefly the amateur radio service for those interested in passing amateur license examinations. Some of the material is a condensation of the FCC publication, "Part 12—Rules Governing Amateur Radio Service," for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. (15 cents). For the precise legal wording the reader is referred to this publication.

Since the beginning of radio there have been many persons interested in experimenting with radio equipment without any pecuniary interest. Such persons are known as *amateurs* solely because they do not accept money for their on-the-air operations. Many of the foremost radio and electronics engineers operate as amateurs during times when they are not occupied professionally.

Anyone can experiment with *receiving* equipment, but as soon as equipment is capable of *transmitting* a radio signal, it must be licensed, or be operated by licensed persons. In the amateur service it is the operators that are licensed. In commercial services transmitters are licensed and are generally operated by licensed operators. A licensed amateur operator can apply for an amateur station license. He will be issued a call sign to use with any transmitting equipment he constructs or places in operation.

Bands of frequencies in the radio spectrum have been set aside for amateur use. On these frequencies amateurs act as a voluntary noncommercial communication service, often providing important and lifesaving emergency communications. Amateurs act as a reservoir of trained operators, technicians, and electronics experts and through their contacts with amateurs in other parts of the world actively enhance international good will. The existence of the amateur service encourages the upgrading of the skills of this group who have proven their ability to contribute to the advancement of both the communication and technical phases of the radio art.

Amateur operators consider their activities on the air as a challenging hobby. Whom will they talk to next? How many foreign countries can they contact? How far can their equipment reach to provide communications? What can be done to the present equipment to make it work better? What frequencies are best to use? What antenna system is most satisfactory? How many messages can they handle?

Operation of these amateur stations is limited to persons holding *amateur* licenses *only.* However, an unlicensed person may talk into the microphone of an amateur transmitter, provided a licensed amateur maintains actual control over the emissions, including turning the carrier on and off for each transmission and signing the station on and off. Only properly *licensed amateurs* may operate the telegraph key of an amateur station.

**33.2 The Novice Class License.** The Novice Class is the simplest amateur license to obtain. It is given to prospective holders by a licensed amateur operator holding a valid General, Advanced, or Extra Class amateur license, by someone designated by the FCC, or by a person having held in the last 5 years a commercial radiotelegraph license.

The prospective Novice operator first writes to the FCC office in his district (Sec. 33.16) requesting the necessary test papers. After filling out the enclosed application and having it notarized, he usually selects a local amateur to give him the required code test at 5 words per minute (wpm), sending and receiving. After passing the code test, the amateur operator watches while the applicant completes the written part of the examination. The papers are then returned to the FCC for grading, and if passed, the Novice license and call letters are issued. The scope of the Novice test is indicated by the amateur questions prefaced by a star at the end of this and other chapters in this book.

The Novice Class license is issued for a period of only 1 year and is *not renewable.* In this year the holder must take the more advanced Technician Class license examination, or increase his code speed to 13 wpm and take the more advanced General Class license examination, or drop out of amateur radio communication entirely.

As a Novice, an operator may operate radiotelegraphic code (CW or A1 emission) on frequency bands 3,700–3,750 kc, 7,150–7,200 kc, 21.10–21.25 Mc, 145–147 Mc. On the last-mentioned band he may also operate radiotelephone and A2 radiotelegraph (Sec. 15.7).

The frequency of all Novice Class transmitters must be determined by crystal-controlled oscillator circuits. The maximum d-c power input to the final amplifier tube(s) must not exceed 75 watts.

A Novice operator may operate any other Novice transmitter or any other class of amateur station provided it is operated according to Novice rules and regulations. (A General, Conditional, or other higher-grade licensed amateur must operate a Novice's transmitter only in accordance with Novice rules and regulations.)

Any applicant who fails a Novice or any other grade amateur license examination must wait for a period of 30 days before he is eligible to be re-examined (except that a person failing a Conditional Class license may take a General Class license examination).

**33.3 The Technician Class License.** This license is similar to the Novice Class in that it is given to the applicant by an amateur operator holding General, Advanced, or Extra Class licenses, by holders of commercial radiotelegraph licenses, or by someone designated by the FCC. A 5-wpm code test is first passed. Then the person administering the test watches while the applicant completes the technical written test. The scope of the written part of this test is indicated by the amateur questions at the end of this and other chapters in this book.

The Technician Class license is issued for a period of 5 years and is renewable upon application.

For a technician, all amateur privileges are available on the 50–54-Mc and 145–147-Mc bands and on all amateur bands above 220 Mc. None of the other more popular amateur bands may be used.

**33.4 The General and Conditional Class Licenses.** The General and the Conditional Class licenses are the lowest grades that give full amateur privileges to the holders. These licenses require a code speed of 13 wpm and a theory test, the scope of which is indicated by the amateur questions at the end of this and other chapters of this book.

The General Class license is taken at an office of the FCC or at any point at which the FCC holds General Class license examinations.

The Conditional Class license is given by a licensed General, Advanced, or Extra Class amateur, by a commercial radiotelegraph license holder, or by someone designated by the FCC, provided the applicant is located more than 125 airline miles from any FCC examining point, or is unable to appear because of physical disability, or because he is in one of the armed services. However, the holder of a Conditional Class license may be required by the FCC to take a General Class license examination under certain conditions.

**33.5 The Advanced Class License.** Examinations for this class license are no longer given. Holders of this license have all amateur privileges, having previously passed an examination of higher grade than the General Class (which was previously known as a Class B) license. These licenses will continue to be renewed as Advanced Class licenses.

**33.6 The Extra Class License.** The highest-grade amateur license is the Extra Class. It consists of a code speed test of 20 wpm sending and receiving and a theory test embracing many of the commercial radiotelegraph and radiotelephone Second and First Class license questions in Elements 3, 4, 6, and 8. It offers no additional privileges to holders at this time. This examination is given only at FCC examination points.

**33.7 Frequencies Available to Amateurs.** The following frequency bands are available to all Extra, Advanced, General, or Conditional Class license holders:

*3,500–4,000 kc.* The "80-meter band." Open to A1 emission. Open to F1 from 3,500–3,800 kc. Open to A3 and narrow-band FM (F3) from 3,800–4,000 kc.

*7,000–7,300 kc.* The "40-meter band." Open to A1 emission. Open to F1 from 7,000–7,200 kc. Open to A3 and narrow-band F3 from 7,200–7,300 kc.

*14–14.35 Mc.* The "20-meter band." Open to A1 emission. Open to F1 from 14–14.2 Mc. Open to A3 and narrow-band F3 from 14.2–14.35 Mc.

*21–21.45 Mc.* The "15-meter band." Open to A1 emission. Open to F1 from 21–21.125 Mc. Open to A3 and narrow-band F3 from 21.25–21.45 Mc.

*28–29.7 Mc.* The "10-meter band." Open to A1 emission. Open to A3 and narrow-band F3 from 28.5–29.7 Mc. Open to special emissions for FM (wideband F3, carrier shift, etc., 29–29.7 Mc).

*50–54 Mc.* The "6-meter band." Open to A1, 50–54 Mc; to A2, A3, A4, and narrow band F1, F2, and F3, 50.1–54 Mc; to A0, 51–54 Mc; to F0, F1, F2, and F3, 52.5–54 Mc.

*144–148 Mc.* The "2-meter band." Open to A1, 144–148 Mc; to A0, A2, A3, A4, F0, F1, F2, and F3, 144–147.9 Mc.

*220–225 Mc.* Similar to the 144–148-Mc band, with some reservations on use in parts of Texas and New Mexico.

*420–450 Mc.* Similar to the 144–148-Mc band, except that the maximum d-c plate power input to the final stage of the transmitter shall not exceed 50 watts. In addition, A5 (television) is authorized in this band.

*1,215–1,300 Mc.* Open to A0, A1, A2, A3, A4, and A5, as well as special emissions for carrier shift and FM.

*2,300–2,450 Mc, 3,300–3,500 Mc, 5,650–5,925 Mc, 10,000–10,500 Mc, 21,000–22,000 Mc, and Any Frequencies above 30,000 Mc.* Similar to the 1,215–1,300-Mc band, with the addition of pulse emissions.

Operation on the 1,800–2,000-kc band, known as the "160-meter band," is subject to specified frequencies and powers according to geographical areas (Table 33.1) to prevent interference with loran stations and may be subject to changes periodically.

**33.8 Equipment and Operation.** In the United States (Territories and possessions) an amateur station may be operated as a fixed, a portable, or a mobile station on any amateur frequency for which it is licensed. Prior written notice must be given to the engineer in charge of the district where portable or mobile operation is proposed in the event such operation exceeds 48 hr away from the licensed location. Whenever such operation exceeds 1 year (and for each additional year) written notice must be given to the engineer in charge of the district in which the station is operated.

The maximum d-c plate power *input* to the final-amplifier tube(s) of any amateur transmitter is 1,000 watts, provided accurate means of

Table 33.1 160-meter Band

| Areas | Frequencies, kc | Daytime power, watts | Nighttime power, watts |
|---|---|---|---|
| Minnesota, Iowa, Wisconsin, Michigan, Pennsylvania, Maryland, Delaware, states to the north, and District of Columbia | 1,800–1,825 | 500 | 200 |
| North Dakota, South Dakota, Nebraska, Colorado, New Mexico, states to the west, except Washington | 1,975–2,000 | 500 | 200 |
| State of Washington | 1,975–2,000 | 200 | 50 |
| Oklahoma, Kansas, Missouri, Arkansas, Illinois, Indiana, Kentucky, Tennessee, Ohio, West Virginia, Virginia, North Carolina, South Carolina, Texas (west of 99°W or north of 32°N) | 1,800–1,825 | 200 | 50 |
| Hawaiian Islands | 1,900–1,925<br>1,975–2,000 | 500 | 200 |
| Texas (east of 99°W and south of 32°N), Louisiana, Mississippi, Alabama, Georgia, Florida, Puerto Rico, Virgin Islands, Alaska, Guam, and other territories not listed above | No authorized operation | | |

measuring the power is used. Otherwise, 900 watts is the maximum (exceptions: see 1,800–2,000-kc and 420–450-Mc bands, Sec. 33.7).

All transmitters using frequencies *below* 144 Mc must use adequately filtered d-c plate power supplies to minimize hum modulation of the emitted carrier. This requires a rectifier and adequate filter if the plate power-supply system is operated from an a-c source.

All transmitters operating with a carrier frequency below 144 Mc must reduce or eliminate, in accordance with good engineering practice, spurious radiations (due to parasitic oscillations, harmonics, key clicks, undesirable sidebands produced by modulating the carrier over 100 per cent, or attempting to modulate in excess of the modulation capability of the equipment). Simultaneous FM and AM is not allowed below 144 Mc.

The maximum percentage of modulation shall be 100 per cent (see chapter on Amplitude Modulation). Means must be employed to insure that the transmitter is not modulated in excess of its modulation capabilities. In the case of narrow-band FM, sidebands must not be broader than those of an amplitude-modulated carrier of the same carrier frequency. With AM the frequency of the audio-modulating voltage determines how far the sidebands will be displaced from the carrier. A

3-kc audio a-c will produce sidebands 3 kc on each side of the carrier. Thus, if the upper edge of an amateur band is 4,000 kc, the carrier frequency would have to be lower by 3 kc than 4,000, or be at 3,997 kc to prevent either sideband from falling outside of the band. If the frequency tolerance of the transmitter is plus or minus 2 kc, the carrier must be 3 kc plus 2 kc less than the band limit, or at 3,995 kc. With a low-frequency band edge at 3,800 kc, the same transmitter would have to be 3 plus 2 kc *above* 3,800, or at 3,805 kc.

The frequency and purity of the emitted carrier wave of a transmitter shall be as constant as the state of the art permits.

Amateurs must provide a means of measuring the frequency of their transmitted carrier wave with sufficient accuracy so as to assure operation within the amateur frequency band used. They must make such measurements regularly.

Amateur stations are not to transmit a carrier wave unless it is modulated for the purpose of communication. Exceptions to this are brief tests or adjustments, and operation on all frequencies above 144 Mc.

An amateur station must transmit its call sign at least every 10 min of operation, or at the beginning and end of each transmission, using either radiotelephone or radiotelegraph, plus station identification with the method of communication in use (such as radioteletype). When a series of communications, each of less than 3 min duration, occurs between two or more stations on the same frequency, in general it is only necessary to identify every 10 min of operation.

As in all other services, distress signals and messages have absolute priority over all other types of communications.

The transmission of music or the broadcasting of programs for the public is forbidden on all amateur frequencies (except code-practice broadcasts). Single-tone signals of short duration may be used for test purposes.

Only plain-language communications may be used. Code and ciphers are prohibited, as are improper language, false signals, unidentified signals, and malicious interference.

Communications between amateurs of different countries are authorized unless specifically forbidden by one or both of the countries. International communications between amateur stations must not be made on behalf of third parties (persons other than the two amateurs operating the stations) unless there is a special arrangement between the countries concerned to allow third-party messages.

Calling and working procedure, Q signals, and the phonetic alphabet in the amateur service generally follow that outlined in the chapters on Communicating by Radiotelegraph and Communicating by Voice. If the calling station is on or near the frequency of the called station, a short call (W6FXA W6FXA W6FXA DE W6BNB W6BNB W6BNB K) is all that may be necessary. If the two stations are removed somewhat in frequency, the called station call letters may be repeated more than three times. When calling CQ (general call to all stations), a satisfactory procedure is to repeat CQ five times and transmit DE and the call letters of the transmitting station three times, repeating CQ and call signs for a period of a minute or more.

It must be remembered that the electrical house wiring carries a potential of 110 volts, which is more than enough to kill anyone if he should make a firm enough contact across it. Be careful. Pull the plug from the outlet before working on transmitters or receivers. Never hold a microphone while tuning a transmitter. Keep one hand in your pocket. Do not ground yourself. Do not experiment or tune when sleepy.

**33.9 Amateur Station Logs.** A log of on-the-air operation must be kept for any amateur station. It must include the date and time of each call or contact made, indicating beginning and ending times to show the period during which the communication was carried on. The signature of the licensed operator must appear on the log, as well as the signature of any other licensed operators at the time they operate the station. It must show the call sign of all stations called or worked, as well as the d-c plate input power to the stage coupled to the antenna, the frequency band used, the type of emission used, numbers of messages handled (messages must be held on file for 1 year), and location of the station if portable or mobile.

Logs must be retained for possible inspection by authorized representatives of the FCC for a period of at least 1 year.

**33.10 Penalties.** The amateur service is operated under the Communications Act of 1934 and international agreements. Amateur operators are therefore subject to the same severe penalties that are mentioned in Sec. 30.2.

**33.11 Classification of Emissions.** The often-used classifications of emissions in the amateur service are A1, A2, A3, F1, and F3. The meanings of these and other possible emissions usable by amateurs are listed in Sec. 15.7.

**33.12 Q Signals.** In both amateur radiotelegraph and radiotelephone communications considerable use is made of Q signals, which are international abbreviations (Sec. 32.23). The Q signals mostly used by amateurs are QRT, QSZ, QSY, QSA, QRK, QRM, QTH, QRZ, QRN, and QRX. The meanings of at least these should be memorized.

**33.13 Emergency Communications.** In the event of a local emergency disrupting normal communications, the FCC may declare that a general state of communications emergency exists and specify the areas and amateur frequency bands (or segments) for use only by amateurs participating in emergency communications. (On other amateur frequencies normal amateur communications may continue.) Certain amateur stations may be designated by the FCC to warn stations of the existence of the emergency. The FCC will notify when the emergency period has ended.

Old amateur regulations stipulated certain times and frequencies for important initial calls referring to the emergency. Such rules are no longer in effect. These calls may be made at any time and on any frequency band designated by the FCC.

**33.14 Conelrad.** Since January, 1957, all amateur stations, fixed, portable, or mobile, must have some means of monitoring a radio service that will indicate if an enemy air attack is imminent. In most cases this can be accomplished by audibly monitoring a local broadcast station before the amateur station starts to transmit and by making a positive check at least every 10 min during a transmission. Automatic alarm devices can be constructed using the loss of AVC voltage at the loss of a signal in a broadcast receiver to actuate an alarm. (See also the conelrad information in the chapter on The Broadcast Station.)

**33.15 RACES.** The Radio Amateur Civil Emergency Service is a temporary radiocommunication service in which authorized amateur stations work in conjunction with a civil-defense plan in their area in case of war or any actual or impending disaster or other incident endangering the public welfare. Only those amateurs and stations that have joined a Civil Defense Communications group may participate. Fixed, portable, and mobile stations are needed in this work. Narrow segments of the 160-, 80-, 10-, 6-, 2-, and 1½-meter bands have been allocated for use in such emergencies. However, these frequencies may be used during nonemergency times for civil-defense or RACES drills. For further information on this subject contact local Civil Defense Communication groups or any office of the FCC.

**33.16 FCC Addresses.** To get in touch with the Engineer in Charge, Federal Communications Commission, regarding tests, extended portable operation, or other information, the closest of the offices listed below may be contacted.

| *Address* | *City* |
|---|---|
| Customhouse | Boston 9, Mass. |
| Federal Bldg., 641 Washington St. | New York 14, N.Y. |
| New U.S. Customhouse, 2d and Chestnut Sts. | Philadelphia 6, Pa. |
| Old Town Bank Bldg, Gay St. and Fallsway | Baltimore 2, Md. |
| Federal Bldg. | Norfolk 10, Va. |
| Federal Annex | Atlanta 3, Ga. |
| P.O. Box 150, Federal Bldg. | Miami 1, Fla. |
| Audubon Bldg. | New Orleans 16, La. |
| U.S. Appraisers Stores Bldg., 7300 Wingate St. | Houston 11, Tex. |
| U.S. Terminal Annex Bldg., Houston and Jackson Sts. | Dallas 2, Tex. |
| U.S. Post Office and Courthouse Bldg., Temple and Spring Sts. | Los Angeles 12, Cal. |

| *Address* | *City* |
|---|---|
| U.S. Customhouse Bldg. | San Francisco 26, Cal. |
| Fitzpatrick Bldg., 918 S.W. Oak St. | Portland 5, Ore. |
| Federal Office Bldg. | Seattle 4, Wash. |
| New Customhouse, 19th St. | Denver 2, Colo. |
| Uptown Post Office and Federal Courts Bldg., 5th and Washington Sts. | St. Paul 2, Minn. |
| Federal Office Bldg., 911 Walnut St. | Kansas City 6, Mo. |
| U.S. Courthouse, 219 S. Clark St. | Chicago 4, Ill. |
| New Federal Bldg. | Detroit 26, Mich. |
| Post Office Bldg., Ellicott and Swan Sts. | Buffalo 3, N.Y. |
| Federal Bldg. | Honolulu 1, T.H. |
| Federal Bldg. | San Juan 13, Puerto Rico |
| 7–8 Shattuck Bldg., 3d and Seward Sts. | Juneau, Alaska |
| Briggs Bldg., 22d and ENW | Washington 25, D.C. |

## AMATEUR LICENSE INFORMATION

Applicants for a Novice Class Amateur license should be able to answer all questions prefaced by a star. Applicants for General, Conditional, and Technician Class Amateur licenses should be able to answer all questions.

**★1.** Under what circumstances may an amateur radio station be used by a person who does not hold a valid license? (33.1)

**★2.** What method of frequency control is required to be used in the transmitter of a station licensed to the holder of a Novice Class license? (33.2)

**★3.** What is the maximum input power permitted to the final stage of the transmitter in a station licensed to the holder of a Novice Class license or operated by such an operator? (33.2)

**★4.** On what frequency bands may the holder of a Novice Class license operate an amateur radio station? (33.2)

**★5.** On what frequency bands may the holder of a Novice Class license operate an amateur radiotelephone station? (33.2)

**★6.** Who may be permitted to operate the transmitter of an amateur radio station licensed to the holder of a Novice Class license? (33.2)

**★7.** What is the term of an amateur Novice Class license? Under what conditions may this license be renewed? (33.2)

**★8.** What is the ruling regarding eligibility for re-examination? (33.2)

**★9.** What are the rules and regulations regarding the measurement of the frequencies of the emissions of an amateur radio station? (33.8)

**★10.** What is the maximum permissible percentage of modulation of an amateur radiotelephone station? (33.8)

**★11.** At what intervals must an amateur station be identified by the transmission of its call sign? May any transmission be made without identification of the station? (33.8)

**★12.** What are the rules and regulations regarding the transmission of improper language, false signals, or malicious interference? (33.8)

**★13.** What are the rules and regulations regarding purity and stability of emissions? (33.8)

**★14.** Why are a rectifier and filter required in the plate power-supply system of an amateur transmitter when operated from a-c? (33.8)

★**15.** Under what conditions is notice of portable or mobile operation required to be given, and to whom in each case? (33.8)

★**16.** What is the log of an amateur station, and what information is required to be entered therein? How long must it be preserved? (33.9)

★**17.** What is the maximum penalty for a violation of the rules and regulations of the FCC? (33.10)

**18.** Why must the percentage modulation of an amateur radiotelephone transmitter not exceed the modulation capabilities of the transmitter? (33.8)

**19.** Given a transmitter frequency tolerance of $\pm x$ kc and a maximum audio frequency in the modulation system of $y$ cycles, how close to the edge of an amateur band may one operate an amplitude-modulated phone transmitter? (33.8)

**20.** The requirement for adequately filtered d-c plate power supply to minimize modulation from this source applies to operation of a transmitter on what amateur frequency bands? (33.8)

**21.** What are the rules and regulations regarding the transmission of music by amateur stations? (33.8)

**22.** Under what condition may third-party traffic be exchanged between amateur stations of different countries? (33.8)

**23.** Is a potential of 110 volts lethal? (33.8)

**24.** What is the length of the time an amateur-station log is required to be retained by the licensee? (33.9)

**25.** When a state of communication emergency has been proclaimed by the FCC, are important initial calls by amateur stations participating in the emergency made at any particular times? (33.13)

# APPENDIX

## Table of Logarithms (Four-place Mantissas)

| No. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 0000 | 0043 | 0086 | 0128 | 0170 | 0212 | 0253 | 0294 | 0334 | 0374 |
| 11 | 0414 | 0453 | 0492 | 0531 | 0569 | 0607 | 0645 | 0682 | 0719 | 0755 |
| 12 | 0792 | 0828 | 0864 | 0899 | 0934 | 0969 | 1004 | 1038 | 1072 | 1106 |
| 13 | 1139 | 1173 | 1206 | 1239 | 1271 | 1303 | 1335 | 1367 | 1399 | 1430 |
| 14 | 1461 | 1492 | 1523 | 1553 | 1584 | 1614 | 1644 | 1673 | 1703 | 1732 |
| 15 | 1761 | 1790 | 1818 | 1847 | 1875 | 1903 | 1931 | 1959 | 1987 | 2014 |
| 16 | 2041 | 2068 | 2095 | 2122 | 2148 | 2175 | 2201 | 2227 | 2253 | 2279 |
| 17 | 2304 | 2330 | 2355 | 2380 | 2405 | 2430 | 2455 | 2480 | 2504 | 2529 |
| 18 | 2553 | 2577 | 2601 | 2625 | 2648 | 2672 | 2695 | 2718 | 2742 | 2765 |
| 19 | 2788 | 2810 | 2833 | 2856 | 2878 | 2900 | 2923 | 2945 | 2967 | 2989 |
| 20 | 3010 | 3032 | 3054 | 3075 | 3096 | 3118 | 3139 | 3160 | 3181 | 3201 |
| 21 | 3222 | 3243 | 3263 | 3284 | 3304 | 3324 | 3345 | 3365 | 3385 | 3404 |
| 22 | 3424 | 3444 | 3464 | 3483 | 3502 | 3522 | 3541 | 3560 | 3579 | 3598 |
| 23 | 3617 | 3636 | 3655 | 3674 | 3692 | 3711 | 3729 | 3747 | 3766 | 3784 |
| 24 | 3802 | 3820 | 3838 | 3856 | 3874 | 3892 | 3909 | 3927 | 3945 | 3962 |
| 25 | 3979 | 3997 | 4014 | 4031 | 4048 | 4065 | 4082 | 4099 | 4116 | 4133 |
| 26 | 4150 | 4166 | 4183 | 4200 | 4216 | 4232 | 4249 | 4265 | 4281 | 4298 |
| 27 | 4314 | 4330 | 4346 | 4362 | 4378 | 4393 | 4409 | 4425 | 4440 | 4456 |
| 28 | 4472 | 4487 | 4502 | 4518 | 4533 | 4548 | 4564 | 4579 | 4594 | 4609 |
| 29 | 4624 | 4639 | 4654 | 4669 | 4683 | 4698 | 4713 | 4728 | 4742 | 4757 |
| 30 | 4771 | 4786 | 4800 | 4814 | 4829 | 4843 | 4857 | 4871 | 4886 | 4900 |
| 31 | 4914 | 4928 | 4942 | 4955 | 4969 | 4983 | 4997 | 5011 | 5024 | 5038 |
| 32 | 5051 | 5065 | 5079 | 5092 | 5105 | 5119 | 5132 | 5145 | 5159 | 5172 |
| 33 | 5185 | 5198 | 5211 | 5224 | 5237 | 5250 | 5263 | 5276 | 5289 | 5302 |
| 34 | 5315 | 5328 | 5340 | 5353 | 5366 | 5378 | 5391 | 5403 | 5416 | 5428 |
| 35 | 5441 | 5453 | 5465 | 5478 | 5490 | 5502 | 5514 | 5527 | 5539 | 5551 |
| 36 | 5563 | 5575 | 5587 | 5599 | 5611 | 5623 | 5635 | 5647 | 5658 | 5670 |
| 37 | 5682 | 5694 | 5705 | 5717 | 5729 | 5740 | 5752 | 5763 | 5775 | 5786 |
| 38 | 5798 | 5809 | 5821 | 5832 | 5843 | 5855 | 5866 | 5877 | 5888 | 5899 |
| 39 | 5911 | 5922 | 5933 | 5944 | 5955 | 5966 | 5977 | 5988 | 5999 | 6010 |
| 40 | 6021 | 6031 | 6042 | 6053 | 6064 | 6075 | 6085 | 6096 | 6107 | 6117 |
| 41 | 6128 | 6138 | 6149 | 6160 | 6170 | 6180 | 6191 | 6201 | 6212 | 6222 |
| 42 | 6232 | 6243 | 6253 | 6263 | 6274 | 6284 | 6294 | 6304 | 6314 | 6325 |
| 43 | 6335 | 6345 | 6355 | 6365 | 6375 | 6385 | 6395 | 6405 | 6415 | 6425 |
| 44 | 6435 | 6444 | 6454 | 6464 | 6474 | 6484 | 6493 | 6503 | 6513 | 6522 |
| 45 | 6532 | 6542 | 6551 | 6561 | 6571 | 6580 | 6590 | 6599 | 6609 | 6618 |
| 46 | 6628 | 6637 | 6646 | 6656 | 6665 | 6675 | 6684 | 6693 | 6702 | 6712 |
| 47 | 6721 | 6730 | 6739 | 6749 | 6758 | 6767 | 6776 | 6785 | 6794 | 6803 |
| 48 | 6812 | 6821 | 6830 | 6839 | 6848 | 6857 | 6866 | 6875 | 6884 | 6893 |
| 49 | 6902 | 6911 | 6920 | 6928 | 6937 | 6946 | 6955 | 6964 | 6972 | 6981 |
| 50 | 6990 | 6998 | 7007 | 7016 | 7024 | 7033 | 7042 | 7050 | 7059 | 7067 |
| 51 | 7076 | 7084 | 7093 | 7101 | 7110 | 7118 | 7126 | 7135 | 7143 | 7152 |
| 52 | 7160 | 7168 | 7177 | 7185 | 7193 | 7202 | 7210 | 7218 | 7226 | 7235 |
| 53 | 7243 | 7251 | 7259 | 7267 | 7275 | 7284 | 7292 | 7300 | 7308 | 7316 |
| 54 | 7324 | 7332 | 7340 | 7348 | 7356 | 7364 | 7372 | 7380 | 7388 | 7396 |
| No. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

Table of Logarithms (*Continued*)

| No. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 55 | 7404 | 7412 | 7419 | 7427 | 7435 | 7443 | 7451 | 7459 | 7466 | 7474 |
| 56 | 7482 | 7490 | 7497 | 7505 | 7513 | 7520 | 7528 | 7536 | 7543 | 7551 |
| 57 | 7559 | 7566 | 7574 | 7582 | 7589 | 7597 | 7604 | 7612 | 7619 | 7627 |
| 58 | 7634 | 7642 | 7649 | 7657 | 7664 | 7672 | 7679 | 7686 | 7694 | 7701 |
| 59 | 7709 | 7716 | 7723 | 7731 | 7738 | 7745 | 7752 | 7760 | 7767 | 7774 |
| 60 | 7782 | 7789 | 7796 | 7803 | 7810 | 7818 | 7825 | 7832 | 7839 | 7846 |
| 61 | 7853 | 7860 | 7868 | 7875 | 7882 | 7889 | 7896 | 7903 | 7910 | 7917 |
| 62 | 7924 | 7931 | 7938 | 7945 | 7952 | 7959 | 7966 | 7973 | 7980 | 7987 |
| 63 | 7993 | 8000 | 8007 | 8014 | 8021 | 8028 | 8035 | 8041 | 8048 | 8055 |
| 64 | 8062 | 8069 | 8075 | 8082 | 8089 | 8096 | 8102 | 8109 | 8116 | 8122 |
| 65 | 8129 | 8136 | 8142 | 8149 | 8156 | 8162 | 8169 | 8176 | 8182 | 8189 |
| 66 | 8195 | 8202 | 8209 | 8215 | 8222 | 8228 | 8235 | 8241 | 8248 | 8254 |
| 67 | 8261 | 8267 | 8274 | 8280 | 8287 | 8293 | 8299 | 8306 | 8312 | 8319 |
| 68 | 8325 | 8331 | 8338 | 8344 | 8351 | 8357 | 8363 | 8370 | 8376 | 8382 |
| 69 | 8388 | 8395 | 8401 | 8407 | 8414 | 8420 | 8426 | 8432 | 8439 | 8445 |
| 70 | 8451 | 8457 | 8463 | 8470 | 8476 | 8482 | 8488 | 8494 | 8500 | 8506 |
| 71 | 8513 | 8519 | 8525 | 8531 | 8537 | 8543 | 8549 | 8555 | 8561 | 8567 |
| 72 | 8573 | 8579 | 8585 | 8591 | 8597 | 8603 | 8609 | 8615 | 8621 | 8627 |
| 73 | 8633 | 8639 | 8645 | 8651 | 8657 | 8663 | 8669 | 8675 | 8681 | 8686 |
| 74 | 8692 | 8698 | 8704 | 8710 | 8716 | 8722 | 8727 | 8733 | 8739 | 8745 |
| 75 | 8751 | 8756 | 8762 | 8768 | 8774 | 8779 | 8785 | 8791 | 8797 | 8802 |
| 76 | 8808 | 8814 | 8820 | 8825 | 8831 | 8837 | 8842 | 8848 | 8854 | 8859 |
| 77 | 8865 | 8871 | 8876 | 8882 | 8887 | 8893 | 8899 | 8904 | 8910 | 8915 |
| 78 | 8921 | 8927 | 8932 | 8938 | 8943 | 8949 | 8954 | 8960 | 8965 | 8971 |
| 79 | 8976 | 8982 | 8987 | 8993 | 8998 | 9004 | 9009 | 9015 | 9020 | 9025 |
| 80 | 9031 | 9036 | 9042 | 9047 | 9053 | 9058 | 9063 | 9069 | 9074 | 9079 |
| 81 | 9085 | 9090 | 9096 | 9101 | 9106 | 9112 | 9117 | 9122 | 9128 | 9133 |
| 82 | 9138 | 9143 | 9149 | 9154 | 9159 | 9165 | 9170 | 9175 | 9180 | 9186 |
| 83 | 9191 | 9196 | 9201 | 9206 | 9212 | 9217 | 9222 | 9227 | 9232 | 9238 |
| 84 | 9243 | 9248 | 9253 | 9258 | 9263 | 9269 | 9274 | 9279 | 9284 | 9289 |
| 85 | 9294 | 9299 | 9304 | 9309 | 9315 | 9320 | 9325 | 9330 | 9335 | 9340 |
| 86 | 9345 | 9350 | 9355 | 9360 | 9365 | 9370 | 9375 | 9380 | 9385 | 9390 |
| 87 | 9395 | 9400 | 9405 | 9410 | 9415 | 9420 | 9425 | 9430 | 9435 | 9440 |
| 88 | 9445 | 9450 | 9455 | 9460 | 9465 | 9469 | 9474 | 9479 | 9484 | 9489 |
| 89 | 9494 | 9499 | 9504 | 9509 | 9513 | 9518 | 9523 | 9528 | 9533 | 9538 |
| 90 | 9542 | 9547 | 9552 | 9557 | 9562 | 9566 | 9571 | 9576 | 9581 | 9586 |
| 91 | 9590 | 9595 | 9600 | 9605 | 9609 | 9614 | 9619 | 9624 | 9628 | 9633 |
| 92 | 9638 | 9643 | 9647 | 9652 | 9657 | 9661 | 9666 | 9671 | 9675 | 9680 |
| 93 | 9685 | 9689 | 9694 | 9699 | 9703 | 9708 | 9713 | 9717 | 9722 | 9727 |
| 94 | 9731 | 9736 | 9741 | 9745 | 9750 | 9754 | 9759 | 9763 | 9768 | 9773 |
| 95 | 9777 | 9782 | 9786 | 9791 | 9795 | 9800 | 9805 | 9809 | 9814 | 9818 |
| 96 | 9823 | 9827 | 9832 | 9836 | 9841 | 9845 | 9850 | 9854 | 9859 | 9863 |
| 97 | 9868 | 9872 | 9877 | 9881 | 9886 | 9890 | 9894 | 9899 | 9903 | 9908 |
| 98 | 9912 | 9917 | 9921 | 9926 | 9930 | 9934 | 9939 | 9943 | 9948 | 9952 |
| 99 | 9956 | 9961 | 9965 | 9969 | 9974 | 9978 | 9983 | 9987 | 9991 | 9996 |
| No. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |

## Table of Natural Trigonometric Functions

| Angle, ° | sin | tan | cot | cos | Angle, ° | Angle, ° | sin | tan | cot | cos | Angle, ° |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | .00000 | .00000 | ∞ | 1.00000 | 90.0 | 6.0 | .10453 | .10510 | 9.5144 | .99452 | 84.0 |
| .1 | .00175 | .00175 | 572.96 | 1.00000 | .9 | .1 | .10626 | .10687 | 9.3572 | .99434 | .9 |
| .2 | .00349 | .00349 | 286.48 | 0.99999 | .8 | .2 | .10800 | .10863 | 9.2052 | .99415 | .8 |
| .3 | .00524 | .00524 | 190.98 | .99999 | .7 | .3 | .10973 | .11040 | 9.0579 | .99396 | .7 |
| .4 | .00698 | .00698 | 143.24 | .99998 | .6 | .4 | .11147 | .11217 | 8.9152 | .99377 | .6 |
| .5 | .00873 | .00873 | 114.59 | .99996 | .5 | .5 | .11320 | .11394 | 8.7769 | .99357 | .5 |
| .6 | .01047 | .01047 | 95.489 | .99995 | .4 | .6 | .11494 | .11570 | 8.6427 | .99337 | .4 |
| .7 | .01222 | .01222 | 81.847 | .99993 | .3 | .7 | .11667 | .11747 | 8.5126 | .99317 | .3 |
| .8 | .01396 | .01396 | 71.615 | .99990 | .2 | .8 | .11840 | .11924 | 8.3863 | .99297 | .2 |
| .9 | .01571 | .01571 | 63.657 | .99988 | .1 | .9 | .12014 | .12101 | 8.2636 | .99276 | .1 |
| 1.0 | .01745 | .01746 | 57.290 | .99985 | 89.0 | 7.0 | .12187 | .12278 | 8.1443 | .99255 | 83.0 |
| .1 | .01920 | .01920 | 52.081 | .99982 | .9 | .1 | .12360 | .12456 | 8.0285 | .99233 | .9 |
| .2 | .02094 | .02095 | 47.740 | .99978 | .8 | .2 | .12533 | .12633 | 7.9158 | .99211 | .8 |
| .3 | .02269 | .02269 | 44.066 | .99974 | .7 | .3 | .12706 | .12810 | 7.8062 | .99189 | .7 |
| .4 | .02443 | .02444 | 40.917 | .99970 | .6 | .4 | .12880 | .12988 | 7.6996 | .99167 | .6 |
| .5 | .02618 | .02619 | 38.188 | .99966 | .5 | .5 | .13053 | .13165 | 7.5958 | .99144 | .5 |
| .6 | .02792 | .02793 | 35.801 | .99961 | .4 | .6 | .13226 | .13343 | 7.4947 | .99122 | .4 |
| .7 | .02967 | .02968 | 33.694 | .99956 | .3 | .7 | .13399 | .13521 | 7.3962 | .99098 | .3 |
| .8 | .03141 | .03143 | 31.821 | .99951 | .2 | .8 | .13572 | .13698 | 7.3002 | .99075 | .2 |
| .9 | .03316 | .03317 | 30.145 | .99945 | .1 | .9 | .13744 | .13876 | 7.2066 | .99051 | .1 |
| 2.0 | .03490 | .03492 | 28.636 | .99939 | 88.0 | 8.0 | .13917 | .14054 | 7.1154 | .99027 | 82.0 |
| .1 | .03664 | .03667 | 27.271 | .99933 | .9 | .1 | .14090 | .14232 | 7.0264 | .99002 | .9 |
| .2 | .03839 | .03842 | 26.031 | .99926 | .8 | .2 | .14263 | .14410 | 6.9395 | .98978 | .8 |
| .3 | .04013 | .04016 | 24.898 | .99919 | .7 | .3 | .14436 | .14588 | 6.8548 | .98953 | .7 |
| .4 | .04188 | .04191 | 23.859 | .99912 | .6 | .4 | .14608 | .14767 | 6.7720 | .98927 | .6 |
| .5 | .04362 | .04366 | 22.904 | .99905 | .5 | .5 | .14781 | .14945 | 6.6912 | .98902 | .5 |
| .6 | .04536 | .04541 | 22.022 | .99897 | .4 | .6 | .14954 | .15124 | 6.6122 | .98876 | .4 |
| .7 | .04711 | .04716 | 21.205 | .99889 | .3 | .7 | .15126 | .15302 | 6.5350 | .98849 | .3 |
| .8 | .04885 | .04891 | 20.446 | .99881 | .2 | .8 | .15299 | .15481 | 6.4596 | .98823 | .2 |
| .9 | .05059 | .05066 | 19.740 | .99872 | .1 | .9 | .15471 | .15660 | 6.3859 | .98796 | .1 |
| 3.0 | .05234 | .05241 | 19.081 | .99863 | 87.0 | 9.0 | .15643 | .15838 | 6.3138 | .98769 | 81.0 |
| .1 | .05408 | .05416 | 18.464 | .99854 | .9 | .1 | .15816 | .16017 | 6.2432 | .98741 | .9 |
| .2 | .05582 | .05591 | 17.886 | .99844 | .8 | .2 | .15988 | .16196 | 6.1742 | .98714 | .8 |
| .3 | .05756 | .05766 | 17.343 | .99834 | .7 | .3 | .16160 | .16376 | 6.1066 | .98686 | .7 |
| .4 | .05931 | .05941 | 16.832 | .99824 | .6 | .4 | .16333 | .16555 | 6.0405 | .98657 | .6 |
| .5 | .06105 | .06116 | 16.350 | .99813 | .5 | .5 | .16505 | .16734 | 5.9758 | .98629 | .5 |
| .6 | .06279 | .06291 | 15.895 | .99803 | .4 | .6 | .16677 | .16914 | 5.9124 | .98600 | .4 |
| .7 | .06453 | .06467 | 15.464 | .99792 | .3 | .7 | .16849 | .17093 | 5.8502 | .98570 | .3 |
| .8 | .06627 | .06642 | 15.056 | .99780 | .2 | .8 | .17021 | .17273 | 5.7894 | .98541 | .2 |
| .9 | .06802 | .06817 | 14.669 | .99768 | .1 | .9 | .17193 | .17453 | 5.7297 | .98511 | .1 |
| 4.0 | .06976 | .06993 | 14.301 | .99756 | 86.0 | 10.0 | .17365 | .17633 | 5.6713 | .98481 | 80.0 |
| .1 | .07150 | .07168 | 13.951 | .99744 | .9 | .1 | .17537 | .17813 | 5.6140 | .98450 | .9 |
| .2 | .07324 | .07344 | 13.617 | .99731 | .8 | .2 | .17708 | .17993 | 5.5578 | .98420 | .8 |
| .3 | .07498 | .07519 | 13.300 | .99719 | .7 | .3 | .17880 | .18173 | 5.5026 | .98389 | .7 |
| .4 | .07672 | .07695 | 12.996 | .99705 | .6 | .4 | .18052 | .18353 | 5.4486 | .98357 | .6 |
| .5 | .07846 | .07870 | 12.706 | .99692 | .5 | .5 | .18224 | .18534 | 5.3955 | .98325 | .5 |
| .6 | .08020 | .08046 | 12.429 | .99678 | .4 | .6 | .18395 | .18714 | 5.3435 | .98294 | .4 |
| .7 | .08194 | .08221 | 12.163 | .99664 | .3 | .7 | .18567 | .18895 | 5.2924 | .98261 | .3 |
| .8 | .08368 | .08397 | 11.909 | .99649 | .2 | .8 | .18738 | .19076 | 5.2422 | .98229 | .2 |
| .9 | .08542 | .08573 | 11.664 | .99635 | .1 | .9 | .18910 | .19257 | 5.1929 | .98196 | .1 |
| 5.0 | .08716 | .08749 | 11.430 | .99619 | 85.0 | 11.0 | .19081 | .19438 | 5.1446 | .98163 | 79.0 |
| .1 | .08889 | .08925 | 11.205 | .99604 | .9 | .1 | .19252 | .19619 | 5.0970 | .98129 | .9 |
| .2 | .09063 | .09101 | 10.988 | .99588 | .8 | .2 | .19423 | .19801 | 5.0504 | .98096 | .8 |
| .3 | .09237 | .09277 | 10.780 | .99572 | .7 | .3 | .19595 | .19982 | 5.0045 | .98061 | .7 |
| .4 | .09411 | .09453 | 10.579 | .99556 | .6 | .4 | .19766 | .20164 | 4.9594 | .98027 | .6 |
| .5 | .09585 | .09629 | 10.385 | .99540 | .5 | .5 | .19937 | .20345 | 4.9152 | .97992 | .5 |
| .6 | .09758 | .09805 | 10.199 | .99523 | .4 | .6 | .20108 | .20527 | 4.8716 | .97958 | .4 |
| .7 | .09932 | .09981 | 10.019 | .99506 | .3 | .7 | .20279 | .20709 | 4.8288 | .97922 | .3 |
| .8 | .10106 | .10158 | 9.8448 | .99488 | .2 | .8 | .20450 | .20891 | 4.7867 | .97887 | .2 |
| .9 | .10279 | .10334 | 9.6768 | .99470 | .1 | .9 | .20620 | .21073 | 4.7453 | .97851 | .1 |
| 6.0 | .10453 | .10510 | 9.5144 | .99452 | 84.0 | 12.0 | .20791 | .21256 | 4.7046 | .97815 | 78.0 |
| Angle, ° | cos | cot | tan | sin | Angle, ° | Angle, ° | cos | cot | tan | sin | Angle, ° |

## Table of Natural Trigonometric Functions (*Continued*)

| Angle, ° | sin | tan | cot | cos | Angle, ° | Angle, ° | sin | tan | cot | cos | Angle, ° |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **12.0** | .20791 | .21256 | 4.7046 | .97815 | **78.0** | **18.0** | .30902 | .32492 | 3.0777 | .95106 | **72.0** |
| .1 | .20962 | .21438 | 4.6646 | .97778 | .9 | .1 | .31068 | .32685 | 3.0595 | .95052 | .9 |
| .2 | .21132 | .21621 | 4.6252 | .97742 | .8 | .2 | .31233 | .32878 | 3.0415 | .94997 | .8 |
| .3 | .21303 | .21804 | 4.5864 | .97705 | .7 | .3 | .31399 | .33072 | 3.0237 | .94943 | .7 |
| .4 | .21474 | .21986 | 4.5483 | .97667 | .6 | .4 | .31565 | .33266 | 3.0061 | .94888 | .6 |
| .5 | .21644 | .22169 | 4.5107 | .97630 | .5 | .5 | .31730 | .33460 | 2.9887 | .94832 | .5 |
| .6 | .21814 | .22353 | 4.4737 | .97592 | .4 | .6 | .31896 | .33654 | 2.9714 | .94777 | .4 |
| .7 | .21985 | .22536 | 4.4373 | .97553 | .3 | .7 | .32061 | .33848 | 2.9544 | .94721 | .3 |
| .8 | .22155 | .22719 | 4.4015 | .97515 | .2 | .8 | .32227 | .34043 | 2.9375 | .94665 | .2 |
| .9 | .22325 | .22903 | 4.3662 | .97476 | .1 | .9 | .32392 | .34238 | 2.9208 | .94609 | .1 |
| **13.0** | .22495 | .23087 | 4.3315 | .97437 | **77.0** | **19.0** | .32557 | .34433 | 2.9042 | .94552 | **71.0** |
| .1 | .22665 | .23271 | 4.2972 | .97398 | .9 | .1 | .32722 | .34628 | 2.8878 | .94495 | .9 |
| .2 | .22835 | .23455 | 4.2635 | .97358 | .8 | .2 | .32887 | .34824 | 2.8716 | .94438 | .8 |
| .3 | .23005 | .23639 | 4.2303 | .97318 | .7 | .3 | .33051 | .35020 | 2.8556 | .94380 | .7 |
| .4 | .23175 | .23823 | 4.1976 | .97278 | .6 | .4 | .33216 | .35216 | 2.8397 | .94322 | .6 |
| .5 | .23345 | .24008 | 4.1653 | .97237 | .5 | .5 | .33381 | .35412 | 2.8239 | .94264 | .5 |
| .6 | .23514 | .24193 | 4.1335 | .97196 | .4 | .6 | .33545 | .35608 | 2.8083 | .94206 | .4 |
| .7 | .23684 | .24377 | 4.1022 | .97155 | .3 | .7 | .33710 | .35805 | 2.7929 | .94147 | .3 |
| .8 | .23853 | .24562 | 4.0713 | .97113 | .2 | .8 | .33874 | .36002 | 2.7776 | .94088 | .2 |
| .9 | .24023 | .24747 | 4.0408 | .97072 | .1 | .9 | .34038 | .36199 | 2.7625 | .94029 | .1 |
| **14.0** | .24192 | .24933 | 4.0108 | .97030 | **76.0** | **20.0** | .34202 | .36397 | 2.7475 | .93969 | **70.0** |
| .1 | .24362 | .25118 | 3.9812 | .96987 | .9 | .1 | .34366 | .36595 | 2.7326 | .93909 | .9 |
| .2 | .24531 | .25304 | 3.9520 | .96945 | .8 | .2 | .34530 | .36793 | 2.7179 | .93849 | .8 |
| .3 | .24700 | .25490 | 3.9232 | .96902 | .7 | .3 | .34694 | .36991 | 2.7034 | .93789 | .7 |
| .4 | .24869 | .25676 | 3.8947 | .96858 | .6 | .4 | .34857 | .37190 | 2.6889 | .93728 | .6 |
| .5 | .25038 | .25862 | 3.8667 | .96815 | .5 | .5 | .35021 | .37388 | 2.6746 | .93667 | .5 |
| .6 | .25207 | .26048 | 3.8391 | .96771 | .4 | .6 | .35184 | .37588 | 2.6605 | .93606 | .4 |
| .7 | .25376 | .26235 | 3.8118 | .96727 | .3 | .7 | .35347 | .37787 | 2.6464 | .93544 | .3 |
| .8 | .25545 | .26421 | 3.7848 | .96682 | .2 | .8 | .35511 | .37986 | 2.6325 | .93483 | .2 |
| .9 | .25713 | .26608 | 3.7583 | .96638 | .1 | .9 | .35674 | .38186 | 2.6187 | .93420 | .1 |
| **15.0** | .25882 | .26795 | 3.7321 | .96593 | **75.0** | **21.0** | .35837 | .38386 | 2.6051 | .93358 | **69.0** |
| .1 | .26050 | .26982 | 3.7062 | .96547 | .9 | .1 | .36000 | .38587 | 2.5916 | .93295 | .9 |
| .2 | .26219 | .27169 | 3.6806 | .96502 | .8 | .2 | .36162 | .38787 | 2.5782 | .93232 | .8 |
| .3 | .26387 | .27357 | 3.6554 | .96456 | .7 | .3 | .36325 | .38988 | 2.5649 | .93169 | .7 |
| .4 | .26556 | .27545 | 3.6305 | .96410 | .6 | .4 | .36488 | .39190 | 2.5517 | .93106 | .6 |
| .5 | .26724 | .27732 | 3.6059 | .96363 | .5 | .5 | .36650 | .39391 | 2.5386 | .93042 | .5 |
| .6 | .26892 | .27921 | 3.5816 | .96316 | .4 | .6 | .36812 | .39593 | 2.5257 | .92978 | .4 |
| .7 | .27060 | .28109 | 3.5576 | .96269 | .3 | .7 | .36975 | .39795 | 2.5129 | .92913 | .3 |
| .8 | .27228 | .28297 | 3.5339 | .96222 | .2 | .8 | .37137 | .39997 | 2.5002 | .92849 | .2 |
| .9 | .27396 | .28486 | 3.5105 | .96174 | .1 | .9 | .37299 | .40200 | 2.4876 | .92784 | .1 |
| **16.0** | .27564 | .28675 | 3.4874 | .96126 | **74.0** | **22.0** | .37461 | .40403 | 2.4751 | .92718 | **68.0** |
| .1 | .27731 | .28864 | 3.4646 | .96078 | .9 | .1 | .37622 | .40606 | 2.4627 | .92653 | .9 |
| .2 | .27899 | .29053 | 3.4420 | .96029 | .8 | .2 | .37784 | .40809 | 2.4504 | .92587 | .8 |
| .3 | .28067 | .29242 | 3.4197 | .95981 | .7 | .3 | .37946 | .41013 | 2.4383 | .92521 | .7 |
| .4 | .28234 | .29432 | 3.3977 | .95931 | .6 | .4 | .38107 | .41217 | 2.4262 | .92455 | .6 |
| .5 | .28402 | .29621 | 3.3759 | .95882 | .5 | .5 | .38268 | .41421 | 2.4142 | .92388 | .5 |
| .6 | .28569 | .29811 | 3.3544 | .95832 | .4 | .6 | .38430 | .41626 | 2.4023 | .92321 | .4 |
| .7 | .28736 | .30001 | 3.3332 | .95782 | .8 | .7 | .38591 | .41831 | 2.3906 | .92254 | .3 |
| .8 | .28903 | .30192 | 3.3122 | .95732 | .2 | .8 | .38752 | .42036 | 2.3789 | .92186 | .2 |
| .9 | .29070 | .30382 | 3.2914 | .95681 | .1 | .9 | .38912 | .42242 | 2.3673 | .92119 | .1 |
| **17.0** | .29237 | .30573 | 3.2709 | .95630 | **73.0** | **23.0** | .39073 | .42447 | 2.3559 | .92050 | **67.0** |
| .1 | .29404 | .30764 | 3.2506 | .95579 | .9 | .1 | .39234 | .42654 | 2.3445 | .91982 | .9 |
| .2 | .29571 | .30955 | 3.2305 | .95528 | .8 | .2 | .39394 | .42860 | 2.3332 | .91914 | .8 |
| .3 | .29737 | .31147 | 3.2106 | .95476 | .7 | .3 | .39555 | .43067 | 2.3220 | .91845 | .7 |
| .4 | .29904 | .31338 | 3.1910 | .95424 | .6 | .4 | .39715 | .43274 | 2.3109 | .91775 | .6 |
| .5 | .30071 | .31530 | 3.1716 | .95372 | .5 | .5 | .39875 | .43481 | 2.2998 | .91706 | .5 |
| .6 | .30237 | .31722 | 3.1524 | .95319 | .4 | .6 | .40035 | .43689 | 2.2889 | .91636 | .4 |
| .7 | .30403 | .31914 | 3.1334 | .95266 | .3 | .7 | .40195 | .43897 | 2.2781 | .91566 | .3 |
| .8 | .30570 | .32106 | 3.1146 | .95213 | .2 | .8 | .40355 | .44105 | 2.2673 | .91496 | .2 |
| .9 | .30736 | .32299 | 3.0961 | .95159 | .1 | .9 | .40514 | .44314 | 2.2566 | .91425 | .1 |
| **18.0** | .30902 | .32492 | 3.0777 | .95106 | **72.0** | **24.0** | .40674 | .44523 | 2.2460 | .91355 | **66.0** |
| **Angle, °** | **cos** | **cot** | **tan** | **sin** | **Angle, °** | **Angle, °** | **cos** | **cot** | **tan** | **sin** | **Angle, °** |

## Table of Natural Trigonometric Functions (*Continued*)

| Angle, ° | sin | tan | cot | cos | Angle, ° | Angle, ° | sin | tan | cot | cos | Angle, ° |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **24.0** | .40674 | .44523 | 2.2460 | .91355 | **66.0** | **30.0** | .50000 | .57735 | 1.7321 | .86603 | **60.0** |
| .1 | .40833 | .44732 | 2.2355 | .91283 | .9 | .1 | .50151 | .57968 | 1.7251 | .86515 | .9 |
| .2 | .40992 | .44942 | 2.2251 | .91212 | .8 | .2 | .50302 | .58201 | 1.7182 | .86427 | .8 |
| .3 | .41151 | .45152 | 2.2148 | .91140 | .7 | .3 | .50453 | .58435 | 1.7113 | .86340 | .7 |
| .4 | .41310 | .45362 | 2.2045 | .91068 | .6 | .4 | .50603 | .58670 | 1.7045 | .86251 | .6 |
| .5 | .41469 | .45573 | 2.1943 | .90996 | .5 | .5 | .50754 | .58905 | 1.6977 | .86163 | .5 |
| .6 | .41628 | .45784 | 2.1842 | .90924 | .4 | .6 | .50904 | .59140 | 1.6909 | .86074 | .4 |
| .7 | .41787 | .45995 | 2.1742 | .90851 | .3 | .7 | .51054 | .59376 | 1.6842 | .85985 | .3 |
| .8 | .41945 | .46206 | 2.1642 | .90778 | .2 | .8 | .51204 | .59612 | 1.6775 | .85896 | .2 |
| .9 | .42104 | .46418 | 2.1543 | .90704 | .1 | .9 | .51354 | .59849 | 1.6709 | .85806 | .1 |
| **25.0** | .42262 | .46631 | 2.1445 | .90631 | **65.0** | **31.0** | .51504 | .60086 | 1.6643 | .85717 | **59.0** |
| .1 | .42420 | .46843 | 2.1348 | .90557 | .9 | .1 | .51653 | .60324 | 1.6577 | .85627 | .9 |
| .2 | .42578 | .47056 | 2.1251 | .90483 | .8 | .2 | .51803 | .60562 | 1.6512 | .85536 | .8 |
| .3 | .42736 | .47270 | 2.1155 | .90408 | .7 | .3 | .51952 | .60801 | 1.6447 | .85446 | .7 |
| .4 | .42894 | .47483 | 2.1060 | .90334 | .6 | .4 | .52101 | .61040 | 1.6383 | .85355 | .6 |
| .5 | .43051 | .47698 | 2.0965 | .90259 | .5 | .5 | .52250 | .61280 | 1.6319 | .85264 | .5 |
| .6 | .43209 | .47912 | 2.0872 | .90183 | .4 | .6 | .52399 | .61520 | 1.6255 | .85173 | .4 |
| .7 | .43366 | .48127 | 2.0778 | .90108 | .3 | .7 | .52547 | .61761 | 1.6191 | .85081 | .3 |
| .8 | .43523 | .48342 | 2.0686 | .90032 | .2 | .8 | .52696 | .62003 | 1.6128 | .84989 | .2 |
| .9 | .43680 | .48557 | 2.0594 | .89956 | .1 | .9 | .52844 | .62245 | 1.6066 | .84897 | .1 |
| **26.0** | .43837 | .48773 | 2.0503 | .89879 | **64.0** | **32.0** | .52992 | .62487 | 1.6003 | .84805 | **58.0** |
| .1 | .43994 | .48989 | 2.0413 | .89803 | .9 | .1 | .53140 | .62730 | 1.5941 | .84712 | .9 |
| .2 | .44151 | .49206 | 2.0323 | .89726 | .8 | .2 | .53288 | .62973 | 1.5880 | .84619 | .8 |
| .3 | .44307 | .49423 | 2.0233 | .89649 | .7 | .3 | .53435 | .63217 | 1.5818 | .84526 | .7 |
| .4 | .44464 | .49640 | 2.0145 | .89571 | .6 | .4 | .53583 | .63462 | 1.5757 | .84433 | .6 |
| .5 | .44620 | .49858 | 2.0057 | .89493 | .5 | .5 | .53730 | .63707 | 1.5697 | .84339 | .5 |
| .6 | .44776 | .50076 | 1.9970 | .89415 | .4 | .6 | .53877 | .63953 | 1.5637 | .84245 | .4 |
| .7 | .44932 | .50295 | 1.9883 | .89337 | .3 | .7 | .54024 | .64199 | 1.5577 | .84151 | .3 |
| .8 | .45088 | .50514 | 1.9797 | .89259 | .2 | .8 | .54171 | .64446 | 1.5517 | .84057 | .2 |
| .9 | .45243 | .50733 | 1.9711 | .89180 | .1 | .9 | .54317 | .64693 | 1.5458 | .83962 | .1 |
| **27.0** | .45399 | .50953 | 1.9626 | .89101 | **63.0** | **33.0** | .54464 | .64941 | 1.5399 | .83867 | **57.0** |
| .1 | .45554 | .51173 | 1.9542 | .89021 | .9 | .1 | .54610 | .65189 | 1.5340 | .83772 | .9 |
| .2 | .45710 | .51393 | 1.9458 | .88942 | .8 | .2 | .54756 | .65438 | 1.5282 | .83676 | .8 |
| .3 | .45865 | .51614 | 1.9375 | .88862 | .7 | .3 | .54902 | .65688 | 1.5224 | .83581 | .7 |
| .4 | .46020 | .51835 | 1.9292 | .88782 | .6 | .4 | .55048 | .65938 | 1.5166 | .83485 | .6 |
| .5 | .46175 | .52057 | 1.9210 | .88701 | .5 | .5 | .55194 | .66189 | 1.5108 | .83389 | .5 |
| .6 | .46330 | .52279 | 1.9128 | .88620 | .4 | .6 | .55339 | .66440 | 1.5051 | .83292 | .4 |
| .7 | .46484 | .52501 | 1.9047 | .88539 | .3 | .7 | .55484 | .66692 | 1.4994 | .83195 | .3 |
| .8 | .46639 | .52724 | 1.8967 | .88458 | .2 | .8 | .55630 | .66944 | 1.4938 | .83098 | .2 |
| .9 | .46793 | .52947 | 1.8887 | .88377 | .1 | .9 | .55775 | .67197 | 1.4882 | .83001 | .1 |
| **28.0** | .46947 | .53171 | 1.8807 | .88295 | **62.0** | **34.0** | .55919 | .67451 | 1.4826 | .82904 | **56.0** |
| .1 | .47101 | .53395 | 1.8728 | .88213 | .9 | .1 | .56064 | .67705 | 1.4770 | .82806 | .9 |
| .2 | .47255 | .53620 | 1.8650 | .88130 | .8 | .2 | .56208 | .67960 | 1.4715 | .82708 | .8 |
| .3 | .47409 | .53844 | 1.8572 | .88048 | .7 | .3 | .56353 | .68215 | 1.4659 | .82610 | .7 |
| .4 | .47562 | .54070 | 1.8495 | .87965 | .6 | .4 | .56497 | .68471 | 1.4605 | .82511 | .6 |
| .5 | .47716 | .54296 | 1.8418 | .87882 | .5 | .5 | .56641 | .68728 | 1.4550 | .82413 | .5 |
| .6 | .47869 | .54522 | 1.8341 | .87798 | .4 | .6 | .56784 | .68985 | 1.4496 | .82314 | .4 |
| .7 | .48022 | .54748 | 1.8265 | .87715 | .3 | .7 | .56928 | .69243 | 1.4442 | .82214 | .3 |
| .8 | .48175 | .54975 | 1.8190 | .87631 | .2 | .8 | .57071 | .69502 | 1.4388 | .82115 | .2 |
| .9 | .48328 | .55203 | 1.8115 | .87546 | .1 | .9 | .57215 | .69761 | 1.4335 | .82015 | .1 |
| **29.0** | .48481 | .55431 | 1.8040 | .87462 | **61.0** | **35.0** | .57358 | .70021 | 1.4281 | .81915 | **55.0** |
| .1 | .48634 | .55659 | 1.7966 | .87377 | .9 | .1 | .57501 | .70281 | 1.4229 | .81815 | .9 |
| .2 | .48786 | .55888 | 1.7893 | .87292 | .8 | .2 | .57643 | .70542 | 1.4176 | .81714 | .8 |
| .3 | .48938 | .56117 | 1.7820 | .87207 | .7 | .3 | .57786 | .70804 | 1.4124 | .81614 | .7 |
| .4 | .49090 | .56347 | 1.7747 | .87121 | .6 | .4 | .57928 | .71066 | 1.4071 | .81513 | .6 |
| .5 | .49242 | .56577 | 1.7675 | .87036 | .5 | .5 | .58070 | .71329 | 1.4019 | .81412 | .5 |
| .6 | .49394 | .56808 | 1.7603 | .86949 | .4 | .6 | .58212 | .71593 | 1.3968 | .81310 | .4 |
| .7 | .49546 | .57039 | 1.7532 | .86863 | .3 | .7 | .58354 | .71857 | 1.3916 | .81208 | .3 |
| .8 | .49697 | .57271 | 1.7461 | .86777 | .2 | .8 | .58496 | .72122 | 1.3865 | .81106 | .2 |
| .9 | .49849 | .57503 | 1.7391 | .86690 | .1 | .9 | .58637 | .72388 | 1.3814 | .81004 | .1 |
| **30.0** | .50000 | .57735 | 1.7321 | .86603 | **60.0** | **36.0** | .58779 | .72654 | 1.3764 | .80902 | **54.0** |
| Angle, ° | cos | cot | tan | sin | Angle, ° | Angle, ° | cos | cot | tan | sin | Angle, ° |

## Table of Natural Trigonometric Functions (*Continued*)

| Angle, ° | sin | tan | cot | cos | Angle, ° | Angle, ° | sin | tan | cot | cos | Angle, ° |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **36.0** | .58779 | .72654 | 1.3764 | .80902 | **54.0** | **40.5** | .64945 | .85408 | 1.1708 | .76041 | **49.5** |
| .1 | .58920 | .72921 | 1.3713 | .80799 | .9 | .6 | .65077 | .85710 | 1.1667 | .75927 | .4 |
| .2 | .59061 | .73189 | 1.3663 | .80696 | .8 | .7 | .65210 | .86014 | 1.1626 | .75813 | .3 |
| .3 | .59201 | .73457 | 1.3613 | .80593 | .7 | .8 | .65342 | .86318 | 1.1585 | .75700 | .2 |
| .4 | .59342 | .73726 | 1.3564 | .80489 | .6 | .9 | .65474 | .86623 | 1.1544 | .75585 | .1 |
| .5 | .59482 | .73996 | 1.3514 | .80386 | .5 | **41.0** | .65606 | .86929 | 1.1504 | .75471 | **49.0** |
| .6 | .59622 | .74267 | 1.3465 | .80282 | .4 | .1 | .65738 | .87236 | 1.1463 | .75356 | .9 |
| .7 | .59763 | .74538 | 1.3416 | .80178 | .3 | .2 | .65869 | .87543 | 1.1423 | .75241 | .8 |
| .8 | .59902 | .74810 | 1.3367 | .80073 | .2 | .3 | .66000 | .87852 | 1.1383 | .75126 | .7 |
| .9 | .60042 | .75082 | 1.3319 | .79968 | .1 | .4 | .66131 | .88162 | 1.1343 | .75011 | .6 |
| **37.0** | .60182 | .75355 | 1.3270 | .79864 | **53.0** | .5 | .66262 | .88473 | 1.1303 | .74896 | .5 |
| .1 | .60321 | .75629 | 1.3222 | .79758 | .9 | .6 | .66393 | .88784 | 1.1263 | .74780 | .4 |
| .2 | .60460 | .75904 | 1.3175 | .79653 | .8 | .7 | .66523 | .89097 | 1.1224 | .74664 | .3 |
| .3 | .60599 | .76180 | 1.3127 | .79547 | .7 | .8 | .66653 | .89410 | 1.1184 | .74548 | .2 |
| .4 | .60738 | .76456 | 1.3079 | .79441 | .6 | .9 | .66783 | .89725 | 1.1145 | .74431 | .1 |
| .5 | .60876 | .76733 | 1.3032 | .79335 | .5 | **42.0** | .66913 | .90040 | 1.1106 | .74314 | **48.0** |
| .6 | .61015 | .77010 | 1.2985 | .79229 | .4 | .1 | .67043 | .90357 | 1.1067 | .74198 | .9 |
| .7 | .61153 | .77289 | 1.2938 | .79122 | .3 | .2 | .67172 | .90674 | 1.1028 | .74080 | .8 |
| .8 | .61291 | .77568 | 1.2892 | .79016 | .2 | .3 | .67301 | .90993 | 1.0990 | .73963 | .7 |
| .9 | .61429 | .77848 | 1.2846 | .78908 | .1 | .4 | .67430 | .91313 | 1.0951 | .73846 | .6 |
| **38.0** | .61566 | .78129 | 1.2799 | .78801 | **52.0** | .5 | .67559 | .91633 | 1.0913 | .73728 | .5 |
| .1 | .61704 | .78410 | 1.2753 | .78694 | .9 | .6 | .67688 | .91955 | 1.0875 | .73610 | .4 |
| .2 | .61841 | .78692 | 1.2708 | .78586 | .8 | .7 | .67816 | .92277 | 1.0837 | .73491 | .3 |
| .3 | .61978 | .78975 | 1.2662 | .78478 | .7 | .8 | .67944 | .92601 | 1.0799 | .73373 | .2 |
| .4 | .62115 | .79259 | 1.2617 | .78369 | .6 | .9 | .68072 | .92926 | 1.0761 | .73254 | .1 |
| .5 | .62251 | .79544 | 1.2572 | .78261 | .5 | **43.0** | .68200 | .93252 | 1.0724 | .73135 | **47.0** |
| .6 | .62388 | .79829 | 1.2527 | .78152 | .4 | .1 | .68327 | .93578 | 1.0686 | .73016 | .9 |
| .7 | .62524 | .80115 | 1.2482 | .78043 | .3 | .2 | .68455 | .93906 | 1.0649 | .72897 | .8 |
| .8 | .62660 | .80402 | 1.2437 | .77934 | .2 | .3 | .68582 | .94235 | 1.0612 | .72777 | .7 |
| .9 | .62796 | .80690 | 1.2393 | .77824 | .1 | .4 | .68709 | .94565 | 1.0575 | .72657 | .6 |
| **39.0** | .62932 | .80978 | 1.2349 | .77715 | **51.0** | .5 | .68835 | .94896 | 1.0538 | .72537 | .5 |
| .1 | .63068 | .81268 | 1.2305 | .77605 | .9 | .6 | .68962 | .95229 | 1.0501 | .72417 | .4 |
| .2 | .63203 | .81558 | 1.2261 | .77494 | .8 | .7 | .69088 | .95562 | 1.0464 | .72297 | .3 |
| .3 | .63338 | .81849 | 1.2218 | .77384 | .7 | .8 | .69214 | .95897 | 1.0428 | .72176 | .2 |
| .4 | .63473 | .82141 | 1.2174 | .77273 | .6 | .9 | .69340 | .96232 | 1.0392 | .72055 | .1 |
| .5 | .63608 | .82434 | 1.2131 | .77162 | .5 | **44.0** | .69466 | .96569 | 1.0355 | .71934 | **46.0** |
| .6 | .63742 | .82727 | 1.2088 | .77051 | .4 | .1 | .69591 | .96907 | 1.0319 | .71813 | .9 |
| .7 | .63877 | .83022 | 1.2045 | .76940 | .3 | .2 | .69717 | .97246 | 1.0283 | .71691 | .8 |
| .8 | .64011 | .83317 | 1.2002 | .76828 | .2 | .3 | .69842 | .97586 | 1.0247 | .71569 | .7 |
| .9 | .64145 | .83613 | 1.1960 | .76717 | .1 | .4 | .69966 | .97927 | 1.0212 | .71447 | .6 |
| **40.0** | .64279 | .83910 | 1.1918 | .76604 | **50.0** | .5 | .70091 | .98270 | 1.0176 | .71325 | .5 |
| .1 | .64412 | .84208 | 1.1875 | .76492 | .9 | .6 | .70215 | .98613 | 1.0141 | .71203 | .4 |
| .2 | .64546 | .84507 | 1.1833 | .76380 | .8 | .7 | .70339 | .98958 | 1.0105 | .71080 | .3 |
| .3 | .64679 | .84806 | 1.1792 | .76267 | .7 | .8 | .70463 | .99304 | 1.0070 | .70957 | .2 |
| .4 | .64812 | .85107 | 1.1750 | .76154 | .6 | .9 | .70587 | .99652 | 1.0035 | .70834 | .1 |
| **40.5** | .64945 | .85408 | 1.1708 | .76041 | **49.5** | **45.0** | .70711 | 1.00000 | 1.0000 | .70711 | **45.0** |
| **Angle, °** | **cos** | **cot** | **tan** | **sin** | **Angle, °** | **Angle, °** | **cos** | **cot** | **tan** | **sin** | **Angle, °** |

## Greek Alphabet

| Upper-case | Lower-case | Name | English equivalent |
|---|---|---|---|
| Α | α | Alpha | a |
| Β | β | Beta | b |
| Γ | γ | Gamma | g |
| Δ | δ | Delta | d |
| Ε | ε | Epsilon | ĕ |
| Ζ | ζ | Zeta | z |
| Η | η | Eta | ē |
| Θ | θ | Theta | th |
| Ι | ι | Iota | i |
| Κ | κ | Kappa | k |
| Λ | λ | Lambda | l |
| Μ | μ | Mu | m |
| Ν | ν | Nu | n |
| Ξ | ξ | Xi | x |
| Ο | ο | Omicron | ŏ |
| Π | π | Pi | p |
| Ρ | ρ | Rho | r |
| Σ | σ, ς | Sigma | s |
| Τ | τ | Tau | t |
| Υ | υ | Upsilon | u |
| Φ | φ, ϕ | Phi | ph, f |
| Χ | χ | Chi | ch |
| Ψ | ψ | Psi | ps |
| Ω | ω | Omega | ō |

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# INDEX

# ANSWERS TO PROBLEMS

For mathematical simplification, long or complex numbers are usually rounded off, correct to the third significant figure. Your answers should agree, within one or two numbers of the third significant figure, with those listed below. Thus, 15,072 is satisfactorily close to an answer given as 15,100.

## Page 27

1. 60 ohms
2. 0.18 amp
3. 25 volts
4. Tripled
5. Doubled
6. ⅔ as much

## Page 32

1. $E = \frac{P}{I} \qquad I = \frac{P}{E}$
2. $X = QR \qquad R = \frac{X}{Q}$
3. $R = \frac{X^2}{Z} \qquad X = \sqrt{ZR}$
4. $1 = F^2LC \qquad C = \frac{1}{F^2L}$

   $L = \frac{1}{F^2C} \qquad F = \sqrt{\frac{1}{LC}}$
5. $X = \frac{L}{3 - A} \qquad L = X(3 - A)$

   $A = 3 - \frac{L}{X}$
6. $Q = 2Z(B - C) \qquad Z = \frac{Q}{2(B - C)}$

   $B = C + \frac{Q}{2Z} \qquad C = B - \frac{Q}{2Z}$
7. 22.9
8. 100
9. 31.6
10. 3.16
11. 0.224

## Page 37

1. 90 watts
2. 0.378 watt
3. 400 watts
4. 1,000,000
5. 2,074 watthr
6. 23 cents
7. 50 amp
8. 16,000 watts
9. 8,000 wattsec
10. 35.2 kwhr
11. 120 volts
12. 3.97 amp
13. 0.02 amp
14. 123 ohms
15. 112 volts
16. 161 or 192 ohms
17. 0.109 watt (¼ watt for safety)

## Page 47

1. 30 volts
2. 6 volts
3. 0.1 amp
4. 13.3 volts
5. 39.9 ohms
6. 7.68 amp
7. 11.5 volts
8. 50 ohms
9. 1 ohm
10. 379 volts
11. 346 ohms
12. 31.1 watts

## Page 53

1. 0.00867 mho
2. 0.0002 mho
3. 180
4. 150
5. 545 ohms
6. 0.973 amp

7. 40.5 volts
8. 0.125 amp
9. 0.125 amp
10. 1.29 amp
11. 63.2 volts
12. 0.201
13. 21 ohms
14. Resistors in parallel

## Page 56

1. *a.* 0.167 amp
   *b.* 0.167 amp
   *c.* 0.1 amp
   *d.* 20 volts
2. *a.* 0.0203 amp
   *b.* 8.12 ma
   *c.* 0.406 volt
3. *a.* 84 ohms
   *b.* 303 ohms
4. *a.* 12BE6 across line; 6BQ6 in series with paralleled 6SN7, 6C4, and resistor
   *b.* 14 ohms, 2.84 watts (5 watts for safety)

## Page 100

1. *a.* 52.6 μh
   *b.* 0.0526 mh
2. *a.* 0.05 sec
   *b.* 0.25 sec
3. 0.875 joule
4. 6 henrys
5. 3.8 henrys
6. 9.76 henrys
7. 3.52 henrys
8. 7,536 ohms
9. 31,400 ohms
10. 15,100 ohms
11. 0.00796 henry
12. 11,900 cycles
13. 0.159 amp
14. 40,000 ohms
15. 189 volts

## Page 133

1. $T_1 = 0.8$ sec
   $T_2 = 4$ sec
2. $C_1 = 0.00236$ μf
   $C_2 = 2{,}360$ μμf
3. *a.* 0.72 joule
   *b.* $15.1 \times 10^{15}$
   *c.* It might.
4. 300 volts
5. 50 ohms
6. 5,320 ohms
7. 105 ohms
8. 30,000 ohms
9. 0.906 amp
10. 60 volts
11. *a.* 120 μf
    *b.* Burn out 80 μf capacitor
12. *a.* Maximum
    *b.* Zero
13. *a.* 250,000 μμf
    *b.* 680 μμf

## Page 144

1. *a.* $Z = 316$ ohms
   *b.* $P_a = 7.9$ watts
   *c.* $P_t = 2.5$ watts
   *d.* pf $= 0.317$
   *e.* $\theta = 71.5°$
   *f.* $P_t = 2.5$ watts
   *g.* $I_L = 0.158$ amp
   *h.* $I_R = 0.158$ amp
   *i.* $I_s = 0.158$ amp
2. *a.* $X_L = 99.4$ ohms
   *b.* $P_a = 102$ watts
   *c.* $P_t = 72.4$ watts
   *d.* pf $= 0.709$
   *e.* $\theta = 45°$
   *f.* $E_z = 84.2$ volts
   *g.* $E_R = 85.1$ volts

## Page 149

1. *a.* 10 ohms
   *b.* 0.6
   *c.* 53.2°
2. *a.* 27.8 ohms
   *b.* 139 volts
   *c.* 0.43
   *d.* 64.5°
   *e.* 75 volts
   *f.* 200 volts
3. *a.* 132 ohms
   *b.* 261 ohms
   *c.* 0.842 amp
   *d.* 0.842 amp
   *e.* 0.506
   *f.* 59.6°
4. *a.* 21.3 ohms
   *b.* 0.707
   *c.* 45°
   *d.* 5.18 amp

### Page 153

1. *a.* 0.0472
   *b.* 21.2 ohms
   *c.* 2 amp
   *d.* 1.25 amp
   *e.* 62.5 watts
2. *a.* 25.8°
   *b.* 1.85 amp
   *c.* 64.8 ohms
   *d.* 222 watts
3. *a.* 521 ohms
   *b.* 0.979
   *c.* 11.8°
   *d.* 0.208 amp
   *e.* 0.211 amp

### Page 156

1. *a.* 140 ohms
   *b.* 0.351
   *c.* Leading
   *d.* 0.857 amp
   *e.* 69.4°
2. *a.* 400-ohm resistor
   *b.* 191 ohms
   *c.* 52.4 watts
   *d.* 41.7 watts
   *e.* 0.7955
   *f.* 37.3°

### Page 169

1. *a.* 3,558 cycles
   *b.* 3,558 cycles
2. *a.* 6.5 ohms
   *b.* 40 amp
   *c.* 7,000 volts
   *d.* 7,000 volts
3. *a.* Zero volts
   *b.* 120 volts
   *c.* 0.316
   *d.* Zero (resistive circuit)
4. *a.* 4.52 ohms
   *b.* 26.8 ohms
   *c.* 24.9 ohms
5. 580,292 cycles
6. 9.9 μμf
7. 250 μh
8. *a.* 3.554 Mc
   *b.* 0.918 Mc
9. *a.* 0.045 amp
   *b.* Zero amp

### Page 175

1. *a.* 2.62325
   *b.* 1.43136
   *c.* 4.62941
   *d.* −1.13033
   *e.* −3.62634
2. 21.9 db
3. 0.045 amp
4. 0.00005 watt
5. −33 db
6. *a.* 65 db
   *b.* 105 db
   *c.* 107.5 db

### Page 380

1. 5 volts, 12.5 volts
2. 300 volts, 312.5 volts
3. 300 volts, 300 volts
4. 100 volts, 250 volts
5. 195 volts, 50 volts

### Page 418

| | $M_1$ | $M_2$ | $M_3$ | $M_4$ | $M_5$ |
|---|---|---|---|---|---|
| **1.** | VL | H | VL | VH | L |
| **2.** | O | H | VL | VH | L |
| **3.** | VL | VH | VL | VH | L |
| **4.** | VL | H | VL | VH | L |
| **5.** | L | H | O | VH | L |
| **6.** | N | N | R | VH | L |
| **7.** | H | L | L | H | L |
| **8.** | L | H | H | VH | O |
| **9.** | N | N | N | N | N |
| **10.** | O | L | VL | VH | L |
| **11.** | VL | O | VL | VH | L |
| **12.** | H | L | O | H | L |
| **13.** | L | H | H | O | O |
| **14.** | N | N | N | N | O |
| **15.** | N | N | N | N | N |
| **16.** | O | L | VL | VH | L |
| **17.** | H | L | O | H | L |
| **18.** | N | N | N | N | N |
| **19.** | O | O | O | VH | L |
| **20.** | H | L | O | O | H |

### Page 419

| | $M_1$ | $M_2$ | $M_3$ |
|---|---|---|---|
| **1.** | H | VH | O |
| **2.** | O | VH | VL |
| **3.** | H | VH | O |
| **4.** | H | O | O |
| **5.** | L | H | O |
| **6.** | L | H | O |
| **7.** | H | O | O |
| **8.** | L | H | O |
| **9.** | VL | VH | O |