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ECY-5

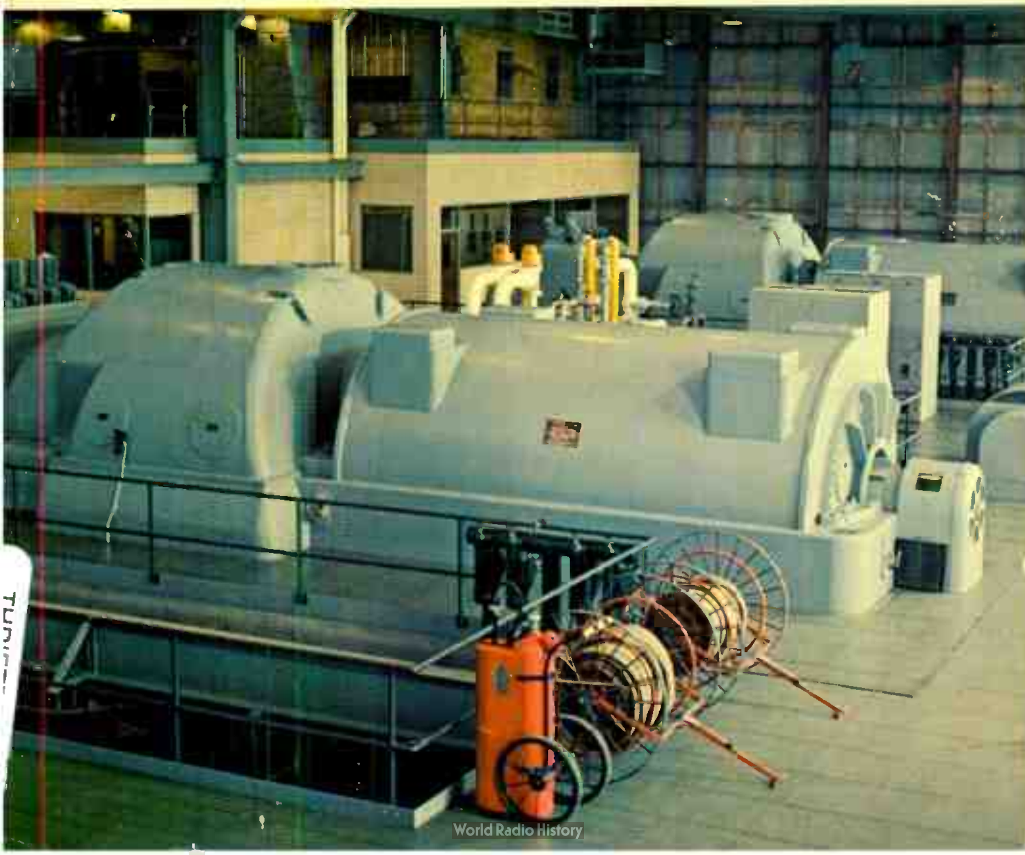
BASIC ELECTRICITY/ELECTRONICS

A Programmed Learning Course

VOLUME 5

- DC Generators
- DC Motors
- AC Generators
- AC Motors
- Three-Phase Systems
- Power Converters
- Servo Systems

MOTORS & GENERATORS—HOW THEY WORK



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BASIC ELECTRICITY/ELECTRONICS
VOLUME 5

MOTORS & GENERATORS—HOW THEY WORK

By Training & Retraining, Inc.

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MOTORS & GENERATORS— HOW THEY WORK

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SEYMOUR D. USLAN, *Editor-in-Chief,*
Training & Retraining, Inc.

Introduction

This volume, the fifth and last in the series, is concerned with the principles of AC and DC motors and generators. The text is designed to provide the reader with a sound understanding of the fundamentals of motors and generators. The characteristics of each type of machine are presented so that the student can relate each type to actual applications. In this way, reader interest is maintained, and the information presented is of practical value.

WHAT YOU WILL LEARN

You will be shown how the operation of motors and generators depends on the basic electrical principles you have already learned. You will see how these principles are put to work to perform specific tasks with electrical machines.

First you will be introduced to the ways in which mechanical energy can be transformed into electrical energy, and vice versa. Such terms as commutator, slip rings, torque, left-hand rule, brush, armature, and many others are explained.

DC generators are discussed in detail. Construction details are given, including bearings, armature cores, etc. Wave windings as well as simplex, duplex, and triplex lap windings are explained. The characteristics of separately excited, shunt, series, and compound generators are described, along with losses (copper loss, eddy-current loss, and hysteresis loss). You will learn about armature reaction and the methods used to counteract it. The methods of paralleling DC generators are given, and maintenance techniques are described.

You will learn that DC motors are similar in construction to DC generators. Counter emf and armature reaction are discussed in addition to the characteristics of shunt, series, and compound motors. Several types of DC motor starters are covered, and the most common methods of motor speed control are listed.

The text on AC generators explains synchronous, induction, single-phase, and polyphase types. Armature reaction, frequency control, and voltage regulation are discussed. Methods of connecting several AC generators in parallel are described.

The application of three-phase electromagnetic fields to motor operation is explained. You will learn about polyphase synchronous and induction motors. You will also learn about several types of single-phase motors, including shaded-pole, split-phase, capacitor, repulsion, repulsion-induction, and universal motors.

The generation and distribution of electrical power by three-phase systems along with the relationships of voltage, current, and power in both wye- and delta-connected systems are described.

You will learn about devices used to convert electric power from one form to another (AC to DC, DC to DC of a different voltage, etc.). Finally, you will learn about servo control systems. Open and closed servo systems, servomotors, AC and DC servo amplifiers, and synchromechanisms are included in this discussion.

WHAT YOU SHOULD KNOW BEFORE YOU START

Before you study this book, it is essential that you have a good background in the principles of electricity and electronics, including the fundamentals of tube and transistor circuits and test equipment. This background can be obtained by studying the first four volumes of this series. With the proper background, however, you should have no trouble understanding this text. All new terms are carefully defined. Enough math is used to give precise interpretation to important principles, but if you know how to add, subtract, multiply, and divide, the mathematical expressions will give you no trouble.

WHY THE TEXT FORMAT WAS CHOSEN

During the past few years, new concepts of learning have been developed under the common heading of programmed instruction. Although there are arguments for and against each of the several formats or styles of programmed textbooks, the value of programmed instruction itself has been proved to be sound. Most educators now seem to agree that the style of programming should be developed to fit the needs of teaching the particular subject. To help you progress successfully through this volume, a brief explanation of the programmed format follows.

Each chapter is divided into small bits of information presented in a sequence that has proved best for learning purposes. Some of the information bits are very short—a single sentence in some cases. Others may include several paragraphs. The length of each presentation is determined by the nature of the concept being explained and the knowledge the reader has gained up to that point.

The text is designed around two-page segments. Facing pages include information on one or more concepts, complete with illustrations designed to clarify the word descriptions used. Self-testing questions are included in most of these two-page segments. Many of these questions are in the form of statements requiring that you fill in one or more missing words; other questions are either multiple-choice or simple essay types. Answers are given on the succeeding page, so you will have the opportunity to check the accuracy of your response and verify what you have or have not learned before proceeding. When you find that your answer to a question does not agree with that given, you should restudy the information to determine why your answer was incorrect. As you can see, this method of question-answer programming insures that you will advance through the text as quickly as you are able to absorb what has been presented.

The beginning of each chapter features a preview of its contents, and a review of the important points is contained at the end of the chapter. The preview gives you an idea of the purpose of the chapter—what you can expect to learn. This helps to give practical meaning to the information as it is presented. The review at the completion of the chapter summarizes its content so that you can locate and restudy those areas which have escaped your full comprehension. And, just as important, the review is a definite aid to retention and recall of what you have learned.

HOW YOU SHOULD STUDY THIS TEXT

Naturally, good study habits are important. You should set aside a specific time each day to study in an area where you can concentrate without being disturbed. Select a time when you are at your mental peak, a period when you feel most alert.

Here are a few pointers you will find helpful in getting the most out of this volume.

1. Read each sentence carefully and deliberately. There are no unnecessary words or phrases; each sentence presents or supports a thought which is important to your understanding of electricity and electronics.

2. When you are referred to or come to an illustration, stop at the end of the sentence you are reading and study the illustration. Make sure you have a mental picture of its general content. Then continue reading, returning to the illustration each time a detailed examination is required. The drawings were especially planned to reinforce your understanding of the subject.

3. At the bottom of most right-hand pages you will find one or more questions to be answered. Some of these contain "fill-in" blanks. Since more than one word might logically fill a given blank, the number of dashes indicates the number of letters in the desired word. In answering the questions, it is important that you actually do so in writing, either in the book or on a separate sheet of paper. The physical act of writing the answers provides greater retention than merely thinking the answer. Writing will not become a chore since most of the required answers are short.

4. Answer all questions in a section before turning the page to check the accuracy of your responses. Refer to any of the material you have read if you need help. If you don't know the answer even after a quick review of the related text, finish answering any remaining questions. If the answers to any questions you skipped still haven't come to you, turn the page and check the answer section.
5. When you have answered a question incorrectly, return to the appropriate paragraph or page and restudy the material. Knowing the correct answer to a question is less important than understanding why it is correct. Each section of new material is based on previously presented information. If there is a weak link in this chain, the later material will be more difficult to understand.
6. In some instances, the text describes certain principles in terms of the results of simple experiments. The information is presented so that you will gain knowledge whether you perform the experiments or not. However, you will gain a greater understanding of the subject if you do perform the suggested experiments.
7. Carefully study the review, "What You Have Learned," at the end of each chapter. This review will help you gauge your knowledge of the information in the chapter and actually reinforce your knowledge. When you run across statements you don't completely understand, reread the sections relating to these statements, and recheck the questions and answers before going to the next chapter.

This volume has been carefully planned to make the learning process as easy as possible. Naturally, a certain amount of effort on your part is required if you are to obtain the maximum benefit from the book. However, if you follow the pointers just given, your efforts will be well rewarded, and you will find that your study of electricity and electronics will be a pleasant and interesting experience.

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1

Understanding Basic Principles

What You Will Learn

In this chapter you will learn about the basic principles of motors and generators. You will learn how generators convert mechanical energy into electrical energy. You will find that generators can provide an AC or DC output depending on whether the generated current is taken from the generator through slip rings or a commutator. You will also learn how AC and DC motors convert electrical energy into mechanical energy.

SOURCES OF ELECTRICITY

Earlier you learned that electrical energy is usually supplied by batteries or electrical power plants. Batteries are generally used where portability is desired and small amounts of current are needed. The voltage and current that can be developed by one cell are small. To increase the voltage, a number of cells must be connected in series. To increase the current capacity, either the cell must be made larger, or a number of cells must be connected in parallel. A battery that supplies both high current and high voltage is bulky and expensive.

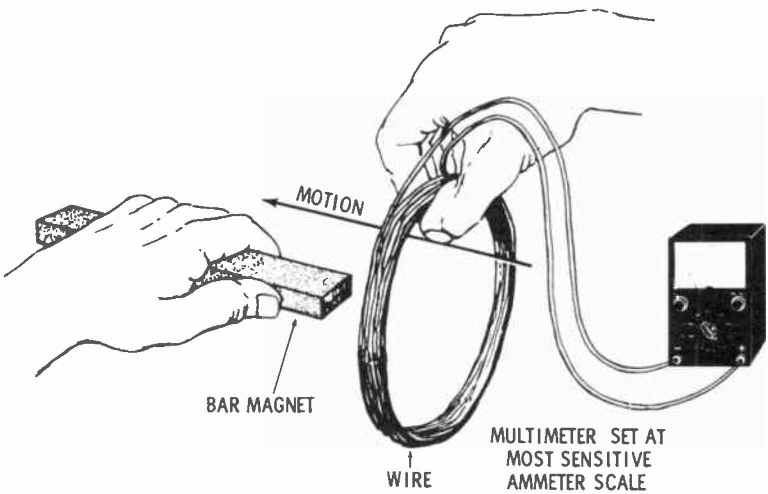
A voltage drop occurs when DC is transmitted over long distances, so batteries must be located near the place where the electrical energy is used. Batteries are usually used when a portable source of small values of DC is needed.

PRODUCTION OF ELECTRICAL ENERGY

Large amount of electrical energy are usually supplied by **generators** in power plants. A generator is defined as **a machine that converts mechanical energy into electrical energy.**

Mechanical energy is converted into electrical energy by **induction.** The following example shows how a voltage is generated by induction. Your hand supplies mechanical energy to move the coil, and the multimeter detects the electrical energy produced.

GENERATING A VOLTAGE BY INDUCTION



If an electric conductor is moved through a magnetic field in such a way that it cuts the lines of force, a voltage is generated, or induced, in the conductor. The induced voltage is greatest when the conductor moves at right angles to the magnetic field, and is zero when the conductor moves parallel to the lines of force.

If the moving conductor is connected to a complete electric circuit, an electric current will flow in the conductor and the circuit. This means that the **mechanical energy** used in moving the conductor through the magnetic field is converted into **electrical energy** which moves the current through the circuit.

Factors Determining Voltage

The amount of voltage generated is determined by: (1) **The speed at which the conductor passes through the magnetic field.** Greater speed causes the conductor to cut more lines of force per second. (2) **The strength of the magnetic field.** A stronger field provides more magnetic lines of force. (3) **The number of loops of wire.** Each additional loop of wire increases the number of conductors in which a voltage may be induced. Since the loops are in series, the generated voltages in each are additive.

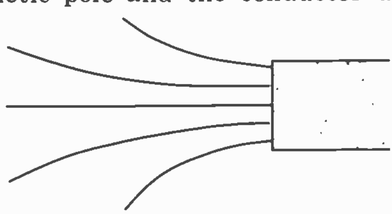
Conditions for Generating a Voltage

Voltage is generated by induction when a conductor is moved through a magnetic field, or when a magnetic field moves in relation to a stationary conductor in the field. In other words, **voltage is generated when a conductor and a magnetic field move relative to each other.**

In a generator the conductor can move, the field can move, or both can move. All of these possibilities as used in practical generators are discussed in this volume.

The amount of voltage induced in a conductor by a magnetic field depends, among other factors, on the distance between the magnetic pole and the conductor. When the distance between the magnetic pole and the conductor de-

FIELD STRENGTH IS GREATEST NEAR A POLE



creases, the magnetic field through which the conductor is moving is stronger. The conductor then cuts through more magnetic lines of force per given distance of movement, and a higher voltage is produced.

Q1. A generator converts mechanical energy into electrical energy by the principle of ---------.

Q2. The amount of voltage generated by induction increases as the ----- between the conductor and the magnetic pole increases.

Q3. Name three ways to generate an emf by induction.

Your Answers Should Be:

A1. A generator converts mechanical energy into electrical energy by the principle of **induction.**

A2. The amount of voltage generated by induction increases as the **speed** between the conductor and the magnetic pole increases.

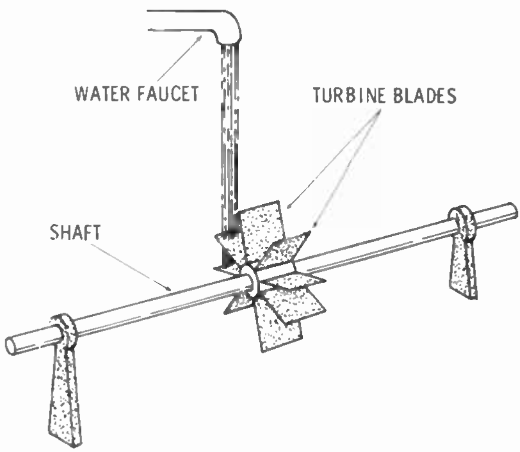
A3. Three ways to generate an emf by induction are:

1. **Moving a conductor through a stationary magnetic field.**
2. **Moving a magnetic field past a stationary conductor.**
3. **Moving a magnetic field and a conductor relative to each other.**

Transmission of Mechanical Energy to the Generator

Mechanical energy is usually transmitted to a generator by a shaft. When a coil, called the **armature,** is mounted on the shaft and the assembly is rotated in a magnetic field, an **emf** (voltage) is induced in the armature.

Energy from waterfalls, wind, tides, or high-pressure steam can be used to turn a **turbine** that will rotate the shaft. A turbine is a machine that converts water or steam pressure into rotation of a shaft.



A SIMPLE TURBINE

POWER-PLANT LOCATION

The location of power plants depends on the availability of a plentiful source of energy that can be used to rotate the generator shaft.

In steam power plants, high-pressure steam is directed against the blades of a turbine which rotates the generator shaft. Coal or oil is used to boil water and create the high-pressure steam. This type of power plant requires large amounts of water, as well as fuel, in order to produce steam.

Hydroelectric plants are located at the base of waterfalls or dams. Water flowing over the waterfall or released by the dam is directed against the turbine blades, causing the generator shaft to rotate.

WHAT IS A MOTOR?

Electrical energy produced by generators is used in many ways, but one of the most important is to turn motors that operate machinery and appliances.

A **motor** is a machine that converts **electrical energy** into **mechanical energy.** This definition is the inverse of the definition of a generator

When electrical energy is supplied to a motor, current flows through the armature. The current flow creates a magnetic field surrounding the armature. This field interacts with a stationary magnetic field. The interaction of the two magnetic fields creates a twisting force, or **torque,** that causes the shaft of the motor to rotate.

Q4. Name three methods that are used to turn a generator shaft.

Q5. When water or high-pressure steam is directed against the turbine blades, the generator shaft will ______.

Q6. What will happen if the force with which the water strikes the turbine blades is increased?

Q7. A twisting force is called ______.

Q8. A motor is a machine that converts ___________ ______ into ___________ ______.

Q9. A water wheel is a simple example of a _______.

Your Answers Should Be:

A4. Some methods that are used to turn a generator shaft are: **turbines** turned by water or high-pressure steam, **windmills**, and **gasoline or diesel engines.**

A5. When water or high-pressure steam is directed against the turbine blades, the generator shaft will **rotate.**

A6. If the force with which the water strikes the turbine blades is increased, the turbine will **rotate at a higher speed.**

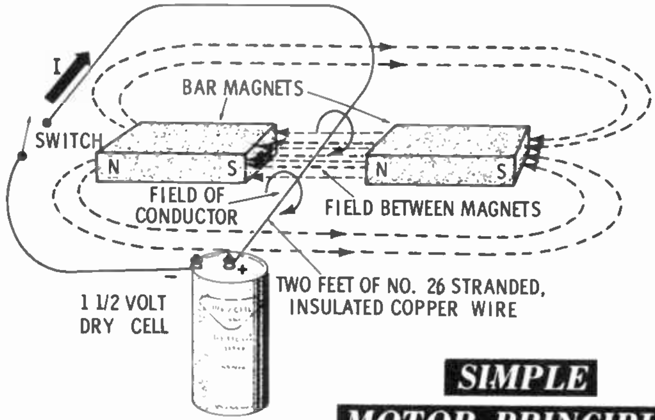
A7. A twisting force is called **torque.**

A8. A motor is a machine that converts **electrical energy** into **mechanical energy.**

A9. A water wheel is a simple example of a **turbine.**

Converting Electrical Energy Into Mechanical Energy

The following experiment demonstrates how forces are created in a motor. If you try the experiment, be careful not to close the switch until you are ready to observe the results. When you close the switch, you should do so for only a few seconds. This is because the battery is short-circuited when the switch is closed. If the switch is not

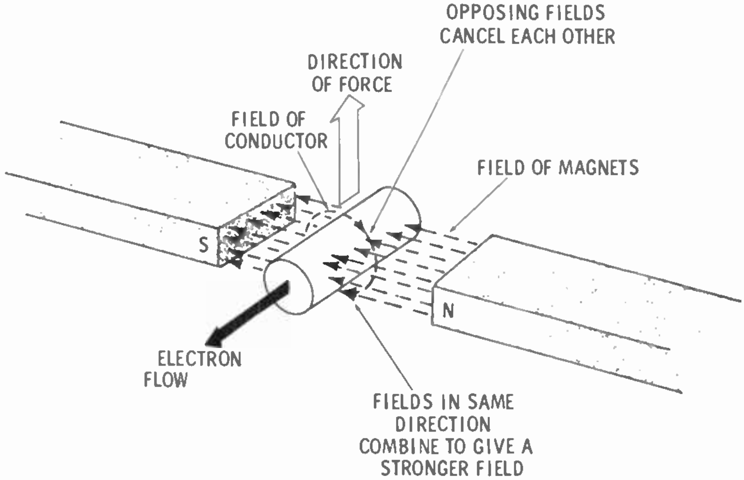


SIMPLE MOTOR PRINCIPLE

reopened quickly, the battery will be drained of its electrical energy. When the switch is closed, the conductor should jump. When the switch is opened, the conductor should return to its original position.

The conductor jumps from between the magnets when the switch is closed because a magnetic field is created by the flow of current through the conductor. The magnetic field around the conductor causes the main magnetic field to be strengthened on one side of the conductor and weakened on the other. This creates a force which pushes the wire away from the stronger part of the field.

CONDUCTOR IN A MAGNETIC FIELD



The direction of the magnetic field surrounding the conductor can be determined by applying the **left-hand rule** for straight conductors. Wrap the fingers of your left hand around the conductor so that your thumb points in the direction of electron flow through the conductor. Your fingers then show the direction of the magnetic field surrounding the conductor. External magnetic fields are considered to flow from the north pole to the south pole.

Q10. State the left-hand rule for straight conductors.

Q11. The difference in the strength of the magnetic field above and below the conductor results in a _ _ _ _ _.

Your Answers Should Be:

A10. The left-hand rule for straight conductors is applied by wrapping the fingers of your left hand around the conductor so that your **thumb** points in the **direction of the electron flow. Your fingers** then show the **direction of the magnetic field surrounding the conductor.**

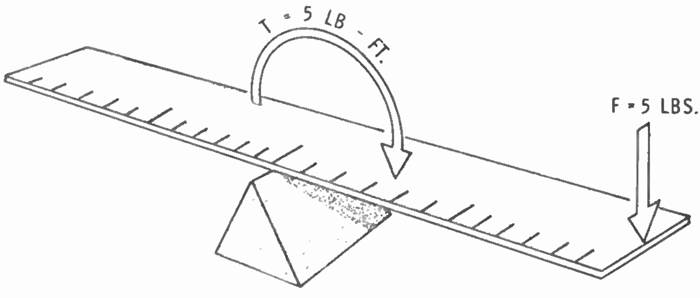
A11. The difference in the strength of the magnetic field above and below the conductor results in a **force.**

What Is Torque?

Torque (pronounced "tork") is a turning force. In a motor, the conductor is formed into a coil and placed on a shaft that is free to rotate. When current flows through the coil, a magnetic field is produced. This magnetic field around the coil reacts with the stationary magnetic field, developing a torque and causing the shaft to turn.

Torque is calculated by multiplying the force times the distance from the center of rotation. The illustration below shows a two-foot ruler balanced at its center. When a force

CALCULATION OF TORQUE

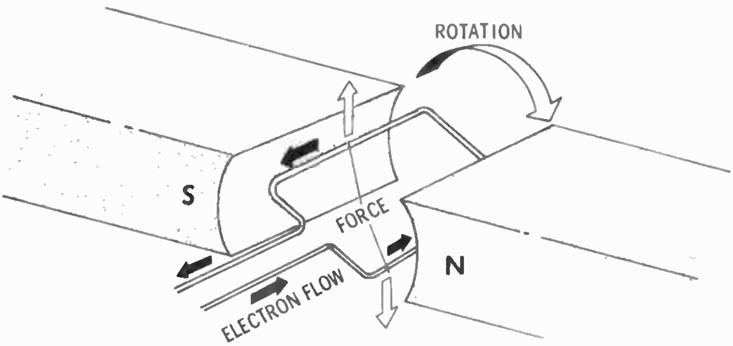


of five pounds is applied to the right end of the ruler, the resulting torque is calculated as follows:

$$\text{Torque} = \text{Force} \times \text{Distance from center of rotation}$$
$$= 5 \text{ pounds} \times 1 \text{ foot}$$
$$= 5 \text{ pound-feet}$$

Shown below is a coil that is free to rotate in a magnetic field. The flow of current out of the left side of the coil

PRODUCTION OF TORQUE



causes the magnetic field below the conductor to be strengthened and the field above to be weakened. This results in an upward force on the left side of the coil and a clockwise direction of rotation. The flow of current into the right side of the coil causes the magnetic field below the conductor to be weakened and the field above to be strengthened. This results in a downward force on the right side of the coil and a clockwise rotation.

The amount of torque generated depends on the strength of the two magnetic fields and on the distance of the sides of the coil from the center of rotation. The strength of the magnetic field around the coil depends on the number of turns in the coil, the current through the coil, the core material of the coil, etc.

Q12. If the ruler shown on the opposite page were six feet long and a force of ten pounds were applied to the right end, how much torque would be developed?

Q13. What factors determine the amount of torque on the coil shown in the figure on this page?

Q14. What factors determine the strength of the magnetic field around the coil shown in the figure at the top of this page?

Q15. Torque is calculated by multiplying _____ times the ________ from the center of rotation.

Your Answers Should Be:

A12. The torque developed is calculated as follows:

Torque = Force × Distance from center of rotation

= 10 pounds × 3 feet = **30 pound-feet**

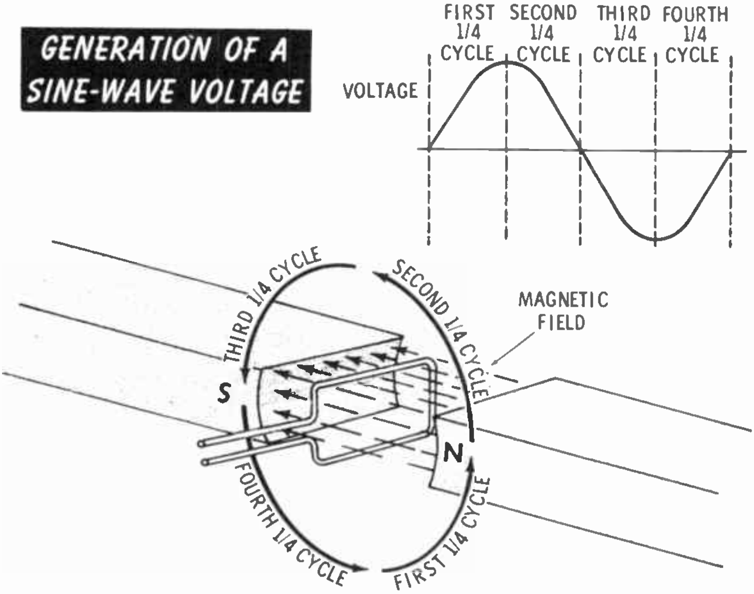
A13. The amount of torque on the coil shown on the preceding page is determined by the **strength of the two magnetic fields** and the **distance** of the sides of the coil **from the center of rotation.**

A14. The strength of the magnetic field around the coil depends on the **number of turns** in the coil, the **current** through the coil, and the **core material,** etc.

A15. Torque is calculated by multiplying **force** times the **distance** from the center of rotation.

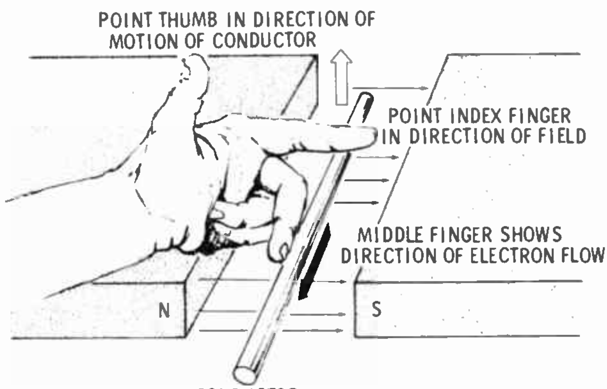
AC AND DC GENERATORS

The output from the armature coil of any generator is an AC voltage. As the coil shown below rotates at constant speed, it cuts more or fewer magnetic lines of force per sec-



ond, depending on its position at any particular instant. When it is moving at right angles to the magnetic field, it is cutting a maximum number of lines of force per second. Therefore, the voltage induced in the coil increases until, when the coil is moving at right angles to the field, the voltage is maximum. Then, as the coil continues to rotate, it cuts fewer and fewer lines of force per second until it is moving parallel to the magnetic field. At that point, no voltage is induced. In the third quarter cycle, the conductor cuts the lines of force in the opposite direction, so the induced voltage has the opposite polarity and again rises to a maximum. In the fourth quarter cycle, the voltage again decreases to zero.

LEFT-HAND RULE FOR GENERATORS



The **left-hand rule** for generators is shown above. This is an easy way of remembering the relationship between the direction of the magnetic field, the direction of motion of the conductor, and the direction of the induced current.

In a generator, the shaft rotation determines the direction that the conductor moves. The direction of the magnetic lines of force is from the north pole to the south pole. If the polarity of a magnet is unknown, it can be determined by using a compass. The south end of the compass needle will point to the north pole of the magnet.

Q16. A(an) __ voltage is induced in a rotating generator coil.

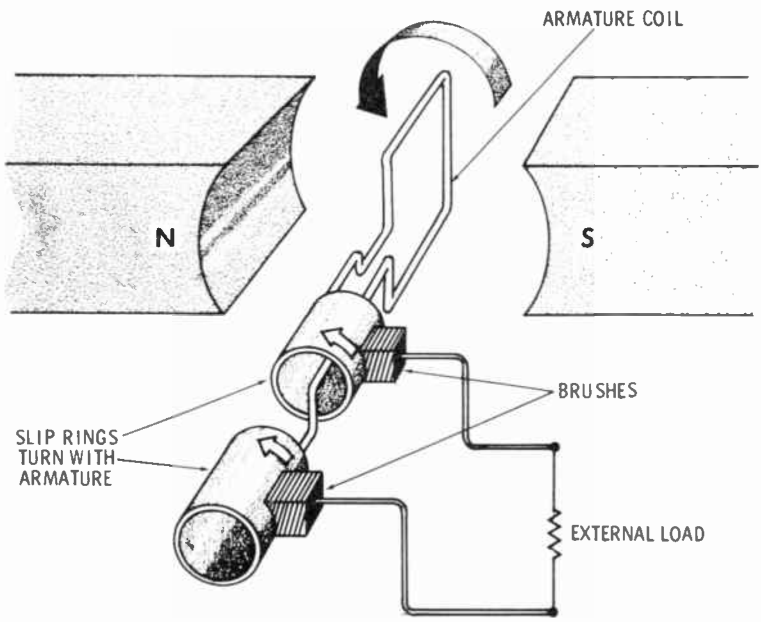
Q17. Describe the left-hand rule for generators.

> **Your Answers Should Be:**
>
> **A16.** An AC voltage is induced in a rotating generator coil.
>
> **A17.** In the left-hand generator rule, the thumb, index finger, and middle finger of the left hand are held at right angles to each other. The **thumb** is made to point in the **direction of motion** of the conductor, and the **index finger** is made to point in the **direction of the magnetic** field. The **middle finger** will then point in the **direction of electron flow.**

The AC Generator

The output from the armature coils of any generator is AC. In order to take the AC output of the generator from

SIMPLE AC GENERATOR

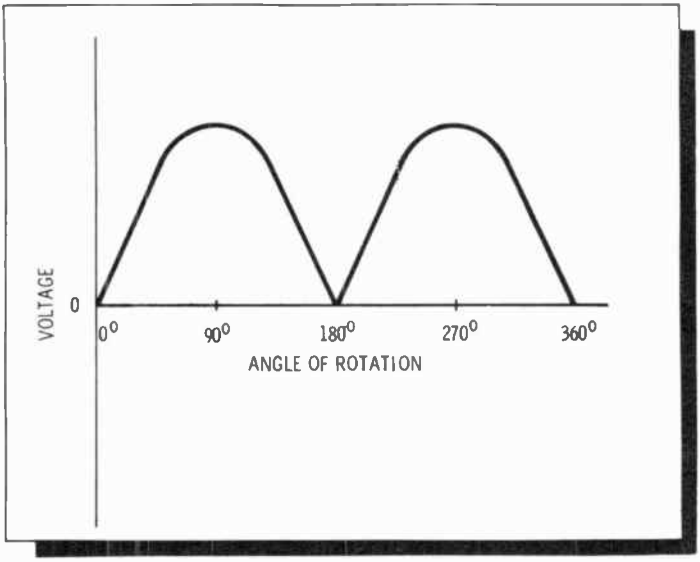


the armature coils, the ends of the coils are connected to **slip rings** which rotate with the armature. Stationary conductors called **brushes** provide a sliding contact on the rotating slip rings. In this way, the brushes and slip rings provide a connection between the armature coils in the generator and any external load that is being furnished power by the generator.

The DC Generator

In a DC generator, the AC output of the armature coils is converted to pulsating DC by the use of a **commutator** in the place of slip rings. The output of a basic DC generator is shown in the figure below. This pulsating DC output is

OUTPUT OF A BASIC DC GENERATOR



obtained because the connections to the armature coil are reversed every half cycle when the voltage is zero and is about to change polarity.

Q18. In an AC generator ____ _____ are used to take the output of the generator from the coils.

Q19. _______ are used to make a sliding contact on the rotating slip rings.

Q20. In a DC generator a __________ is used to convert the AC output of the armature coils into pulsating DC.

Your Answers Should Be:

A18. In an AC generator **slip rings** are used to take the output of the generator from the coils.

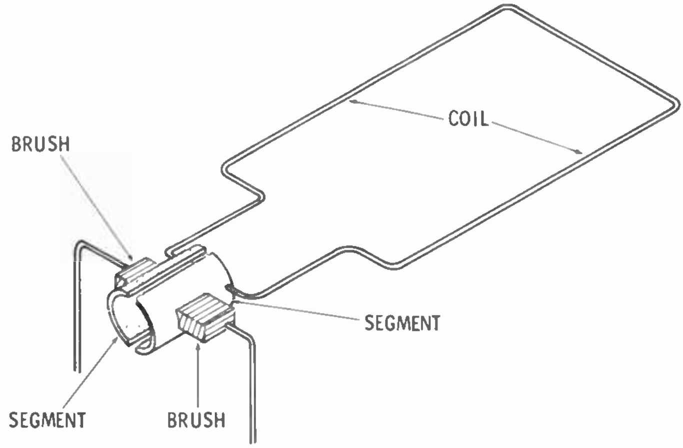
A19. **Brushes** are used to make a sliding contact on the rotating slip rings.

A20. In a DC generator a **commutator** is used to convert the AC output of the armature coils into pulsating DC.

What Is a Commutator?

A basic commutator is simply a slip ring split into two semicircular halves, called **segments**. The segments are insulated from each other and from the shaft. One end of the armature coil is connected to one segment and the other end

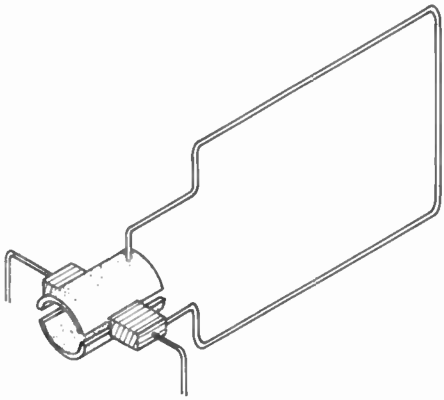
A BASIC COMMUTATOR



of the coil is connected to the other segment. Two brushes touch opposite sides of the commutator. As the commutator turns, the two sides of the coil are short-circuited for a moment as the brushes touch both segments of the commutator at once. Then the connections are reversed.

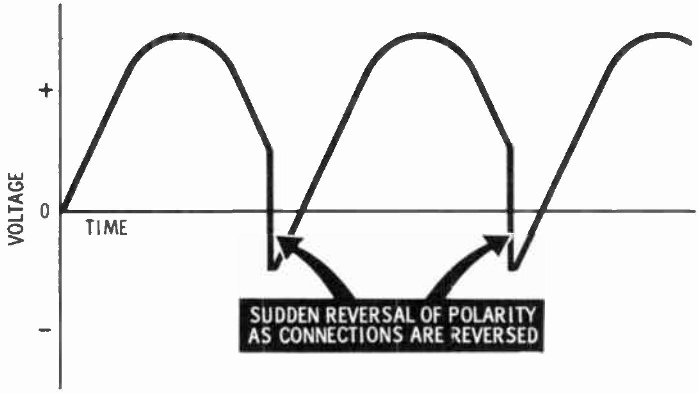
If the armature coil is short-circuited by the brushes while an emf is being induced in the coil, a heavy current will flow in the armature coil. This is because the circuit formed by the coil and the brushes has a very low resistance. This excessive current may cause serious damage to the armature

COIL SHORT-CIRCUITED BY BRUSHES



coils. Also, if the commutator of a DC generator is not adjusted to reverse the armature coil connections at the moment when the induced emf is zero, the output of the generator will not be DC. Instead, it will be AC as shown in the figure below.

GENERATOR OUTPUT WHEN SWITCHING OCCURS AT THE WRONG TIME



Q21. At what point in the AC cycle should the commutator reverse the coil connections?

Q22. Give two reasons why proper adjustment of a commutator is important.

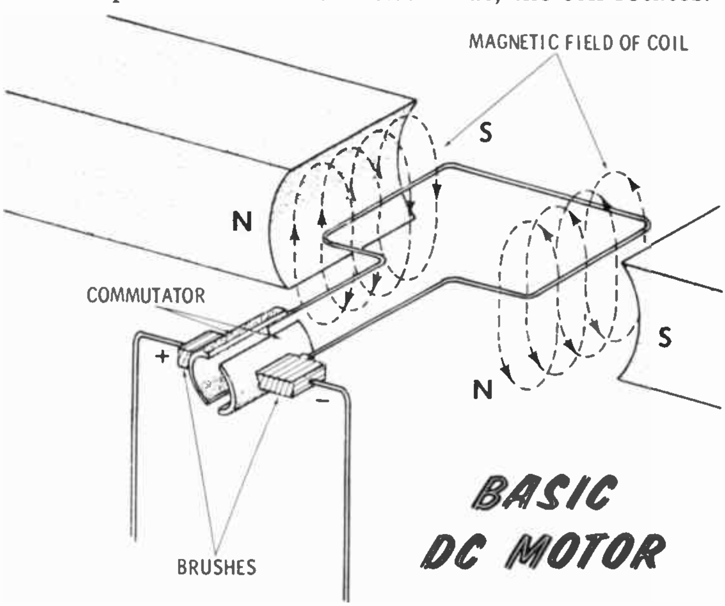
Your Answers Should Be:

A21. The commutator should reverse the coil connections when the **induced emf is zero.**

A22. If the commutator is not properly adjusted, the **generator coils may be damaged** by a heavy current through the short circuit created when the brushes touch both segments. Also, the output of the generator will **not be pure DC,** but will reverse polarity periodically.

DC MOTORS

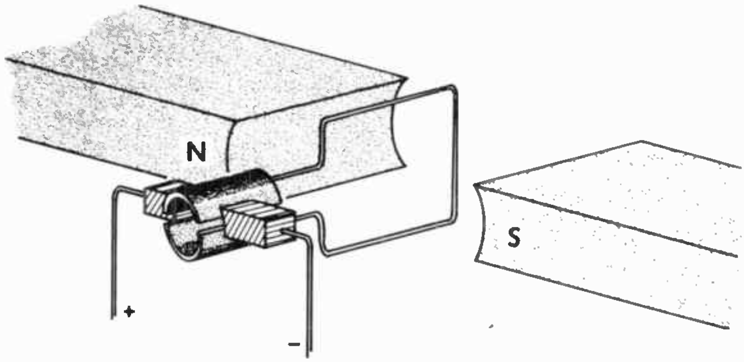
DC motors also have commutators. In fact, a basic DC generator can also act as a DC motor. When a DC current passes through the coil, the current creates a magnetic field. The north pole of the coil is attracted to the south pole of the outside magnetic field, and the south pole of the coil to the north pole of the outside field. Thus, the coil rotates.



You can analyze the magnetic forces acting on the simple coil by using the left-hand rule for straight conductors. The figure above shows the field around the coil.

When the coil reaches the position shown in the figure below, the brushes touch both commutator segments at the same time. No current flows in the coil, and there is no turning force on the coil. However, the coil is turning and

MOTOR COIL AT DEAD CENTER



its inertia, tending to keep it turning, carries it past dead center. As the coil rotates past dead center, the commutator reverses the direction of current flow through the coil. The polarity of the magnetic field around the coil is reversed, and the pole of the coil next to the south pole of the external field now becomes the south pole of the coil. The new south pole of the coil is now attracted toward the north pole of the external field, so the coil keeps on rotating. The same switching process is repeated when the coil has rotated another 180°.

In the figure above, the commutator causes a momentary short circuit across the power source when the coil is at dead center. You can see why this simple commutator-brush arrangement is not used in practical motors. The basic principle of all commutators is the same, however. As you have seen, the commutator in a DC motor converts the DC power supplied to the motor into AC for the armature coil.

Q23. Would the motor just described rotate if you supplied AC to the coil through slip rings?

Q24. The commutator in a DC motor changes DC into __.

Q25. There is no magnetic field developed around the coil when it is at ____ ______.

Your Answers Should Be:

A23. Yes. If the motor is supplied with AC, it does not need a commutator.

A24. The commutator in a DC motor changes DC into AC.

A25. There is no magnetic field developed around the coil when it is at dead center.

WHAT YOU HAVE LEARNED

1. A generator is a machine that converts mechanical energy into electrical energy by induction.
2. For induction to occur there must either be a conductor moving in a stationary magnetic field, a moving magnetic field surrounding a stationary conductor, or a moving magnetic field containing a moving conductor.
3. The strength of the induced emf depends on how fast magnetic lines are being cut by conductors, the strength of the magnetic field, the number of conductors in which an emf is being induced, and the distance between the source of the magnetic field and the conductor.
4. The direction of the induced emf depends on the direction of motion of the conductor and the direction of the field through which it is moving.
5. AC is generated in the armature coils of all generators.
6. The output of a generator will be AC if the output of the rotating armature coils is removed through slip rings and brushes.
7. The output of a generator will be DC if the output of the rotating armature coils is removed through a commutator and brushes.
8. Motors are machines that convert electrical energy into mechanical energy.
9. A DC motor is supplied with DC voltage and current which is converted into AC by the commutator for use in the armature coils.
10. An AC motor does not need a commutator.

2

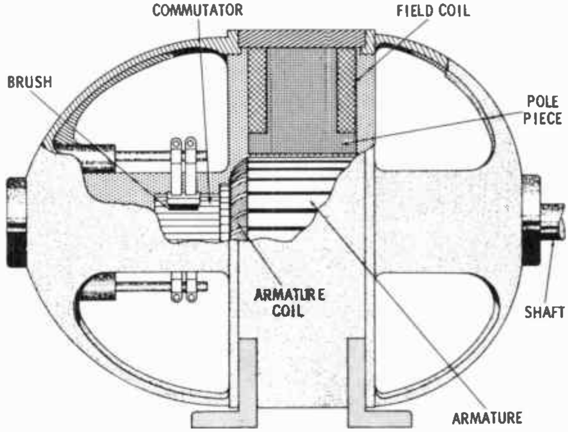
DC Generators

What You Will Learn

In this chapter you will learn about DC generator construction. You will learn to recognize each part and to know its function. You will be able to recognize effects within the generator that waste power, and how to minimize them. You will also learn the characteristics of the various kinds of DC generators.

CONSTRUCTION

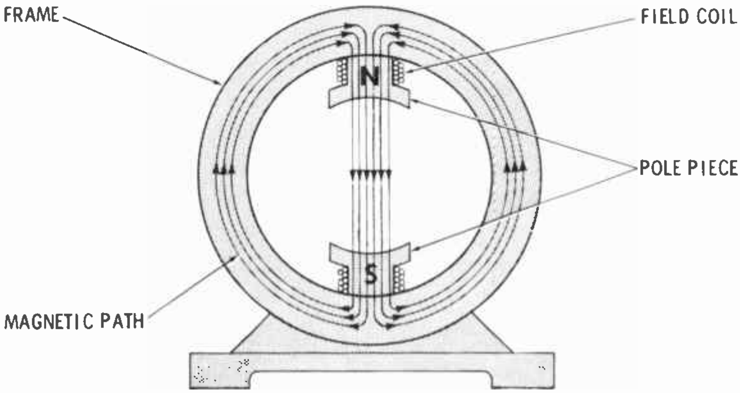
The major parts of a DC generator are the frame, end bells, pole pieces, shaft, armature assembly, commutator assembly, and brush assembly. The illustration below shows the construction of a DC generator.



Frame (Yoke)

The **frame,** or yoke, supports the generator. The frames of most modern generators are constructed of steel because this metal is an excellent conductor of magnetic lines of force. When the magnetic circuit is completed through a good magnetic conductor, as shown below, the field between the poles is stronger.

MAGNETIC PATH IN A GENERATOR FRAME



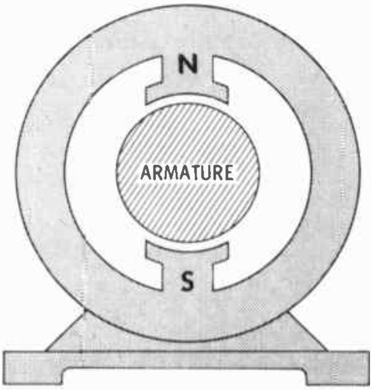
At one time, most generator frames were made of cast iron. Cast iron is heavier than steel and has a poorer **permeability** (ability to conduct magnetic lines of force), so it is used less frequently now. The frames of large generators are made of steel castings; those of smaller generators are made of rolled sheet steel. The frame of the generator also includes a base or mounting brackets.

There are three types of frames: open, semiclosed, and closed. An **open frame** has the ends open so that air can circulate freely through it. A **semiclosed frame** has a wire screen or a metal grille in its end bells to prevent foreign matter from entering the machine. A **closed frame** has solid end bells, and the machine is airtight.

Pole Pieces

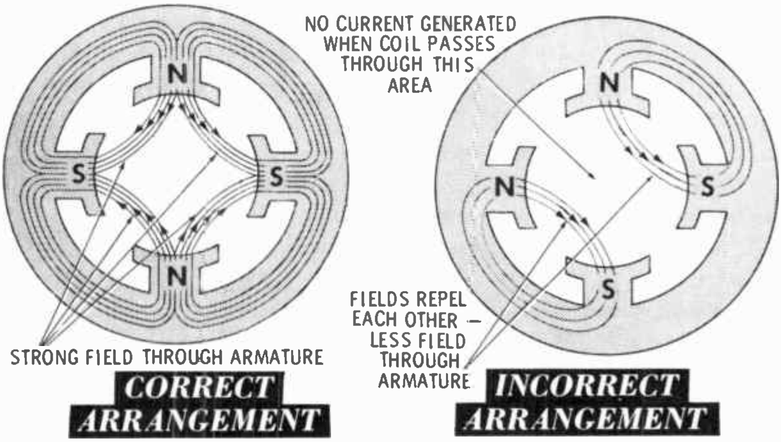
The **pole pieces** (also called pole shoes) of a generator are always used in pairs and are bolted to the frame. They support the field windings which are used to produce a north pole facing the armature on one side, and a south pole directly opposite on the other side.

ARRANGEMENT OF TWO GENERATOR POLES



More than one pair of poles are sometimes used in order to produce a stronger magnetic field. When this is done, opposite poles are always next to each other. You can see from the following illustration how this arrangement creates the strongest magnetic field through the armature.

ARRANGEMENT OF FOUR GENERATOR POLES



Q1. The permeability of a material refers to how well the material conducts _________ _____ __ _____.

Q2. Magnetic pole pieces are placed in a generator so that poles of (the same, opposite) polarity are next to each other.

Your Answers Should Be:

A1. The permeability of a material refers to how well the material conducts **magnetic lines of force.**

A2. Magnetic pole pieces are placed in a generator so that poles of **opposite** polarity are next to each other.

End Bells and Bearings

The **end bells** are bolted to each end of the frame and contain the bearings that support the armature shaft. The three types of bearings most commonly used in generators are: **ring-oiled** (sleeve), **yarn-packed**, and **ball** bearings.

The ring-oiled, or sleeve, bearing contains an oil ring that rides on the shaft. As the shaft turns, oil is carried from a reservoir to the top of the shaft for distribution to the bearing surface.

The yarn-packed bearing consists of a bundle of wool yarn looped on the armature shaft. Both ends of the yarn loop are in the oil reservoir. Oil soaks into the yarn and lubricates the revolving shaft.

Both oil-ring and yarn-packed bearings are provided with oil seals at each end of the bearing in order to prevent oil from escaping and causing damage to the parts of the generator carrying electricity.

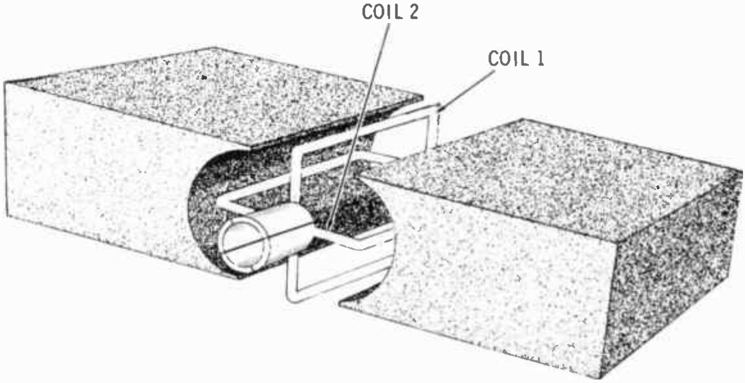
Ball bearings may be either the open or closed type and are packed with their own grease or lubricant. This type of bearing contains an outer ring, or race, and an inner ring. The outer ring does not move and is firmly held in position by the frame. The inner race rotates with the turning shaft. Between the inner and outer races are a number of very finely machined steel balls packed in grease. This arrangement provides an almost friction-free rotation of the inner race while the outer race is stationary.

Armature and Commutator

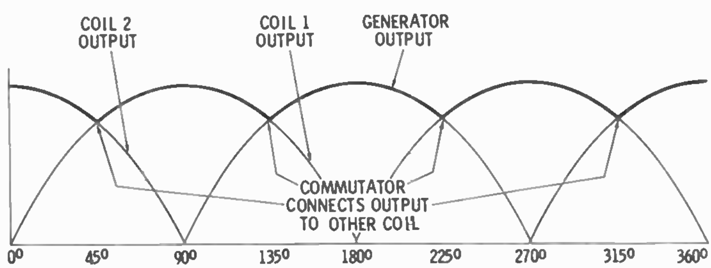
As you learned in Chapter 1, the commutator used with a single coil produces a pulsating DC output. By using more coils and combining their output, a smoother waveform can be obtained.

When a second coil is added to the armature and placed perpendicular to the first coil, the resulting output will be as shown below.

OUTPUT OF A TWO-COIL DC GENERATOR



COIL ARRANGEMENT



OUTPUT WAVEFORM

Notice that an emf is induced at all times. Although the DC still pulsates, the output is smoother. In practical generators, many coils are added to the armature to produce a still smoother DC output.

Q3. Which type of bearing is usually lubricated with grease rather than oil?

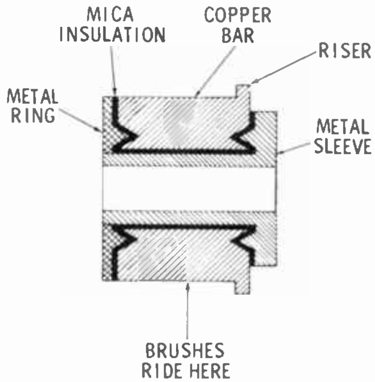
Q4. A generator using two coils (does, does not) have a smoother output than one using one coil.

> **Your Answers Should Be:**
>
> A3. **Ball bearings** are usually lubricated with grease rather than oil.
>
> A4. A generator using two coils **does** have a smoother output than one using one coil.

Commutator Connections

Each armature coil in a DC generator is connected to two commutator segments, one segment for each end of the coil. A generator with many coils will also have many commutator segments.

In a practical commutator, the segments are usually made of copper. Mica is used to insulate the commutator segments from each other and from the commutator sleeve. The ends of the armature coils are connected to the raised portions of



CROSS SECTION OF A COMMUTATOR

the segments. The raised part of the segment is called a **riser** and is slotted to hold the coil ends. The brushes ride on the lower portions of the commutator segments.

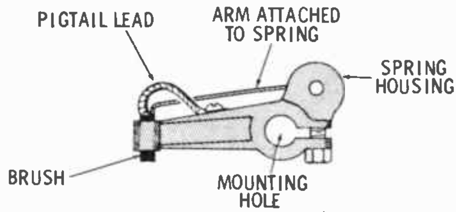
Brush Assembly

The brush assembly shown in the illustration on the opposite page consists of the brush, brush holder, adjustable brush-holder springs, and pigtailed connections.

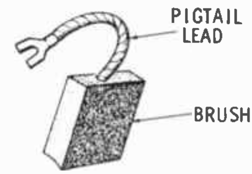
In normal operation, both the commutator segments and the brushes wear. The adjustable brush-holder spring allows the brush pressure on the commutator to be adjusted to compensate for this wear. The spring should apply only enough pressure to make a good connection between brush and commutator.

The pigtailed connections are braided copper wires that provide a low-resistance and flexible connection between the brush and the brush holder.

BRUSH ASSEMBLY



COMPLETE ASSEMBLY



BRUSH

Brush Materials

The type and operating conditions of a generator determine the material used for brushes. **Graphite brushes** are easily distinguished by their silvery appearance and soft, flaky texture. This type of brush is for general-purpose use. **Carbon brushes** are used on generators that have both low rotation speeds and low current output.

Electrographitic brushes are made from the same material as carbon brushes but are processed at high temperatures in an electric furnace. This process increases the ability of the brush to conduct both electrical and heat energy. These brushes are nonabrasive and cooler running. They have very low friction and a higher current capacity than carbon brushes.

Copper-graphite brushes are made from a mixture of powdered copper and powdered graphite pressed together and baked at low temperatures. This type of brush is used on low-voltage generators.

Q5. Normal wear of the commutator segments and the brushes of a generator is adjusted with the _____ ______ ______.

Q6. ______ ________ brushes are used in low-voltage generators.

Your Answers Should Be:

A5. Normal wear of the commutator segments and the brushes of a generator is adjusted with the **brush-holder spring.**

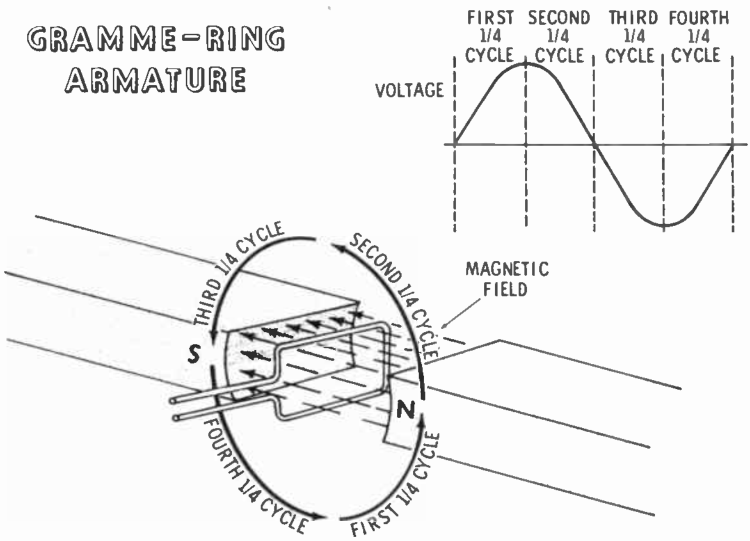
A6. **Copper-graphite** brushes are used in low-voltage generators.

THE ARMATURE CORE

Armature coils are wound on cores of either the **Gramme-ring** or **drum** type. The Gramme-ring armature core is an older type and is usually not found on newer machines.

Gramme Ring

In a Gramme-ring armature, the windings are wound on the surface of an iron or steel ring. The armature winding is tapped at regular intervals for connection to the commutator.



Since the armature windings of the Gramme-ring core are wound on the surface of the core, the distance between the core and the pole pieces must be great enough that there is no danger of the armature windings touching the pole pieces. This causes a reduction in the strength of the magnetic field. The weakened field results in reduced output from the generator.

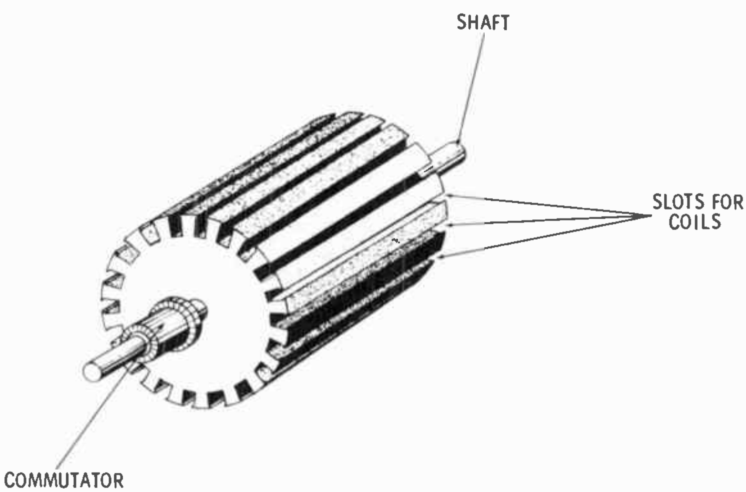
The Gramme-ring core offers a lower **reluctance** (magnetic equivalent of resistance) to the lines of force than the air gap inside the ring. The magnetic lines of force follow the circular path of the core and do not cross the center air gap. Thus they are not cut by the conductors on the inside surface of the core and, therefore, do not induce an emf in these conductors.

For these and other reasons the Gramme-ring armature is rarely used. Nearly all modern DC generators use drum-type armatures.

Drum

The drum armature core is newer and more efficient. Coils are placed in slots and are generally a fraction of an inch below the outer surface of the core. This type of construction and coil placement eliminates the danger of the armature coils rubbing against the pole pieces while the armature is rotating.

DRUM ARMATURE CORE



Q7. What are two disadvantages of the Gramme-ring armature?

Your Answer Should Be:

A7. The Gramme-ring armature core must be kept **farther from the pole pieces** than the drum type. This results in reduced magnetic field strength. Only the parts of the conductors on the **outside of the core** have voltages induced in them.

Advantages of the Drum Armature Core

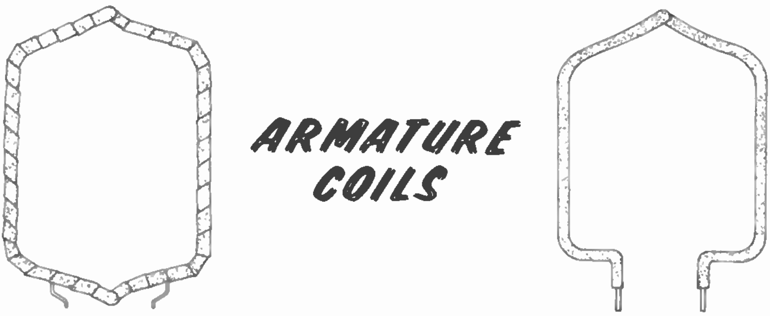
One of the advantages of the drum armature core is that a smaller air gap exists between the armature and the pole pieces. The smaller air gap permits the armature coils to cut through a magnetic field of greater density, and thus a greater emf is induced in the armature coils.

Since the drum armature core is more compact than the Gramme-ring armature core, the drum armature can be rotated at a higher speed, thus producing a greater emf.

THE ARMATURE COIL

The coils used on drum armature cores are usually preformed. That is, they are wound in their final shape before being put on the armature.

The sides of the preformed coil are placed in the slots of the drum armature core. The two slots for each coil are usually the same distance apart as adjacent magnetic poles. This distance is called the **pole pitch, or pole span.** As you recall, adjacent magnetic poles are of opposite polarity, so that the emf induced in one side of the armature coil is reinforced by the emf induced by the opposite pole on the second side of the armature coil.



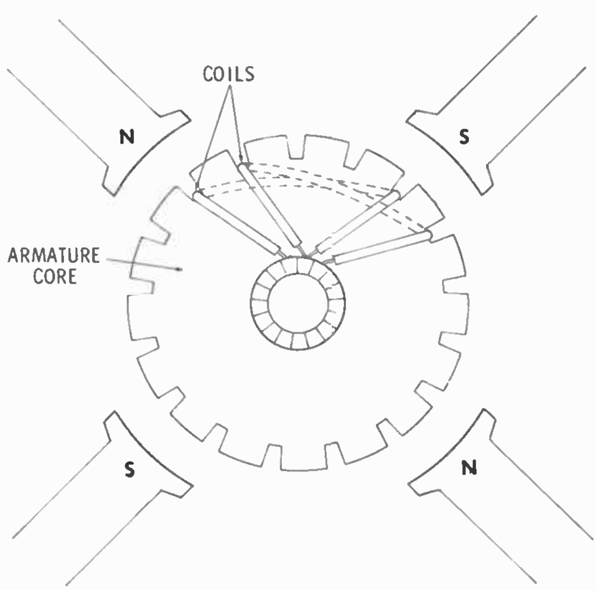
Sometimes the distance between the two sides of an armature coil is not equal to the distance between the adjacent magnetic poles. When this distance is less than the pole pitch, the coil is called a **fractional-pitch winding.**

Fractional-pitch windings are used when it is necessary to save copper. The emf induced in a fractional-pitch coil is not as great as the emf induced in a coil whose pitch is equal to the pole pitch. This is because the voltages induced in the two coil sides do not reach their maximum values at the same time.

Lap and Wave Windings

There are two ways the coils can be connected—**lap winding** and **wave winding.** In a **simplex lap winding,** the ends of each coil are connected to adjacent commutator segments. In this way, all the coils are connected in series. This is shown in the figure below.

SIMPLEX LAP WINDING



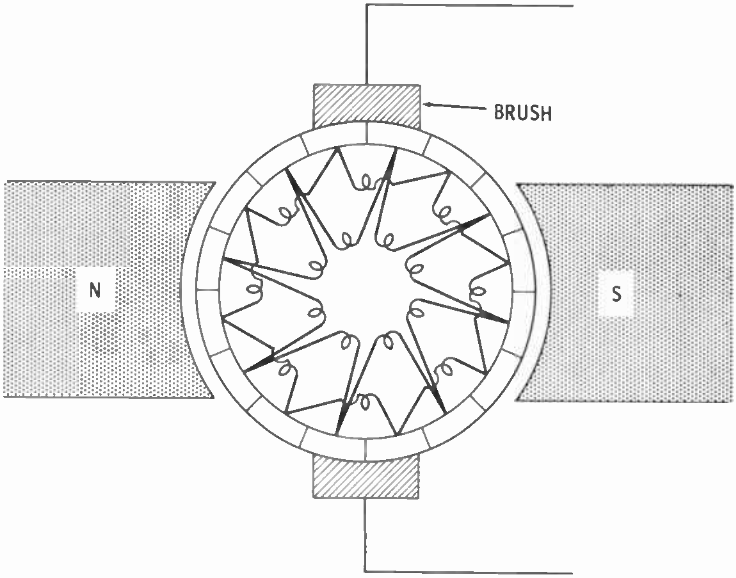
Q8. What are some advantages of the drum armature core?

Your Answer Should Be:

A8. The drum armature core makes possible a **smaller air gap.** The drum armature can be **rotated** at a **higher speed** than the Gramme-ring type. Both these effects make possible **a higher induced voltage.**

In a **duplex lap winding,** there are in effect two separate sets of coils, each set connected in series. The two sets of coils are connected to each other only by the brushes.

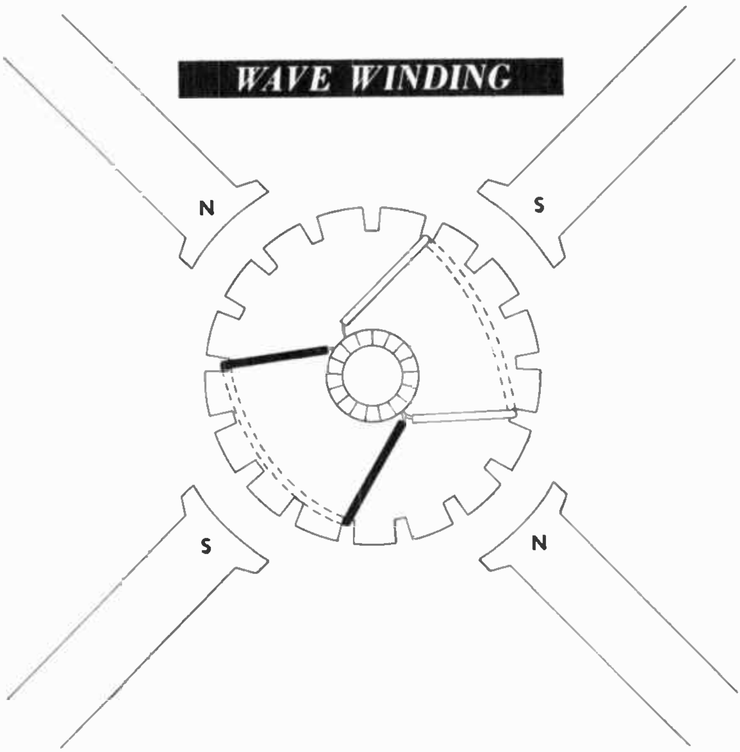
DUPLEX LAP WINDING



Similarly, a **triplex lap winding** is in effect three separate sets of series-connected coils. In a simplex lap winding, a single brush shorts the two ends of a single coil.

In a **wave winding,** the ends of each coil are connected to commutator segments two pole spans apart. Instead of shorting a single coil, a brush will short a small group of coils in series. There will be as many coils in the group as there are **pairs** of magnetic poles.

The figure below shows part of a wave winding.



The Neutral Plane

The area in the generator where no emf can be induced in an armature coil is called the **commutating,** or **neutral, plane.** This plane is midway between adjacent north and south field poles (somewhat shifted from this position under load). In this plane the moving armature coils cut no lines of force and so generate no voltage. The brushes are always set so that they short-circuit the armature coils passing through the neutral plane while, at the same time, the output is taken from the other coils.

Q9. In a wave winding, the coil ends are connected to commutator bars two ____ _____ apart.

Q10. Of what does a duplex winding consist?

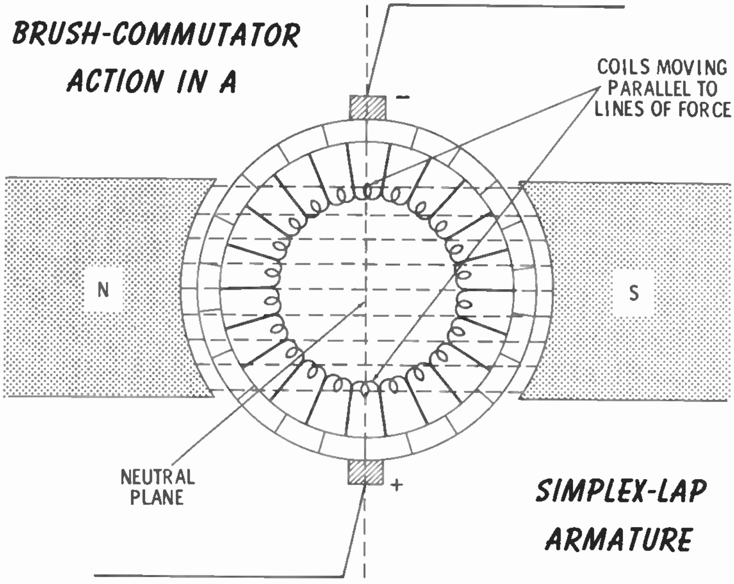
Your Answers Should Be:

A9. In a wave winding the coil ends are connected to commutator bars two **pole spans** apart.

A10. A duplex winding consists of **two separate sets of coils.**

Commutator Output

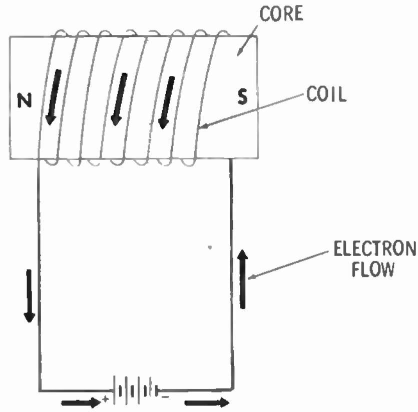
While the brush is short-circuiting one armature coil, it is receiving the emf and current induced in the other armature coils. This is accomplished by connecting one end of two different coils to the same commutator segment.



The illustration above shows an armature with 22 coils connected to 22 commutator segments. There are two brushes. The positive brush is short-circuiting armature coil 11 while the negative brush is short-circuiting armature coil 22. There is no emf being induced in either of these coils. The two coil groups, 1 through 10 and 12 through 21, are connected in parallel by the brushes. This is possible because the voltages in both coil groups have the same polarity. The brushes also connect the generated emf to the load.

POLE PIECES

Permanent magnets can only produce magnetic fields of limited strength and are used mainly in small generators called **magnetos.** Most generators use electromagnets to produce the magnetic field. Electromagnets consist of a metal core with a coil of wire wrapped around it.



AN ELECTROMAGNET

When a current flows through the coil, a magnetic field is produced around the coil. If the core conducts the magnetic lines of force easily, it becomes a temporary magnet when current flows through the coil. The current supplied to an electromagnet is DC, since AC would cause the polarity to constantly change.

To find the polarity of the core when current is flowing through a coil, imagine that you wrap the fingers of your left hand around the coil in the direction of the electron flow through the turns. Your thumb then points to the north pole of the core.

The electromagnetic poles are mounted on the frame of a DC generator. This enables the frame to complete the magnetic circuit.

Q11. The magnetic field of most electromagnets is (stronger, weaker) than the magnetic field of a permanent magnet.

Q12. Why is there no large flow of current in a generator coil shorted by a brush?

Your Answers Should Be:

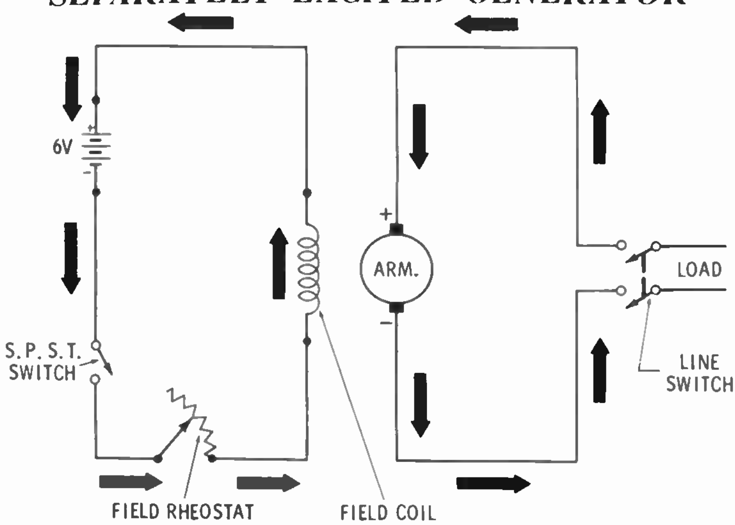
A11. The magnetic field of most electromagnets is **stronger** than the magnetic field of a permanent magnet.

A12. There is no large flow of current in a generator coil when shorted by a brush because, by proper adjustment, **no emf is induced** in the coil during that time.

THE SEPARATELY EXCITED GENERATOR

The current for the electromagnetic field of a generator may be generated by a separate source of DC. This source could be a battery or a separate DC generator. With either source, the generator is said to be **separately excited.**

SEPARATELY EXCITED GENERATOR



Notice that the separately excited magnetic-field circuit is completely independent of the generator circuit. The strength of the externally excited magnetic field depends directly on the amount of current supplied by the external DC source. A rheostat is used to vary the strength of the magnetic field. This provides a very sensitive control of the generator output.

THE SELF-EXCITED GENERATOR

The current for the electromagnetic field of a DC generator may be developed in the armature coils of the generator itself. The current is taken from the commutator by the brushes and then fed to the field coils. The three types of circuits used to feed current to the field coils are the series, shunt, and compound.

The electromagnetic field of a self-excited DC generator depends on current induced in the armature coils of the generator by an electromagnetic field. Since a field is required to produce current, how can a self-excited DC generator build up a voltage?

An electromagnet has a small amount of magnetism even when the electromagnetic coil is not energized. This small amount of magnetism is called **residual magnetism.** Usually, the residual magnetism in the electromagnetic core is strong enough that a weak voltage is induced in the armature coils. This voltage causes a small amount of current to flow in the field windings. The current causes the magnetic field to increase. This increases the voltage which again increases the current, and so on. In this way the generator voltage builds up to its maximum value. This process is called **building up.**

When there is not enough residual magnetism in the field core, the generator will not build up. In this case the electromagnetic field must be excited temporarily from an external DC source. This is called **flashing the field.** Reversing the connections to the field windings can also cause a generator to fail to build up.

Q13. A generator that has a separate source of current for its field windings is said to be ---------- --------.

Q14. A -------- is used to control the amount of current flowing in the field winding.

Q15. A rheostat provides (poor, sensitive) control of the output of a generator.

Q16. The small amount of magnetism that remains in the core of an electromagnet when the current is removed is called -------- ----------.

Your Answers Should Be:

A13. A generator that has a separate source of current for its field windings is said to be **separately excited.**

A14. A **rheostat** is used to control the amount of current flowing in the field winding.

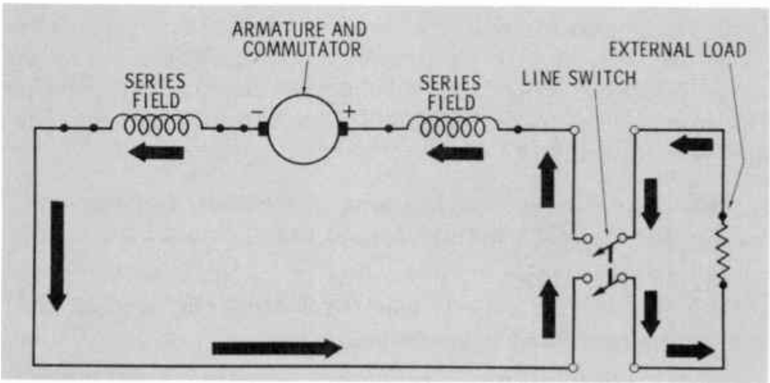
A15. A rheostat provides **sensitive** control of the output of a generator.

A16. The small amount of magnetism that remains in the core of an electromagnet when the current is removed is called **residual magnetism.**

The Series Generator

In a series generator the field windings, armature windings, commutator, brushes, and the external load are all connected in series. In order for a self-excited series generator to produce voltage, the external load must be connected. Without the external load connected, the series circuit is incomplete, and the small generator voltage is due only to residual magnetism.

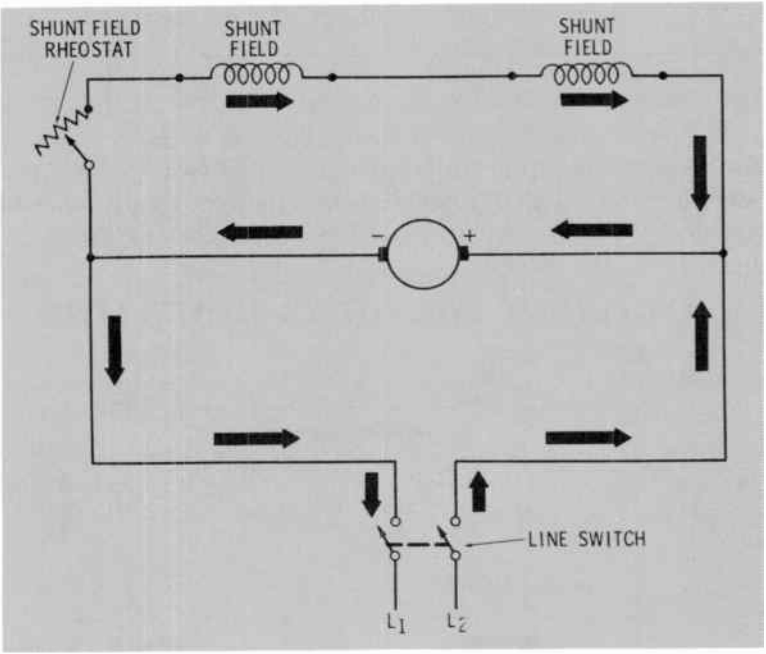
A SERIES GENERATOR



The Shunt Generator

The shunt generator is connected as a parallel (shunt) circuit. The parallel circuit is used to provide separate paths for supplying current to the electromagnetic field and to the external load. In the shunt generator, the DC current induced in the armature coils is taken from the commutator by the brushes. From the brushes, part of the current is supplied to the electromagnetic field windings, while the main current flow is delivered to the external load.

A SHUNT GENERATOR



Building up in a self-excited shunt generator does not require that the external load be connected to the generator because the current supplied to the electromagnetic field does not flow through the external load. This means the generator can be started, and the full strength of the magnetic field and the induced emf reached before the external load is connected.

Q17. How will an increase in the current drawn by the load affect the current through the field coils of a series generator?

Q18. What will be the effect of varying the resistance of the shunt-field rheostat?

Your Answers Should Be:

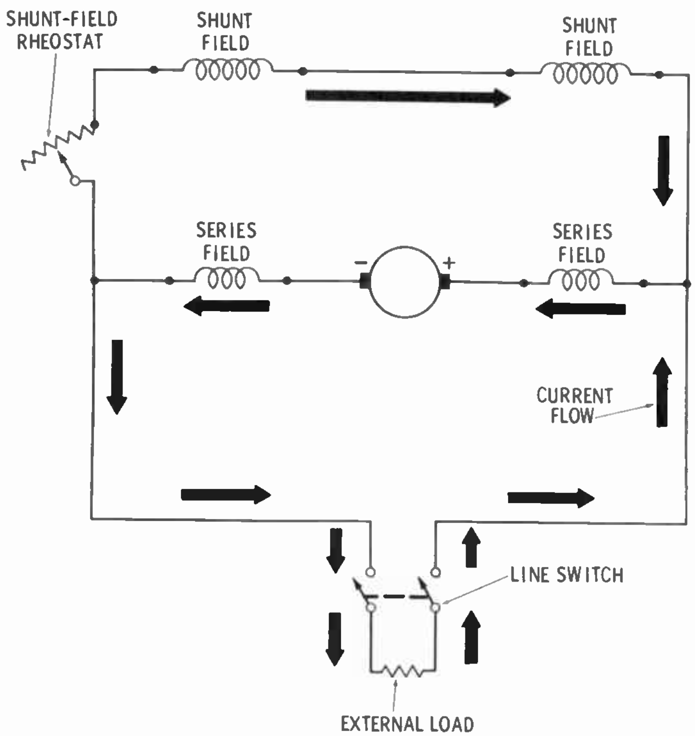
A17. An increase in load current will **increase the current through the field coils,** which tends to **increase the output voltage.**

A18. Varying the resistance of the shunt-field rheostat will vary the **strength of the magnetic field** and therefore the **output voltage** of the generator.

The Compound Generator

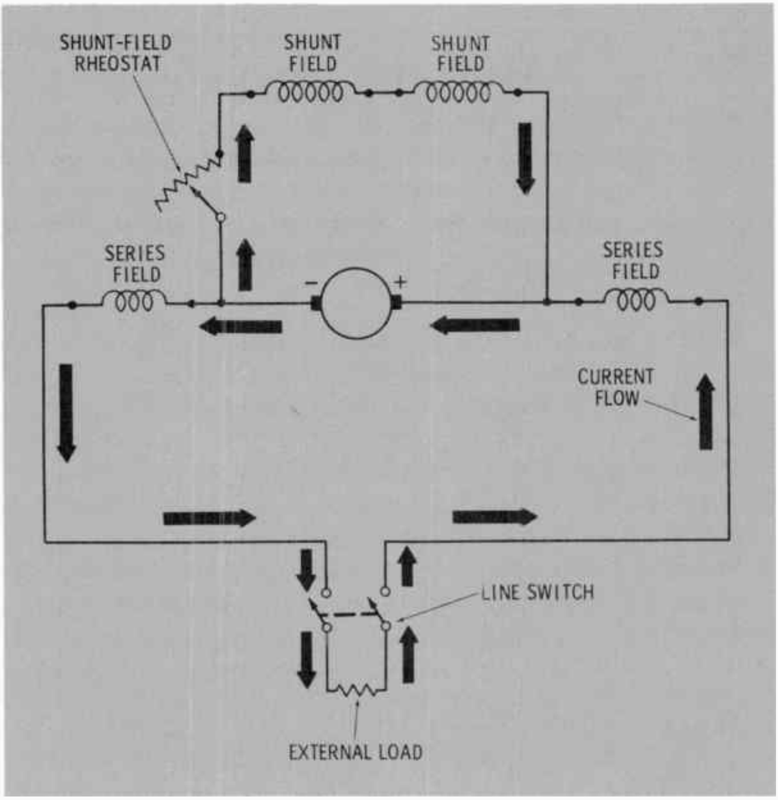
A compound generator is a combination of both a series and shunt generator. It has a series field winding on the pole pieces along with a shunt field winding. The total field strength will thus be increased or decreased as the load increases or decreases.

LONG-SHUNT COMPOUND GENERATOR



In a **long-shunt** compound generator, the shunt field winding is connected to the ends of the series field windings away from the armature. In a **short-shunt** compound generator, the ends of the shunt field winding are connected **between** the series field windings and the armature.

SHORT-SHUNT COMPOUND GENERATOR



There is no difference between the short- and long-shunt compound generators as far as the operation and output are concerned. The only difference is in the point where the series field is connected.

Q19. Compound-generator pole pieces have both ______ and _____ field windings.

Q20. Name the three types of circuits used to supply current to the field of a self-excited generator.

Your Answers Should Be:

A19. Compound-generator pole pieces have both **series** and **shunt** field windings.

A20. **Series, shunt,** or **compound** circuits may be used to supply current to the electromagnetic field of a self-excited DC generator.

GENERATOR LOSSES

There are several effects that take place within a generator. It is necessary to know how these effects are created and how they are corrected in order to maintain electrical equipment in top operating condition. These effects include copper loss, eddy currents, and hysteresis loss.

Copper Loss

Copper loss is due to the resistance of the copper wire used in the armature coils. As current flows through the resistance of the armature coils, there is an I^2R (power) loss.

When current flows through any metal, heat is produced. The resistance of metals increases when their temperature increases. Current flowing through the armature windings causes the resistance of the windings to increase. For example, if the no-load temperature of an armature winding is 68°F and the full-load temperature is 122°F, the resistance of the armature winding will increase by about 20% when the temperature rises to the full-load value.

Most generators are constant-voltage devices. The current induced in the armature windings depends on the demands of the external load. As the current demand varies, the copper loss in the armature will vary also.

Eddy Currents

When the conductors of the armature coils rotate through the magnetic field, an emf is induced. Current is caused to flow in the armature coils as determined by the requirements of the external load.

The armature core is also a conductor and rotates in the same magnetic field. Therefore, an emf and current are produced in the armature core. These are called **eddy currents.**

The power used in generating eddy currents comes from the generator power source and represents a loss of output power. This is because it is power taken from the power source but not converted into the desired output; it lowers the efficiency of the generator. (Besides being a waste of power, this energy results in undesirable heating of the iron.) Eddy currents are reduced by **laminating** the core. That is, the core is made of a number of thin layers of metal, all insulated from each other. Lamination reduces the length of the conductor in which the eddy currents flow and therefore reduces the amount of I^2R (power) loss in the armature core.

Hysteresis Loss

Hysteresis loss is a heat loss due to the magnetic properties of the armature. This also is a power loss since this energy, too, is taken from the prime mover. When the armature core is rotating, the magnetic particles of the core tend to line up with the magnetic field. Since the core is rotating, the magnetic field keeps changing direction. The movement of the magnetic particles as they keep trying to align themselves produces friction which, in turn, produces heat. This heat result in an increase in armature resistance and an additional copper loss. Hysteresis loss varies with the speed of the armature and the amount and type of iron in the core.

To limit hysteresis loss, an armature-core material is used in which the magnetic particles line up with the constantly changing direction of the magnetic field with relative ease. The most commonly used material is dynamo sheet steel. Using this material reduces the hysteresis loss but does not eliminate it completely.

Q21. What two types of power loss are limited by constructing an armature core of dynamo sheet-steel laminations?

Q22. What happens to the temperature of the armature as the load increases?

Q23. What effect will this change in temperature have on copper loss in the generator?

Your Answers Should Be:

A21. **Eddy-current and hysteresis losses** are limited by constructing armature cores of dynamo sheet steel.

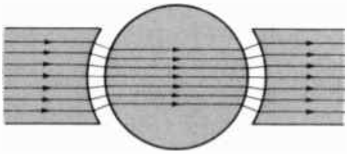
A22. As the load increases, the temperature of the armature will **increase.**

A23. An increase in temperature will increase the resistance of the armature coils and therefore **increase the copper loss.**

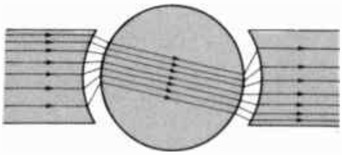
ARMATURE REACTION

Armature reaction is the result of the magnetic field surrounding the armature due to the electric current flowing through the armature coils. This field acts on the main magnetic field of the generator and distorts it. This effect is called **cross magnetization.** It only occurs when current is flowing through the armature.

Distortion of Magnetic Field



No Armature Reaction



With Armature Reaction

You have learned that the best place to take the output from an armature is from commutator bars in the **neutral,** or commutating, plane. When there is no current flowing through the armature, the neutral plane is at right angles to the main generator field. With armature current flowing, the distorted magnetic field due to cross-magnetization will cause the neutral plane to shift to a new position. The position of the neutral plane will shift with every change in current flow in the armature.

Identifying and Correcting Armature Reaction

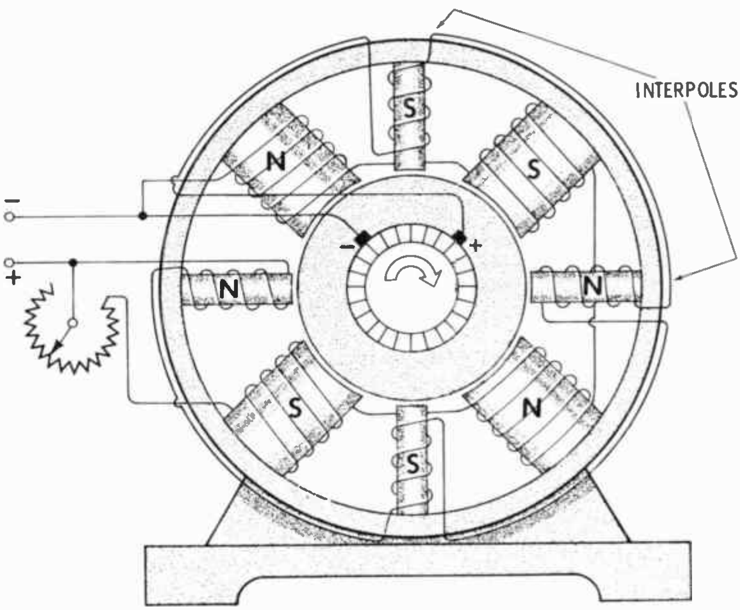
When sparking occurs between the commutator and brushes, you should suspect armature reaction. The neutral plane may be found by moving the brushes on the commutator until sparking stops. The neutral plane will, of course, shift each time the current changes.

One way of compensating for armature reaction is to cancel the armature field with an opposing magnetic field. Interpoles and compensating windings operate on this principle.

Interpoles

Interpoles, or **commutating poles,** are narrow auxiliary poles located midway between adjacent main magnetic poles. Interpoles tend to neutralize the armature reaction created by the magnetic field of the armature. This effect takes place only within the area of the interpole magnetic field.

SHUNT-FIELD GENERATOR WITH INTERPOLES



Interpole windings are connected in series with the armature windings and are wound in such a direction that the polarity of the interpole always has the same polarity as the nearest main-field pole in the direction of rotation.

Q24. What causes armature reaction?

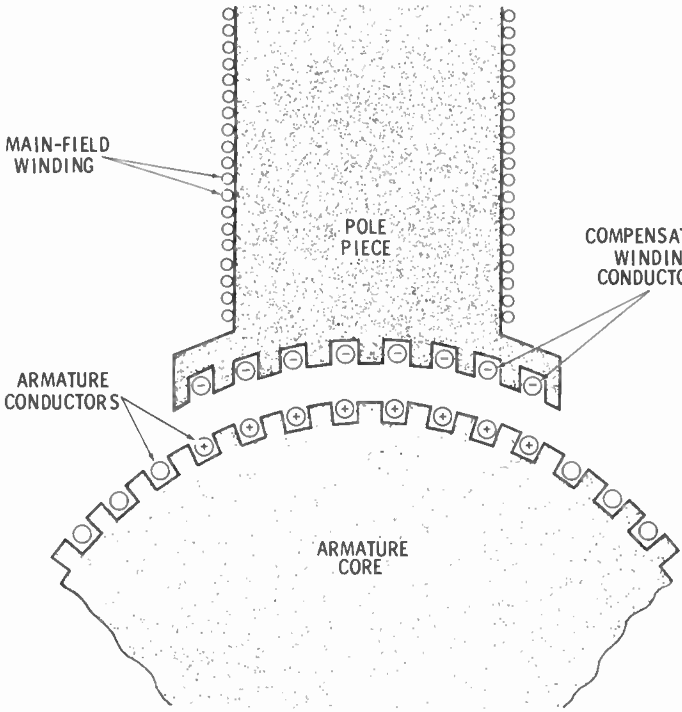
Q25. What symptom indicates armature reaction?

> **Your Answers Should Be:**
>
> A24. Armature reaction is caused by the **magnetic field around the armature due to the flow of armature current.**
>
> A25. The symptom of armature reaction is **sparking between the commutator and brushes.**

Compensating Windings

When a generator must operate at high efficiency under varying external load demands, **compensating windings** are used. The compensating windings are normally embedded

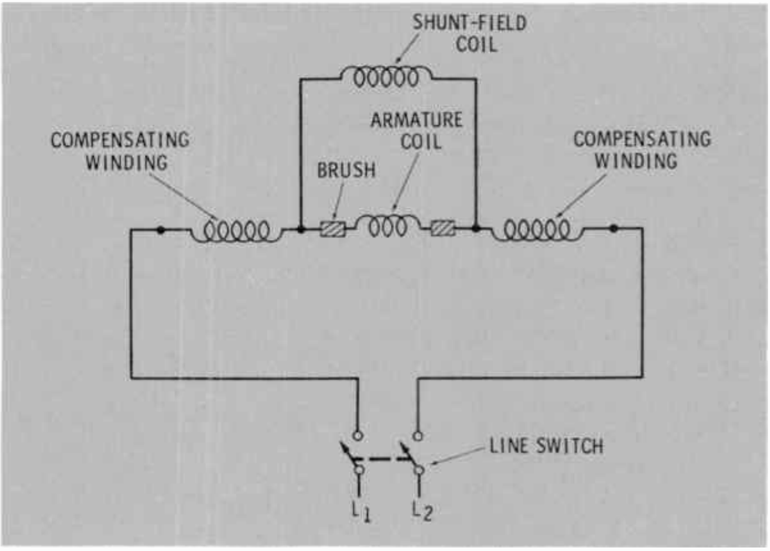
LOCATION OF COMPENSATING WINDINGS



in the faces of the pole pieces. They are connected in series with the armature coils, like interpoles, but are wound in the opposite direction from the armature coils. The field of the compensating windings completely cancels the field of the armature that would tend to distort the main field of the generator.

Compensating windings are a very efficient but expensive method for eliminating armature reaction. The use of compensating windings is limited almost exclusively by their high cost.

SHUNT-FIELD DC GENERATOR WITH COMPENSATING WINDINGS



Motor Reaction in a Generator

When current flows in the armature coils, a generator will tend to act as a motor. The magnetic field surrounding the armature coils weakens the main magnetic field on one side of the coil, but strengthens it on the other side. As a result, a torque is developed that opposes the rotation of the generator shaft. This is why the rotating armature presents a mechanical load to the prime mover. Due to this reaction, the prime mover "feels" an opposition to turning the generator shaft.

Q26. Why are compensating coils wound in a direction opposite that of the armature coils?

Your Answer Should Be:

A26. Compensating coils are wound in a direction opposite that of the armature coils because **the magnetic field of the armature will be opposed by compensating coils wound in the opposite direction.** The fields will **vary the same amount** when the coils are fed the same current in series.

SERIES DC-GENERATOR CHARACTERISTICS

To obtain an output voltage, a series DC generator must be operated with the line switch closed. This enables the series circuit to be completed by including the external load. Without the external load connected to the series circuit, the series generator will not build up.

Building Up

When a complete series circuit exists and the armature is rotating in the magnetic field, an emf is induced in the armature. At first, this emf is due to the residual magnetism present in the iron core of the field poles. This small emf causes a small load current to flow through the series field winding. This causes an increase in the number of magnetic lines of force. When the number of lines of force generated by the series field winding increases, the voltage induced in the armature coils increases.

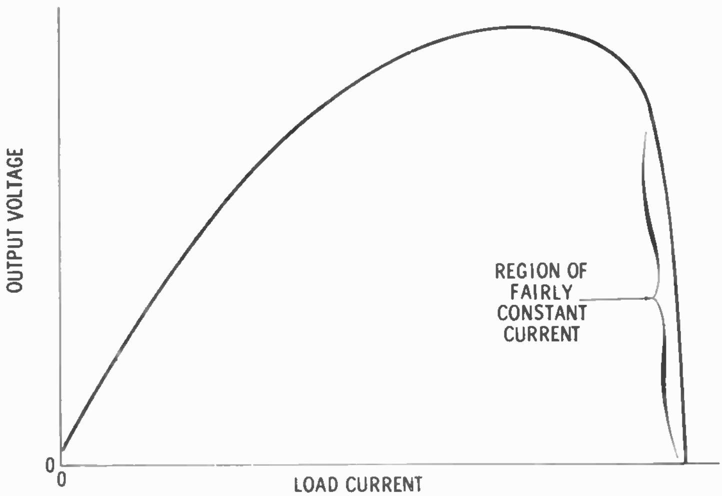
The output voltage in the series machine continues to rise until the iron core of the series field becomes **saturated;** that is, it cannot contain any additional lines of force. When the magnetic field reaches saturation, the output voltage will be maximum, and any additional current required by the external load will not increase the output voltage.

Characteristics Under Load

Drawing more current from the armature than required to achieve maximum voltage output will create a drop in the output voltage of the generator. This decrease in voltage is due to armature reaction and the voltage drop across the resistances of the armature and the field. A graph of the output of a DC generator is shown on the next page.

The most important conclusion that can be reached about the series-wound DC generator is that it is best suited for **constant-current applications.**

Output-Voltage Characteristics of a Series Generator



As more current is demanded (within practical limits) from a series-wound DC generator, the output voltage increases. When the practical limit of current is reached, a further demand has a reverse effect. The practical limit is reached when the magnetic field strength reaches its maximum value.

Examining the characteristic curve of the series-wound DC generator shows that the voltage drops off sharply. Therefore, it is possible to obtain a fairly constant current for a wide voltage range.

Q27. In order to obtain output voltage, a series generator must be operated with the ____ connected.

Q28. The series DC generator is best suited for ________ ________ applications.

Q29. The output voltage of a series generator first __________ and then __________ as the output current increases.

Your Answers Should Be:

A27. In order to obtain output voltage, a series generator must be operated with the **load** connected.

A28. The series DC generator is best suited for **constant-current** applications.

A29. The output voltage of a series generator first **increases** and then **decreases** as the output current increases.

SHUNT DC-GENERATOR CHARACTERISTICS

The field coils of a shunt-wound DC generator are connected in parallel with the armature and the external load. The number of magnetic lines of force produced by the pole pieces does not depend directly on the load current. However, the load current does have an indirect effect. As the load current increases, the generator output voltage decreases. This is due to increased armature reaction and the voltage drop across the resistance of the armature coils. When the generator output voltage decreases, the current through the shunt field coils also decreases. This causes an additional decrease in the output voltage. The output voltage is therefore less than it would be if the field windings were connected to a source of constant voltage.

A rheostat is usually placed in series with the shunt field windings. By adjusting the rheostat, the current through the windings can be controlled. In this way, the strength of the magnetic field can be changed to make up for a decrease in output voltage.

Building Up

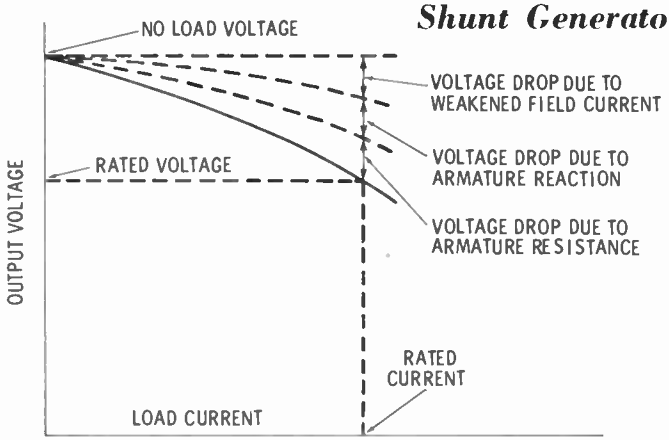
The line switch to a shunt DC generator can be left open since it is not necessary for the external load to be connected during buildup. When the generator is turning, the armature coils cut the weak, residual magnetic field of the iron shunt-field core. The weak magnetic field causes a weak voltage to be induced in the armature coils. This voltage, in turn, causes a weak current to flow from the armature coils, through the shunt-field rheostat, and through the shunt field coils. The weak shunt field current generates additional lines of force which strengthen the magnetic field. The strength of the electromagnetic field and the voltage induced in the armature coils increase until the terminal voltage of the generator reaches its no-load voltage.

Characteristics Under Load

In order for the shunt DC generator to deliver power to the external load, the line switch is closed. The load requirements are met by adjusting the shunt-field rheostat.

As the amount of current required by the external load increases, the output voltage of the generator decreases as shown in the following characteristic curve.

Output-Voltage Characteristics of a Shunt Generator



The shunt DC generator is well suited for **constant-voltage applications** at a specified rated output. When an additional load (beyond a critical limit) is placed on the generator, the output voltage falls off almost to zero. Any attempt to force a shunt DC generator to deliver more than its rated output could cause it to break down.

Q30. A shunt DC generator is used mainly for constant _______ applications.

Q31. When more current is required by the external load than the critical limit of a shunt generator, the additional load will cause the output voltage to ____.

Your Answers Should Be:

A30. A shunt DC generator is used mainly for constant-**voltage** applications.

A31. When more current is required by the external load than the critical limit of a shunt generator, the output voltage **drops.**

COMPOUND DC-GENERATOR CHARACTERISTICS

You have learned that there are two types of compound DC generators, the long shunt and the short shunt. The build-up, loading, and general characteristics of the two are very similar. The short-shunt generator is in wider use because of its simpler circuitry. On the next few pages the compound DC generator will be discussed in terms of the short-shunt design. The series field of a short-shunt, compound DC generator is connected between the load and the parallel shunt field and armature. Basically, the compound DC generator takes advantage of the characteristics of both the series and shunt DC types.

Building Up

One of the advantages of the shunt generator is also present in the compound generator. It is not necessary to start a compound generator with the external load connected. The building-up process is similar to that of the shunt type.

Characteristics Under Load

When the no-load terminal voltage has been reached, the line switch is closed. The output voltage is then adjusted with the shunt-field rheostat which controls the resistance of the shunt field circuit. As described before, this varies the strength of the magnetic field. The output voltage changes directly with the strength of the magnetic field controlled by the shunt-field rheostat.

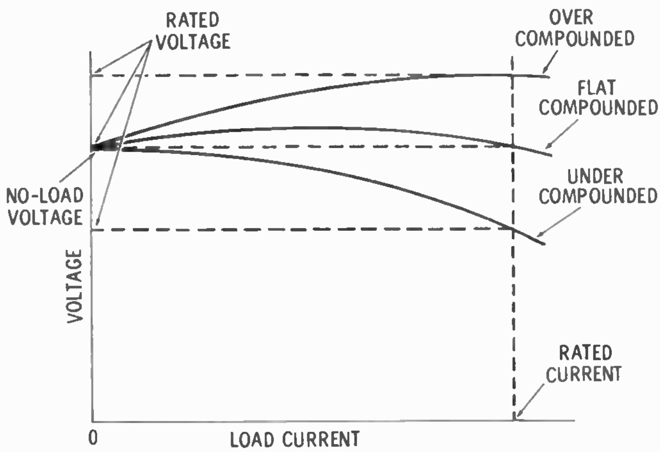
The purpose of the series field windings in a compound generator is to control the output voltage of the generator in relation to the external load. The series field windings help to offset the voltage decrease that occurs when a shunt field alone is used.

Compounding Effects

When the effect of the series winding produces the same terminal voltage at rated load as at no load, the generator is said to be **flat compounded.**

When the effect of the series winding produces a smaller terminal voltage at rated load than at no load, the generator is said to be **undercompounded.**

Compound-Generator Characteristics



When the effect of the series winding produces a greater terminal voltage at rated load than at no load, the generator is said to be **overcompounded.** Compound generators are usually wound so that they are slightly overcompounded.

In some generators, the degree of compounding is controlled by a variable resistor in parallel with the series field. This resistor is called a **diverter.** It determines the fraction of the load current that flows through the series field. This gives the same effect as changing the number of turns in the winding.

Q32. A compound generator most resembles a ----- generator in its operation.

Q33. A compound generator in which the rated-load voltage is equal to the no-load voltage is said to be ---- ----------.

Your Answers Should Be:

A32. A compound generator most resembles a **shunt** generator in its operation.

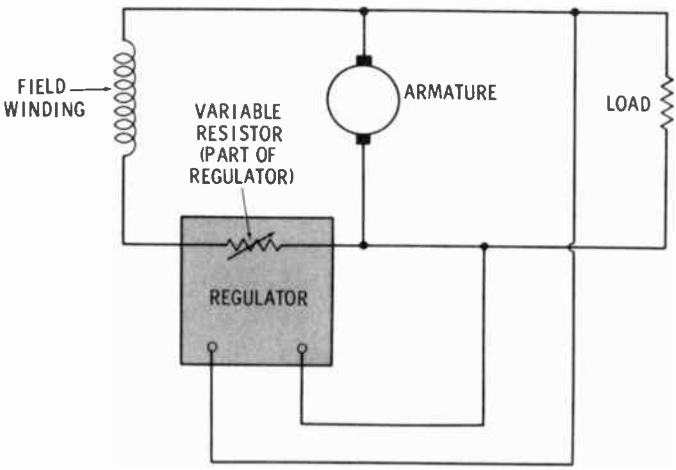
A33. A compound generator in which the rated-load voltage is equal to the no-load voltage is said to be **flat compounded.**

AUTOMATIC VOLTAGE REGULATION

It is possible to use an automatic device to keep the output voltage of a shunt generator nearly constant, even if the load changes. Such a device is called a **voltage regulator.** These regulators automatically change the current through the shunt field winding every time the output voltage starts to vary.

Some regulators have a variable resistance in series with the field winding. If the output voltage decreases, the resistance is decreased, and the voltage is brought back almost to its original value. If the voltage increases, the resistance increases, and the voltage again is returned almost to normal.

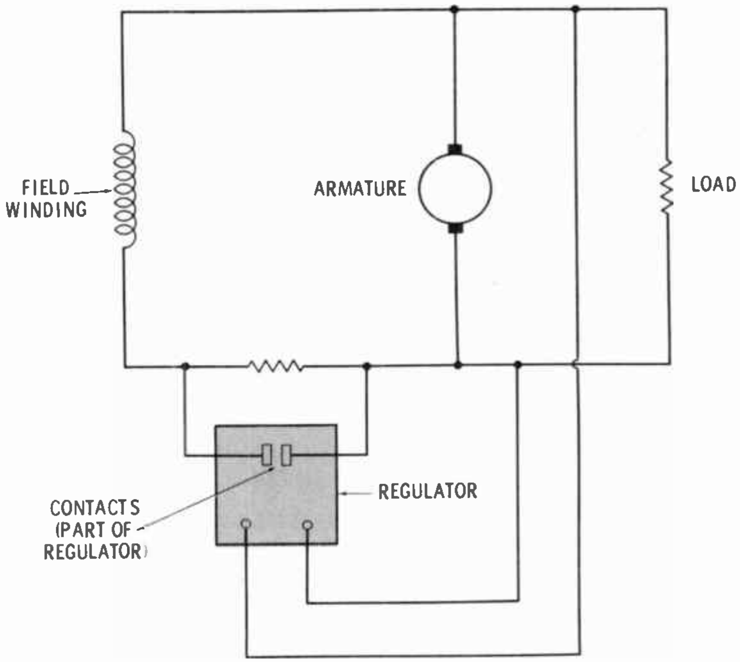
VOLTAGE REGULATION BY VARYING FIELD RESISTANCE



In another type of regulator, a pair of contact points is used to short-circuit a fixed resistor in the field circuit.

When the contacts are open, the resistor limits the field current and keeps the output voltage below the desired value. When the contacts short-circuit the resistor, the voltage rises above the desired value. In operation the regulator causes the contacts to vibrate (open and close rapidly). The average current through the field winding depends on how rapidly the contacts vibrate. This, in turn, is determined by the value of the output voltage.

VOLTAGE REGULATION BY USING VIBRATING CONTACTS



More complicated arrangements are sometimes used to regulate the voltage of shunt generators. However, they all operate by controlling the amount of current flow in the shunt field winding.

Q34. The voltage of a shunt generator is regulated by varying the _____ _____ current.

Q35. A device that automatically keeps the output voltage of a generator nearly constant is called a _______ __________.

Your Answers Should Be:

A34. The voltage of a shunt generator is regulated by varying the **shunt-field** current.

A35. A device that automatically keeps the output voltage of a generator nearly constant is called a **voltage regulator.**

PARALLEL OPERATION OF DC GENERATORS

At times it is necessary for more than one generator to supply electrical energy to the same load. This may be due to peak load demands or the need for continuous service should one generator become disabled.

In order to have more than one generator supply the external load, it is necessary to connect them in parallel. The same general precautions should be taken when connecting DC generators in parallel as are used when connecting batteries in parallel. Polarity and voltage must be the same. It is important to remember that **different paralleling procedures are used for AC than for DC generators.**

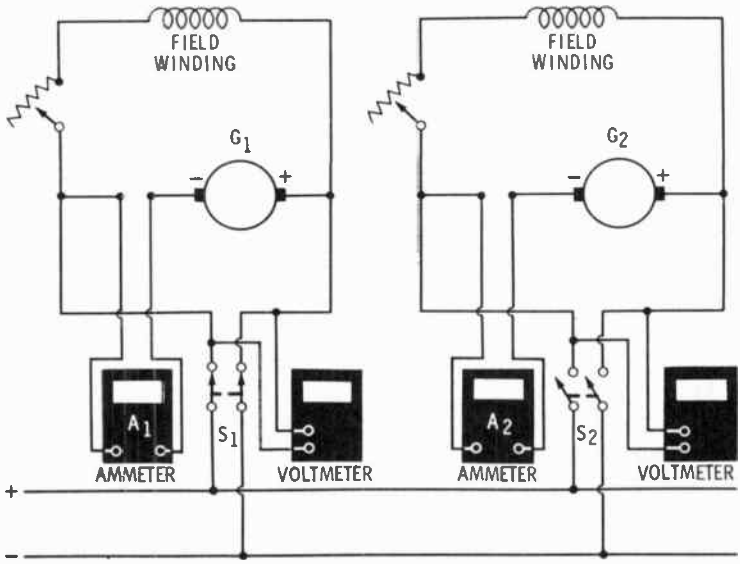
Paralleling Two DC Generators

The figure on the opposite page shows two generators that can be connected to the same load by means of switches. The procedure for connecting them in parallel is as follows.

1. Generator G_1 is supplying the external load; generator G_2 is to be placed into parallel operation with G_1.
2. Switch S_2 must be open to prevent generator 1 from trying to operate generator 2 as a motor.
3. Adjust the shunt-field rheostat of generator 2 to the lowest position.
4. Bring generator 2 up to its rated speed.
5. Adjust the shunt-field rheostat so that generator 2 is supplying slightly more voltage than generator 1. The polarity must be as shown.
6. Close switch S_2 to bring generator 2 into parallel operation with generator 1. NOTE: Generator 2 should be carrying a small portion of the external load.
7. Adjust the shunt-field rheostat of generator 2 to dis-

tribute the load equally. At the same time the shunt-field rheostat of generator 1 is adjusted to maintain the normal voltage.

TWO DC GENERATORS CONNECTED IN PARALLEL



Removing a DC Generator From Parallel Operation

1. Weaken the field of the generator to be removed from operation and at the same time strengthen the field of the remaining generator.
2. When the outgoing generator is no longer carrying any of the load, open the switch so that the generator is removed from operation.

Q36. Are the same procedures used in paralleling AC and DC generators?

Q37. When paralleling DC generators, the positive terminal of one generator must be connected to the ________ terminal of the other.

Q38. The load is transferred from one generator to the other by adjusting the _____ _____ __________.

Your Answers Should Be:

A36. A **different** procedure is used for paralleling AC generators than for paralleling DC generators.

A37. When paralleling DC generators, the positive terminal of one generator must be connected to the **positive** terminal of the other.

A38. The load is transferred from one generator to the other by adjusting the **shunt-field rheostats.**

MAINTENANCE

In order to operate any machine properly, you must be familiar with the construction details and maintenance procedures for the machine. Maintenance should not be confined to the repair and replacement of units that have failed in operation. Regular checks on operating equipment aid in detecting many problems before they become serious.

The nameplate on the generator should list the **maximum temperature rise** for the machine. This is the maximum amount by which the machine should be warmer than the surrounding air.

Check for generator hot spots by touching with the palm of your hand. Check for faulty bearing operation by feeling the bearing caps on the end bells. Naturally, you must be careful to avoid injury when touching the generator. The table on the next page lists some causes and remedies of hot spots.

When the bearings are checked for overheating, you should also test for any vibration. Vibration may be caused by excessive speed of the rotating shaft, and is usually quite loud. If not corrected, this can result in permanent damage to the machine. Excessive speed, if maintained for any length of time, can result in the machine tearing itself apart. Vibration may also be caused by poorly balanced rotating parts or by worn bearings.

It is important to follow the manufacturer's instructions for lubrication and maintenance of bearings. This information is usually contained in the manual that accompanies the equipment. **Follow the manufacturer's instructions exactly.**

Pointers About Lubrication

Remember these things about lubrication. Improper lubrication, either too little or too much, can cause serious damage to moving and electrical parts. Too little lubrication causes friction and wear of moving parts. Excessive lubrication can cause electrical damage—shorting the commutator segments, fouling the commutator brush assembly, or soaking the armature coils.

GENERATOR HOT SPOTS—CAUSES AND REMEDIES

Possible Causes	Remedy
1. Insufficient lubrication.	1. Lubricate.
2. Excessive load on generator.	2. Check ammeter reading with current rating of the generator. If overloaded: a. Reduce generator load. b. Place a second generator in parallel to share the load.
3. Clogged cooling vents.	3. With generator off, blow out with clean, dry air at low pressure.

Q39. How would you determine the allowable temperature rise for a generator?

Q40. What could cause a generator bearing to become too hot?

Q41. What are some causes of vibration in a generator?

Your Answers Should Be:

A39. The allowable temperature rise for a generator is usually given on its **nameplate.**

A40. A generator bearing can become too hot because of **too little lubrication.**

A41. Vibration in a generator can be due to **excessive speed, poorly balanced rotating parts,** or **worn bearings.**

WHAT YOU HAVE LEARNED

1. The main parts of a DC generator are the frame, end bells, pole pieces, shaft, armature, commutator, and brushes.
2. The armature contains a number of coils in order to produce a relatively smooth output.
3. Various types of carbon and graphite brushes are used to take voltage and current from the commutator segments.
4. Most armatures consist of a drum-type iron core with windings set in slots in the core.
5. Armature coils are connected to the commutator in simplex, duplex, or triplex patterns.
6. Coils can be connected in a lap-wound or wave-wound pattern. In a lap-wound pattern, a single coil is shorted by a brush; in a wave-wound pattern, a small group of coils in series is shorted.
7. The neutral plane is the plane where no emf is induced in a coil. The brushes should be set to this position.
8. The electromagnetic field of a DC generator can be either separately excited by an external DC source or self-excited from the generator output in a series, shunt, or compound circuit.
9. A self-excited generator can start with its own residual magnetism or, if necessary, it can be started by flashing the field with an external DC source.
10. Generator losses are copper loss (due to armature re-resistance), eddy-current loss, and hysteresis loss.

11. Armature reaction results in the shifting of the neutral plane due to interaction of the magnetic field caused by current flow in the armature with the main magnetic field.
12. A series generator and its external load must be connected in order to obtain voltage from the generator.
13. The current flow in a series generator varies with the current required by the external load and causes the strength of the magnetic field to vary.
14. The series generator is best suited for constant-current applications.
15. The shunt generator does not require that the external load be connected during buildup of that generator.
16. The no-load terminal voltage of a shunt generator is greater than the rated voltage (voltage after external load is connected) because the load-current flow causes power losses within the generator.
17. The current supplied by a shunt generator varies with the external load requirements, but a fairly constant voltage is maintained.
18. The compound generator is basically a shunt generator with a series field used to offset the falling voltage when large amounts of current are required by the external load.
19. The ability of the series field of a compound generator to produce a greater, equal, or lesser terminal voltage than no-load voltage determines if the generator is over, flat, or undercompounded.
20. Regulators can be used to keep the output voltage of a shunt generator nearly constant.
21. A shunt generator can be connected in parallel with another shunt generator only when it has reached a voltage slightly above the voltage of the other generator.
22. Generators should be checked regularly for hot spots and vibration.
23. It is important to follow the manufacturer's instructions for the lubrication and maintenance of generators.

3

DC Motors

What You Will Learn

In this chapter you will learn about DC motors. You will see how they are constructed and find out what reactions occur inside them. You will be able to recognize the different types of DC motors and know the advantages and disadvantages of each. You will learn about starting devices for DC motors, why they are needed, and how they work. You will also learn about the various methods used to control the speed of DC motors.

BASIC DC-MOTOR CONNECTIONS

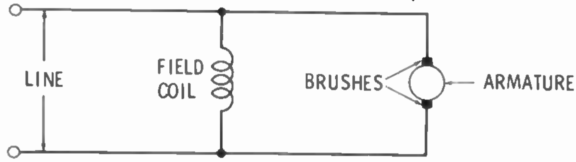
The parts of a DC motor are essentially the same as the parts of a DC generator. A DC motor consists of a frame, end bells, pole pieces, shaft, armature assembly, commutator assembly, and brush assembly. The construction of these parts is essentially the same as for the generator, with minor changes for practical reasons.

The field windings on the pole pieces (also called the **stator**) are supplied with DC. The commutator and armature (sometimes called the **rotor**) are also supplied with DC which is converted to AC, as you learned in Chapter 1. It would be possible, of course, to supply the two windings from different DC sources, but normally they are both supplied from the same source.

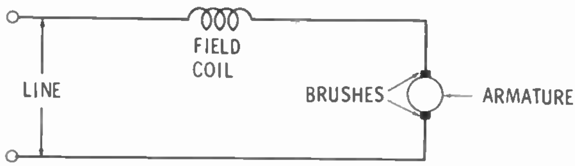
The two windings (stator and rotor) then become parts of the same circuit. The methods of connecting the two windings determine the different types of DC motors. The three basic types are **shunt, series** and **compound** motors.

Notice that the DC motors in the diagrams below are similar to the three types of DC generators.

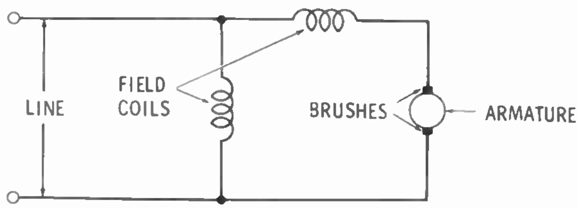
TYPES OF DC MOTORS



SHUNT

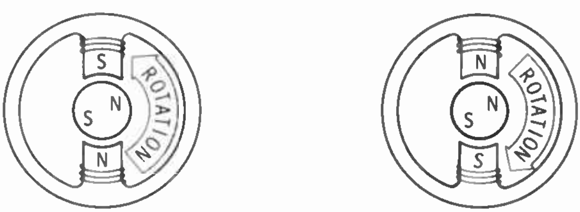


SERIES



COMPOUND

The direction of rotation of any DC motor can be reversed by reversing the leads of the field coils but leaving the armature connections unchanged. If both the field-coil and armature leads are reversed at the same time, the motor will continue to run in the same direction.



EFFECT OF REVERSING FIELD CONNECTIONS IN A DC MOTOR

Reversing the leads of the field coils reverses the polarity of the magnetic field. The armature field remains unchanged. This causes the motor to run in the opposite direction, as shown in the figure at the bottom of the opposite page. The magnetic poles of the rotor and stator, as shown, attract each other until the field connections are reversed. Then the poles repel each other. If both the field and armature connections were reversed, the poles would continue to attract each other, and the motor would not reverse direction.

ARMATURE LOSSES

Armature losses occur in a DC motor for exactly the same reasons they occur in a DC generator. The losses in the armature of a DC motor are copper loss, hysteresis loss, and eddy-current loss. The same kinds of construction are used in DC motors to reduce the armature losses as in DC generators. Armature cores in motors are usually built of laminated steel.

ARMATURE REACTION

Just as in a generator, the interaction of the armature and main magnetic fields distorts the main field. This causes the commutating plane of the motor to shift. There will be excessive sparking when the brushes are not properly aligned in the commutating plane. Armature reaction in the motor can be limited by interpoles and compensating windings.

Q1. What happens to the direction of rotation of a DC motor if the leads of the field but not of the armature are reversed?

Q2. There are armature losses in a DC generator. Are there similar losses of power in a DC motor?

Q3. Armature reaction occurs in a DC generator. Is there armature reaction in a DC motor?

Q4. Another name for the stationary field assembly in a motor is the ______.

Q5. Another name for the rotating armature is the _____.

Your Answers Should Be:

A1. If only the field leads are reversed, the motor **reverses its direction of rotation.**

A2. **There are armature losses in a DC motor** just as there are in a DC generator.

A3. **Armature reaction distorts the main magnetic field** and shifts the commutating plane **in a DC motor just as it does in a DC generator.**

A4. Another name for the stationary field assembly in a motor is the **stator.**

A5. Another name for the rotating armature is the **rotor.**

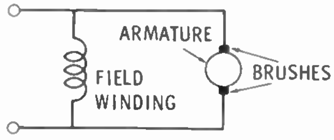
COUNTER EMF

When the armature conductors of a motor rotate in the main magnetic field, an emf is generated. This always happens when a conductor cuts magnetic lines of force. This emf opposes the applied line voltage. The faster the motor turns, the greater the **counter emf** becomes.

When a DC motor is started, a very large current will flow unless a starting resistor is used to limit this current. As the motor builds up speed, however, the counter emf increases and limits the current by reducing the effective voltage across the armature coils.

DC SHUNT MOTORS

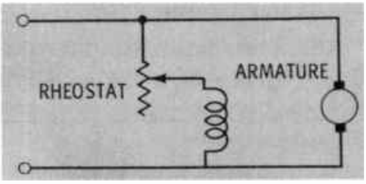
The shunt field winding consists of many turns of small wire and is connected in parallel with the armature winding, or across the line, as shown below.



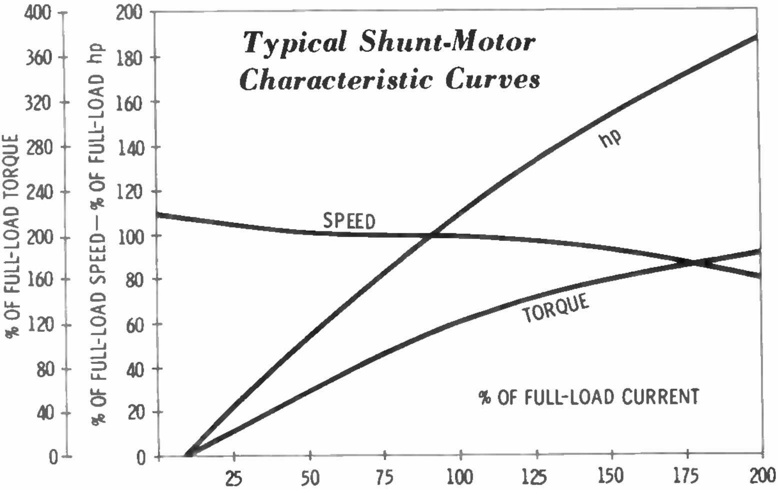
A DC SHUNT MOTOR

The shunt-type motor is used when it is desired to vary the rotational speed above and below the normal speed. Increasing the resistance in series with the shunt field will cause the motor to speed up. (If the field circuit is broken and voltage is still applied to the armature, the motor may run so fast that it damages itself.) A resistor connected in series with the armature will decrease the speed of the motor. The characteristics of any type of motor need to be

DC SHUNT MOTOR WITH FIELD RHEOSTAT



known so that the motor may be used properly. The following figure indicates typical characteristics for a shunt motor.



The main characteristics of a shunt motor are its constant speed and low starting torque. This means that DC shunt motors cannot be used for hard-starting loads.

Q6. **The counter emf ---------- when armature speed increases.**

Q7. **What are the two main characteristics of a DC shunt motor?**

Q8. **A resistance added in series with the shunt field ---------- the speed of the motor.**

Your Answers Should Be:

A6. The counter emf **increases** when armature speed increases.

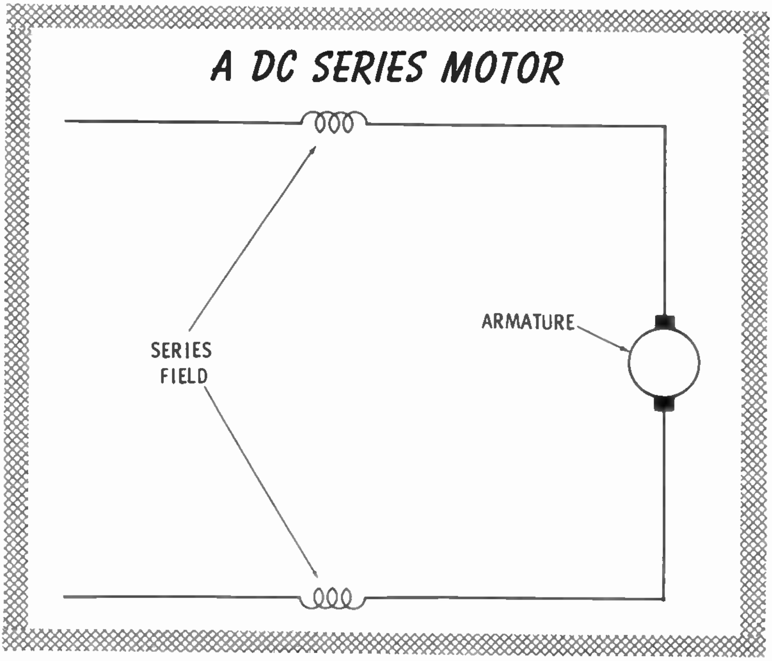
A7. The two main characteristics of a DC shunt motor are its **relatively constant speed** and its **low starting torque.**

A8. A resistance added in series with the shunt field **increases** the speed of the motor.

DC SERIES MOTORS

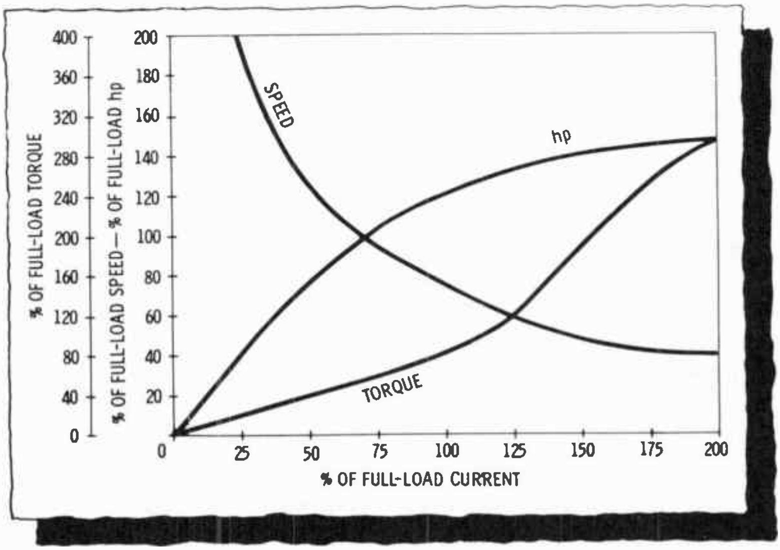
DC series motors have the field and armature windings connected in series. Both sets of windings therefore carry the same current.

The field coil, therefore, must be of much heavier construction than the field of a DC shunt motor in order to withstand the heavy currents. Below is a schematic diagram of a DC series motor.



The starting and stalling torque of a series motor is excellent. It will start and carry very heavy overloads. Speed regulation, however, is very poor. The speed decreases as the load increases. Therefore, the motor turns slower with

Typical Series-Motor Characteristic Curves



a heavy load and faster with a light load. If a DC series motor is run without any load, it may run so fast that it may damage itself. Series motors are seldom used in applications requiring belt coupling to the load; if the belt should break, the motor would be without a load. A typical use of a series motor is the automobile starter.

Q9. Why is the field winding of a series motor wound with larger wire than the field winding of a shunt motor?

Q10. A series motor has a (large, small) starting torque.

Q11. What happens to the speed of a series DC motor operated with no load connected to its shaft?

Q12. The armature current of a series motor (does, does not) flow through the field windings.

Your Answers Should Be:

A9. The field winding of a series motor is wound with larger wire than a shunt field winding because the **series field carries a much larger current.**

A10. A series motor has a **large** starting torque.

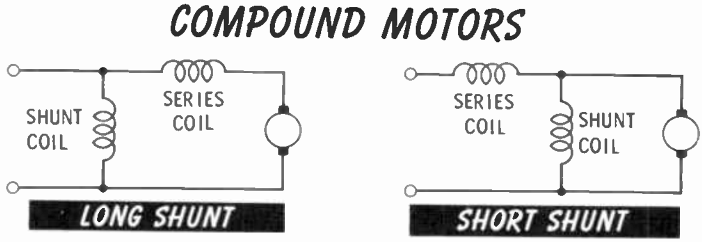
A11. If a series DC motor is operated without load, it runs at a **dangerously high speed.**

A12. The armature current of a series motor **does** flow through the field windings.

DC COMPOUND MOTORS

As the name implies, the DC compound motor is a combination of a DC shunt motor and a DC series motor. It has both a series and a shunt field winding. Its characteristics are a combination of the characteristics of the DC series motor and the DC shunt motor. When the shunt field coil and the series field coil act to aid each other, the machine is said to be a **cumulative-compound** motor. With the shunt field coil and the series field coil opposing each other, the machine is called a **differential-compound** motor.

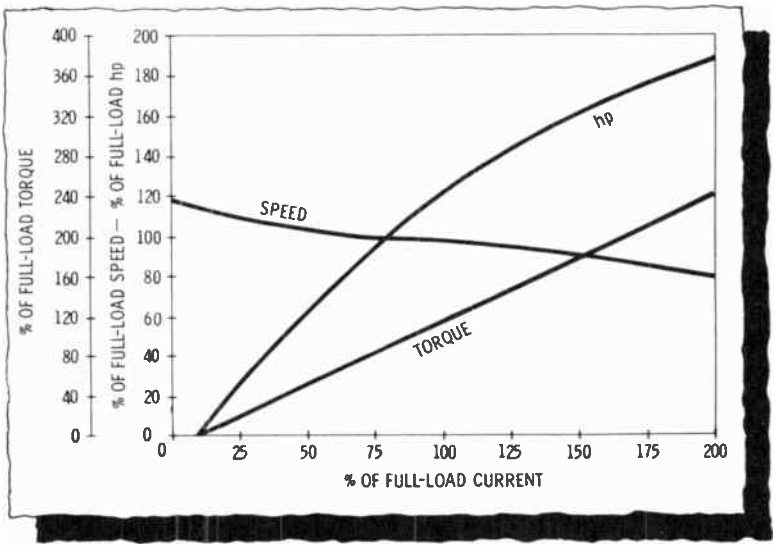
Compound motors are divided into two groups according to the manner in which the series field coil is connected with respect to the shunt field coil. These two groups are known as **short-shunt** and **long-shunt** compound motors.



By proper control of the relative strength of the two field coils, the compound motor may be used to meet any requirement that can be met by a pure series motor or a pure shunt motor. The characteristics shown on the opposite page apply to a typical compound motor, but not necessarily to every compound motor.

Examination of the chart below reveals that the speed of a compound motor is almost as constant as that of a shunt motor and the starting torque is almost as high as that of a series motor. A compound motor does not run dangerously fast even at no load. Compound motors can be designed to have different characteristics.

Typical Shunt-Motor Characteristic Curves



The compound motor has two field windings. For this reason, a compound motor is usually more expensive than either a series or shunt motor of the same capacity.

Q13. What type of DC motor has the highest starting torque?

Q14. What type of DC motor should never be started without a mechanical load connected?

Q15. What type of DC motor has a constant speed characteristic?

Q16. DC shunt motors have a ___ starting torque.

Q17. The same current flows through the armature and field coils in a DC ______ motor.

Q18. How does a short-shunt compound motor differ from a long-shunt compound motor?

Your Answers Should Be:

A13. A **series** DC motor has the highest starting torque.

A14. A **series** motor should always have a mechanical load.

A15. A **shunt** DC motor has a constant speed characteristic.

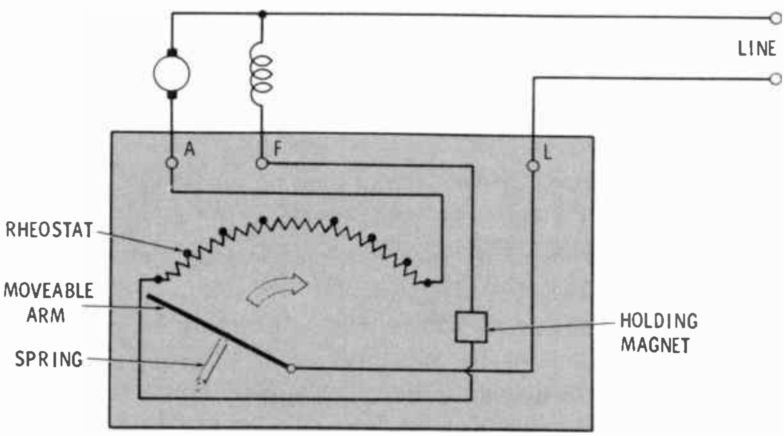
A16. DC shunt motors have a **low** starting torque.

A17. The same current flows through the armature and field coils in a DC series motor.

A18. A short-shunt motor has its shunt field connected **directly across the armature.** A long-shunt motor has the **series field between the armature and the connection to the shunt field.**

MANUAL STARTERS

A DC motor presents a very low resistance to a voltage source whenever the armature is at rest. For instance, a motor normally drawing 50 amperes at full load may have a starting current of 500 amperes or more. This inrush current could easily damage the motor. In order to prevent this condition, starters are often used. Starters are usually

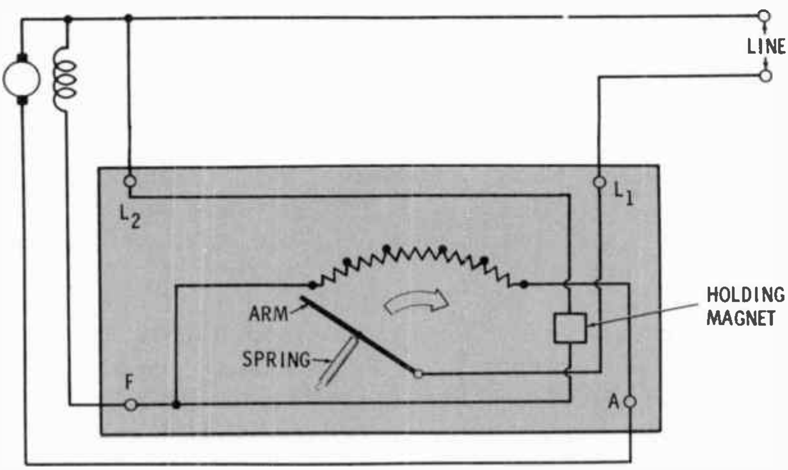


THREE-POINT STARTING BOX

required only with machines rated at more than ¼ horsepower. In most cases, the starters are rheostats connected in series with the armature. These rheostats are usually contained in an enclosure called a **starting box.**

In a **three-point** starting box the connections are made as shown in the figure on the opposite page. When the voltage is turned on, the rheostat in series with the armature limits the armature current to a reasonable level. As the motor gains speed, the operator turns the rheostat arm in the direction of the arrow, one step at a time. Some of the resistance is also in series with the shunt field, but is small enough to be neglected. The holding magnet is energized by the field current so that when the arm has been pushed across the entire rheostat, the holding magnet will hold it in this position. If the field circuit should become open, the arm is released and returns to the off position.

FOUR-POINT STARTING BOX



The operation of the **four-point** starting box is similar to that of the three-point starting box. However, the holding magnet releases the arm when the voltage, rather than the field current, is lost. The four-point box is the more common.

Q19. How many external connections are there on a three-point starting box?

Q20. When is the arm on a four-point starter released?

Your Answers Should Be:

A19. A three-point starting box has **three** external connections: line, armature, and field.

A20. The arm on a four-point starter is released when the **supply voltage is lost.**

AUTOMATIC STARTERS

Automatic starters are commonly used when frequent starting of DC machines is necessary. These starters can be operated by relatively inexperienced personnel since they involve only button pushing.

The motor in the figure on the opposite page is a compound motor, but the circuit would apply equally well to shunt motors (by removing the series field coil) or to series motors (by removing the shunt field loop).

As the starting push button is depressed, line voltage is applied to coil M. The coil closes the two normally open contacts, M_1 and M_2. M_1 causes continued current flow through coil M. M_2 causes the armature to receive voltage. The three series resistors R_1, R_2, and R_3 limit the armature current to a safe value. Relays A, B, and C (whose coils are not shown) are operated in order as the counter emf in the armature increases.

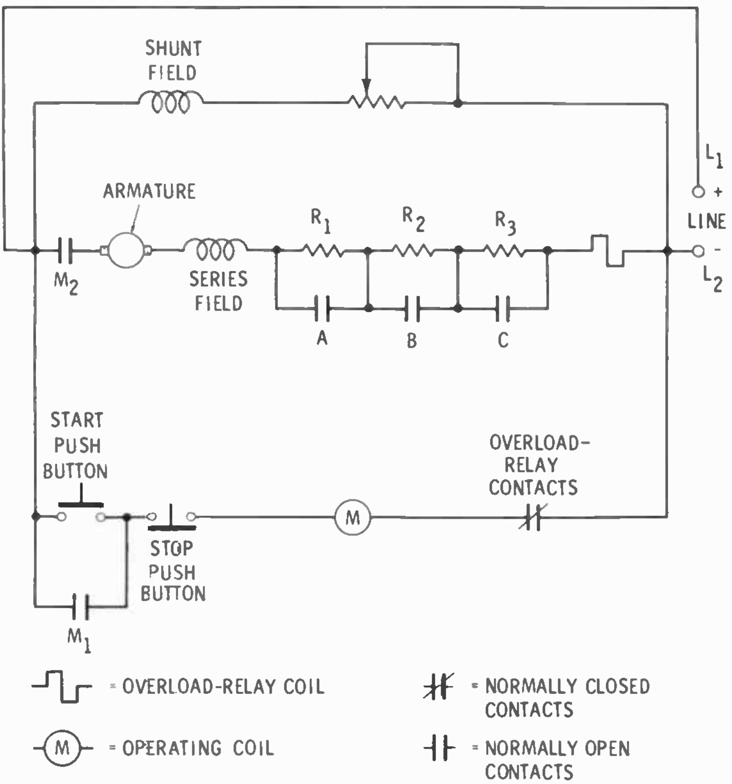
Contact A closes first, thus short-circuiting R_1 and leaving less resistance in the armature circuit. Contact B closes next and short-circuits R_2. Finally contact C closes. This leaves no external resistance in the armature circuit.

When the stop button is pressed, coil M is de-energized, and both M_1 and M_2 open. As the motor comes to a stop, contacts A, B, and C open.

If an overload occurs during normal motor operation, the heavy current will activate the overload relay and open its contacts. This is equivalent to pushing the stop button.

The short-circuiting of the resistances in series with the armature can be accomplished by time-delay relays, voltage-sensitive relays, or current-sensitive relays. The theory always remains the same—use series resistance to start and lower the resistance value as the motor picks up speed. Voltage-sensitive relays operate as the counter emf in the armature increases. Current-sensitive relays operate as the armature current decreases.

AUTOMATIC-STARTER CIRCUIT



Q21. What is the purpose of DC-motor starters?

Q22. Name the three types of relays that can be used to short-circuit resistors in an automatic starter.

Q23. Voltage-sensitive relays respond to the __________ in the armature.

Q24. In a motor starter, current-sensitive relays act when the current __________.

Q25. Under what conditions are automatic starters commonly used?

Your Answers Should Be:

A21. DC-motor starters are designed to **limit the starting current** to prevent damage to the armature.

A22. **Voltage-sensitive, current-sensitive,** and **time-delay** relays can be used to short-circuit resistors in an automatic starter.

A23. Voltage-sensitive relays respond to the **counter emf** in the armature.

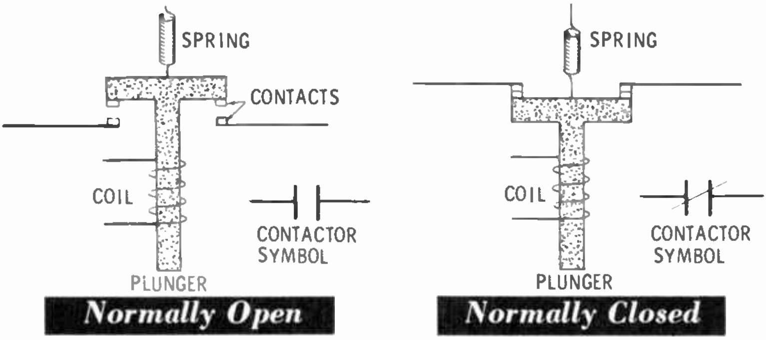
A24. In a motor starter, current-sensitive relays act when the current **decreases.**

A25. Automatic starters are commonly used when **frequent starting** is necessary.

RELAYS

There are several types of relays used in DC-motor controllers. The simplest is a switch closed or opened by an electromagnet when the current through the relay coil reaches a certain level.

SIMPLE RELAYS



It is often desirable for a relay to operate only after a certain time delay. For example, the automatic starter just described may use time-delay relays to assure that the motor reaches its full load current after a given time, no matter what the load on the motor. Or it may not be desirable to have an overload relay disconnect the motor as a result of a momentary overload. A time-delay relay can be used for this purpose also.

Thermal Time Delay

Several types of relays can offer a time delay. One type often used for overload protection is the **thermal overload relay.** This relay is operated by heat rather than magnetism. A strip of brass and a strip of copper are fastened together to form a **bimetal strip.**

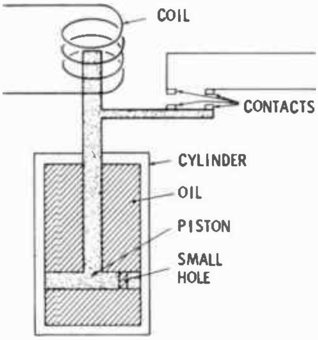
A SIMPLE THERMAL-OVERLOAD RELAY

When the bimetal strip is heated, the brass expands more than the copper, and the strip bends away from the fixed contact and opens the circuit. The action of this relay depends on the heating effect of the current. That is, it depends on both the amount and the duration of the current. If a heavy current flows for a short time but not long enough to cause overheating of the motor, the relay will stay closed.

Dashpot Time Delay

Automatic starters generally use magnetic time-delay relays. One type, the **dashpot** timing relay, uses a cylinder containing oil (called a dashpot) to slow down the motion of a plunger.

A DASHPOT RELAY



Q26. Two types of time-delay relays depend on a _______ _____ or a _______ to determine the amount of time delay.

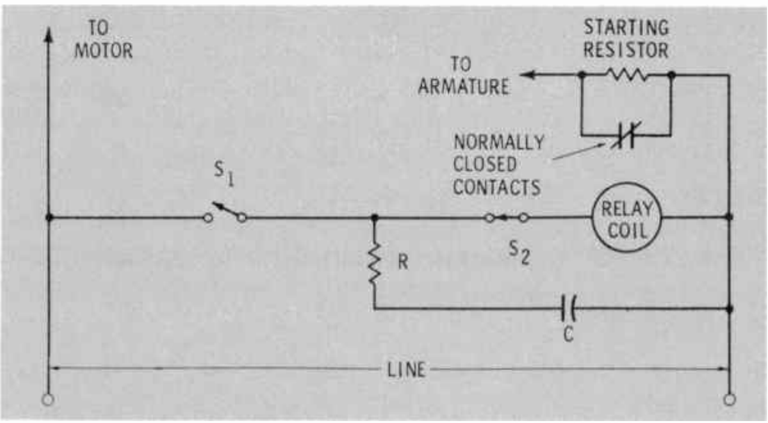
Your Answer Should Be:

A26. Two types of time-delay relays depend on a **bimetal strip** or a **dashpot** to determine the amount of time delay.

Resistance-Capacitance Time Delay

It is also possible to make use of the RC time constant of a resistor and capacitor to establish a time delay. For practical purposes, a current strong enough to operate a relay will flow from a discharging capacitor for a period equal to about five time constants.

A CAPACITOR TIME DELAY



In the simplified circuit shown above, S_1 is closed and S_2 is open when the motor is off. The capacitor becomes charged. When the motor is started, S_1 is opened and S_2 is closed. The capacitor discharges through resistor R and the relay coil. During the first moments after the motor is turned on, enough current flows through the relay to hold its contacts open. This causes the starting resistor to limit the armature current. When the capacitor-discharge current decreases below a certain value, the relay contacts close, short-circuiting the starting resistor. Armature current is no longer limited except by the counter emf which is now high enough to protect the armature.

MOTOR EFFICIENCY

Before motor efficiency can be discussed, the term efficiency must be thoroughly understood. **Efficiency** is the ratio of the amount of power obtained from a machine to the amount of input power required to operate it. Therefore, efficiency is a ratio of the power output to the power input of a system. This statement can be written as follows:

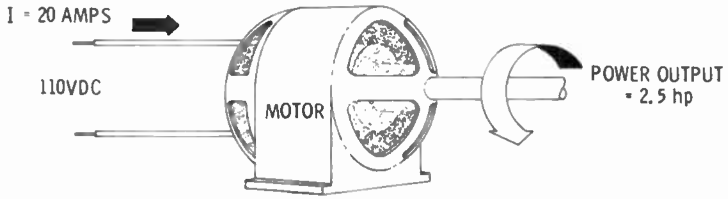
$$\text{Eff} = \frac{P_o}{P_i}$$

If a system requires 1,000 watts at the input while delivering 800 watts at the output, its efficiency is:

$$\text{Eff} = \frac{P_o}{P_i} = \frac{800}{1{,}000} = 0.80 \text{ or } 80\%$$

Efficiency is usually expressed as a percentage. In a motor, the output (mechanical power) is measured in horsepower (HP) while the input (electrical power) is measured in watts. The output is multiplied by 746 in order to obtain its equivalent in watts. For example, 1 HP = 746 W, so 2 HP = 2 × 746 = 1,492 W.

What is the Efficiency of This Motor?



To find the efficiency of the motor above, you must calculate the power input (in watts) and power output (in watts), and then use the formula to find efficiency.

$$P_i = E \times I = 110 \times 20 = 2{,}200 \text{ W}$$

$$P_o = \text{hp} \times 746 = 2.5 \times 746 = 1{,}865 \text{ W}$$

$$\text{Eff} = \frac{P_o}{P_i} = \frac{1{,}865}{2{,}200} = 0.85, \text{ or } 85\%$$

Q27. If a motor requires an input of 30 amperes at 230 volts when its output is 8 HP, what is its efficiency?

Your Answer Should Be:

A27. $P_i = 230 \times 30 = 6{,}900$ W; $P_o = 8 \times 746 = 5{,}968$W

$$\text{Eff} = \frac{P_o}{P_i} = \frac{5{,}968}{6{,}900} = 0.86, \text{ or } 86\%.$$

Motor Losses That Affect Efficiency

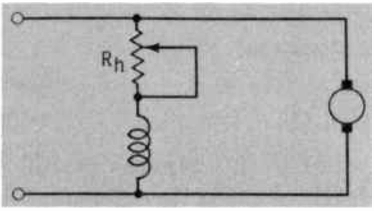
Now that you know how to calculate efficiency, the question of why the output power is smaller than the input power should be answered. A motor has several electrical losses. There are armature losses, losses in the field windings, and losses in the shunt-field rheostat.

There are also mechanical losses in the form of friction. The armature runs on bearings, and the brushes "rub" against the commutator. In addition, the entire armature has to overcome air friction while spinning. The power necessary to provide for these friction losses must be supplied from the input source. A fan is connected to one end of the armature to cool some motors. This amounts to an additional loss due to air friction. All these mechanical losses depend mainly on the speed.

Motor efficiency increases as the physical size of the motor increases. For fractional-horsepower motors, efficiencies are about 40-50%. In the 10-HP range the efficiency is about 85%. This is because the mechanical losses do not increase with the motor size at the same rate as power output.

SPEED CONTROL

One of the great advantages of DC motors over AC motors is that the speed of DC motors can be controlled easily. There are three basic methods for speed control. These make use of a **shunt-field rheostat, resistance in the armature circuit,** or **armature-voltage control.**



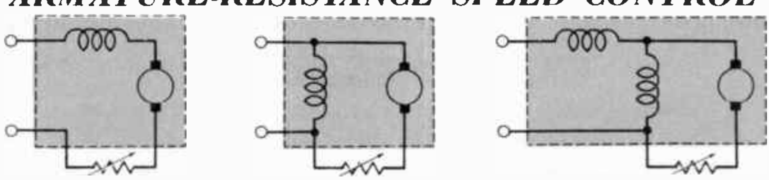
SPEED CONTROL WITH SHUNT-FIELD RHEOSTAT

Look at the figure at the bottom of the opposite page. As the rheostat (R_h) is changed to increase the resistance in the circuit, **less current** flows in the field coil, and the speed of the motor **increases.** When the resistance is completely short-circuited, the full voltage is impressed on the field coil, and the motor rotates at its lowest possible speed.

If the resistance of the rheostat is increased, the strength of the main field will decrease. The counter emf generated in the armature will also decrease. The current through the armature will then increase, and the speed of the motor will increase. When the resistance is decreased, the opposite action takes place, and the motor slows down.

As a motor speeds up, the commutator begins to spark (every commutator has a practical speed limit), and the mechanical stresses within the rotor increase sharply due to centrifugal force and vibration. If the speed continues to increase, the armature may fly apart.

ARMATURE-RESISTANCE SPEED CONTROL



Series Motor ***Shunt Motor*** ***Compound Motor***

Armature-resistance speed control is obtained by inserting an external variable resistance in series with the armature circuit, as shown above. Speed control for series motors is usually not required since they are used where varying speed is permissible. While this system meets the requirement of excellent speed control, the main disadvantage is the considerable amount of power loss in the control rheostat. This, in turn, makes the motor efficiency very low.

Q28. What are the mechanical losses in a DC motor?

Q29. Why is more power lost in an armature speed-control rheostat than in a shunt-field rheostat?

Q30. When the shunt-field resistance is increased, the speed of a motor ----------.

Q31. When the armature resistance is increased, the speed of a motor ----------.

Your Answers Should Be:

A28. Mechanical losses in a DC motor include **bearing friction, commutator friction, and air friction.**

A29. More power is lost in an armature speed-control rheostat than in a shunt-field rheostat because the **armature** normally **carries more current than the field coils.**

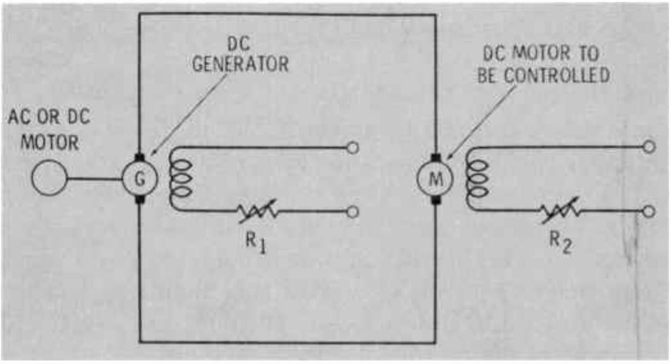
A30. When the shunt-field resistance is increased, the speed of a motor **increases.**

A31. When the armature resistance is increased, the speed of a motor **decreases.**

Ward Leonard Speed Control

The speed of a DC motor can be controlled by varying the armature voltage. This is done by the Ward Leonard system shown in the figure below. This system is the most accurate but also the most expensive method of motor-speed control.

WARD LEONARD SPEED CONTROL



The shunt fields of both the generator and motor are supplied from a constant-voltage source. The DC-generator output voltage is controlled by rheostat R_1. The voltage variation (out of G and into M) gives a wide range of speed control. In addition, by varying the motor rheostat (R_2), a wider speed range can be obtained.

This system requires three machines instead of one. A source of voltage for the field windings is also needed. In some cases this may be a fourth machine. However, in many cases the higher cost of this system is justified by the complete range of speed control it makes possible. With it the speed can be varied accurately from zero to maximum.

Q32. The Ward Leonard system controls the motor speed by varying the ________ ________.

Q33. Which type of speed control gives full-range control of speed?

WHAT YOU HAVE LEARNED

1. The main parts of a DC motor are the frame, end bells, pole pieces, shaft, armature assembly, commutator assembly, and brush assembly.
2. A DC motor has armature losses of the same sort as a DC generator: copper losses, eddy currents, and hysteresis losses.
3. Armature reaction occurs in a DC motor and can be limited by interpoles and compensating windings.
4. A motor, when it is turning, also acts as a generator and creates a counter emf that opposes the applied voltage and limits the flow of current through the armature.
5. There are three main types of DC motors—shunt, series, and compound.
6. Shunt motors have a low starting torque and a relatively constant speed regardless of load.
7. Shunt motors must not be operated without field current because the motor will then run at a dangerous speed.
8. Series motors have a high starting torque, but their speed varies greatly as the load changes.
9. Series motors must never be operated without a load because under that condition the speed will be so great that the armature may fly apart.
10. Compound motors combine the characteristics of both series and shunt motors in proportions that depend on the construction of the particular motor.
11. DC motors are started with a resistance in series with the armature to limit the starting current.

Your Answers Should Be:

A32. The Ward Leonard system controls the motor speed by varying the **armature voltage.**

A33. The **Ward Leonard** system gives full-range control of speed.

12. Two common ways of providing starting resistance for DC motors are the three-point and four-point starting boxes. In these devices, a contact is moved by hand to bypass the starting resistance as the motor gains speed. A magnet holds the contact in place while the motor is operating.
13. Automatic starting boxes perform the starting function automatically by using relays to bypass the resistance as speed builds up or after a time delay.
14. Thermal overload relays are operated by the heating effect of a current and can be used to protect motors from overheating.
15. Dashpot time-delay relays use an oil-filled piston to slow down the action of the relay.
16. An RC circuit can be used to provide a time delay for the operation of a relay.
17. Motor efficiency is found by dividing the output power by the input power. One horsepower is equal to 746 watts.
18. Motor speed can be controlled by use of a shunt-field rheostat.
19. Motor speed can also be controlled through the use of an armature speed-control rheostat. The disadvantage of this system is that it reduces motor efficiency considerably through power loss in the rheostat.
20. The most useful system of speed control is armature-terminal–voltage speed control (the Ward Leonard system), which uses an independent generator to provide voltage to the armature. This system allows a wide range of accurately controlled speeds, but it is complex and expensive.

4

AC Generators

What You Will Learn

The principles of AC-generator operation are presented in this chapter. You will learn the applications of the various generator types and how to recognize them. You will become familiar with the characteristics of AC generators and how they are regulated.

ALTERNATORS

AC generators are also known as **alternators.** They vary in size from no larger than a walnut to bigger than a house. Almost all electrical power for homes and industry is supplied by alternators in power plants. An AC generating system consists of the **armature, field,** and **prime mover.**

The Armature

The armature is that part of a generator in which the output voltage is induced. The current that flows to the load also flows through the armature. In an alternator, the armature is an assembly of coils, as in a DC machine. The armature may be either the rotating (rotor) or stationary (stator) member of an AC generator.

The Field

DC is supplied to the field winding in an alternator. This DC current creates a magnetic field which is cut by the armature winding. A separate DC source is usually used for the field. The field in alternators supplying up to 50 KW is usually the stationary part (stator). In larger machines the field is the rotating component (rotor). Electrically, it makes no difference whether a rotating winding cuts a stationary field or a rotating field cuts a stationary winding.

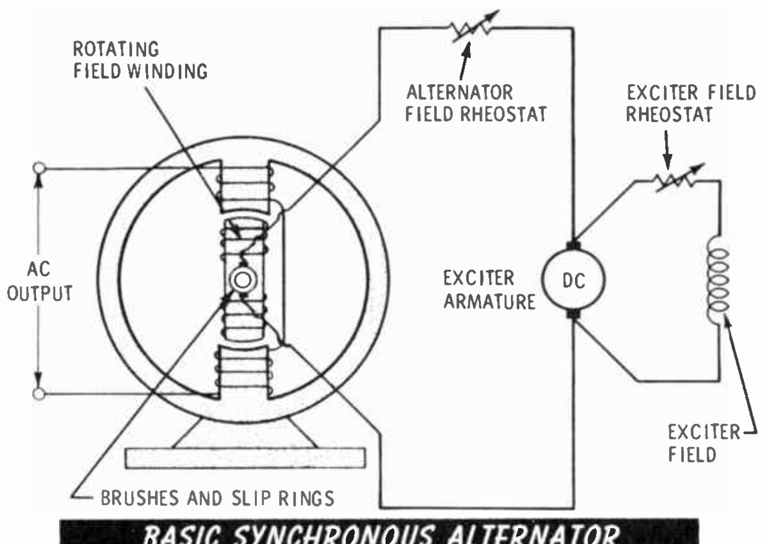
The field requires relatively low voltage and current compared to the high voltage and current generated in the armature of a large alternator. It is easier to connect this low voltage and current to a rotor through slip rings than it is to connect high AC voltage and current. This is why the field is the rotating part in large alternators.

The Prime Mover

The **prime mover** is the source of mechanical power which drives the rotor of the alternator. It can be a gasoline engine, a steam turbine, a water turbine, or any such source. The prime mover can even be an electric motor.

SYNCHRONOUS ALTERNATORS

The synchronous alternator is the basic and most common AC generator. The DC excitation is provided from an outside source, usually a small DC generator. The shaft of the alternator is driven at a constant speed, usually 1,800 or 3,600 rpm. As has been mentioned before, either the armature or the field of the alternator can be the rotor.



BASIC SYNCHRONOUS ALTERNATOR

Field Current

DC current can be supplied to the field in several ways. In most cases it is supplied by a DC generator called an **exciter.** The exciter may supply a DC line (called a **bus**) that is tapped to supply several loads. In other cases, the DC generator may be connected directly to the same shaft as the alternator, or it may be driven from the alternator shaft by a belt connection. Belt-connected exciters are used with relatively slow machines.

Since generators cannot operate without DC excitation, power plants usually have one or two spare exciters capable of taking over in case of an exciter failure. The exciter is usually a compound-wound DC generator that is flat compounded and rated at either 125 or 250 volts according to the size of the alternator. A flat-compound DC generator is used for excitation current because this type of machine gives the most constant voltage regardless of load.

Inductor Alternator

Inductor alternators are used to produce voltages at frequencies between 500 and 10,000 cycles per second. They are used for supplying power to induction furnaces for melting or heating metals.

In an inductor alternator both the armature and the field are stationary. The only rotating element is a toothed steel rotor which distorts the magnetic field of both the field and the armature. The motion of the steel teeth produces a rapidly vibrating magnetic field which induces a very high-frequency voltage in the armature winding.

Q1. What type of alternator is used to supply household current?

Q2. What type of alternator would be used to obtain a 5,000-cps AC current?

Q3. What is the minimum number of generators you could expect to find at an AC power-supply installation?

Q4. Why do large synchronous alternators have rotating fields and stationary armatures?

Q5. Why is a flat-compound generator used as an exciter for a synchronous alternator?

Your Answers Should Be:

A1. A **synchronous alternator** supplies household current.

A2. An **inductor alternator** would be used to obtain a 5,000-cps AC current.

A3. You would expect to find at least **two generators** at an AC power installation—an alternator and a DC exciter.

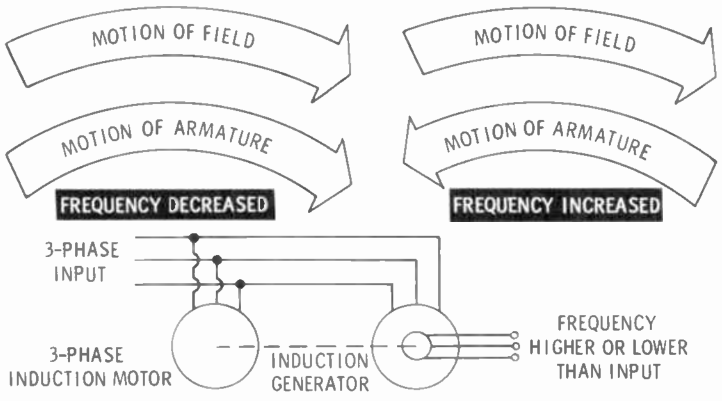
A4. Large synchronous alternators have rotating fields because the **field current and voltage are much smaller than the armature current and voltage.**

A5. A flat-compound generator provides a **constant output voltage** over a wide variation of load.

THE INDUCTION GENERATOR

The induction generator can be used to develop special frequencies for special applications. For example, some high-speed tools are operated by AC voltages at frequencies of 90, 100, 175, or 180 cps. Induction generators can also supply AC voltages at 25 or 50 cps. An induction generator may be considered a device for changing the frequency of AC, since it uses a three-phase AC power source.

PRINCIPLE OF FREQUENCY CHANGING



The power source is used to drive an AC motor. At the same time, it is used to establish a rotating magnetic field.

In the figure on the opposite page, the magnetic field itself rotates and the field coils remain stationary. (You will see how this is done in the following chapter when induction motors are discussed.) If the armature of the induction generator is standing still, the voltage induced in it will have the same frequency as the rotating magnetic field. The action is very similar to that of a transformer. However, if the armature is made to turn, the frequency of the induced voltage is no longer the same as the frequency of the field. If the armature turns in the same direction as the rotating field, the generated frequency will be lower. In fact, if the armature turns at the same speed as the rotating field, the induced frequency will be zero. When the armature is moving in a direction opposite from that of the rotating field, the relative speed is increased and the frequency is higher.

SINGLE PHASE AND POLYPHASE

Single phase refers to the type of generator discussed in Chapter 1. Single-phase alternators have only one armature winding whose leads deliver the output of the alternator. They deliver an AC output between two wires only.

Polyphase machines have more than one winding and deliver an output between several pairs of wires. The most common type of polyphase machine is the three-phase type. Two-phase machines are also sometimes used. Three-phase generators are widely used because large amounts of power can be transmitted more efficiently with a three-phase system than with a single-phase system.

Q6. What type of generator could be used to obtain a 120-cps output?

Q7. When an induction generator supplies an output frequency higher than the input frequency, is the rotor turning in the same direction as the magnetic field?

Q8. What is the advantage of a three-phase power system over a single-phase power system?

Q9. A single-phase generator delivers voltage between only ___ wires.

Your Answers Should Be:

A6. An **induction generator** could provide a 120-cps output.

A7. **No.** When the output frequency of an induction generator is higher than the input frequency, the rotor is turning in the **opposite** direction from the magnetic field.

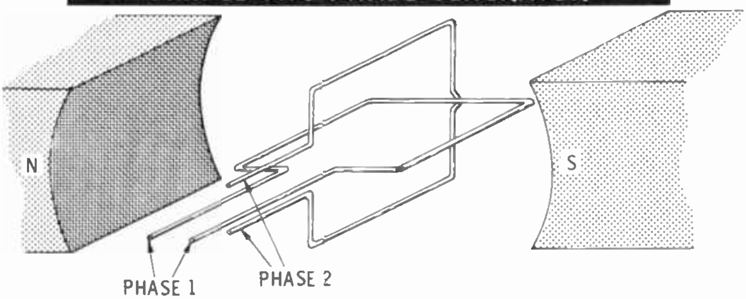
A8. Power is **transmitted more efficiently** in a **three-phase** system than in a **single-phase** system.

A9. A single-phase generator delivers voltage between only **two** wires.

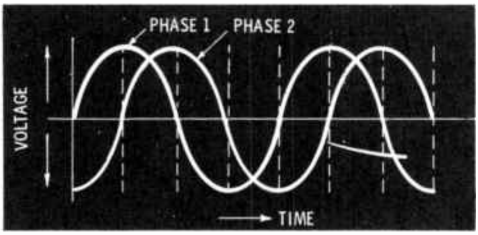
Two-Phase Alternator

The **two-phase alternator** is, as the name implies, a machine that has two separated windings on its armature. Usually the two windings are mounted 90 electrical degrees

SIMPLE TWO-PHASE GENERATOR



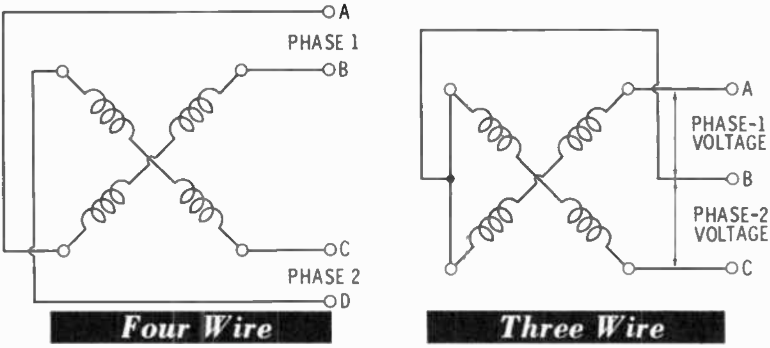
apart. Thus, when the voltage in one coil reaches its peak, the other one is at zero, and vice versa. The figure below indicates the phase relationships in a two-phase alternator.



PHASE RELATIONS IN A TWO-PHASE GENERATOR

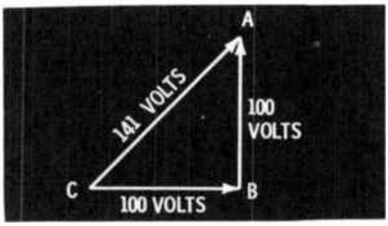
The armature windings of a two-phase generator can be connected in two different ways. It is possible to simply make individual connections to the two separate windings. This arrangement gives four output connections and is called a **four-wire system.**

TWO-PHASE SYSTEMS



It is also possible, however, to combine two of the output connections to produce what is called the **three-wire system.** In this system the voltages of the two separate phases remain the same. Phase 1 appears between A and B. Phase 2 appears between B and C. But a third voltage is also available, the voltage between A and C. This voltage is the **vector sum** of the other two voltages.

VOLTAGE RELATIONSHIPS IN A TWO-PHASE GENERATOR



In the figure above, single-phase voltages of 100V exist between A and B and between B and C. The voltage between A and C is 1.41 times the single-phase voltage if the two phase voltages are equal.

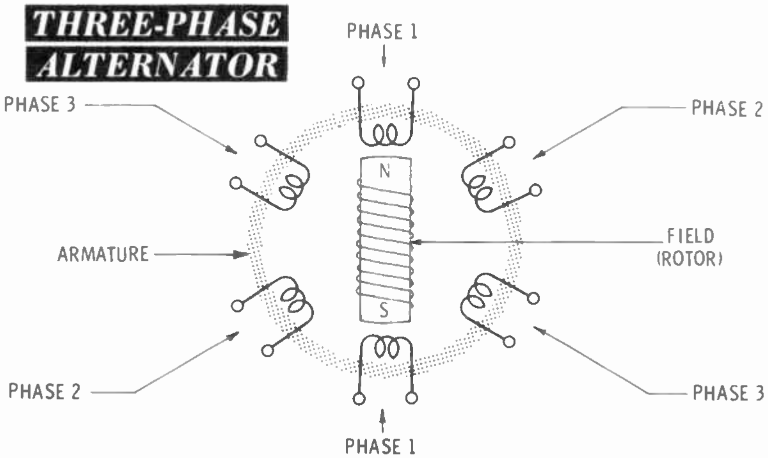
Q10. In a three-wire, two-phase system, how can the combined voltage of the two phases be calculated if the individual phase voltages are equal?

> **Your Answer Should Be:**
>
> A10. The combined voltage is **1.41 times the voltage of one phase,** provided the phase voltages are equal.

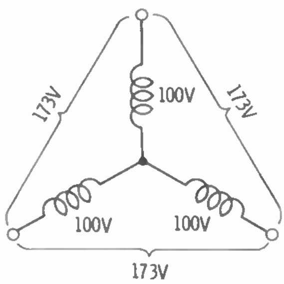
Three-Phase Alternator

A three-phase alternator has three separate armature windings connected in either a **delta** or **wye** (Y-shaped) pattern. A detailed discussion of these methods of connection is given in Chapter 6 of this volume. (In the figure below, each phase winding is made up of two parts.)

THREE-PHASE ALTERNATOR

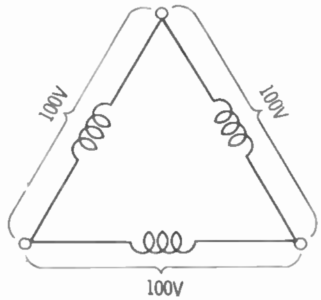


The three single-phase voltages of a three-phase alternator are usually 120 electrical degrees apart. As in the two-phase machine, it is possible to obtain single-phase voltages and also voltages between phases. The relationship



VOLTAGES IN A WYE-CONNECTED, THREE-PHASE ALTERNATOR between these voltages depends on whether a delta or wye connection is used.

VOLTAGES IN A DELTA-CONNECTED, THREE-PHASE ALTERNATOR



As you will see in Chapter 6, three-phase power can be transmitted more economically than single-phase power can be transmitted.

GENERATOR RATINGS

The ratings of an AC generator are usually given on a nameplate attached to the outside of the frame of the machine. The following information is usually given:

1. Manufacturer's serial and type numbers.
2. Number of phases.
3. Speed (rpm).
4. Number of poles.
5. Maximum voltage ratings (output).
6. Frequency of output.
7. KVA (or KW) rating.
8. Armature current (in amps per phase).
9. Ambient temperature and temperature rise.
10. Field current (in DC amps).
11. Power-factor limits.

Additional information, such as whether the generator can be operated continuously, may be given.

Q11. If the single-phase voltage of a three-phase, wye-connected alternator is 120V, what is the voltage between phases?

Q12. How many between-phase outputs can be obtained from a three-phase machine?

Your Answers Should Be:

A11. $120V \times 1.73 = 208V$.

A12. You can obtain **three** between-phase outputs.

ARMATURE REACTION

Armature reaction occurs in an alternator just as it does in a DC generator. The magnetic field of the armature interacts with the main field. With a purely resistive load, this effect is similar to that in a DC machine. There is some distortion of the main magnetic field which changes the waveform of the output voltage.

However, current in an AC circuit is not always in phase with the applied voltage. This means, also, that current in the armature is not always in phase with the induced voltage. This fact gives rise to an interesting effect. When the load is highly inductive and the current lags behind the load voltage, the phase shift of the current causes the magnetic field of the armature to oppose the main field and partly cancel it. If an inductive load is applied to an alternator, there is a drop in output voltage. Exactly the opposite happens with a capacitive load. Here, the load current leads the load voltage, and the armature field now adds to the main field. The output voltage of an alternator will be higher with a capacitive load.

FREQUENCY

In all alternators the frequency is controlled by the speed of the rotor. The relationship between the speed of the rotor and the output frequency of an alternator is given by the following formula:

$$f = \frac{P \times S}{120}$$

where,

f is the frequency in cps,
P is the number of poles,
S is the speed in rpm.

This formula applies regardless of the number of phases.

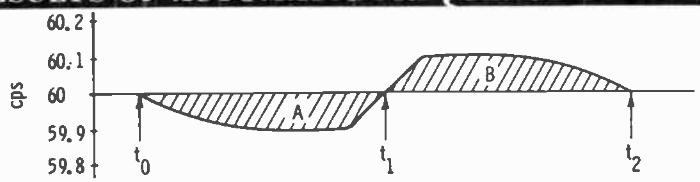
FREQUENCY CONTROL

Generators must maintain very steady frequencies since so many electrical devices require an accurate supply frequency. For example, all electric clocks depend on an accurate frequency to maintain the correct time. A variation of only 1 cycle per second would mean a change of 24 minutes every 24 hours. Many devices, such as timers, are operated by synchronous motors because of the constant speed of this type of motor. The constant speed of a synchronous motor depends directly on a constant-frequency input.

The frequency of an alternator depends on the speed of the prime mover. If the steam turbine, hydraulic turbine, or fuel engine driving the generator has a reliable speed regulation, the generator frequency will be constant.

In large power plants, very accurate frequency-recording instruments and means of compensating for any speed changes are maintained. Thus, if the frequency should drop for a short period, a control device will overspeed the shaft to make up for the loss. The following figure shows a frequency-time diagram for such automatic correction.

RESULTS OF AUTOMATIC FREQUENCY CONTROL



At time t_0 a situation such as a heavy load lowered the frequency to 59.9 cps. At time t_1 the automatic device sensed the loss and forced the frequency to 60.1 cps until time t_2. At that time the machine had caught up with itself. Shaded areas A and B on the diagram must be equal in order for the machine to be caught up.

Q13. What would be the frequency of a 4-pole alternator operated at a speed of 1,500 revolutions per minute?

Q14. Does the number of phases affect the frequency of the output? Why?

Q15. What happens to the output voltage of an alternator when the load is capacitive?

Your Answers Should Be:

A13. $f = \frac{P \times S}{120}$

$$f = \frac{4 \times 1{,}500}{120} = 50 \text{ cps}$$

A14. **No. One complete revolution generates one complete cycle** in each winding.

A15. When a capacitive load is connected to an alternator, the **output voltage rises.**

VOLTAGE REGULATION

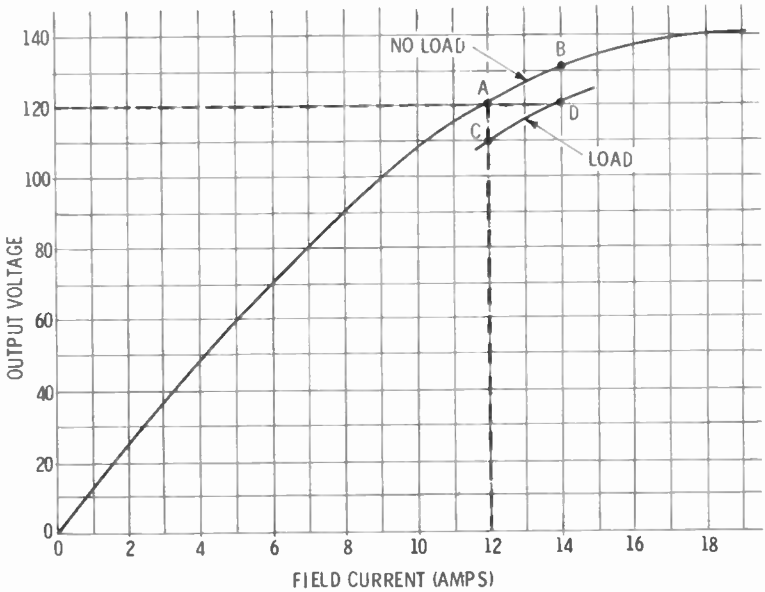
The best way to understand the need for regulating the output voltage of a generator is to determine what would happen if the voltage were not steady. One of the most disturbing things would be the constant flickering of electric lights. Certain motors would not maintain a constant speed. Radio and TV sets would not operate properly.

The voltage of an alternator depends on the speed of the machine, the number of turns in the winding, and the strength of the magnetic field. The speed of the shaft is maintained constant in order to maintain a constant frequency, so speed variation cannot be used to regulate voltage. The number of turns on the armature is fixed by the machine design and cannot be varied to regulate voltage.

The field strength is the only other factor that can be varied, but even it can be varied only a limited amount. The graph at the top of the next page shows how the no-load voltage of a typical alternator depends on the DC field current. An alternator operating at no load requires a minimum amount of field current—say 12 amps DC (point A). If the field current is increased to 14 amps, the voltage will be increased to 135V (point B).

Suppose the alternator is operating at 120V with no load. A load is now applied to the generator. The voltage output will change if the field current remains the same. In this case it drops to 110 volts (point C). Now if the field current is increased to approximately 14 amps, the voltage will go up again to 120V (point D).

RELATIONSHIP OF OUTPUT VOLTAGE AND FIELD CURRENT IN A TYPICAL ALTERNATOR



You can see that whenever a load is applied to an alternator, an increased field current should be applied in order to make up for the drop in output voltage. During the course of one day the load varies considerably. Such field-current changes must therefore be made automatically. A device for regulating the output voltage of a generator is called a **voltage regulator.**

Q16. Is the speed of an AC generator varied to control the output voltage? Why?

Q17. When a load is connected to an alternator, the output voltage of the alternator _______ if the field current is not changed.

Q18. Changes in the output voltage of an alternator can be corrected by changing the _____ ________.

Q19. A device that automatically maintains a constant generator output voltage is called a _______ __________.

Your Answers Should Be:

A16. The speed of an AC generator **cannot** be varied to control the output voltage because the speed **also determines the output frequency.**

A17. When a load is connected to an alternator, the output voltage of the alternator **changes** if the field current is not changed.

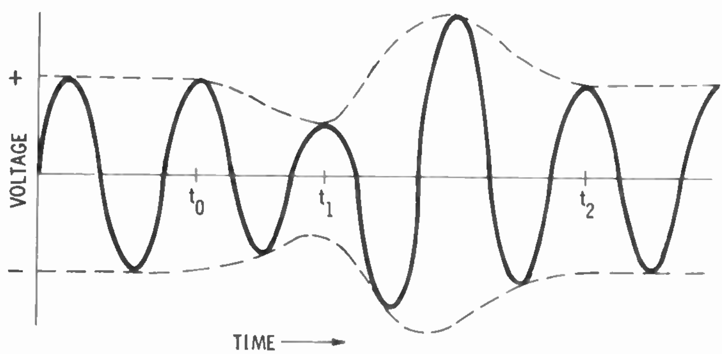
A18. Changes in the output voltage of an alternator can be corrected by changing the **field current.**

A19. A device that automatically maintains a constant generator output voltage is called a **voltage regulator.**

VOLTAGE REGULATORS

A voltage regulator must sense any change in output voltage and vary the DC field current so as to correct the change. There are many voltage regulators on the market, but they can be divided into two basic groups—those with moving parts and those without moving parts. An example of the first type will be given on the next page. For simplicity, only the basic parts will be shown.

The figure below shows the voltage sine wave during a voltage-regulating operation. The voltage begins to drop at t_0. The voltage regulator senses the drop and at t_1 begins to operate. The voltage first goes up and then gradually

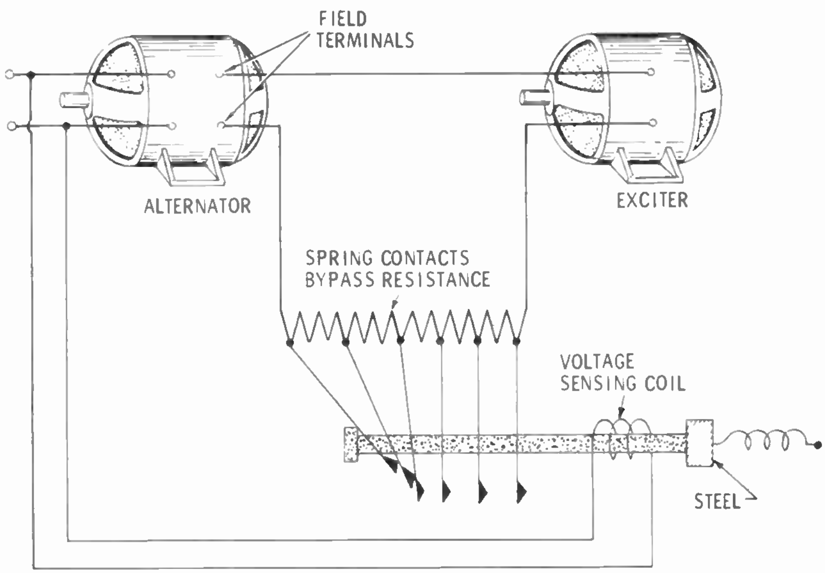


AUTOMATIC VOLTAGE REGULATION

returns to normal. The time required to return to normal varies from a few cycles, as shown in the figure, to a few seconds.

An example of a mechanical voltage regulator is shown in the figure below. If the voltage rises, the magnetic field of the coil increases, and the steel piece moves toward the coil. This causes some of the spring contacts to open, and

A MECHANICAL VOLTAGE REGULATOR



the resistance between the exciter and the alternator increases. This causes less field current to flow to the alternator, and the output voltage decreases to normal. If the voltage falls, the spring is able to pull the steel piece away from the coil. This closes more of the contacts. The resistance then decreases and the field current and output voltage increase. The resistance could also be placed in the exciter shunt-field circuit.

Q20. In the voltage regulator shown above, why is the resistance decreased when more of the contacts are closed?

Q21. Why does decreasing the resistance increase the output voltage?

Your Answers Should Be:

A20. Each pair of contacts **short-circuits part of the resistance.** Therefore, the total resistance decreases when more of the contacts are closed.

A21. Decreasing the resistance **increases** the field current. This causes the output voltage to increase.

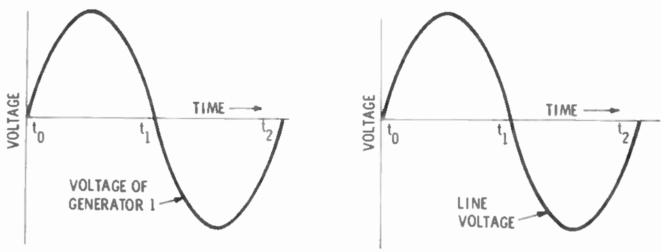
PARALLEL OPERATION

Most power plants have several generators operated in parallel. The advantage of this method is that it provides more reliable operation.

In a large power distribution system it is possible that power used in one area may come from generators operating several states away. This is because many power companies have their networks interconnected. In any large network, the line voltage is kept constant by the individual voltage regulation of each generator.

In order for generators to operate in parallel their frequencies must be equal, their voltages must be equal, and they must be in phase with each other (**synchronized**). While most power plants are strictly three-phase systems, the following paragraphs deal with a single-phase system for better understanding.

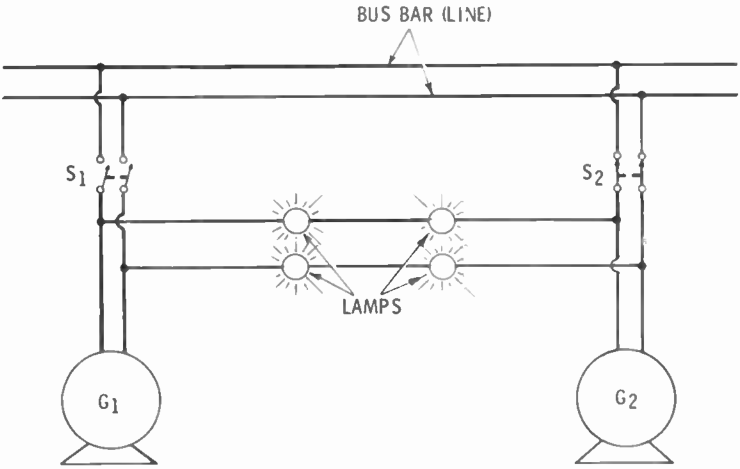
When a generator is being paralleled with others it is said to be brought "on the line." It must first be brought to line voltage and proper frequency, and then it must be synchronized. This means that its voltage and the line voltage must go through the same parts of their cycles at the same time.



OUTPUTS OF TWO SYNCHRONIZED GENERATORS

There are many methods of synchronizing generators, but the most common is by the **lamps method.** The circuit is shown below. Generator G_2 is supplying the load, and G_1 is to be brought on the line.

METHOD OF SYNCHRONIZING GENERATORS



The voltage of G_1 is brought up to line voltage. If the bulbs are lighted, there is a voltage difference between the generators, and therefore they are **not** in phase. In actual practice, the lights flash rapidly at first, as the operator adjusts the speed of G_1, then more and more slowly until they become dark. At this point the operator closes S_1, and the machine is on the line. The lights flash because the voltages are going in and out of phase with each other when the generators do not have exactly the same frequency. Considerable damage may result if the switch is closed when the lights are flashing, so this operation must be done only by qualified operators.

Q22. Why do the lights flash instead of remaining constantly lighted?

Q23. What three conditions must be met before two AC generators can be paralleled?

Q24. When synchronizing generators by the method above, what indicates that it is not safe to close the switch?

Your Answers Should Be:

A22. The lights flash because the voltages come **in and out of phase** with each other when the generators **do not have exactly** the same frequency.

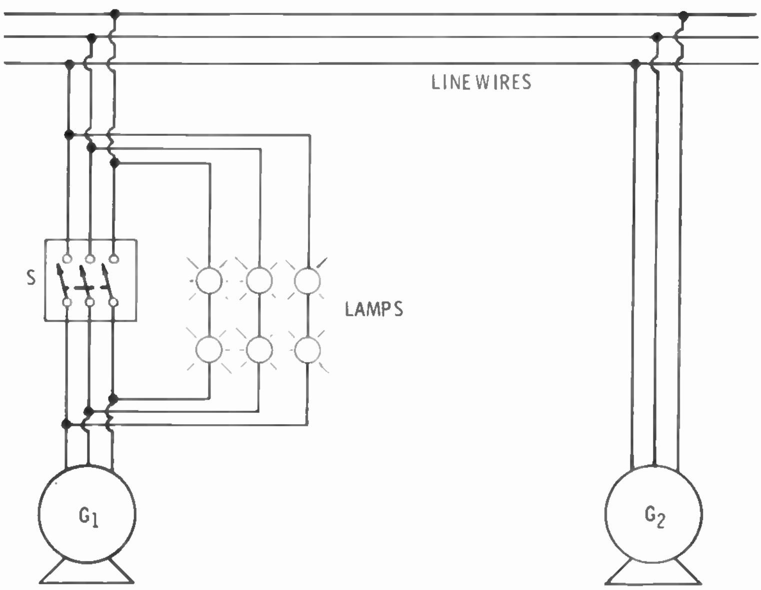
A23. Before two generators are paralleled their **frequencies must be equal, their voltages must be equal,** and they must be **in phase with each other.**

A24. The switch must **not** be closed **when the bulbs are lighted.**

Paralleling Three-Phase Generators

The same general principles apply when paralleling three-phase generators as when paralleling single-phase generators. The voltages must be the same, the frequencies must be equal, and the generators must be synchronized.

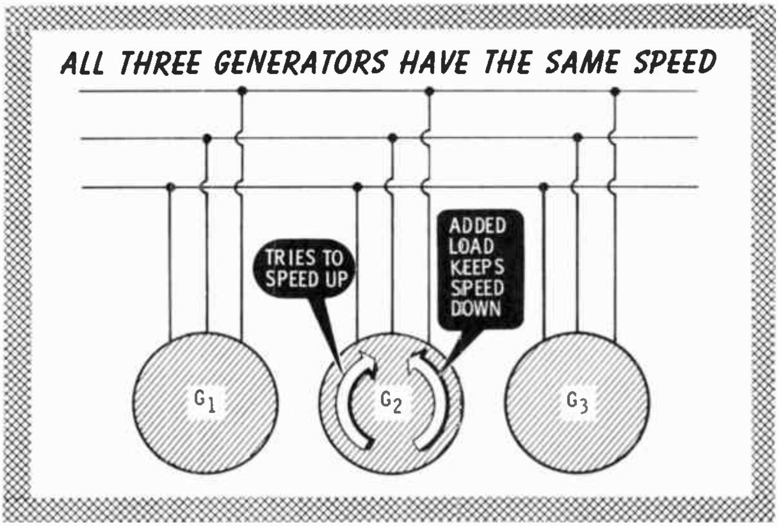
PHASING OUT A GENERATOR



Care must be taken that the three phases are in the right sequence. If the phases are reversed in the generator being placed on the line, it will be damaged. In order to avoid this situation, the following test is performed before paralleling the machine. This is called **phasing out** the generator.

Look at the figure at the bottom of the opposite page. With both G_1 and G_2 operating at the proper voltage and frequency, all lights must flash together and grow dark together. If they take turns in flashing, the connections to two of the phases of G_1 must be exchanged. When all the lights are dark, the machines are synchronized, and the switch (S) may be closed. This brings G_1 on the line.

When generators are operating in parallel, the frequency of all the generators remains the same. If one generator were to try to speed up or slow down, it would immediately be overloaded or underloaded and returned to the correct speed.



For instance, say that G_2 in the figure above tries to speed up. Additional load is immediately placed on this generator. This tends to hold the speed down. This action keeps all of the generators operating at the same speed.

Q25. Why is it necessary to phase out a three-phase generator before paralleling it with another three-phase generator?

Q26. What is indicated if all the bulbs do not flash at the same time when phasing out a generator?

Your Answers Should Be:

A25. Phasing out a three-phase generator before paralleling it with another generator is necessary to be sure the **phases of both generators are in the same sequence.**

A26. If all the bulbs do not flash at the same time, the connections to **two phases** of the oncoming machine have been exchanged.

WHAT YOU HAVE LEARNED

1. AC generators are called alternators and are composed of three basic parts—armature, field, and prime mover.
2. The armature of an alternator is the assembly of coils in which the output voltage and current are induced.
3. The armature is often the nonrotating part of an alternator because it is easier to take high voltages and currents from it in this arrangement.
4. The field of an alternator is produced by a DC current in the field windings.
5. The prime mover of an alternator can be any sort of device that turns the generator shaft.
6. The synchronous alternator is the basic AC generator.
7. A synchronous alternator is usually supplied with DC exciter current from a flat-compounded DC generator which is often coupled to the shaft of the alternator.
8. The inductor alternator is used to generate very high frequencies by means of a vibrating magnetic field.
9. The induction alternator is used to convert normal frequencies of AC to higher or lower frequencies for special purposes. It uses three-phase AC to set up a rotating magnetic field and a motor to vary the relative motion of the armature and the field.
10. A single-phase alternator delivers a single sine-wave output between two terminals.
11. Polyphase alternators have several independent windings and provide several sine-wave outputs.

12. The outputs of a two-phase alternator are normally 90 electrical degrees apart.
13. The two outputs of a two-phase alternator can be connected separately in a four-wire system, or one side of each output can be combined to provide a three-wire system.
14. In a three-wire, two-phase system, the two equal voltages of each phase combine to give a between-phase voltage 1.41 times the single-phase voltage.
15. A three-phase alternator has three phases 120° apart.
16. The between-phase voltage of a three-phase, wye-connected machine is 1.73 times the single-phase voltage.
17. Three-phase power is more efficiently and easily transmitted than single-phase power.
18. The type of load causes the voltage change due to armature reaction to vary. An inductive load causes the voltage to drop; a capacitive load causes the voltage to rise.
19. The frequency of an alternator depends on the number of field poles and the speed; it can be found by the formula $f = \frac{P \times S}{120}$. P is the number of poles and S is the speed in rpm.
20. Large power plants have devices for automatic frequency control because the speed of most motors, clocks, etc., depends on frequency.
21. Power plants also have automatic voltage regulation to provide a relatively constant voltage output.
22. The output voltage of an alternator is regulated by varying the DC exciter current with a mechanical or electronic voltage-sensitive device.
23. To be placed in parallel, alternators must be at the same voltage, at the same frequency, and synchronized.
24. Lamps can be used to synchronize alternators. When the lamps connected between the lines to be paralleled all flash at the same time and then go dark, the two machines are synchronized. There is no voltage difference between the lines when the lamps are dark.

5

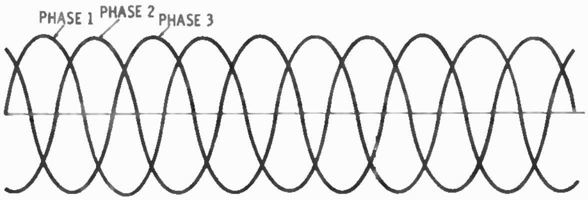
AC Motors

What You Will Learn

In this chapter you will learn how a three-phase AC power supply is used to create a rotating magnetic field. You will discover how this rotating field is used to turn synchronous and induction motors. You will find out how to recognize these motors, and you will learn their characteristics and applications. You will become familiar with the basic types of starting devices for AC motors, when they are needed, and their advantages and disadvantages.

THREE-PHASE FIELDS

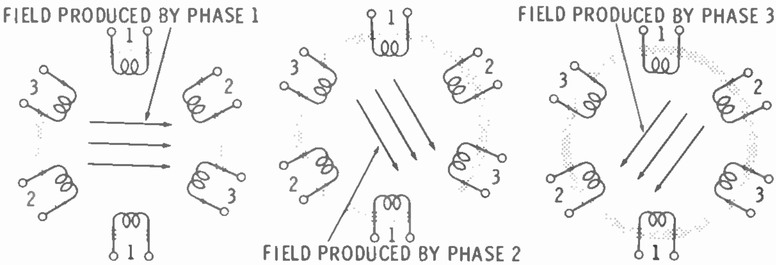
Remember that single-phase power is generated when a single constant magnetic field is rotated through a single winding (or vice versa). Three-phase power is generated in a similar manner when a magnetic field rotates in a three-phase winding. When single-phase power is fed into a single-phase winding, only a pulsating magnetic field is created. But a rotating magnetic field is created when three-phase power is fed into a three-phase winding.



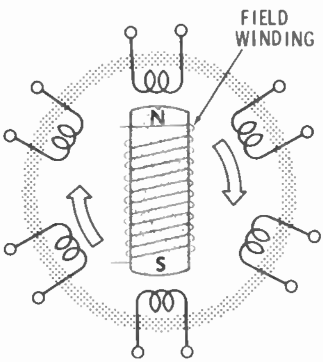
THREE-PHASE CURRENTS

The figure below shows the direction of the magnetic field produced by each phase winding. In the figure at the bottom of the opposite page, the current in phase 1 does not

PRODUCTION OF A ROTATING FIELD



stop suddenly, nor does the current start suddenly in phase 2. In other words, the phase-2 current is increasing at the same time that the phase-1 current is decreasing. In the same way, the phase-1 field does not suddenly disappear, and the phase-2 field does not suddenly appear. The phase-1 field decreases while the phase-2 field increases. The combined field does not jump suddenly from the position shown in part A of the figure above to the position shown in part B. Instead, it moves smoothly from one position to the other as the phase-1 current decreases and the phase-2 current increases. In a similar way, the field moves from the position shown in B to the position shown in C as the phase-2 current decreases and the phase-3 current increases. The magnetic field produced by the three-phase winding rotates just as the field winding in the alternator below rotates.

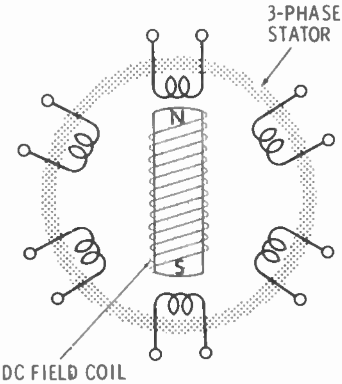


AN ALTERNATOR

SYNCHRONOUS MOTORS

Three-phase synchronous motors are similar in construction to three-phase synchronous generators. Both have a three-phase stator and a DC-powered field coil wound on the rotor. The electrical similarity can be seen from a comparison of the figure below with the figure at the bottom of the opposite page.

THREE-PHASE SYNCHRONOUS MOTOR



As the magnetic field in the stator rotates, the constant DC field rotates to keep aligned with it. As you can see, the speed of this motor depends on how fast the magnetic field rotates. The speed of the magnetic field depends on the frequency of the three-phase AC source. The synchronous motor cannot operate at any speed except that of the rotating field, which is called **synchronous speed.** Synchronous motors are used where it is important to maintain constant speed.

Q1. What sort of magnetic field is created in a single-phase winding fed with a single-phase AC current?

Q2. Three-phase power fed to a three-phase winding creates a _ _ _ _ _ _ _ _ magnetic field.

Q3. The speed of the rotating field produced by a three-phase winding is called _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _.

Q4. What type of three-phase motor is used when it is necessary to maintain a constant speed?

Your Answers Should Be:

A1. A single-phase current in a single-phase winding creates a **pulsating** magnetic field.

A2. Three-phase power fed to a three-phase winding creates a **rotating** magnetic field.

A3. The speed of the rotating field produced by a three-phase winding is called **synchronous speed.**

A4. A three-phase **synchronous** motor is used when constant speed is necessary.

POWER FACTOR

It was explained earlier that the power factor of the load determines how much DC field current an alternator requires to maintain a given output voltage. An inductive load (lagging power factor) causes a large voltage drop due to armature reaction, and a relatively high DC excitation is therefore required to maintain a given voltage. A capacitive load (leading power factor) requires relatively low excitation because the armature reaction strengthens the main field. A resistive load requires a normal amount of excitation.

Something similar to what happens in an alternator happens in a synchronous motor. The power factor of a synchronous motor can be controlled by varying the field current. The amount of DC current required to cause a motor (at a given load) to operate at unity power factor is known as a normal excitation.

If the DC current to the machine is less than the normal value, the motor will operate with a lagging power factor (like an inductor). If the DC current to the machine is higher than the normal value, the motor will operate with a leading power factor (like a capacitor).

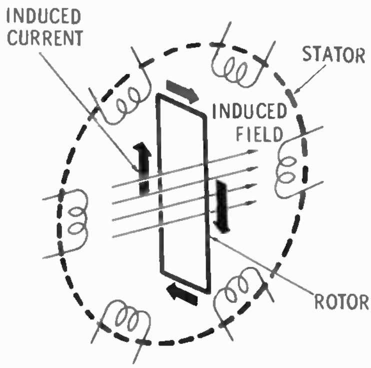
Synchronous motors are often operated at less than rated load but with overexcitation so that they help correct the power factor of a system. When a synchronous motor operates at no load and strictly for the purpose of correcting a system power factor, it is called a **synchronous capacitor.**

POLYPHASE INDUCTION MOTORS

The most important type of polyphase induction motor is the 3-phase motor. Induction motors have two types of rotors, the **wound rotor** and the **squirrel-cage rotor.** The principle of operation is the same for both types.

A basic induction motor has neither slip rings nor a commutator. The rotating three-phase field of the stator induces a voltage in the rotor windings (hence the name induction

BASIC THREE-PHASE INDUCTION MOTOR



motor). This voltage, in turn, creates a large current in the rotor circuit. The current is large because the only resistance opposing it is the resistance of the wires. This high current in the rotor loop creates a magnetic field of its own. The rotor field and the stator field tend to attract each other. This situation creates a torque which spins the rotor in the same direction as the rotation of the magnetic field produced by the stator.

Q5. The power factor of a synchronous motor can be varied by varying the _____ ________.

Q6. A synchronous motor operated without load and used only to provide power-factor correction is called a ____________ __________.

Q7. Current is induced in the rotor of an induction motor by the rotating _________ _____ of the stator.

Q8. Two types of rotors used in induction motors are the _____ rotor and the _________ ____ rotor.

Your Answers Should Be:

A5. The power factor of a synchronous motor can be varied by varying the **field current.**

A6. A synchronous motor operated without load and used only to provide power-factor correction is called a **synchronous capacitor.**

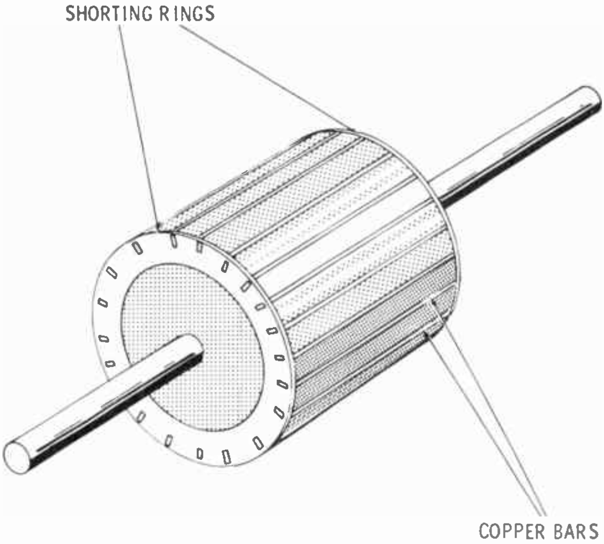
A7. Current is induced in the rotor of an induction motor by the rotating **magnetic field** of the stator.

A8. Two types of rotor used in induction motors are the **wound** rotor and the **squirrel-cage** rotor.

Squirrel-Cage Motors

Squirrel-cage induction motors are extremely rugged and trouble-free machines. They have heavy copper bars around

A SQUIRREL-CAGE ROTOR

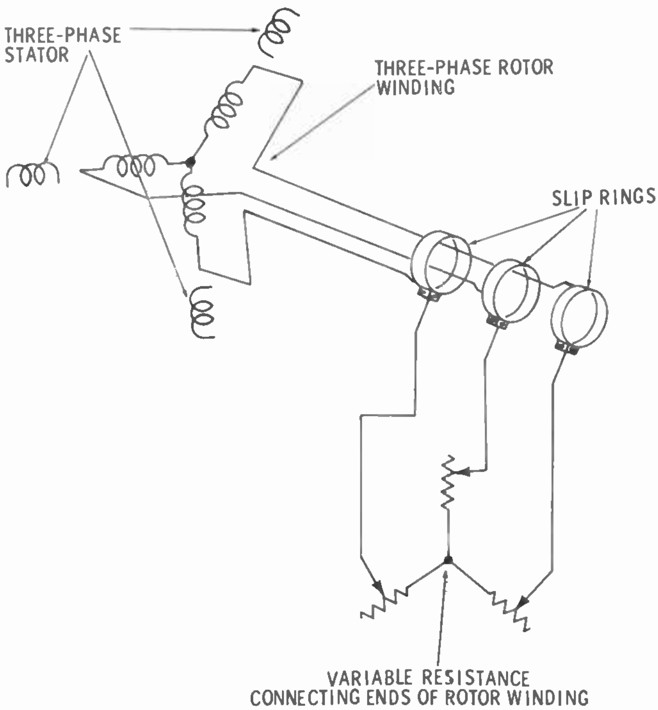


the rotor instead of a wire winding. The winding resembles a squirrel cage, from which it derives its name. The squirrel-cage motor has the advantages of requiring practically no maintenance and of costing much less than a wound-rotor motor.

Wound-Rotor Motors

In the wound-rotor motor, the rotor is not connected to any outside source of power. In order for this type of motor to operate, the terminals of all the rotor windings must be connected together either directly or through a resistor bank. This is accomplished by means of brushes and by slip rings connected to the ends of each winding. In effect, this allows the operator to control the resistance of the rotor windings.

WOUND-ROTOR INDUCTION MOTOR



Q9. In a squirrel-cage rotor, ______ ____ serve as the conductors.

Q10. Name two advantages of squirrel-cage motors.

Q11. Do the brushes feed external power into the rotor of a wound-rotor motor?

Your Answers Should Be:

A9. In a squirrel-cage rotor, **copper bars** serve as the conductors.

A10. Squirrel-cage motors are very rugged and require **almost no maintenance.** They are **relatively inexpensive.**

A11. The brushes **do not feed external power into the rotor** of a wound-rotor motor; they simply connect the ends of the windings.

SLIP

The speed of an induction motor can never be quite equal to synchronous speed. Synchronous speed is the speed of the rotating field (3,600 rpm for 2-pole machines and 1,800 rpm for 4-pole machines if the frequency is 60 cps). If the rotor moved at this speed, no magnetic lines of force would move across its conductors and no voltage would be induced in the rotor. An induction motor cannot be operated at synchronous speed; it can only approach it.

The difference between the synchronous speed of the magnetic field and the actual speed of the motor is called **slip.**

$$\text{Slip} = \text{Synchronous speed} - \text{Actual speed}$$

Percentage of slip in an induction motor is given by the formula:

$$\%\ \text{Slip} = \frac{S_S - S_A}{S_S} \times 100$$

where,

S_S is the synchronous speed in rpm,
S_A is the actual speed in rpm.

For example, what is the slip and the percent of slip in a two-pole, 60-cps induction motor whose speed at full load is 3,450 rpm?

$$\begin{aligned}\text{Slip} &= \text{Synchronous speed} - \text{Actual speed}\\ &= 3{,}600 - 3{,}450 = 150 \text{ rpm}\end{aligned}$$

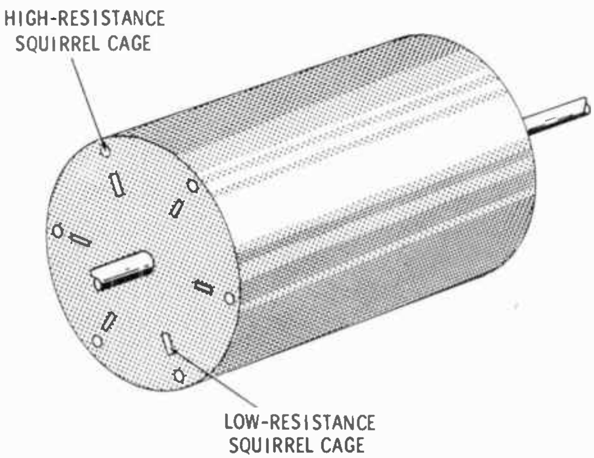
$$\%\ \text{Slip} = \frac{3{,}600 - 3{,}450}{3{,}600} \times 100 = \frac{150}{3{,}600} = 4.16\%$$

In most induction machines the full-load slip varies from 4 to 6%. The number of phases, whether one, two, or three, does not matter when calculating slip values.

The resistance of the rotor circuit can be varied in a wound-rotor motor. The slip depends on this resistance (a greater resistance causes a greater slip). Therefore, it is possible to control the speed of a wound-rotor motor by choosing the proper resistance bank in the rotor circuit. When starting induction motors which have a load attached at all times (such as a flywheel), maximum starting torque can be provided by varying the resistance of the wound rotor to the correct value.

A **double-squirrel–cage** motor takes advantage of the same effect to obtain improved starting torque. This type of motor has two separate squirrel-cage windings. One has a high resistance to provide good starting torque. The other has a

BASIC CONSTRUCTION OF A DOUBLE-SQUIRREL-CAGE ROTOR



Q12. What is synchronous speed?

Q13. What is slip?

Q14. If a four-pole motor is supplied from a 60-cycle source and operates at 1,750 rpm, what is the percentage of slip?

Q15. The speed and torque of an induction motor can be controlled by varying the ---------- of the rotor circuit.

Your Answers Should Be:

A12. Synchronous speed is the **speed of the rotating magnetic field.**

A13. Slip is the **difference** between the **synchronous speed** and the **actual speed** of the motor.

A14. Synchronous speed for a four-pole, 60-cycle motor is 1,800 rpm.

$$\% \text{ Slip} = \frac{1{,}800 - 1{,}750}{1{,}800} \times 100 = 2.8\%$$

A15. The speed and torque of an induction motor can be controlled by varying the **resistance** of the rotor circuit.

SINGLE-PHASE AC MOTORS

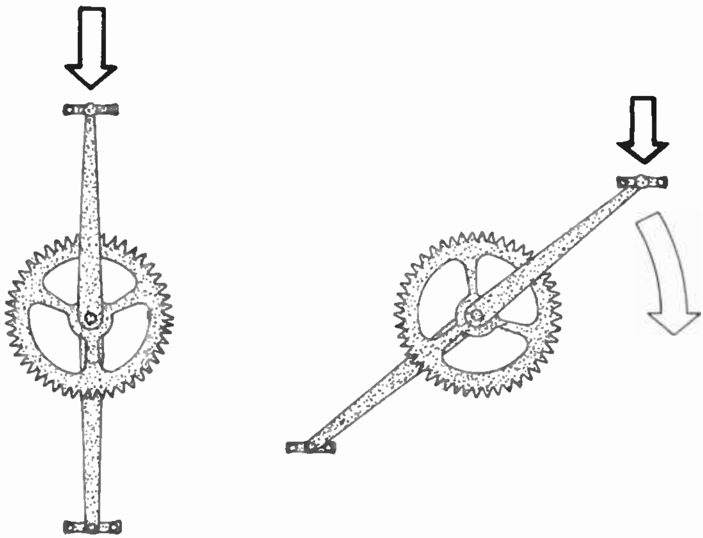
Single-phase AC motors are usually limited in size to about two or three horsepower. There are many different types found in almost every household and industrial building. In the home there are single-phase motors in air conditioners, air heaters, refrigerators, sewing machines, fans, ventilating units, and many other household appliances.

Since they have so many uses, there are many different types of single-phase motors. Some of the more common types are repulsion, universal, and single-phase induction motors. Single-phase induction motors include shaded-pole, split-phase, capacitor, and repulsion-induction motors.

Single-Phase Induction Motors

Single-phase induction motors have no means of starting by themselves. In a single-phase motor the field of the stator windings does not rotate as it does in a three-phase induction motor. The magnetic field set up in the stator by the AC power supply stays lined up in one direction. This magnetic field, though stationary, pulsates as the voltage sine wave does. The pulsating field induces a voltage in the rotor windings, but the rotor field can only line itself up with the stator field. Therefore, since the stator field is stationary, the rotor field is also stationary. Before it can start, the rotor must be turning so that there is, in effect, some slip and the two fields are not exactly lined up.

The single-phase induction motor acts much like the pedals of a bicycle. When the pedals are exactly lined up with the direction of the up-and-down motion of the rider's feet, the pedals will not turn. Once a slight turn has started them, inertia carries the pedals past the center point, and the pulsating up-and-down motion keeps the rotating motion going.



It is necessary then to find some means of giving the single-phase AC motor a means of starting the rotor into motion. Once the rotor is spinning at a reasonable rpm, its inertia will carry it through the dead-center position so that it will be kept rotating by the stationary field. An auxiliary starting system is required. The starting methods make up the primary differences between induction-motor types.

Q16. What is the largest size in which single-phase motors are usually made?

Q17. Name the three types of single-phase motors.

Q18. What are four types of single-phase induction motors?

Q19. The magnetic field of a single-phase motor (does, does not) rotate.

Your Answers Should Be:

A16. The largest size in which single-phase motors are usually made is **two to three horsepower.**

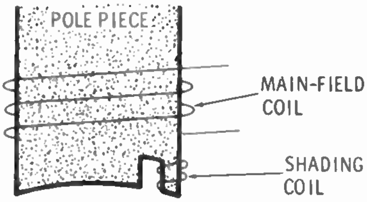
A16. Three types of single-phase motor are the **repulsion, universal,** and **single-phase induction** motor.

A18. Single-phase induction motors include **shaded-pole, split-phase, capacitor,** and **repulsion-induction** motors.

A19. The magnetic field of a single-phase motor **does not** rotate.

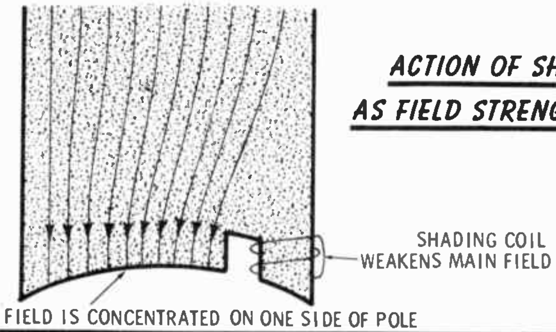
Shaded-Pole Motors

Shaded-pole motors are usually very small. They have a constant speed, and are usually in a size range of about 1/50 HP. The stator windings are arranged as shown below.



STATOR WINDINGS IN A SHADED-POLE MOTOR

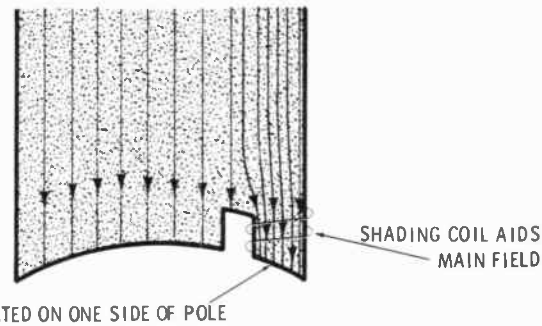
The shading coil is short-circuited. As the field in the pole piece builds up, a current is induced in the shading coil. This current causes a magnetic field that opposes the main field. The main field will therefore concentrate on the oppo-



ACTION OF SHADING COIL AS FIELD STRENGTH INCREASES

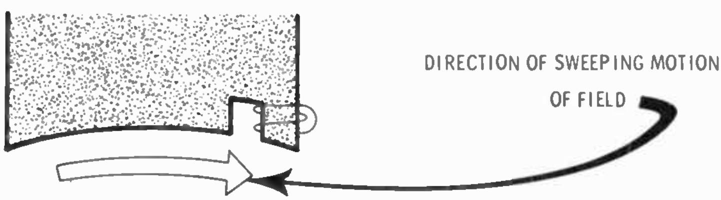
site side of the pole piece. The result is that the field in the part of the pole piece inside the shading coil reaches a maximum intensity later than the rest of the field. As the field in the part of the pole opposite the shading coil begins to decrease, the shading-coil field will start aiding the main field, and the concentration of flux moves to the other edge of the pole piece. The resulting field in the part of the pole piece inside the shading coil reaches zero after the main field.

ACTION OF SHADING COIL AS FIELD STRENGTH DECREASES



The effect of the shading coil is to produce a small sweeping motion of the main field from one side of the pole piece to the other as the field pulsates. This slight rotating motion is enough to start the motor.

APPARENT MOTION OF FIELD PRODUCED BY SHADING COIL



Q20. Shaded-pole motors usually have _____ horsepower ratings.

Q21. The field in the part of the pole piece inside the shading coil reaches maximum _____ the rest of the field.

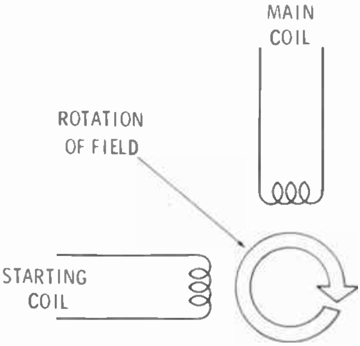
Your Answers Should Be:

A20. Shaded-pole motors usually have **small** horsepower ratings.

A21. The field in the part of the pole piece inside the shading coil reaches maximum **after** the rest of the field.

Split-Phase Motors

Split-phase motors usually have ratings of ¾ HP or less. They have two separate coils—a main coil of large wire and a starting coil of small wire. Both coils are placed in the motor in the same positions they would have if the machine were a two-phase motor. If the coils have the same number of turns, they have the same inductance. However, the starting coil has a higher resistance because it is wound with smaller wire. When the same voltage is applied to both windings, the current in the main coil lags behind the current in the starting coil. The two windings produce a rotating field in much the same way that a rotating field is produced in a two-phase motor. This rotating field causes the motor to start.



PRINCIPLE OF THE SPLIT-PHASE MOTOR

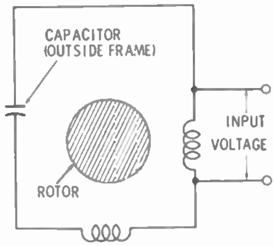
If used to run the motor, the starting winding is likely to burn out because of the small wire from which it is made. For this reason, a centrifugally operated switch is used to disconnect the starting winding when the motor reaches about 60% of operating speed.

Capacitor Motors

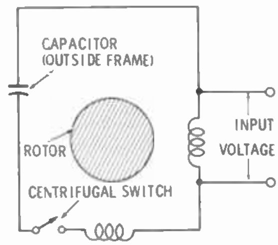
Capacitor motors have two stator windings. A large capacitor is connected in series with one of the windings. The single-phase input voltage produces two currents (one in each winding). One current is shifted out of phase with the applied voltage by the capacitor. This creates a starting torque similar to that of a two-phase motor.

Capacitor-Start, Capacitor-Run Motor—In this type of motor the starting capacitor stays in the system at all times. This type of machine is made in sizes from ⅛ to 10 HP. It has a relatively high power factor.

CAPACITOR MOTORS



Capacitor-Start, Capacitor-Run



Capacitor-Start With Centrifugal Switch

Capacitor-Start Motor—This motor starts with a capacitor in series with one of the windings. At about 75% of full speed a centrifugal switch opens the capacitor-winding circuit, and the motor operates as a single-phase inductor motor. This type is made in sizes from ⅛ to ¾ HP.

Two-Value, Capacitor-Start, Capacitor-Run Motor—This type combines the features of both capacitor-start and capacitor-start, capacitor-run motors. It has two capacitors in series with one winding and a centrifugal switch which cuts out one capacitor at about 75% of full speed. This type of machine has ratings from ⅛ to 10 HP. It has many industrial applications.

Q22. The various starting methods for single-phase induction motors all create a _________ magnetic field.

Q23. Why is a centrifugal switch used in a split-phase motor?

Your Answers Should Be:

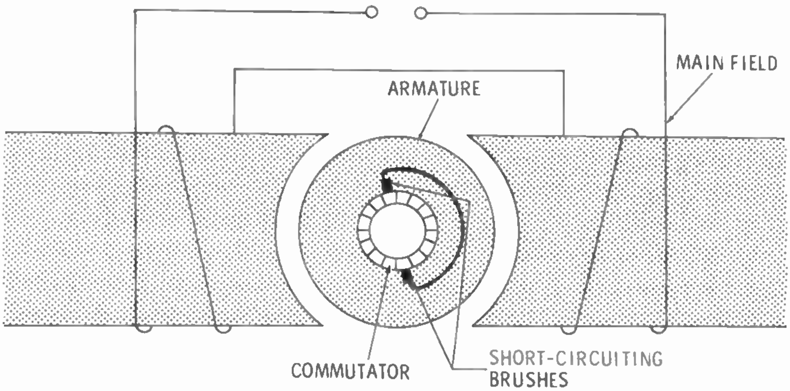
A22. The various starting methods for single-phase induction motors all create a **rotating** magnetic field.

A23. The **starting winding** of a split-phase motor would overheat if left connected. The centrifugal switch **disconnects the starting winding** when the motor reaches about 60% of full speed.

Repulsion Motors

The **repulsion motor** has an armature and commutator similar to that of a DC machine. The two brushes are connected by a low-resistance wire.

REPULSION-INDUCTION MOTOR



The stator windings (actually two windings in series) produce a current in the rotor windings by induction. This current produces magnetic poles in the rotor, their location depending on the position of the brushes. When the field of the rotor is at an angle with the main field, a torque is created by the interacting fields. The rotor moves in a direction to turn its field away from the main field, but as it moves, the brushes come into contact with a different pair of commutator segments and shift the field back.

There is no starting problem in a repulsion motor. They have good starting torque and are used where heavy starting loads are expected.

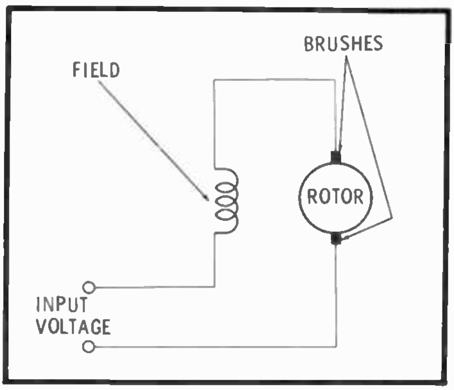
Repulsion-Induction Motors

The **repulsion-induction motor** has a wound rotor with a commutator. Shorting brushes make contact with the commutator, and the motor starts as a repulsion motor. As the motor nears full speed, a device short-circuits all the commutator bars. The motor then runs as an induction motor and operates at nearly constant speed. Its speed cannot be adjusted. This type of motor is made in sizes ranging from ½ HP to 10 HP.

Universal Motors

One of the most versatile motors is the **universal motor** which operates on either DC or single-phase AC. These machines have high starting torque and high slip. They are usually in the fractional-horsepower range and are used in small appliances, electric drills, etc.

UNIVERSAL MOTOR



As you recall, a DC series motor will continue to turn in the same direction if the line connections are reversed. A series DC motor will therefore work on AC. In fact, a universal motor is simply a DC series motor whose windings and pole pieces are designed to operate efficiently with AC power.

Q24. A repulsion motor (does, does not) have a commutator.

Q25. Repulsion motors have a ____ starting torque.

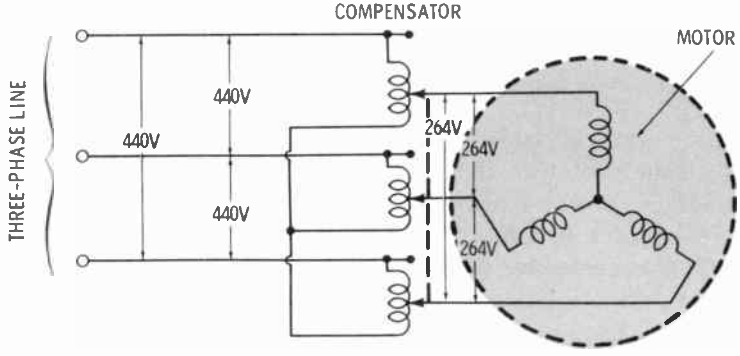
Q26. A universal motor can be operated on both __ and __.

Your Answers Should Be: A24. A repulsion motor **does** have a commutator. A25. Repulsion motors have a **high** starting torque. A26. A universal motor can be operated on both AC and DC.

INDUCTION-MOTOR STARTING

When voltage is first applied to a three-phase induction motor, the current drawn is sometimes six or seven times higher than the normal running current. However, this current decreases rapidly as the machine gathers speed. In the case of a squirrel-cage induction motor, the starting current will not usually damage the motor itself, but it may create an undesirable voltage fluctuation in the power system. It is therefore customary when starting to apply full rated voltage only to the smaller squirrel-cage induction motors. Reduced starting voltage is applied to the larger-sized machines. The reduced voltage can be applied by means of an autotransformer, a series resistor, or a series reactor.

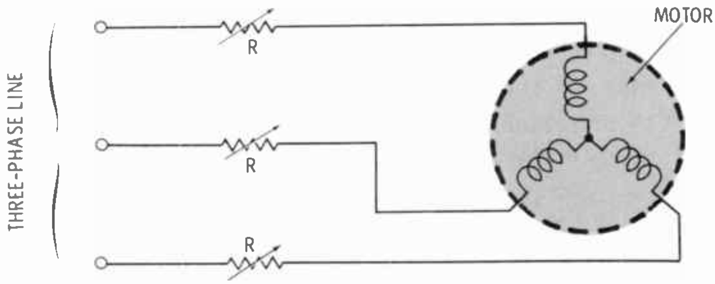
STARTING A SQUIRREL-CAGE MOTOR WITH A COMPENSATOR



The autotransformer method is shown above. The group of autotransformers used to limit starting current is called a **compensator.** When the motor reaches running speed, the compensator is bypassed and the full voltage is applied. The autotransformer will dissipate almost no power. (Only a negligible amount will be dissipated by the resistance of its windings.)

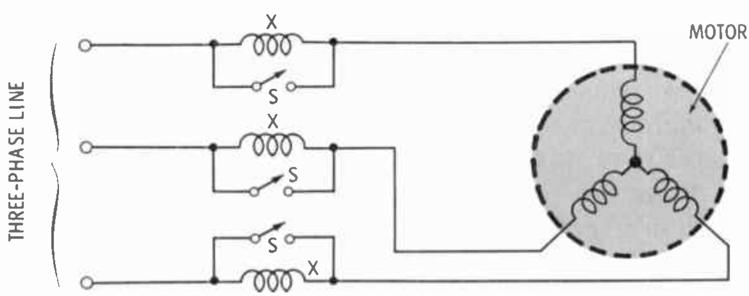
Another method of starting is to insert a resistor in series with each of the three motor windings, as shown below. The resistors will dissipate power.

STARTING A SQUIRREL-CAGE MOTOR WITH RESISTORS



A third method of starting a squirrel-cage motor is to use series coils (reactors). A coil with relatively high inductive reactance is inserted in series with each of the motor coils as shown below. When the motor has picked up speed, the switches are closed to bypass the reactors.

STARTING A SQUIRREL-CAGE MOTOR WITH INDUCTORS



Q27. Name three methods of limiting the starting current in an induction motor.

Q28. Would a ¼-horsepower, single-phase, squirrel-cage induction motor normally require a starter?

Your Answers Should Be:

A27. The starting current in an induction motor can be limited by using **compensators** (autotransformers), **series resistors,** or **series reactors** (coils).

A28. A ¼-horsepower, single-phase, squirrel-cage induction motor **normally requires no starter.**

WHAT YOU HAVE LEARNED

1. When three-phase power is supplied to a three-phase winding, a rotating magnetic field is created.
2. A synchronous three-phase motor has a DC-excited field that interacts with the rotating field created by the three-phase AC power supply and causes the rotor to turn at the same speed as the magnetic field.
3. Synchronous motors are used to provide constant speeds.
4. The power factor of a synchronous motor varies according to the amount of DC excitation. When the DC field current is below normal, the motor has a lagging power factor and behaves as an inductor. When the DC field current is at the normal excitation value, the machine presents a purely resistive load and has a power factor of one (unity). When the DC field current is above the normal excitation value, the motor has a leading power factor and acts as a capacitor.
5. In a polyphase induction motor, the rotating magnetic field induces a current in a short-circuited rotor winding, and motor action occurs when the field created in the rotor interacts with the main field.
6. There are two types of polyphase induction motors—squirrel-cage and wound-rotor.
7. A squirrel-cage motor has a rotor winding composed of copper bars embedded in the iron rotor core. A wound rotor has conventional wire windings.
8. Squirrel-cage motors are rugged and require very little maintenance. Therefore, they are relatively inexpensive.
9. An induction motor cannot operate at synchronous

speed. The difference between the speed of the rotating magnetic field and the motor speed is called slip.

10. The greater the resistance of the rotor winding of an induction motor, the greater is the slip.
11. Wound-rotor induction motors have a variable rotor resistance that is controlled by the operator and connected to the rotor through slip rings and brushes.
12. Single-phase induction motors must have some arrangement to create a rotating magnetic field for starting the machine. Single-phase induction motors are classified according to the starting method used.
13. Shaded-pole motors create a rotating-field effect by means of a short-circuited shading coil on one edge of the pole piece. This coil produces a field that first weakens and then aids the main field.
14. Split-phase motors have a high-resistance starting winding whose current and field are more nearly in phase with the applied voltage than those of the main winding. The combined field of the two windings creates a rotating-field effect.
15. A centrifugal switch is used to disconnect the high-resistance starting winding after a split-phase motor has picked up speed. This is done so that the starting winding will not burn out.
16. Capacitor motors use capacitors in series with one of the windings to produce a phase shift similar to that of a split-phase motor.
17. Capacitor-start, capacitor-run motors keep the capacitive winding in the circuit at all times. Capacitor-start motors have a centrifugal switch to disconnect the capacitive winding after the motor has started.
18. Repulsion motors have a wound rotor and a commutator that is short-circuited by brushes. This motor has a high starting torque.
19. A universal motor is similar to a series DC motor.
20. Starting current for large induction motors is limited in one of three ways—with a compensator (autotransformers), with series resistors, or with series reactors.

6

Three-Phase Systems

What You Will Learn

In this chapter you will learn how three-phase power is generated and distributed. You will become acquainted with the various ways in which three-phase alternators, motors, and transformers can be connected. You will be able to tell the difference between line voltage and current and phase voltage and current, and you will learn how to find one if the other is known. You will also learn how to calculate and measure power in three-phase systems.

THREE-PHASE GENERATION AND DISTRIBUTION

Throughout the world, power plants produce huge quantities of electrical power in order to supply the ever increasing requirements for light, electric heating, and heavy industry. Nearly all of this power originates from three-phase generators. The voltage is stepped up by transformers for transmission and further transformed to lower and higher voltages according to need. The power is eventually used in either three-phase or single-phase devices.

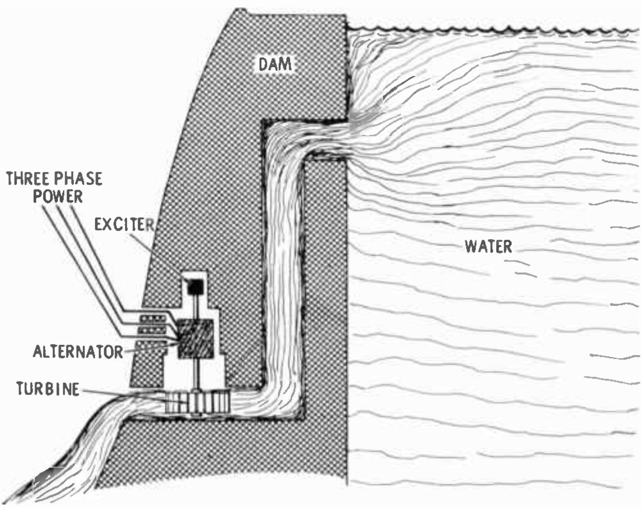
Voltages and frequencies are usually standardized. In the United States, for example, the frequency is 60 cycles per second for the major portion of the country. A frequency of 25 cps was quite common at the beginning of this century, and a few 25-cps units are still in operation. In Europe, both 50 cps and 60 cps frequencies are used, but the trend is toward adopting a uniform 60-cps frequency.

The great majority of the generators producing three-phase power are synchronous generators. This type is chosen because of its very high efficiency—as high as 99% for very large units—and for its ability to maintain a very steady voltage and frequency output.

All large power-generating systems have three basic components—a prime mover, a three-phase alternator, and a DC field exciter. The prime mover provides the mechanical power necessary to turn the rotor of the alternator and the exciter. Hydraulic turbines (driven by falling water), steam turbines, and Diesel engines are all possible prime movers. Steam and hydraulic turbines are the most common.

The three-phase alternator produces three-phase electricity at a given voltage and frequency. The voltage output may be varied to some extent by changing the DC excitation value, and the frequency may be varied by changing the speed of the rotor. Voltage and frequency regulating equipment is used to keep these quantities constant.

The DC field excitation provides control of the output voltage. The DC is monitored and controlled by a voltage regulator. The DC generator is usually mounted directly on the same shaft as the alternator or coupled to the alternator shaft by a belt drive.

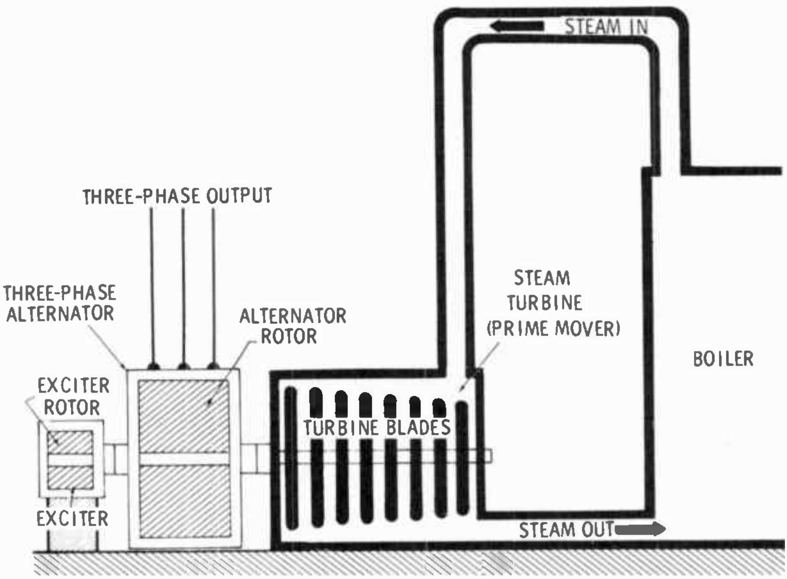


HYDROELECTRIC GENERATING PLANT

Water-driven generators are operated at low speeds. A typical speed is 200 rpm. Falling water enters the turbine case and spins the turbine which is connected to a shaft. This shaft rotates the alternator and exciter rotors. All units are usually mounted vertically. Such a generating system is called a **hydroelectric** plant.

The speed of a steam-driven generator is normally 3,600 rpm (for 60 cps). Some generators operate at 1,800 rpm, although these are less common. In a steam-generator plant, the components are arranged horizontally. Steam from an oil- or coal-fired boiler system, or from a system heated by an atomic reactor, is piped to the turbine. The steam expands and pushes against the blades, causing the turbine shaft to rotate. The shaft turns the rotors of the alternator and exciter.

STEAM GENERATOR PLANT



Q1. The standard frequency for AC in most of the world is __ ___.

Q2. Three essential parts of a generating system are the _____ _____, __________, and _______.

Your Answers Should Be:

A1. The standard frequency for AC in most of the world is **60 cps.**

A2. Three essential parts of a generating system are the **prime mover, alternator,** and **exciter.**

Transmission of Power

After power is generated at the power plant, the voltage is usually stepped up for transmission. Voltages such as 69,000V are common. By stepping the voltages up to these high values, it is possible to transmit large amounts of power with relatively low currents. The low currents can be carried by smaller wires in the transmission lines. Less copper is needed and less power is lost. (Power loss in a line is equal to I^2R.) As you will see, three-phase power lines use less copper than lines designed to carry the same amount of single-phase power at the same voltage.

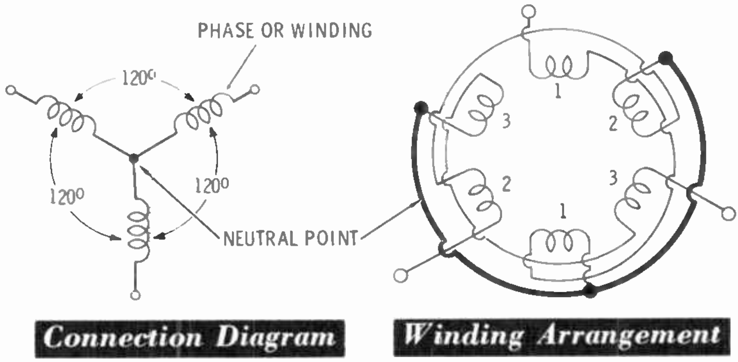
For most household uses the three-phase power is finally split up into single-phase, 120-volt AC. For many industrial applications, it is used as three-phase power. For example, three-phase power is used to drive three-phase induction and synchronous motors. The winding connections used in three-phase alternators, transformers, and motors make it possible to transmit power with four or even three conductors. Since these systems of winding connections appear wherever three-phase power is used, it is important for you to understand them.

WYE CONNECTION

The **wye-connected** system is probably the most common type of three-phase connection. The wye connection is also called a **star connection.** It is usually diagrammed as shown on the next page. Generators, motors, transformer windings, capacitors, resistors, etc., can all be connected in the same arrangement. Each phase is 120 electrical degrees away from the other two phases. The diagram resembles the letter Y, from which the name "wye" was taken.

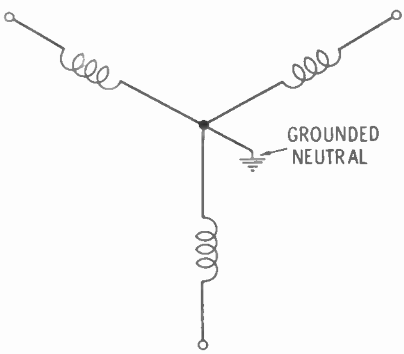
The three windings in a wye connection are not only 120 electrical degrees apart, but they are also connected to a single common point. The ends of the three arms of the Y represent the three external ends of the windings. The center of the Y represents the three ends that are connected together and is called the **neutral point** or **common point.**

WYE CONNECTION



The neutral point is normally grounded (connected to the earth or a large mass of metal), in which case the wye connection is as shown below. This system is called a three-phase, four-wire wye connection.

WYE CONNECTION WITH GROUNDED NEUTRAL



Q3. Why is the generator voltage stepped up before power is transmitted?

Q4. In a wye connection, one end of each phase or wind- is connected to the _______ point.

Q5. The neutral point is usually ________.

Your Answers Should Be:

A3. High transmission voltages are used so that power can be transmitted with **lower currents.**

A4. In a wye connection, one end of each phase or winding is connected to the **neutral** point.

A5. The neutral point is usually **grounded.**

Voltage in a Wye-Connected System

In the case of a wye-connected generator with grounded neutral, there are several voltages that can be measured at its outputs. These voltages are shown in the diagram below and are as follows:

E_{AB}—The voltage between A & B

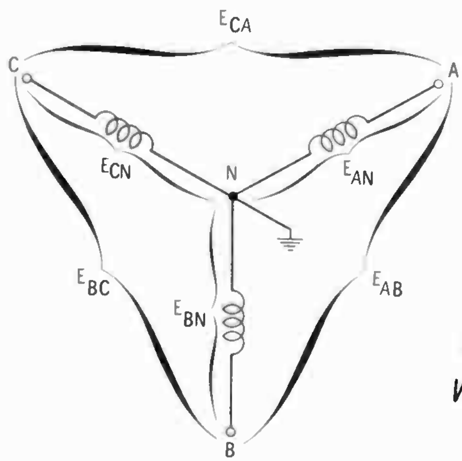
E_{CA}—The voltage between C & A

E_{BC}—The voltage between B & C

E_{AN}—The voltage between A & neutral (N)

E_{BN}—The voltage between B & neutral

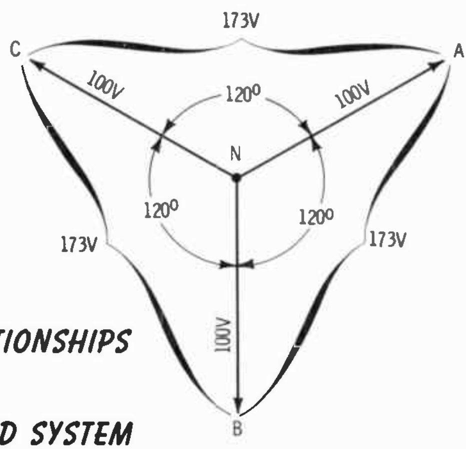
E_{CN}—The voltage between C & neutral



VOLTAGES IN A WYE-CONNECTED SYSTEM

In most cases, the voltages between each phase terminal and the neutral are equal. Thus, $E_{AN} = E_{BN} = E_{CN}$. The voltages between any two phases will then also be equal. Thus, $E_{AB} = E_{BC} = E_{CA}$.

The diagram below indicates how the voltages add. Just as the distance from A to B is greater than the distance from A to N, the voltage between A and B is greater than that between A and N, and so on. The voltage between any one phase terminal and the neutral (say E_{AN}) is considerably lower than any phase-to-phase voltage (say E_{AB}).



VOLTAGE RELATIONSHIPS IN A WYE-CONNECTED SYSTEM

The phase-to-phase voltage is the between-the-lines voltage, or simply the **line voltage.** The voltage between a line and the neutral is the **phase voltage.** Because of the phase relationships, the line voltage is 1.73 times the phase voltage in a wye-connected system if the phase voltages are equal.

Q6. The voltage between any two lines of a wye-connected, three-phase transmissions system is called the ____ _______.

Q7. The voltage between one line and ground is called the _____ _______.

Q8. How are these voltages related?

Your Answers Should Be:

A6. The voltage between any two lines of a wye-connected, three-phase transmission system is called the **line voltage.**

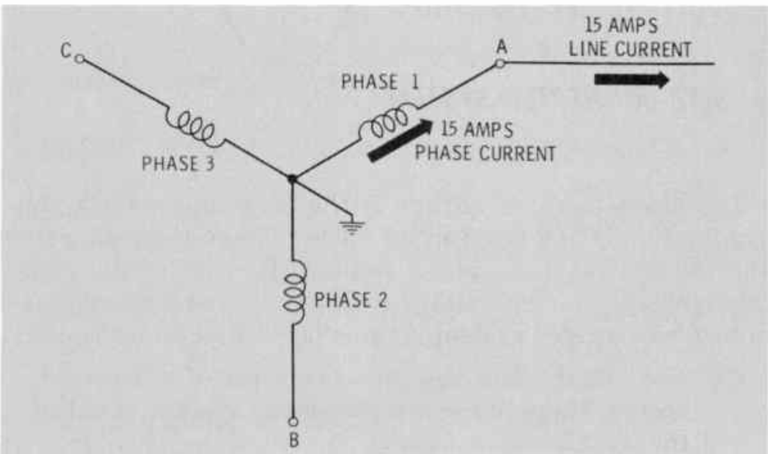
A7. The voltage between one line and ground is called the **phase voltage.**

A8. The line voltage **in a wye-connected system** is 1.73 **times the phase voltage** if the phase voltages are **all equal.**

Current in a Wye-Connected System

The current flowing in a given line is called the **line current.** The current flowing through any one winding is the current in a single phase and is called the **phase current.**

The same current that flows through a line also flows through the windings to which it is connected in the wye system. Thus, the line current is equal to the phase current in a wye system. Note that this relationship applies to each phase individually. The current in one line does not necessarily equal the current in another phase.



CURRENT RELATIONSHIPS IN A WYE-CONNECTED SYSTEM

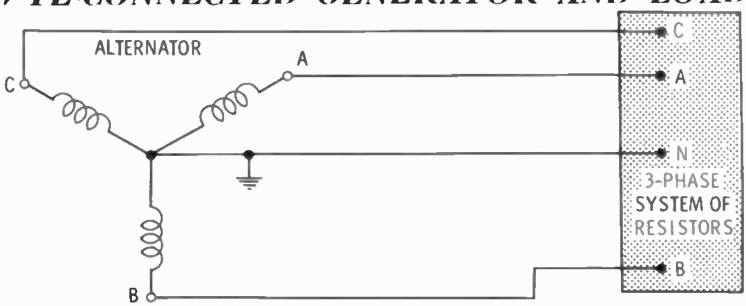
Summary of Wye-Connected Systems

If a three-phase, wye-connected system is operating in the normal way, and if the phase voltage from A to N is 100V rms, the voltages from B to N and C to N will also be 100V rms. The line voltage from A to B will be 1.73 times the phase voltage, or 173V rms. Line voltages from A to C and from B to C will also be 173V rms. If the current through line A is 15 amps, the phase current through winding A will also be 15 amps.

Note that the **effective** values of voltage and current are usually used. These are the rms values (also called the root-mean-square values). The rms values determine how much power is dissipated. The same relationships between line and phase voltage and between line and phase current are also true if you wish to consider peak values. Remember that when comparing voltages or currents they must all be in the same units (peak, rms, etc).

Here is a typical problem. Suppose a resistive load, as shown below, is supplied power from a three-phase, wye-connected alternator. The voltage between A and C is 208V and the current in each line is 10 amperes.

WYE-CONNECTED GENERATOR AND LOAD



Q9. What is the line voltage in this system?

Q10. What is the phase voltage?

Q11. What is the line current?

Q12. What current flows through the alternator windings?

Q13. What is the power used in each single-phase circuit in this system?

Q14. What is the total power in all three phases?

Your Answers Should Be:

A9. The line voltage is **208V.**

A10. The phase voltage is the **line voltage divided by 1.73.**

$$\frac{208V}{1.73} = 120V$$

A11. The line current is **10 amps.**

A12. The line current of **10 amps** flows through the alternator windings.

A13. The power in each single-phase circuit is E × I × power factor.

$$120 \times 10 \times 1 = 1{,}200 \text{ watts}$$

A14. Since there are three single-phase circuits, the total three-phase power is 3 × 1,200 = 3,600 watts.

Balanced Loads

In the preceding example, all three line currents (and all phase currents) were equal. When **all 3 currents** in the lines **are equal** and are 120 electrical degrees apart, the load is said to be **balanced.**

When a load is balanced, the three currents meet at the neutral point of the load and at the neutral point of the generator and cancel. This cancelling effect is due to the phase relationships of the currents to each other. As long as all three are equal, there is no current in the neutral wire.

If the load is not balanced, current will flow in the neutral wire. The amount depends on the amount of current in each line and the phase relationships of the line currents to each other. It is always good practice to balance the load in any three-phase system when it is possible.

Power

You have found the power in a three-phase, wye-connected system with a balanced resistive load. This was done by multiplying phase current times phase voltage for each phase and then adding to find the total power.

Of course, if the load is inductive or capacitive, you must also multiply by the power factor. The formula for finding the power in any kind of balanced load in a wye-connected, three-phase system is:

$$P_T = I_p \times E_p \times 3 \times \cos\theta$$

where,

P_T is the total power,
I_p is the phase current,
E_p is the phase voltage,
$\cos\theta$ is the power factor.

There is also another way of finding power in a three-phase, wye-connected system with a balanced load. Since the phase voltage is always equal to the line voltage divided by 1.73, then:

$$P_T = \frac{\text{line voltage} \times \text{line current} \times 3 \times \text{power factor}}{1.73}$$

Note that line current is the same as phase current and also that 1.73 is the square root of 3. Therefore, $\frac{3}{1.73} = 1.73$. When the formula is simplified, it becomes:

$$P_T = I_L \times E_L \times 1.73 \times \cos\theta$$

where,

P_T is the total power,
I_L is the line current,
E_L is the line voltage,
$\cos\theta$ is the power factor.

Q15. Is the load balanced in a three-phase, wye-connected system whose line currents are 10 amps, 10 amps, and 15 amps?

Q16. In the system in Question 15, will there be any current in the neutral wire?

Q17. A balanced, wye-connected, three-phase system has a line voltage of 208V and a line current of 5 amps. The power factor of the load is 0.8. What is the total power supplied to the load? What is the current in the neutral?

Your Answers Should Be:

A15. If the currents are not equal, **the load is not balanced.**

A16. There will **be current** in the neutral wire.

A17. $P_T = I_L \times E_L \times 1.73 \times \cos\theta$

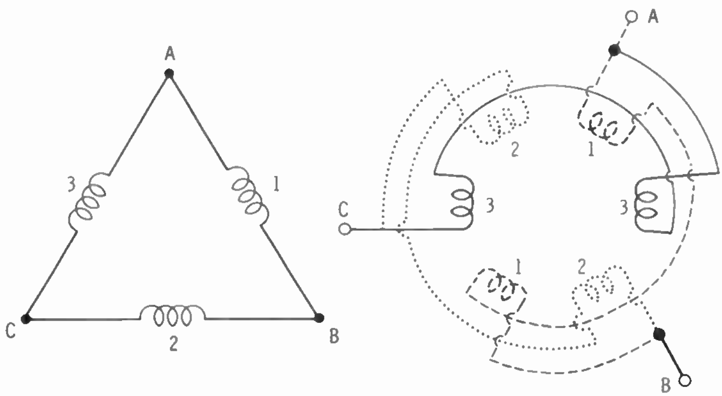
$P_T = 5 \times 208 \times 1.73 \times 0.8 = 1439$ **watts**

The load is balanced, so the **current in the neutral is zero.**

DELTA CONNECTION

The three-phase, **delta-connected** system gets its name from the appearance of the diagram of its connections. Delta is the name of the Greek letter Δ.

DELTA CONNECTION



The windings are connected end to end in a sort of loop. When the system is properly balanced, almost no current flows around the loop because of the phase differences of the voltages. The delta-connected system has no neutral point. Delta-connected systems are not usually grounded.

The wye connection is essentially a series connection. The phase voltages combine to produce a higher line voltage because the line voltage is developed across two windings in series. The phase current and line current are the same. The delta connection, however, is essentially a parallel connection. The line voltage is simply the voltage developed across an individual winding, so the line voltage is equal to the phase voltage. The currents from two windings combine to give the line current. The amount of the line current depends on both the amount of the phase currents and the phase difference between them. If the load is balanced and the voltages are equal, the line current is 1.73 times the phase current.

In a balanced delta-connected system, the power can be found by multiplying phase voltage times phase current times the number of phases times the power factor:

$$P_T = I_P \times E_P \times 3 \times \cos\theta$$

The line voltage is equal to the phase voltage. The phase current is equal to the line current divided by 1.73. This leads to the following formula:

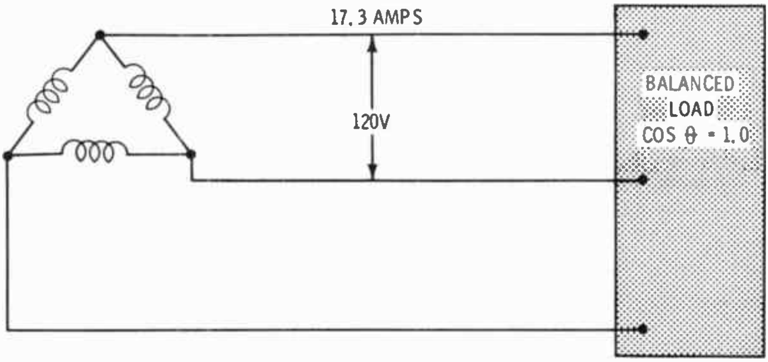
$$P_T = I_L \times E_L \times 1.73 \times \cos\theta$$

where,

P_T is the total power,
I_L is the line current,
E_L is the line voltage,
$\cos\theta$ is the power factor.

Note that the two power formulas for delta-connected systems are the same as the two for wye-connected systems.

Q18. For the circuit below, what is the line voltage, line current, phase voltage, phase current, and total power?



> **Your Answers Should Be:**
>
> **A18.** Line current, **17.3 amps**; line voltage, **120V**
> Phase current, **10 amps**; phase voltage, **120V**
> Power $= I_L \times E_L \times 1.73 \times 1 =$ **3,600 watts**
> or $I_P \times E_P \times 3 \times 1 =$ **3,600 watts**

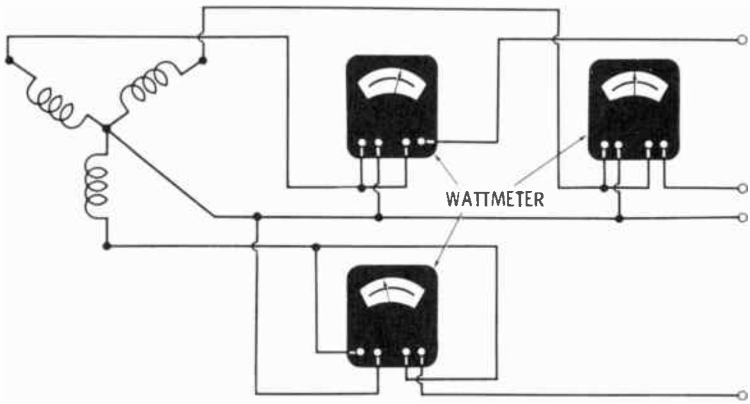
POWER MEASUREMENT

So far, you have learned how power is calculated but not how it is measured. In practical cases, all the information needed to calculate power may not always be available. The power factor of the load may be unknown, the load may not be balanced, or the voltage may fluctuate. In many cases, therefore, it may be necessary to measure power with a wattmeter.

Wattmeters have as inputs the factors one needs to know in order to calculate power—voltage and current. In effect, a wattmeter measures I and E and then calculates P mechanically. A wattmeter has a series connection to the line to measure current and a shunt connection to measure voltage. On power circuits, the wattmeter is connected to the main lines by a set of special instrument transformers which step down the voltage and current to safe values.

The Three-Wattmeter Method

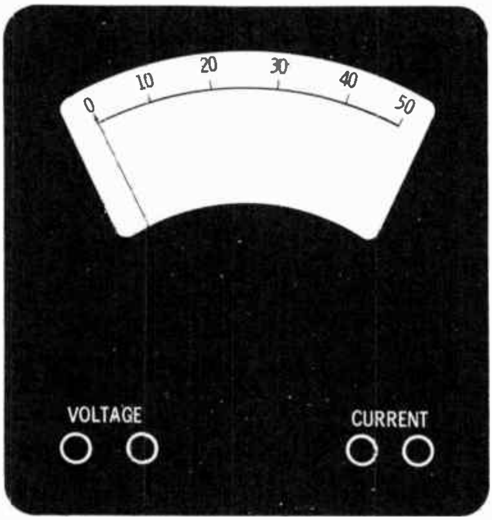
The three-wattmeter method is used primarily with three-phase, four-wire circuits. It can measure power in both bal-



anced and unbalanced systems. Three wattmeters are simply used to measure the power in all three phases. A typical connection is shown at the bottom of the opposite page.

In the three-wattmeter method, each wattmeter measures a separate phase. The meter receives as inputs the phase

A SIMPLE WATTMETER



voltage and phase current and gives a reading indicating phase power. In order to find the total power, add all three readings directly.

Q19. The power in a three-phase, four-wire, wye-connected system is measured by the three-wattmeter method. The individual meter readings are as follows for different loads. Find the three-phase power values. Which load is balanced?

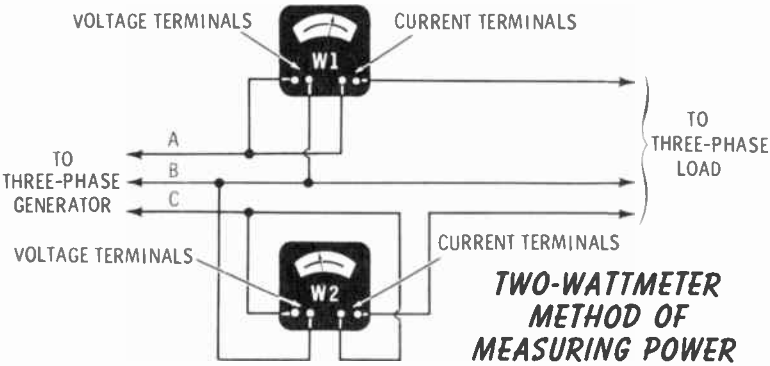
	W_1	W_2	W_3
A	30W	40W	20W
B	20W	20W	20W
C	60W	60W	20W

Your Answers Should Be:

A19. (A) $P_T = 30 + 40 + 20 = 90W$
(B) $P_T = 20 + 20 + 20 = 60W$
(C) $P_T = 60 + 60 + 20 = 140W$
Only B is balanced since all its readings are equal.

The Two-Wattmeter Method

The two-wattmeter method employs line voltages and line currents and is suitable for either wye or delta connections. The two-wattmeter method can be used to measure power in both balanced and unbalanced circuits.



TWO-WATTMETER METHOD OF MEASURING POWER

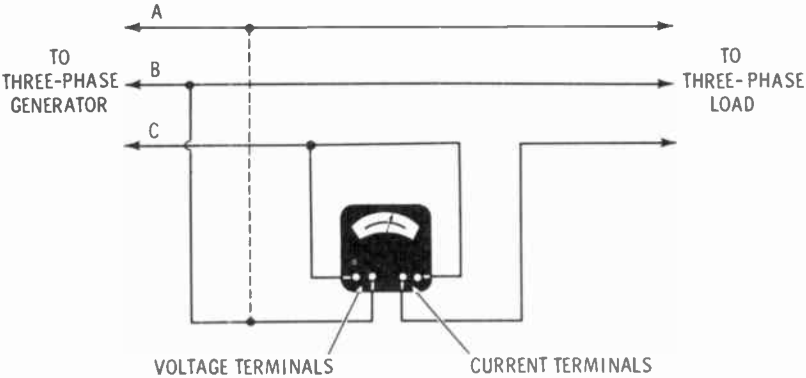
Total power is found by adding the two readings shown on the wattmeters. If the power factor of the load is less than 0.5, the wattmeter readings must be subtracted to obtain the total power. The sum (or difference) of the meter readings gives the total power because of the phase relationships of the voltages and currents in the three-phase system.

You can make a test to determine whether the power factor is less than 0.5. Connect the wattmeters as shown and so that both give an up-scale reading. (If the pointer of one of the wattmeters moves in the wrong direction, the voltage leads of this wattmeter must be reversed to obtain a reading.) Then temporarily move the voltage lead of W1 from line B to line C. (Or move the lead of W2 from line B to line A.) If the wattmeter then moves down-scale, the power factor is less than 0.5, and the smaller reading must be subtracted from the larger reading.

The One-Wattmeter Method

If the three-phase load is **balanced**, one wattmeter can be used to measure the total power as shown below. A reading

ONE-WATTMETER METHOD OF MEASURING POWER



is taken with one voltage lead connected to line B. The lead is then moved to line A, and another reading is taken. The sum of the readings gives the total power. A power factor less than 0.5 produces the same result in the one-wattmeter system as in the two-wattmeter system.

Of course, switches can be used to change the voltage leads in either the one- or two-wattmeter method. Wattmeters that have negative-zero-positive scales may also be used in both methods.

Q20. The two readings recorded from measuring the power by the two-wattmeter method are +20W and +40W. Find the total three-phase power.

Q21. The two readings recorded from measuring the power in a circuit by the two-wattmeter method are +40W and —15W respectively. Find the total three-phase power.

Q22. Four sets of readings found by the one-wattmeter method are:

A. +40, —20
B. +40, +40
C. +15, +20
D. —15, +30

Find the total power for each set of values.

Your Answers Should Be:

A20. $P_T = P_1 + P_2 = 20 + 40 = 60W$

A21. $P_T = P_1 - P_2 = 40 - 15 = 25W$

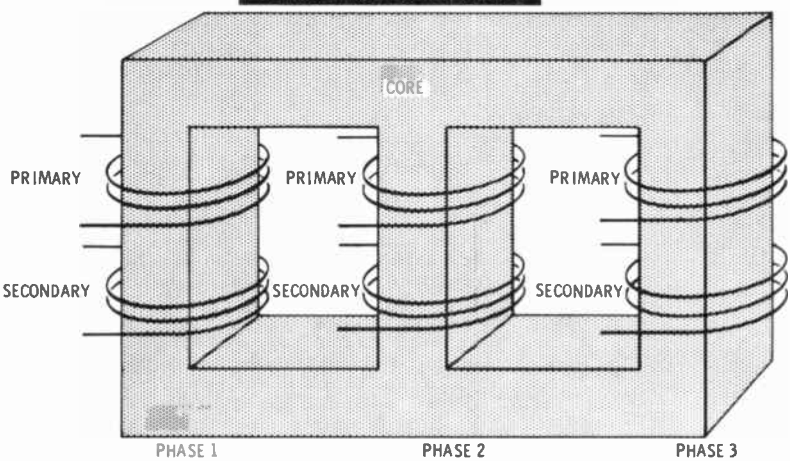
A22. (A.) 20W, (B.) 80W, (C.) 35W, (D.) 15W

TRANSFORMER CONNECTIONS

Wye and delta connections are used in many types of equipment. Three-phase motors are wye- or delta-connected, as are alternators. Another important type of a three-phase device is the three-phase transformer. Since power is often transmitted three-phase and since its voltage is transformed up and down at several points according to the needs of the distribution system, three-phase transformers are quite important.

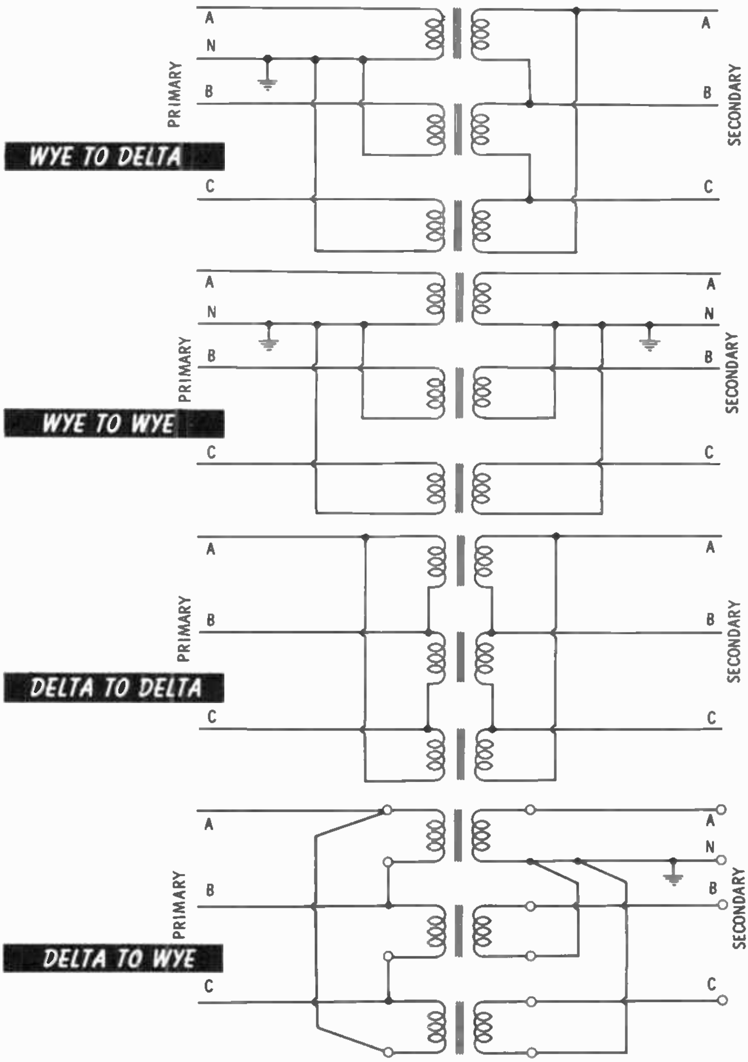
Three-phase transformers consist of either three single-phase transformers connected together or a single-core, three-phase winding, as shown below.

THREE-PHASE, SINGLE-CORE TRANSFORMER



The primaries and the secondaries can be connected in any combination of delta and wye. For example, the primaries can be wye-connected and the secondaries delta-connected, or vice versa. Or both the primaries and the secondaries can be wye- or delta-connected.

THREE-PHASE TRANSFORMER CONNECTIONS



Q23. Name the four ways in which transformers can be connected in a three-phase system.

Q24. What are the two kinds of three-phase transformers?

Your Answers Should Be:

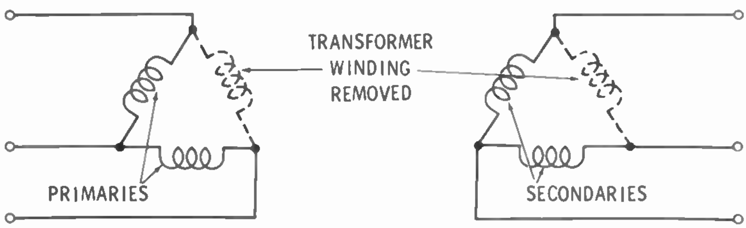
A23. Three-phase transformers can be connected in **wye-to-delta, wye-to-wye, delta-to-delta,** and **delta-to-wye** arrangements.

A24. A three-phase transformer can be made up of **three single-phase** transformers or a **single-core, three-phase** winding.

Both three-phase transformers and three single-phase transformers have their advantages. These are listed in the table below.

ADVANTAGES	
Three-Phase Transformer	Three Single-Phase Transformers
Lower initial cost Higher efficiency Less total weight Less total floor space Lower installation and transportation cost	Cheaper spare parts A single unit can be replaced in case of trouble Lower repair cost More voltage flexibility

Overall, the three-phase transformer is considered a better unit in most situations. One minor advantage of using three single-phase transformers in a delta connection is that it is possible to remove one of the transformers altogether and still have the system operate at reduced capacity. This arrangement is called **open delta.**

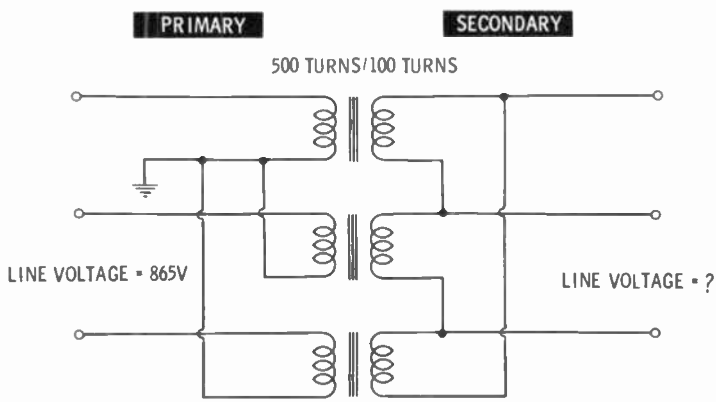


OPEN-DELTA CONNECTIONS

When using wye-to-delta or delta-to-wye connections, there is one important fact to remember. Line voltage and phase voltage are equal in the delta connection and line voltage is 1.73 times phase voltage in the wye connection. These facts can be used to get an additional step up or step down of voltage without adding extra turns to the transformers.

For example, suppose you are using a group of single-phase transformers with turns ratios of one to five to step up a three-phase voltage of 100 volts (line voltage). If the primaries of the transformers are delta-connected, the primary phase voltage is 100 volts. The **phase voltage** at the secondary will be 500 volts, but if the secondary is **wye-connected,** the **line voltage** will be $1.73 \times 500 = 865$V. If both sets of windings had been connected in the same way (both wye or both delta), the secondary line voltage would have been only 500 volts.

Q25. What is the secondary line voltage in the circuit below?



Q26. Draw a diagram showing three single-phase transformers connected in a wye-to-delta arrangement.

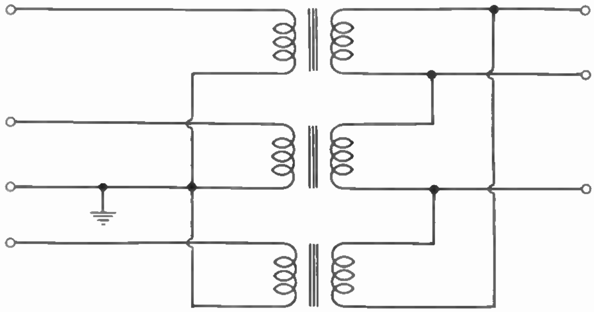
Q27. A delta-to-wye, three-phase transformer has a turns ratio of 10 to 1 and is used as a step-down transformer. If the input line voltage is 1,000V, what is the output line voltage?

Q28. What is one disadvantage of using the open-delta connection?

Your Answers Should Be:

A25. The phase voltage of the wye-connected primary is $865/1.73 = 500V$. The phase voltage in the secondary is 100V. Since the secondary is delta-connected, the **line voltage** is also **100V.**

A26.



A27. The primary phase voltage is 1,000V. The secondary phase voltage is $1{,}000/10 = 100V$. Since the secondary is wye-connected, the **secondary line voltage is 173V.**

A28. In the open-delta connection the transformers must be operated at **reduced capacity.**

WHAT YOU HAVE LEARNED

1. The power for most household and industrial use is generated and distributed as three-phase.
2. Three-phase power is usually generated in hydraulic or steam power plants.
3. In hydroelectric plants, falling water drives a generator at low speed.
4. In steam plants steam drives a turbine at high speed. In steam plants the turbine, alternator, and DC exciter are arranged horizontally.
5. Wye and delta connections make it possible to transmit three-phase power with four or even three conductors.
6. In the wye connection, one end of each winding is connected to a common point which is often grounded.

7. In the wye connection the voltage between the lines is called line voltage and is 1.73 times the voltage generated in any phase winding.
8. The voltage in a phase winding is called phase voltage, and appears between a line and neutral in the wye connection.
9. In the delta connection the windings are connected to form a closed loop. No current flows around this loop.
10. In the delta connection, line voltage and phase voltage are equal.
11. In the delta connection, line current is 1.73 times phase current.
12. In any three-phase system the total power is equal to the sum of the powers in all three phases.
13. The power in a three-phase system can also be found from line voltages and currents by the formula:

$$P_T = 1.73\ I_L\ E_L \cos\theta$$

14. Power in three-phase systems can be measured using one, two, or three wattmeters.
15. In the three-wattmeter method, power is simply measured in each phase. It is used primarily with three-phase, four-wire, wye-connected systems.
16. In the one-wattmeter and two-wattmeter methods, two readings must be either added or subtracted (depending on the power factor) to find the power in the system.
17. Transformers can be connected in wye or delta patterns.
18. The primary and secondary of a three-phase transformer need not be connected in the same pattern.
19. By connecting the primary of a transformer in wye and the secondary in delta, or vice versa, it is possible to have a greater change in voltage than is produced by the turns ratio of the transformer alone.
20. Three-phase transformers can either be three-phase units or combinations of three single-phase transformers.
21. Three single-phase transformers can be connected in open delta.

7

Power Converters

What You Will Learn

There are a number of devices that convert one type of power to another. You will now find out how DC can be converted to AC and AC to DC. You will learn how AC frequency can be changed and DC voltages stepped up or down. You will also learn how to draw schematics for some of these changes and how to choose the correct device for a particular application.

THE NEED FOR CONVERTERS

Electrical energy is generated and transmitted primarily as three-phase AC, usually at 60 cps and very high voltages. The voltages are transformed to lower values before being used. Sometimes only one phase is used for a particular piece of equipment. The most common type of power supplied to homes is single-phase AC.

Occasionally, DC is required at a remote location in rather large quantities. **Converters** provide a means of changing available AC currents to DC currents. Sometimes the supply source is DC, but AC currents are needed. A different kind of converter meets this need. Sometimes special frequencies of AC are required or high DC voltages are needed. Converters can provide these also.

The word **converter** actually includes any of the following changes in electrical form: AC to DC, AC to AC of a different frequency, DC to AC, DC to higher-voltage DC, DC to lower-voltage DC, etc.

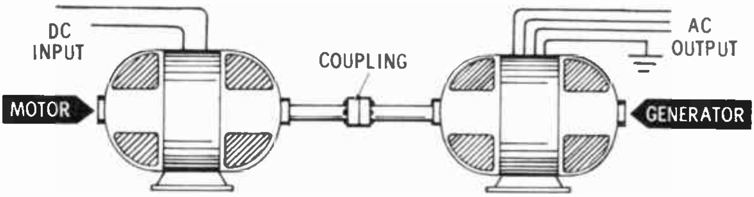
DC-TO-AC CONVERTERS

The conversion of DC to AC usually takes place when a DC source is available and a rather specialized AC frequency is required. The two basic methods of converting DC to AC are by means of a motor-generator (M-G) set and by vibrator action.

Motor-Generators

In the simplest form of M-G set, a DC **motor** drives an AC **generator.** Depending on the type of AC generator chosen, a DC-to-AC converter may deliver single-phase, two-phase, or three-phase AC power. Most generators in this type of converter are three-phase synchronous units.

DC-TO-AC MOTOR-GENERATOR SET



A DC motor chosen as the prime mover in an M-G set must have speed characteristics that are very constant. If the speed of the motor varies considerably as the load increases, the frequency of the AC generator will vary accordingly. (Frequency is directly proportional to the speed of the prime mover.) One suitable type of DC motor is the shunt motor, although compound motors are also used to a great extent. A series motor could not normally be used because of its poor speed control.

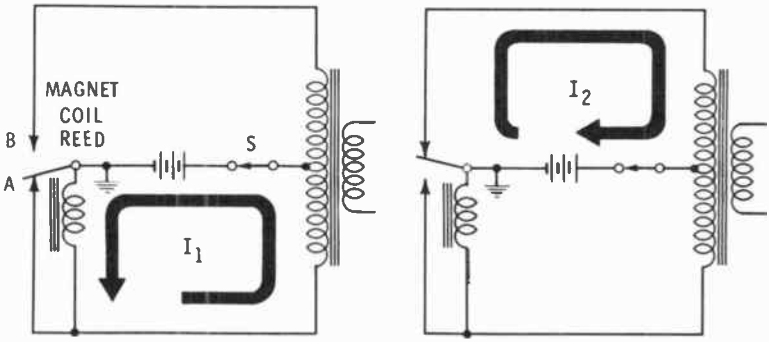
Vibrators

Vibrators are used in DC-to-DC converters and DC-to-AC converters but usually are able to deliver only very small amounts of power. The figure at the top of the opposite page shows a simple vibrator circuit. (The filtering components have been deliberately omitted so that the reader may better understand how it works.)

When switch S is closed, the current will flow through the magnet coil. This action causes the coil to attract the reed and thus closes contact A. When the reed touches contact

A, it short-circuits the magnet coil, thus releasing the reed from its position. The reed is released, it springs back, and its inertia sends it into contact with point B. By this time, the magnet coil again has current flowing through it, so it pulls the reed back to point A, and the cycle repeats itself.

A VIBRATOR CIRCUIT



CURRENT THROUGH LOWER WINDING

CURRENT THROUGH UPPER WINDING

The vibrating reed causes the current to flow through first the lower section of the transformer primary and then the upper section. This is very much like having an alternating current flowing in the primary. This action causes an AC voltage to be induced in the secondary of the transformer. The voltage is not a sine wave, however, but has a generally rectangular shape. Filtering action can smooth out the waveform.

The magnitude of the induced voltage depends on the turns ratio of the transformer. The frequency of the voltage depends on the speed with which the reed changes from A to B. The speed, in turn, varies with the weight of the reed and the strength of the magnetic field.

Q1. Do you think a special converter would be used to convert low-voltage AC to high-voltage AC? How would this be done?

Q2. Why it is necessary to use a constant-speed motor in a DC-to-AC motor-generator set?

Q3. The moving part of a vibrator is a ______________.

Your Answers Should Be:

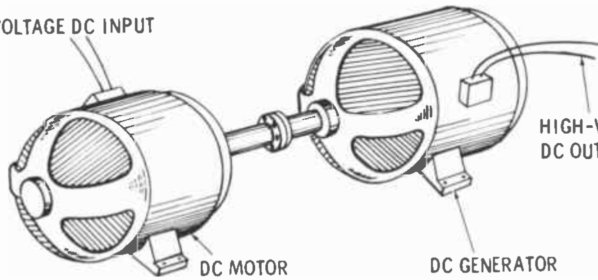
A1. No, a **transformer** changes the voltage of AC simply and efficiently.

A2. If **the speed** of the M-G set varies, the **frequency of its output also varies.**

A3. The moving part of a vibrator is a **vibrating reed.**

DC-TO-DC CONVERTERS

A simple means of obtaining a higher DC voltage from an existing DC source is to use an M-G set in which both the motor and the generator are DC machines.



DC-TO-DC MOTOR-GENERATOR SET

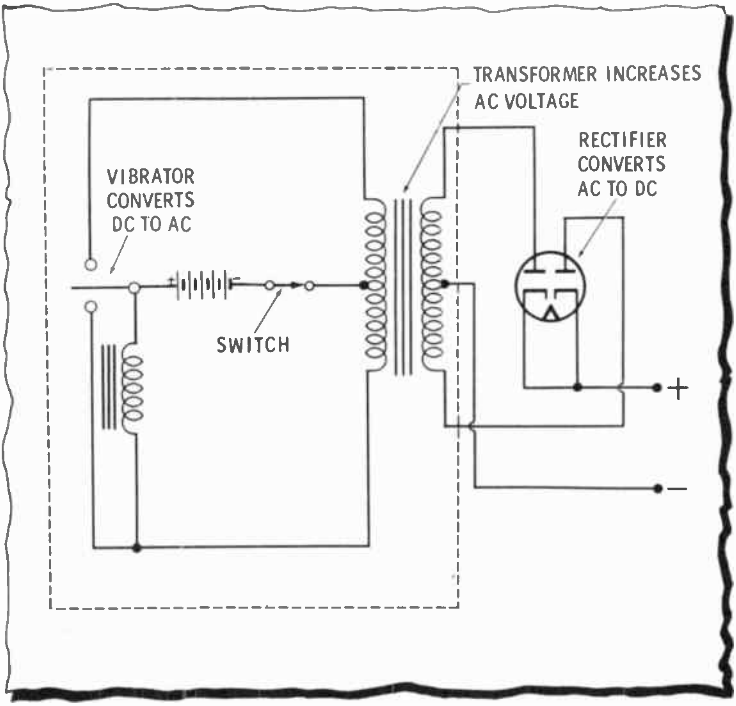
A shunt or compound DC motor is best because it has relatively constant speed for varying loads. The output voltage of the generator depends on the speed. A shunt or compound DC generator is best suited for use in M-G converters because it has good voltage regulation for varying loads.

When only a small DC output is required, a vibrator can be successfully employed. The vibrator converts the DC to higher-voltage AC. Then the AC is converted back to DC at this higher voltage. A typical circuit is shown on the opposite page.

The advantage of the DC-to-DC vibrator converter is that the AC output produced by the parts enclosed in the dashed line in the illustration can be converted to a DC voltage which is higher than that of the battery. The means by which AC can be converted back to DC will be discussed in the following section. The device shown is a **full-wave rectifier,** a type of electronic converter.

The DC-to-AC devices discussed so far are often called **inverters.** This distinguishes them from the more common AC-to-DC devices that are called **converters.**

DC-TO-DC VIBRATOR CONVERTER



Q4. **What sort of DC motor would be best suited for use in a motor-generator set used as a DC-to-DC converter? Why?**

Q5. **What sort of DC generator would be best suited for this application? Why?**

Q6. **In one device for raising the voltage of small amounts of DC power, the DC is converted to __, and then the voltage is raised by a ____________. The AC is then converted to __.**

Q7. **An inverter is a device for converting __ to __.**

Your Answers Should Be:

A4. **Shunt or compound** DC motors are best for this purpose because of their relatively **constant speed.**

A5. **Shunt or compound** DC generators are best for this purpose because their **output voltage does not change greatly with varying loads.**

A6. In one device for raising the voltage of small amounts of DC power, the DC is converted to AC, and then the voltage is raised by a **transformer.** The AC is then converted to DC.

A7. An inverter is a device for converting DC to AC.

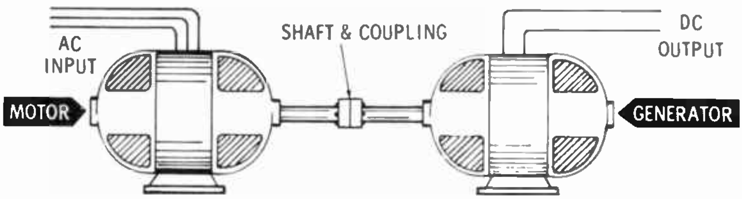
AC-TO-DC CONVERTERS

There are several ways of converting AC to DC. This can be done by any of the following: motor-generator set, synchronous converter, electronic rectifier, or contact rectifier.

Motor-Generator Sets

The use of M-G sets as AC-to-DC converters is quite similar to the method used in inverters. An AC motor drives a DC generator.

AC-TO-DC MOTOR-GENERATOR SET



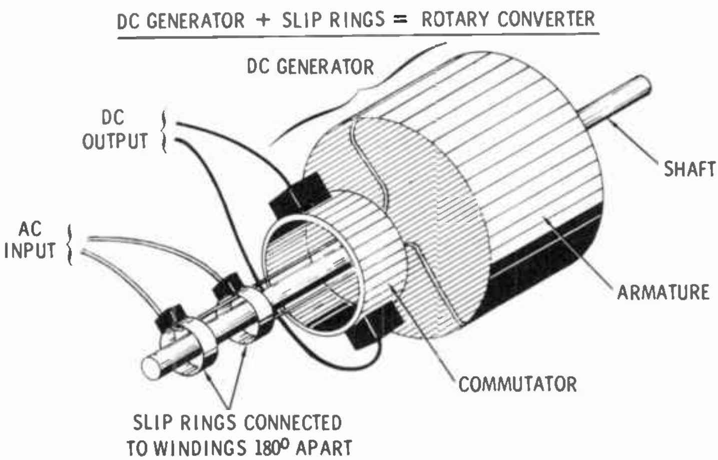
It is customary to use three-phase motors of either the induction or synchronous type. The induction motor has the advantage of being lower priced and more rugged in construction than the synchronous motor. The induction motor can be wound for voltages as high as 13,500 volts, thus eliminating the need for step-down transformers in many cases.

Synchronous motors have the advantage of constant speed and higher power factor. In large converter installations, the synchronous motor is usually preferred. By overexciting a synchronous motor, the overall power factor of the system can be improved. The overexcited synchronous motor becomes a synchronous capacitor. (That is, it does the job of a huge capacitor.)

The Synchronous Converter

The synchronous converter is sometimes called a **rotary converter.** It changes AC to DC. The synchronous converter consists of a DC field and a DC armature equipped with slip rings in addition to a commutator. You can consider it as a synchronous motor whose armature is equipped with a commutator to provide a DC output.

ARMATURE OF A SYNCHRONOUS CONVERTER



Under ordinary conditions, an alternating voltage is connected to the motor portion of the converter through slip rings, causing the machine to rotate at synchronous speed like an AC synchronous motor. At the same time, the machine also acts like a DC generator. This DC output is taken from the commutator by brushes and can be used to provide current for the field winding. This DC output can, in addition to energizing the field winding, furnish DC to an external load.

Q8. A synchronous converter has an armature equipped with ____ _____ and a __________.

Q9. The DC output is taken from a synchronous converter through the __________ brushes.

Your Answers Should Be:

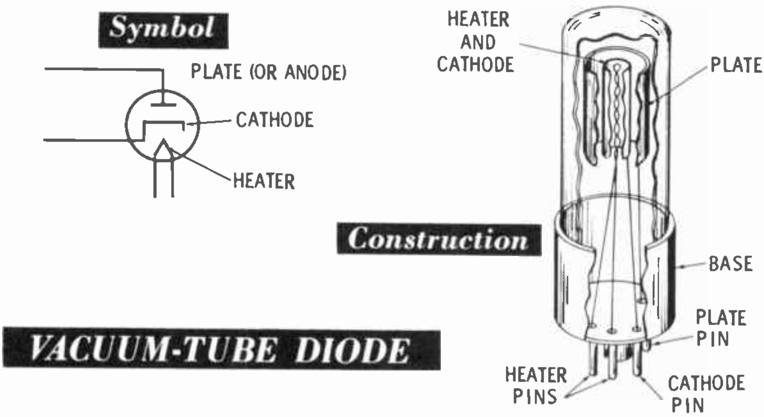
A8. A synchronous converter has an armature equipped with **slip rings** and a **commutator.**

A9. The DC output is taken from a synchronous converter through the **commutator** brushes.

Electronic Rectifiers

The simplest and most common type of electronic rectifiers are diode vacuum tubes (electron tubes). The principles of operation of electron tubes are covered more thoroughly in Volume 3 of this series.

A vacuum-tube diode usually consists of three parts enclosed in a glass bulb from which the air has been removed to create a vacuum. The parts are the plate, cathode, and heater. In some tubes, the filament also serves as the cathode; this is called a directly heated cathode.

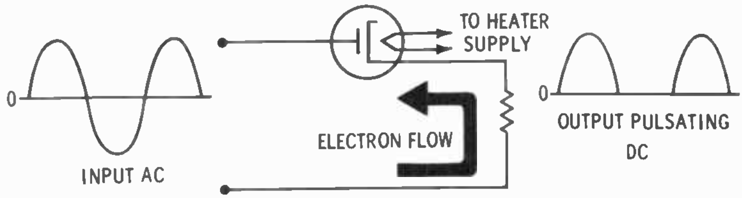


VACUUM-TUBE DIODE

In a vacuum-tube diode, heating the cathode drives electrons off the cathode. If a positive voltage (with respect to the cathode) is applied to the plate, the plate will attract the electrons emitted from the cathode. The movement of electrons is, in effect, a current flow. If the plate is more negative than the cathode, no current flows since there is no positive charge to attract the electrons. The vacuum-tube diode thus acts as a valve. It conducts in one direction but not in the other.

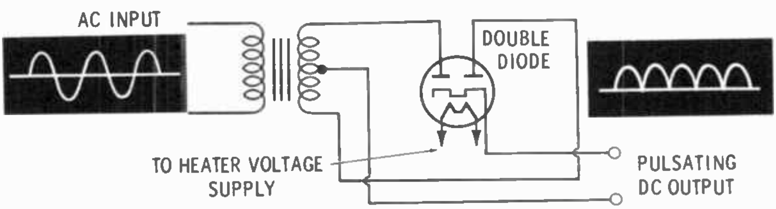
Look at the circuit diagram below. During the positive half cycle of the AC input, the plate is positive with respect to the cathode, and current flows. (A voltage drop appears across the load resistor, but it is a little less than the input voltage.) During the negative half cycle, the plate is negative with respect to the cathode, and no current flows.

HALF-WAVE RECTIFIER



The device just described is called a **half-wave rectifier** because only half of the AC sine wave appears in the output. Although this current never reverses direction, it is a very rough, pulsating DC which is not satisfactory for must purposes. A smoother DC can be obtained from a **full-wave rectifier.**

FULL-WAVE RECTIFIER



Both halves of the AC sine wave appear in the output of the full-wave rectifier. The output is still a pulsating DC, but it is smoother than the half-wave output. With proper filtering, the output of a full-wave rectifier can be smoothed further into a steady DC current.

Q10. A vacuum-tube diode conducts only when the plate is _________ with respect to the cathode.

Q11. The output from a ____ ____ rectifier is easier to smooth than the output from a ____ ____ rectifier.

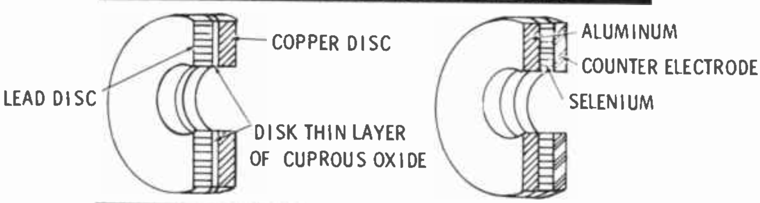
> **Your Answers Should Be:**
>
> **A10.** A vacuum-tube diode conducts only when the plate is **positive** with respect to the cathode.
>
> **A11.** The output from a **full-wave** rectifier is easier to smooth than the output from a **half-wave** rectifier.

Contact Rectifiers

Contact, or **barrier-layer,** rectifiers are devices which permit current flow in one direction only. (Actually, they present a very high resistance in the reverse direction.) They produce very much the same result as a vacuum-tube diode. Two very common types of metallic barrier-layer rectifiers are copper-oxide and selenium rectifiers.

The **copper-oxide** rectifier is produced by heating a copper disc to a high temperature and then quenching it in water. This produces a thin layer of red cuprous oxide sandwiched between the copper disc and a thick outer layer of green cupric oxide. The cupric oxide is then removed and a lead disc is pressed against the cuprous oxide. Electrons flow more easily from lead to copper than from copper to lead.

CONTACT RECTIFIERS



Copper Oxide **Selenium**

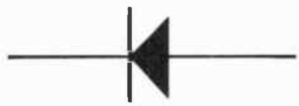
The **selenium** rectifier is made by depositing a layer of selenium on an aluminum plate. An alloy with a low melting point is then sprayed onto the selenium surface. This alloy is called the **counterelectrode.** The current-blocking layer is the surface between the selenium and the alloy. Electrons flow through this surface easily in one direction but not in the other.

Another type of rectifier is the **semiconductor** rectifier. The rectifying action is produced by the junction of P-type and N-type materials. Electrons flow easily from the N-type to the P-type material, but not in the reverse direction. You can learn more about the theory of semiconductor materials in Volume 3 of this series.

Small rectifier cells are often called **rectifier diodes** since they perform the same rectifying action as the diode vacuum tube. If large quantities of electricity need to be rectified, **rectifier stacks** are used. These are composed of a number of rectifier elements assembled and connected together.

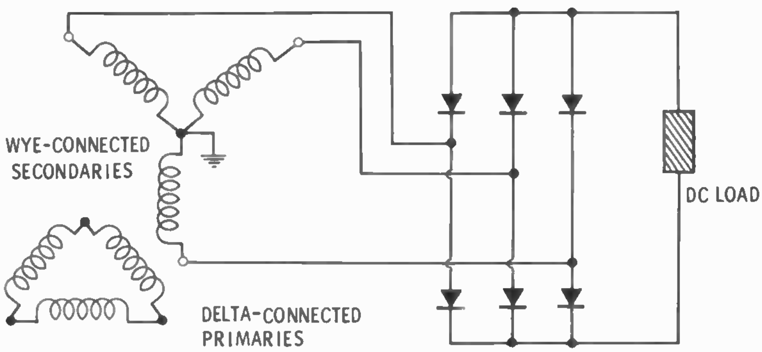
The symbol for a rectifier is shown in the figure below. The arrowhead points **against** the direction in which electrons move through the rectifier.

Contact-Rectifier Symbol



The rectifiers shown so far have had single-phase inputs. Three-phase current can also be rectified, as shown in the following illustration.

THREE-PHASE RECTIFIER CIRCUIT



Q12. Name three types of rectifier cells.

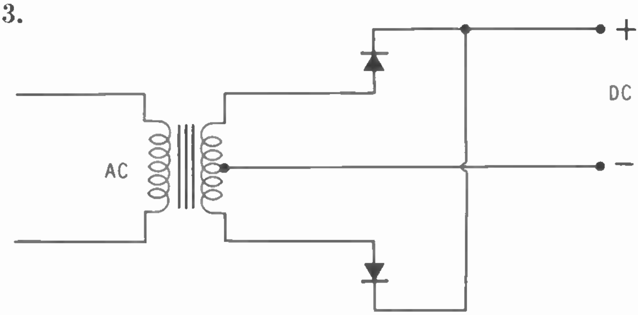
Q13. Draw a schematic of a full-wave rectifier using two rectifier cells.

Q14. What property of rectifiers makes them useful in converting AC to DC?

Your Answers Should Be:

A12. Three types of rectifier cells are: **copper oxide, selenium,** and **semiconductor.**

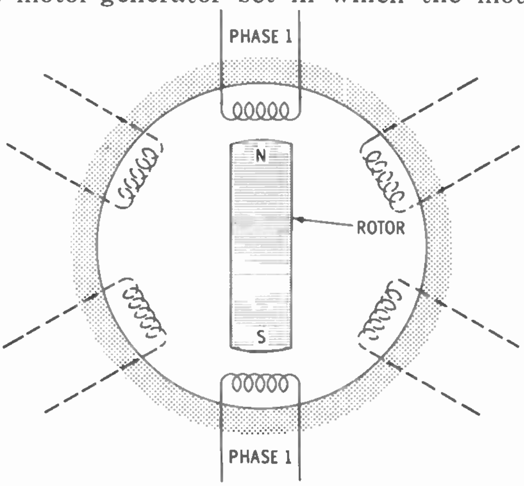
A13.



A14. Rectifiers have a **high resistance** to current flow **in one direction** and a **low resistance in the other direction.**

FREQUENCY CONVERTERS

The last type of converter to be discussed is the frequency converter. The simplest way of changing frequency is to provide a motor-generator set in which the motor is AC

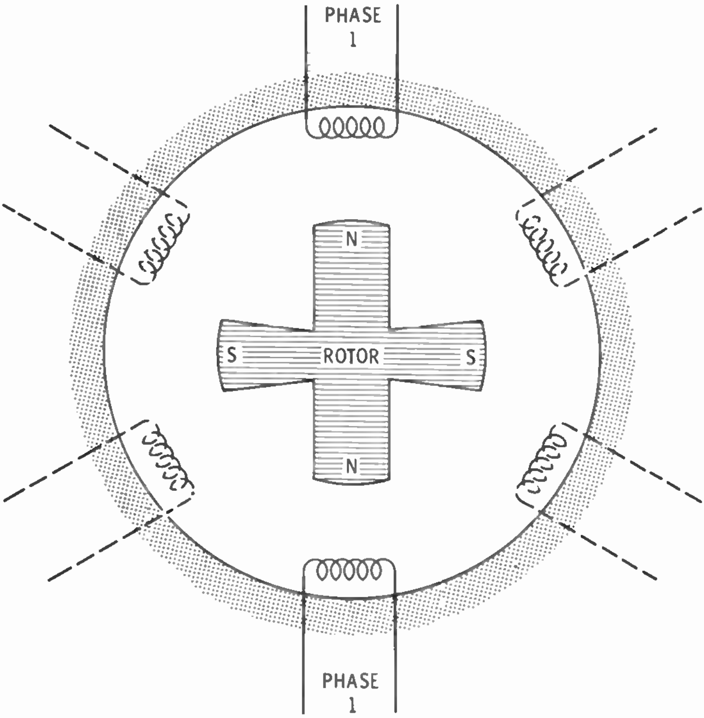


TWO-POLE MACHINE

(preferably synchronous) and the generator is an AC synchronous unit, but with different number of poles.

Look at the figure on the opposite page. If the machine is a generator, the emf induced in each winding goes through a complete cycle every time two unlike poles pass the winding. In the illustration, this happens once for every revolution of the rotor. If the machine is a synchronous motor, the rotor will make a complete revolution for each cycle of current in the windings.

FOUR-POLE MACHINE



Now look at the figure above. This machine has four poles on the rotor. **Four** poles pass each winding during each revolution. Therefore there are **two** complete cycles of current in each winding for each revolution of the rotor. A machine with **eight** poles will have **four** complete cycles of current in each winding for each revolution of the rotor, etc.

The formula relating the frequency to the speed and to the number of poles in a synchronous generator or motor is as follows:

$$S = \frac{120 \times f}{p}$$

or,

$$f = \frac{S \times p}{120}$$

where,

S is the speed (rpm),
f is the frequency (cps),
p is the number of poles.

Thus, if the motor in an M-G set is a two-pole machine operating at 60 cps, the speed of the shaft will be:

$$S = \frac{120 \times f}{p}$$

$$S = \frac{120 \times 60}{2} = 3{,}600 \text{ rpm}$$

If this motor is used to drive a generator having **six** poles, the output frequency will be:

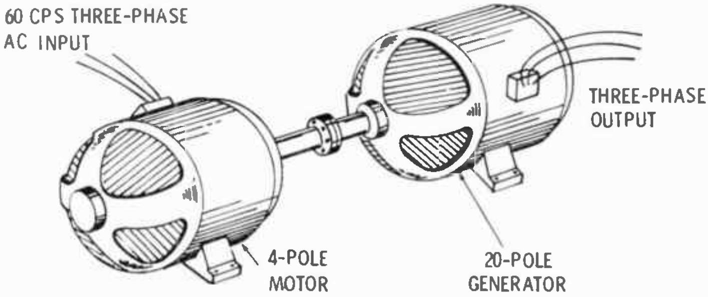
$$f = \frac{S \times p}{120} = \frac{3{,}600 \times 6}{120} = 180 \text{ cps}$$

The AC-to-AC motor-generator set is probably the simplest frequency-converting device. However, a number of other devices can be used for this purpose.

The **induction generator** discussed in Chapter 4 is basically a frequency-converting device. As you remember, it can be used to decrease the frequency if the rotor is driven in the same direction as the rotating magnetic field. If the rotor is driven in the opposite direction, the frequency is increased.

Higher frequencies for small amounts of current can be obtained with **vibrators** operated by AC instead of DC. Very small quanties of power at almost any frequency can be developed by an electronic **oscillator.** Since this type of device is used mainly in electronic work, it is discussed in Volumes 3 and 4 of this series. The oscillator is basically a DC-to-AC converting device.

Q15. Find the output frequency of the M-G set below.



Q16. Does a four-pole generator have to turn faster or slower than a two-pole machine to generate the same frequency?

Q17. A four-pole synchronous motor turns (faster, slower) than a two-pole synchronous motor receiving the same frequency.

Q18. Find the output frequencies when the motor input frequency is 60 cps and the poles are as shown.

	Motor Poles	Generator Poles
A	2	8
B	4	10
C	16	4
D	10	70

Q19. What device with no moving parts would you use to convert a moderate amount of AC to DC?

Q20. What type of device would you use to convert 60-cycle AC to 120-cycle AC?

Q21. What type of device would you use to obtain heavy DC currents from AC?

Q22. What type of device would you use to obtain a small AC current from DC?

Q23. How could you step up the voltage of a small amount of DC power?

Q24. The word inverter is often used to refer to a device that converts __ to ___.

Your Answers Should Be:

A15. The speed of the motor is:

$$S = \frac{120 \times f}{p} = \frac{120 \times 60}{4} = 1{,}800 \text{ rpm}$$

The frequency of the generator is:

$$f = \frac{S \times p}{120} = \frac{1{,}800 \times 20}{120} = 300 \text{ cps}$$

A16. A four-pole generator turns at **half the speed** of a two-pole machine to generate the same frequency.

A17. A four-pole synchronous motor turns **slower** than a two-pole motor receiving the same frequency.

A18. (A) **240 cps**, (B) **150 cps**, (C) **15 cps**, (D) **420 cps**

A19. A **rectifier** has no moving parts and can be used to convert a moderate amount of AC to DC.

A20. **An M-G set with twice as many poles on the generator as on the motor** will convert 60 cps to 120 cps.

A21. **An M-G set with a synchronous motor and a shunt or compound DC generator** will convert heavy AC currents to DC.

A22. A **vibrator** will provide a small AC current from a DC input.

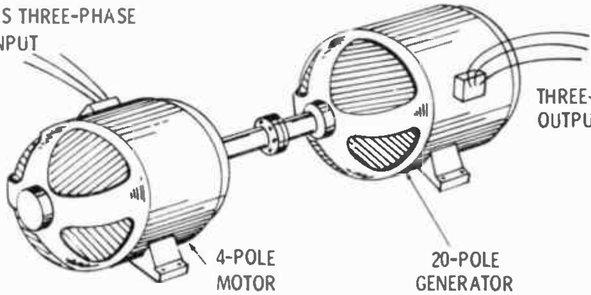
A23. **A vibrator combined with a transformer and a rectifier** can step up DC voltages.

A24. The word inverter is ofen used to refer to a device that converts **DC to AC.**

WHAT YOU HAVE LEARNED

1. Power converters are used to change one type of power to another. For example, they change AC to DC, DC to AC, AC to AC of a different frequency, or DC to higher-voltage DC.
2. DC can be converted to AC by use of a motor-generator set or by a vibrator.
3. An M-G set consisting of a DC motor and an AC gen-

Q15. Find the output frequency of the M-G set below.



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The frequency of the generator is:

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A17. A four-pole synchronous motor turns **slower** than a two-pole motor receiving the same frequency.

A18. **(A) 240 cps, (B) 150 cps, (C) 15 cps, (D) 420 cps**

A19. A **rectifier** has no moving parts and can be used to convert a moderate amount of AC to DC.

A20. **An M-G set with twice as many poles on the generator as on the motor** will convert 60 cps to 120 cps.

A21. **An M-G set with a synchronous motor and a shunt or compound DC generator** will convert heavy AC currents to DC.

A22. A **vibrator** will provide a small AC current from a DC input.

A23. **A vibrator combined with a transformer and a rectifier** can step up DC voltages.

A24. The word inverter is ofen used to refer to a device that converts **DC to AC.**

WHAT YOU HAVE LEARNED

1. Power converters are used to change one type of power to another. For example, they change AC to DC, DC to AC, AC to AC of a different frequency, or DC to higher-voltage DC.
2. DC can be converted to AC by use of a motor-generator set or by a vibrator.
3. An M-G set consisting of a DC motor and an AC gen-

8

Servo Control Systems

What You Will Learn

In this chapter you will learn how a servo control system can move and precisely position a heavy load through application of a small input signal. You will become acquainted with the basic principles of servo and synchromechanisms and how these devices can be used in controlling the direction and amount of rotation of an electric motor. You will discover how synchromechanisms can be used to transmit data from one location to another.

WHAT IS A SERVO CONTROL SYSTEM?

There are many load-positioning tasks which man has neither the muscle, mental ability, nor desire to perform. For the accomplishment of such tasks, he uses a servo control system. A servo system is used to move the heavy rudder of a ship, position the beam of large searchlights, or sight an observatory telescope, weighing several tons, on a distant star.

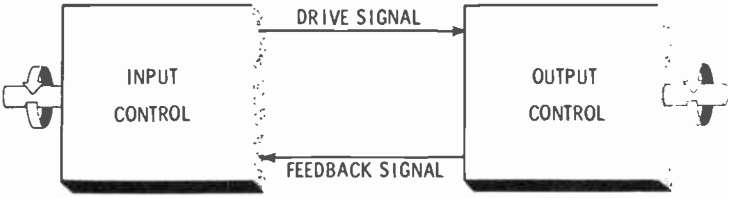
Servo systems can be designed for automatic operation. These systems can be used with radar for automatic tracking of targets, in weapons systems for automatic aiming of guns or missile launchers, in aircraft for automatic positioning of control surfaces, in missiles for automatic guidance through prescribed flight paths, and in many other installations where automatic and precise control is desired.

THE SERVO PRINCIPLE

The terms **servo system, servomechanism,** and **servo** are often used interchangeably to identify a complete system or one of its parts. To prevent confusion, an individual device will be identified by its noun name, servomotor for example, and a working combination of these devices will be called a servo (or control) system.

The Basic Servo System

All servo systems perform two functions. These functions are called **input control** and **output control.**



The figure above shows a shaft feeding a rotational signal to the input control which causes the output control to rotate its shaft in the same direction. The turning of the output shaft moves a load to a desired position. The output control continuously feeds a signal back to the input to reveal the precise position (in a rotational direction) of the output shaft. If there is a difference between input and output shaft positions, the latter will continue to turn until the desired amount of rotation is attained. All servo systems operate in accordance with this principle.

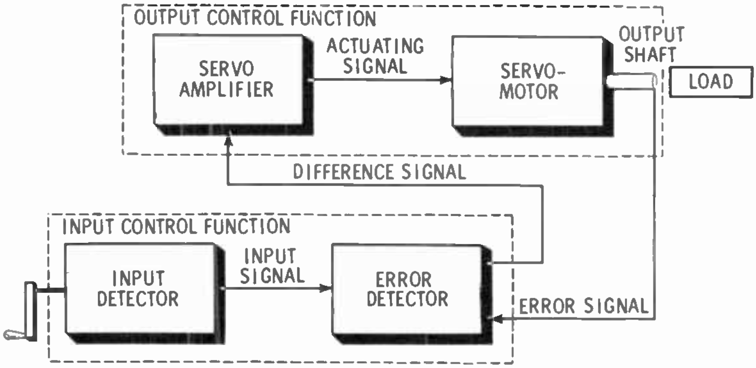
Electrical, mechanical, hydraulic, or air-pressure devices may be used for control mechanisms or transmission of signals between the two control functions. Because of their economy, reliability of operation, and ease of control, most servo systems employ electrical or electromechanical devices. Transmission of signals between control devices is nearly always done electrically. This is particularly true when the input control is located at some point remote from the output control.

Since it reveals position difference between input and output, the feedback signal is frequently called an **error signal.** Sometimes the drive signal is called an **actuating signal.**

Basic Parts of a Servo System

A servo system may have as few as two or three devices or as many as a hundred or more. The number and variety depend on the complexity of the system and the type of work it must perform. A modern radar, for example, must aim its antenna in elevation (up and down) and in bearing (left and right) as a result of manual or semiautomatic control. It must then automatically follow the target when it has been "locked-on." However, any servo system basically consists of four functional devices shown in the figure below.

BASIC PARTS OF A SERVO SYSTEM



The input detector senses any movement of the input shaft and sends a signal to the **error detector** where it is matched with an error signal which reveals the position of the output shaft. If the shafts are not in the same position, a difference signal is generated and then amplified by the **servo amplifier** to a value which will turn the **servomotor.** The motor will continue to turn until the difference between the input and the error signals is zero. When this occurs, the two shafts will be in the same angular position.

Q1. What are the two signals which reveal the positions of the input and output shafts?

Q2. When a difference signal is generated, input and output shafts (are, are not) in alignment.

Q3. What are the basic parts of the input and output control functions, respectively?

Your Answers Should Be:

A1. The **input signal** shows the position of the **input shaft.** The **error signal** reveals the position of the **output shaft.**

A2. When a difference signal is generated, input and output shafts **are not** in alignment.

A3. **Input and error detectors** are part of the **input control.** **Servo amplifiers and motors** are found in the **output control.**

OPEN AND CLOSED SERVO SYSTEMS

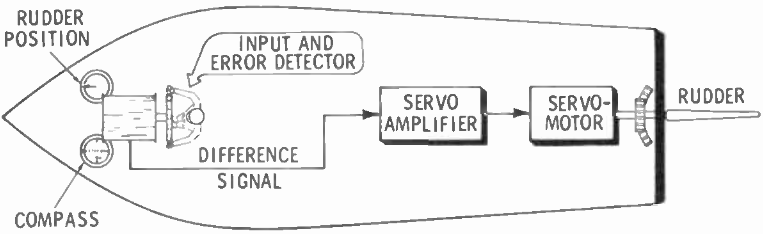
A servo system may be defined as either open or closed. In an **open system** the behavior or position of the output shaft is not automatically matched with the input position. Matching or correction is accomplished by manual or semi-automatic methods.

In a **closed system,** input and error signals are automatically compared to bring input and output conditions into automatic alignment.

An Open Servo System

The figure below shows an example of an open servo system. It is a steering system that could be used on a ship. The rudder turns in a direction and an amount determined by the rotation of a wheel in the pilot house. Since the rudder is large and heavy, it is pivoted by a servomotor.

AN OPEN SERVO CONTROL SYSTEM

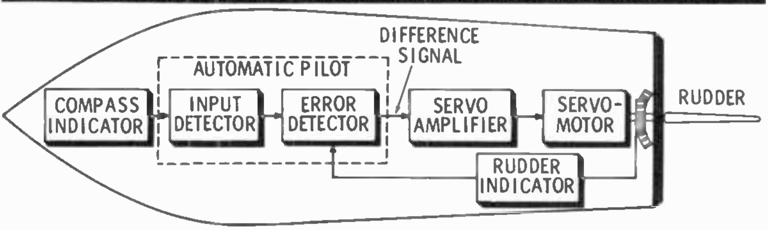


In this case, the man at the wheel is the input and error detector. He moves the wheel to maintain the ship on a specified course. He does this by watching the direction on a compass. When wind or ocean currents move the ship off course, he turns the wheel (and consequently the rudder) to bring the ship back on course. Because it is not automatic, the system is open.

A Closed Servo System

By replacing the man with an electric device, sometimes called an automatic pilot, the steering system can be made into a closed servo system as shown in the figure below.

A CLOSED SERVO CONTROL SYSTEM



When the ship drifts off course, the change in compass heading generates a voltage signal which is transmitted to the error detector. Since the rudder and heading (compass) positions no longer agree, a difference signal is sent to the servo amplifier and motor to turn the rudder an amount and in the direction required to bring the ship back on course. When the ship is back on course, the rudder will have been returned to its amidships (straight ahead) position.

If the ship is heading west (270° compass reading), for example, and the wind pushes it to a heading of 265°, there will be a 5° angular difference between the established positions of rudder and compass. A difference signal of an amount required to compensate for the deviation will be generated. The rudder will be turned to the right five degrees. Now the compass and rudder positions are the same, and the difference signal is zero. As the ship turns back to 270°, the rudder angle is decreased correspondingly and is returned to amidships when the ship heading becomes due west again. This system is a closed servo system.

Q4. A system which continuously self-compensates for differences between input and output is a(n) ______ servo system.

Q5. The difference signal will be zero when the _____ signal is equal to the _____ signal.

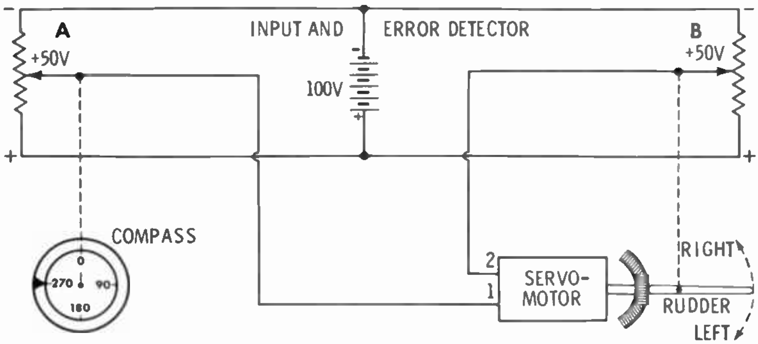
Your Answers Should Be:

A4. A system which continuously self-compensates for differences between input and output is a **closed** servo system.

A5. Difference signal will be zero when the **input** signal is equal to the **error** signal.

OPERATION PRINCIPLES

This is a simplified diagram of the steering servo system.



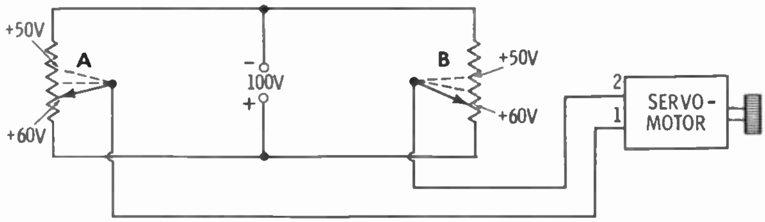
The input and error detectors contain a **balanced potentiometer**—the resistances of both potentiometer legs are identical. Potentiometer arm A responds to the turning of a compass. Arm B follows the movement of the rudder. Arms A and B are connected to the servomotor at terminals 1 and 2, respectively. A 100-volt battery is connected across the potentiometer.

When the ship is steering 270°, arm A is at the midpoint of the resistance. When the rudder is amidships, arm B is likewise at the midpoint of its resistance. Thus, both arms are selecting 50 volts. Since the voltage difference is zero, the motor will not turn.

If the ship swings 10° to the right, the compass will rotate to show a 280° heading. Arm A will be moved downward. Assume that it is now selecting +60V. The rudder is still amidships and arm B is still selecting +50V. Terminal 1 of the servomotor is now +10V with respect to terminal 2. The motor is so wired that it will turn the rudder 10° left.

When the rudder has reached the 10° position, arm B will have been moved to the +60V position. The potential difference at the motor terminals is zero and the motor is stopped. This situation is shown in the illustration below.

COMPASS AND RUDDER POSITIONS RETURNING TO ZERO



The angle of the rudder now turns the ship to the left. Since 0° on the compass always points north, the compass scale remains steady, and the ship, in effect, turns under it. The heading of the ship begins to move from 280° back to the desired 270°. As it does, arm A makes a corresponding movement back to its midpoint. If, for example, arm A is selecting +58V while arm B is still at +60V, terminal 2 is now two volts positive with respect to terminal 1. The servomotor turns in a direction to decrease the rudder angle. Arm B follows the rudder movement, decreasing its distance from the center resistance point.

As the ship continues to turn back to 270°, arm A is continuously leading arm B. Theoretically, arms A and B arrive at their midpoints simultaneously, and the difference signal becomes zero. This type of input control, however, is subject to overcompensation and will cause the ship heading to swing past the desired setting. Since the rudder will always follow, the ship will steer a winding course, weaving back and forth across the desired heading.

Q6. The resistances of a(n) ________ ______________ are equal.

Q7. If arms A and B (in the example given on these two pages) are selecting ⅔ and ⅓ of their resistances, respectively (measured from the negative ends), what is the voltage across the servomotor terminals?

Q8. Assuming the rudder is amidships at the beginning of Q7 conditions, which way will it be turned?

Your Answers Should Be:

A6. The resistances of a balanced **potentiometer** are equal.

A7. If arms A and B are selecting ⅖ and ⅗ of their resistances, respectively, **terminal 2 will be 20V positive with respect to terminal 1.**

A8. Under the conditions given, an amidships **rudder will be turned to the right.** The heading of the ship will be to the left of its desired course, and the polarity of the difference signal is such that it will rotate the servomotor in a direction which will turn the rudder to the right. This will bring the ship back to its desired course.

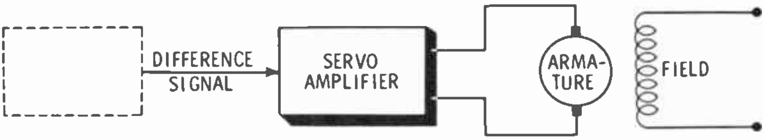
SERVOMOTORS

The preceding example used a DC servomotor to position a load. If the voltage source had been AC, an AC servomotor could have been substituted. Requirements of a motor used in a servo system include ability to drive a load in either direction and at varying speeds.

DC Servomotors

DC motors are selected for use in servo systems because of their high-stall torque characteristics and their ability to be operated at varying speeds. A **shunt-field motor,** the most predominant type of DC servomotor, is shown below.

SHUNT-FIELD DC SERVO MOTOR

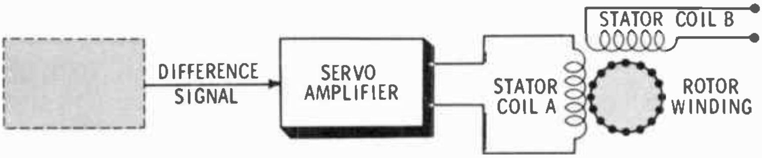


Voltage across the shunt field is obtained from a source separate from the servo system. This produces a uniform magnetic field. Voltage fed to the armature is controlled by the output of the servo amplifier (DC). Speed of the motor is determined by the magnitude of the voltage difference between terminals 1 and 2. Direction of armature rotation is determined by the polarity of these voltages.

AC Servomotors

Where low power and low speed ranges are permissible in a servo system, an AC servomotor is used. A distinct advantage is the ability to use a comparatively simple servo amplifier when an AC power source is available.

TWO-PHASE INDUCTION AC SERVO MOTOR



The diagram illustrates a **two-phase induction** motor, the type most frequently used in AC servomotor applications. Either a squirrel-cage or short-circuited rotor may be used.

The two stator coils are physically displaced 90°. Coil B, connected to a separate excitation source, develops a steady magnetic field in the top and bottom poles. Coil A magnetizes the left and right poles and its magnetic field depends on the magnitude and phasing of the AC voltage obtained from the servo amplifier. As you learned in a previous chapter, the rotor will turn when voltages applied to coils A and B are 90° out of phase.

The direction of rotor rotation is reversed when the servo amplifier reverses the direction of current through coil A. Speed of rotation is controlled by varying the strength of the magnetic field which, in this case, depends on the amount of current flowing through coil A.

In most installations, the value and direction of current flow is controlled by the characteristics of the difference signal fed to the servo amplifier. Since the difference signal will be AC, the servo amplifier can be a relatively simple electronic amplifier. In small servo systems, the difference signal may be fed directly to the servomotor.

Q9. (DC/AC) servomotors are used in servo systems requiring high torque to move a load.

Q10. (DC/AC) motors have the wider range of speeds.

Q11. DC servomotors are normally the ---------- type and AC servomotors are the ---------- type.

Your Answers Should Be:

A9. DC servomotors are used in servo systems requiring high torque to move a load.

A10. DC motors have the wider range of speeds.

A11. DC servomotors are normally the **shunt-field** type and AC servomotors are the **induction** type.

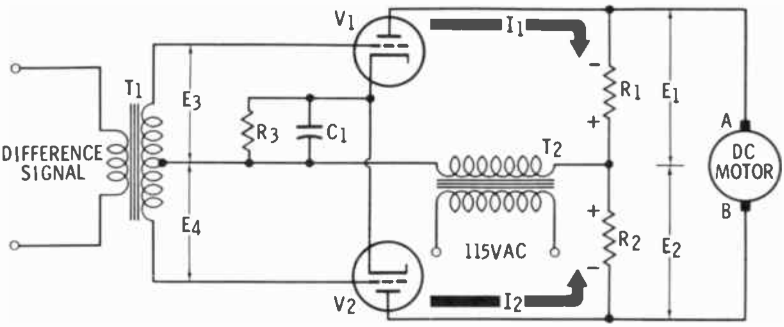
SERVO AMPLIFIERS

A **servo amplifier,** as you recall, converts the difference signal into a voltage or current to drive a servomotor at a desired speed and in the correct direction. DC servo amplifiers can be either electronic or electromechanical. AC servo amplifiers are usually electronic.

Vacuum-Tube DC Servo Amplifier

There are several varieties of electronic circuits used as DC servo amplifiers. Since nearly all difference signals are AC voltages, these circuits are designed to convert an AC signal into a DC output and to be sensitive to changes in phase. The circuit shown below is typical.

A SINGLE-STAGE DC SERVO AMPLIFIER



The servomotor used in such a circuit will probably be one with permanent-magnet poles. The secondary of T_2 applies an AC voltage to the plate of V_1 and V_2. As can be seen, the plate voltages are in phase. The difference signal enters through T_1 and is applied to the two grids 180° out of phase. C_1 and R_3 form the common-cathode bias for both tubes. With no signal applied across the primary of T_1, each grid is at the same potential and the plate currents are therefore equal. Voltage drops across the load resistors are equal and there is no difference of potential between points A and B of the motor armature. Therefore, the servomotor does not turn when there is no difference signal.

When a difference signal is applied across T_1, one of the grids will become positive with respect to the secondary center tap and the other grid negative with respect to the same point. Since the primaries of T_1 and T_2 receive power from the same line, one of the grids will be in phase with its plate voltage and the other 180° out of phase.

Assume that E_3 is causing the grid of V_1 to become more positive (the plates are going positive at the same time) while E_4 is causing the grid of V_2 to go negative by the same amount. Plate current I_1 through V_1 will increase and I_2 through V_2 will decrease. E_1 will increase (negative to positive from top to bottom) and E_2 will decrease (negative to positive from bottom to top). The voltage appearing across the DC servomotor armature will be the algebraic sum of E_1 and E_2. Since E_1 is greater than E_2, the armature voltage will be negative at A with respect to B. Current will flow through the armature from A to B, causing it to turn in a given direction.

When the difference signal reverses in phase, I_2 becomes greater than I_1. The difference between E_2 and E_1 causes an armature voltage which is negative at B with respect to A. The armature will now turn in the opposite direction.

Although the voltage across A and B is pulsating DC, its waveform is sufficiently smoothed out to cause armature rotation. The speed of armature rotation is determined by the magnitude of the difference signal.

Q12. The plates of V_1 and V_2 are always (in phase, 180° out of phase).

Q13. The grids of the two tubes are always (in phase, 180° out of phase).

Q14. The grid of which tube is always in phase with its plate?

Q15. ______ and __________ of the difference signal determine armature direction and speed, respectively.

Your Answers Should Be:

A12. The plates of V_1 and V_2 are always **in phase.**

A13. The grids of the two tubes are always 180° **out of phase.**

A14. The grid of **either** tube can be in phase with its plate, depending on the difference-signal phase.

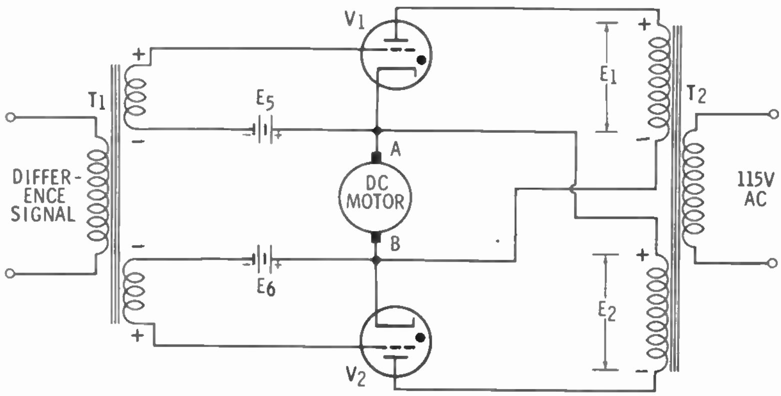
A15. **Phase** and **magnitude** of the difference signal determine armature direction and speed, respectively.

Thyratron DC Servo Amplifier

One way to obtain a greater amount of power from a DC servo amplifier is to use **thyratron** tubes. A thyratron is a gas-filled tube capable of passing eight or more amps as compared to the milliamps of a vacuum tube.

A thyratron has a **firing potential** determined by its plate and grid voltages. Assuming a given bias voltage on the grid, plate voltage can be gradually increased until it reaches a value which overcomes the repelling effect of the grid. At this point, plate current immediately rises from zero to a value determined solely by the plate voltage. The grid no longer has control over the current. The usual method of interrupting the plate current is to shut off the plate voltage.

A typical thyratron servo amplifier is shown below.



A BIDIRECTIONAL THYRATRON DC SERVO AMPLIFIER

T_2 is connected so that the plate voltages of V_1 and V_2 are 180° out of phase. E_5 and E_6 place a bias on each grid of sufficient value so that no plate current will flow when the difference signal is zero. T_1 is connected so grid voltages are in phase with each other as shown in the diagram.

Assume a difference signal on T_1 that causes the grids to swing positive while the plate voltage of V_1 is going positive. V_1 will conduct. Current will flow in the secondary of T_2, through the DC servomotor from B to A, and back to the cathode of V_1. During this half cycle the plate of V_2 is negative and the tube will not conduct. When the plate of V_2 becomes positive during the next half cycle, its grid signal is going negative and prevents the thyratron from conducting.

When the phase of the difference signal is reversed, the grid of V_2 is going positive at the same time as its plate. Current flows through the servomotor in the opposite direction, from A to B, causing it to rotate in the other direction.

As in the vacuum-tube amplifier, the direction of motor rotation is determined by the phase of the difference signal with respect to the voltage phase on the thyratron plates. Rotation speed is controlled by the magnitude of the signal.

Duration of plate current flow varies in accordance with the magnitude of the input difference signal. A low value signal allows the tube to remain at firing potential only a short period of time. To obtain a longer firing duration, some amplifiers use a means of phase-shifting control. A separate voltage, 120° out of phase with the plate transformer voltage, is added to the difference signal, allowing the grid to rise to firing potential sooner.

Q16. A thyratron conducts (more, less) current than a vacuum tube.

Q17. What is the difference between the schematic symbols for a thyratron and a vacuum tube?

Q18. Firing potential of a thyratron is determined by the ---- and ----- potentials.

Q19. When E_1 is negative to positive (top to bottom) and the grid of V_1 is going positive, which tube will conduct? (See illustration on opposite page.)

Your Answers Should Be:

A16. A thyratron conducts **more** current than a vacuum tube.

A17. The schematic symbol for a thyratron has a **large dot within its envelope**; a triode does not.

A18. Firing potential of a thyratron is determined by the difference of potential between **grid** and **plate.**

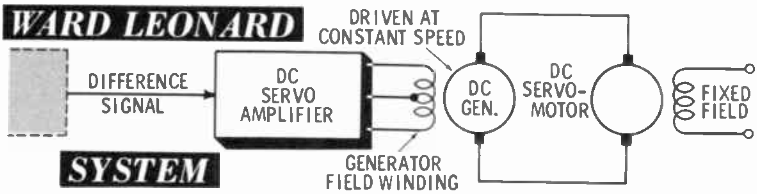
A19. With the conditions indicated, V_2 **will conduct.** When the plate of V_1 is negative, the plate of V_2 will be positive and the tube is capable of conducting. Since the input voltages to the grids are in phase, the grid of V_2 will also be going positive, allowing plate current to flow.

ELECTROMECHANICAL DC SERVO AMPLIFIERS

When large amounts of power are required to move a load, electromechanical DC servo amplifiers are used. Two of these are the Ward Leonard system and the amplidyne.

The Ward Leonard System as an Amplifier

The principles of a **Ward Leonard system** were explained in a previous chapter. When used in a servo system, it is connected as shown below.



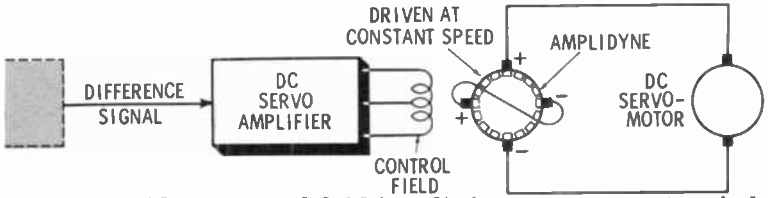
The field winding of the DC generator is in the output circuit of a vacuum-tube amplifier. The output of the generator is controlled by the strength of its magnetic field. The value of current through the field will be determined by the size of the amplified difference signal. A large difference signal will cause the servomotor to attain high speed; a smaller signal a lower speed.

When the phase of the difference signal reverses, the output polarity of the servo amplifier will also reverse, changing the direction of the magnetic field in the generator. The polarity of the generator output will reverse and the armature of the servomotor will change its direction.

An Amplidyne as an Amplifier

The **amplidyne** is a modified DC generator capable of power amplification of more than 10,000 times. A DC generator, described in an earlier chapter, uses about 100 watts of power in its field coils to generate 10 kilowatts of power. During its operation, the rotating armature develops a large reaction flux at right angles to the field. By short-circuiting the armature at this point, as shown in the diagram below, and reducing the power applied to the field to 1 watt, the same amount of power can be developed as before.

AMPLIDYNE IN A SERVO SYSTEM



The amplidyne control field is split into two separate windings and connected to the output of the servo amplifier. With no difference signal, the voltages across the two coils are equal and opposite, causing no generator output. With a difference signal fed to the servo amplifier, its output and the coil voltages become unbalanced. The coil with the higher voltage determines the direction of the magnetic field. The amplidyne amplifies the power of the field in exciting the armature of the servomotor.

Q20. Number the following DC servo amplifiers in descending order of power output level. The device having the largest output should be labeled #1.

Thyratron amplifier
Vacuum-tube amplifier
Amplidyne
Ward Leonard system

Q21. The Ward Leonard system consists of a(n) __ generator and a(n) __ servomotor.

Q22. An amplidyne has ___ pairs of brushes; one pair is _____ __________ to increase output.

Your Answers Should Be:

A20. In descending order of power output level, the DC servo amplifiers should be listed as: (1) Amplidyne, (2) Ward Leonard system, (3) Thyratron amplifier, and (4) Vacuum-tube amplifier.

A21. The Ward Leonard system consists of a DC generator and a DC servomotor.

A22. An amplidyne has **two** pairs of brushes; one pair is **short-circuited** to increase output.

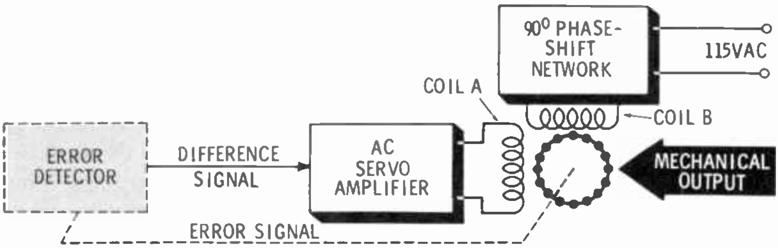
AC SERVO AMPLIFIERS

In most DC applications, the excitation voltages are applied to the servomotor armature; in AC servomotors, the voltages are applied to the stator.

A Basic AC Servo Amplifier

The illustration below shows an AC servo amplifier connected to an AC servomotor, a two-phase induction type.

BASIC AC SERVO AMPLIFIER AND MOTOR



Coil B, the reference winding, is excited from an AC line through a 90° phase-shifting network. Since the same line feeds the rest of the servo system, the difference signal, in phase or 180° out of phase with the line, will either lead or lag the voltage in coil B by 90°. The servo amplifier amplifies the difference signal before it is applied to coil A.

Since the magnetic fields in the coils are 90° out of phase, the motor will rotate in a direction to correct the error signal fed back to the error detector. If the phase of the difference signal changes, the magnetic field in coil A reverses, changing the direction of motor rotation.

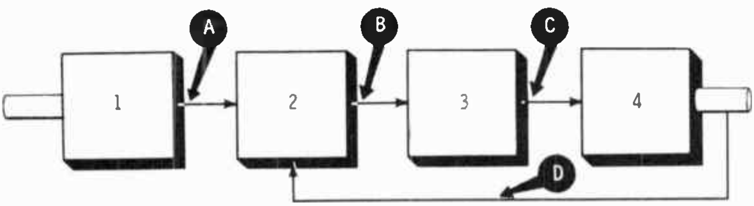
Types of AC Servo Amplifiers

AC servo amplifiers are always of the electronic type. The three most predominant types of circuits used include thyratron, multistage, and single-stage vacuum-tube amplifiers.

Thyratron Amplifier—Like its DC counterpart, the AC amplifier employs thyratrons in pairs. However, only one of the tubes will conduct during one phase of the difference signal.

Multistage Vacuum-Tube Amplifier—There are usually at least three stages in such an amplifier. The first stage adjusts the phase of the difference signal to insure that the two induction-motor fields will be 90° out of phase. The second is a stage of phase inversion to permit the final stage to operate as a push-pull amplifier for maximum output.

Single-Stage Vacuum-Tube Amplifier—In servo systems where power-output requirements are low, a cathode follower with one of the induction-motor coils in its cathode circuit will serve the purpose.



Q23. Provide the proper titles for the numbered blocks in the servo-system diagram above.

Q24. What is the signal that appears at A above?

Q25. What determines the magnitude of signal B?

Q26. The name of signal D is _____ ______.

Q27. In most applications, the output of block 3 is a(an) __ or pulsating __ voltage.

Q28. Block 4 can be an AC __________ motor or a DC _____ field motor.

Q29. Electronic servo amplifiers employ either ___________ or ______ _____; the ____ ________ system and the __________ are electromechanical servo amplifiers.

Your Answers Should Be:

A23. The titles for the blocks in the servo system diagram are: **(1) Input Detector, (2) Error Detector, (3) Servo Amplifier, (4) Servomotor.**

A24. A in the diagram is the **input signal; it identifies the rotational position of the input shaft.**

A25. The magnitude of B, the difference signal, is **determined by the amount of difference existing between the input (A) and error (D) signals.**

A26. The name of signal D is **error signal.**

A27. In most applications the output of the servo amplifier is an **AC** or pulsating **DC** voltage.

A28. Block 4 can be an AC **induction** motor or a DC **shunt**-field motor.

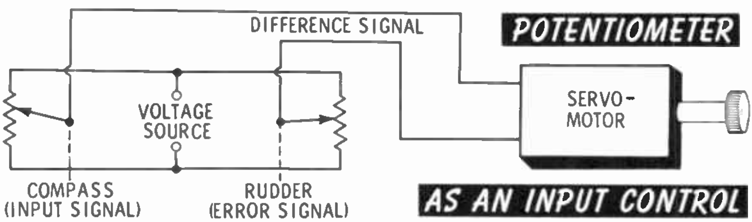
A29. Electronic servo amplifiers employ either **thyratrons** or **vacuum tubes**; the **Ward Leonard** system and the **amplidyne** are electromechanical servo amplifiers.

INPUT CONTROL FUNCTIONS

Thus far you have learned how the output control devices (servo amplifiers and motors) perform the function of positioning a load in response to a signal from the input control section. The question that remains to be answered is how the input control devices detect and match the input and error signals to generate a difference signal.

Input Control Devices

Earlier in this chapter you were introduced to a hypothetical ship steering system. A simplified version of the system is shown below.



POTENTIOMETER AS AN INPUT CONTROL

Synchromechanisms as Input Control Devices

Although a potentiometer is used for input and error detection for many small servo systems, there are devices which accomplish these functions better. The most widely used is a device called a **synchro**, or **synchromechanism.**

A synchro is basically a transformer with one of its windings free to rotate. Using this principle, a combination of synchros can transmit positional data electrically from one location to another or detect and compute the difference existing between two or more shaft positions. There are five different types of synchro units.

Synchro Transmitter—This unit is sometimes called a **synchro generator.** When its **rotor** (rotating winding) is turned mechanically, the generator develops a set of voltage signals which identify the position of the rotor shaft.

Synchro Receiver—This receiver is sometimes called a **synchro motor, repeater,** or **follower.** It has the same electrical construction as the synchro transmitter and receives voltage signals to position its rotor at the same positional angle as the transmitter rotor.

Differential Synchro Transmitter—This transmitter develops and transmits the sum or difference (depending on connections) of an electrical and a mechanical input signal.

Differential Synchro Receiver—This receiver develops a mechanical (rotational) output representing the sum or difference of two electrical input signals.

Synchro Control Transformer—This transformer has both an electrical and a mechanical input. It computes, in the form of an electrical signal, the positional difference of the two inputs. The output can be used as the input to a servo amplifier.

Q30. In the diagram on the opposite page, the potentiometer arms are selecting the same amount of resistance. The servomotor (will, will not) turn.

Q31. A synchro unit acts like a(n) ___________ with a(n) ________ winding.

Q32. Which syncho unit can be used to transmit a compass direction to a remote location?

Q33. Which synchro unit can be used as an error detector in a servo system?

Your Answers Should Be:

A30. The servomotor **will not** turn. If the resistances at the arms are equal, the selected voltages will be equal. The voltage difference at the motor terminals will be zero.

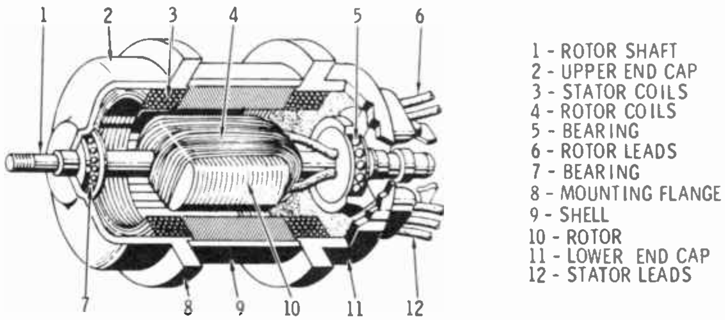
A31. A synchro unit acts like a **transformer** with a **rotating** winding.

A32. A **synchro transmitter** (develops voltages which identify the angular position of its rotor) can be used to transmit a compass direction.

A33. Since it computes the positional difference of an electrical and a mechanical input, a **synchro control transformer** can be used as an error detector in a servo system.

SYNCHRO FUNDAMENTALS

You have learned that a synchro unit is constructed physically as a generator (or motor) but operates electrically as a transformer. The figure below shows the construction details of a synchro transmitter. A synchro receiver is identical with the exception that it has a mechanical damper to prevent free-running or oscillation of its rotor. The differential units and the control transformer have three rotor windings instead of one.

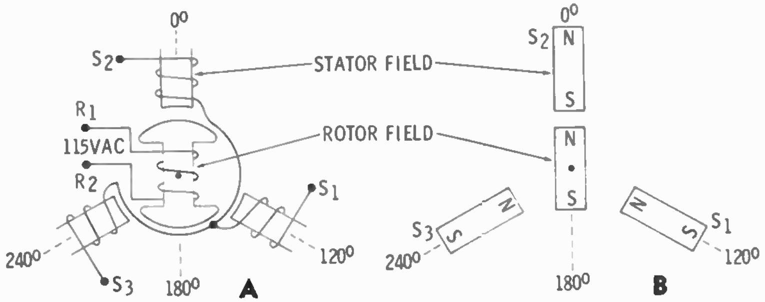


SYNCHRO-TRANSMITTER CONSTRUCTION

Magnetic Fields in a Synchro

In the illustration below, Part A shows the schematic symbol for a synchro transmitter or receiver. Figure B substitutes bar magnets for the rotor and stator fields.

REPRESENTATION OF A SYNCHRO UNIT



Schematic Symbol | **Magnetic Analogy**

S_1, S_2, and S_3 are the three stator windings of a synchro. They are physically displaced 120° apart, or at equal distances around a circle. The rotor is free to rotate and is said to be positioned at 0° when the axis of the rotor is in line with the axis of winding S_2, as shown in part A.

Assuming that the windings are energized, their magnetic fields can be represented by the bar magnets shown in part B. Regardless of its angular position at the time the fields are energized, the rotor will turn to the position shown. The north pole of the rotor will be attracted to the south pole of S_2. The north poles of S_1 and S_3 are at equal distances to the left and right of the rotor and will pull the south pole of the rotor to the 180° position. No matter how the rotor is manually rotated, it will return to the position shown.

If the polarities of all four magnets are reversed at the same time, as in the case of AC magnetic fields, the rotor will remain in the same position. If the three stator magnets are rotated together to the left or right, the rotor magnet will follow the rotational movement.

Q34. If magnet S_2 in part B above is removed, in which direction, if any, would the rotor turn?

Q35. If magnet S_1 is removed, in which direction, if any would the rotor turn?

Your Answers Should Be:

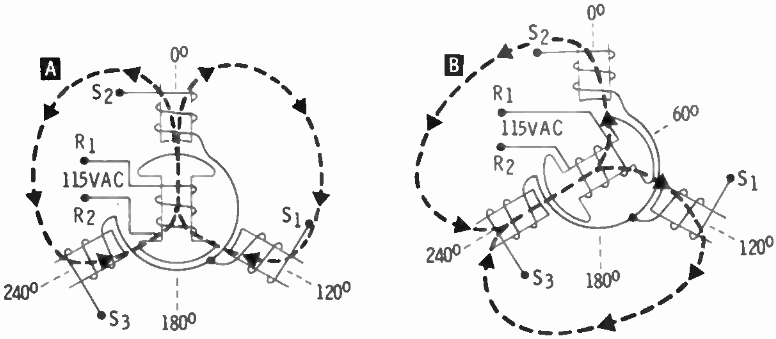
A34. The rotor will not turn if magnet S_2 is removed. The north poles of S_1 and S_2 will retain an equal attraction for the south pole of the rotor, keeping it in the same position.

A35. The rotor will turn clockwise if magnet S_1 is removed. It will turn until its N and S poles are at equal distances from S_2 and S_3, respectively.

Transformer Action in a Synchro Unit

It is apparent that the rotor will align itself with the resultant field of the three stator windings. In the diagram shown below, the rotor winding is the primary and the stator windings the secondary.

TRANSFORMER ACTION IN A SYNCHRO TRANSMITTER



In part A, the rotor is positioned at zero degrees. When 115V AC is applied to the rotor winding (the primary), a magnetic field is developed. As in any transformer, lines of flux cut the secondary windings inducing a voltage in them.

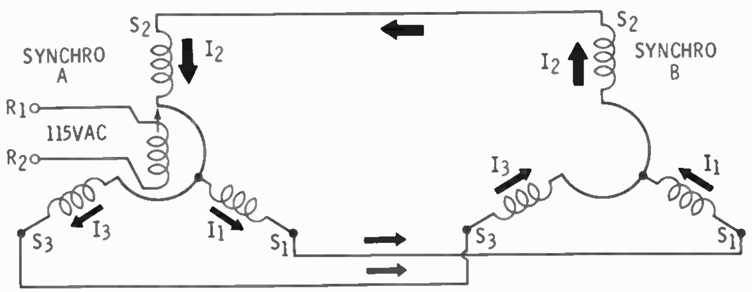
The amount of voltage induced depends on the relative position of the rotor and stator windings. In part A, maximum voltage is induced in the S_2 winding because the rotor winding is exactly parallel to it. (Lines of flux are cutting the coil turns at right angles.) Windings S_1 and S_3 have a smaller induced voltage since the rotor winding and its magnetic field are at a 60° angle to their axes. The resultant induced magnetic field is shown by broken lines.

In part B, the rotor is at the 60° position and aligned parallel to the S_3 winding. If the stator terminals are again short-circuited to permit current flow, maximum voltage will be developed across S_3. Since the rotor is now displaced 60° to either side of S_1 and S_2, lesser but equal voltages are developed in their windings. The resultant magnetic field is shown by broken lines.

Now imagine the rotor positioned at 30°. In this position it is 90° from (at right angles to) the S_1 winding. The lines of flux are parallel to the S_1 coil turns and not cutting across them. No current or voltage is induced. The rotor axis is 30° from S_2 and S_3, and lines of flux are cutting across these windings at an angle that is 30° less than maximum (right angles). The voltage induced is greater than that of the 60° rotor position in part B.

In the figure below, the stator windings of two synchro units are connected together. Because of the position of the

CURRENT FLOW IN TWO SYNCHRO UNITS



rotor in the left-hand synchro unit, maximum voltage is developed across S_2 and lesser voltages across S_1 and S_3. The voltages are such that induced current I_2 is equal to the sum of I_1 and I_3 induced in S_1 and S_3, respectively. Identical currents are flowing through the respective stators of synchro B. As a result, the voltages developed across the synchro-B stator windings are equal to those across the respective windings of synchro A.

Q36. Stator windings are placed ____ degrees apart.

Q37. The direction of the resultant magnetic fields in the two synchros above (will, will not) be the same.

Q38. Why is AC instead of DC used in a rotor winding?

Your Answers Should Be:

A36. Stator windings are placed 120 degrees apart.

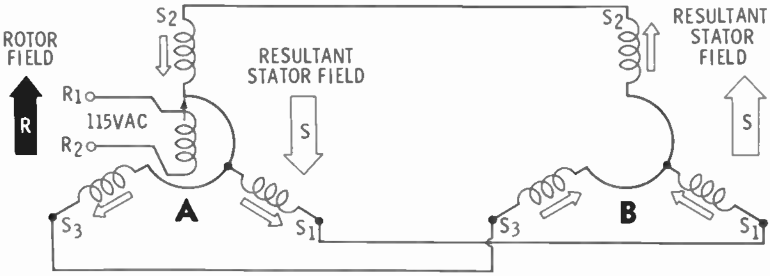
A37. The direction of the resultant magnetic fields in the two synchros **will not** be the same. Current flows through the stator coils of synchro B in a direction opposite to that in synchro A.

A38. AC is applied to a rotor winding because its **varying current will produce an increasing and decreasing magnetic field.**

A SYNCHRO TRANSMITTER-RECEIVER SYSTEM

The magnetic field produced by the primary of a transformer induces a current in the secondary. Current in the secondary winding develops a magnetic field that is opposite in polarity to the field in the primary. The diagram below shows a similar action occurring in a synchro. Direction of the rotor field is shown by a dark arrow. The induced fields in the individual stator winds are represented by small white arrows showing a direction in opposition to the rotor field. The large white arrow shows the direction of the resultant stator magnetic field.

COMPARISON OF RESULTANT MAGNETIC FIELDS

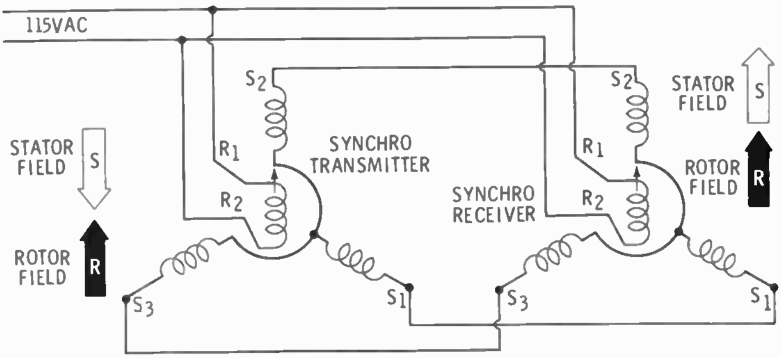


In synchro A, the direction of the developed rotor field is up, as shown. The induced magnetic fields in the individual stators are along their axis but in a downward direction. The combination of all the stator fields produces the resultant field shown by the large white arrow. It is an induced field and is directly opposite to the rotor field.

The induced stator currents flowing in synchro B take an opposite direction to those in A. Therefore, the individual stator fields produced are also in an opposite direction. And the resultant stator field is in an opposing direction to its counterpart in synchro A. Therefore, the synchro-B stator field takes the same direction as the synchro-A rotor field.

Following is a synchro transmitter and receiver. Note that the two rotors are connected to the same AC source.

MAGNETIC FIELDS IN A TRANSMITTER-RECEIVER SYSTEM



Since the rotor currents are in phase, the directions of their magnetic fields will be identical. The stator field in the transmitter is opposite to the rotor field. However, the stator field of the receiver will be in the same direction as the transmitter rotor field. The rotor field of the receiver will be attracted to align itself in the stator field direction.

If the transmitter rotor is turned, the stator fields in both synchros will rotate the same amount. The receiver stator field will maintain the same direction as the transmitter rotor field. Thus, the rotor of the receiver will follow the stator field.

Q39. If a synchro transmitter rotor is pointing toward 90°, the transmitter stator field is pointing toward ____, the receiver stator field is pointing toward ____, and the receiver rotor is pointing toward ____.

Q40. For proper operation, the _ _ _ _ _ _ of the transmitter and receiver must be connected to the same voltage source.

Your Answers Should Be:

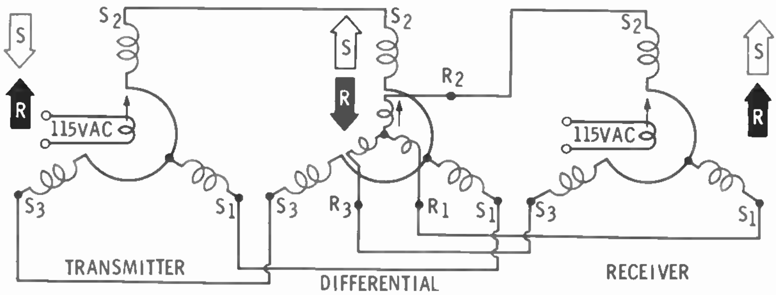
A39. If a synchro transmitter rotor is pointing toward 90°, the transmitter stator field is pointing toward 270°, the receiver stator and rotor fields are pointing toward 90°.

A40. For proper operation the rotors of the transmitter and receiver must be connected to the same voltage source.

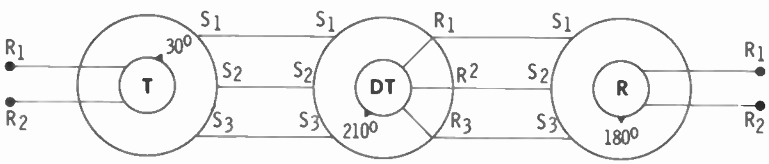
DIFFERENTIAL SYNCHROS

Differential synchro transmitters and **receivers** are similarly constructed and have a three-winding rotor.

TRANSMITTER-DIFFERENTIAL-RECEIVER SYNCHRO SYSTEM



Zero position for a synchro differential is where R_2 lines up with S_2. The stator windings of the transmitter develop a magnetic field in the differential stators as shown. This field induces an opposing differential rotor field which develops a receiver stator field in the opposite direction. The interaction of these fields when the transmitter and differential rotors are turned cause the receiver rotor to turn to the difference between the other two rotor positions.

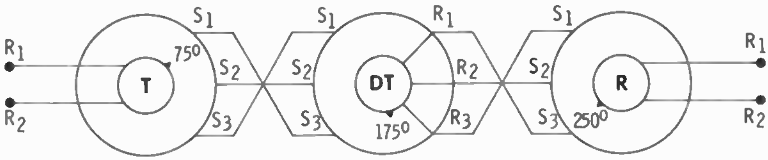


SUBTRACTION BY A T-DT-R SYNCHRO SYSTEM

With T and DT motors mechanically turned to 30° and 210°, the interacting magnetic fields will cause rotor R to electrically turn to the difference position, 180°.

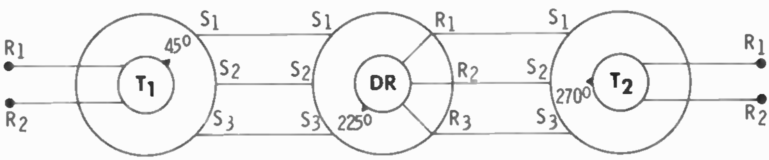
Differential transmitters will add if connected in the manner shown below. Here, S_1 and S_3 of T are crossed to S_3 and S_1 of DT. R_1 and R_3 of DT are crossed to S_3 and S_1 of R. The angular positions of 75° on T and 175° on DT are added to produce an R rotor position of 250°.

ADDITION BY A T-DT-R SYNCHRO SYSTEM



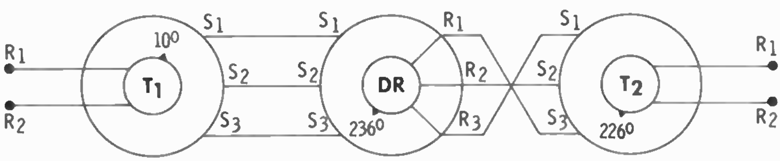
When connected to two synchro transmitters, the DR rotor position is the sum or difference of the rotor positions of the two generators. The synchros below are connected for subtraction.

SUBTRACTION BY A T-DR-T SYNCHRO SYSTEM



Addition with a differential receiver recording a sum of two angles is accomplished by the following connections.

ADDITION BY A T-DR-T SYNCHRO SYSTEM



Q41. In a T-DR-T system, the inputs to the DR are (electrical, mechanical) and its output is

___________.

Q42. In a T-DT-R system, one DT input is electrical and the other mechanical; the output is

___________.

Your Answers Should Be:

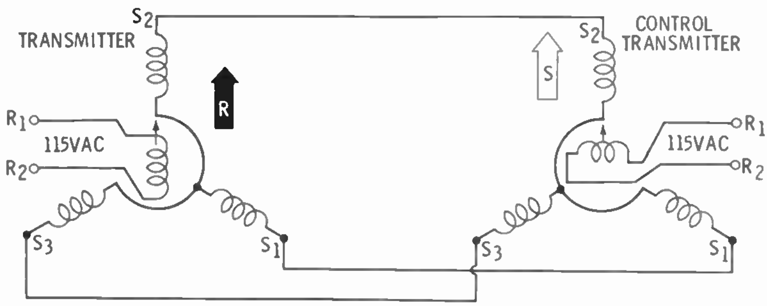
A41. In a T-DR-T system, the inputs to the DR are **electrical** and its output is **mechanical.**

A42. In a T-DT-R system, one DT input is electrical and the other mechanical; the output is **electrical.**

THE SYNCHRO CONTROL TRANSFORMER

A control transformer (CT) has three stator windings. Its rotor is designed to generate a voltage, the amplitude of which represents the difference between two angular positions and the phase of which shows the direction of difference.

A SYNCHRO TRANSMITTER-CONTROL TRANSFORMER SYSTEM



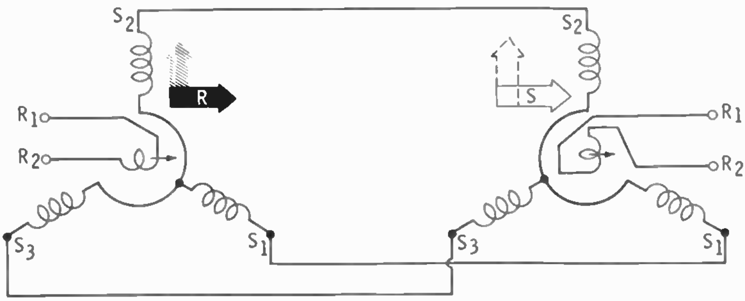
The rotor of a control transformer is at zero position when it is at right angles to S_2 as shown in the diagram above. The induced stator field in the CT will be in the same direction as the rotor field of T. In the positions shown, no voltage will be produced between R_1 and R_2 of the CT.

If the T rotor is moved in a clockwise direction, the CT stator field will follow. As the stator field of the CT rotates, its flux lines cut the rotor winding. Rotation in a clockwise direction will produce a voltage in the rotor in phase with the AC on the T rotor. When the CT stator field is 90°, the voltage between R_1 and R_2 is maximum. A 360° rotation of the stator field will produce an AC sine wave.

If the T rotor is turned in a counterclockwise direction, the flux lines of the CT stator field will cut its rotor winding in the opposite direction. This will produce a voltage across the CT rotor 180° out of phase with the T rotor voltage.

The rotor of the control transformer will not turn as the result of the moving stator field. It can be rotated by manually turning the rotor shaft. The following diagram demonstrates what occurs when the rotor is turned.

ROTATING CT ROTOR TO REDUCE VOLTAGE OUTPUT TO ZERO



Assume that the T rotor has been turned clockwise from 0° to 90°. The CT stator field will make the same rotation. If the CT rotor remains at 0°, maximum voltage in phase with the AC line voltage can be measured across R_1 and R_2. If the CT rotor is now turned to 90°, the voltage reading will reduce to zero. In this position the rotor winding is at right angles to the stator field.

It is evident that this type of synchro system can be used to develop the difference voltage for a servo system. The synchro transmitter rotor can reflect the desired angular position and the CT rotor the present position of a load. If there is a difference in positions, the magnitude of the voltage on the CT rotor will be proportional to the amount of difference, and the phase of the voltage will reveal the direction of difference.

If more than two position readings are required in a servo system, a differential transmitter can be substituted in place of the synchro transmitter. The output of the DT to the CT will be the sum or difference (depending on the stator and rotor connections) of two position conditions.

Q43. When the stator field of a CT rotates in a(n) ---------- direction, the developed voltage is in phase with transmitter rotor voltage.

Q44. Maximum voltage is developed if the stator field and rotor winding are (at right angles, parallel).

Your Answers Should Be:

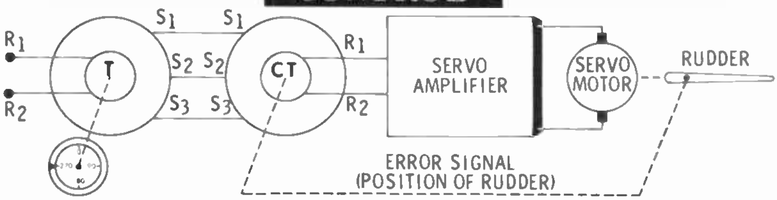
A43. When the stator field of a CT rotates in a **clockwise** direction, the developed voltage is in phase with transmitter rotor voltage.

A44. Maximum voltage is developed when the stator field and rotor winding are **parallel.**

THE COMPLETE SERVO SYSTEM

The diagram below illustrates a complete system.

SYNCHRO SYSTEM USED AS INPUT CONTROL



The rotor of the synchro transmitter is physically connected to a compass. As the ship swings right or left of the established course (set at rotor zero position), the stator field of the control transformer will follow the transmitter rotor. This will generate a voltage across the rotor of the control transformer. The amplitude of the voltage will be proportional to the difference between compass and rudder positions. The phase will show whether the compass has rotated clockwise or counterclockwise.

The voltage output of the CT rotor is fed to the servo amplifier as the difference signal. This unit amplifies the signal to the level of power required to operate the servo motor. The amplitude of the signal will determine how fast the motor will turn the rudder. The phase of the signal will control the direction in which it will be turned.

When the rudder angle has matched the off-course angle of the compass, the motor will stop. Since the rudder is connected to the rotor of the control transformer, an error signal is returned to this synchro unit. As the rudder is turned to its desired position, the CT rotor is approaching right angle (zero voltage) alignment with the stator field. This causes the difference signal to decrease in amplitude until zero voltage is reached when compass and rudder angles are the same.

The rudder angle causes the ship to swing back to its course. A new difference signal is generated in the opposite phase. The motor turns the rudder in the opposite direction and toward amidships again. When the ship is finally on course, transmitter and control transformer rotors are in alignment and the difference signal is zero.

SERVO SYSTEM APPLICATIONS

Commercial and military aircraft use servo systems to operate the control surfaces of airplanes and as an automatic pilot to keep the plane on a desired course and altitude. Servos are also used in analog computers to detect and compute rates of change of quantities. With an amplidyne, industry uses servo systems to move and position heavy loads.

Military applications include the positioning of radar and heavy directional radio antennas, pointing of guns and missile launchers, automatic control of missile steering mechanisms, and other uses requiring precise positioning of a load or rapid data computation.

Q45. In the diagram on the opposite page, the _______ ____________ is an input detector, and the _______ ____________ is an error detector.

Q46. Since the servo amplifier output is being applied to the armature of the servo motor, the motor is (DC, AC).

Q47. If the motor were (DC, AC), the output would be applied to one of two fields in the motor.

Q48. The following synchro units have three windings on their rotors: (a) _____________ ____________; (b) _____________ _________.

Q49. The following synchro units have a single winding on their rotors: (a) ____________; (b) _________; (c) ________ ____________.

Your Answers Should Be:

A45. In the diagram on the opposite page, the **synchro transmitter** (T), is an input detector, and the **control transformer** (CT) is an error detector.

A46. Since the servo amplifier output is being applied to the armature of the servo motor, the motor is **DC.**

A47. If the motor were AC, the output would be applied to one of two fields in the motor.

A48. The following synchro units have three windings on their rotor: (a) **differential transmitter;** (b) **differential receiver.**

A49. The following synchro units have a single winding on their rotors: (a) **transmitter;** (b) **receiver;** (c) **control transformer.**

WHAT YOU HAVE LEARNED

1. A servo system is a combination of devices which permit automatic control and positioning of a load. Each system, large or small, includes two functions—input control and output control. The former detects a deviation between desired and existing position of a load and sends a correcting signal to the output control function which realigns the load.
2. The input control function contains an input detector and an error detector. The output control function has a servo amplifier and a servomotor. Two of these operations can be contained in a single device, or several mechanisms may be required to perform a single operation.
3. An open servo system has some of its operations performed by manual or semiautomatic means. A closed system is completely automatic.
4. An AC servomotor, normally an induction type, is used in a control system when low power and low speed are permissible. High torque and/or a wide speed range calls for a shunt or permanent magnet DC motor.

5. The purpose of a servo amplifier is to convert a difference signal into sufficient power and polarity to turn a servomotor in the correct direction at the desired speed.
6. Electronic servo amplifiers, vacuum-tube or thyratron, can be designed to drive either an AC or DC servomotor.
7. When large amounts of power are required to move a load in a servo system, electromechanical DC servo amplifiers are used. Examples are the Ward Leonard DC generator-motor and the amplidyne. Because it has a short-circuited generator armature, an amplidyne has a power amplification factor of up to 10,000 or greater.
8. The most widely used device to perform the input control function of input- and error-signal detection is the synchro. A synchro unit is basically a transformer with one of its windings free to rotate. Synchro units may also be used to transmit data between remote locations.
9. A synchro transmitter or receiver contains three stator windings (placed 120° apart) and a rotor with a single winding. If AC is applied to the rotor, the magnetic field induces current and a magnetic field in the stator windings. The rotor and stator fields lie along the same axis but take opposite directions. If the stator terminals of two synchro units are connected, the induced stator field of the second unit will take the same direction as the rotor field of the first unit.
10. A data-transmission system can be formed by connecting the stator windings of a synchro transmitter to those of a synchro receiver. Since the receiver stator field follows the rotation of the transmitter rotor field and since the receiver rotor field will line up with its stator field, the receiver will precisely duplicate the angular position of the transmitter.
11. Differential synchro transmitters and receivers have three stator windings and three rotor windings. A differential transmitter receives an electrical and a mechanical input and delivers an electrical output. A differential receiver accepts two electrical inputs and delivers a mechanical output. When connected to other synchro units, a differential will develop the sum or difference of two positions, depending on the connections.

12. A control transformer has three stator windings and a single-coil rotor which will develop a voltage of an amplitude proportional to the difference of its rotor and stator fields, and of a phase representative of the direction of difference. When a synchro transmitter is connected to a control transformer, the pair can perform the input control function of a servo system.

Index to the Series

Boldface numeral indicates volume number: lightface numeral indicates page in that volume. For example:

Ampere, **1**-48, **3**-18

means that ampere appears on page 48 of Volume 1 and on page 18 of Volume 3.

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