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Volume 1.

The first of three progressive
steps in the training of a
competent radio engineer

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Each book has been written by an expert in the subject, who is also a skilled teacher as will readily be apparent from the text. Ultimately, it is intended to produce a full range of text-books to cover the whole field.

Initially the series will be confined to the scientific, technical and commercial subjects but, as it becomes possible to do so, the more traditional subjects of the curriculum will be included. The reason for this is the important one that technical education must be regarded as a whole if the fullest value is to be obtained from it.

It is the whole man (or woman) whom we seek to educate, and those who enter industry on the technical side are better persons as well as more useful workers, if their needs in the fundamental subjects are more specifically catered for than they are at present.

I am confident that this new series will contribute usefully both to the specific and general aspects of technical education. MAJOR-GENERAL C. LLOYD,
C.B., C.B.E., T.D., B.Sc., F.Inst.P.

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(In preparation)

RADIO

BY

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EDITOR'S INTRODUCTION

THE future of this country depends entirely upon the personal qualities and skills of its people. Economically we must produce or perish and we must, moreover, produce goods which are thoroughly up-to-date and saleable at prices which will allow us to compete in world markets. The key to productivity lies largely in the increasing application of science and technology to industrial processes, and this application is determined by the technical skill and knowledge of the personnel engaged in industry. This skill and knowledge is obtained partly in the technical college and partly in industry itself but the ultimate responsibility rests fairly and squarely on the shoulders of the individual, who often has to study on his own. For this reason, the provision of suitable and good scientific and technical text-books is of the greatest importance, since they can do much for the individual student to supplement the work of the teacher in the classroom, the laboratory and at the bench.

This series—The General Technical Series—is intended for those studying technical subjects for the General Certificate of Education, ordinary and advanced levels, up to the level of the National Certificates, and the examinations of the City and Guilds of London Institute. Each book has been written by an expert in the subject who is also a skilled teacher, as will readily be apparent from the text. Ultimately, it is intended to produce a full range of text-books to cover the whole field. Initially the series will be confined to the scientific, technical and commercial subjects, but, as it becomes possible to do so, the more traditional subjects of the curriculum will be included. The reason for this is the important one that technical education must be regarded as a whole if the fullest value is to be obtained from it. It is the whole man (or woman) whom we seek to educate, and those who enter industry on the technical side are better persons, as well as more useful workers, if their needs in the fundamental subjects are more specifically catered for than they are at present. I am confident that this new series will contribute usefully both to the specific and general aspects of technical education.

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INTRODUCTION

THIS book, comprising three volumes, has been written specially for students studying for the Examinations in "Radio" held by the City and Guilds of London Institute, and therefore follows very closely the appropriate syllabus.

The first volume covers the work required by the syllabus for "Radio I", together with the fundamental knowledge necessary for the "Radio Amateurs Examination". Chapter 1 has been written to provide the amateur with a knowledge of the necessary basic principles, and it need not be studied by students taking the examination in "Radio I".

The authors have endeavoured not to overlap the work of the Telecommunications syllabus for the corresponding stage, and treatments applicable to that syllabus have been omitted. *Telecommunications* (*Principles*), Vol. II, should be studied in conjunction with *Radio*, Vol. I, for the fundamental electric circuit theory, which is necessary for a complete understanding of the art of radio.

Owing to the different treatments required by the syllabus, particularly in relation to the construction and use of components, it is inevitable that mention must be made of some details in several parts of the volume.

The authors have presented to the student the facts necessary for a clear understanding of the work without unnecessary additions, which are properly the subject of later stages.

They wish to acknowledge the valuable assistance rendered by their colleagues, C. H. J. Beaven, B.Sc., and H. C. Chandler, B.Sc. (Eng.), A.M.I.E.E., A.C.G.I., throughout the work.

For the illustrations of components, acknowledgments are due to the kindness of: Erie Resistor, Limited; The Ever Ready Company (Great Britain), Limited; The General Electric Company, Limited; A. H. Hunt, Limited; Jackson Brothers (London), Limited; Morganite Resistors, Limited; Wright and Weaire, Limited, and to the British Broadcasting Corporation for Plate I, while grateful thanks are due to K. A. White, who prepared the diagrams.

JOHN D. TUCKER
DONALD F. WILKINSON

CONTENTS

SUMMARY OF SYMBOLS

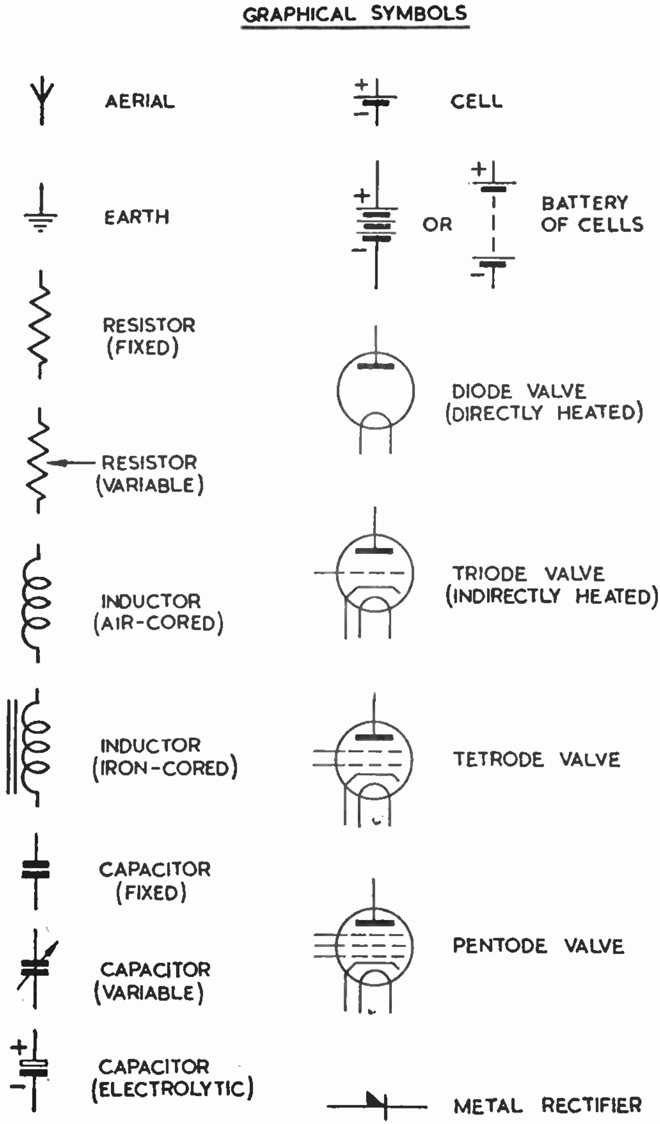
A	ampere (amp.)—unit of current
A	area
c	cycle
C	capacitance
E	e.m.f. (volts)
f	frequency
F	farad—unit of capacitance
g	mutual conductance
h	height of aerial
H	henry—unit of inductance
I	current
k	amount of coupling
l, L	length or distance
L	self-inductance
m	metres—unit of length
m	magnification (of amplifier)
M	mutual inductance
P	power
Q	" goodness " of tuned circuit
Q	quantity of electricity
r, R	resistance
s	second—unit of time
t	time
v	velocity
V	potential difference (volts)
W	energy or work done
W	watt—unit of power
X	reactance
Z	impedance

Greek Symbols

λ (lambda)	wavelength
ω (omega)	$2\pi \times$ frequency
π (pi)	ratio of circumference to diameter of circle
μ (mu)	amplification factor (of valves)
ρ (rho)	resistivity
Σ (sigma)	algebraic sum of

Prefixes

k	kilo	(1,000)
m	milli	$\left(\frac{1}{1{,}000}\right)$
M	meg(a)	(1,000,000)
μ	micro	$\left(\frac{1}{1{,}000{,}000}\right)$
$\mu\mu$ or p	micro-micro pico	$\left(\frac{1}{1{,}000{,}000{,}000{,}000}\right)$



Some Common Symbols in Radio

CHAPTER 1

ELECTRICITY AND MAGNETISM

The Electron Theory

Matter is composed of particles of electricity, which form themselves into groups called molecules. A molecule is the smallest portion of a substance which still retains all the properties of that substance. In its turn a molecule may be subdivided into particles known as atoms, an atom being the smallest portion of a chemical element which can take part in a chemical reaction.

The Elements

While the number of different kinds of molecules appears to be unlimited, only a relatively small number of elements has been discovered and the kinds of molecules comprise different combinations of atoms.

An element is a simple material containing only one kind of atom, *e.g.*, hydrogen, copper, carbon, sulphur, and the molecules consist entirely of atoms of the same kind. A compound comprises molecules of atoms of different kinds, for instance water, a very common compound, contains atoms of hydrogen and oxygen locked together in a particular way. Elements and compounds can also exist in three forms, viz., solid, liquid and gas, so that ice, water and steam are the three forms of this particular substance.

Atoms

The atoms of an element consist of three kinds of particles, which are the same in all elements, and which are known as protons, electrons and neutrons. A proton is a tiny positive charge of electricity, and an electron is an equal charge of opposite, negative electricity. A neutron is an uncharged particle. These particles are, of course, much too small to be visible by any known means, and their presence and nature have been deduced by scientific experiments.

Different atoms are formed by different arrangements of electrons and protons, which are normally possessed by an atom in equal numbers; an atom with eight protons will have eight electrons so that the number of positive charges equals the number of negative charges, the effect being to make the atom electrically neutral.

The protons have a much greater mass than the electrons and are concentrated in the "nucleus" of the atom, while some of the electrons rotate continually round the nucleus, like the planets in their orbits round the sun.

The simplest atom, that of hydrogen (Fig. I.1), consists of only one proton and one " planetary" electron circling round the proton. Helium has in the nucleus two protons and two neutrons (Fig. I.2). There are also two planetary electrons, which, being of opposite electric charge to the protons, are strongly attracted towards them. Every chemical element is known by its atomic number, which corresponds to the number of planetary electrons in one atom; these planetary electrons have orbits in different shells. Helium has two planetary electrons both in orbits of the same radius, in other words in the same shell. This first and smallest shell never contains more than two electrons in a neutral atom, that is, an atom having no electric charge.

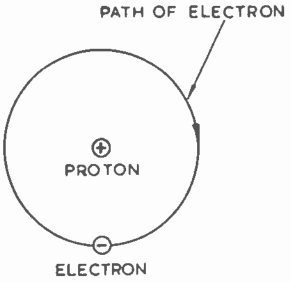


FIG. I.1.—The Hydrogen Atom

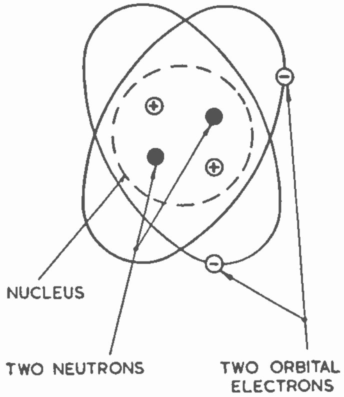


FIG. I.2—The Helium Atom

The next largest atom in the series, lithium, has three planetary electrons, two in the first shell and the remaining one in the second shell. The nucleus contains three protons and also four neutrons. The second shell of electrons can contain up to eight electrons, and this number is reached with the element neon, atomic weight 10, with 10 neutrons and 10 protons in the nucleus, and a total of 10 planetary electrons, 2 in the first shell and 8 in the second. In this way we proceed through the atomic table with successive shells containing electrons as follows: 1st shell 2, 2nd 8, 3rd 8, 4th 18, 5th 18, 6th 32, 7th unknown.

States of Matter

We have already mentioned the fact that elements can exist in solid, liquid or gaseous forms. These forms exist at different temperatures, starting as a solid at a low temperature, and as the temperature is raised, melting into a liquid at the " melting point " of the particular element. Further rise of temperature results in the transformation into the gaseous state when the " boiling point " of the element is reached. Now it is believed that the average speed of movement of the molecules is increased in accordance with the increase in energy provided by the heat given to the substance to raise its temperature. Greater speed will result in the space occupied by each atom increasing, in other words the matter expands, or, if it is not allowed to do so, the pressure increases. In some materials some of the planetary electrons actually escape from the atoms at high temperatures.

Molecules

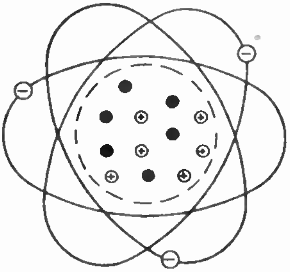
By the combination of two or more atoms in any of a large possible number of ways molecules are formed which constitute chemical compounds. The theory of chemical compounds is greatly elucidated by the conception of electronic shells discussed above. For instance, an atom having one electron in its third shell will combine with another atom having seven electrons in the third shell, since the combination will have eight electrons; it is found that the outer shells of stable compounds always contain their full quota of electrons. Those elements, the atoms of which already have their outer shells full, very rarely combine chemically with any other elements. They are Helium, Atomic No. 2, two electrons in first shell; Neon, Atomic No. 10, eight electrons in second shell; Argon, Atomic No. 18, eight electrons in third shell; Krypton, Atomic No. 36, eighteen electrons in fourth shell; Xenon, Atomic No. 54, eighteen electrons in fifth shell; Radon, Atomic No. 86, thirty-two electrons in sixth shell. All these elements are gaseous at normal temperatures.

We thus find that all matter is composed of minute particles known as neutrons, protons and electrons having respectively zero, positive and negative charges of electricity. Substances vary in complexity of arrangement of these particles, from the simple hydrogen atom through the more complex atoms to the highly complicated molecules of compounds.

Electric Charge

If we can find a means of removing some of the planetary electrons from the atoms or molecules of a substance, the balance of electric charge is upset and there will be an excess of protons over electrons (Fig. I.3). The substance is then said to be positively charged, and will exhibit a force of attraction to an oppositely charged body (Fig. I.4). Alternatively, we may add some electrons to the substance, when it will become negatively charged, and will exhibit a similar force of attraction.

There are many ways in which electrons may be added to or subtracted from the molecules of a body, but to charge a body by change of the proton population is exceedingly difficult, owing to the immense forces locking the protons into the nucleus. A corollary of this phenomenon of " charging " molecules is, that in some cases electrons can be caused to leave their parent atom and



NUCLEUS CONTAINS 12 PROTONS AND 6 ELECTRONS THERE WOULD NORMALLY BE 6 PLANETARY ELECTRONS, BUT 3 HAVE BEEN REMOVED LEAVING A SURPLUS OF PROTONS, SO THAT THE ATOM IS POSITIVELY CHARGED.

Fig. I.3.—A Charged Carbon Atom

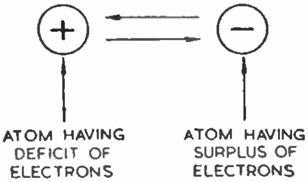
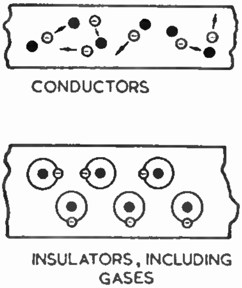


Fig. I.4.—Attraction between Charged Bodies



IN A CONDUCTOR STRAY ELECTRONS MOVE IN A RANDOM MANNER TO OTHER NUCLEI

IN AN INSULATOR THE ELECTRONS DO NOT LEAVE THEIR ORBITS, EXCEPT UNDER GREAT STRESS

Fig. I.5.—Conductor and Insulator

to transfer themselves to a nearby atom, particularly if an odd electron occupies an outer shell, far removed from the attraction of the nucleus. Metals exhibit this property very greatly, while those substances which are gaseous at normal temperatures exhibit it only under great stress (Fig. I.5).

Effect of Electric Charge

Suppose that a metal body has been charged negatively, that is, it has more electrons than protons (Fig. I.6), it will have a great attraction for positive electricity and will repel negative electricity. If it is brought near to a body which is in a balanced state of charge, the electrons on the second body closest to the charged body will be repelled and will move as far away as they are able—round to the opposite side, so that the distribution of (but not the total) charge of the second body is altered. This phenomenon leads to " charging by induction ", for if a means of escape is provided for the electrons, they will leave the body and it will become positively charged (Fig. I.7).

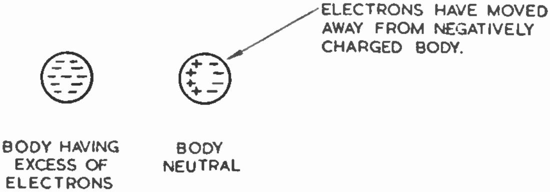


FIG. I.6.—Electron Displacement by a Charged Body

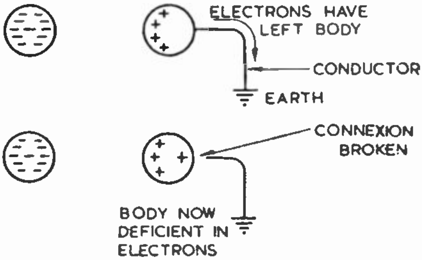


FIG. I.7.—Charging by Induction

Ionisation

When an atom or group of atoms is charged, having either more or less electrons than protons, it is said to be " ionised " and is known as an " ion ", being called positive or negative respectively when it has a deficit or surplus of electrons. These terms are applied more to atoms of gaseous or liquid substances, and when the atoms of such a substance are ionised they will suffer attraction or repulsion by charged bodies according to their polarity. The ions will migrate to the charged bodies and will endeavour to balance their state of charge (Fig. I.8).

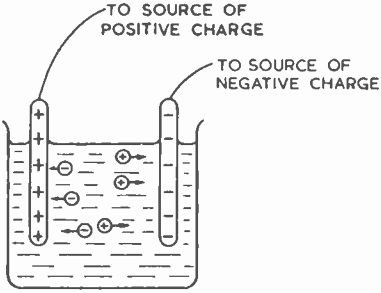


FIG. I.8.—Ion Flow

Electric Current

The last three paragraphs have described three types of electric current, as a flow of electrons is called. To summarise, they are: (1) conduction currents, where electrons leave one atom and travel to one nearby, as in metals (Fig. I.5); (2) displacement currents, as in the case of charging by induction (Fig. I.6); (3) convection currents, which flow through the agency of ions, and which take place in gases, vapours and liquids (Fig. I.8).

Electromotive Force

In order to cause a flow of electrons, or an electric current, as we shall now call it, a force is necessary which is known as an electromotive force. We can produce an electromotive force (abbreviated to e.m.f.) in at least four ways:

1. By friction, known as the electrostatic method.
2. By chemical action, as in cells.
3. By heat.
4. By electro-magnetic means.

In general, a source of e.m.f. is a device in which energy of any other form is converted into electrical energy.

To enlarge on these methods in turn, electrostatic generators are not of any interest to us for the time being. It is well known that a piece of amber, glass or ebonite, when rubbed with silk or cloth, will attract pieces of paper. When the hair is dry and is combed vigorously a crackling noise is often heard, which is due to charges on the comb. This method operates by rubbing off some of the outer electrons from the molecules of the substance, which becomes charged as a result.

Chemical Cells

Chemical action taking place when two dissimilar conducting substances are placed in an acid or alkaline solution causes one of the conductors to acquire a surplus of electrons at the expense of the other conductor. The generation of an e.m.f. by this method will be dealt with in Chapter 7.

Thermo-electric e.m.f.s

When two dissimilar conductors are placed in mechanical contact and the junction is raised in temperature, there will be an e.m.f. between the conductors.

The electro-magnetic method will be dealt with later in this chapter.

Conductors and Insulators

We know that some materials conduct electricity and some do not; for instance, an electric-light switch has " live " metal parts inside it, and if we touch them we know that they are charged by reason of the nervous convulsions we suffer. However, we feel nothing from the cover of the switch, because the electricity is unable to reach it. Some parts of the switch are made of an " insulating " material, which does not conduct electricity. Observation shows us that metals, in general, conduct electricity, and we know that copper is usually used for conductors.

Metallic Conduction

In metals some of the " orbital " electrons of an atom pass very close to neighbouring atoms, and accordingly are attracted by the nuclei of these other atoms. As a result of this, electrons frequently adopt other parent atoms, and a random interchange of electrons is continually occurring (see Fig. I.5). The application of an e.m.f. to a conductor results in a steady migration of these electrons which is superimposed on the random motion according to the rule we have already observed. This happens in an endeavour to balance the electron deficit caused by the e.m.f. (Fig. I.9).

The source of e.m.f. appears as if one of its terminals, known as the negative, has a surplus of electrons (negative electricity), while the other terminal has an equal deficit of electrons or surplus of protons and is called the positive terminal. This state of affairs is brought about by one of the actions mentioned on page 6.

Connexion of the two terminals by a conducting substance then causes electrons from the conductor adjacent to the positive terminal to be attracted to it, while electrons are repelled by the

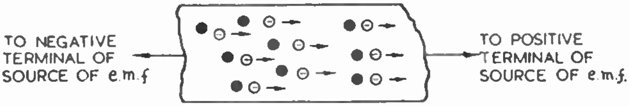


FIG. I.9.—Metallic Conduction

negative terminal of the source. In this way the migration of electrons is caused, and can be deduced by various phenomena which result.

Insulation

We have mentioned the insulating properties of some materials, and it is found that in such materials the planetary electrons are much more strongly attracted to their " parent " nuclei than to any other neighbouring atom, and therefore do not interchange as do the electrons in conductors. The application of an e.m.f.

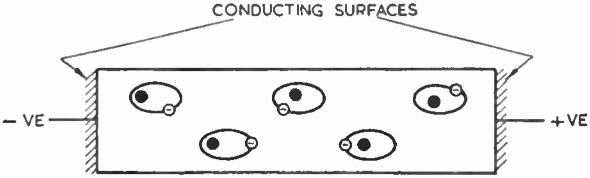


FIG. I.10.—Insulator in Electric Field

to an insulator causes a *displacement* of electrons (Fig. I.10), but not a *flow*, unless the e.m.f. is very great, in which case it is possible to tear electrons from atoms forcibly and to cause the " breakdown " of the insulating properties of the substances. A smaller e.m.f. may cause occasional electrons to detach themselves from atoms and thus cause a very small current to flow, since no material can be a perfect insulator.

Degree of Conduction

In conductors, too, some materials have more " free " electrons than others, so that electrons can wander about more easily. These free electrons which move to form an electric current determine the resistance which the material offers to a flow of electrons. The less free electrons there are in a given piece of conductor, the greater the difficulty which the e.m.f. has in causing a flow of current, or the greater the electrical resistance of the material.

The three best conductors are silver, copper and aluminium, in that order.

Ohm's Law

Ohm discovered that there is a definite relationship between the current in a conductor and the e.m.f. causing that current to flow, and formulated his law, which states that in any conductor at a constant temperature the current flowing is proportional to the e.m.f. in the circuit.

In order to make use of this relationship, units are required to denote the amounts of e.m.f., and of the current flowing and also some means of denoting the relative difficulty with which a certain conductor carries a current.

Units of e.m.f. and Current

The unit of e.m.f. is the volt, named after Volta, an Italian physicist, and that of current is the Ampere, commonly abbreviated to amp. The unit of resistance is known as the ohm (Ω), and is such that an e.m.f. of 1 volt will cause a current of 1 amp. to flow through a circuit having a resistance of 1 ohm. Ohm's Law states that current and e.m.f. are proportional, so that:

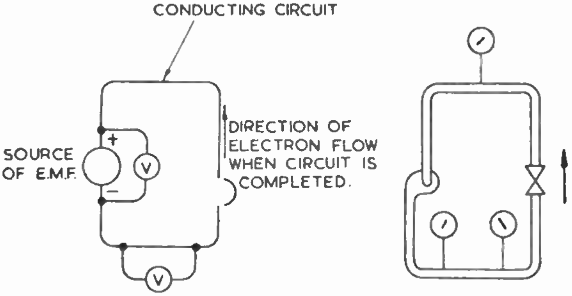


FIG. I.11.—Hydraulic Analogy

$$\text{volts/amps.} = \text{a constant for a given circuit}$$
$$= \text{resistance in ohms.}$$

We have discussed the means by which a current can be made to flow in a conductor, namely, the application of an e.m.f. to the circuit. The source of e.m.f. is often likened to a pump, circulating water, the molecules of which correspond to the electrons in the conducting parts of the circuit. The circuit corresponds to the pipe system (Fig. I.11) containing the water. A valve in the water system corresponds, when closed, to a break in the electric circuit. Opening the valve corresponds to joining up the break in the circuit, and this operation permits water to flow, at a rate determined by the friction which tends to stop movement of the water.

If we measure the pressure at various points along our pipe we shall find that the pressure falls as we travel from the outlet of the pump back to the inlet. If we consider the length of pipe between two points where we have measured the pressure, we can say that the water is being forced through that particular distance by the difference of pressure indicated by our gauges.

A similar state of affairs exists in our electric circuit. We can use an electrical instrument known as a voltmeter, which indicates when one of its terminals is connected to a point of greater electrical pressure than the other. When we connect this instrument across the source of e.m.f. it will indicate the value of this e.m.f. or the "potential difference" between the two points.

Potential Difference

Suppose that our circuit consists of a length of uniform conductor, of the same cross-section throughout, and that we connect our voltmeter to one end of the conductor and to the mid-point of the conductor. We should find that the reading would be exactly one-half that given when connected across the whole circuit. The electrical force or pressure is known as potential, and, like e.m.f., is measured in volts. We say that there is a " potential difference " between two points on a conductor, and this is what we were measuring when we connected our voltmeter across part of the circuit. In applying Ohm's Law to a circuit, or to part of a circuit, it is more correct to say that the resistance of a circuit is proportional to the ratio of the potential difference (p.d.) across it to the current flowing through it, than to speak of the e.m.f.

Electron Flow

We have discussed our theories of electricity so far by using the electron theory as a basis and considering that our electric currents consist of electrons leaving the source of e.m.f. at its negative terminal (the one having an excess of electrons), flowing round the circuit and returning to the positive terminal of the source.

Conventional Current Flow

Historically, electric currents and their manifestations preceded the electron theory, and some knowledge of electricity became well known before this theory was firmly established. In those days it was thought that electric currents flowed from the positive terminal of a source, through the external circuit and back to the negative terminal of the source. This may be understood to follow from the idea that electricity would flow like water, from a point at a high potential (pressure) to a point at a lower potential (pressure). This direction of current flow is known as the " conventional " direction, and is still much used in electrical engineering and electro-magnetism (Fig. I.12).

When we speak of " current ", we shall be speaking of current in the " conventional " direction to distinguish it from the direction of electron flow, which we shall always describe as such.

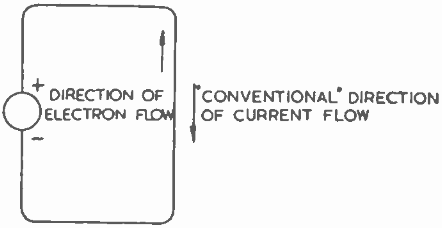


Fig. I.12.—Conventional Direction of Current Flow

The direction of flow which we have discussed according to the electron theory is, again, that of electron flow. It is important to understand these two conceptions from the beginning.

International Units

A current of 1 International Ampere is defined as that current which, passed through a solution of silver nitrate in water, deposits silver at the rate of 0·001118 gram per second, and can thus be ascertained with relative ease.

The International Ohm is the resistance of a uniform column of mercury of 1 sq. mm. cross-section, 106·300 cm. long, at the temperature of melting ice (0° C.) ; and by Ohm's Law (Volts = Current × Resistance) the International Volt is determined as being the potential difference across a conductor having a resistance of one international ohm when a current of one international ampere is passed through it. To assist us in making calculations, the following symbols are used :

Potential difference, V, measured in volts.
Current, I, measured in amperes.
Resistance, R, measured in ohms.
$V = IR$ in the above units.

To distinguish an e.m.f. from a p.d., the former is represented by E though both are measured in volts. We shall see the need for the distinction when we deal with sources of e.m.f.

Resistance of Conductors and Resistivity

The resistance of a conductor depends on its shape, as well as on the material of which it is made. It is immediately obvious that the resistance depends on the length of the conductor, and will be proportional to that dimension. We should also expect the resistance to depend on the cross-sectional area of the conductor, since the moving electrons will be more crowded in a thin wire than in a thick one, and will therefore have more difficulty in moving. We therefore deduce that, if the length of a conductor is L and its cross-section is A, then R is proportional to L/A. By inserting a quantity ρ, known as the resistivity, or specific resistance of a material, we can put $R = \frac{\rho L}{A}$, where ρ is numerically equal to the resistance between two opposite faces of a unit cube of the material. If L and A are measured in cm. and sq. cm. respectively, ρ must be numerically equal to the resistance of a cube having sides of 1 cm. Similarly, all dimensions may be in inches, but ρ will now have a different value.

Resistors in Series

We are very often concerned with circuits containing a number of resistors connected together. Fig. I.13 shows three resistors, R_1, R_2 and R_3, connected so that the same current flows through all of them; they are then said to be connected in " series ".

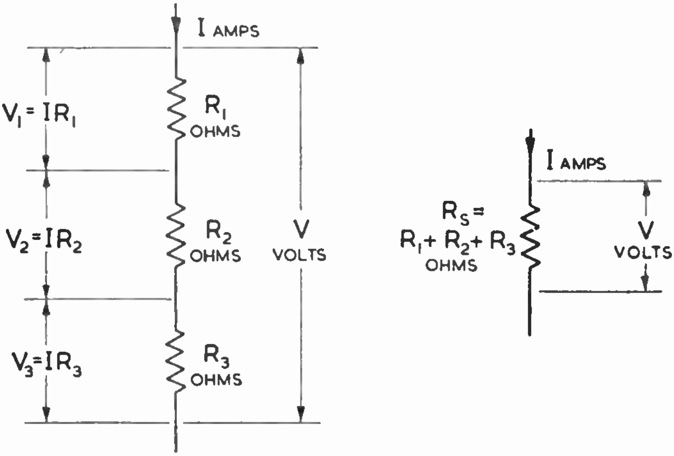


FIG. I.13.—Resistors in Series

The total p.d. round the circuit, V, is equal to the sum of the three individual p.d.s, V_1, V_2 and V_3, developed across the resistors by the passage of the current I. Now Ohm's Law tells us that :

$$\begin{aligned} V_1 &= IR_1 \\ V_2 &= IR_2 \\ V_3 &= IR_3 \end{aligned}$$

so that

$$\begin{aligned} V = V_1 + V_2 + V_3 &= IR_1 + IR_2 + IR_3 \\ &= I(R_1 + R_2 + R_3) \\ &= IR_s \end{aligned}$$

where R_s is the one resistor which would develop the same p.d. as the three resistors R_1, R_2 and R_3 when the same current flows. When resistors are connected in series, then we can find out what will happen in the circuit by adding their values together and using the one single value thus obtained in our calculation.

Resistors in Parallel

It is also possible to connect resistors so that the same p.d. appears across every one. Fig. I.14 shows our three resistors R_1, R_2 and R_3 connected in " parallel ", as it is called, and the p.d. across them is V volts.

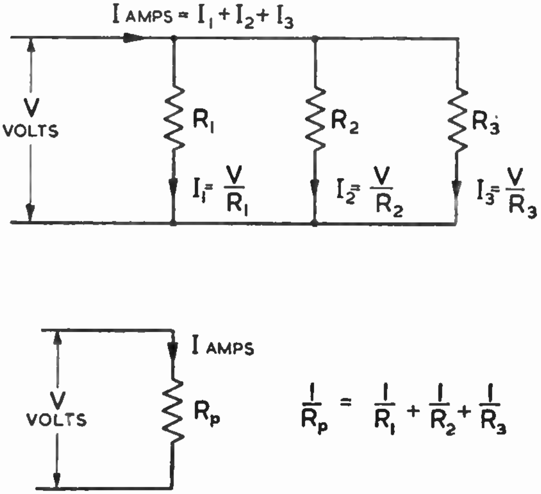


FIG. I.14.—Resistors in Parallel

The current in R_1 is $I_1 = \frac{V}{R_1}$ amps.

,, ,, in R_2 is $I_2 = \frac{V}{R_2}$ amps.

,, ,, in R_3 is $I_3 = \frac{V}{R_3}$ amps.

and in the external circuit is

$$\begin{aligned} I &= I_1 + I_2 + I_3 \\ &= \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \\ &= V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) \\ &= \frac{V}{R_p} \end{aligned}$$

where R_p is the single resistor which would pass the same current at the same p.d. as the three it replaces.

We see that $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$, etc., so that the reciprocal of the resistance of the combination is given by the sum of the reciprocals of the resistances of the individual components.

Units of Power and Energy

We now make our acquaintance with some other units which we shall frequently meet in our work. These are the units of power and energy. Power is defined as the rate of doing work, and may also be the rate at which energy is transformed, while energy is the total work done or total energy transformed.

In electricity these units are based upon the " erg ", a unit of work or energy equal to that done when a force of one dyne acts through a distance of one centimetre. These are basic units in the centimetre–gram–second system which is used for electrical theory.

The " erg " is an extremely small unit, so that a practical unit called the " joule ", equal to 10 million (10^7) ergs is used, which is in the same system as the volt, ohm and ampere.

The ampere is determined by the rate of flow of electrons past any cross-section of a circuit, and one ampere is equal to a rate of flow of $6{\cdot}29 \times 10^{18}$ electrons per second. If a certain current I amps. is maintained in a circuit for t seconds, then $6{\cdot}29 \times 10^{18} \times I \times t$ electrons will have passed round the circuit. A movement of electrons or a current is the transference of a quantity of electricity. Again, the electron is too small for practical purposes, and the unit known as the coulomb, equal to $6{\cdot}29 \times 10^{18}$ electrons, or

1 ampere-second, is used. In the example given above, the quantity of electricity in coulombs, denoted by Q, is equal to $I.t$.

If a part of a circuit has a p.d. across it of 1 volt and 1 coulomb of electricity passes through the circuit, then the electrical energy converted into some other form of energy is 1 joule, the unit of energy, denoted by W. Therefore W (joules) $= V$ (volts) $\times Q$ (coulombs), and this is the energy relationship for a part of the circuit to which W and V are appropriate (Fig. I.15).

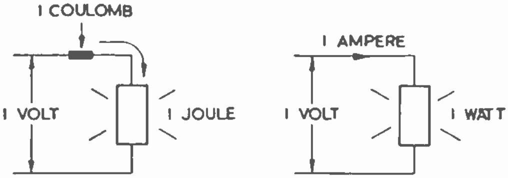


FIG. I.15.—Illustrating Work and Energy

Power is the rate of doing work, so that dividing W by t will give us the power involved $\frac{W}{t} = V \times \frac{Q}{t} = V \times I$.

The unit of power (P) is the watt, so that

$$P = VI \text{ watts or joules per second.}$$

When a larger unit of energy is required the watt-hour, or a multiple thereof, is used.

One watt-hour equals 3,600 watt-seconds or joules, and is the energy transformed when a power of 1 watt is dissipated for 1 hour. Electrical engineers use the kilowatt-hour, equal to one thousand watt-hours, and one kilowatt-hour is called a Board of Trade Unit. It is the unit of energy used in selling electricity commercially.

The M.K.S. System of Units

There exist in fundamental physics several systems the units of which are defined differently while still being based on the centimetre, gram and second. Engineers use the international electrical units which we have already discussed, and these involve the use of different factors to convert from the various C.G.S. systems. This state of affairs led to proposals for a more convenient common system.

Giorgi in Italy in 1901 and independently Robertson in England in 1904 proposed a scheme for a system based on the metre, kilogram and second—the M.K.S. system. The watt is the unit of any form of power, and the electrical and mechanical units are so related that the international volt and the international ampere are the units of electrical pressure and current.

Units like the volt, ampere, ohm, henry, farad, watt and joule are exactly the same in the M.K.S. system as in the " practical " system, while the mechanical unit of force (M.K.S.) is the " newton ", which is of such a magnitude that one newton-metre is equal to one joule or watt-second.

Mechanical units of length, area, density are the metre, square metre, kilogram per cubic metre respectively, and other units are derived in the same way. The use of this system by scientists has the advantage that their results can be at once put to practical use without the necessity for conversion of units, and during recent years a number of text-books published in other countries have made use of the M.K.S. system.

Heating Effect of a Current

In an ordinary electrical circuit, the conductors are found to rise in temperature when current is passed through them. This happens because the electrical energy, determined by the product of the p.d. across the circuit and the quantity of electricity passed through, is being converted into heat energy. When a conductor has a high resistance, the p.d. across it will be high for a given current, so that the energy converted, equal to VIt joules, is higher than in a circuit of low resistance. This is in accordance with our physical explanation of current flow, since an increased resistance corresponds to a conductor having few free electrons, which can only move with difficulty. It is reasonable to suppose that the substance of the conductor will be warmed up as a result of the difficulty of movement.

The p.d. across a circuit having a resistance R is given by $V = IR$. The power in that circuit we know to be VI watts

$$\therefore \quad P = VI = IR \times I = I^2R \text{ watts.}$$

Also

$$P = VI = V \times \frac{V}{R} = \frac{V^2}{R} \text{ watts.}$$

These expressions show that in a circuit of given resistance, the power is proportional to the square of the current or the square of the p.d., and it follows that too great an increase in p.d. or current (which are proportional to each other) will soon cause overheating of the conductors.

Electric Field

An electric field is defined as the region in the neighbourhood of electric charges where forces are exerted on other charges.

We have already seen that oppositely charged bodies attract each other and that similarly charged bodies repel each other. Between any two bodies at different potentials an electric field is imagined to exist, the direction of this field being defined as that in which a positive charge would move when placed in the field. The strength of the field at any point is defined as the force exerted on unit positive charge placed at that point.

The force of attraction or repulsion between charged bodies may always be estimated by assuming that the lines describing the electric field are elastic, tend to straighten themselves, and repel each other. Fig. I.16 shows the electric field between two spheres. The direction of the field is from the positive charge to the negative charge, as that is the direction in which another positive charge would be urged. A single charged body has an electric field which terminates on surrounding objects at earth potential.

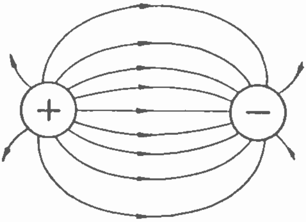


FIG. I.16.—Distribution of Electric Field

Capacitance

When a body is charged by adding electrons to it, or by removing them from it, the flow of electrons constitutes a flow of electricity to or from the body. There is a change in the quantity of electricity in the body, and this is accompanied by a change in its potential. Potential in this case is defined as the work done in bringing a unit positive charge from an infinite distance up to the charged body (work done = force × distance).

The ratio of charge to potential is known as the " Capacitance " of the body, and the practical unit is the Farad. A body has a capacitance of one farad if its potential is changed by one volt when one coulomb of electricity is added to or taken from it. The unit is inconveniently large, and we use the microfarad, which is one-millionth (10^{-6}) of a farad, and the picofarad or micro-microfarad (10^{-12} of a farad). These units are denoted by μF and pF or $\mu\mu$F respectively.

A capacitor is a system of conductors arranged to give a certain value of capacitance, and in order to produce a large capacitance in a small space, the two conductors are arranged with a small gap between them. The space or non-conducting substance between the two conductors is known as the " dielectric ".

Because of the necessity of changing the quantity of electricity in a capacitor so as to change its potential, current must flow to effect the change. The quantity of electricity (Q) in coulombs is given by the product of the capacitance (C) in farads, and the p.d. across it (V) in volts, *i.e.*, $Q = CV$. If the quantity of electricity is changed from Q_1 to Q_2 in time t seconds, the mean current is given by

$$\frac{Q_2 - Q_1}{t} = \frac{CV_2 - CV_1}{t} = \frac{C(V_2 - V_1)}{t} \text{ amps.}$$

If the space between the conductors is filled with a material such as paper, glass, mica, paraffin wax, etc., it is found that the charging current of the capacitor is increased, *i.e.*, for the same p.d. there is a greater charge. The ratio of charge when the dielectric is completely filled with the substance to that when filled with air is known as the permittivity of the substance. Thus the capacitance of a system may be increased by using a dielectric of high permittivity.

The electrical work done is given by the mean p.d. $\frac{(V_1 + V_2)}{2}$ multiplied by the current and the time:

$$W = \frac{C(V_2 - V_1)}{t} \times \frac{V_1 + V_2}{2} \times t = \tfrac{1}{2}CV_2^2 - \tfrac{1}{2}CV_1^2 \text{ joules.}$$

A capacitor is thus a means of storing electrical energy, which can be reclaimed by connecting a load to its terminals.

Magnetism

We now turn to a phenomenon which has been known for a great number of years. Certain natural ores, in particular " Lodestone ", were found to exhibit a mutual attraction to iron, and, if suspended, to point in a certain direction. Use was made of this phenomenon to make a compass, which always pointed to the North and South magnetic poles of the earth. Materials exhibiting these properties were called " Magnetic ". Steel can be made magnetic (magnetised) by stroking it with a piece of lodestone, but since the discovery that a conductor carrying an electric current also exhibits magnetic properties, magnets have been made by using that phenomenon. The magnetic effect of a current was discovered early in the nineteenth century, and the discovery probably began the rapid development of electrical science which took place during that century.

Polarity

As in the case of electrical charges, magnetic poles of opposite polarity attract each other, while like poles repel each other.

If a magnet is suspended and allowed to settle down, the end which points to the North magnetic pole of the earth is called the " N " pole, while the other end is called the " S " pole. Lines of magnetic force are considered to act from " N " to " S " outside the magnet, since that is the direction in which a free unit " N " pole would move if placed in the field.

If an ordinary bar magnet be taken and a small compass needle brought near, it will be found that the needle sets itself in a direction depending on its position relative to the bar magnet (Fig. I.17). If the compass is brought very close to one end, or pole, of the bar magnet, the needle will be seen to point along a line emerging from the magnet. If we move the compass in the direction in which it points, we shall find that it follows a curved path back to the other pole of the magnet. Such a line is called a magnetic "Line of Force", since at any point on that *line*, a compass needle will lie tangentially owing to the magnetic *force* upon it. These lines are assumed to travel from the " N " pole to the " S " pole outside the magnet. Such a line can be traced anywhere in the neighbourhood of a magnet, that is, within its field of influence, or as we say, in the " field " of a magnet, and such a region is called a magnetic field, the lines of force denoting the direction of the field.

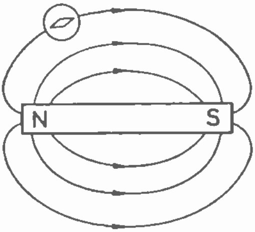


FIG. I.17.—Bar Magnet and Compass Needle

Two magnetic poles exert a mechanical force on each other. The direction of the force is determined by plotting the magnetic field from the facts that lines of force tend to shorten themselves, as if in a state of tension, that they repel each other and can never cross. The mechanical force is proportional to $\frac{m_1 m_2}{d^2}$ where m_1 and m_2 are the pole strengths and d is their distance apart. The strength of the magnetic field is denoted by the density of the lines of force, or " flux density ".

Magnetic flux is the name given to the imaginary lines of force which exist as a result of a magnetic field.

Magnetism has been explained by a theory somewhat akin to the electron theory. It is assumed that all molecules of a substance are magnetised and can be likened to tiny bar magnets. In the normal state of a material these little magnets are all pointing in different directions, so that the total magnetic effect is zero. In a piece of material exhibiting magnetism, more of the molecular magnets are pointing in one direction than in any other, so that there is an external manifestation of magnetism having poles in that particular direction. Such a material exists naturally in lodestone, and by subjecting steel to the influence of a magnetic field, some of the molecules can be pulled round into a particular direction, where they will remain unless disturbed by the influence of another magnetic field, or by hammering or heating, when they tend to slip back to a random orientation.

This theory indicates that magnetism can be induced by placing a substance in a magnetic field, when the molecular magnets will orient themselves into the direction of the inducing field. This phenomenon occurs to a useful extent only in " ferro-magnetic " materials, viz., nickel, iron, cobalt and certain alloys of these and other elements.

Electro-magnetism

A magnetic field also surrounds all current-carrying conductors, as can be demonstrated by bringing a compass needle near to such a conductor. There is a definite relation between the direction of the field and the direction of current flow, and this is easily remembered by the use of the " Corkscrew Rule ". The lines of force due to a current form a series of concentric circles around the conductor, and the direction of the field is the same as that in which a right-handed corkscrew would have to be turned in order to travel in the conventional direction of the current (positive to negative, and opposite to electron flow) (Fig. I.18).

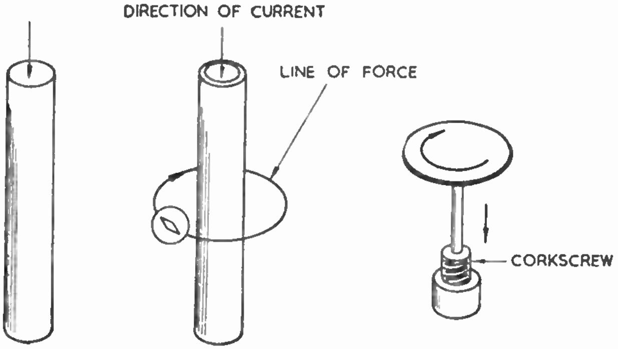


FIG. I.18.—The " Corkscrew " Rule

The field of a single conductor carrying a current consists of concentric tubes about the conductor. This effect can be greatly increased by winding a helical coil of wire and passing current through it (Fig. I.19). Such a coil is known as a " solenoid ", and may have one or more layers of wire. The result of passing current through a solenoid is a strong, nearly uniform field inside the coil, parallel to the axis of the coil.

If a piece of ferro-magnetic material is placed inside the coil it becomes magnetised, so that " N " and " S " poles appear at either end. Furthermore, the flux density is greatly increased by the presence of the " core " as it is called, since the magnetic lines of force can pass much more easily through this material than through air. The ratio of the flux density in the magnetic material to the density which existed in air before the introduction of this material is known as the "permeability" of the material (μ). The state of the magnetic material after switching off the current in the solenoid depends on the material, and if it be soft iron, the induced poles will disappear so that the bar is no longer a magnet. In the case of cast iron or steel, the bar will remain weakly magnetised, and this effect can be increased by alloying cobalt with the steel. It has more recently been found that certain alloys of aluminium and nickel and of aluminium, nickel and cobalt have great powers of retaining such induced magnetism, and these alloys are now widely used for production of " permanent " magnets.

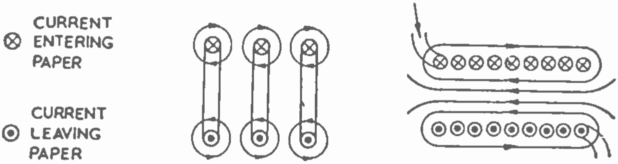


FIG. I.19.—A Solenoid and its Magnetic Field

Generation of e.m.f.

The theory of electro-magnetism also embraces the generation of e.m.f. by a magnetic field, as well as the production of a magnetic field by a current-carrying conductor. There is an important difference between these two reverse processes, however, in that, although a magnetic field exists about a conductor as long as a current is flowing through it, an e.m.f. is induced in a conductor only while there is relative motion between the conductor and the field, or while the field is changing in strength.

Faraday enumerated the Laws of Electro-magnetic Induction as follows : The e.m.f. induced is proportional to the rate of change of flux-linkages (that is, the product of total flux and the turns linked with them) with time.

Let us take two similar solenoids and place them end to end as in Fig. I.20. The passage of a current through one of these coils will set up a flux, and some of the lines of force will pass through the second coil. If we now connect a voltmeter to this second coil, we find that no e.m.f. exists. When we switch off the current in the first coil, the magnetic field collapses, and in doing so, the flux cutting the second coil falls suddenly to zero, generating momentarily an e.m.f. which causes the needle of the voltmeter to kick. We also find that switching on the current in the first coil causes a kick of the voltmeter in the opposite direction. This is known as the " transformer principle ".

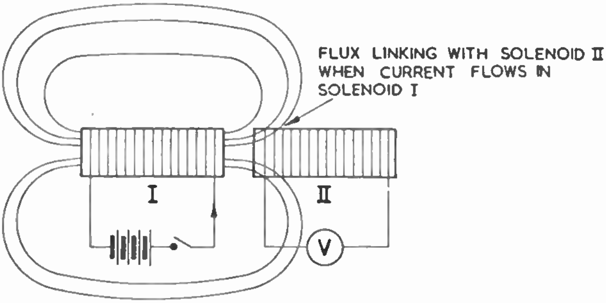


FIG. I.20.—Generation of an e.m.f.—Transformer Principle

If, while the current is switched on in the first coil, we move either coil, we find that an e.m.f. is generated all the time there is relative motion between the coils, and this is known as the "generator principle" (Fig. I.21). Clearly, the source of magnetic field in the second case could equally well be a permanent magnet.

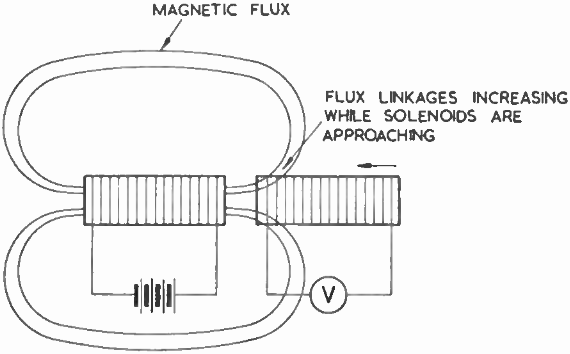


FIG. I.21.—Generation of an e.m.f.—Generator Principle

Returning to our first experiment, in which we " induced " an e.m.f. in the second coil by changing the current in the first coil, it is reasonable to expect that changing the flux will also produce an e.m.f. in the windings of the first coil. It is found that the current in the first coil rises gradually, not immediately, to its final value, showing that an e.m.f. is generated in the coil by the rising current, which is opposite to the applied e.m.f. (Fig. I.22). This is the " e.m.f. of self-induction ", and the fact that it always opposes the applied e.m.f. is known as Lenz's Law.

The property of generation of an e.m.f. in a coil by a current in the same or another coil is known as " Inductance ", and is referred to as " Self-inductance " when the e.m.f. is generated by current in the same coil, and as " Mutual inductance " when dealing with the e.m.f. generated in one coil by the change of current in another. A coil has an inductance of one " henry " (the unit of inductance) if an e.m.f. of one volt is induced in it by a current changing at the rate of one ampere per second. Similarly, the mutual inductance between two coils is one henry if an e.m.f. of one volt is induced in one of them when the current in the other is changed at the rate of one ampere per second.

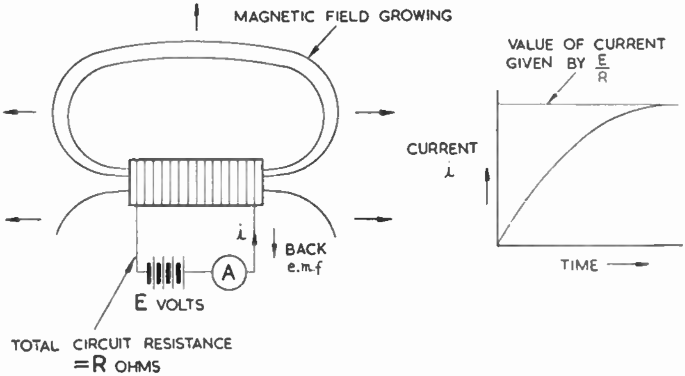


FIG. I.22.—The Effect of the e.m.f. of Self-induction

The Generator

The sources of e.m.f. we have considered so far have been chemical cells whose terminals have a constant, unidirectional potential difference. The numerous possible mechanical arrangements of an electro-dynamic generator working on the principle of relative motion between a conductor and a magnetic field provide us with means of generating e.m.f.s which vary with time and which are known as alternating quantities. Let us consider a single turn of wire rotating in a uniform magnetic field, as shown in Fig. I.23. The e.m.f. in a conductor is proportional to the rate at which it cuts lines of force, and as this rate will vary continually with the rotation of the conductor, the e.m.f. across the ends of a turn will change smoothly and regularly during one revolution. Since the two sides of the turn are cutting the field in opposite directions, the e.m.f.s in the two sides will be opposite but will be additive because of the method of connexion. The e.m.f. between the ends of the turn will be twice that in one side of the turn, since the e.m.f. in each side will have the same value. It will vary from a maximum when the coil is moving at right angles to the field to zero when moving in the plane of the field, then to a maximum in the reverse direction, back to zero and so to a maximum in the original direction. This is accomplished during one revolution of the coil, and the complete chain of events from maximum e.m.f. through zero, to maximum in the reverse direction, and through zero back to maximum in the original direction, is known as one "Cycle". In the particular device we have just discussed one cycle occupies one revolution of the coil. A graph of the e.m.f. is shown, and the names given to important values are indicated; such an e.m.f. is termed an "alternating" quantity. Apart from the values indicated, an important quality of an alternating e.m.f. is its "frequency", which is the number of

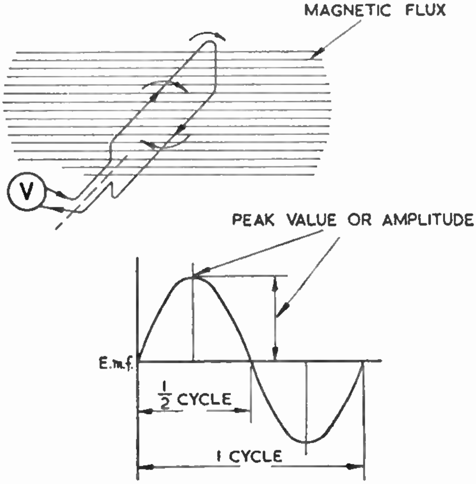


FIG. I.23.—A Simple Generator

times the e.m.f. goes through its cycle in a given time. For instance, an e.m.f. having a frequency of 50 cycles per second (50 c/s) will go through 50 complete cycles in every second of time. The current which flows in a circuit to which an alternating e.m.f. is applied is known as an alternating current, abbreviated to " a.c.". A supply of alternating e.m.f. is known as an alternating supply to distinguish it from a source of unidirectional e.m.f., which is termed a direct supply.

It should be clear now that an alternating supply has advantages for many purposes when compared with a direct supply. Returning to our pair of coils mentioned on page 22, if one of the coils is now connected to a source of alternating e.m.f., an alternating current will flow, setting up a continually changing magnetic field. This alternating field will induce an alternating e.m.f. in the second coil having the same frequency as that of the supply. By Lenz's Law, there will also be a " back " e.m.f. set up by the magnetic field in the first coil, which limits the amount of current which can flow; in fact, the applied e.m.f. will have reversed before the current can reach the maximum value according to the graph of Fig. I.22, so that the current will never reach the value equal to E/R in the circuit.

It is sufficient to note here that the current flowing in an inductor is given by

$$I = \frac{V}{2\pi fL}$$

where I is the current in amperes; V is the applied alternating p.d. in volts; f is the frequency of the applied p.d. in c/s; L is the inductance in henrys.

Capacitor in a.c. Circuit

If an alternating p.d. is applied to a capacitor, the current is given by

$$I = V \times 2\pi fC$$

where I is the current in amperes; V is the alternating p.d. in volts; f is the frequency in c/s; C is the capacitance in farads.

CHAPTER 2

RADIO COMMUNICATION

ALMOST everybody uses Radio Communication in the form of the domestic radio receiver, or " wireless set ". " Radio " as a technical term has taken the place of " wireless ", which was an abbreviation for " wireless telegraphy " or " wireless telephony ". These terms were developed to denote communication over a distance without connecting wires, using telegraphy (code) or telephony (speech). Everyone is also familiar with the telephone, which enables us easily to speak to someone else who is also connected to the same system.

Before telephony was developed, messages were transmitted electrically over long distances by telegraphy—a signalling system using a well-known code of signals to denote letters of the alphabet, punctuation marks, numbers, etc. Earlier still, signals were sent by visual methods : semaphore or lamp signalling.

In its infancy radio communication was realised to be the only method of passing messages to ships at sea, and for ships to send distress signals in emergency, and the rapid development of the art at the beginning of the present century was no doubt due to this fact.

The Thermionic Valve

Until the " wireless valve " was developed, radio communication was carried out by telegraphy. The thermionic valve enabled telephony to be transmitted by wireless, and in 1922 the first regular radio transmission of entertainment in England was sent out from London.

The Radio Receiver

To return to our domestic receiver, there are several features common to all radio sets used for receiving programmes sent out for our entertainment.

In the first place, they all have some means of choosing which programme they reproduce. There is usually a dial, marked with a number of names of " stations ", and with a series of numbers called " wavelengths ". Often there are two, three or even more series of numbers, and associated station names. Turning a knob moves a pointer over this dial, and some, or all, of the marked stations can be heard. If some stations cannot be received, we are told that they are too weak, or too far away, or that the aerial is not good enough.

The aerial is the second thing which all receivers have. Some sets have a " mains aerial ", a " frame aerial " or a " self-contained aerial ". We also learn that the aerial " picks up the station ". Before finding out just what the aerial " picks up ", let us note two other common features.

One is that our receiver reproduces the programme through a " loudspeaker ", and the reproduced sound is fairly life-like.

The other important point is that our set needs electrical power to make it work. It has either to be connected to the electricity supply or we have to use batteries, which must be renewed or re-charged periodically.

Wireless Waves

We have reverted to the old term, wireless, for a moment, because it seems more appropriate here.

When we are listening to a programme, it is sent out by a transmitting station, and picked up by our receiver, which contains what is necessary to reproduce the programme. Later on we shall find out what goes on inside our receiver, but we are now going to see how the programme comes to us.

When we use a telephone there is a metallic electrical circuit over which our messages are carried between us and the speaker at the other end. When we listen to a radio programme, it is carried by wireless waves, which take the place of the electrical circuit which is part of the telephone system.

Wireless waves are of the same nature as light waves, and travel through the same medium. They are known as " electromagnetic " waves and are thought to travel through the æther, a medium which is imagined to fill all space and matter.

Wavelength

Our receiver dial is marked in wavelengths, so we must see what connexion this term has with our transmission.

When we drop a stone into a pool of still water, the surface is covered with ripples which spread outwards from the point where the stone entered the water. The stone forced upwards the water round it, and then sucked the water down after it as it sank. The surface of the water was made uneven by this occurrence, and Fig. II.1 shows a section through this pool of water. The distance between the crests of two adjacent waves is called a wavelength, and so, for that matter, is the distance between any two similar, adjacent points.

Our diagram of water waves can teach us more about wave-motion. Just before the stone enters the water there are no waves on its surface. A second later there is a ring of waves. Another second later, the circle is twice as large and so on. In other words, the waves travel across the water surface at a definite speed. This speed is called the " Velocity of Propagation " (Fig. II.2).

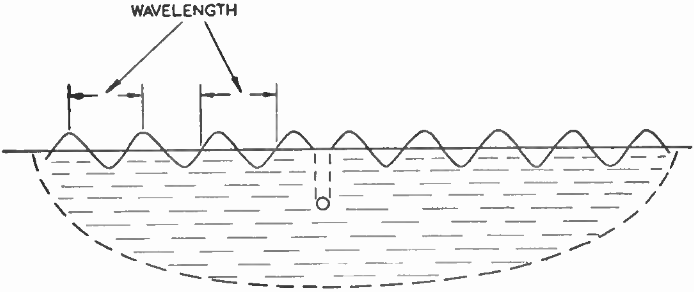


Fig. II.1.—Illustrating Wavelength

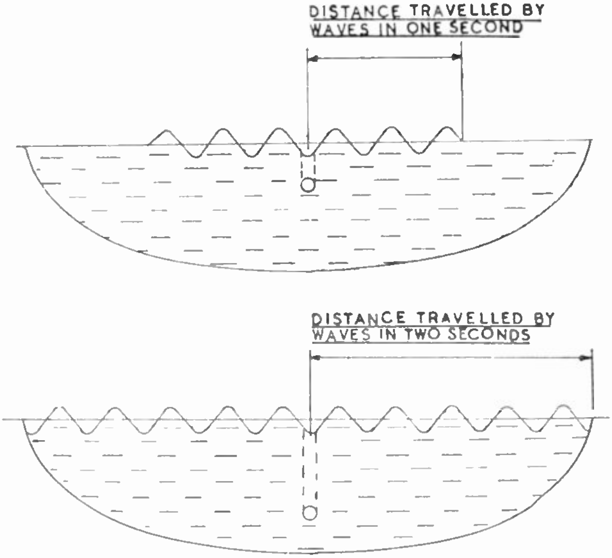


Fig. II.2.—Velocity of Propagation

Suppose that we look at a particular point on the surface of the water—marked perhaps by a feather. We shall see that, although the waves spread outwards, this feather remains in the same vertical plane and simply moves up and down as the waves pass it. If we count the number of up-and-down movements of the feather in a second, we shall find out the number of waves passing that point every second, and that is known as the " frequency " of the waves. Frequency is expressed as so many " cycles " per second, in the same manner as the frequency of alternating current which we described in Chapter 1.

There is a connexion between wavelength, velocity and frequency which is true for all kinds of waves. Suppose that N waves (that is N crests, or N troughs) pass our point every second,

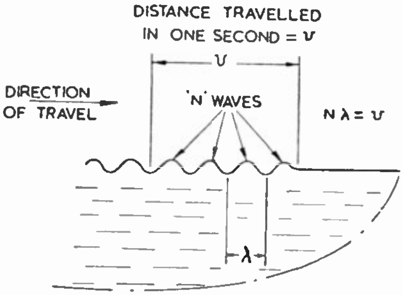


FIG. II.3.—Concerning Wave-motion

then the frequency is N cycles per second. The distance between crests is the wavelength, and we denote that by the Greek letter λ (lambda) to avoid confusion with l for length or distance. If the velocity of propagation is v, in the same units of length as λ, one crest travels through a distance v in one second. Therefore the number of crests included in this distance pass any one point in a second. But we have already seen that this number is N; if we multiply N by λ we have the distance v, or $v = N\lambda$, provided that the units are correctly chosen (Fig. II.3). This is a very important equation.

Velocity of Wireless Waves

Our wireless waves, as we have already said, are of the same nature as light waves and travel at the same speed. This speed is approximately equal to 186,000 miles per second, or, in the metric system, about 300,000,000 metres per second. The wavelengths on our receiver dials are in metres because the metric system is fundamental in electrical and physical work.

There is a frequency corresponding to every wavelength, and one can be found from the other by our equation $v = N\lambda$. v is

300,000,000 metres per second, so with λ in metres and N in cycles per second

$$N\lambda = 300{,}000{,}000$$

or

$$N = \frac{300{,}000{,}000}{\lambda \text{ (metres)}} \text{ cycles per second.}$$

We find it useful to avoid some of these 0's and we often talk of kilocycles per second—kc/s (thousands of cycles per second) or of megacycles per second—Mc/s, which are millions of cycles per second, so that

$$N(\text{kc/s}) = \frac{300{,}000}{\lambda \text{ (metres)}}$$

and

$$N(\text{Mc/s}) = \frac{300}{\lambda \text{ (metres)}}.$$

The Electro-magnetic Spectrum

Fig. II.4 illustrates how wireless waves fit in with light waves,

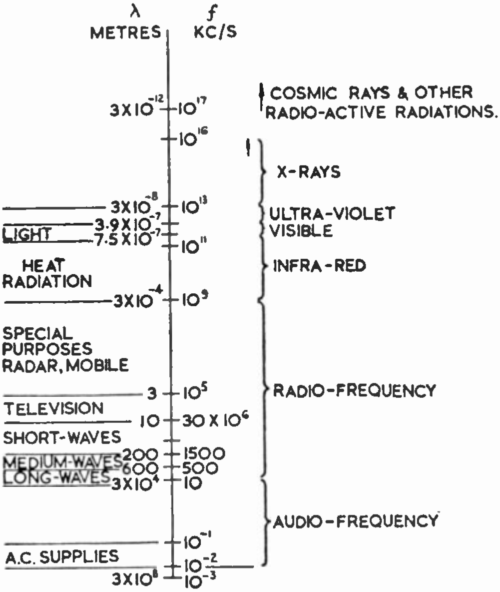


FIG. II.4.—The Electro-magnetic Spectrum

X-rays and so on. Wireless waves have a wavelength between 30,000 metres (about 19 miles) and 0·03 cm. Very short waves of the order of centimetres and less are difficult to produce, and are used only for special purposes.

Wavelengths for Broadcasting

Stations used for " local " broadcasting, that is up to about 50 miles, operate between 200 and 600 metres, and their exact wavelengths are allotted by international agreement. These wavelengths were found to give reliable, strong reception within a distance of about 50 miles.

For longer distances, up to several hundred miles, wavelengths between 900 and 2,000 metres are used on the European continent. Droitwich, on 1,500 metres, is well received over most of Great Britain.

When it is required to transmit over great distances—thousands of miles—the short wavelengths are employed. Since wireless waves have similar properties to light waves and travel in straight lines, they can only be sent over great distances by reflecting them just as light waves are reflected by mirrors.

Reflecting Layers

High above the earth's surface—60 to 100 miles up—there are two principal layers of electrified air which act as reflectors to wireless waves of high frequency, or short wavelength.

The wavelengths used for long-distance transmission are between 13 and 60 metres; waves of length less than about 10 metres are not reflected, but pass through these layers.

Radio Transmission

Wireless waves are " launched off " from an aerial system, which consists of an electrical conductor suitably arranged. Plate I shows the aerial systems at Droitwich, the Midland transmitter of the B.B.C.

The aerial system is connected to one terminal of a source of alternating p.d. having a frequency corresponding to the wavelength being transmitted, as determined by the equation we developed on page 29, while the other terminal of the source is connected to the earth. The alternating supply is generated in electrical circuits incorporating thermionic valves, and the frequency is determined by the components in the circuits.

As the potential of the aerial conductors is raised with respect to earth, so an electric field of increasing intensity forms between the aerial and the neighbouring surface of the earth. This field spreads outwards with the speed of light (300,000,000 metres per second) the intensity decreasing rapidly as the distance from the aerial increases. After the aerial potential passes its maximum value, and decreases, the electric field also diminishes in intensity, and shrinks back on to the aerial, again at the speed of light.

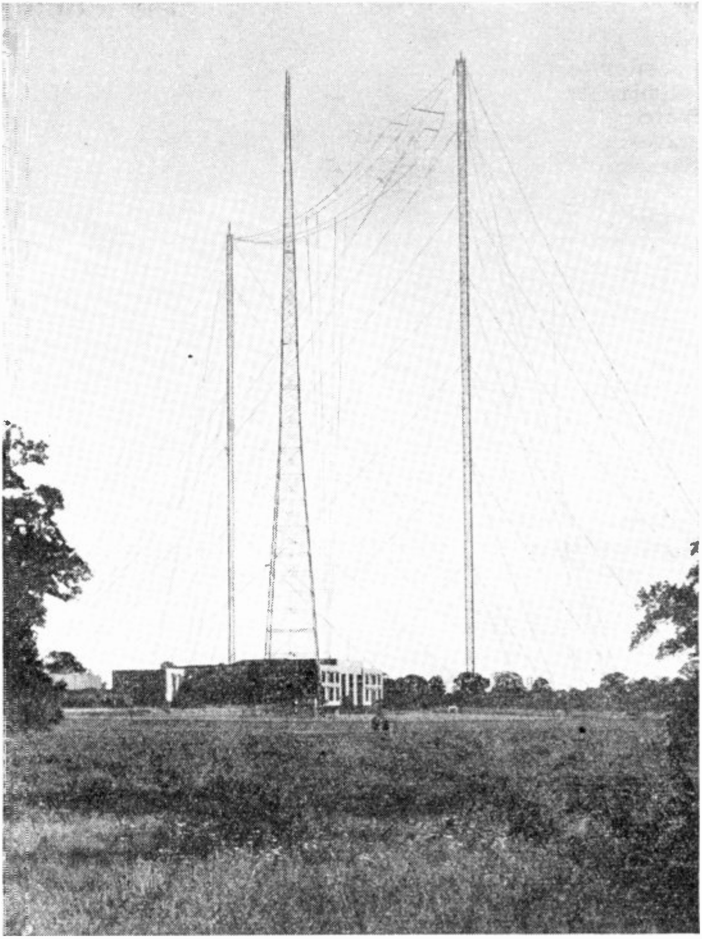


PLATE I.—B.B.C. Transmitting Station—Droitwich

Foreground : A " mast radiator ", 350 ft. high.
Background : Wire aerials supported by 700 ft. masts.

See also p. 43 *et seq.*

The aerial potential passes through zero with respect to the surrounding earth, and then increases in the opposite direction, setting up an electric field in the opposite direction. Owing to the rapidity with which these changes of potential and field strength occur, the electric field which had travelled farthest during the previous half-cycle of aerial potential does not all have time to return to the aerial before a new field of opposite polarity is set up, which forces it away again. A portion of the field is detached from the aerial system each half-cycle, provided that the system is large enough and that the frequency of the applied p.d. is high enough.

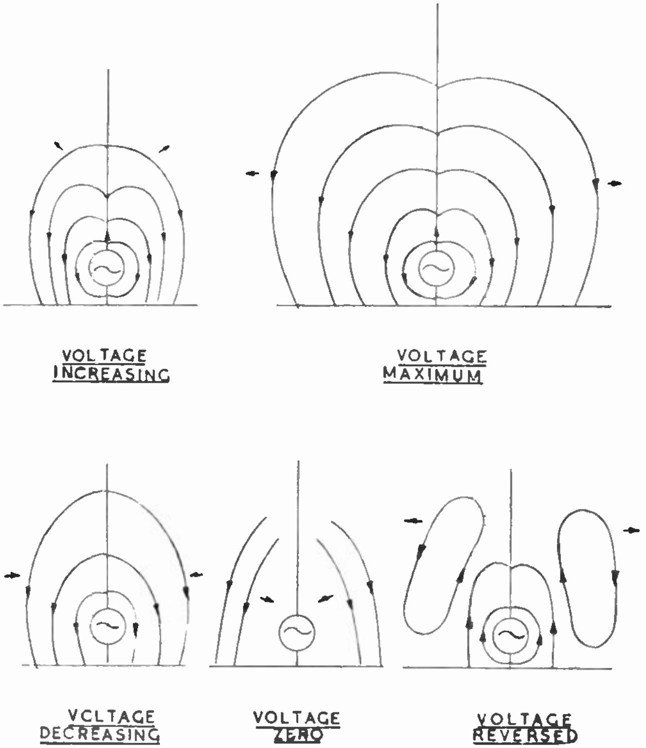


FIG. II.5.—Transmission of an Electro-magnetic Wave

The aerial system has a considerable capacitance to earth, and so takes a current from the source of potential. In flowing in the aerial conductors, this current sets up a magnetic field surrounding the aerial, part of which becomes detached, in the same way as the electric field. The radiation of an electric field is therefore accompanied by a magnetic field, and the two are inseparable, travelling together through the æther with the speed of light. They will cause an e.m.f. to be induced in any conductors which intercept them.

The launching-off of an electro-magnetic wave, as such a radiation is called, is illustrated in Fig. II.5.

The most general method of transmitting telephony (speech or music) is by varying the amplitude of the alternating supply in accordance with the signals corresponding to the sounds being transmitted, using microphones which produce varying p.d.s when sound waves fall on them. These p.d.s are increased in amplitude by thermionic-valve amplifiers, and are then used to control the alternating supply to the aerial.

Telegraphy is transmitted by switching the transmitter on and off according to the code being used.

Radio Reception

The aerial which is necessary at the receiver end is the means of collecting the transmitted signals and applying them to the circuits of the receiver.

The dial on the receiver is coupled to a component in the receiver circuit which enables us to select the frequency of the transmission we wish to receive, and it is marked in wavelengths, because the public in Great Britain is more accustomed to talking in terms of wavelengths than of frequency.

In the remaining chapters of this book we shall be learning in more detail about the circuits and components inside the receiver.

CHAPTER 3

AERIALS AND TUNING

CHAPTER 2 introduced us to the means of transmitting electromagnetic waves of a frequency determined at the transmitter, and we shall now study the aerial in more detail and discuss the method of selecting the station to which we listen at the receiving end.

A transmitter aerial radiates a wave, which consists of electric and magnetic fields of varying intensity, and if a conductor is placed in these fields, an e.m.f. will be induced into it due to the motion of the fields. Such a conductor becomes a receiving aerial. Owing to the innumerable magnetic fields of varying magnitudes present in the æther, a great number of e.m.f.s will be induced across the ends of any aerial.

In order to receive the radiated signals then, it is necessary to use an aerial, which at the moment we will consider simply as a conductor.

Tuning

A general requirement is for the receiver to select a band of frequencies corresponding to the signal from the " wanted " station, and to reject all the unwanted signals also brought in by the aerial. Tuning is the means employed to select the wanted signal, and generally (though not always) takes place in the receiver immediately following the aerial.

Having established the need for tuning, let us examine the properties of suitable circuits, and then return to the aerial itself.

Resonance—Series and Parallel

Consider an alternating p.d. V at a frequency f c/s applied to a capacitor C farads. If I is the current through the capacitor, then the current will be $I = V \times 2\pi fC$; the circuit is shown in Fig. III.1(*a*) and the vector diagram in Fig. III.1(*b*). Now let us replace C by an inductor L. Fig. III.2 shows the circuit and vector diagrams.

Let us assume that the capacitor is perfect and dissipates no energy, but that the inductor does introduce a power loss which may be represented by a resistance R. The product of R with the square of the current flowing through the circuit gives the power dissipation of the inductor, and R is known as the " effective resistance " at the frequency concerned (Fig. III.3); this resistance is found to increase with frequency due to greater losses. The effective resistance may be several times greater than the resistance measured at low frequency or with direct current. The reactance of the inductor $X_L = \omega L$ is proportional to frequency, and the ratio $\frac{\omega L}{R}$ is a useful " yardstick " for inductors. This ratio is a measure of the " goodness " of an inductor, and is given the symbol Q. The " power factor " of an inductor is

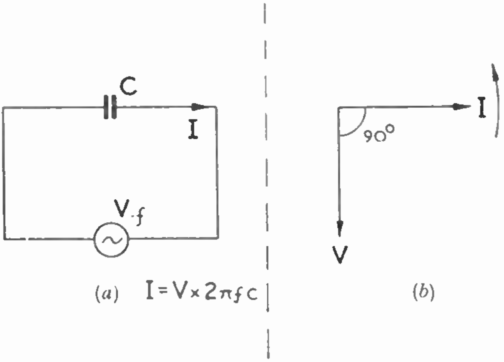


FIG. III.1(*a*).—Alternating p.d. Applied to a Capacitor; (*b*) the Vector Diagram

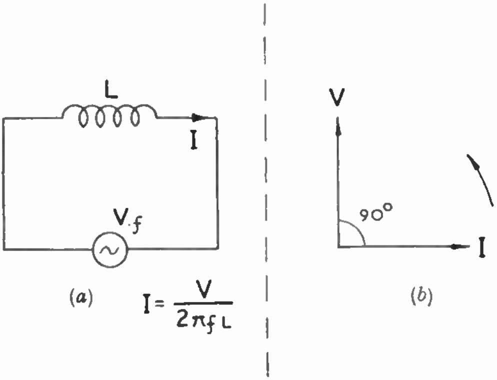


FIG. III.2(*a*).—Alternating p.d. Applied to an Inductor; (*b*) the Vector Diagram defined as the ratio of the effective resistance (R) to the impedance $\sqrt{(R^2 + X_L^2)}$, but in practice R is small compared with X_L, so that the angle ϕ in Fig. III.3 is very nearly 90°, and the power factor is given by $\frac{R}{\omega L}$, which is the reciprocal of Q. It is usual to use the symbol " $\cos \phi$ " when referring to the power factor of a circuit. Since both ωL and R are measured in ohms, Q is a numerical ratio. It is desirable to keep R as low as possible so that a high value of Q is obtained. Notice that the p.d. across the resistance, V_R, is in phase with the current I and that this current is now lagging on the p.d. across the coil V_L not by 90°, but by some angle less than 90°, the magnitude of which is determined by the loss in the inductor. Let us now combine

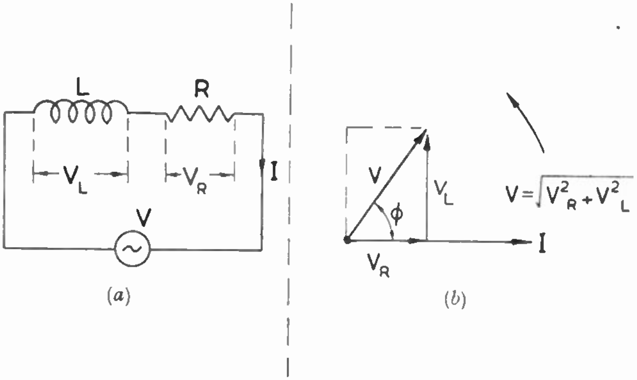


FIG. III.3(*a*).—Practical Inductor; (*b*) Vector Diagram

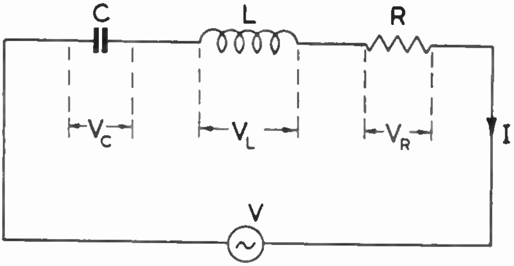


FIG. III.4.—Series Resonant Circuit

the circuits shown in Figs. III.1 and III.3 and connect them as shown in Fig. III.4.

Series Resonance

The reactance of a capacitor of C farads is given by $\frac{1}{\omega C}$, and that of an inductor of L henrys by ωL, where $\omega = 2\pi \times$ frequency, so that there is a value of ω at which the two reactances are equal to each other. By definition, when a circuit containing capacitance C farads and inductance L henrys in series has zero reactance the circuit is said to be in resonance.

This occurs when

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

or

$$4\pi^2 f_r^2 LC = 1$$

$$\therefore \quad f_r = \frac{1}{2\pi\sqrt{LC}}$$

where L is in henrys and C is in farads.

Now in Fig. III.5, $V_C = V_L$, *i.e.*, $X_C = X_L$ and $\Sigma X = 0$.

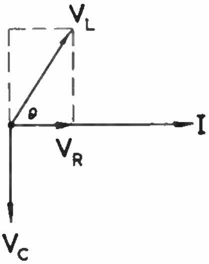


FIG. III.5.—Vector Diagram for Series Resonant Circuit

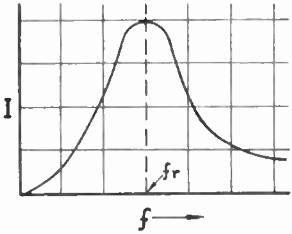


FIG. III.6.—Current in Series Resonant Circuit

The impedance of the circuit is now simply R ohms and is a pure resistance. For any given values of L and C the resultant reactance will be zero only at one frequency.

The current I through the circuit is given by $\frac{V}{Z}$ (Z = impedance of the circuit) and at resonance $I = \frac{V}{R}$.

Consider the value of I if there were no loss in L; at resonance, Z would be zero and $I = \frac{V}{0}$, which is obviously very large. At resonance the circulating current I is a maximum and the p.d.s V_L and V_C are much larger than the applied p.d. V as the vector diagram shows. The ratio Q is also equal to the magnification of a resonant circuit containing a perfect capacitor, and if V is the p.d. applied to the circuit the p.d. appearing across the inductor L or the capacitor is given by $V_L = V_C = Q.V$. A method of finding Q is thus given by $Q = \frac{V_L}{V}$ or $Q = \frac{V_C}{V}$ at resonance. Fig. III.6 shows the current I in a series resonant circuit plotted against a base of frequency. Notice that the maximum value of I is at f_r, the resonant frequency of the circuit and that the curve is roughly symmetrical about this point.

Selectivity

The selectivity of a resonant circuit is defined as the ratio of the current at the resonant frequency to the current at frequencies off resonance (see Fig. III.7). Now the value of I at resonance we have already found to depend on the value of R and the applied p.d., and since R is contained only in the inductor, the ratio $\frac{\omega L}{R}$ or Q is a measure of the selectivity of a circuit. This is very important in radio work, where it is desired, as we have already seen earlier in the chapter, to receive a signal of one frequency and reject others. Notice the difference in current value, of d_1 between the resonant point of the high Q circuits and points f_1 and f_2, and the corresponding change d_2 in the circuit having a low Q.

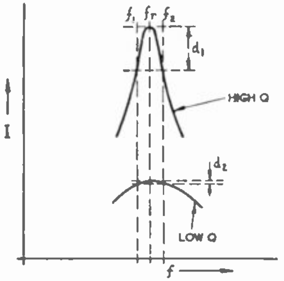


FIG. III 7.—Illustrating Selectivity

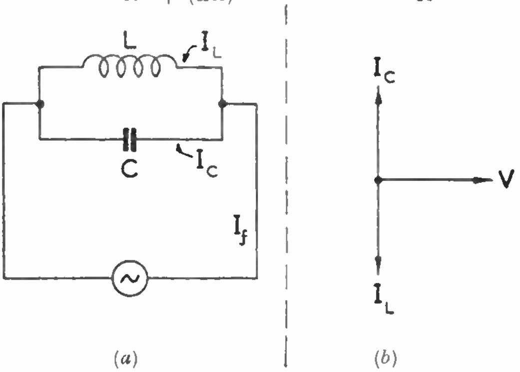
This shows that for a small deviation of frequency (from f_r) the change of I depends on the Q of the circuit.

Parallel Resonance

Consider now a perfect inductor L in parallel with a perfect capacitor C, Fig. III.8(*a*). If a p.d. V is applied to the arrangement, the current I_L through the coil will lag, and the current I_C through the capacitor will lead the applied p.d. (Fig. III.8(*b*)). Let $X_C = X_L$, then the two currents I_C and I_L will be equal in magnitude but 180° out of phase with each other. The current drawn from the supply (which is known as the "feed current"), I_f, is the vector sum of I_C and I_L, and in this case it will be zero, so that the impedance will be infinitely great.

As mentioned before, there must be a power loss associated with inductance, and Fig. III.9 shows a more practical arrangement with the loss of the inductor included. Fig. III.10 shows the vector diagram for this circuit.

$$I_L = \frac{V}{R^2 + (\omega L)^2} \quad \text{and} \quad \tan\phi = \frac{\omega L}{R}.$$



(*a*) (*b*)

FIG. III.8.—Parallel Resonant Circuit and Vector Diagram

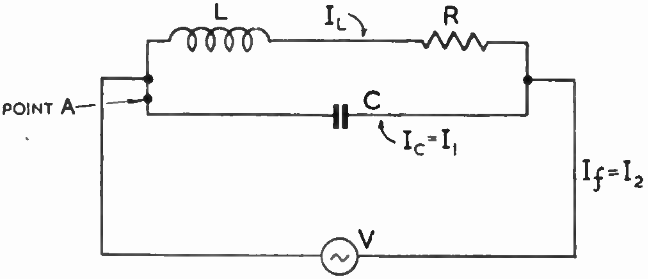


FIG. III.9.—Practical Parallel Resonant Circuit

In Fig. III.10 the triangles *OAB*, *CDO* are similar, and

$$\frac{I_1}{I_2} = \tan\phi, \text{ or } I_2 = \frac{I_1}{\tan\phi} = I_1\frac{R}{\omega L}.$$

Now

$$I_1 = I_C$$

$$\therefore \quad I_2 = I_C\frac{R}{\omega L}$$

$$= V\omega C\frac{R}{\omega L} = I$$

$$\therefore \quad \frac{V}{I_f} = \frac{V\omega L}{V\omega CR} = \frac{L}{CR} \text{ at resonance.}$$

This quantity $\frac{L}{CR}$ is known as the "dynamic resistance" of the circuit, and may be represented by a pure resistance, very different in value from the effective resistance of the inductor.

The vector diagram shows that the vectorial sum of I_L and I_C is in phase with the applied p.d. V.

An important point is that change of effective value of L, C or R with frequency will cause a change of dynamic resistance.

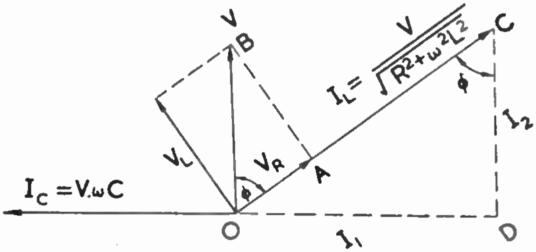


FIG. III.10.—Vector Diagram for Parallel Resonant Circuit

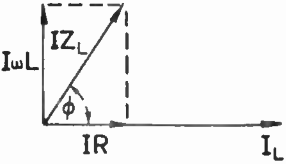


FIG. III.11.—Impedance Vector for Fig. III.9

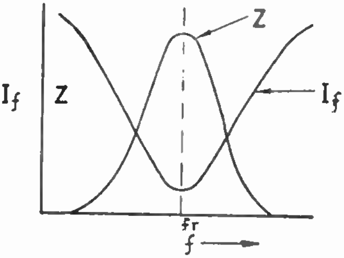


FIG. III.12.—Characteristics of Parallel Resonant Circuit

Consider the circuit of Fig. III.9, broken at the point A. The Q of the series circuit so formed by L, R and C in series is $\frac{\omega L}{R}$ or $\frac{1}{\omega CR}$, so that, at the frequency given by $\omega L = \frac{1}{\omega C}$ (that is $f = \frac{1}{2\pi\sqrt{LC}}$ and for most practical purposes known as the parallel resonant frequency) $\frac{L}{CR} = \frac{\omega L}{\omega CR} = Q\omega L$ or $\frac{Q}{\omega C}$. Fig. III.11 shows the vector diagram for the inductive arm of Fig. III.9; $Z_L = \sqrt{R^2 + \omega^2L^2}$ and $\sin \phi = \frac{\omega L}{\sqrt{R^2 + \omega^2L^2}}$ which is the same as in Fig. III.10.

Now $Z_L = \sqrt{R^2 + \omega^2 L^2}$ and $\sin\phi = \dfrac{\omega L}{\sqrt{R^2 + \omega^2 L^2}}$ as in Fig. III.10.

If R is zero then $\sin\phi = \dfrac{\omega L}{\omega L} = 1$, therefore $\phi = 90°$.

Circulating Current

In practice R can be made very small compared with ωL, and it can be shown that the magnitude of this resistance controls the value of the circulating current thus :

$$V \,.\, \omega C = I_C$$

but

$$\frac{V}{I_f} = \frac{L}{CR} \qquad \therefore \quad V = \frac{LI}{CR}$$

$$\therefore \quad I_C = \frac{L}{CR} \,.\, I_f \,.\, \omega C$$

$$= \frac{\omega L}{R} \,.\, I_f = Q \,.\, I_f.$$

and similarly $I_L = QI_f$. Therefore a parallel tuned circuit at (or near) resonance has large circulating currents, a high dynamic resistance and a comparatively low feed current. Typical curves of feed current I_f and impedance Z to a base of frequency for a parallel tuned circuit are shown in Fig. III.12.

Adjustment of Resonant Frequency

From the equation we have developed $\left(f_r = \dfrac{1}{2\pi\sqrt{LC}}\right)$ we see that a variation of L and/or C will cause a change of resonant frequency both in series and parallel resonant circuits. From a consideration of the condition for resonance, $f_r = \dfrac{1}{2\pi\sqrt{LC}}$, an increase in L or C (or both) will result in a lowering of the resonant frequency and vice versa. Further, it is desirable (in most radio work) that any change of f_r should be smooth and produced by changing as few components as possible.

Now it is more convenient to manufacture variable capacitors than variable inductors, and modern practice is to have a fixed inductance and variable capacitance. It is usual to arrange to change the inductance in steps by switching a new value into circuit when changing from, say, one range of frequencies covered by the full variation of the capacitance to another, and using the same variable capacitor for all bands.

Aerials—Equivalent Circuit and Natural Frequency

Previously we have been speaking of " frequency ", but it is more usual and convenient in the study of aerials to work in terms of wavelengths measured in metres. The relationship between frequency f and wavelength λ is simply, $\lambda \text{ (metres)} = \frac{3 \times 10^5}{f}$, where f is in kilocycles per second. Any straight conductor possesses inductance distributed along its length, and self-capacitance. A vertical conductor of height h, inductance L and capacitance C may be considered as a parallel tuned circuit (Fig. III.13).

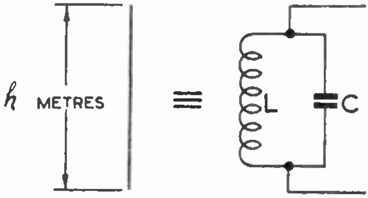


FIG. III.13.—Equivalent Parallel Circuit for Aerial

Clearly the resonant frequency of this arrangment is dependent upon the value of h and is termed the " Natural Frequency " of the aerial. L is very small, and for resonance at the desired frequency to be obtained inductance is often placed in series with the aerial as shown in Fig. III.14. The physical height of the aerial has not been altered, but by the addition of a " lumped-inductance " L_L the electrical length may have been very considerably altered, depending on the value of L_L. In Fig. III.14 the inductance L_A is that due to the aerial only, and it is in series with the added inductance L_L.

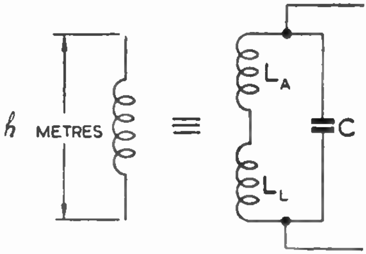


FIG. III.14.—Equivalent Parallel Circuit of Loaded Aerial

A convenient formula for calculating the wavelength of such an arrangement is derived from

$$f = \frac{1}{2\pi\sqrt{LC}} \quad \text{and} \quad \lambda = \frac{3 \times 10^5}{f} \quad \text{and is}$$

$$\lambda \text{ (metres)} = 1885\sqrt{LC}$$

where L is in microhenrys and C is in microfarads. Remember that in the above formula $L = L_A + L_L$ and that for Medium and Long Wavelengths L_A is very small compared with L_L. For Short Wavelengths L_L is not generally employed, as L_A becomes large enough to resonate at the required frequency. It is usual to tune only transmitting aerials.

Radiation Resistance

The total power radiated from an aerial of height $2h$ is given by

$$P_r = \frac{320\pi^2 h^2 I^2}{\lambda^2} \text{ watts}$$

where h and λ are in the same units and I is the r.m.s. value of the current in amperes. Let us assume for the moment that the current distribution in the aerial is uniform; the power radiated is proportional to I^2. Therefore $\frac{(320\pi^2 h^2)}{\lambda^2}$ represents a fictitious resistance which when multiplied by I^2 gives the radiated power. This is known as the "Radiation Resistance" (R_r).

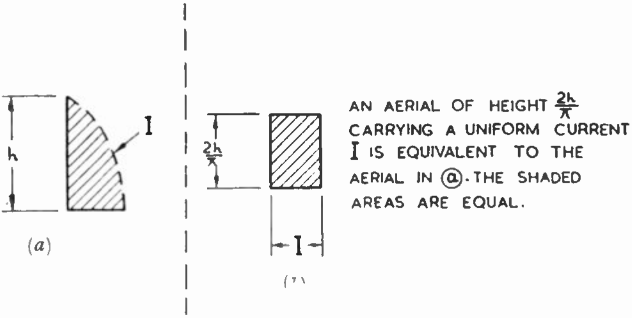


FIG. III.15.—Effective Height of Aeria

We assumed that the current distribution in the aerial was uniform, but this is not true, and the distribution is as given in Fig. III.15(a). It can be shown that the mean value of the current is equivalent to that given in Fig. III.15(b).

This uneven distribution of current has the effect of reducing the power radiated, and so for the same value of I, the aerial height is effectively reduced. Referring back to our formula for radiation resistance, the value of h should be the effective height (h_e) or "radiation height" as it is sometimes called.

The Hertz Half-wavelength Dipole and Marconi Quarter-wavelength Aerial

Clearly it is possible to express the physical height or length of an aerial in terms of wavelength. There are two very important cases which we have to consider where the physical dimensions are equal to a half-wavelength and a quarter-wavelength. The radiation resistance for all half-wavelength aerials in free space is given by $R = \frac{320\pi^2 h_e^2}{\lambda^2}$ but this formula is for an aerial of height $2h$. Then for a $\frac{\lambda}{2}$ aerial $\lambda = 4h$ and $h_e = \frac{2h}{\pi}$ and, substituting in the above formula, we have $R_r = \frac{320\pi^2 \frac{4h^2}{\pi^2}}{16h^2} = 80$ ohms. (Fig. III.16).

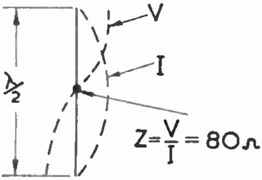


FIG. III.16.—Centre-fed Half-wave Dipole

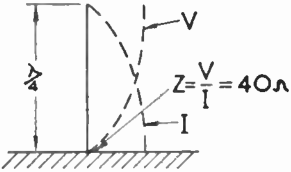


FIG. III.17.—End-fed Quarter-wave Aerial

Since the current I is a maximum at the centre point of the aerial, then the impedance Z given by $\frac{V}{I}$ is a minimum at this point. This impedance increases to some thousands of ohms at the ends of the aerial.

Fig. III.17 shows a Marconi quarter-wavelength aerial. If it is assumed that the earth is a perfect conductor and therefore absorbs no energy, the Marconi quarter-wavelength aerial may be considered as a half-wavelength dipole cut centrally. With the assumption made above for the half-wavelength aerial the radiation resistance of a Marconi quarter-wavelength aerial is 40 ohms.

Unlike the half-wavelength aerial, the ratio $\frac{V}{I}$ is least at the lower end of the aerial, and increases towards the upper end.

Basically a transmitting aerial consists of a straight vertical conductor into which is fed the signal to be radiated. The radiation of an electro-magnetic wave by such a conductor was dealt with in Chapter 2, and this principle is not affected by the form of the transmitting aerial.

Receiving Aerials and Field Strength

The travelling electro-magnetic wave comprises magnetic and electric components, and if a suitably placed conductor intercepts the magnetic component at right angles, an e.m.f. will be induced in it. If the e.m.f. induced in an aerial having an effective length of one metre is found to be one volt, then the " field strength " at that point is said to be " one volt per metre ". The field strength necessary for the successful operation of receivers in the Medium Wave band depends on the field strengths of transmitters on nearby frequencies and on the amount of interference set up by electrical apparatus. A minimum value for entertainment is probably 10–50 μV per metre in rural areas, and values of ten to one hundred times this may be needed in industrial areas.

E.m.f. Induced into an Aerial by an Electro-magnetic Wave

Provided that the wavelength is large compared with the dimensions of the aerial, then the induced e.m.f. is given simply by :

$$E = e \, . \, h_e \text{ volts}$$

where e is the field strength in volts per metre and h_e is the effective height of the aerial in metres.

Methods of Coupling

Clearly the best type of coupling is one that will produce the maximum transfer of energy from one circuit to the next, whether it be from aerial to receiver input, transmitter output to aerial or between intermediate circuits. This occurs when the impedance of the two circuits is made equal. We have already seen that an aerial is equivalent to a parallel tuned circuit, and therefore the p.d. across it will be dependent (amongst other things) upon the Q of this equivalent circuit. Due to the inherent resistance in an aerial its Q is low, and for this reason the tuning is " flat ". This means that if an aerial were connected directly to a receiver the resultant selectivity of the arrangement would not be very good. It is mainly for this reason that aerial coupling is employed. By a suitable coupling the Q, and hence the selectivity of the circuit, may be greatly improved.

Typical examples of coupling by " mutual inductance " are shown in Figs. III.18 and III.19.

In Fig. III.18 the aerial is connected in series with an inductor L_1 having mutual inductance with another coil L_2. The capacitor C_1 and inductor L_2 form the first tuned circuit of the receiver, and C_1 is adjusted so that C_1 and L_2 resonate at the frequency of the wanted signal. If one tuned circuit does not provide sufficient selectivity, more may be added (Fig. III.19). The aerial itself may be tuned by adding inductance or capacitance. Although additional tuned circuits increase the selectivity, the operation of adjusting the resonant frequency of all of them is made more difficult, and losses are increased.

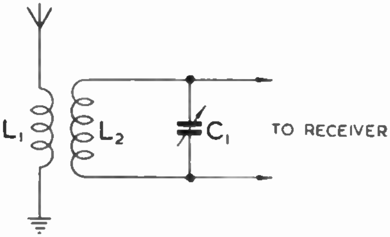


FIG. III.18.—Inductively Coupled Input Circuit

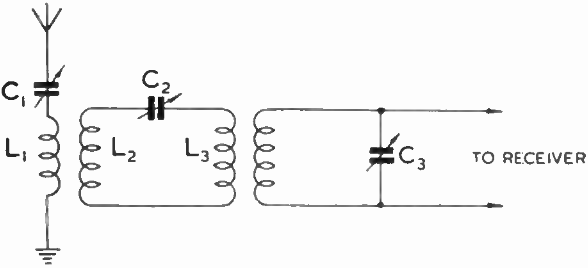


FIG. III.19.—Aerial Input with Two Tuned Circuits

Due to the advantages of making the tuning as independent of the aerial characteristics as possible, it is unusual to employ aerial tuning on commercial broadcast receivers.

Coupling Factor

In resonant circuits coupled by mutual inductance, the amount of coupling, k, has a considerable effect (Fig. III.20).

If this value of k is high, then the coupling is said to be " tight " and gives rise to a " double-humped " effect, having two peaks f_1 and f_2 which are displaced equally above and below the resonant frequency f_r. If the value of k is low, then the coupling is said to be " loose " and the circuit is very selective but transfer of energy is less at resonance (and of course at other frequencies as well).

A value of *k* between these two extremes may be obtained, which is referred to as " critical coupling ", and circuits are usually adjusted to this condition. A band of frequencies around the wanted signal is then passed while other frequencies are rejected strongly.

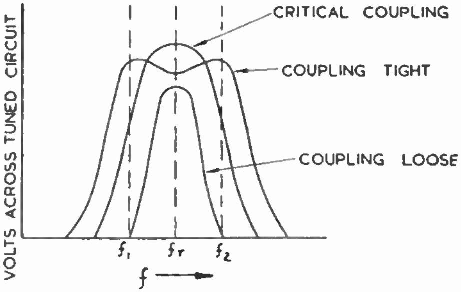


FIG. III.20.—Effect of Amount of Coupling

Practical Notes on Transmitting Aerials

In order to radiate a good proportion of the power fed to it, an aerial should theoretically be half a wavelength or a quarter of a wavelength long. If the aerial is made half a wavelength long, it is fed at the centre, and usually consists of an arrangement of conductors supported by steel towers or masts suitably insulated. It is possible to use this construction only for short-wave aerials, as it is not practicable to build structures of the necessary height when the wavelength becomes considerable. Apart from considerations of mechanical strength and of cost, the danger to aircraft must also be remembered.

In practice the effective height of an aerial is modified by the proximity of the earth and other conductors, and corresponding corrections have to be made. For medium and long wavelengths the aerial is made as near a half- or quarter-wavelength as is practicable and then tuned to series resonance by means of added reactance.

A medium- or long-wavelength aerial consists of a vertical steel mast insulated at the foot and supported by insulated guy wires. It may be provided with either an " umbrella " or horizontal top which lowers the impedance of the aerial, increases the current and therefore the power radiated (proportional to the square of the current).

CHAPTER 4

COMPONENTS AND VALVES

THE range of values of the various types of components used in radio equipment is extremely wide, and the construction of the article depends on its value and the purpose for which it is used.

Resistors

Values of resistance from a few ohms to several million ohms are used, and they fall into two main classifications.

(1) *Wire-Wound Resistors*

For applications where constancy of value or high power dissipation is required, wire-wound resistors are generally used, and they are made in values from about 1 ohm up to about 100,000 ohms.

Smaller values are difficult to adjust because of the effect of the resistance of the leads, and resistors of larger value have to be wound with very thin wire if their size is not to be excessive. Resistors for high power ratings are wound on ceramic (porcelain) formers with a wire of nickel–chrome or a similar alloy. This material is satisfactory at high temperatures, and has a reasonably high resistivity, and so keeps down the bulk of the component. In many cases the resistor is coated with vitreous enamel so that the safe temperature is raised even higher, to as much as 400° C., without danger of the wire oxidising, which would change its effective diameter and resistance.

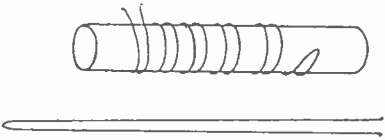


FIG. IV.1.—Bifilar Winding for Resistors

All wire-wound resistors are in the form of a coil, and therefore possess inductance, which makes them unsuitable for use at high frequencies. This disadvantage can be overcome to a certain extent by " low inductance winding ", one method being known as " Bifilar " winding, in which the wire is first doubled and then wound on the former (Fig. IV.1). Thus the two halves of the coil are carrying currents which flow in opposite directions, and, as they are close together, their external magnetic field is small, and therefore the inductance will also be small.

(2) *Composition Types*

This class of resistor is very cheap to produce in large numbers, and is generally used where the power rating and the stability required permit. There is the additional advantage that the inductance is very small, and for high-frequency work this type is almost essential.

The method of manufacture again depends on the desired accuracy of the component, and for the general-purpose range of composition resistors the following method of manufacture is employed :

A suitable " mix ", consisting of powdered carbon, a filling material and a binder to give it the correct consistency, is extruded, cut into short lengths and then fired at a high temperature. In some types wires are then firmly wound round the ends of the resistors, and the whole is coated with moisture-proof varnish and subsequently colour coded to indicate its value. If the resistor is of the insulated variety, the extruded rod has end caps, incorporating the leads, pressed on and is inserted into a ceramic tube. The resistor is then waxed or varnished, and coded as before (Plate II).

When the circuit demands higher stability of value than can be obtained by the above method, a thin carbon layer is deposited on a smooth ceramic rod by a special technique. The process varies among manufacturers, but in general consists of breaking down a material such as benzene into carbon, which settles on the rod much as a piece of glass becomes covered with soot when held in a candle flame. The conditions are carefully controlled, and the layer is finally baked to give it permanence.

As it is difficult to produce high resistance values directly, together with great enough stability, a method known as " spiralising " is adopted to increase the resistance. After baking, a helical groove is ground in the rod using specially shaped grinding-wheels. Thus the length of the resistance path is increased and the resistance raised to the required value. The end caps and leads are then attached, and the resistor is given a coat of moisture-proof varnish on which the resistance value and tolerance are marked.

Variable Resistors

These are commonly known as " rheostats ", " potentiometers " or " volume controls ". The name " rheostat " is more correctly applied to series resistors in high power circuits, while the name " potentiometer " refers to an accurately calibrated resistor with a known tapping point. They operate by mechanically varying the length of resistance element between two contacts, one fixed and the other movable.

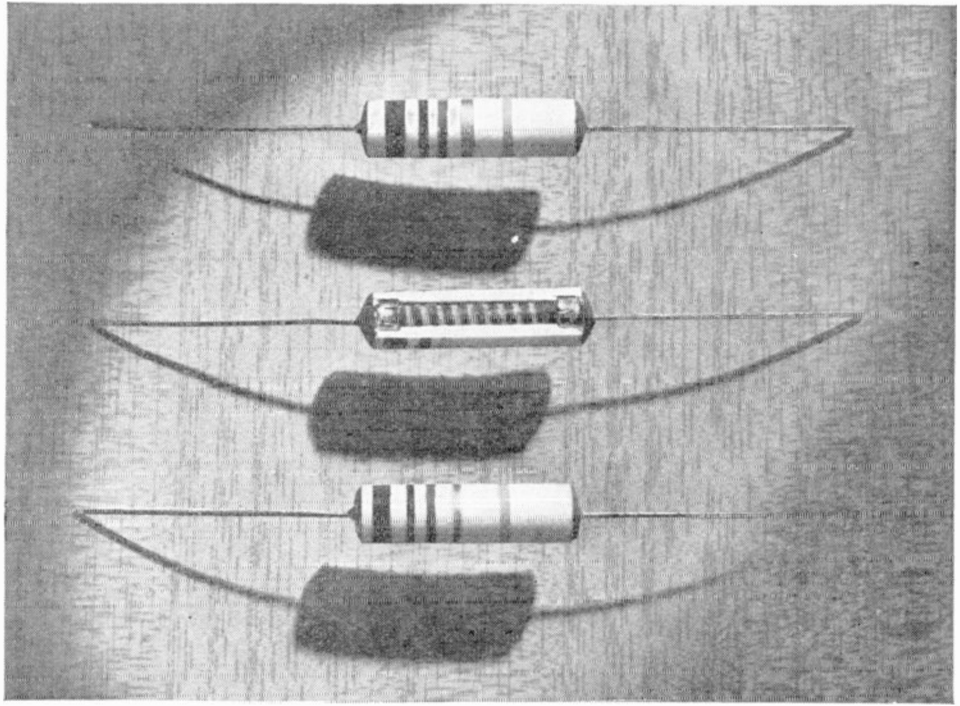


PLATE II.—Insulated Composition Resistors

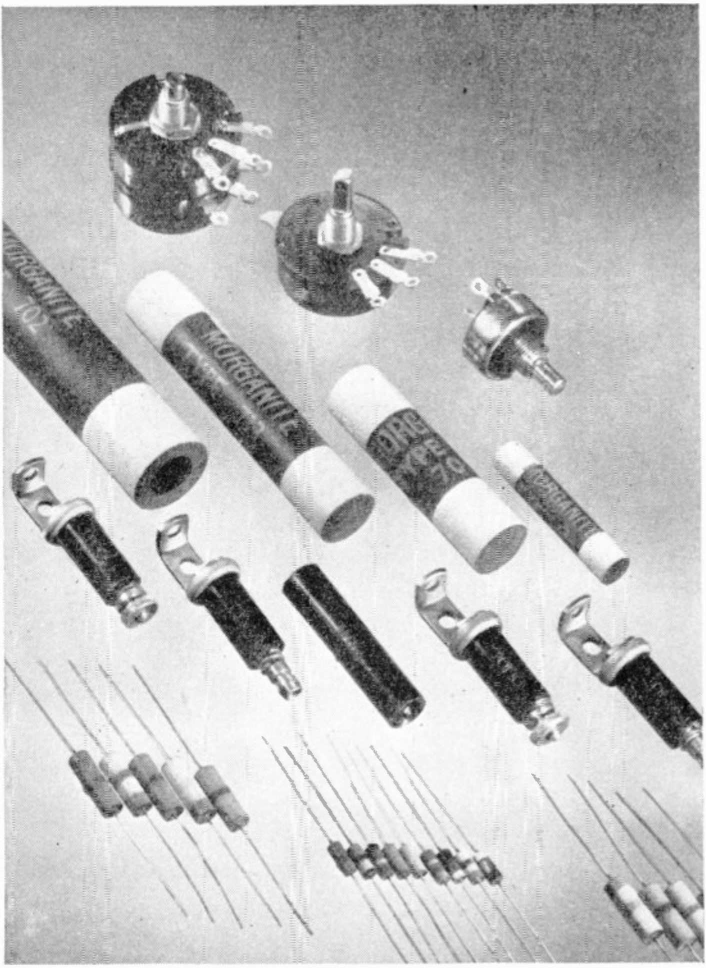


PLATE III.—Carbon Resistors

Top : Variable resistors
Second row : High-power carbon resistors
Third row : Resistors for interference suppression on cars
Bottom row : Insulated composition types

High-power wire-wound types have their elements wound on a cylindrical ceramic or vitreous-enamelled metal tube. The moving contact consists of a carbon or laminated metal brush carried on a metal bar which forms one connexion, the other being made to one end of the element. The moving contact has an insulated finger-grip, and a protecting cover is sometimes provided.

For general use a rotary control is desirable, and in this case, the element is "toroidally" wound on a ceramic ring or, for the lower powers, on an insulating strip which is then bent into a circle. The element is fixed in a body carrying the spindle, on which is an insulating piece holding the moving contact. Connexion is made to the moving contact via a fixed metal ring on which one end bears. The larger components of this type are unprotected or are fitted with a perforated metal case, while the smaller ones are enclosed in a moulding.

Carbon variable resistors are made in great numbers, and consist of an insulating base on which is sprayed or moulded a carbon track. The moving contact is supported from the spindle by an insulating block, and external connexion is made via a metal ring, while metal inserts connect to the track at its ends. The whole is fitted in a metal or moulded case. (Plate IV.)

A table of types of resistors is given at the end of the chapter.

Capacitors

Basically any capacitor consists of two conducting surfaces separated by an insulator (the dielectric), and the capacitance depends on the area of the plates, the distance between them and the type of dielectric.

The principal types of capacitor are as follows; they are classified by their dielectrics and method of manufacture:

1. Rolled paper.
2. Stacked mica.
3. Silvered mica.
4. Silvered ceramic.
5. Electrolytic capacitors.

A short table is given on page 80 showing the application of various types of capacitors. (Plate V.)

Paper Dielectric Capacitors

Completely dry paper is a useful insulator, it has a high dielectric strength (*i.e.*, it will withstand a comparatively high p.d. without breaking down), and the losses in it are not excessive except at high frequencies. Its disadvantage is that it readily absorbs moisture, and in order to take advantage of the low cost and ready availability of this material in capacitor manufacture suitable impregnating substances must be used.

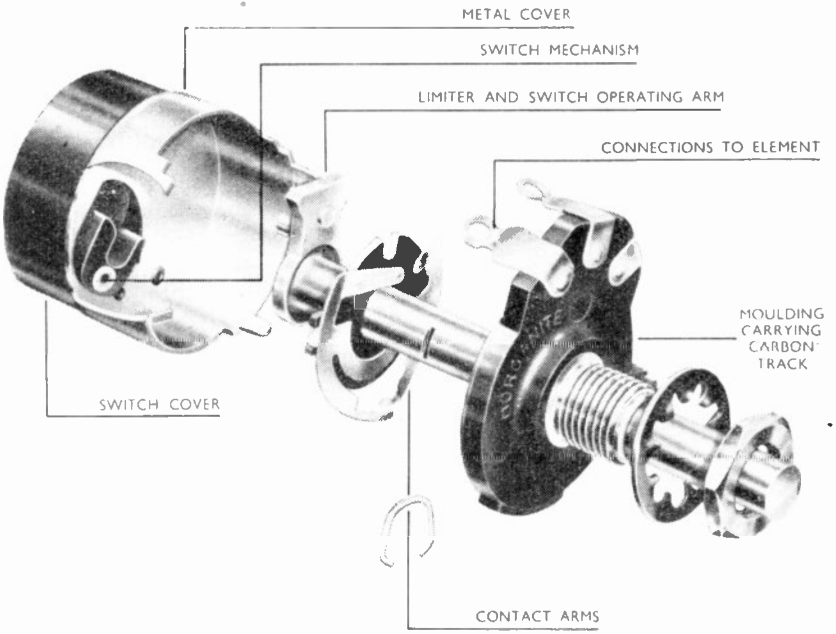


PLATE IV.—The Construction of a Carbon Variable Resistor

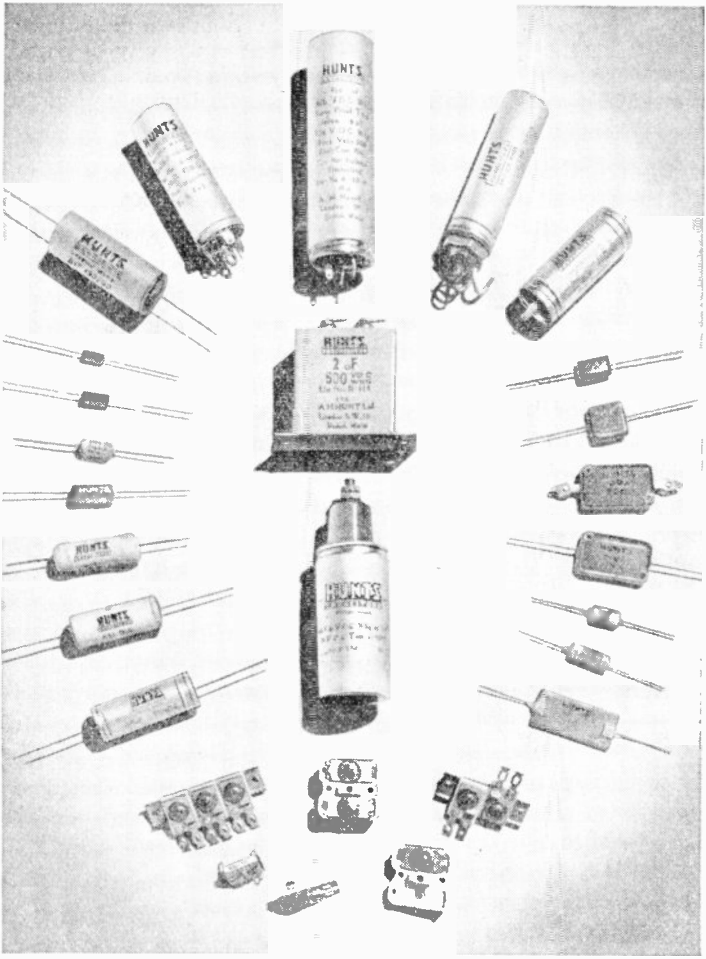


PLATE V.—Fixed Capacitors

Top five : Electrolytic
Centre two : Paper, in cans
Left-hand seven : Paper, tubular
Right-hand seven : Mica, moulded and waxed types
Lower six : Compression trimmers

Paper capacitors are made as follows :

Long strips of metal, usually aluminium about two-thousandths of an inch thick, are sandwiched between two layers of paper, the thickness of which governs the working p.d. Two such sandwiches are then placed together and rolled up very tightly, thus packing into quite a small space a capacitor which would be very bulky. If connexion to the aluminium foils were made at one end only, the capacitor as so made would have considerable inductance, and in order to reduce this effect, each strip of aluminium has a number of tags. The strips are so arranged that the tags project on opposite sides, then when the capacitor is rolled, all those tags on one side are joined together to form one connexion and those on the opposite side form the other.

After the connexions have been made, the capacitor is inserted in a container of some kind; a waxed-cardboard case for normal use, a metal can if the capacitor is physically large or a plastic case for special conditions. Impregnation with wax or bitumen to prevent ingress of moisture then follows to complete the manufacture.

For higher p.d.s it is usual to place the rolled-paper capacitor into a large metal can filled with oil, specially treated to free it from corrosive chemicals. Connexions are brought out through insulating bushes, and the can is then hermetically sealed, space being left to allow for expansion of the oil if the temperature changes.

Stacked-mica Capacitors

Mica is one of the best dielectrics; it has a high breakdown p.d. and causes very little loss. Its use is therefore essential in cases where high-frequency currents are flowing and the losses in the circuit must be low. The earliest form of mica capacitor was of the stacked type, in which layers of metal foil are interleaved with sheets of mica, and alternate foils are connected together. Leads are then attached to opposite ends, and the whole is enclosed in a case, usually of moulded plastic. The disadvantage of this type is that it is not very stable.

Silvered-mica Capacitors

In order to overcome the disadvantage of the stacked-mica type, a process was devised in which silver is deposited by chemical means, directly on to the mica sheets. In addition to reducing the size for a given capacitance, this method has the advantage that the metal, being very thin and strongly attached to the mica surface, is constrained to expand and contract with it. In this way buckling of the foil is eliminated. To obtain the required capacitance, several of these plated-mica sheets may be connected together in parallel, and the finished product is consolidated by applying a layer of insulating varnish or a wax coating.

Silvered-ceramic Capacitors

A further development in capacitor manufacture is the use of ceramic insulation as the dielectric. The advantage of this material is that its dielectric constant is high, so that a large capacitance may be obtained in a relatively small space, but it suffers from the disadvantage of having higher losses than mica.

A later development of this type is known as " high *K* " ceramic, which has extremely high dielectric constants of the order of 2,000 or 3,000. This makes possible very small capacitors of high value, and in cases where size must be reduced to the minimum this type is used in spite of the higher losses in the component.

The method of construction is similar to that of silvered-mica capacitors, with the difference that the ceramic insulation may be made in the form of tubes as well as plates.

Electrolytic Capacitors

For the very high capacitances needed in power-supply circuits electrolytic capacitors are generally used. They have higher losses than paper capacitors and a maximum working p.d. of the order of 600 volts. However, their cheapness and small size have made their use in such positions practically universal, and a good modern electrolytic capacitor is unequalled for the task it has to perform, when size is taken into consideration.

The principle of operation is as follows :

When an electric current is passed through a solution of ammonium borate or sodium phosphate using aluminium electrodes, a layer of aluminium oxide forms at the positive electrode. This film is a partial insulator and is very thin so that the plates of the resulting capacitor are very close together. A very high capacitance may thus be obtained in a small component.

In this type the chemicals are in a liquid solution. These are known as " wet electrolytics ", and possess the advantage that the oxide layer will re-form after being broken down if an excessive p.d. is applied. However, their disadvantages, which are : (1) evaporation of the solution, (2) the necessity for mounting vertically, and (3) higher losses, have led almost entirely to the use of the so-called " dry type ". Both types are " polarised ", and are only suitable for use on direct supply, while they must also be connected up with the right polarity.

The method of manufacture of the dry type is not unlike that of paper capacitors, but the material dividing the two foil electrodes consists of paper impregnated with suitable chemicals.

As before, the long strips are rolled up very tightly and completely enclosed and sealed in a metal can. A direct p.d. is then applied to the terminals until the current through the " cell " falls to a suitably small value. The process is known as " forming " the capacitor, during which the layer of oxide is deposited at one electrode.

Variable Capacitors

Where it is necessary to alter the capacitance in a circuit, as, for example, in adjusting the resonant frequency of a tuned circuit, it is necessary to make a special component. Those which are intended for a continuous variation in order to control a circuit are called " variable capacitors ", whereas those intended to be set up as an adjustment and then locked are called " pre-set " or " semi-variable ". The difference is emphasised, as although the two classes merge imperceptibly into one another, there are essential differences of manufacture. In the first place, where a component is to be continually adjusted, the bearings and the method of connexion to a moving part are of paramount importance; but for pre-sets or " trimmers " the primary requirement is stability once the required setting has been determined.

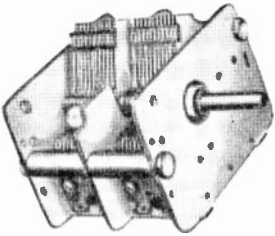


Plate VI.—A Two-gang Variable Capacitor

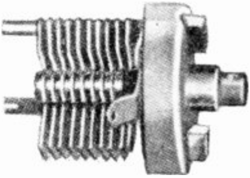


Plate VII.—An Air Trimmer

Variable capacitors are made with up to four units mounted in one frame, all controlled by one spindle. When there is more than one unit, the component is known as a " ganged " capacitor.

Most variable capacitors are of the rotating-vane type, in which a set of moving plates and a set of fixed plates are brought in or out of mesh by the rotation of a spindle. The construction of a typical capacitor is shown in Plate VI. The fixed vanes are attached by ceramic insulation to the main body or chassis of the capacitor. This usually takes the form of two end plates fixed together with metal rods. The end plates also carry the bearings for the spindle on which the moving plates are mounted, and although there is metallic contact between the end plates and the spindle, it is usual to provide some form of spring-contact leaf in order to minimise electrical noise.

If the capacitor is part of a tuned circuit and is being used to control the frequency of resonance, it is often useful to calibrate the dial of the capacitor in frequency or wavelength. It is then necessary to have a particular law connecting the resonant frequency and the angular position of the capacitor, so that a particular vane shape will be required in order to follow accurately the required law.

To reduce the number of types of capacitor, manufacturers have now standardised one or two vane shapes, and mass production is thus simplified. This may cause some departure of the scale shapes from true linearity, but this is not of great importance where domestic radio receivers are concerned.

Some manufacturers adjust their capacitors to a given law before they are installed in the circuit, a process which is usually carried out by making one or two vanes so that they are easily bent to correct the errors caused by necessary manufacturing tolerances. The simplest way of obtaining this object is to slot the end vanes of the moving set, which are adjusted during test.

Although it is possible to use dielectrics other than air in variable capacitors, the associated problems are such that except for isolated instances their use has practically died out.

Compression Trimmers

In these a number of springy metal plates are interleaved with mica insulation, much as in the stacked-mica type of fixed capacitor. The spacing between the plates, however, is controlled by a screw which passes through and is insulated from the plates, being attached to the main body—usually a ceramic block. If this screw is tightened, pressure is increased and the plates brought closer together, thus increasing the capacitance. In some cases the spring pressure of the plate itself is sufficient to prevent the screw turning, but usually some form of sealing material, such as special wax or varnish, is applied after adjustment. (Plate V.)

Air Trimmers

In most cases this type is very similar to an ordinary variable capacitor except that the spindle is provided with a screw-driver slot. The variation of capacitance is much smaller than in an ordinary variable capacitor, and the setting can be locked either by mechanical means or by a sealing material. (Plate VII.)

Inductors (Coils, Chokes and Transformers)

Inductance is the property, possessed by an electric circuit, of opposing any change of the current through it. There are many different applications of this property, and it is the purpose of this section to deal with the manufacture of the various types of coils used in practical circuits.

The subdivisions of inductors may be classified as follows :

(1) Radio-frequency coils.
(2) Audio-frequency chokes.
(3) Audio-frequency transformers.
(4) Power chokes and transformers.

Radio-frequency Coils

Under this heading come coils of inductance from about 100 mH to 1 μH, and the methods of winding are as follows :

(*a*) Single-layer solenoids.
(*b*) Universal or wave-wound coils.

(a) *Single-layer Solenoids*

This method is used for the smallest inductance values, and the turns, usually of fairly thick wire, are wound either close or spaced apart (see Fig. IV.2). At high frequencies it is usual to use wire as thick as 16 or 18 gauge, when the coil can be made self-supporting. This method avoids the use of insulating material within the field of the coil, thus keeping losses to a minimum. The reason for the use of a thick wire is due to " skin effect ", which tends to make radio-frequency currents flow only in the outer skin of a conductor. Thus the conductivity of a wire at high frequencies depends on its surface area. This means that the inside of the wire is carrying very little current, and therefore tube can often be used to save weight. Another method of overcoming skin effect is mentioned in the next section.

FIG. IV.2.—Close-wound and Self-supporting Coils

(b) *Universal or Wave Winding*

Self-capacitance, that is the capacitance between the turns of a coil, is always present in any inductor, and must be kept to a minimum, or otherwise the component will resonate at a low frequency, and the range over which it will tune with a given variable capacitor will be smaller than is desirable. If a multi-layer coil is wound with its turns very close to one another, the potential difference between adjacent turns is large, resulting in a high self-capacitance. Various methods have been devised of spacing the turns in such a fashion that the self-capacitance is kept down. The most popular of these methods is known as "universal" or "wave" winding. The method is as follows:

A width of coil is fixed, and the wire is taken across this width one or more times for each revolution. The winding machine is so arranged that after one revolution the wire does not return exactly to its starting point, but advances slightly so that the next turn lies somewhat farther round the former, much as a ball of string is wound. This system produces a very compact and rigid coil, completely self-supporting, but at the same time there are relatively large air spaces and also the potential between adjacent turns is kept to a minimum. Practically all modern radio-frequency coils of more than a few μH inductance are wound in this manner. (Plate VIII.)

The universal winding technique makes it possible to wind a number of piles on a given former in order further to reduce the capacitance of a given winding, or to have several separate windings coupled to each other, thus producing a radio-frequency transformer.

At frequencies between about 20 kc/s and 2 or 3 Mc/s it has been found that the type of wire called "Litzendraht", or "Litz" for short, is very useful in keeping losses to a minimum. This wire is made up from a number of very thin strands insulated from each other and woven in such a way that each strand is near the surface of the composite wire for the same proportion of the total length. In this way the skin effect is reduced, because the currents flowing in the wires are more evenly spread over its cross-section. Its use is restricted to the frequency range mentioned, because it is very expensive to manufacture, and at lower frequencies the skin effect is not so serious as to justify its use, while at higher frequencies smaller inductances are in general needed, and it is therefore possible to get as good a performance as is obtained with Litz wire by using solid conductors of slightly larger total cross-section.

Radio-frequency Chokes

In this type of inductor it is desirable that the coil should have as high an impedance as possible to a wide band of frequencies. The losses are not so important as in tuning coils, but in order to keep the self-capacitance low two types of winding are used, one of which is the single-layer solenoid previously mentioned, but made very long and thin so that the capacitance is small. The second method is to use a number of wave-wound sections all connected in series and spaced by a distance roughly equal to the width of each coil. Of course, every coil may tune to a resonant frequency with its own self-capacitance, and care must be taken to see that it is used well below this frequency.

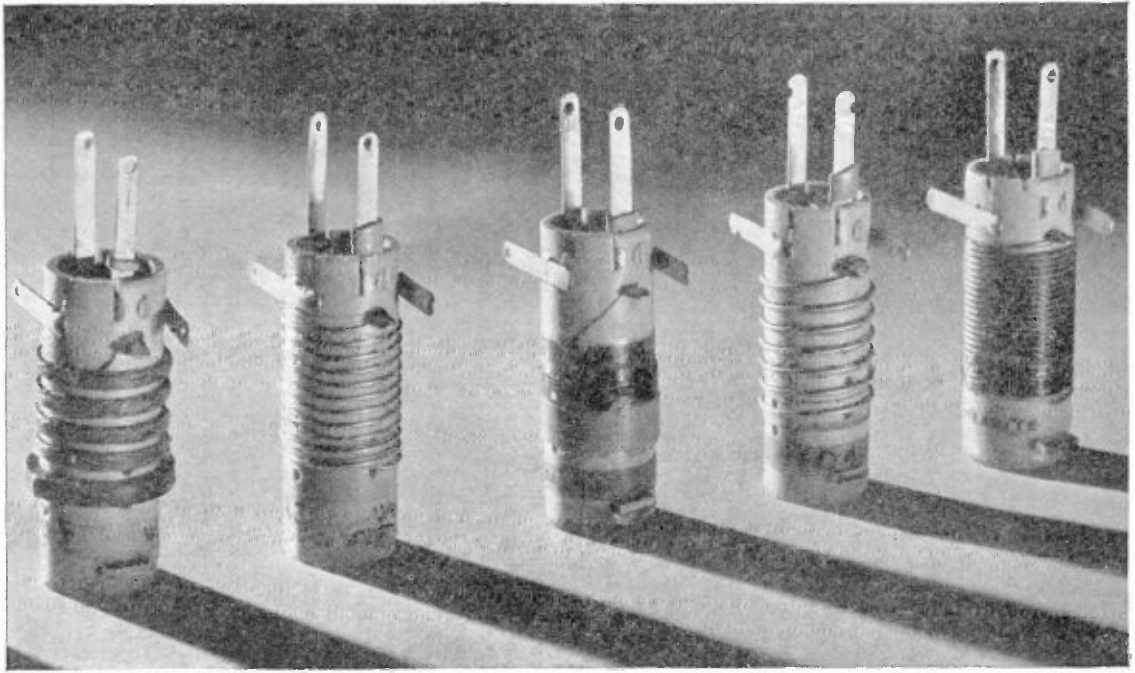


Plate VIII.—Wave-wound and Single-layer r.f. Coils

General Notes on Radio-frequency Coils

Enamel-covered copper wire is used for radio-frequency coils where possible, but owing to the thinness of the enamel and to the losses it causes, either double-silk-covered (DSC) or single silk and enamel (SS & E) wire is used for most purposes, as adjacent wires are then further spaced from each other and the self-capacitance tends to be lower. Another advantage of the fabric covering is that mechanical damage is less likely. As alternatives to silk, where economy is the prime consideration both cotton and an artificially produced material known as " regenerated cellulose " are also used, but these have not such good high-frequency properties.

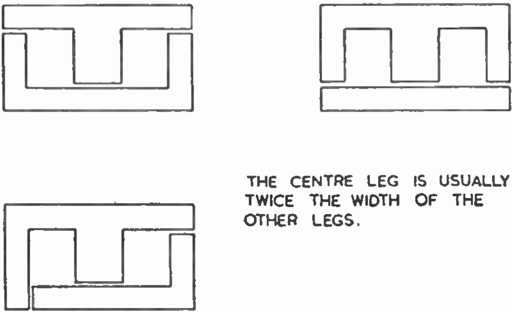
Most radio-frequency coils are now impregnated with special low-loss waxes which prevent atmospheric corrosion. The increased stability obtained by this method is considered to justify the slightly higher losses caused by the wax.

The use of a magnetic material to increase the field inside an inductor, and so to increase its inductance without increase of resistance, is essential at low frequencies, but at radio frequencies it is necessary to have the magnetic material in the form of very small particles. If the material were in the form of a solid block or a sheet, e.m.f.s would be induced in it which would cause currents to flow. These currents, flowing in the material, would cause power to be dissipated, which must be supplied from the circuit in which the coil is connected. The currents circulating in the core material are known as " eddy currents ", and it is always necessary to minimise them where changing magnetic fields occur.

Recently the development of magnetic cores for high-frequency circuits has advanced to such a point that moulded iron-dust cores have been used at frequencies up to 60 Mc/s. These cores are manufactured by suspending very thin particles of iron or iron alloy in an insulating material. The mixture is then pressed into the desired shape and fired at a high temperature to give it permanence. The higher the frequency at which it is desired to work the core, the smaller must the iron particles be, and thus the average permeability of the core will drop until at about 60 Mc/s the gain obtained by using them is becoming very small, so that above this point air-cored coils are usually used.

Audio-frequency Chokes and Transformers

The impedance offered by an inductance to a current of a given frequency is directly proportional to that frequency, and, in the audio range, the value of inductance necessary to work, for instance, as the anode load of a valve, is relatively high. For example, to obtain reasonable amplification from a valve, it is desirable to have an impedance greater than about 10,000 ohms. At 500 c/s this means that an inductance of over 3 henrys is required. Now the space taken up by an air-cored inductor of this value with a reasonable value of resistance is of the order of a 9-in. cube, and its use would be impossible in a radio receiver which has to fit into a box 12 × 10 × 9 in. However, it is possible to reduce the size by winding the coil on a core of a ferro-magnetic material. A table of some of these magnetic materials is given at the end of the chapter.



THE CENTRE LEG IS USUALLY TWICE THE WIDTH OF THE OTHER LEGS.

FIG. IV.3.—Typical Laminations

At audio frequencies the losses due to eddy currents can be made sufficiently small by making the core from a number of very thin sheets which are insulated from each other. These " laminations ", as they are called, are made in a number of standard shapes and sizes to facilitate choke and transformer design. Some of these shapes are shown in Fig. IV.3, and it is usual to wind the coil on the centre leg of a completely closed iron circuit.

Methods of Winding for Audio-frequency Chokes and Transformers

As in radio-frequency work, the self-capacitance of a winding is of great importance and must be kept as low as possible, but as so many turns of wire are needed to obtain the necessary inductance, the problem is much more difficult.

Simple Multi-layer Coils

In this case a bobbin is made up of insulating material, usually bakelised paper. This bobbin fits over the centre leg of the iron core as shown in Fig. IV.4. The wire is then wound layer by layer on the bobbin until the required number of turns have been put on. It is usual to insulate each layer with one or two thicknesses of thin paper to prevent the mechanical stress of winding from embedding one layer in another. If this happens, the insulation of the wire may be broken and cause contact between turns, which would make the component useless. When there is more than one winding to be put on the same bobbin, the first one is insulated by several layers of oiled paper or a thin insulating board; the second winding is then put over this insulation and completed in the same way (Fig. IV.4). The self-capacitance of these windings may be reduced by spacing the layers farther apart by using insulation having large air spaces. If the depth of the winding is very large compared with its width, the two ends of the coil tend to be separated from each other, which also helps to keep down the capacitance. For transformers in which the capacitance between windings as well as the self-capacitance of each winding must be kept small, the type of construction known as " sectionalised " winding is adopted. In this method instead of one simple bobbin being used, the " window space " of the core is filled with a number of bobbin sections (Fig. IV.5). Each winding or each part of a winding is wound in these sections so that deep, narrow coils are obtained. If the space between different windings is kept large, then the capacitance will be small. Most good coupling and output transformers are made in this way.

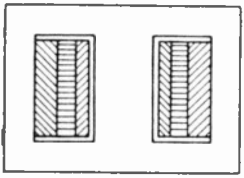


FIG. IV.4.—Layer-wound Transformer

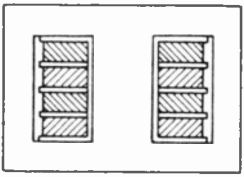


FIG. IV.5.—Sectionalised Transformer

Coils of this type are wound with enamel-insulated copper wire, as this insulation occupies the smallest space and is very reliable under working conditions. Its only disadvantage is that it is liable to mechanical injury, and careful handling is necessary, while the winding apparatus must be free from rough edges.

After the bobbin has been wound it is necessary to assemble the core by inserting the laminations, and if there is to be no direct flux in the core, the laminations are interleaved, *i.e.*, alternate pairs are inserted from opposite ends of the bobbin, giving the smallest possible air gap, and the result is shown in Fig. IV.6. However, if there is a flux due to a direct current the core is liable to become fully magnetised, and in order to prevent this the pairs of laminations are assembled as shown in Fig. IV.7, with a small air gap where they butt together. This prevents the flux from rising to too high a value, and the alternating-current characteristics are then more constant with variation of the direct current than if the core were interleaved. However, the average permeability is lowered when there is an air gap, and thus more turns are required for a given inductance.

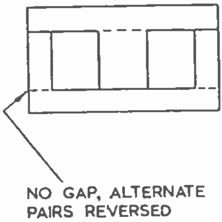


Fig. IV.6.—Interleaved Core

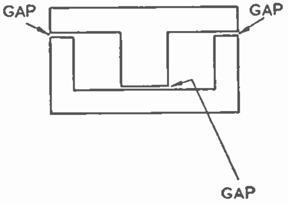


Fig. IV.7.—Gapped Core

As with other components, coils and transformers must be moisture-proof, and this is usually accomplished by impregnating with wax or a bituminous compound. A bakelite or other protective covering is often used to enclose a coil, thus preventing mechanical damage, if conditions warrant it. If it is required to screen the component from external fields or to prevent its own field affecting other parts of the circuit, it can be completely enclosed in a metal box which isolates it.

Mains Transformers and Low-frequency Chokes

Where equipment is to be driven from an alternating supply, a transformer between the supply and the equipment is useful in two respects. First, there is no direct connexion between the mains and the rest of the circuit, and, second, a wide range of e.m.f.s may be obtained with a very little loss of power. The first point is important both with respect to safety regulations, because one side of the output may be earthed, and also from the point of view of the circuit, in which it may be undesirable to have any part connected to the mains.

The construction of mains transformers in general is similar to that of audio-frequency transformers, with the difference that the power-handling capacity is an important consideration and the design must take into account factors such as permissible temperature rise and efficiency of operation. Here again, standard forms of laminations are the starting point of the design. Capacitance is not important in this case, so that the type of winding generally used is the simple multilayer coil, similar to that in the illustration in Fig. IV.4. Insulation, however, is vital in order that there shall be no direct connexion to the mains and also that such faults as shorted turns shall not occur. Mains transformers are therefore always wound with paper interleaved between each layer, of a thickness depending on the p.d. appearing between the layers, and separate windings are covered with adequate thicknesses of paper or board. The core is then inserted into the finished bobbin, and the interleaved arrangement is always employed.

The rectified output of a power supply has a ripple component, and for most circuits it is necessary to reduce this variation as much as possible. An essential part of the " filter circuit " which removes this ripple is a low-frequency choke, or smoothing choke, as it is usually called. The features of this component are that it must carry the full direct current and at the same time possess an inductance high enough to present a reasonable impedance at the ripple frequency. A simple multi-layer coil wound on a bobbin is used as before, and the core always has an air gap, as in the case of a transformer carrying direct current. Insulation between layers is not so important as for mains transformers, but is usually employed in order to prevent shorted turns.

Enamelled copper wire is mainly used in these chokes and transformers, but in some cases, especially for high-current filament windings, double-cotton-covered wire is used, because in the very thick gauges copper wire is difficult to bend, and therefore must be hand wound, which is safer with cotton- or silk-insulated wire than enamel. Impregnation is always employed to prevent corrosion, and is usually bitumen, which, although it has fairly high losses at the high frequencies, is quite satisfactory at supply frequency and is preferable because of its greater resistance to corrosion than that given by wax.

Methods of Connexion to Inductors

Radio-frequency Coils

The ends of the coil have to be anchored, and connexions must be made to them without imposing strain on thin wires, so that soldering tags or terminals are fixed in convenient positions on the body of the component and leads taken to the winding. Very thin wires are usually brought out with flexible leads, the joint being well insulated on the bobbin or former and anchored by an adhesive. It is only justifiable to use wire ends on large components which are separately mounted and the wires of which are thick enough to stand mechanical stress.

Litz wire must always be brought out to a tag, as it is essential that each strand is properly cleaned and tinned and that good connexion is made, as even if one strand is not connected some of its advantage will be lost.

Iron-cored Components

In order to bring out connexions, holes are necessary in the cheeks of the bobbin, and the wire of the coil is usually stout enough to be brought out. A board made of bakelised paper with tags or terminals is provided for the external connexions. Another method is to join a multi-strand flexible wire to the end of the coil and to take this flex to the circuit of which the component forms a part.

Where a winding is tapped at one or more points, several methods of making connexion are employed. A long loop of wire may be twisted to form a kind of flexible lead, while preserving the continuity of the winding, or each section may be treated as a separate coil and the leads joined externally. In both cases, however, the leads out must be insulated from the main body of the winding and allowance made for the disturbance of the smooth winding surface by additional insulation, which, although electrically unnecessary, must be used to prevent the possibility of mechanical damage by the pressure of succeeding layers.

Screening

In many cases, both at high and low frequencies, the field of an inductor may extend to other parts of a circuit, or it may itself be influenced by the proximity of other components. To reduce this interaction a ferro-magnetic sheet is placed between the two components concerned, or for convenience one or both of them may be enclosed in a box of ferro-magnetic material. The stray magnetic field then passes through this " screen " as it is called, thus screening the components from each other electromagnetically.

In a similar way electrostatic interaction can occur by coupling through the electric field. This form of coupling is minimised by interposing an earthed conductor between the components concerned, or by enclosing them in an earthed metal case.

Low-frequency components may also be shrouded in this fashion. There is, however, often considerable capacitance between two windings of a low-frequency transformer, and an additional electrostatic screen may be necessary. This consists of a turn of metal foil spaced between the two windings, and arranged so that the ends of this turn are insulated from each other, as otherwise there would be a complete turn of very little resistance. This would reduce the inductance of the windings so much that it would make the component of no use.

Valves

Radio as we know it has only become possible as a result of the development of the "Thermionic Valve". Its name is derived from the fact that it can only pass current in one direction, in a similar fashion to the valve on a motor-car tyre, which will permit air to pass into the tyre but not out of it. "Thermionic" is derived from two Greek words meaning "hot" and "wanderer", and indicates that the current-carrying medium, a stream of electrons, is produced by heat. Nowadays the term "ion" is used for charged atoms, and electrons are treated separately in view of their much smaller mass. However, strictly speaking, electrons may be classed as ions in that they are free charged particles.

At ordinary temperatures the electrons in a conductor are fairly free to move about inside it, and permit the ordinary phenomenon of the electric current. At low temperatures the electron is unable to escape into the space outside, as there exists an electrical barrier due to the attraction of the rest of the conductor to any electron attempting to leave the surface.

As the temperature is raised, the energy of the particles in a body increases, and eventually, when the conductor is hot enough, electrons possess sufficient energy to overcome the barrier and pass into the surrounding space in large numbers. If no external electric field is present, the electrons cannot move far from the conductor, as it becomes positively charged when they leave it, and thus attracts the electrons back again, forming a "space charge".

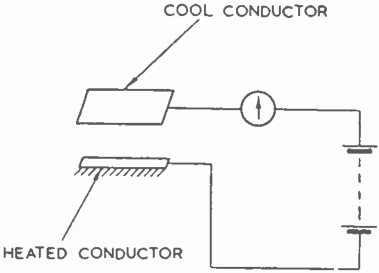


FIG. IV.8.—Thermionic Emission

If we now put another conductor near the first but do not heat it, and join them by a battery and galvanometer as shown in Fig. IV.8, we shall see that a small current flows if the positive terminal is joined to the unheated conductor. In air at ordinary pressures, however, the electrons are unable to pass across the gap very easily as they bump into the molecules of air. So both conductors, or "electrodes" as they are called, are put into an evacuated glass envelope, with leads coming out through air-tight seals. The electrons can then pass fairly easily across the space between the electrodes when a potential is applied in the right direction, but will be unable to cross when the unheated conductor is made negative, as this will then repel the electrons emitted from the heated electrode. The application of this principle to the detection of radio waves was first realised by J. A. Fleming in 1904.

This then is the primary function of a valve: to pass a current only when the unheated electrode (the anode) is positive with respect to the heated electrode (the cathode).

Types of Cathode

The simplest way to heat a wire inside an evacuated envelope is to pass a current through it, and the earliest cathodes were thin tungsten wire, through which a current was passed to raise its temperature to about 2,200° C. Pure tungsten cathodes are now used only in high-power transmitting valves, where a robust cathode is essential.

Thoriated Tungsten Cathode

If a tungsten wire is coated with thorium oxide and is subjected to a forming process, the oxide is broken down to pure thorium, which can emit electrons at a lower temperature than tungsten (about 1,700° C.), so that to obtain the same emission a lower heating current is necessary.

Oxide-coated Cathode

The carbonates of the alkaline-earth metals, strontium and barium, if coated on a suitable base, usually nickel, and suitably treated have the useful property of emitting electrons at a dull red heat (about 900° C.). The process consists in heating them in a vacuum to a bright-red heat and simultaneously applying an electric field. A chemical reaction takes place, and it appears that a very thin layer of barium metal is formed on the surface from which electrons are readily emitted.

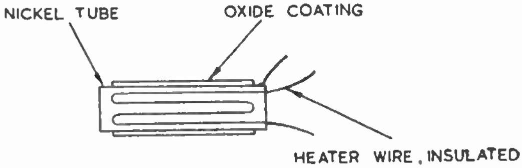


FIG. IV.9.—Indirectly Heated Cathode

With the two former types of emitting surface mentioned above (tungsten and thoriated tungsten) it is only possible to reach sufficiently high temperatures if the heating element forms part of the cathode. When the heater and the cathode are integral in this way the cathode is called " directly heated ". It is, however, possible to heat an oxide-coated cathode by a separate heating element which is insulated from it, owing to the fact that it works at such a low temperature. This is very convenient, as it enables the cathode to be at a potential different from that of the heater (Fig. IV.9).

Almost all receiving valves have cathodes of the oxide-coated variety, and for mains sets the indirectly heated type of cathode is used except for rectifiers, some of which may be directly heated. In battery sets where the heater power is low, the valves employed generally have directly heated cathodes.

Types of Seal

One type of lead-out for the connecting wires is called the " pinch " method, in which special alloy wires of the same coefficient of expansion as glass are threaded through a glass moulding. The glass is then raised to its softening point and squeezed round the wires so that an airtight seal is formed. When all the subsequent operations have been performed on the valve,

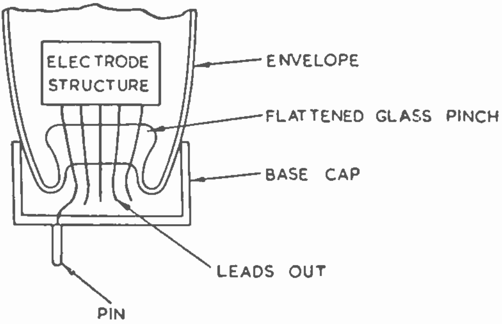


FIG. IV.10.—Pinch-type Valve Construction

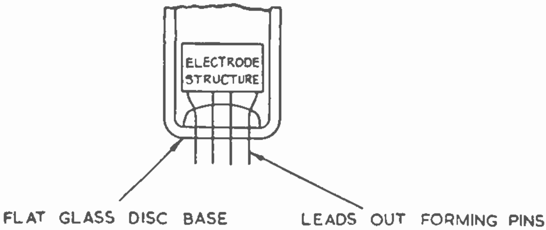


FIG. IV.11.—Glass-base Valve Construction the lead-out wires can be connected to a suitable base. The pinch method, however, has certain disadvantages, both at high potentials and high frequencies, due to the small space between the wires and the relatively large distance between the electrodes themselves and the base.

A type of construction is therefore becoming almost universal in which the base and lead-out seal are one and the same thing, and the special glass moulding needed for this process is made complete with pins before the valve proper is mounted on it. Pictures of both these types of base are shown in Figs. IV.10 and IV.11.

Valve Manufacture

Although there are so many different types of valves, the principles of their construction are all very similar, and depend on the following considerations :

(1) Insulation between electrodes must be very good.

(2) During manufacture very high temperatures are necessary in order completely to free the valve of gas which is trapped in the metal forming the electrodes.

(3) During the life of the valve it is undesirable that gas previously retained in the materials should find its way into the evacuated space.

To satisfy all these conditions we are limited to a very few materials. For the external envelope glass or quartz is almost universally used. For the mounting of the electrodes relative to each other mica, and, more recently, certain ceramics, are the only materials which possess the required insulating properties. The electrodes, other than the cathode, may be made of nickel, tungsten, molybdenum or, in some types, carbon.

Spot welding is the most popular method of joining metals inside the valve, as no corrosive or volatile materials are necessary.

When the electrode assembly, together with the mica insulators, has been mounted on the base of the valve, the envelope is sealed on, and the valve is evacuated from a small glass tube. In order to get rid of the last traces of gas, one or two further processes are necessary. First, the electrodes are heated by placing them in a magnetic field set up by a powerful high-frequency generator which causes eddy currents to flow in the metal electrodes. This drives off any gas that may have been present in the metals. The valve is then sealed by collapsing the evacuating tube. Small traces of gas, however, still remain, and these are removed or " cleaned up " by a second process known as " gettering ". Metals such as magnesium and barium combine with oxygen and other gases to form a non-gaseous compound, although the metal itself vaporises at a reasonably low temperature. In the electrode assembly a small pellet of such a metal is enclosed in a metal cup so as to preserve it while the valve is being pumped, and is attached to one of the lead wires or supports. This " getter ", as it is called, is then brought to a bright red heat by an eddy-current heating coil, and the metal evaporates into the surrounding space. It rapidly combines with the remaining traces of gas, and is deposited as a silvery film on the inside of the valve envelope.

Types of Valves

There are four basic types of thermionic valve which have particular characteristics, and it will usually be found that valves at first thought to be different are combinations of one or more of these four :

(*a*) Diode or two-electrode valve.
(*b*) Triode or three-electrode valve.
(*c*) Tetrode or four-electrode valve (often called the " Screen-grid valve ").
(*d*) Pentode or five-electrode valve.

Diodes

This is the simplest type of valve, and consists of a cathode and an anode. The cathode may be either directly or indirectly heated, the latter being essential for signal circuits, for which purpose also the dimensions are kept small. Power rectifiers are also diodes, with larger dimensions to dissipate a greater power and with greater spacing between electrodes to withstand the large p.d.s which are applied.

Triodes

These were the first development of the diode, and resulted from the discovery by Lee de Forrest in 1907 that the insertion of a gauze mesh or " grid " between the cathode and the anode made it possible to control the intensity of the electron stream flowing to the anode, by varying the potential of this grid.

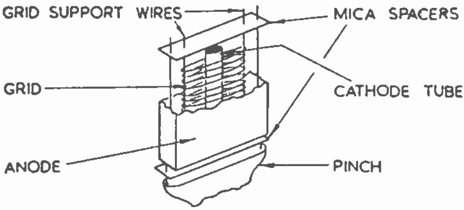


FIG. IV.12.—Construction of Triode Valve

In modern valves the grid consists of a helix of nickel wire

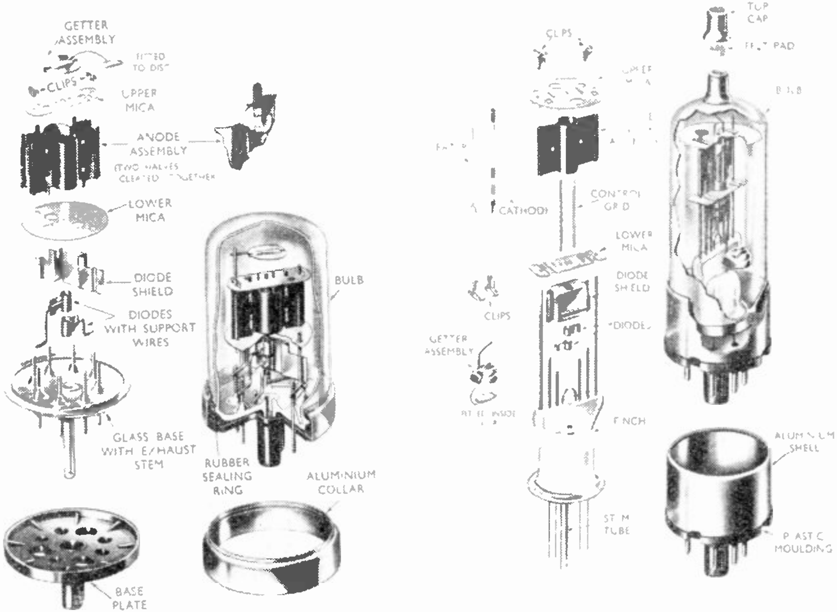


PLATE IX.—Glass Base and Pinch-type Construction of a Multiple Valve—Two Diodes and a Triode in One Envelope completely surrounding the cathode and supported by two nickel wires which are spot welded either to the lead-out wires in a pinch-type valve or direct to the pins in an all-glass type of valve. The anode is supported in a similar way (Fig. IV.12).

Tetrodes

A disadvantage of the triode valve is that the electrostatic capacitance between grid and anode is large, and this makes its operation difficult at radio frequency. This difficulty can be overcome to a large extent by the insertion of a further grid, called the " screen " grid, between the first or control grid and the anode. If this electrode is held at a fixed potential, it acts as an electrostatic screen, and so isolates the input circuit from the output circuit. This grid, too, is wound on nickel supporting wires, but its mesh is more open than that of the control grid. This is necessary as, being at a relatively high potential, it tends to attract the electrons which should go to the anode, so that if it is kept sufficiently open, the proportion of current that it takes is kept low. The anode in a tetrode valve usually consists of two small plates, one on either side of the grid, so that the screening effect of the second grid may be more nearly complete.

Pentodes

If the characteristics of a screen-grid valve are examined (see Fig. VI.7), it will be seen that at certain points the anode current tends to decrease as the anode potential is raised. This effect is due to what is called " secondary emission " from the anode. When electrons strike a surface at a sufficiently high velocity they tend to knock other electrons from this surface, and if there is a positive electrode near they will be attracted to it. In a screen-grid valve when the anode potential is sufficiently high for the arriving electrons to eject secondaries, these may be attracted by the positive screen grid away from the anode, causing the total anode current to drop. If, however, the anode potential is made still higher, the electrons will return to the anode and the current will rise again.

In order to overcome this kink in the screen-grid valve characteristics, a third grid may be inserted between the second grid and the anode and kept at a low potential, usually that of the cathode. Secondary electrons emitted from the anode are repelled by the third grid because it is negative with respect to their source and they cannot reach the screen grid, so that the kink in the curve is smoothed out. This third grid, called the " suppressor ", is also of a very open mesh, as its function again is not to collect electrons but to influence them by electrostatic action. A similar effect is also obtained by inserting a pair of plates, connected to the cathode, at the sides of the grid structure. The valve is then strictly a tetrode, although its characteristics resemble those of a pentode.

General Notes on Construction

Plate IX shows the details of two types of construction of an electrode assembly, and it will be apparent that many component parts are common to a number of valve types. An indirectly heated cathode is usually a nickel tube with the cathode material sprayed on to it, and the heating element, which is coated with a refractory oxide such as magnesia, is inserted into this tube.

Directly heated filaments are usually thin, flat strips held on springs either in a V-shape or with more bends if they are very long. Punched-mica plates are used at the ends of the electrode assembly to hold each electrode in its proper relative position, and these plates are frequently coated with magnesium oxide to prevent surface deterioration.

Special Valves

Sometimes, for special purposes, types of valves other than those mentioned above are needed in radio equipment. These may take the form of multi-electrode valves or more than one electrode system in the same envelope, such as that shown in Plate IX. Sometimes, too, it is advantageous to introduce small traces of mercury or of a rare gas such as argon, neon or helium into the envelope, but these special types do not come within the scope of this volume, and will not be considered here.

Metal Rectifiers

It has been found that the resistance across a layer of oxide on certain metals is much higher if the current flows in one direction than if it flows the reverse way. The two commercially used materials are copper and selenium, and both types have their special applications.

If a graph of current against applied voltage is taken, the resulting curve is similar to that of Fig. IV.13, which shows typical values for a selenium and a copper oxide rectifier of similar size. It is usual to call the direction in which current flows most easily the " forward " direction, and the opposite one the " reverse " direction. It will be seen that if the applied p.d. in the forward direction is below a certain value called the " threshold ", very little current flows. In the case of copper oxide rectifiers this threshold is very broad and occurs at about 0·25 volt, but in selenium rectifiers it is much more sharply defined and occurs at about 0·5 volt.

Further, the maximum reverse p.d. which a single copper oxide layer will stand without breaking down is about 10 volts, while the corresponding value for selenium is about 30 volts. Copper oxide is therefore more suitable where very low p.d.s are involved, and it is widely used for instrument rectifiers. The higher breakdown p.d. of selenium means that fewer elements are needed in series to withstand a given reverse p.d., and it is widely used for power rectification.

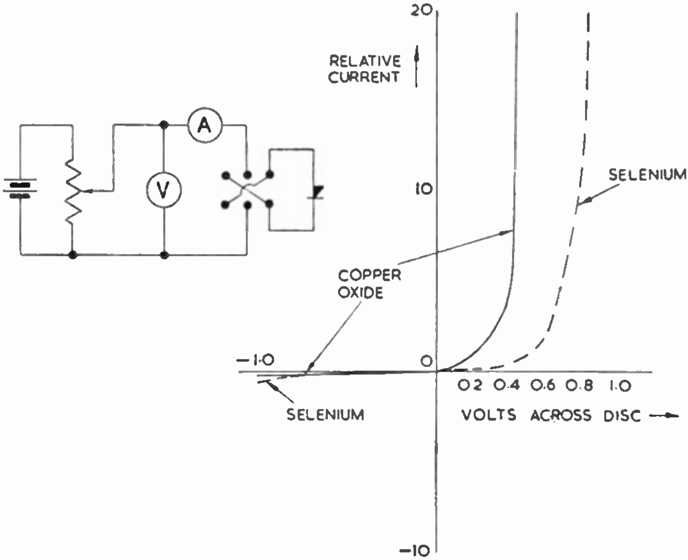


FIG. IV.13.—Characteristics of Metal Rectifiers

Constructional Details

Copper Oxide Rectifiers

Copper discs oxidized on one side are threaded on an insulating tube alternately with lead washers and cooling fins. At each end of the assembly are placed several spring washers and a coloured insulating bush to indicate the direction of easy current flow. The whole is then clamped very tightly by a bolt passing through the centre of the insulating tube. This pressure is necessary in order to make good contact between the lead washers and the oxide layer, so that the forward resistance may be kept low.

The unit must be kept free from air and moisture internally, and it is usually finished with a coat of insulating paint.

Connexions are made to the discs through the cooling fins.

Selenium Rectifiers

With selenium rectifiers the forward resistance for a given area of disc is usually slightly greater than for a corresponding copper oxide unit, so that although fewer discs are needed to stand the operating p.d., the heat developed per disc tends to be slightly more. The discs are assembled with a few small washers between them in order to improve the heat dissipation. Cooling fins are also used in this case, but lead washers to improve contact are not necessary. The whole is assembled with an insulating tube and bolt in the same way as the copper oxide rectifier.

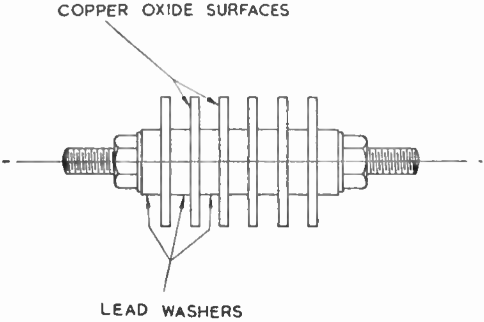


FIG. IV.14.—Construction of Copper Oxide Rectifier

Fig. IV.14 shows the general construction of metal rectifiers. The size of the discs is chosen according to the current to be handled, while the number of discs in series is determined by the applied p.d. and the type of circuit.

Table Showing Applications of Various Types of Resistors

Type.	Dissipation, watts.	Range of values, ohms.	Material.	Finish.	Typical uses.	Tolerances on value.	Notes.
Wire-wound fixed	2–100	1–100,000	Nickel–chrome	Bare or vitreous enamel	High-power dissipation	1–20%	—
	Low	Up to 100,000	Manganin Constantan	Varnish	Meter shunts and multipliers; bridge circuits	Up to 1%	Resistance does not change with temperature
Carbon fixed	$\frac{1}{16}$–3	10–10,000,000	Carbon mix	Varnish or ceramic tube	Radio circuits not requiring great accuracy	5–20%	Cheap to manufacture
High-stability carbon fixed	$\frac{1}{2}$–2	10–10,000,000	Carbon on ceramic rod	Varnish	Measuring equipments, balanced circuits	1–5%	—
Wire-wound variable	1–100	Up to 100,000	Nickel–chrome	Various, depends on power rating	Instruments	1–20%	—
Carbon variable	$\frac{1}{2}$–2	10–2,000,000	Carbon track	Moulded or metal case	Radio receivers	20%	—

TABLE SHOWING TYPICAL APPLICATIONS OF CAPACITORS

Type.	Capacitance range and tolerance.	Order of maximum working p.d. Volts.	Typical uses.
Tubular rolled paper	0·5–0·001 μF 10–20%	1,000	Coupling and decoupling
Rolled paper in metal can	10–0·001 μF 10–20%	10,000 at least	Coupling, decoupling and smoothing
Stacked mica	0·01 μF–50 pF 5–20%	2,000	Radio-frequency coupling and decoupling
Silvered mica	0·01 μF–10 pF ½–20%	1,000	Radio-frequency resonant circuits and measuring circuits
Silvered ceramic	0·001 μF–2 pF 1–20%	350	Radio-frequency by-pass capacitors, low radio-frequency circuits
High *K* ceramic	0·01 μF–50 pF 20%	350	Used where size is important
Electrolytic	64–2 μF 20%	600	Smoothing and decoupling
	1,000–50 μF 20%	200–50	Decoupling and by-pass
Variable capacitors	500–15 pF 0·5–5%	2,000	Tuning circuits
Mica trimmers	3,000–50 pF	350	} Aligning and adjusting tuned circuits
Air trimmers	100–8 pF	350	

TABLE SHOWING THE RANGE OF INDUCTANCE VALUES MET IN RADIO WORK

Type.	Frequency.	Inductance.	Type of winding.	Type of core.
Mains transformers	25–100 c/s	1–20 H	Multi-layer	Interleaved, laminated iron or silicon steel
Smoothing chokes	25–200 c/s	1–100 H	Multi-layer	Gapped, laminated iron or silicon steel
Audio-frequency chokes and transformers	20 c/s–15 kc/s	0·1–100 H	Multi-layer and sectionalised	Laminated silicon steel or nickel–iron alloy, gapped if necessary
Radio-frequency coils and chokes	50 kc/s–2 Mc/s	100 μH–10 mH	Wave wound	Air or dust iron
	2–10 Mc/s	10–50 μH	Close-wound single-layer solenoid	Air or dust iron
	5–60 Mc/s	0·25–10 μH	Single-layer solenoid with spaced turns	Air or dust iron

TABLE SHOWING THE PROPERTIES OF VARIOUS CORE MATERIALS

Material.	Permeability.	Maximum flux density, lines/sq. cm.	Losses at maximum flux density, watts/lb.	Uses.
Iron	1,000–2,000	10,000	1	Low-frequency chokes and transformers
Silicon steel	1,000–9,000	12,000–14,000	1–2	
Nickel-iron alloys :				
(*a*) High permeability	10,000–100,000	8,000	0·05	Special applications where size or losses are important at frequencies up to 1 Mc/s
(*b*) Medium permeability	2,000–15,000	15,000	0·5	
(*c*) High resistance	250–8,000	9,000	0·5	
Iron dust cores	2–100	—	—	Radio-frequency coils

CHAPTER 5

AUDIO-FREQUENCY AMPLIFIERS

In Chapter 4 we discussed the construction of thermionic valves, and we shall now learn how to use them to amplify signals of the kind obtained from microphones. The frequencies with which we shall be concerned are called " Audio Frequencies ", and lie typically within the range 20 c/s to 20 kc/s. They are thus below the lowest radio frequencies commonly used.

Valve Operation

The valve-amplifier circuit requires electrical power for its operation, (1) for heating the cathode, or source of electrons, and (2) for causing the electron current to flow in the anode circuit.

The supply for heating the cathode is of the order of 1·5–13 volts, and is commonly called the " heater " or " low-tension " (L.T.) supply. The supply for the anode circuit is from about 50 volts upwards, and is known as the " anode supply " or the " high-tension " (H.T.) supply. For the present we shall assume that these sources of power are available, and we shall deal with them in detail in Chapter 7.

The triode operates by virtue of the fact that the current through the valve consists simply of a flow of electrons from cathode to anode, which has to pass through the grid structure. By altering the potential of the grid relative to the cathode, the flow of electrons can be controlled, because if the grid is made negative the electrons are repelled, and unless the anode has sufficient attraction for them (that is, it is sufficiently positive with respect to the cathode), they will not leave the vicinity of the cathode and there will be no anode current. If the grid is made less negative, the attraction of the anode will have more effect and the anode current will increase. Fig. V.1 shows diagrammatically how the electron flow is affected by grid potential. The electron flow is fundamental in the operation of the valve, but for convenience in practice the corresponding " conventional " current, from anode to cathode within the valve, is considered in the circuits we shall be discussing.

If the grid is made positive with respect to the cathode, an increased flow of electrons from the cathode is caused, and some will flow to the grid, constituting a current in the grid circuit. If the grid never becomes positive, however, there will be no grid current and there is no power in the grid circuit.

In dealing with valve circuits, potential differences are always referred to the negative terminal of the anode supply, which in radio receivers is usually connected to the metal chassis on which the components are assembled. This in turn is normally " earthed " by connexion to a water-pipe or a conductor buried in the ground, and so the point of reference is known as " earth ".

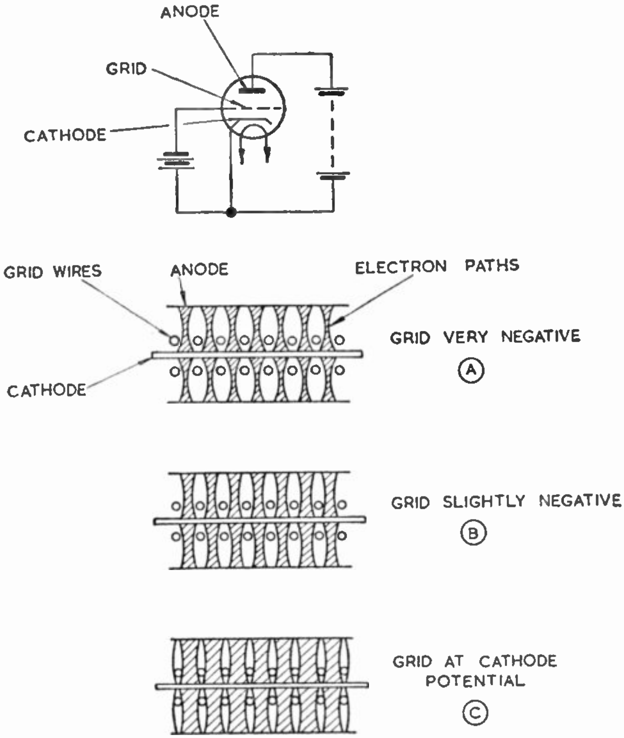
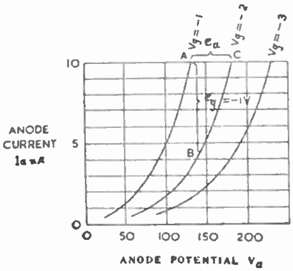


FIG. V.1.—Grid Control of Electron Flow

Valve Parameters—Amplification Factor

The anode current is affected by the potentials of both anode and grid with respect to the cathode. If the anode current is reduced by making the grid more negative, it can be restored to its original value by making the anode more positive, as shown in

Fig. V.2. If the grid potential is changed by e_g volts and the change necessary in anode potential to restore the original current is e_a volts, then the ratio of e_a to e_g is known as the "amplification factor" of the valve, and is given the symbol μ.



IF THE VALVE IS OPERATING AT POINT 'A' AND V_g IS CHANGED FROM −1V TO −2V, THE NEW OPERATING POINT IS 'B'. TO RESTORE THE ANODE CURRENT TO ITS ORIGINAL VALUE V_a MUST BE INCREASED FROM 125V TO 175V THAT IS TO POINT 'C'. $\mu = \frac{175-125}{1} = 50$. AT POINT 'B' $I_a = 4.5$mA AND $V_a = 125$V, AT 'C' $I_a = 10$mA AND $V_a = 175$V, $r_a = \frac{(175-125) \times 1000}{10-4.5} = \frac{50,000}{5.5} = 9,000\,\Omega$

FIG. V.2.—Valve Characteristics

Anode Resistance

If the grid potential is kept constant and the anode potential is varied, it can be seen from Fig. V.2 that the anode current will vary. If the anode potential is changed by e_a and the anode current changed by I_a, then the ratio of e_a to I_a is known as the "Anode Resistance" of the valve, given the symbol r_a.

In practice, the amplification factor of triodes varies typically from 5 to 80, depending on the use to which the valve is to be put, while the anode resistance generally lies between 1,000 and 100,000 ohms.

Mutual Conductance

There is another parameter pertaining to valves which is very important, known as the "Mutual Conductance". It is the ratio of (change in anode current) to (change of grid potential causing it) when the anode potential is kept constant. In symbols the mutual conductance $g_m = \frac{I_a}{e_g}$, and is expressed in milliamps. per volt (mA/V).

Fig. V.3 shows the characteristics of the triode in another form, which illustrates the meaning of mutual conductance.

Summary of Valve Constants

(1) $\mu = \frac{e_a}{e_g}$ (anode current constant).

(2) $r_a = \frac{e_a}{I_a}$ (grid potential constant).

(3) $g_m = \frac{I_a}{e_g}$ (anode potential constant).

If we divide μ by r_a we have $\frac{\mu}{r_a} = \frac{e_a/e_g}{e_a/I_a} = \frac{I_a}{e_g} = g_m$, so that

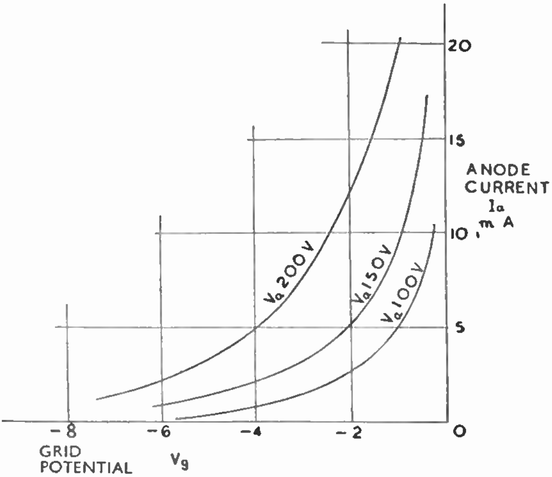


FIG. V.3.—Grid Characteristic of a Triode

$\frac{\mu}{r_a} = g_m$ and the three constants are inter-related. Care must be taken always to use the proper units in this equation.

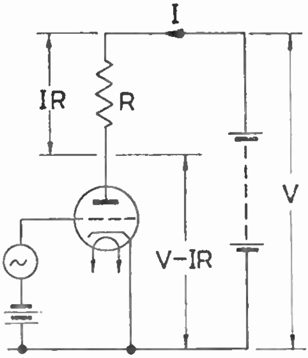


FIG. V.4.—Triode with Anode Load

Operation as a Voltage Amplifier

We wish to obtain a voltage variation from the valve, and this can be done by passing the anode current through a resistor, across which a potential drop is obtained proportional to the current flowing through it. Fig. V.4 shows a triode valve with a resistor in its anode circuit, a source of e.m.f. to raise the anode potential and another source of e.m.f. in the grid circuit which keeps the grid at a suitable negative potential. The signal which we require to amplify is connected in series with this negative e.m.f., which is known as the " grid bias ".

Grid Bias

It is necessary to choose this grid-bias so that when the signal is applied, the grid does not become positive, nor does it become sufficiently negative to prevent the flow of anode current. This means that the signal which may be applied is limited by the valve characteristics.

Effect of Signal

Under the influence of the steady e.m.f. from the anode supply and of the grid bias, a certain value of current will flow in the anode circuit and a proportional potential drop appears across the anode resistor, as shown in the diagram. When a signal is applied in series with the grid bias, it will cause the grid to become alternately more and less negative. If the grid is more negative, the anode current is reduced so that the potential drop across the anode resistor decreases and the anode becomes more positive. Conversely, when the grid is less negative, the anode current is increased and the potential drop across the anode resistor increases, causing a fall in the anode potential. The application of a signal to the grid thus causes a change of anode potential, which may be many times greater in amplitude.

The Anode Load

The value of the anode-load resistor will have some effect on the output we can obtain from the valve. Obviously, if the resistance is of a very low value—say 500 ohms—and the change in anode current produced by the signal has a maximum value of 2 mA—varying from 4 mA to 2 mA, the p.d. across the resistor will vary from $\frac{4}{1{,}000} \times 500$ to $\frac{2}{1{,}000} \times 500$, *i.e.*, from 2 volts to 1 volt. The input required to cause this change of current will also be about 1 volt, so that the valve is not giving us any amplification.

Conversely, a very high value of anode resistor will drop the anode potential and limit the maximum output.

It is usual to choose the anode-load resistor to have a value of about three times the anode resistance of the valve, as this is a good compromise between reducing the gain by having too low a value of resistance and limiting the current and maximum output severely by having too high a value.

The Equivalent Circuit

In examining the operation of an amplifier valve, it is helpful to think of the valve as a generator of an alternating e.m.f., in series with a resistance equal to its own anode resistance, and to ignore the steady direct current flowing in the anode circuit.

The anode load is then the load on this generator, because the d.c. supply which is necessary offers very little impedance to the alternating current.

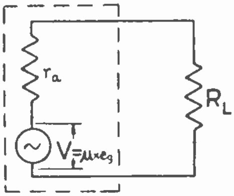


FIG. V.5.—Equivalent Circuit of a Triode

Fig. V.5 shows the " equivalent circuit " of Fig. V.4, and the valve is now shown as a generator with an output equal to the grid input multiplied by the amplification factor of the valve. The anode resistance is r_a and the load is R_L, so that the fraction of the output available externally is $\frac{R_L}{R_L + r_a}$. The amplification of the circuit is therefore

$$m = \mu \frac{R_L}{R_L + r_a}.$$

There is another way of writing the amplification of the valve, making use of the relationship between μ and g_m:

$$m = \mu \frac{R_L}{R_L + r_a} = g_m r_a \frac{R_L}{R_L + r_a} = g_m \frac{r_a R_L}{r_a + R_L}.$$

Making Use of the Output

Our valve amplifier as shown in Fig. V.4 will provide us with an output from its anode which alternates above and below the mean positive direct potential of the anode. If we wish to add another stage of amplification, which we can do by feeding from the anode of one valve to the grid of another, we must in some way remove this " direct component ", as we call it, from the output

Resistance–Capacitance Coupling

This is most easily done by using a capacitor C_1, as shown in Fig. V.6, and by taking our output from R_2 we have a potential alternating above and below the negative terminal of our anode supply.

Consider what happens when there is no signal. The valve anode is at some positive potential, less than that of the anode supply by the drop in R_1 due to the valve current. One side of the capacitor C_1 is connected to the valve anode, and the other to the negative terminal of the anode supply (" earth ") through R_2, which is known as the " Grid Resistor ". A charging current flows through R_1 and R_2 into C_1 until the potential across C_1 is equal to that between anode and earth. When this has happened, no current is flowing in R_2, while R_1 carries only the steady valve current.

When a signal is applied to the grid of the valve, its anode potential alternates about its mean value, and carries one plate of the capacitor C_1 with it. Now the potential across a capacitor remains constant until a charging (or discharging) current flows, and such a current can only flow through R_2. If we make R_2 very high in value (*e.g.*, 1 MΩ), then only a very small current can flow through it to alter the p.d. across C_1.

When the anode is less positive than its steady value, the end *A* of R_2 will be negative with respect to point *B*, and a small current will flow in R_2, tending to reduce the charge on C_1 and to lower the p.d. across it. When the anode is more positive, then *A* is positive with respect to *B*, and a current flows in the opposite direction, tending to increase the charge on C_1 and to increase the p.d. across it, so that the mean charge on C_1 remains constant, and the mean potential of *A* is the same as that of *B*.

However, if the signal frequency is very low, then the charging currents may have time to affect the charge of C_1 to a noticeable extent in alternate directions. In this case, the full output of the valve is not developed across R_2. The effect of this charging current on the p.d. across C_1 depends on the values of C_1 and R_2, and their values have to be chosen to pass on the lowest desired frequency without appreciable reduction of gain.

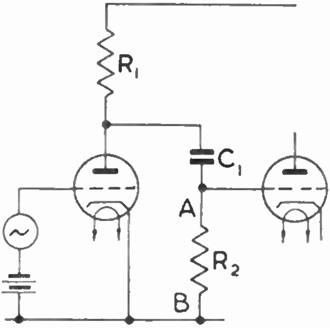


FIG. V.6.—Resistance-capacitance Coupling

Typical values to pass a 50-c/s signal are :

$$C_1 = 0{\cdot}02\ \mu\text{F},\ R_2 = 1\ \text{M}\Omega$$

or

$$C_1 = 0{\cdot}1\ \mu\text{F},\ R_2 = 0{\cdot}22\ \text{M}\Omega.$$

Grid bias for the following stage is applied to the lower end of R_2.

Transformer Coupling

Fig. V.7 shows a triode valve with one winding of an audio-frequency transformer included in the anode circuit, in place of the resistance load previously used. The equivalent circuit of this arrangement is shown in Fig. V.8, and if r_a is small compared with the reactance of the transformer winding, the whole of the generated e.m.f., μe_g, will be applied to the transformer winding. The p.d. across the output, or secondary winding, is equal to the p.d. across the winding in the anode circuit, or primary winding, multiplied by the ratio of secondary turns to primary turns. This means that it is possible to obtain a greater output from the secondary winding than the output from the valve, and suitable transformers have ratios of up to about 7 to 1. The secondary e.m.f. is isolated from the anode circuit of the valve, so that the problem of removing the direct component is solved.

The disadvantages of transformer coupling are :

1. The direct current in the anode circuit sets up a magnetising force in the transformer core, which reduces its permeability and so lowers the reactance of the primary.

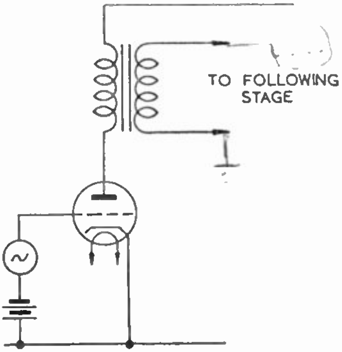


Fig. V.7.—Transformer Coupling

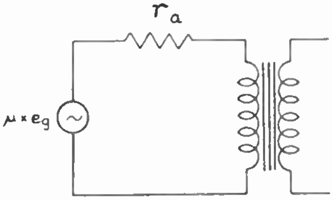


Fig. V.8.—Equivalent Circuit for Transformer Coupling

2. It is difficult to construct a transformer capable of passing on faithfully voltages of all audible frequencies, and it is often cheaper to use an extra stage of resistance–capacitance-coupled amplification than to obtain increased gain by trying to use a high-ratio transformer.

3. In apparatus working from an alternating supply, there are often other transformers connected to the supply which set up magnetic fields at mains frequency. It is difficult to prevent some of the fields due to these transformers from causing interference and inducing an e.m.f. at mains frequency in the coupling transformer.

Parallel-fed Transformers

The effect of the direct current in the primary can be overcome by the circuit of Fig. V.9, in which we have a resistance load on the valve and its output is fed to the transformer through a coupling capacitor. This enables a smaller transformer to be built, still maintaining adequate reactance at low frequency, because there is no direct current to reduce the permeability of the core.

Transformer coupling enables an increased gain to be obtained from the stage, but is seldom met in receivers operated from electricity mains. It is mainly of use in battery sets, where a reduction in the number of valves decreases the load on the batteries. Battery valves usually have a slightly lower mutual conductance than their indirectly heated counterparts, so that the combination of valve and transformer is a very useful arrangement.

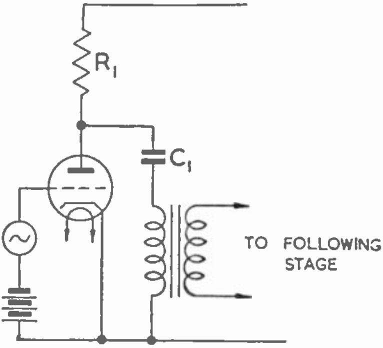


FIG. V.9.—Parallel-fed Transformer

Output Stage

A most important part of a low-frequency amplifier is the output stage. We have so far been concerned only with valves as voltage amplifiers, but to produce sound, power is required.

The device used for reproducing sound in a receiver is usually a loudspeaker; in special receivers for communication purposes head telephones are also used.

A moving-coil loudspeaker requires only a low e.m.f. at a high current for its operation, and so requires a transformer. The anode load of a valve, as we stated earlier in this chapter, should be high, so that the valve produces large changes of potential at a small current (large p.d./small current = high resistance). By using, between the valve and the loudspeaker, a transformer having many turns on the primary and few on the secondary, we obtain the desired low p.d. and high current (Fig. V.10).

The transformer turns ratio is given by :

$$\sqrt{\frac{\text{anode load resistance of valve } (\Omega)}{\text{loudspeaker impedance } (\Omega)}}$$

and the proper value of load resistance for this purpose is given by the valve manufacturers.

When headphones are used, a transformer is often put in the circuit to prevent the anode-supply potential from reaching the headphones, with the consequent risk of electric shock to the user.

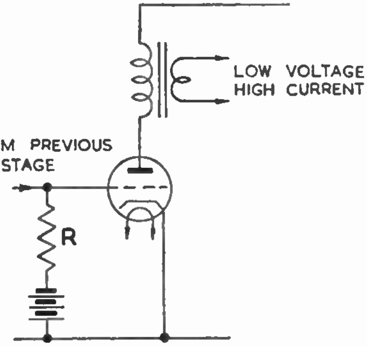


FIG. V.10.—Output Stage

Headphones usually have a high enough resistance to be connected in the anode circuit of a valve, so the transformer is then arranged to give out the same p.d. as it receives from the valve, and its turns ratio is 1 : 1.

Grid Bias

When we started to discuss valves as amplifiers, we found that it was necessary to prevent the grid of the valve from becoming positive with respect to the cathode, and to do this we applied grid bias—a direct potential negative with respect to the cathode. The signal was applied in series with this bias.

Battery Bias

The first and most obvious way of providing this p.d. is from a battery, the positive terminal of which is connected to the valve cathodes.

Fig. V.11 shows two stages of low-frequency amplification, which require two values of grid bias. These are given by the battery shown, and typical values for battery valves are: 1·5 volts for an early stage, 4·5–9 volts for an output valve. These are multiples of 1·5, being obtained from dry cells.

Automatic Bias

This takes two forms, one in which each valve has its own source of bias, and the other in which all valves use the same source.

Fig. V.12 shows a valve having an indirectly heated cathode, with a resistor in the cathode lead. The negative terminal of the anode supply is taken to the junction of the cathode resistor, R_k, and the grid resistor, R_g.

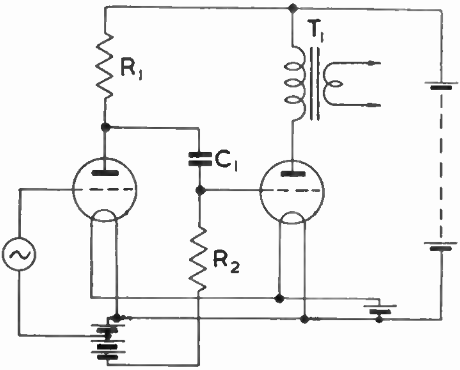


Fig. V.11.—Battery Bias

The steady current through the valve causes a p.d. across R_k, the value of which can be found from $V = IR$. This p.d. makes point A positive with respect to point B, which itself is at the same potential as the grid of the valve. The grid is therefore negative with respect to the cathode, and we have biased the valve as we wished. When, however, a signal is applied to the valve, the current in the cathode circuit, which is the same as the anode current, varies, and will cause the bias to vary. To prevent this, a large capacitor is connected across R_k, which keeps the p.d. constant in spite of the varying signal current. The value of the bias resistor is calculated by Ohm's Law. For example, a valve requiring a bias of 4 volts at an anode current of 5 mA will have a cathode resistor of $R_k = \frac{V}{I} = \frac{4}{5/1000} = 800\ \Omega$. The capacitor is usually of 50 μF or more. A suitable resistor is included in the cathode circuit of each valve.

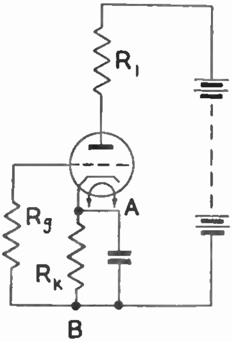


Fig. V.12.—Automatic (Cathode) Bias

Fig. V.13 shows a two-stage amplifier, having a resistor in the negative lead to the anode supply. The combined anode current of the two valves flows through this resistor, and point *B* becomes negative with respect to *A*. The resistor is of a value sufficient to cause the p.d. between *A* and *B* to be equal to the largest bias voltage required, which in this case will be for the second stage, and the grid resistor of stage II is taken to *B*. The grid bias for stage I is taken from a tapping on the resistor, at a point at the proper potential relative to *A*. As before, a large capacitor is connected across this resistor and the value of the resistor is calculated from the total current through it, that is, the sum of the two valve currents and the greatest value of grid bias required. The position of the tap is determined by simple proportion.

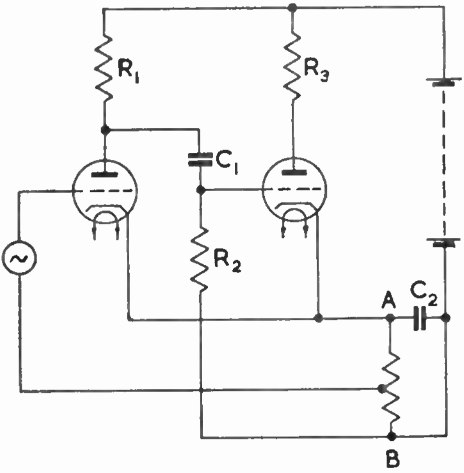


FIG. V.13.—Common Automatic Bias

This method is equally applicable to equipment with directly heated and indirectly heated valves, and is usually used in modern battery-operated receivers.

Instability of Low-frequency Amplifiers

It is possible under some conditions for the normally steady anode currents of the valves to vary and to cause a fluctuating output, sometimes at an audible frequency. Such a condition is very undesirable, and to prevent its occurrence, its cause must be known.

Fig. V.14 shows a three-stage amplifier using indirectly heated triodes.

The valves are labelled V_1, V_2 and V_3, and we shall call their electrodes g_{V_1} for "grid of V_1", and a_{V_2} for "anode of V_2" respectively. The steady currents in the circuit are indicated in the diagram. During the positive half-cycle of the input to V_1, g_{V_1} is less negative than its steady value, so that V_1 takes more current than its steady value, or I_1 increases. This causes the p.d. across R_1 to increase, a_{V_1} becomes less positive and so, by virtue of the coupling capacitor C_1, g_{V_2} is made more negative than its steady value. This means that the anode current in V_2 is reduced, the p.d. across R_3 decreases and a_{V_2} goes more positive. The coupling to V_3 causes g_{V_3} to become less negative, so that V_3 takes more current and the anode potential of V_3 falls due to the increased p.d. across R_5. The diagram shows all these changes, and of course during the negative half-cycle of the signal the whole process is reversed.

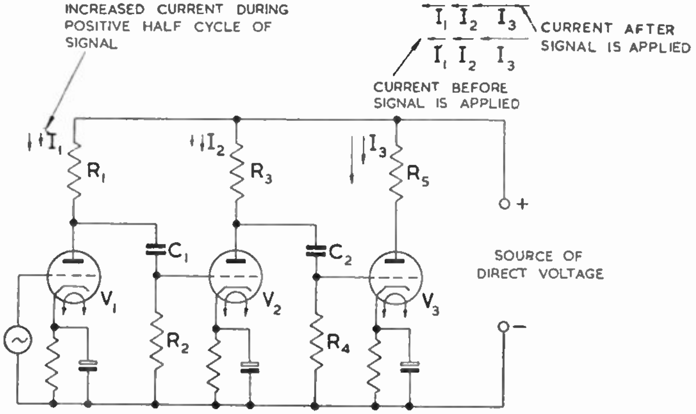


FIG. V.14.—Illustrating Instability

It is important to note that the changes in anode current become greater as we proceed from one stage to the next, because the input to V_2 is greater than that to V_1 by the amplification of V_1 and that to V_3 is greater than that to V_2 by the amplification of V_2. The total current flowing is therefore varying with the signal, mainly due to the changes in I_3. The arrows in the diagram indicate the nature of these changes.

Suppose that a resistance R_6 is present in the common lead supplying the three valves, between the source and the amplifier (Fig. V.15). The p.d. across this resistance will have a steady value determined by the steady current taken by the three valves, and the variations in the p.d. will be mainly affected by the changes in I_3, and will cause the supply to the three valves to be varied slightly while the signal is applied. When the signal goes positive I_3 increases, so that the p.d. across R_6 increases, thus lowering the p.d. V_b. This fall in V_b will coincide with an increase in I_1 and a fall in the potential of a_{V_1} and g_{V_2}, and will cause an additional fall in the potential of a_{V_1} and g_{V_2}. If R_6 is large enough, the fall in potential of a_{V_1} due to the fall in V_b may be larger than that due to the signal, and it will be found that the whole circuit has no steady operating conditions, but " oscillates " and gives an output even when no signal is applied.

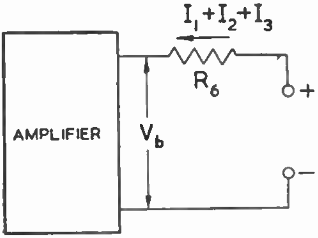


FIG. V.15.—Source Resistance

The cure for this undesirable state of affairs is, clearly, to prevent the changes in V_b from reaching the anode of V_1, and this is done by a resistance–capacitance network as shown in Fig.

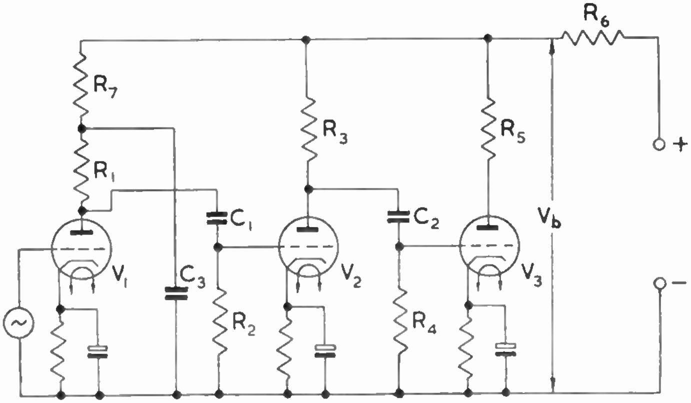


FIG. V.16.—Decoupling of First Stage

V.16. Alternating variations in V_b appear across R_7 but not across C_3 because it is necessary to change the charge on C_3 to alter the p.d. across it. This is a " decoupling " circuit preventing unwanted potential variations from one stage from being coupled back to another. Such circuits are essential in apparatus supplied from the mains, as the effective value of R_6 in Fig. V.16 may be large. When batteries are used, the value of R_6 is the internal resistance only, and is low when the batteries are in good condition; as they deteriorate their internal resistance increases, and the use of decoupling circuits may allow an older battery to be used than would be the case if no decoupling were incorporated.

Control of Low-frequency Amplifiers

We have seen that a low-frequency amplifier consists of one or more valves coupled successively. The output of the first stage is equal to the input multiplied by the gain of the stage. This output may then drive a second stage, the output of which is equal to its input multiplied by its gain. The output of the second stage is therefore equal to the input to the first stage multiplied by the product of the gains of the two stages. For example, if the first stage has a gain of 30 times, and the second stage 15 times, the total gain is $30 \times 15 = 450$ times.

It is desirable to be able to control this gain, in order to control the volume of sound which is given by the reproducer, and this is done by the circuit of Fig. V.17.

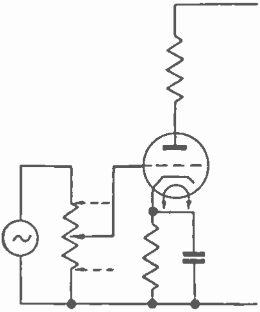


FIG. V.17.—Volume Control

The input to the amplifier is fed into a resistor with an adjustable tapping, known as a " Potentiometer " or " Volume Control ". The amplifier is fed from the tapping on the potentiometer and from one end of it, so that the input to the amplifier can be any desired fraction of the signal.

Hum

In equipment operated from an alternating supply, it is possible for the output to contain a " hum " signal at the supply frequency or at some multiple of that frequency, and it is so called because of the noise such an output causes to be reproduced.

Since an amplifier may have a total gain of some hundreds or even thousands, a very small input signal is sufficient to cause appreciable output.

If the input to the amplifier and the lead to the grid of the first stage happen to be near to any other leads carrying current at supply frequency, there may be sufficient electrostatic or electromagnetic coupling to induce a small e.m.f. in the input circuit. The electrostatic coupling may be reduced by careful arrangement of the leads and components and by " screening " the sensitive leads by surrounding them with a conducting sheet which is connected to the chassis. Electro-magnetic interference is reduced by twisting together the two leads of the circuit carrying current at supply frequency so that the fields set up by the leads, being always due to currents flowing in opposite directions, cancel each other. Inside the valve itself, the heater and cathode are in very close proximity, and electrostatic induction is reduced by keeping the heater and cathode within a few volts of each other. Electro-magnetic induction inside the valve is looked after by the valve manufacturer, who makes the heater in such a form that it has no magnetic field, just as we have prevented it outside the valve by twisting leads.

The output from the rectifier circuit contains a small p.d. at a frequency of twice that of the supply, if a full-wave rectifier is in use. If this " ripple " reaches the anodes of the early stages of the amplifier, it will be fed forward and amplified in the same way as the unwanted p.d. we discussed in the section on decoupling. This can be prevented from occurring by the same decoupling circuit, but it may also require the use of a decoupling circuit in a stage where oscillation could not occur.

If an iron-cored transformer is used in the circuit, care must be taken to prevent the mains transformer from inducing flux in its core and setting up a hum e.m.f. This can be prevented by mounting the components with their cores at right angles to each other.

Use of Audio-frequency Amplifiers

In radio work low-frequency amplifiers are used at the transmitting end to amplify the very small signals produced by microphones, and to raise them to a suitable level for sending along cables from the studio to the transmitting station.

At the transmitter the signals are further amplified, to control the radio frequencies applied to the aerial.

In receivers an output stage is essential, and it may be fed directly from the detector stage, or it may require one or more additional stages in between.

For the reproduction of gramophone records two or three stages in all are necessary, and so most modern radio receivers have two stages of low-frequency amplification.

CHAPTER 6

RADIO-FREQUENCY AMPLIFIERS

In a circuit operating at radio frequency we are concerned only with the amplification of one particular frequency, or of a narrow band of frequencies; and so a radio-frequency amplifier will differ from an audio-frequency amplifier, which must operate over a wide range of frequencies. It is therefore natural to make use of the tuned circuits which we developed in Chapter 3. In an audio-frequency amplifier we made use of a resistor in the anode circuit of a valve and obtained the output from the variation of current through the resistor.

A parallel-tuned circuit acts like a high resistance at its resonant frequency, but has a very low resistance to d.c., and is suitable for inclusion in the anode circuit of a valve, as in Fig. VI.1. It has the advantage that its apparent impedance is less at all other frequencies than that at the resonant frequency, so that the greatest amplification is obtained at the resonant frequency of the tuned circuit, which is given by :

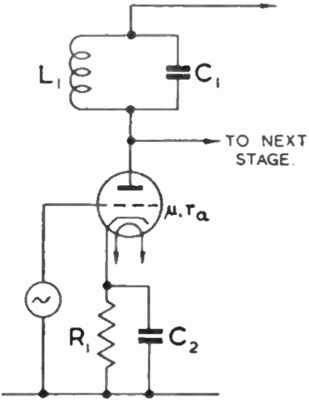


Fig. VI.1.—Simple r.f. Amplifier

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where f is in cycles per second; L is in henrys; C is in farads.

Gain per Stage

If R_D is the dynamic resistance of the tuned circuit, the gain of the stage is given by $\mu \dfrac{R_D}{r_a + R_D}$ at the resonant frequency. The gain of the stage depends on frequency as indicated in Fig. VI.2.

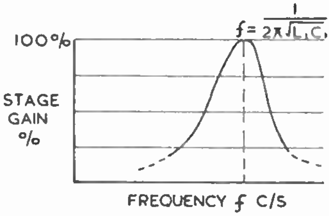


Fig. VI.2.—Stage Gain of r.f. Amplifier

Let us consider the practical arrangement of Fig. VI.1 in greater detail. The valve consists of three conducting members, a cathode, a grid and an anode, which are in close proximity to each other. It follows that there is a small capacitance between all three of these parts and the connexions to them.

Effect of Valve Capacitances

The capacitance between grid and cathode places a capacitive load on the source feeding the valve. It is possible to improve matters by making the input a second tuned circuit, the input capacitance of the valve forming part of the tuning capacitance (Fig. VI.3). The grid circuit now appears to the input source to be just another resistance of high value equal to the dynamic resistance of the tuned circuit, and the high capacitive load does not appear.

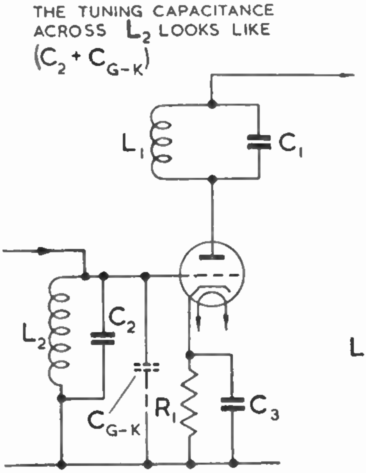


FIG. VI.3.—Effect of Valve Capacitances

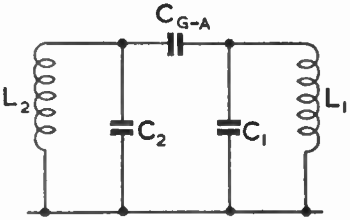


FIG. VI.4.—Equivalent Circuit for Fig. VI.3

The capacitance between anode and grid is usually higher than the grid–cathode capacitance. The effect of this capacitance on the two tuned circuits is shown by re-drawing Fig. VI.3 as in Fig. VI.4. Fig. VI.4 is similar to Fig. III.19, which is a diagram of two coupled tuned circuits.

The coupling capacitor, now equal in value to the capacitance between anode and grid of the valve (C_{G-A}) is a means of transferring energy from one tuned circuit to the other. In this case, due to the amplification of the valve, the energy in the anode circuit will be many times greater than that in the grid circuit, and some of this energy will be transferred back to the grid circuit through C_{G-A}. This will result in a condition of "oscillation" where the valve input is derived from its own output, and an alternating p.d. at the resonant frequency of the tuned circuits (which must be identical for the circuit to function as an amplifier) will appear at the anode without any external signal being applied.

The simplest way of preventing this from occurring is to reduce C_{G-A} to a sufficiently small value so that the energy fed back through it cannot cause oscillation. This cannot be done with a triode valve without complicating the circuit, but may be done by introducing an electrostatic screen inside the valve between the anode and grid, which is held at a fixed potential relative to the cathode. It is arranged at the same time to allow the electron flow to the anode to be maintained. This screen constitutes a fourth electrode, and the valve is known as a tetrode (tetra = four), or more popularly as a "screened-grid valve". The internal arrangement of such a valve is shown in Fig. VI.5, and its construction was described in Chapter 4. In order to keep the anode–grid capacitance to an absolute minimum, the anode connexion is taken to a terminal on the top of the valve envelope, and not to a pin in the base, where the other electrodes are led out. The introduction of the screen has two important effects on the characteristics of the valve.

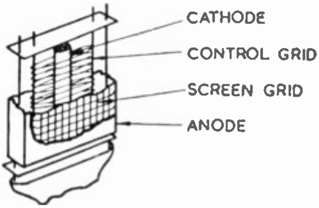


FIG. VI.5.—Sketch of Screened-grid Valve

Characteristics of Screened-grid Valves

Since the screen is sufficiently effective to reduce the anode-to-grid capacitance almost to zero, it also reduces the effect of the anode potential on the flow of electrons. For a given change of anode potential, the change of anode current is many times less than in a triode, so that the ratio of these changes, and hence the anode resistance, is also much higher than in a triode. The amplification factor of the valve (equal to $g_m \times r_a$) is therefore much greater, and the damping effect of the anode resistance on the anode tuned circuit is greatly reduced. In practice it is of the order of 1 MΩ. The mutual conductance is about 1 mA/volt, so that the amplification factor is in the region of 1,000 instead of 20–80 for a triode. Of course, the amplification obtainable is less than this figure, because the same equations apply for the stage gain.

Fig. VI.6 shows the circuit of a radio-frequency amplifier using a screened-grid valve.

The stage gain $m = \mu \frac{R_D}{r_a + R_D}$, for the circuit values shown.

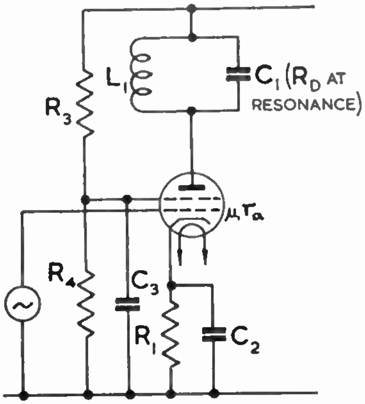


Fig. VI.6.—R.f. Amplifier using Screened-grid Valve

In order to attract electrons from the cathode in the direction of the anode, the screen has to be made positive with respect to the cathode, usually being operated at about $\frac{1}{3}$ to $\frac{1}{2}$ of the anode potential. The screen therefore collects some of the electrons itself and so takes current, but being of mesh construction this current is small. Its potential is obtained from a chain of resistors across the anode supply, and is kept constant by a capacitor C_3 of about 0·1 μF. This is necessary, since the screen current also varies at signal frequency, and 0·1 μF is large enough to prevent change of the screen potential at any radio frequency.

Secondary Emission

The ejection of secondary electrons, which was noted in Chapter 4, will occur at the anode of the valve if its potential is high enough to attract electrons to it. If the anode potential is below that of the screen, the secondary electrons will travel to the screen and will constitute a current from the anode in the opposite direction to the desired direction, thus reducing the net anode current. As a result, the characteristic of the tetrode valve is like the curve of Fig. VI.7.

To enable a greater output to be obtained from the screened-grid valve, the secondary electrons must be prevented from reaching the screen, and a fifth electrode between anode and screen produces a valve with a long, smooth anode-characteristic curve. The fifth electrode is kept at cathode potential and repels the secondary electrons, to which it appears to be very negative. The valve is now called a " pentode ", having five electrodes in all, and this fifth electrode is known as the " Suppressor Grid ", because it suppresses the effects of secondary emission. The alternative method of producing the same effect on the characteristic, mentioned in Chapter 4, gives us the " kinkless tetrode " or " beam tetrode ", and this type is loosely called a pentode. Because of its more useful characteristics it has replaced the ordinary tetrode for radio-frequency amplification. Both types have characteristics otherwise similar to the screened-grid valve, as shown in Fig. VI.7. The modern pentode valve usually has its grid connexion on top of the valve envelope, this having been found more convenient than having the anode there and its mutual conductance may reach 10 mA/V. Miniature valves have all their connexions in the base, and the capacitance is kept low by judicious arrangement of the connexions. Screened-grid and pentode valves require grid bias in just the same way as triodes, and when a cathode resistor is used to obtain the bias, it must be remembered that the cathode current is the sum of the screen and anode currents.

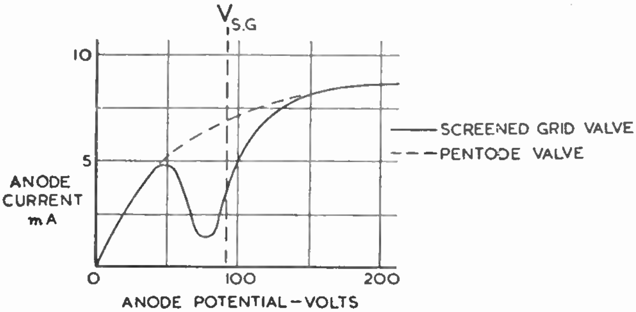


FIG. VI.7.—Characteristics of Screened Valves

Inter-stage Coupling

Most radio-frequency amplifiers are transformer coupled, because that method keeps the valve circuits separate as in the case of audio amplifiers. Fig. VI.8 shows two stages of radio-frequency amplification following the first tuned circuit, to which the aerial is transformer coupled. The tuned circuits have variable tuning capacitors, which are mechanically coupled together, so the whole amplifier can be tuned over a range of frequencies by the rotation of one spindle. Note the arrangements for feeding the screens of the valves, which are pentodes, and also the cathode bias resistors, which are shunted by capacitors of about 0·1 μF to keep the bias constant during variations of the signal voltage.

Only one winding of the transformer is tuned, as to tune both windings would require a large number of sections on the tuning capacitor, and the difficulties of ensuring that the resonant frequencies of all the circuits are identical would involve very accurate workmanship in all the components. Both windings are tuned when the amplifier is only required to work on one narrow band of frequencies, because the capacitors can then be separate and individually adjusted.

It is usual to provide one or two stages of radio-frequency amplification in receivers, since the magnitude of the signal at the first tuned circuit is too small to operate the following stages without making these later stages more complex and difficult to operate.

In order to cover a sufficiently wide range of frequencies it is necessary to change the values of the inductors in each tuned circuit. This is commonly done by a number of switches coupled mechanically, one for each tuned circuit, which select suitable coils. Fig. VI.9 shows how this is arranged for two values of inductance in each stage; the principle can be extended to as many coils as are needed to cover the frequencies for which the receiver is designed. The range of frequencies covered on each value of inductance due to the variable tuning capacitor is about $2\frac{1}{2}$ to 1, that is, if the lowest frequency on one coil is 600 kc/s the highest on the same coil will be about 1,500 kc/s.

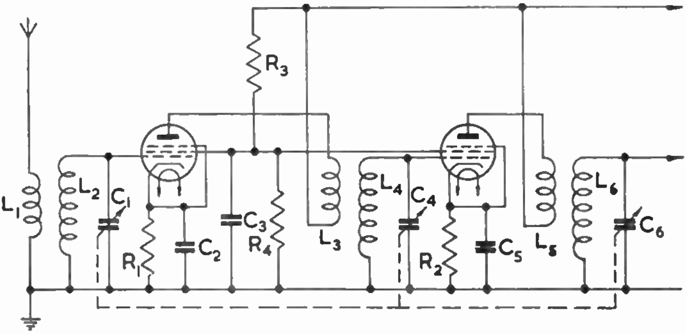
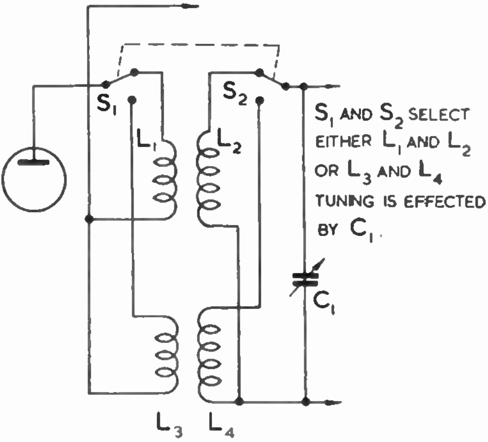


FIG. VI.8.—Two-stage r.f. Amplifier

The addition of tuned circuits, made possible by the use of radio-frequency amplifiers, enables greater selectivity to be obtained. Suppose that the gain of one stage at the resonant frequency is 100 times, while at some other frequency the gain is 5 times due to the lower impedance of the tuned circuit. The ratio of gains at desired and undesired frequencies is 100/5 or 20 to 1.

If a second similar stage is added, the total gain at the resonant frequency will be 100 × 100 = 10,000, and at the same unwanted frequency will be 5 × 5 = 25. The ratio of gains is now 10,000/25 = 400 to 1, so that the ratio is also multiplied (20 × 20 = 400 also). This shows that where high selectivity is essential, a number of tuned circuits and associated amplifying valves will be necessary. The number of stages it is possible to use is limited by the possibility of self-oscillation, due to feedback from the output of the amplifier to the input stage. This feedback can be minimised by attention to the electrostatic and electro-magnetic screening, but it may be necessary to work the valves under such conditions that they do not give the maximum amplification of which they are capable, so that the overall gain is not great enough for self-oscillation to occur. It is unusual for more than three stages of radio-frequency amplification to be used in any kind of receiver, and a single stage is very common in modern domestic receivers.



S_1 AND S_2 SELECT EITHER L_1 AND L_2 OR L_3 AND L_4 TUNING IS EFFECTED BY C_1.

FIG. VI.9.—Switching for Two Ranges

Practical Aspects of Radio-frequency Amplifiers

At higher frequencies, the voltages which are induced in circuits by mutual inductance and by capacitive coupling are appreciable, even with small values of mutual inductance or of capacitance.

The layout of the components is therefore important, and it is necessary to reduce inter-stage coupling to a low value as already stated. Apart from screening for electostatic purposes, coils are usually mounted with their axes mutually perpendicular to reduce inductive coupling. At radio frequencies it is also easy to obtain satisfactory electro-magnetic screening by enclosing coils in aluminium or copper cans. This screening reduces the Q of the coil, and care is necessary when high values of Q are required.

When high amplification at a high frequency is required, the valves are arranged in a long, straight line, with the components of each stage close to their valve, and the input is fed in at one end, while the output is taken from the other end.

CHAPTER 7

POWER SUPPLIES

In earlier chapters we assumed that the supplies necessary to operate thermionic valves were available, and we shall now deal with methods of producing them.

Generally speaking, there are two main supplies required, they are:

1. Low tension (L.T.) for heating the valve cathodes.
2. High tension (H.T.) for the anode supply.

L.T. supplies may be either direct or alternating, because it is only the heating of the cathode that liberates electrons, and A.C. may be used for this purpose, with certain limitations.

Sources of L.T. Supply

(*a*) Primary cells (d.c.).
(*b*) Secondary batteries (d.c.).
(*c*) Secondary of transformer (a.c.).

(a) *Primary Cells*

A primary cell converts chemical energy into electrical energy.

The simplest type consists of a copper and zinc plate in a solution of dilute sulphuric acid (Fig. VII.1). As long as there is no connexion between the two plates no chemical action will take place, but there will be a p.d. set up between them. When the two plates are connected by means of a wire, a current will flow from zinc to copper via the sulphuric acid (which is known as an electrolyte), and from copper to zinc via the wire. The copper plate becomes the positive terminal, and the zinc the negative terminal.

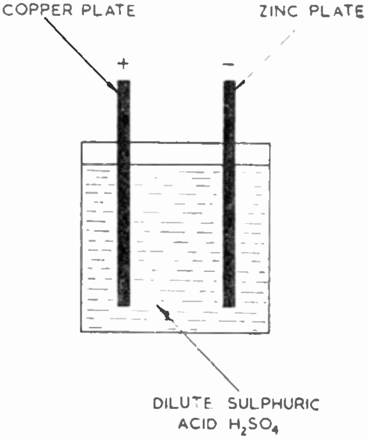


Fig. VII.1.—Simple Primary Cell

The chemical action has two parts:

(1) the zinc reacts with the electrolyte, forming zinc sulphate, and

(2) hydrogen is liberated at the surface of the copper.

The chemical action, after external connexion, is as under

$$Zn + H_2SO_4 = ZnSO_4 + H_2$$

Zinc + Sulphuric acid gives Zinc sulphate + Hydrogen.

This action will continue, while there is an external connexion, until there is no zinc or no sulphuric acid left. There is no reaction on the copper plate, but the liberation of hydrogen has a profound effect on the operation of the cell.

Polarisation of Cells and Internal Resistance

When a current is taken the SO_4 of the solution combines with the zinc plate, forming zinc sulphate, which is dissolved in the solution. The hydrogen collects around the copper plate, and is finally liberated into the surrounding air. The cell is said to be polarised when these bubbles of hydrogen form around the positive plate. The conductivity of hydrogen is less than that of the electrolyte, and the passage of current through the cell is seriously affected. This effect is conveniently visualised as an increase in " internal resistance ", which will result in a decrease in cell terminal p.d. when an appreciable current is taken from the cell, and a subsidiary effect of the hydrogen is to decrease the e.m.f. of the cell. The removal of the hydrogen is achieved by chemical action; the material that is used to remove the hydrogen is termed a depolarisor. The depolarisor (of which manganese dioxide is the most commonly used) is located around the positive plate, *i.e.*, where the hydrogen is formed.

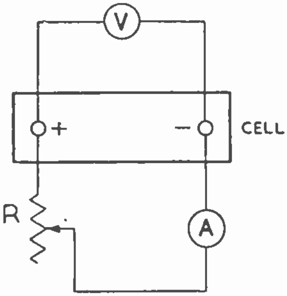


FIG. VII.2.—Cell on Load

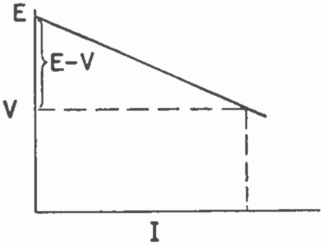


FIG. VII.3.—Characteristic of Cell

A way of visualising internal resistance is suggested by the following experiment:

A box with two terminals is connected to a voltmeter, ammeter and variable resistor (R) as shown in Fig. VII.2. As the resistance R is decreased, the current flowing (I) as indicated by the ammeter is observed to increase, and the voltmeter reading falls. If a series of readings is taken and a graph is plotted of voltage (V) against current (I) for different settings of resistor R, the graph obtained will be similar to that shown in Fig. VII.3. This result would be obtained if the box contained a source of constant e.m.f. E in series with a resistor r as shown in Fig. VII.4. A cell may be considered to be identical, electrically, with the box described above, *i.e.*, having resistance.

The e.m.f. of the cell depends on the nature of the electrodes and the electrolyte used, and not on the physical size of them. This latter condition determines the " life " of the cell, *i.e.*, the larger the quantities used the longer will the life of the cell become.

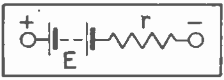


FIG. VII.4.—Equivalent Circuit of Cell

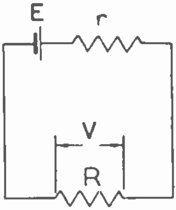


FIG. VII.5.—Calculation of Internal Resistance

The electrolyte used will obey Ohm's Law, and its resistance will vary directly with its length and inversely with its area. Therefore, the larger the area of the plates and the nearer they are together, the smaller will be the internal resistance of the cell. (It will be zero when they are touching, but then so will the terminal p.d.)

We have already seen the effect of internal resistance on cells, and now we will consider this effect in a more general form. In Fig. VII.5, E is the open-circuit e.m.f. of the source (cell, generator, etc.), r is the internal resistance of the source, R is a resistor the value of which is known accurately and V is the p.d. across resistor R.

$$\frac{E}{R+r} = I \text{ and } V = RI$$

$$\therefore \quad V = \frac{ER}{R+r}$$

$$V(R+r) = ER$$

$$rV = ER - VR$$

$$\text{From which } r = \frac{(E-V)}{V} \times R \text{ ohms.}$$

Leclanché Cells

These cells have been highly developed, and consist essentially of a zinc rod which is the negative terminal, immersed in a solution of ammonium chloride (sal ammoniac), together with a porous pot containing a carbon plate (positive terminal), surrounded by powdered manganese dioxide (depolarisor), and carbon granules (Fig. VII.6); the latter acts as a virtual positive electrode due to the fact that manganese dioxide is a very poor electrical conductor.

$$\text{e.m.f. of cell} \simeq 1{\cdot}0 - 1{\cdot}4 \text{ volts}$$

$$\text{internal resistance} \simeq 0{\cdot}6 - 1{\cdot}0 \text{ ohms.}$$

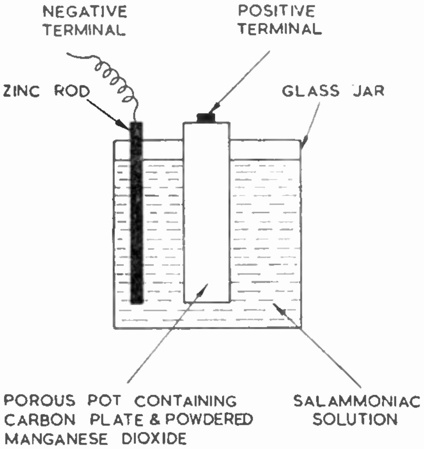


Fig. VII.6.—Leclanché Cell

There is no chemical reaction whatever (if the zinc is pure) until the external circuit is completed; when this is done the following reaction takes place:

The ammonium in the sal ammoniac changes places with the zinc, which is partly used to form zinc chloride, ammonia gas and hydrogen. Now the zinc chloride dissolves in the sal ammoniac solution, the ammonia gas combines with water to form ammonium hydrate and the hydrogen is set free. This is the hydrogen which, as we saw previously, gives us trouble, and it must be removed by means of the depolarisor.

As the hydrogen is liberated at the carbon plate it immediately comes into contact with the manganese dioxide, some of the oxygen of which combines with the hydrogen to form water, leaving manganese sesquioxide.

$$\begin{array}{ccccccccc} \mathrm{Zn} & + & \mathrm{2NH_4Cl} & = & \mathrm{ZnCl_2} & + & \mathrm{2NH_3} & + & \mathrm{H_2} \\ \text{Zinc} & & \text{Sal ammoniac} & & \text{Zinc chloride} & & \text{Ammonia gas} & & \text{Hydrogen} \end{array}$$

This H_2 liberated around the positive terminal combines with the MnO_2 thus :

$$\begin{array}{ccccccc} \mathrm{H_2} & + & \mathrm{2MnO_2} & = & \mathrm{Mn_2O_3} & + & \mathrm{H_2O} \\ \text{Hydrogen} & & \text{Manganese dioxide} & & \text{Manganese sesquioxide} & & \text{Water.} \end{array}$$

Leclanché cells are only suitable for taking current intermittently for short durations and then " having a rest ". There is a limit to the amount of depolarisation possible, and when this limit is exceeded the terminal p.d. falls rapidly, due to the increase in internal resistance of the cell with increase of current. This is what happens if a continuous current is taken from a Leclanché cell, and therefore they are most suitable for bell circuits, etc., where their period of life will be long because the current taken will be of short duration.

Dry Cells

All dry cells are improvements on the Leclanché cell (sometimes referred to as dry Leclanché cells), and are wrongly named, since their useful life ceases when they are quite dry. However, there is no free liquid in this type of cell, so there is some justification for their name. A typical construction uses a zinc cylinder, in the centre of which is a carbon rod insulated from the bottom of the cylinder, and round which a mixture of powdered manganese dioxide and carbon is tightly packed. The zinc cylinder has an external connexion brought out from it forming the negative terminal, the carbon rod forms the positive terminal and the manganese dioxide is the depolarising agent.

The " solution " in this type of cell surrounds the depolarising agent, and consists of a paste containing ammonium chloride with plaster of Paris and flour added. The chemical reactions are similar to those of a wet Leclanché cell, and the e.m.f.s of the two are identical. Provision is made for the escape of gases by vents through the top of the cell, and the whole cell is enclosed in a cardboard container.

The efficiency of operation of the cell depends on :

(1) Freedom from impurities in the chemicals used.

(2) The electrical contact between the pastes, the carbon and zinc used.

(3) The ability of the pastes to remain " wet " as long as possible.

The internal resistance of dry cells can be as low as 0·1–0·5 Ω, but when the cell begins to " dry-up " the internal resistance increases rapidly with a resultant fall in p.d. on load. The construction of modern cells enables them to be used satisfactorily for supplying the heater power of valve circuits. (Plate X.)

Plate X.—A Unit-type Dry Cell, Suitable for Supplying up to 0·3 A

(b) *Secondary Cells* (*Accumulators*)

Definition—a cell in which chemical energy may be restored in return for electrical energy.

A simple form of cell consists of two lead plates immersed in an electrolyte of dilute sulphuric acid (Fig. VII.7). In order that this arrangement should be capable of producing an e.m.f. the plates must undergo a change in their composition, which is known as " forming ". Briefly this is achieved by passing a current through the cell (from a direct supply) which causes a chemical change of the plates. When the forming is complete the positive plate of the cell is coated with lead peroxide (PbO_2) and has a chocolate-brown appearance, whilst the negative plate is still lead and has a light-slate-grey colour, having become spongy.

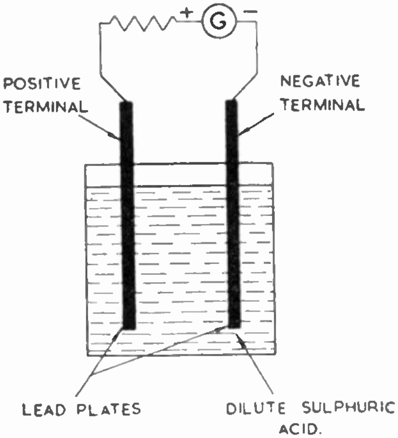


Fig. VII.7.—A Simple Secondary Cell

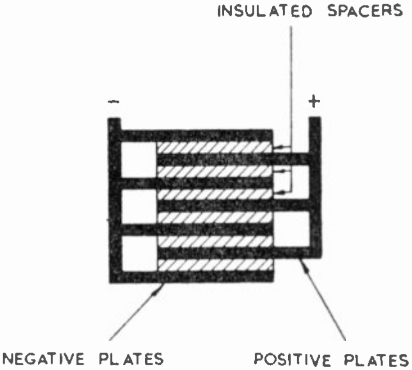


Fig. VII.8.—Arrangement of Multi-plate Accumulator

In practice, it is usual to have a multi-plate cell in which several plates are in parallel (there being one more negative plate than positive) and the plates are separated by insulating strips (Fig. VII.8).

The whole assembly is contained in a glass or plastic vessel which contains the electrolyte.

Indications that the cell is charged and ready for use are:

(1) Positive plates are a chocolate-brown colour and negative plates a light slate grey.

(2) Specific gravity of acid–water electrolyte approximately 1·22 (or as stated by the manufacturer).

(3) Plates gassing freely. The gassing is due to the liberation of hydrogen at the negative plate, and a smaller volume of gas (oxygen) at the positive plate.

(4) E.m.f. 2·2–2·5 volts on open circuit.

The internal resistance of secondary cells is of the order of 0·001–0·1 ohms, and because of this low internal resistance they are prone to damage if they are short-circuited. Consider a cell of 2 volts e.m.f., internal resistance 0·05 ohm, having a short-circuit applied to it. The current passing $I = \frac{2}{0 \cdot 05} = 40$ amperes and the power $= 2 \times 40 = 80$ watts, which is a considerable amount dissipated in a comparatively small space, and will cause local heating and distortion of the plates.

Nickel–Iron (Ni–Fe) Alkaline Cell

This is another type of secondary cell which is commonly called a "**Nife cell**".

It consists of an anode of nickel oxide (usually in a nickel-steel frame), a cathode of iron and an electrolyte of potassium hydroxide (caustic potash). It is lighter in weight than the lead–acid cell, and has no acid content; the e.m.f. is 1·3–1·4 volts, and is practically independent of electrolyte strength. Compared with the lead–acid type, (1) it is mechanically stronger, and (2) it will stand up to overcharging and excessive discharging. Its disadvantages are:

(1) variation of e.m.f. during discharge (1·4 volt–1 volt);

(2) it is more bulky than a lead–acid cell of corresponding energy capacity.

(c) *Secondary of Transformer*

This method of obtaining L.T. simply consists of a separate winding on the mains transformer.

In most practical mains transformers there are several l.t. windings and a winding for providing the anode supply (Fig. VII.9).

"Filament transformers", as their name implies, are used for filament supplies only. They consist of a primary and two or more secondary windings as required, and are used in equipment having many valves.

An alternating supply may be used for cathode heating, provided that there is no change of cathode temperature during the alternation of the heater current, which would cause a corresponding change in the anode current of the valve. This limitation does not apply to valves used in the output stage, which is relatively insensitive, and is overcome in other stages by the use of the indirectly heated type of valve.

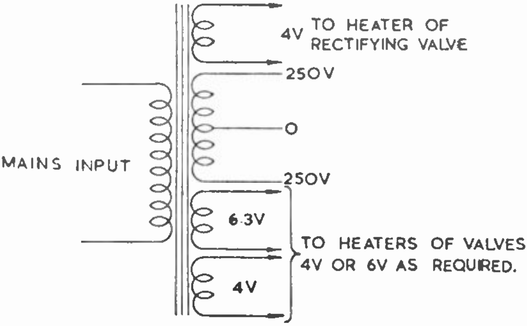


FIG. VII.9.—Typical Mains Transformer

Copper oxide and selenium rectifiers are means of obtaining direct l.t. supplies from such windings.

H.T. Supplies

- (*a*) h.t. primary batteries.
- (*b*) Diode half-wave rectifier.
- (*c*) Double-diode full-wave rectifier.
- (*d*) Metal rectifier.
- (*e*) Vibrator power supplies.

(a) *H.T. Primary Batteries*

These are identical in principle to the l.t. primary cells discussed previously, and are simply a number of these cells in series conveniently mounted in a single cardboard container. The e.m.f. of such units lies between 22½ and 135 volts and in some types tapping points are provided (Plate XI).

(b) *Diode Half-wave Rectifier*

The circuit shown in Fig. VII.10 shows a typical diode employed as a single-phase half-wave rectifier, and its operation is described below. The cathode of the diode is heated by a separate winding on the transformer.

Points *A* and *B* in Fig. VII.10 will be alternately positive and negative. Consider the instant when *A* is positive and *B* is negative; then since the anode is positive with respect to the cathode, there will be a flow of electrons from cathode to anode, or from one plate of the capacitor C_1 to the other, so that C_1 is charged and a p.d. is established across it. During the negative half-cycle (*i.e.*, when B is positive and A is negative) there will be no flow of electrons from cathode to anode, because the anode will be negative with respect to the cathode.

Plate XI.—A Dry Battery of Layer-type Cells

Suitable for miniature equipment; current drain 1 mA.

If the system is not supplying power (*i.e.*, if there is no circuit across C_1) the p.d. across C_1 will be equal to the peak value of the alternating p.d. Until the system supplies a load current (assuming no losses in the capacitor C_1) the anode will never be positive with respect to the cathode, therefore there will be no increase in potential across the capacitor C_1. When a load is applied there is a continuous current drain and the p.d. across the capacitor will fall during the time the diode V_1 is non-conducting, the result being that the output contains a " ripple " or is " pulsating " (Fig. VII.11). The ripple frequency is the frequency of the supply, and its amplitude may be reduced by the use of a suitable filtering circuit.

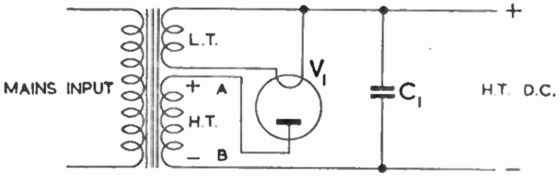


FIG. VII.10.—Diode Half-wave Rectifier Circuit

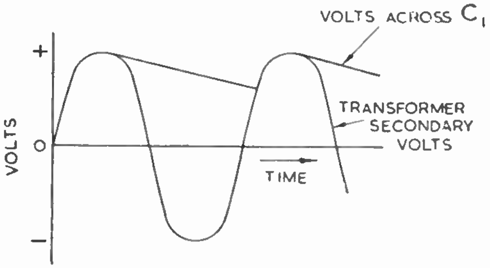


FIG. VII.11.—Operation of Half-wave Rectifier

Half-wave rectification is seldom used in practice because of two serious disadvantages given below :

(1) The secondary of the transformer carries the rectified current, thus producing direct magnetisation in the transformer core.

(2) The heating of the transformer windings is large in proportion to the current delivered, because of the short, heavy pulses of current.

(c) *Double-diode Full-wave Rectifier*

This method of rectification is usually employed (on single-phase supplies) and uses a centre-tapped transformer in conjunction with two diodes, the latter being contained in the same glass envelope and known as a double-diode or full-wave rectifier. The operation is the same for each diode as in the half-wave rectifier described above, and the arrangement is also known as a " bi-phase half-wave " rectifier or a " centre-tap " circuit.

Point *x* in Fig. VII.12 is always negative to point *a* or *b*, and V_1 conducts on one or the other of its anodes according to the sign of the secondary potential. The opposite ends of the transformer secondary are positive and negative alternately, and the alternating p.d. applied to the anodes of V_1 is half the secondary p.d. across points *a*, *b*. Furthermore, at the instant of time when there is maximum positive potential on one anode there will be maximum negative potential on the other anode. In the bi-phase rectifier the output will have less time in which to fall before the next half-cycle is rectified and the potential on C_1 is restored. There will, however, be a ripple in the rectified output which has a frequency of twice the supply frequency. In series with the load is an iron-cored choke of large inductance, and as we have previously found, inductance opposes changes of current and will produce an e.m.f. to oppose these changes. By the time the capacitor C_2 is charged a reasonably steady d.c. supply is obtainable with the ripple amplitude considerably reduced. Capacitors C_1 and C_2 are usually electrolytic capacitors, because a larger value of capacitance (which is necessary) can be obtained in a smaller size than if paper capacitors are used.

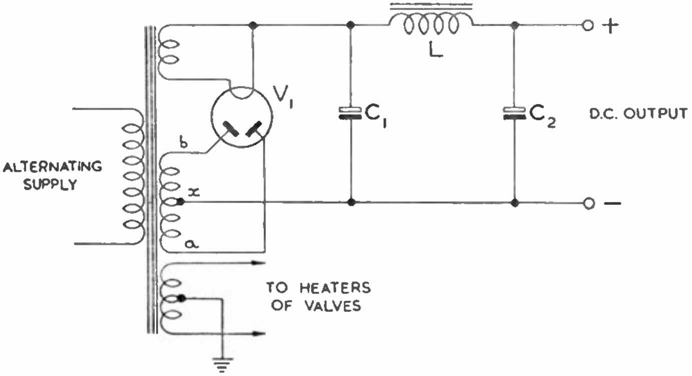


FIG. VII.12.—Double-diode Full-wave Rectifier Circuit

Typical values of components are :

C_1 = 16 μF, 500 volts d.c. working electrolytic (sometimes as high as 32 μF) ;

C_2 = 16 μF (or larger) 500 volts d.c. working electrolytic;

L = 10–30 H (at required current rating);

Typical maximum d.c. output—250 volts at 60 mA, or 350 volts at 120 mA, depending on the requirements;

Typical maximum filament current 2–10 amperes from l.t. windings on the same transformer.

Advantages of full-wave rectifiers over half-wave rectifiers are that they produce a more constant rectified output than the latter, and they cause no resultant transformer-core magnetisation due to direct current flow through the secondary, because of the cancellation of the direct current flowing in each half of the transformer secondary in opposite directions.

(d) *Metal Rectifier*

The construction of metal rectifiers has already been discussed (Chapter 4), and they can be used in the circuits already described for diode valves. The metal rectifier has the advantage of requiring no heater supply. A single-phase half-wave rectifier circuit is shown in Fig. VII.13, and the arrow-head shows the direction of easy current flow (conventional). The remainder of this circuit is similar to Fig. VII.14.

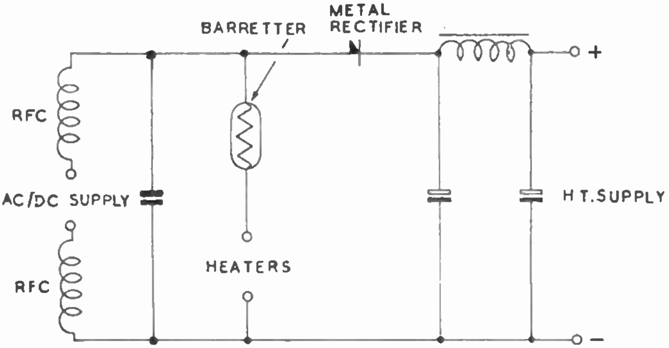


FIG. VII.13.—A.c./d.c. Circuit with Metal Rectifier

Metal rectifiers are generally used for providing low direct potentials for charging secondary cells or for particular applications where direct l.t. supplies are required, and they are found to some extent serving as rectifiers for h.t. supply, although when high powers are involved they are more bulky than valve rectifiers.

Power Supplies for Alternating or Direct Current Working

It is impossible to operate a transformer on direct current, and in order to reduce the heater load current in a.c./d.c. circuits the valve heaters are connected in series, *i.e.*, the heater current of each valve is the same. Two typical power-supply units for a.c./d.c. working are given in Figs. VII.14 and VII.15.

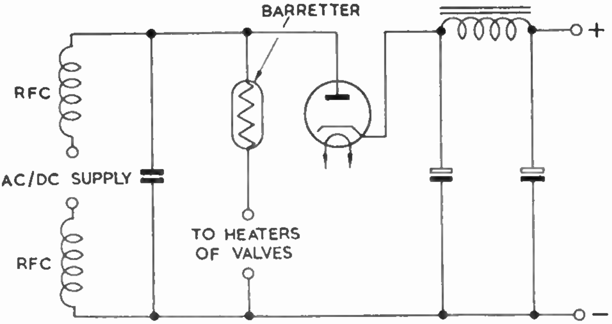


FIG. VII.14.—A.c./d.c. Circuit

Power supplies of this type necessarily employ half-wave rectification, and when d.c. supplies are used the diode conducts all the time, appearing simply as a low resistance in the circuit. Often valves manufactured for a.c./d.c. working have their heaters

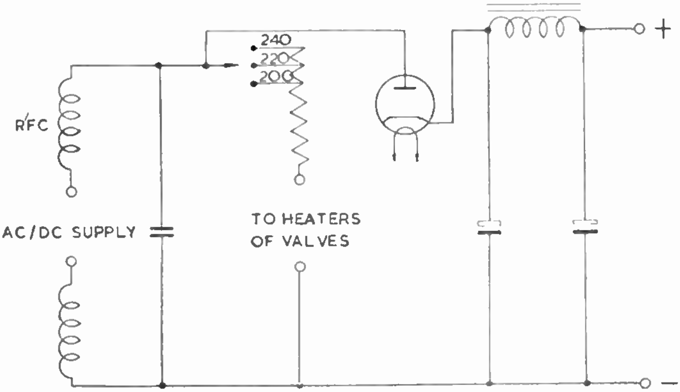


FIG. VII.15.—A.c./d.c. Circuit

designed to work at a higher p.d. than valves primarily intended for a.c. working. Such a.c./d.c. valves having heater p.d.s lying between 30 and 115 volts are quite common. By means of a suitable resistor from the supply line, valve heaters may be supplied with their correct heater p.d.s. In Fig. VII.14 a "barretter" is employed for the heater supply, whilst in Fig. VII.15 a "dropping resistor" is used with tappings for various supplies.

A " barretter " is a device for maintaining a constant current in a circuit when the p.d. across it is changed, and consists, in one type, of a resistor of iron wire contained in a glass envelope filled with hydrogen.

Metal rectifiers are often used in this type of circuit, as the valve rectifier has to be constructed with good insulation between heater and cathode, and so requires a considerable time to warm up. (Fig. VII.13.)

Regulation

It is important in all types of power supplies that when current is taken from the supply the terminal p.d. does not fall appreciably.

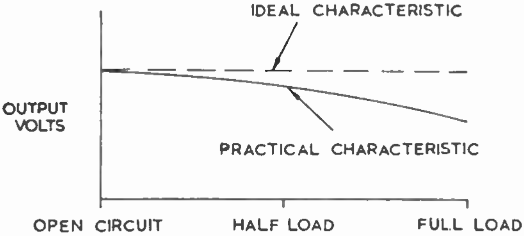


FIG. VII.16.—Regulation of Power Supply

The ideal arrangement would be for the terminal p.d. to remain constant from " no load " to " maximum load " (Fig. VII.16).

The amount of deviation from the no-load condition is determined by the loss in the components used, which in turn will vary with the current flowing through them. The " goodness " of a power supply is termed its regulation, and is defined as the ratio of :

$$\frac{\text{No load terminal p.d.} - \text{maximum load terminal p.d.}}{\text{No load terminal p.d.}}.$$

Regulation is generally expressed as a percentage, and in practice, regulations of the order of 30 per cent. are usual.

(e) *Vibrator Power Supplies*

Where space is important (*e.g.*, vehicles, aircraft, etc.) and a low-potential d.c. source is available, high potentials can be produced by using a vibrating contact to change direct current into alternating current. This is then applied to a step-up transformer and rectified. A typical arrangement of a non-synchronous vibrator is shown in Fig. VII.17, and the operation is as follows: At the instant of switching on current will flow through the half of the primary winding marked BC only because there is no circuit via points AB. Coil X is energised, and the vibrating tongue is attracted to the bottom contact H. This short-circuits coil X, and the vibrating tongue is released and overshoots the central position to close on to the top contact F. The current now flows through the half of the primary winding marked AB, and the vibrating tongue tends to return to a central position. However, coil X is energised once more, and the vibrating tongue is attracted to the bottom contact H, and the whole sequence of events is repeated. This action causes a p.d. to be applied across one-half of the transformer and then across the other half in the opposite direction, thus producing an alternating p.d. on the transformer secondary. Resistors R_1,R_2 and capacitor C_1 are employed to prevent damage to the contacts due to sparking. Owing to the repeated making and breaking of circuits, unwanted surges are produced of radio frequencies which would be passed on to associated equipment, and to reduce this interference C_2 is placed across the transformer secondary. Choke L_2 prevents this radio frequency from being fed back into the direct supply, and C_3 is to reduce any radio frequency that may be present after rectification. Capacitors C_4, C_5, and inductor L_1 are normal filter components already discussed. Fig. VII.18 shows how an additional pair of contacts, on either side of the vibrating tongue, can be used to rectify the output from the secondary of the trans-

Should be shown in central position

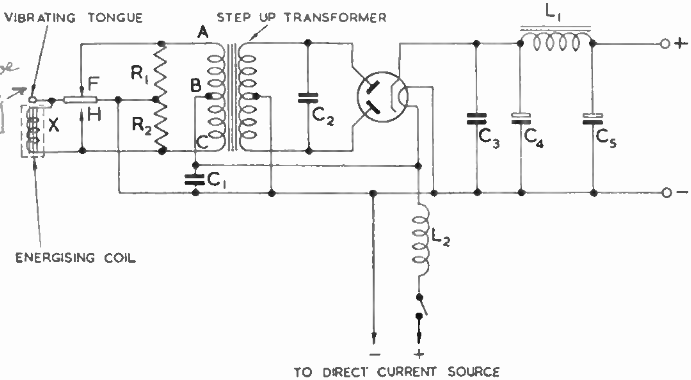


Fig. VII.17.—Simple Vibrator h.t. Unit

former, and thus to eliminate the need for a rectifying valve. This arrangement is known as a synchronous vibrator. Vibrator power supplies have several disadvantages:

(1) They require periodical attention to keep them in good working order.

(2) They produce unwanted "clicks", "sparks", etc., and are therefore electrically noisy.

(3) They require secondary batteries to drive them.

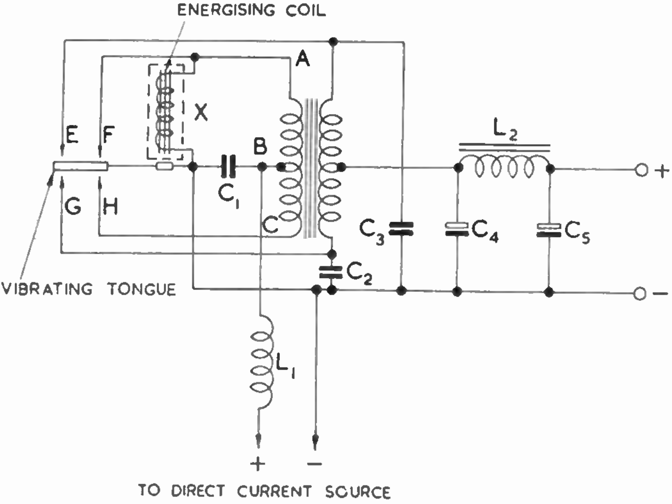


FIG. VII.18.—Self-rectifying Vibrator Unit

They are necessary for use in mobile equipment or in isolated areas where only low-potential direct supplies are available.

Choice of Power Supplies

The type of power supply used is largely dictated by the nature of the equipment.

For domestic receivers, mains supply is preferable whenever it is available, as it is cheaper and its use permits more efficient valves to be employed. If an alternating supply is available, the usual arrangement is the bi-phase rectifier circuit and l.t. supplied from a separate winding on the mains transformer. Receivers intended to be transportable are usually fitted with a.c./d.c. valves and the appropriate circuit in order to avoid the additional weight of the mains transformer and to cater for the possibility of being operated from a direct supply. Where mains supply is not available, h.t. battery and l.t. accumulator or dry cell is the usual arrangement, but for use in remote districts where batteries may not be readily obtained, a secondary battery and vibrator system must be used, as it is always possible to provide some means of re-charging the secondary battery.

Lightweight portable receivers use dry h.t. battery and dry-cell l.t., sometimes of specially small dimensions and weight if length of useful life is not very important.

Amplifiers and high-powered equipment are operated at relatively high potentials if possible, and are best fed from an alternating supply, which may be obtained by rotating machinery if only a direct supply is available.

Receivers for use on ships and aircraft are operated either from a direct source using vibrators or from a special alternating source usually installed for the purpose.

CHAPTER 8

OSCILLATORS

IN radio work the electronic generator or " oscillator " is used in many forms. In this chapter it is intended to discuss further the properties of resonant circuits and to consider the principles of some well-known oscillators.

Natural Frequency

In Chapter 3 an expression was given for the resonant frequency (f_r) of a circuit, which is the frequency at which the maximum current flows for a given applied e.m.f.; the current which flows under these conditions is a " forced oscillation " of current.

There is another frequency at which the circuit would oscillate if allowed to, which is known as the " natural frequency " (f_n) and is the frequency of " free " oscillations. Numerically $f_n = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$, but in practice $\frac{R^2}{4L^2}$ is small compared with $\frac{1}{LC}$, and may therefore be neglected so that the expression is very closely equal to

$$f_n = \frac{1}{2\pi\sqrt{LC}} \text{ c/s}$$

where L is in henrys and C is in farads.

This formula is identical with the one given for the resonant frequency (f_r), and it so happens that the approximation for f_n is identical to f_r, although the two results are arrived at from entirely different and independent considerations.

For all but the most exact purposes $f_r = f_n$, but it must be remembered that theoretically f_n is always lower than f_r.

Fig. VIII.1 shows a resonant circuit with a switch to enable it to be broken. While the switch is open, the capacitor C is charged from a suitable source. The switch S is then closed, and the p.d. across the capacitor C will cause a current i to flow

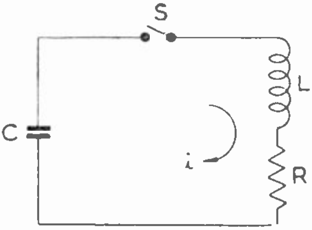


FIG. VIII.1.—Simple Resonant Circuit

through the inductor L and resistor R, the value of which depends on L and R. A magnetic field will be set up around L by the current i, which will induce a back e.m.f. in L according to Lenz's Law, opposing the rise of current. At the same time energy is put into the magnetic field. When the p.d. across C has fallen to zero, there will be no energy in the capacitor. The energy is now stored in the magnetic field surrounding L, and some energy was lost in the resistor R due to the current in it and the p.d. across it. The magnetic field then collapses and induces an e.m.f. in L, which charges the capacitor in the opposite direction, and the whole sequence of events is repeated. Fig. VIII.2 shows how the current i varies with time; the frequency remains constant, but the amplitude decreases with time. Such a discharge is known as a "damped" oscillation, the word "damped" referring to the decreasing amplitude due to resistance R; finally, as Fig. VIII.2 shows, the oscillation dies away to zero.

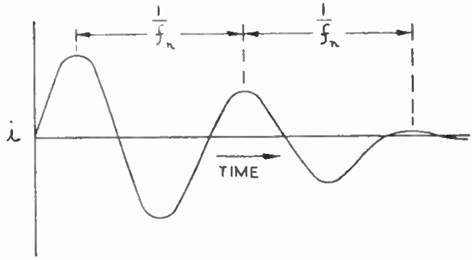
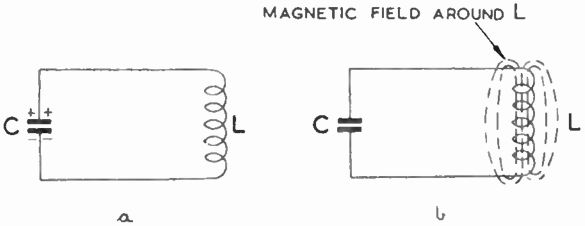


Fig. VIII.2.—Damped Oscillation



TOTAL ENERGY STORED IN CAPACITOR

TOTAL ENERGY NOW TRANSFERRED TO COIL L

Fig. VIII.3.—Energy in Oscillatory Circuit

Circuits containing inductance and capacitance which do not "oscillate" in this way are said to be "aperiodic". Referring back to the expression for f_n, this condition arises when $\frac{R^2}{4L^2}$ is greater than $\frac{1}{LC}$. When $\frac{1}{LC} = \frac{R^2}{4L^2}$, then the circuit is said to be "critically damped", and any discharge around the circuit is expended in one direction.

In practice it is possible to make $\frac{R^2}{4L^2}$ negligible compared with $\frac{1}{LC}$, so that almost all of the energy from, say, the capacitor will be transferred to the coil and vice versa (Fig. VIII.3).

Under these conditions the energy equations will be very nearly equal.

i.e., Maximum energy stored in capacitor $= \frac{1}{2}CV^2$ joules, where V is the maximum p.d.

Maximum energy stored in coil $= \frac{1}{2}LI^2$ joules, where I is the maximum current through the inductor

and $\frac{1}{2}CV^2 = \frac{1}{2}LI^2$ very closely.

Negative Resistance and the Dynatron Oscillator

When a circuit is caused to oscillate, it does so for a relatively small number of cycles of decreasing amplitude, owing to the expenditure of energy in the resistance of the circuit. In order to sustain the oscillations, there must be no expenditure of energy, or the resistance of the circuit must be zero. Since there must be some resistance in the components, this could be achieved theoretically by adding a "Negative Resistance" to the circuit, thus making the total circuit resistance zero.

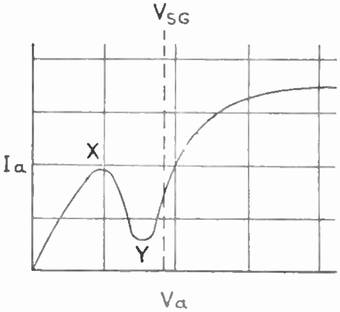


FIG. VIII.4.—Characteristic of Tetrode Valve

Resistance is that property of a conductor which causes the current through it to increase when the p.d. across the conductor is increased, so that negative resistance must be that property which causes the current to decrease when the p.d. is increased. This effect can be produced by making use of a valve. Consider the I_a/V_a curve of a tetrode valve (Fig. VIII.4). From the graph, over the portion XY, an increase in V_a produces a decrease in I_a, and the anode circuit has a resistance r_a which is apparently negative.

In a tetrode valve this condition can be obtained when the screen is operating at a higher positive potential than the anode (Chapter 6, page 102). Having obtained the effect of a negative resistance and also having a parallel resonant circuit, a suitable combination of the two will permit the generation of sustained oscillations. Fig. VIII.5 shows such a combination, which is known as a dynatron oscillator.

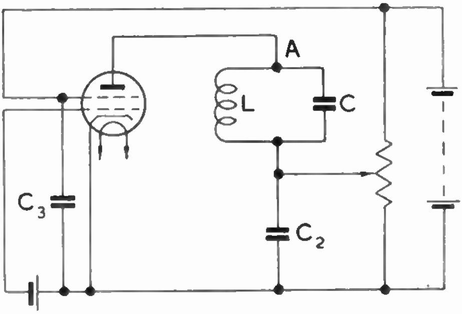


FIG. VIII.5.—Dynatron Oscillator

Triode Oscillators

The production of continuous oscillations is also achieved by replacing the energy lost in the resistance of the resonant circuit. This can be done by a valve arranged as an amplifier, taking its input from the tuned circuit, and delivering its output back to the tuned circuit in such a way as to replace the losses (Fig. VIII.6). Another conception of the effect of the valve on the tuned circuit is to consider that the p.d. across the tuned circuit will be increased, which is the same thing as saying that the resistance of the circuit has been decreased or the effect of a negative resistance introduced.

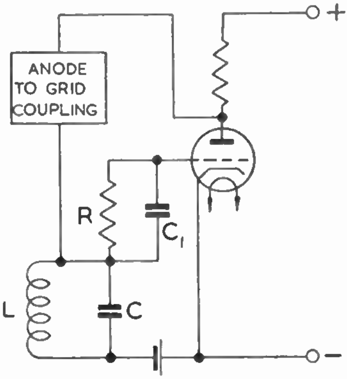


FIG. VIII.6.—Principle of Triode Oscillator

All feed-back oscillators consist of an amplifier providing its own input, and the conditions for oscillation to occur (and be maintained) are that the energy fed back shall provide sufficient input to the system, in the correct phase to assist oscillation. There are many circuits fulfilling these requirements, and in this volume we shall consider only the well-known basic circuits.

The Colpitts Oscillator

In the Colpitts oscillator the tuned circuit consists of an inductor L in parallel with two capacitors C_1 and C_2, which are in series with each other (Fig. VIII.7). When an oscillatory p.d. is produced across the parallel tuned circuit, the points A and G will have potentials in anti-phase to each other, and the point K will have a potential between the potentials of A and G. As the anode and grid potentials of a valve are also in anti-phase the circuit is self-oscillatory. It will be noticed that the potential applied to the grid is obtained from C_2, and the degree of coupling between anode and grid is dependent upon the relative values of C_1 and C_2. For conditions of maximum power in the oscillatory circuit the impedance (or dynamic resistance) of the oscillatory circuit should be equal to the r_a of the valve. This is also the condition of maximum efficiency. From Chapter 3 the dynamic resistance of an oscillatory circuit is given by $\frac{L}{CR}$, where R is the resistance of the inductive arm. This value $\frac{L}{CR}$ is made equal to the r_a of the valve, and its value may be altered by providing tapping points on L and connecting point A to the appropriate tap.

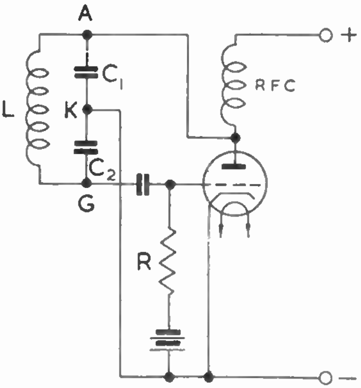


FIG. VIII.7.—The Colpitts Oscillator

The frequency of operation is determined by the tuned circuit and is given by :

$$= \frac{1}{2\pi\sqrt{L\,\frac{(C_1C_2)}{(C_1 + C_2)}}} \text{ c/s}$$

where L is in henrys and C_1, C_2 are in farads.

The Hartley Oscillator

The Hartley circuit is very similar to the Colpitts, but instead of the coupling being capacitive (as in the Colpitts) it is inductive. There are two basic arrangements of Hartley oscillators, they are :

(*a*) the series fed,
(*b*) the shunt fed.

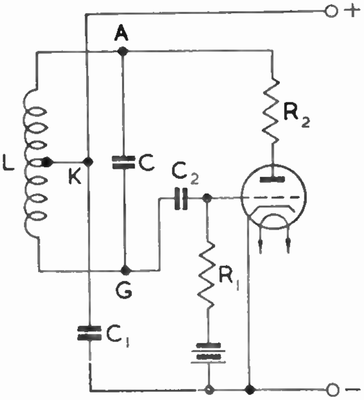


Fig. VIII.8(*a*).—Series-fed Hartley Oscillator

The difference between the two types lies in the isolation of the tuned circuit from the H.T. supply in the shunt-fed type which is often desirable. Both arrangements, however, have the same basic principle of operation. Fig. VIII.8(*a*) shows a series fed, and Fig. VIII.8(*b*) shows a shunt-fed Hartley circuit.

As in the Colpitts circuit, when an oscillation is set up in the tuned circuit an oscillatory p.d. is produced between *G* and *K*, and for self-oscillation to occur this p.d. must be in anti-phase to that existing between anode *A* and cathode *K*. Clearly *K* must always be at some intermediate value between *G* and *A*, and considering *G* to

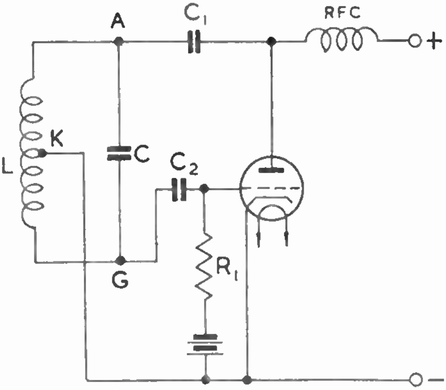


Fig. VIII.8(*b*).—Shunt-fed Hartley Oscillator be positive to K at any instant, then A must be negative to K at the same instant and vice versa, thus the circuit is self-oscillatory.

The degree of coupling is determined by the position of the tap K and the frequency of operation is given by $f = \frac{1}{2\pi\sqrt{LC}}$.

The Tuned-Anode Oscillator

This circuit employs yet another method of feed-back, namely "mutual coupling". Fig. VIII.9 shows a typical Tuned-Anode oscillator, and when oscillations are set up in the tuned circuit, which is between anode and cathode, an oscillatory e.m.f. is induced between grid and cathode by means of the mutual coupling existing between the two coils, and the two potentials are 180° out of phase with each other. The degree of coupling between anode and grid is dependent on the amount of coupling existing between the two coils. The frequency of operation is determined by the tuned circuit as before.

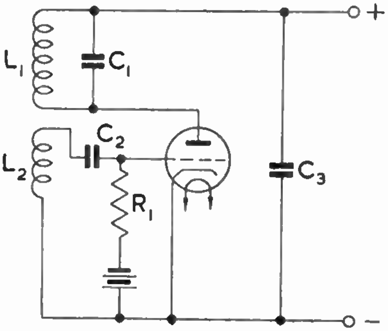


FIG. VIII.9.—Tuned-Anode Oscillator

Obtaining Output from Oscillators

All oscillators are means of generating an alternating e.m.f. at some desired frequency, and to make use of them it is necessary to obtain this e.m.f. from a convenient point. This may be done by connecting a small capacitor to the anode of the valve, and taking the output from the other side of the capacitor and from the cathode line (Fig. VIII.10(*a*)).

Another method of obtaining the output is to use a winding of a few turns inductively coupled to the coil of the oscillatory circuit (Fig. VIII.10(*b*)). The coupling is always arranged to have as small an effect as possible on the tuned circuit, so that variations in the load imposed do not alter the resonant frequency of the oscillator to a serious extent.

Oscillators of the types discussed can be used for the production of alternating e.m.f.s at any frequency, provided that suitable values of inductance and capacitance are obtainable. For the generation of radio-frequency between 20 kc/s and 100 Mc/s

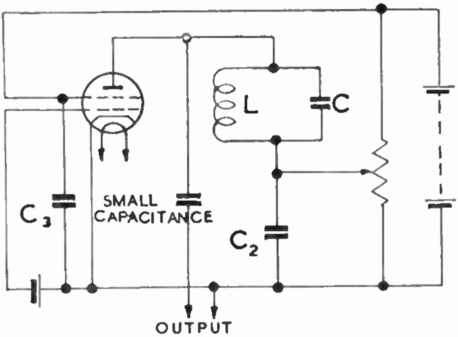


FIG. VIII.10(*a*).—Capacitive Coupling to Oscillator

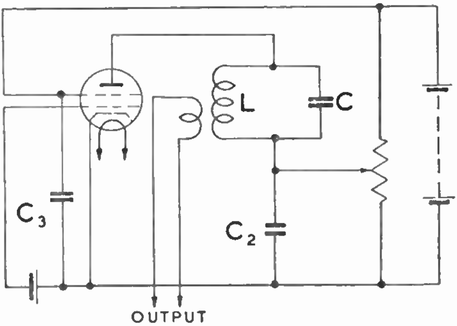


FIG. VIII.10(*b*).—Inductive Coupling to Oscillator

these circuits are satisfactory, although the dynatron is a more difficult type to operate, as it depends on the physical characteristics of the valve for secondary emission to occur at the anode.

CHAPTER 9

MODULATION AND DETECTION

Transmission of Intelligence

In Chapter 2 it was mentioned that telephony was transmitted by controlling the amplitude of the radio-frequency applied to the aerial. The use of different wavelengths for transmission over different distances was also mentioned, and in Chapter 3 the use of aerial systems of a size according to the wavelength of operation was discussed.

The direct transmission of audio frequencies is rendered impossible by the wide range of frequencies (20 c/s to 20 kc/s) involved, as well as by the fact that it is impossible to achieve appreciable radiation of energy at the low frequencies, while it would also be impossible to separate wanted and unwanted transmissions, because all stations would be transmitting similar frequencies simultaneously.

Carrier Waves

The method of transmission adopted is to use a radio frequency which is peculiar to the station concerned, and the same frequency is allocated to another station only if it is far enough away geographically to prevent mutual interference, or if both stations are transmitting the same programme. The frequency is chosen according to the distance over which it is desired to transmit, and the radio frequency is known as the " carrier " frequency, while the radiation it causes is known as the " carrier wave ". This wave induces a corresponding e.m.f. in receiving aerials, and is only passed through receivers tuned to the appropriate frequency.

Modulation

One method of transmitting a programme is to regulate the envelope of the carrier wave in accordance with the audio-frequency signals from the studio. The carrier wave is then said to be amplitude modulated. Various methods of combining the two frequencies (carrier and audio) may be employed. It is not sufficient merely to inject the two frequencies into a common circuit, but the common circuit must have special features. These features have the effect of multiplying the two instantaneously applied signals together so that if the audio frequency is represented by $v_{af} = V_m \sin pt$ and the carrier frequency by $v_r = V_m \sin \omega t$, then the resultant modulated carrier is

$$v = V_m \sin \omega t \, (1 + m \sin pt)$$

(where m = modulation depth described below).

Modulation Depth

Fig. IX.1(*a*) shows the intelligence frequency, Fig. IX.1(*b*)

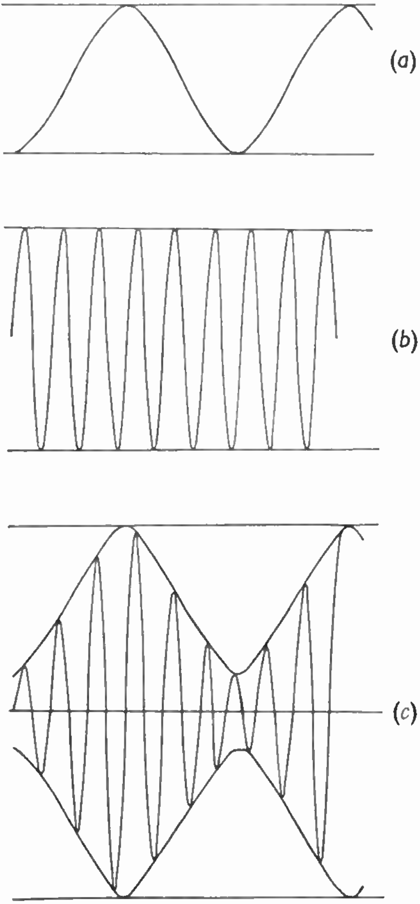


FIG. IX.1.—Illustrating Amplitude Modulation

shows the carrier frequency, and Fig. IX.1(*c*) shows the resultant amplitude modulated wave or envelope as it is sometimes called.

When the amplitude of the modulated envelope varies from maximum to zero value the carrier wave is said to be modulated to a depth of 100 per cent.; this represents the maximum modulation depth possible without introducing distortion. Another way of expressing this is to refer to the degree of modulation denoted by the symbol m, and in the case considered above

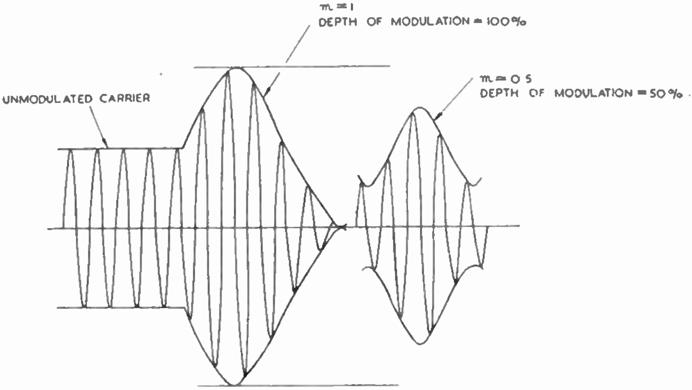


FIG. IX.2.—Illustrating Depth of Modulation

$$m = 1$$
$$= \frac{\text{average envelope amplitude} - \text{minimum envelope amplitude}}{\text{average envelope amplitude}}$$

Fig. IX.2 shows a carrier wave modulated by a single sinusoidal audio frequency to a depth of 100 per cent. ($m = 1{\cdot}0$) and to 50 per cent. ($m = 0{\cdot}5$).

Side Bands

Consider the simple case of a pure sinusoidal audio-frequency signal of a single frequency f_m. When the carrier frequency f_c is amplitude modulated by f_m, the resultant modulated wave may be resolved into three distinct waves:

(1) The carrier wave at frequency f_c.

(2) A wave at a frequency of $(f_c + f_m)$—known as the *upper side frequency*.

(3) A wave at a frequency of $(f_c - f_m)$—known as the *lower side frequency*.

When f_m is made of several frequencies then $(f_c + f_m)$ and $(f_c - f_m)$ will each comprise a band of frequencies known as the upper and lower sidebands respectively.

Expanding on the above a little further, we can say that the carrier wave is the same whether modulation is present or not, and itself conveys no intelligence, so that all the intelligence is contained in the side bands. Furthermore, for every modulation frequency there will be two side bands (one upper and one lower) present in the modulated wave, the amplitude of each of which will be one-half of the modulation depth. The extent of the side bands is entirely dependent on the frequencies modulating the carrier wave, and any restriction of the side bands will result in a corresponding loss of intelligence. The amount of power contained in the side bands is proportional to m^2, and so the energy in the side bands will decrease rapidly as the modulation depth decreases.

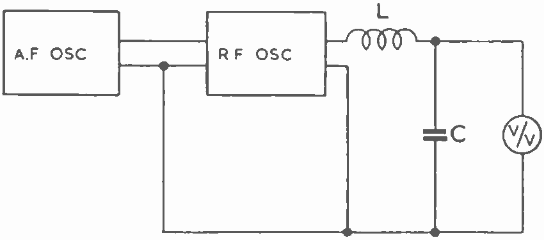


FIG. IX.3.—Method of Detecting Presence of Side Frequencies

It must be realised that what has been said about the make-up of an amplitude-modulated wave is not a " mathematical trick " but is a physical fact, and may be demonstrated very well with an audio-frequency oscillator, radio-frequency signal generator, series tuned circuit and a valve voltmeter connected as shown in (Fig. IX.3). If the audio-frequency oscillator is made to modulate the radio-frequency signal generator and the p.d. across the capacitor is measured at various frequencies, then the carrier frequency and two side bands may be readily identified.

Anode Modulation

Modulation is carried out at a convenient stage in the transmitter. It may be applied direct to the oscillator, as in the method employed originally by Heising, and for simplicity we shall take this case first. Heising employed a low-frequency choke in the anode of the modulating valve, and for this reason it is often referred to as " choke modulation ".

A typical circuit is given in Fig. IX.4. V_1 is the radio-frequency oscillator valve, which is suitably coupled to a tuned circuit and thence to the transmitting aerial. V_2 acts as a normal audio-frequency amplifier, and L_4 is a high impedance to all audio frequencies. The potential of the anode of V_2, and therefore of V_1, will vary in accordance with the audio input. L_3 is a radio-frequency choke to prevent radio-frequency signals from reaching the anode of V_2. With no input to V_2 the amplitude of the carrier frequency from the radio-frequency oscillator will be constant. If an input is now applied to the grid of V_2 so that the anode current of V_2 is reduced, a back e.m.f. will be set up across L_4, which will increase the p.d. across it (Lenz's Law) and so increase the anode potential of both valves; the current in V_1 will increase accordingly. If now the audio input of V_2 is such that it causes the anode current of V_2 to be increased, the anode potential of both valves will be reduced. The output of the radio-frequency oscillator depends on its anode potential, and the amplitude of the carrier frequency from the radio-frequency oscillator is varied in the same manner as the audio-frequency input of V_2. The result is an amplitude-modulated wave similar to that shown in Fig. IX.1(*c*). The disadvantages of this method are mainly due to the position of the choke L_4, which must be capable of dealing with large changes of anode potential and current without introducing distortion. Further, when an oscillator valve has its anode potential varied appreciably the frequency of oscillation varies slightly, so that unless precautions are taken, high modulation will cause the carrier frequency to be affected. By modulating a radio-frequency amplifier instead of the oscillator the variation of oscillator anode supply is eliminated, and thus one of the dis-

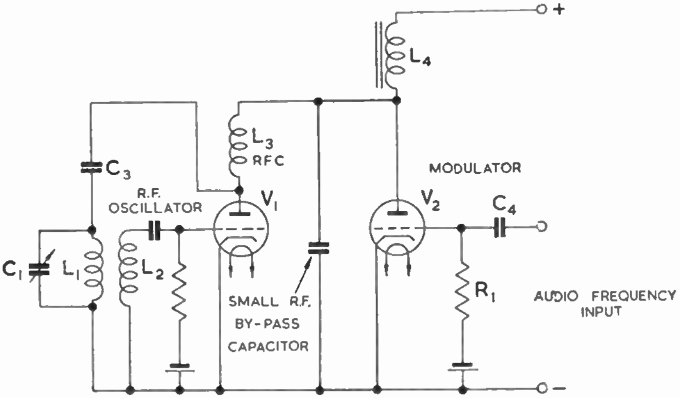


FIG. IX.4.—Anode Modulation

advantages of the previous method is overcome. This arrangement, however, requires the use of a previous stage to produce the radio-frequency carrier.

Series Modulation

Another arrangement of the above method is to place the two valves in series, as in Fig. IX.5, instead of effectively in parallel.

V_1 is the high-frequency amplifier valve with a radio-frequency choke L_1 as its anode load. The carrier-frequency input is applied between grid and cathode of V_1. Across the anode and the cathode of V_1 is a resonant circuit tuned to the required frequency by means of C_2L_2. The radio-frequency amplifier presents a load to the modulator-valve anode V_2, and the audio-frequency input is applied between the grid and cathode of V_2. The changes in the input of V_2 due to the audio signal give rise to corresponding changes in h.t. supply to V_1, with the result that the radio-frequency carrier amplitude is varied accordingly.

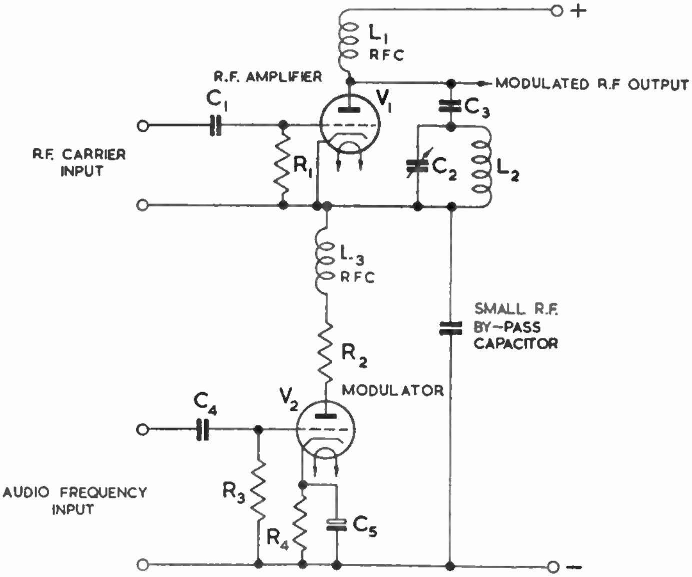


FIG. IX.5.—Series Modulation

One disadvantage with this system is the large value of H.T. required in order to operate two valves in series as shown in Fig. IX.5. Also the cathode of V_1 is at a considerable potential above earth, and precautions are necessary for the successful operation of such a system.

Grid Modulation

The simplest form of this method of modulation consists of a radio-frequency oscillator operating at the carrier frequency, the audio frequency being introduced into the grid of the oscillator valve (Fig. IX.6).

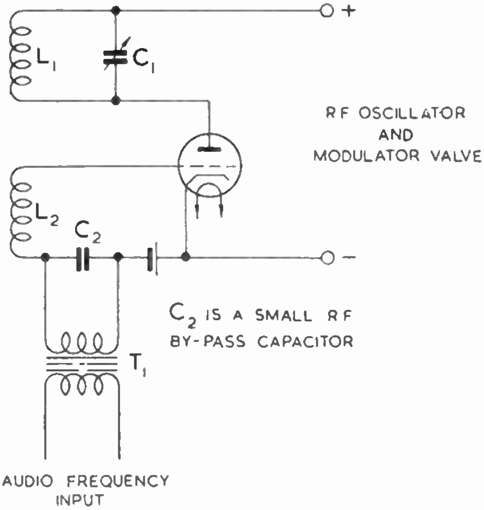


FIG. IX.6.—Grid Modulation

The audio-frequency input to the grid circuit varies the grid bias and modulates the radio-frequency carrier amplitude in accordance with the variations of the audio input. At high values of percentage modulation, amplitude distortion occurs, and it is mainly for this reason that this method of modulation is seldom used.

Detection of Amplitude-modulated Waves

The " detection " (also referred to as " rectification " or " demodulation ") of radio waves is the process of obtaining the intelligence transmitted from the modulated wave, and ideally the intelligence is reproduced exactly as it was applied to the modulated wave. If there is not exact reproduction, then some form of distortion is present.

A detector is essentially a non-linear device, *i.e.*, a device that will pass current more readily in one direction than the other for example, a valve.

The Simple Diode Detector

In Fig. IX.7 is shown a simple circuit employing a diode as a detector.

Consider the time when the rising portion of the positive half-wave of the signal is applied to the anode of the diode. Because the anode is at a higher potential than the cathode, current will flow and charge the capacitor C_2. Later during the radio-frequency cycle the input will be such that the anode is negative to the cathode and no anode current will flow. During the time when the diode is non-conducting, the capacitor C_2 is being discharged by the resistor R_1, which is of the order of 0·25–3 MΩ. On each cycle of the radio frequency the whole sequence of events is repeated, and across C_2R_1 appears the intelligence from the modulated wave. The values of R_1 and C_2 are chosen so that the

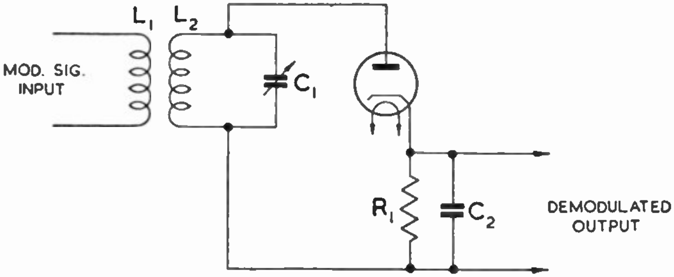


FIG. IX.7.—Diode Detector

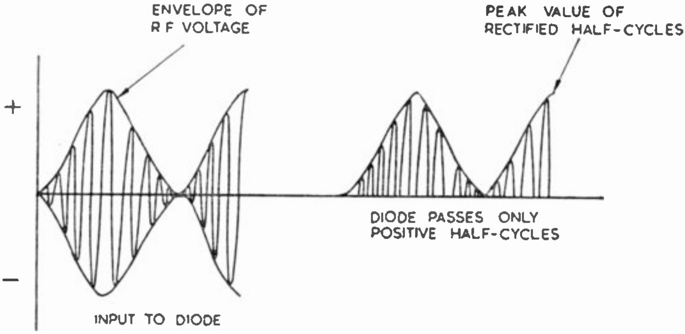


FIG. IX.8.—Operation of Diode Detector

necessary discharge of C_2 by R_1 can be accomplished at the highest modulation frequencies transmitted. The discharge of C_2 sets a limit to the frequency at which the circuit will operate without distortion, because it is not always possible to arrange the C_2R_1 combination so that the discharge of C_2 is rapid enough to follow the modulation frequency. Further distortion may be introduced by curvature of the diode characteristic.

The operation of the diode detector is shown in Fig. IX.8, and it will be seen that the output consists of the positive half-cycles of the radio-frequency input, so that its value is varying at the modulation frequency. It is desirable to filter out the radio frequency before passing the signal on to later stages, and this is done by the circuit of Fig. IX.9. The choke has a high reactance at radio frequencies, but offers little impedance to audio frequencies, while the capacitor has relatively low reactance at radio frequencies and high reactance at audio frequencies. This is so because of the high ratio of radio frequency to audio frequency—at least 10 to 1 and usually much greater. The output from the filter circuit is simply the smoothed value of the input. A resistor is often used in place of the radio-frequency choke, this being cheaper and occupying less space.

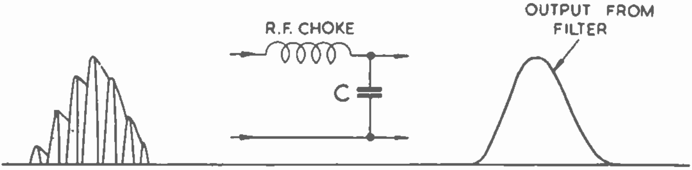


FIG. IX.9.—R.f. Filter

The Cumulative Grid Detector

This type of detector employs a triode, the grid of which functions as the anode of a diode detector. Fig. IX.10 shows a typical circuit, and as before the C_2R_1 combination is selected for the highest modulation frequency desired.

The operation of the cumulative grid detector is precisely similar to that of the diode detector. The grid and cathode act as anode and cathode of the diode detector, and because the grid takes current if driven positive, the right-hand plate of the capacitor C_2 becomes charged. The potential of the grid is shown in Fig. IX.11, and is of a similar form to that obtained from the diode circuit of Fig. IX.7, but of opposite polarity because of the different connexion of the diode. An amplified version of the

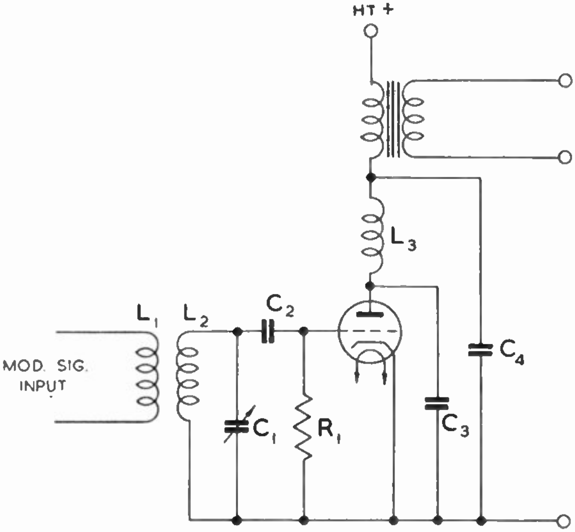


FIG. IX.10.—The Cumulative Grid Detector

grid potentia appears at the anode of the triode, and the radio-frequency component is filtered out as before.

Anode-bend Detector

In this detector a triode (or pentode) is biased back to cut-off (Fig. IX.12). When a modulated signal is applied between the

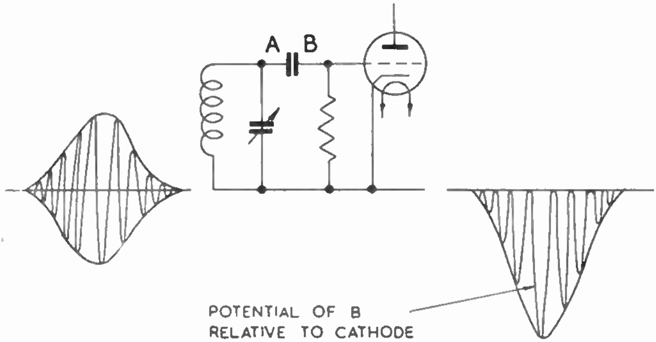


FIG. IX.11.—Operation of the Cumulative Grid Detector

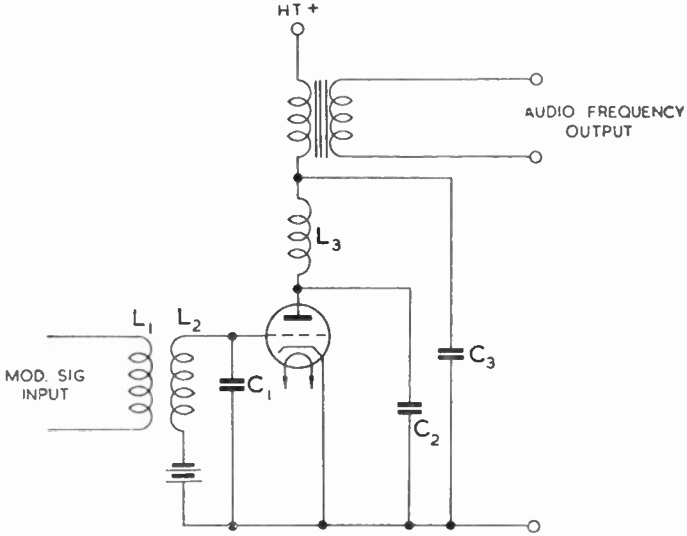


FIG. IX.12.—The Anode-bend Detector

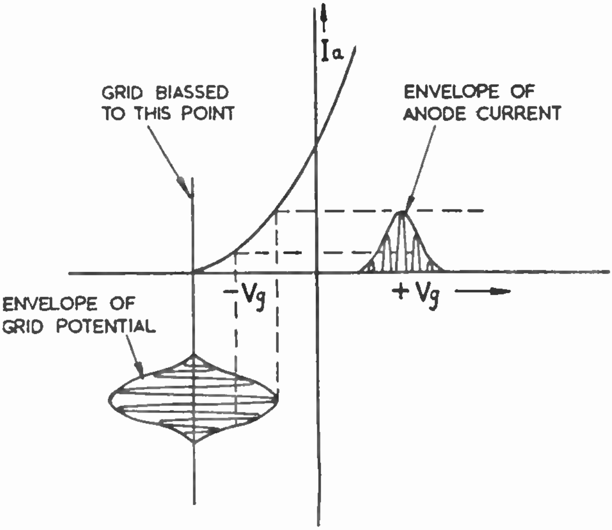


FIG. IX.13.—Operation of the Anode-bend Detector grid and cathode of the valve, the positive-going peaks will drive the grid positive so that the valve conducts, and during the negative peaks the valve is driven beyond cut-off, as shown in Fig. IX.13. If the valve is biased almost to cut-off, the positive half-cycles cause an increase in anode current much greater than the decrease due to the negative half-cycles, and rectification still occurs. Use is made of this fact to operate an anode-bend detector with self-bias by means of a cathode resistor shunted by a large capacitor. At the anode is produced the audio frequency plus the radio-frequency carrier, again amplified by the triode. The radio frequencies are by-passed as before, and only the audio frequencies appear across the anode load. The anode-bend detector follows a square law, owing to the curvature of the valve characteristics, and it therefore introduces more distortion than other types. Its name is derived from the fact that it operates on the bend of the anode-current/grid-voltage characteristic of the valve.

Other Types of Detector

Any device of a non-linear nature, such as a crystal or metal rectifier, may be used in the diode circuit just described. The valve is most commonly used in modern domestic receivers because the diode can be contained in the same envelope as another valve, thus economising in space.

There are slight variations in circuit arrangements which are often found, but the three detectors described are the bases of all others.

Other Features of Detector Circuits

The detector affects the adjoining circuits in a receiver by the way it loads the previous stage and by the output it provides.

The diode and grid detectors both load the driving stage by virtue of the resistor which is necessary to discharge the capacitor. If the input is supplied from a tuned circuit, the detector will damp the tuned circuit, and the amount of damping can be reduced by increasing the diode-load resistance. The limit to this is set by the necessity of discharging the capacitor at a high rate to deal with the higher modulation frequencies.

The anode-bend detector does not impose any load on the input circuit, as there is no resistive path.

The diode detector does not give any amplification, and is preferred when a reasonably high signal can be applied to it; under such conditions it introduces very little distortion.

The grid detector gives high amplification, but it is possible to overload it by cutting the valve off as far as anode current is concerned, while if the input signal is too small, distortion may be introduced by the curvature of the diode characteristic of the valve grid. When properly operated, it is a very good detector circuit.

The anode-bend detector also gives amplification, which depends to some extent on the signal level. That is because small signals operate the valve only on the lower bend of its characteristic, while large signals operate it on the steeper part and the different values of amplification cause distortion.

CHAPTER 10

RECEIVERS

We have now discussed all the kinds of circuits needed to understand how simple receivers work. We shall begin with the kind of receiver known as a " straight " set, in which radio-frequency amplification is used at the signal frequency. Later we shall deal with another kind of receiver, in which all signals are converted to one particular frequency, at which most of the radio-frequency amplification is done.

Aerial Circuits

The signals which we wish to receive are brought to the receiver via the aerial, whatever its form, and provision must be made to introduce the signals to the first tuning circuit. We mentioned these circuits in Chapter 3, and the most common method of coupling the aerial is by transformer. Fig. X.1 shows the aerial-input circuit L_1C_1 and the first tuned circuit L_2C_2, which is adjustable, and if necessary other coils of different values of inductance can be connected in place of L_2 so as to be able to cover all frequencies we wish to receive.

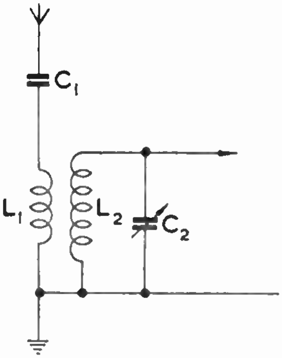


Fig. X.1.—Aerial-input Circuit

C_1 prevents a large aerial from damping L_2C_2 excessively, and so helps to maintain the selectivity of the first tuned circuit.

Radio-frequency Amplifier

This consists of valves with transformer coupling between them, in the same manner as we discussed in Chapter 6.

The p.d. developed across L_2C_2 is applied to the grid of the first radio-frequency amplifier valve V_1. As this is our first complete receiver, it will be a battery-operated equipment, and we shall later see how a similar kind of circuit would be built up in a mains-driven receiver.

Grid bias is often unnecessary with battery-operated radio-frequency pentode valves, because one end of the cathode (the filament in this case) is positive with respect to the end to which the tuned circuit is connected; and no part of the filament is negative with respect to the grid. Therefore the grid is unlikely to become positive with respect to the filament, because the signal applied to the grid of the first valve will never be more than a small fraction of a volt.

The screen of the first stage is fed from the resistor R_1, and its potential is kept steady by the capacitor C_3 (Fig. X.2). In the anode circuit of V_1 is the primary winding of the coupling transformer, L_3, and L_4C_4 is the second tuned circuit. C_4 is coupled mechanically to C_2, and L_4 is similar to L_2, so that both circuits can be tuned by operating a single knob. L_3 and L_4 are coupled by transformer action, and the p.d. across L_4C_4 will be about one hundred times that applied to the grid of V_1.

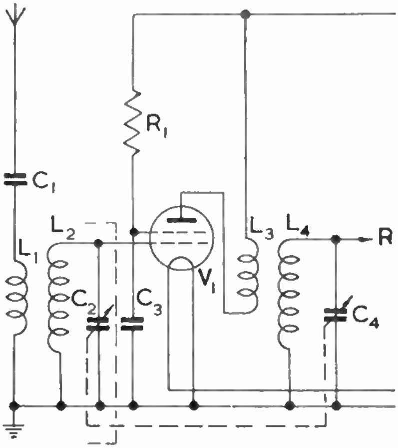


FIG. X.2.—R.f. Amplifier

Detection

The signal obtained from L_4C_4 will be great enough to operate a sensitive detector valve, when receiving strong stations, and as this is only a simple receiver, we must not expect too much from it. Fig. X.3 shows the circuit so far, and includes the second valve, V_2, which is going to "detect" or demodulate, the received signal. A grid detector will give excellent results in this type of circuit, and if the grid leak, R_2, is made high (*e.g.*, 2 MΩ) the damping imposed on the tuned circuit L_4C_4 will not be excessive.

R_3 is the anode-load resistor of the detector, and the audio signal voltage is developed across it. In order to prevent any radio frequency from being passed on to the next stage, C_6 is connected between the anode of the detector and the return line of the anode supply. C_6 has a value of about 100 pF and is sufficiently large to by-pass radio frequency, while allowing the wanted audio frequencies to appear at this point.

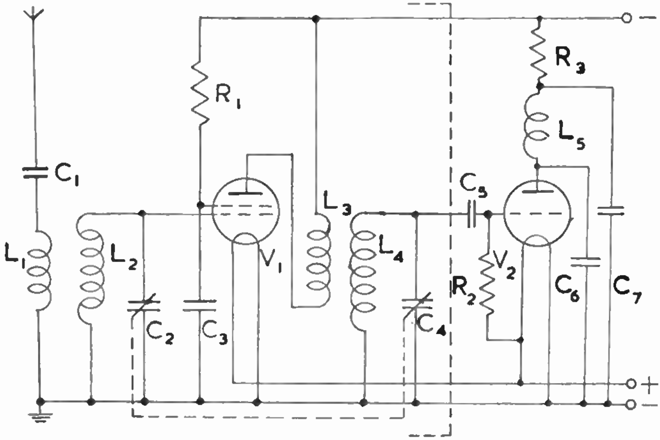


FIG. X.3.—The Detector is Added

The inductor L_5 is a radio-frequency choke, the reactance of which is high at radio frequency and low at low frequency. It serves as an additional precaution against radio frequency being passed on to the following stage. It is assisted in this duty by another small capacitor of 100 pF (C_7) connected to the negative line of the anode supply.

Audio-frequency Amplifier

The audio signal is passed on by the coupling capacitor in exactly the same way as if V_2 were an audio-frequency amplifier.

We now come to the final stage of our first receiver, which is an audio-frequency amplifier operating the reproducer, which may be head-telephones or a loudspeaker. It has a grid resistor through which bias is supplied, and the signal from C_8 is connected to the grid of the valve in the usual manner in an audio-frequency amplifier. The anode load takes the form of either headphones or loudspeaker.

Grid bias for the low-frequency amplifier is supplied from a dry battery of appropriate e.m.f.; the anode supply is obtained from another battery of dry cells, and the valve filaments are heated by a single secondary cell of 2 volts. Fig. X.4 shows the complete circuit.

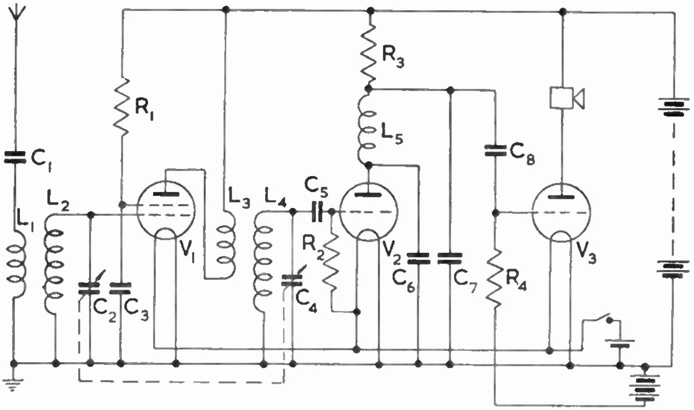


FIG. X.4.—Three-valve Straight Set

Performance of a Simple Receiver

We have just built up our receiver by making use of a number of circuits of which we have learnt in previous chapters. The logical method of building a receiver is to obtain an amplification and selectivity according to the signals we wish to receive.

The selectivity of the receiver is determined by the two tuned circuits it employs, and could be improved by using three tuned circuits, two in the form of a band-pass filter before the first valve, or between the radio-frequency amplifier and the detector, to reduce the width of the band of frequencies received at one setting of the tuning control.

The sensitivity as well as the selectivity of a receiver can be increased by employing two radio-frequency stages, and the operation of a grid detector is improved by giving it a greater signal and by reducing the value of the grid leak. The increase in damping imposed on the previous tuned circuit can be tolerated.

In view of the large number of high-power transmitters in Europe between 200 and 500 metres, we should expect interference from stations other than the one we wish to hear, and a third tuned circuit will greatly improve the performance of the receiver in that respect.

Having noted these shortcomings in our first receiver, we shall attempt to overcome them in our second, which we shall also make suitable for operating from the electricity supply.

A.C. Mains-operated Receiver

By working backwards from the output stage, we can see how the circuit is built up. An indirectly heated output triode will need a signal of the order of 15 volts at its grid to load it fully. This can be obtained from a grid detector under average conditions by giving it a signal of about 2 volts at radio frequency.

If the two radio-frequency stages give a total gain of 7,000, allowing for the damping imposed by the detector, a signal of $\frac{2}{7,000} = 0{\cdot}00028$ volt will be necessary from the first tuned circuit, which itself may provide a gain of some ten to twenty times. A signal at the aerial terminal of $\frac{280}{10} = 28\ \mu\text{V}$ will probably give full output, and the receiver will be capable of giving good reception on a number of stations.

The complete circuit of the receiver is shown in Fig. X.5, the two radio-frequency stages being transformer coupled and similar to those described in Chapter 6. To control the output from our receiver, we incorporate a potentiometer as the grid resistor of the output stage.

The components necessary for obtaining the supplies for the anode circuits are shown to the right of this diagram, and the cathodes of the valves are heated from a suitable winding on the mains transformer.

The dropping resistors and decoupling capacitors for the radio-frequency stages are shown; each stage is individually biased, and the detector circuit is similar to that described in Chapter 9. The detector anode circuit contains two small capacitors and a radio-frequency choke to prevent radio frequencies from reaching the output stage exactly as in the previous receiver.

Constructional Features

It is customary to build radio equipment on a metal chassis, which is connected to the negative side of the anode supply, or to the positive end of the bias resistor when common bias is used. This point is a reference level for signals and valve-electrode potentials, and is connected to the earth in order to complete the aerial–earth circuit of our receiving system.

A metal chassis is very convenient for manufacturing equipment on any scale, as it is simple to arrange for the mounting of valve-holders and large components. Small components—

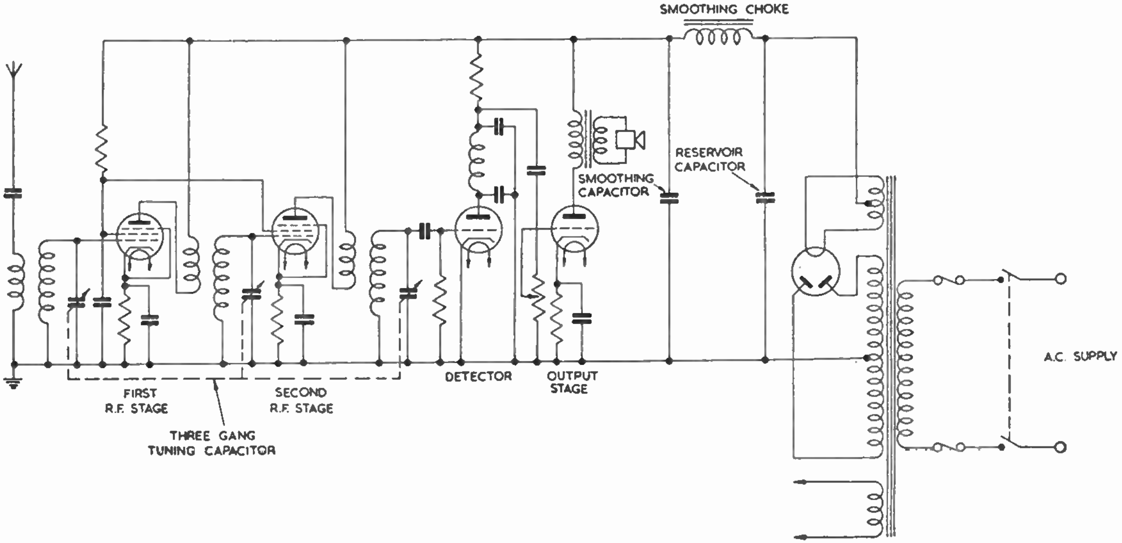


FIG. X.5.—Four-valve a.c. Mains Receiver resistors and small capacitors—are mounted on insulated panels fixed to the chassis, or supported in the wiring.

The metal chassis acts as an electrostatic screen, and this fact is utilised by mounting components which must be screened from each other above and below the chassis.

The chassis is protected by placing it inside a cabinet, which is of wood or plastic for domestic receivers, or of metal for commercial equipment, which needs to be more robust.

There will be three controls to a receiver, or more if it is a more elaborate circuit than we have discussed so far. These three are :

1. Tuning control.
2. Wave-range selector.
3. Volume control.

A means of switching the supplies on and off is also necessary, and is sometimes combined mechanically with the wave-range selector or the volume control.

The components are arranged on the chassis in a convenient way for connecting up according to the circuit, and their layout is also governed to some extent by the frontal appearance of the cabinet.

It is usual for the tuning control and dial to occupy a central position, and this means that the tuning capacitor must also be central on the chassis. The tuning coils are closely associated with the tuning capacitor, and are mounted either adjacent to the capacitor or below it. The wave-range selector switch is also associated with the tuning coils, and must be nearby. These requirements dictate the positions of the radio-frequency and detector stages, and the remaining components and stages are disposed in a logical manner in the space that is left. In the case of a battery receiver a shelf or other space must be provided for the batteries, while in a mains receiver the mains transformer, rectifier and smoothing capacitors are mounted on the chassis, usually near the output circuits, so as to be remote from the sensitive input stage.

Reception of C.W. Signals

A popular method of transmitting messages by telegraph is known as Continuous Wave (C.W.) Transmission. The transmitter is switched on only according to the code being transmitted and is off during the spaces of the code, and the transmitted wave is unmodulated ; that is, it is of constant frequency and amplitude. Fig. X.6 is a graphical representation of the letter " A " (dot–dash) being sent by Morse code in C.W.

If we tune a straight receiver in to this signal, we shall hear only a click in our reproducer each time the transmitter is switched on or off, because there is no audio modulation of the transmitted radio frequency. In order to render the dot–dash audible, the " Heterodyne " method is used.

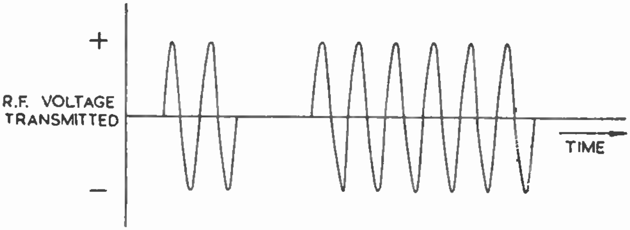


Fig. X.6.—C.W. Transmission

Heterodyning

Fig. X.7(*a*) shows graphically a radio-frequency wave of 100 kc/s, and Fig. X.7(*b*) shows radio-frequency wave of 90 kc/s. If we combine these voltages the resultant is shown in Fig. X.7(*c*), which is a wave the amplitude of which varies from one maximum to the next in $\frac{1}{10,000}$ second.

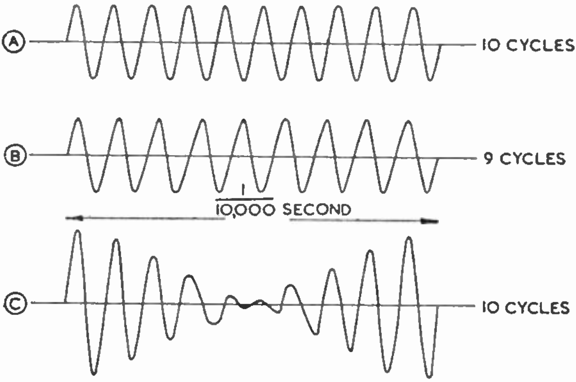


Fig. X.7.—Heterodyning

This wave is exactly like that which we should produce if we modulated a carrier with a 10-kc/s note, and if we pass it through a detector, an audible note at 10 kc/s will be produced while the 100-kc/s signal is being received (Fig. X.8). Stopping the 100-kc/s (or the 90-kc/s) wave causes the audible output to stop also, so that our C.W. code transmission has become audible. The principle of combining e.m.f.s of two frequencies to obtain another is called "heterodyning", and e.m.f.s of a number of other frequencies are produced.

The above frequencies were chosen to simplify Fig. X.7, which has shown us that a frequency of 10 kc/s can be produced by combining e.m.f.s at 100 kc/s and 90 kc/s and passing them through a detector. One component of the detector output voltage has a frequency given by the difference between the two input frequencies, and to obtain an audio frequency from two radio frequencies this component must be used.

From an operator's point of view, a more suitable frequency for the audible output would be 1 kc/s, and this can be produced by combining a 99-kc/s wave to the incoming 100-kc/s signal. It is also produced if the local signal is at 101 kc/s; it does not matter whether the incoming frequency is above or below that of the locally generated signal.

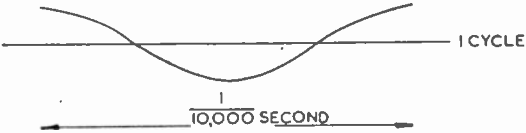


FIG. X.8.—Result of "Detecting" Fig. X.7(*c*)

This fact is very useful when an interfering transmission is also audibly received. Suppose our wanted transmission is at a frequency of 100 kc/s, and another transmission is heard at 102 kc/s, we can set our local frequency at 99 kc/s and two notes are heard. The wanted signal is at 100 − 99 = 1 kc/s, and the unwanted one at 102 − 99 = 3 kc/s. It is possible to distinguish between these two sounds, but matters can be improved by having a circuit in the low-frequency end of our receiver, which only passes frequencies in the region of 1 kc/s on to the reproducer. Such a circuit is often called a note-filter.

In the above example, if we set our local frequency at 101 kc/s, then both transmissions would produce audible signals of 1 kc/s and they would not be distinguishable from each other. If the local frequency is set to 102 kc/s, the unwanted station is inaudible, while the wanted signal gives a beat at 2 kc/s.

Fig. X.9 shows how heterodyne reception is carried out, the only modifications necessary to an ordinary receiver being in the detector circuit. An additional valve is arranged as an oscillator, and its tuned circuit is adjustable over a range suitable for the reception of the desired transmissions. This extra stage is known as a " Beat Oscillator ", because the e.m.f. it generates is made to " beat " with the incoming signals to produce an audible note. The tuned circuit L_1C_1 of the local oscillator is arranged to be physically near to the tuned circuit forming the detector-input circuit L_2C_2, and an e.m.f. is induced in L_2 by mutual inductance coupling from L_1. L_2C_2 also receives the incoming signal by mutual coupling from the previous stage, and the incoming signal and local signal are fed together to the detector. The detector output, after removal of the radio frequencies by the usual capacitor–choke network, has a frequency equal to the difference between the signal frequency and that of the local oscillator, and this is passed to an audio-frequency amplifier, through a note-filter if desired. The audio-frequency amplifier is similar to those we have already discussed.

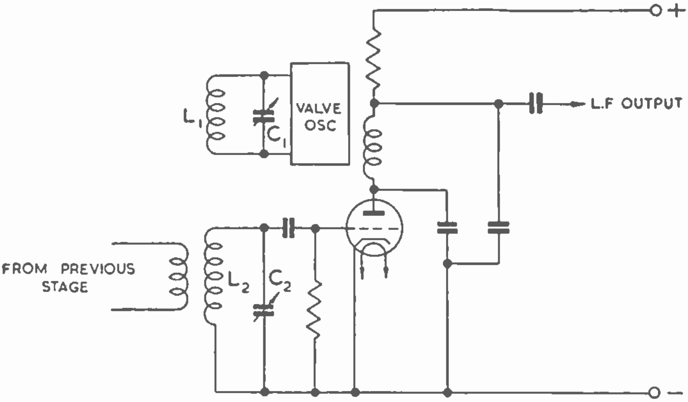


FIG. X.9.—Circuit for Heterodyne Reception

Super-heterodyne Reception

In a super-heterodyne receiver (commonly abbreviated to " superhet "), the heterodyne principle is used to produce a beat frequency higher than can be heard, that is, " supersonic ". Super-heterodyne is short for supersonic heterodyne. The beat frequency can be of any desired value, and common values used in receivers are 100–300 kc/s, 380–479 kc/s, and higher values for special purposes. The beat frequency is chosen to lie in a part of the spectrum that is little used for communication purposes. The principle is suitable for reception of C.W. and telephony, and the majority of modern receivers are superhets.

Fig. X.10 is a diagram showing the stages in a superhet receiver. The incoming signals are fed to a tuned circuit in the usual way in order to select a band of frequencies, including the wanted signal, which is then passed to a radio-frequency amplifier stage.

After amplification (which is not essential, and is often not used in simple receivers), it is fed to the " first detector " stage, where it is mixed with the e.m.f. generated by the local oscillator. The local oscillator frequency now differs from the signal frequency by a much higher value than in the case of heterodyne reception of C.W. For instance, if the wanted signal is 908 kc/s and the required beat frequency is 465 kc/s, the local oscillator could be working at 908 — 465 = 443 kc/s or 908 + 465 = 1,373 kc/s—the higher value is usually chosen for practical reasons.

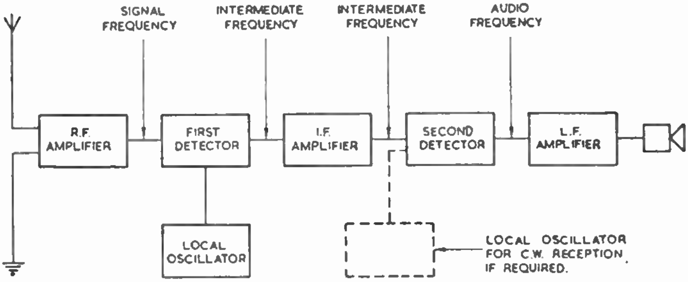


FIG. X.10.—Block Diagram of Super-heterodyne Receiver

The output from the first detector is taken to a tuned circuit the resonant frequency of which is equal to the beat frequency, and is passed through one or more stages of amplification.

The amplified beat frequency is then fed to the " Second detector " stage, where the signal is demodulated, the audio-frequency output of the second detector being amplified in the usual way.

The amplifier dealing with the signal at the beat frequency is usually called the " Intermediate frequency " (i.f.) amplifier, because it works at a frequency between the signal frequency and the audio-frequency.

The advantage of the superhet receiver lies in the greater selectivity obtainable in the i.f. amplifier, which works over a narrow, fixed, frequency band, enabling a number of tuned circuits to be employed without the necessity of re-tuning them all each time a different signal is to be received.

In order to receive a number of signals, the local oscillator frequency is varied at the same time as the signal-frequency circuits are adjusted, and by a suitable circuit arrangement this can all be done by mechanically coupled capacitors, so that only one tuning knob is necessary.

If C.W. is to be received on a superhet, a second local oscillator is necessary, the frequency of which differs from the I.F. of the receiver by the audio frequency desired.

There is only a signal at intermediate frequency when there is an incoming signal of the appropriate frequency, and so an audible beat note is produced only while the transmitter is on, just as in the reception of C.W. in a straight receiver.

RELATIVE PROPERTIES OF STRAIGHT AND SUPER-HETERODYNE RECEIVERS

A. *Straight Receivers*

1. All valves give good amplification.
2. Simple circuits only need be used.
3. Easy to adjust.
4. Total amplification which can be utilised is limited by possibility of feed-back and self-oscillation.
5. Selectivity limited because it is impracticable to use more than four tuned circuits (four-gang capacitor).
6. Selectivity not constant over a wave-band.

B. *Super-heterodyne Receivers*

1. High selectivity if required.
2. High total amplification possible because it is done at two different frequencies.
3. Selectivity is practically constant at all signal frequencies, being mainly obtained in the i.f. tuned circuits.
4. Some valves do not contribute to the total amplification—the local oscillator contributes nothing, and the first detector less than if it were operated as an amplifying stage.
5. Initial adjustment of circuits more complicated than in straight receiver.
6. Circuits require more components.

CHAPTER 11

MEASUREMENTS IN RADIO WORK

THERE is a great variety of measurements which have to be made on radio equipment. In the first place, it is necessary to ascertain the supply potentials and currents to the valves in the circuit. Secondly, the actual potentials at the valve electrodes must be measured. Thirdly, the signal p.d.s at various points in the circuit are required to be known.

These three kinds of measurements place an increasing demand on the measuring instruments used.

Measurement of Supply Potentials and Currents

In a normal receiver the anode supply is from 50 volts upwards and is unidirectional. The instrument used is a moving-coil voltmeter, which requires a current of about 1 mA for full-scale deflexion and which reads the mean value of the current. The range of the instrument depends on the resistance included in its circuit. For example, a meter requiring a current of 1 mA for full deflexion and having a total resistance of 5,000 ohms will read full scale when a p.d. of $V = IR = \frac{1}{1,000} \times 5,000 = 5$ volts is applied to its terminals. If, by adding more resistance, the total is made up to 500,000 ohms, then $\frac{1}{1,000} \times 500,000 = 500$ volts will be necessary to give full deflexion. An instrument may thus be arranged to give full-scale deflexion for any p.d. by adjustment of the resistance of its own circuit (Fig. XI.1). This resistor is known as a " multiplier ".

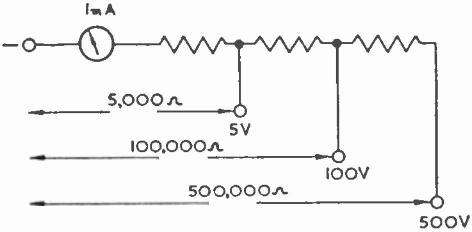
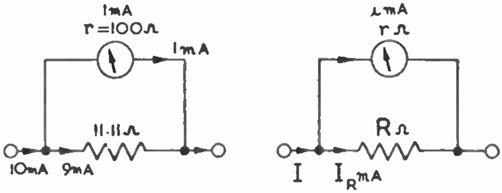


FIG. XI.1.—Multi-range Voltmeter

Sometimes instruments require a higher current for full deflexion, *e.g.*, 5 mA. When measuring the potential available for supplying the valve circuits, such an instrument is quite suitable, and its range is adjusted in just the same way as was described in the previous paragraph.

Voltmeters are usually described as having a resistance of " so-many ohms per volt ", and the resistance referred to is that of the voltmeter circuit which would cause full-scale deflexion if I volt were applied to its terminals. To ascertain the resistance of the voltmeter circuit when the full-scale reading is 200 volts we multiply 200 by the " ohms per volt " of the instrument.

An important point in all measurements is to avoid altering the circuit conditions too much by connecting the instrument into the circuit. The current taken by the instrument must therefore be only a small fraction of that being taken by the circuit under test; this condition is easily fulfilled in the case of anode and heater supplies.



$$ir = I_R R$$
$$I = i + I_R$$
$$= i + \frac{ir}{R}$$
$$= i\left(1 + \frac{r}{R}\right)$$

FIG. XI.2.—Theory of Ammeter Shunt

The heater supply may be alternating or direct. In the former case we must use a moving-iron or a rectifier type of moving-coil instrument, but in the latter case the same instrument as was used for the measurement of the anode supply will serve by suitable adjustment of its range. A moving-iron instrument has the advantage of reading the r.m.s. value.

Grid-bias supplies will always be direct, and the moving-coil instrument will again serve. If the grid bias is obtained " automatically ", care must be taken to fulfil the condition just mentioned concerning alteration of the circuit conditions; this will be the case provided that the resistance of the instrument is at least ten times the value of the bias resistor.

The current in any part of the circuit may be measured with a suitable ammeter. The only alternating current to be measured would be the mains input or the heater current in a receiver working from an alternating supply, and the instrument would be either of the moving-iron or moving-coil-plus-rectifier type. All other currents will be direct, and can be measured with a moving-coil instrument. In order to use a moving-coil instrument for measuring a current greater than that necessary to give full-scale deflexion, a resistor is connected in parallel with the instrument and is made of such a value that the excess current passes through it (Fig. XI.2). This resistor is known as a " shunt ". The total current flowing is determined from the ratio of the shunting resistance to the resistance of the instrument.

Precautions to be Observed

We have already mentioned the importance of excessive alteration of circuit conditions when using a voltmeter. This is particularly important when measuring the actual anode potential of valves, because of the anode load resistance. By using an instrument on a higher range than is necessary, its resistance is increased, and this helps greatly when measuring anode potentials. For instance, by measuring a p.d. of 100 volts on the 500-volt range of a meter requiring 1 mA for full deflexion, the current taken by the instrument would be $\frac{100}{500} = 0{\cdot}2$ mA. The deflexion will be only to one-fifth of full scale, but the effect on the circuit will be greatly reduced and the accuracy of the measurement will be increased. Some modern instruments require only 200 μA or even less for full deflexion, and are therefore very suitable for this type of measurement.

When measuring current there are two points to be given attention. The first is that the ammeter has some resistance, and so has some p.d. across it when carrying current. This potential drop is only of importance in low-potential heater circuits. The second point concerning the use of current-measuring instruments is the position in the circuit in which the instrument is connected. It should always be connected where the signal is a minimum. When measuring the anode current of a valve, the meter should be connected at the supply end of the anode load, and not at the anode end. This precaution should always be observed, because the connexion of the meter to the anode adds capacitance between anode and earth. This will affect tuning if the valve is in a radio-frequency stage, and the wandering instrument lead may also cause feed-back to occur with the consequent possibility of self-oscillation of the circuit.

Valve Voltmeters

Instruments of the type we have just discussed are not suitable without some modification for the measurement of radio-frequency p.d.s or currents. For their operation they require a small amount of power which is drawn from the circuit under test, and this power is not always available in a radio-frequency circuit. It is natural that the amplifying properties of the thermionic valve should be used to operate instruments, and the combination of some form of valve amplifier and an indicating instrument is known as a " Valve Voltmeter "; many varieties are possible and are available commercially.

The mere use of a valve amplifier for operating instruments does not inherently overcome the difficulty of connecting long leads to points in the circuit where signals are being measured. We shall see how this precaution is observed when we discuss the various types of valve voltmeter.

Diode Valve Voltmeter

In order to measure radio frequencies with a moving-coil instrument, it is first necessary to rectify the p.d. At audio frequencies this may be done with a metal rectifier, but the

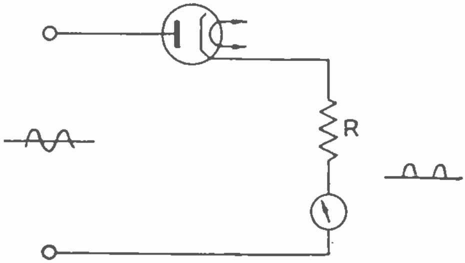


FIG. XI.3.—Diode Valve Voltmeter

capacitance between the plates has too low an impedance at radio frequency, and a thermionic rectifier is therefore used. Two methods of connexion are possible; Fig. XI.3 shows the series diode circuit which we have already seen in Chapter 9. In this circuit the current through the resistance R is proportional to the mean value of the alternating p.d., and measurement of the current is therefore a possible way of determining the p.d. The disadvantages of the circuit are that the cathode of the diode is at some potential, possibly high, above the low-potential terminal, and the capacitance of the diode itself may be sufficient to upset the operation at high frequency.

Fig. XI.4 shows the shunt diode circuit which overcomes these

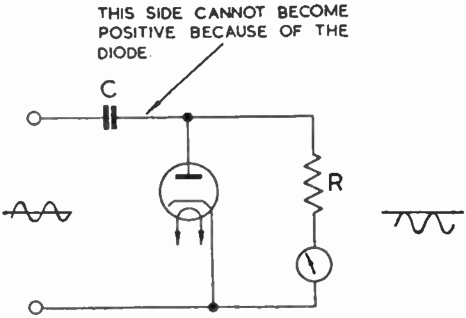


FIG. XI.4.—The Shunt Diode Circuit

two difficulties, and it is very commonly used. The p.d. across *R* is unidirectional, but is varying as shown in the diagram. In order to obtain a high input impedance, and thus have a small effect on the circuit being examined, the resistance *R* must be high, and the current through it will therefore be small. The

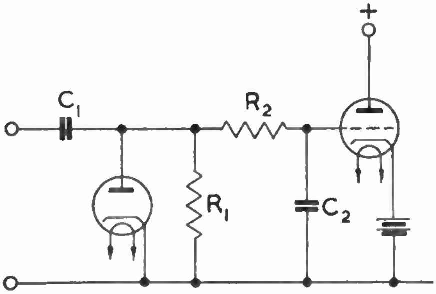


FIG. XI.5.—Shunt Diode with Amplifier

potential is fed to a filter circuit and applied to a triode valve which acts as an amplifier (Fig. XI.5). The filter circuit comprises a resistor R_2 and capacitor C_2, and the p.d. across C_2 is practically constant. The valve is biased so that grid current cannot flow, and therefore no load is imposed on the filter network. The application of the p.d. from the filter network causes the current in the valve to change; this change can be used to operate a moving-coil instrument.

There are two possible methods of connecting the instrument, shown in Figs. XI.6 and XI.7. Fig. XI.6 shows the meter connected in the anode circuit. When there is no p.d. applied to the terminals, the grid of the amplifier is at the same potential as the negative supply terminal, and the valve passes a current determined by the valve characteristic and the anode load R_3 and cathode bias resistor R_4. The resistance of R_6 is adjusted so that the point A is at the same potential as the triode anode, B, and there is no current in the meter.

When a signal is applied to the terminals, the grid of the triode is made negative and the valve current decreases. The p.d.s across R_3 and R_4 therefore decrease. The reduction of p.d. across R_3 means that B becomes more positive than before, so that current flows through the meter from B to A.

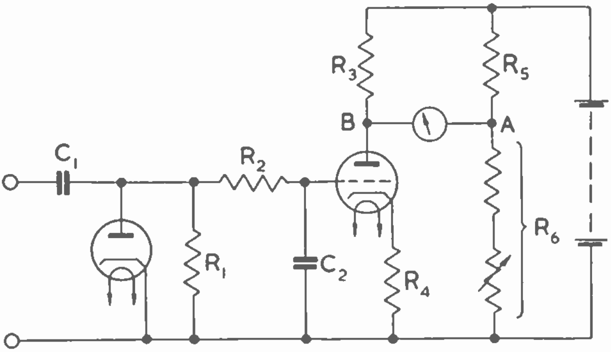


FIG. XI.6.—Simple Valve Voltmeter

The reduction of p.d. across R_4 causes the cathode of the valve to become less positive, so that the change of potential between the grid and cathode of the valve is less than the p.d. across C_2. It is not possible to keep the p.d. across R_4 constant by connecting a capacitor across it, because the valve current is not varying about a mean level as it is when amplifying an alternating p.d. This change of cathode potential reduces the change of valve current compared with the change which would occur if R_4 were not in the circuit, but it has the effect of making the circuit less dependent on the valve constants. For example, suppose that the mutual conductance of the valve decreases as the valve becomes aged—the change of current due to the p.d. across C_2 becomes less, but so also do the changes in p.d. across R_3 and

R_4 become less. The p.d. between grid and cathode is therefore slightly greater than before, thus giving some compensation for the loss of amplification in the valve.

Fig. XI.7 shows the meter connected in the cathode circuit of the valve, and the operation is exactly as before. When the grid is made negative the cathode potential falls and current flows through the meter from *A* to *B*.

In both types of instrument the meter is calibrated by applying a known p.d. to the input terminals and marking the dial of the meter accordingly.

By connecting the grid of the amplifier valve to taps on the resistor R_1, the sensitivity of the instrument can be altered to any desired range, up to the maximum rating of the diode valve.

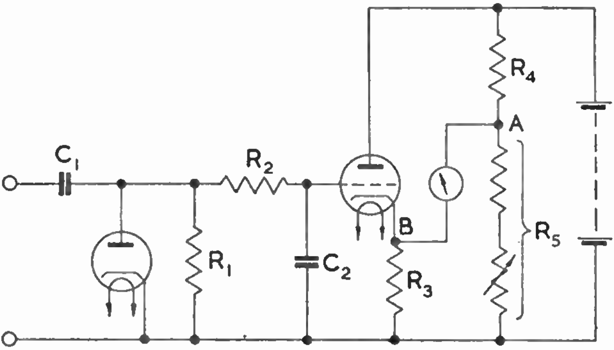


Fig. XI.7.—Simple Valve Voltmeter

This type of instrument, in which the alternating p.d. being measured is rectified by a small diode and then filtered, is very suitable for overcoming the difficulty concerning long connexions to live points. The diode, capacitor and filtering circuit are contained in a small box, known as a " probe ", which can be brought right up to the circuit under test. A flexible lead connects the probe unit to the case of the instrument, which contains the amplifier, indicating meter, controls and power supplies. The flexible lead carries a heater supply for the diode and the rectified, filtered output from the diode circuit.

Triode-valve Voltmeters

In Chapter 9 we saw that the anode current of a grid or anode-bend detector changes when a signal is applied. This fact is sometimes used in simple types of valve voltmeter using only one valve. The circuit of the grid-leak type of valve voltmeter is shown in Fig. XI.8, and it will be seen that the now familiar arrangement for bringing the indicating instrument to zero when there is no input is included ($R_3 - R_4$). Application of an alternating potential causes rectification to take place at the grid, the average potential of which becomes negative, thus reducing the anode current. The instrument is calibrated by applying known p.d.s to the terminals and marking the meter scale accordingly.

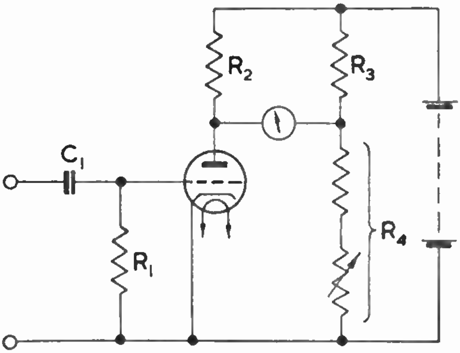


FIG. XI.8.—Grid-leak Valve Voltmeter

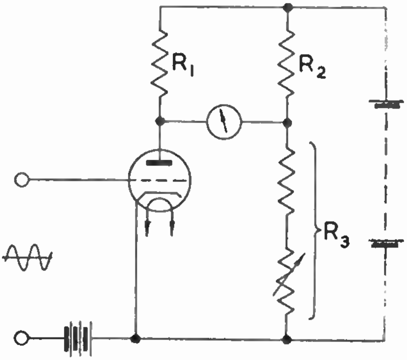


FIG. XI.9.—Anode-bend Valve Voltmeter

Fig. XI.9 shows the circuit of the anode-bend type of valve voltmeter, which is exactly like that of the anode-bend detector. A source of negative bias is required with this instrument, and the anode current of the valve is low when there is no input. The meter current is brought to zero by the adjustment of R_2 or R_3, and when a signal is applied, the valve current increases more on the positive half-cycles of input than it decreases on the negative half-cycles, so that the average anode current is increased. The instrument is calibrated in the same way as the grid-leak voltmeter.

A third type of triode valve voltmeter which is sometimes used is operated on the " slide-back " principle. Fig. XI.10 shows the circuit diagram and the principle of operation. A triode is biased so that it passes a very small current, which is indicated by a meter in its anode circuit, M_2. When an alternating p.d. is applied in series with the direct bias, the valve current increases in the same way as in the anode-bend type, and the new current is indicated on the meter M_2. The bias is then increased negatively until the valve current has fallen to its initial small value. This increase in bias is indicated by the meter M_1 and is very closely equal to the peak value of the alternating p.d., as shown in the diagram.

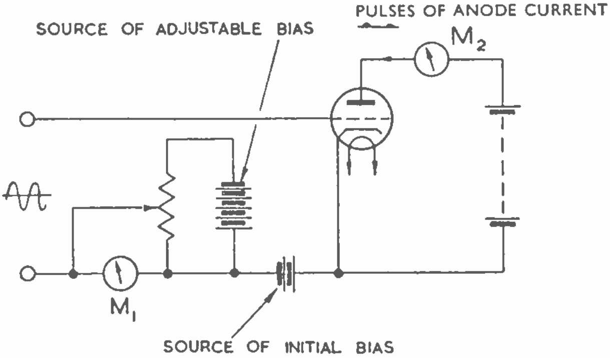


FIG. XI.10.—Slide-back Valve Voltmeter

Wavemeters

Absorption Wavemeter

The measurement of frequency is of great importance in radio work, and a simple method of finding it depends on using a tuned circuit having known values of inductance and capacitance. Fig. XI.11 shows a tuned circuit across which is connected a diode voltmeter, the combination being known as a " wavemeter ". This name is generally applied to apparatus of this kind, and dates from the time when radio frequencies were described in terms of wavelength rather than frequency.

If the inductor L_1 of the wavemeter is brought near to another coil L_2 carrying current at radio frequency and the capacitor C_1

is varied, the p.d. across the coil L_1 depends on the resonant frequency of L_1 and C_1. When the resonant frequency of L_1 and C_1 given by $f = \frac{1}{2\pi\sqrt{L_1C_1}}$ is equal to the frequency of the current in L_2, the p.d. across L_1 and C_1 rises to a maximum and is indicated by the diode voltmeter (Fig. XI.12). If the values of L_1 and C_1 are known, f can be calculated. In practice, a wavemeter includes a number of inductors, and the capacitor is usually fitted with a dial marked in degrees. Associated with each inductor is a calibration graph of resonant frequency against capacitor scale reading.

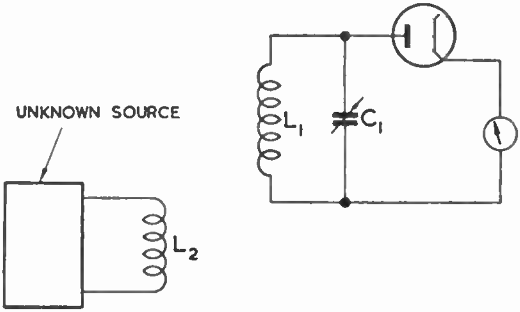


FIG. XI.11.—Absorption Wavemeter

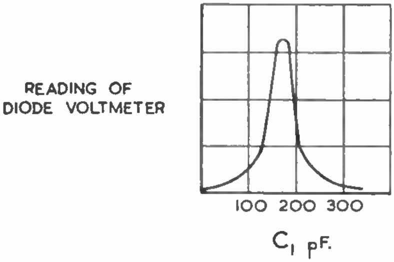


FIG. XI.12.—Effect of Tuning Wavemeter

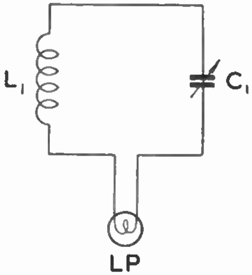


FIG. XI.13.—Wavemeter with Lamp Indicator

Sometimes wavemeters of this kind, known as the " absorption " type, have a lamp as the indicator (Fig. XI.13). When the resonant frequency of the circuit L_1C_1 is the same as that of the signal being measured, the current in the lamp and the resonant circuit is also a maximum, and the lamp glows most brightly. This arrangement is not suitable when measuring on very low power circuits, for obviously the power to light the lamp must be taken from the circuit under test, and the diode voltmeter arrangement is more sensitive than the lamp.

Owing to the absorption of power from the source by the wavemeter, the resonant frequency of the source may be changed slightly by the introduction of the wavemeter coil. The accuracy of indication is also restricted by the accuracy with which :

1. The capacitor can be adjusted to the peak of the resonance curve (Fig. XI.12).
2. The capacitor scale can be read and translated into terms of frequency.

Heterodyne Wavemeter

Another type of wavemeter consists of an oscillator with a variable tuned circuit, together with a detector circuit. The signal from the source of unknown frequency and from the loca oscillator of known frequency are mixed in a detector circuit, and the detector output is fed to a pair of telephones. The detector output consists of a beat frequency in the same way as in the heterodyne reception of C.W. previously discussed. If the local, adjustable oscillator can be adjusted to the same frequency as the unknown, an audible beat will be heard as the frequency is altered, and the beat note falls to zero as the frequencies are equalised. The unknown frequency is then equal to the frequency to which the known, local oscillator has been set. The heterodyne method is subject to a possibility of error. The local oscillator, besides generating the frequency to which it is adjusted, is likely to produce frequencies of twice, three times and possibly higher multiples of that frequency, due to distortion occurring in the oscillator valve. The amplitudes of these multiples of the basic or fundamental frequency are always less than that of the fundamental frequency, and the higher multiples are usually of such small amplitude that they do not cause trouble. It is possible to ascertain whether one is on the fundamental frequency by adjusting the local oscillator to twice the original frequency at which a beat was heard. If there is no beat, or the beat is much weaker, the original frequency was correct. The same trouble may arise if the source of unknown frequency is also generating harmonics, as the multiple frequencies are called.

Some wavemeters are provided with an amplifier stage, which reduces the amount of energy taken from the circuit under test. Provided that a sufficiently good capacitor, scale and drive are incorporated, an instrument of either the indicating or heterodyne type is then capable of very accurate work.

BOOKS RECOMMENDED FOR FURTHER STUDY AND REFERENCE

Elementary Principles

Concise General Science, by Musson and Reid (English Universities Press Ltd.).

Preliminary

Mathematics for Telecommunications, Volume I, by Grinsted and Spooner (E.U.P.).

Telecommunications (Principles), Volume I, by Harbottle and Hanman (E.U.P.).

Electro-Technology for National Certificate, Volume I, by Teasdale and Walton (E.U.P.).

Complementary

Mathematics for Telecommunications, Volume II, by Grinsted and Spooner (E.U.P.).

Telecommunications (Principles), Volume II, by Harbottle and Hanman (E.U.P.).

The Admiralty Handbook of Wireless Telegraphy, Volumes I and II (H.M.S.O.).

Notes for Wireless Operators (H.M.S.O.).

The Radio Amateurs' Handbook (Incorporated Radio Society of Great Britain).

A Text-book of Electronics, by J. M. A. Lenihan (E.U.P.).

Radio Technology, by W. H. Date (Longmans, Green & Co. Ltd.).

EXAMPLES

The following selection of examination questions is reproduced by the courtesy of the City and Guilds of London Institute.

1. A tuned circuit, having negligible resistance, has an inductance L and a capacitance C, and is tuned at a frequency f. When L is increased by 240 μH, the tuned frequency falls to $0{\cdot}5\,f$. Find the value of L. (Radio Communication, Grade I, 1946.)

2. Describe a simple type of absorption wavemeter and its use in measuring the wavelength of a radio transmitter. (Radio I, 1947.)

3. Describe the operation and draw the circuit of a valve oscillator covering the frequency range 500–1,000 kc/s. Assuming that the tuned circuit inductance is 100 μH, what are the necessary maximum and minimum values of capacitance to cover the quoted range? (Radio I, 1947.)

4. If the effective series inductance and capacitance of a vertical aerial are 100 μH and 100 μμF respectively, what is the resonant frequency? If a capacitor of 200 μμF capacitance is connected in series with the aerial, what is the new value of the resonant frequency? (Radio I, 1948.)

5. Give the circuit and describe the operation of a valve voltmeter suitable for the measurement of voltages (1–10 volts r.m.s.) over the frequency range 0·1–20 Mc/s. (Radio I, 1948.)

6. Draw and describe the circuit for a single-phase full-wave rectifier to provide the h.t. supply for a broadcast receiver. Indicate the form of the output voltage obtained: (*a*) with a smoothing circuit and (*b*) without a smoothing circuit. (Radio I, 1947.)

7. Give the circuit diagram and state the functions of the stages of a three-valve straight receiver suitable for broadcast signals in the range 500–1,500 kc/s. (Radio I, 1948.)

8. Sketch the circuit of a two-stage transformer-coupled amplifier for audio-frequency operation, incorporating cathode resistors to provide grid bias.

Assuming the anode current in the output stage is 15 mA and the value of the associated cathode resistor is 400 ohms, what is the resulting grid-bias voltage on this stage? (Radio I, 1947.)

9. Describe the essential features of a super-heterodyne receiver suitable for the reception of continuous-wave telegraph signals. Assuming the mid-band frequency of an intermediate frequency

amplifier is 465 kc/s, what first oscillator frequencies may be used for the reception of a radio signal on 10 Mc/s? (Radio I, 1947.)

10. Why is a detector necessary to obtain audio signals from an amplitude-modulated (telephony) radio carrier? Describe one form of valve-detector circuit. (Radio I, 1947.)

11. Describe one method of modulating the amplitude of a radio-frequency carrier wave with speech signals, and the nature of the resulting modulated wave. (Radio I, 1947.)

12. The allocated frequency of a radio transmitter is 30 kc/s, but measurement using an accurate wavemeter shows that the wavelength is 10,100 metres. Determine the percentage error in the frequency of the transmission. If the total capacitance in the tuned circuit of the oscillator is 1,000 $\mu\mu$F, what capacitance change is necessary in order to adjust the frequency to the assigned value? (Radio I, 1948.)

13. Why is a beat oscillator necessary for the reception of continuous wave (C.W.) telegraph signals?

A straight receiver incorporating a 1-kc/s narrow-band note-filter is required to receive a C.W. telegraph signal on 115 kc/s, and there is an interfering carrier on 117 kc/s. To what frequency would the beat oscillator preferably be set and why? (Radio I, 1948.)

14. Why are pentode or tetrode valves commonly used in preference to triode valves in the radio-frequency amplifiers of receivers? (Radio I, 1948.)

15. Given a voltmeter of resistance 5,000 ohms (full-scale deflection 5 volts) and several 100-ohm resistors, describe a method whereby the anode current of each of the stages in a radio receiver could be determined. What is the relation between the voltmeter reading and the anode current? (Radio I, 1948.)

16. The anode tuned circuit of the radio-frequency stage of a medium-wave broadcast receiver has a Q-factor of 100. If the circuit is damped to reduce the Q-factor to 25, explain by means of sketches the effects on the selectivity curve and on the voltage developed across the tuned circuit at resonance. (Radio I, 1948.)

17. Describe the construction of an indirectly heated pentode valve of the receiving type, stating materials used. (Radio I, 1947.)

18. (i) State the relation between the frequency and wavelength of a radio wave.

(ii) What are the frequencies corresponding to radio signals of wavelengths 20 km., 150 m. and 10 cm.?

(iii) State approximately wavelengths and frequencies suitable for: (*a*) a local broadcast transmission, and (*b*) an overseas radio-telephone transmission. (Radio I, 1947.)

NUMERICAL ANSWERS

1. 80 μH.
3. 1,012 μμF and 253 μμF.
4. 1·59 Mc/s; 1·95 Mc/s.
8. 6 V.
9. 10·465 Mc/s and 9·535 Mc/s.
12. 20·1 μμF.
13. 114 kc/s.
18. (ii) 15 kc/s, 2 Mc/s., 3,000 Mc/s.

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