

# CHAPTER 4

## ALTERNATING CURRENT MOTORS

### LEARNING OBJECTIVES

Upon completion of this chapter you will be able to:

1. List three basic types of ac motors and describe the characteristics of each type.
2. Describe the characteristics of a series motor that enable it to be used as a universal motor.
3. Explain the relationships of the individual phases of multiphase voltages as they produce rotating magnetic fields in ac motors.
4. Describe the placement of stator windings in two-phase, ac motors using rotating fields.
5. List the similarities and differences between the stator windings of two-phase and three-phase ac motors.
6. State the primary application of synchronous motors, and explain the characteristics that make them suitable for that application.
7. Describe the features that make the ac induction motor the most widely used of electric motors.
8. Describe the difference between the rotating field of multiphase motors and the "apparent" rotating field of single-phase motors.
9. Explain the operation of split-phase windings in single-phase ac induction motors.
10. Describe the effects of shaded poles in single-phase, ac induction motors.

### INTRODUCTION

Most of the power-generating systems, ashore and afloat, produce ac. For this reason a majority of the motors used throughout the Navy are designed to operate on ac. There are other advantages in the use of ac motors besides the wide availability of ac power. In general, ac motors cost less than dc motors. Some types of ac motors do not use brushes and commutators. This eliminates many problems of maintenance and wear. It also eliminates the problem of dangerous sparking.

An ac motor is particularly well suited for constant-speed applications. This is because its speed is determined by the frequency of the ac voltage applied to the motor terminals.

The dc motor is better suited than an ac motor for some uses, such as those that require variable-speeds. An ac motor can also be made with variable speed characteristics but only within certain limits.

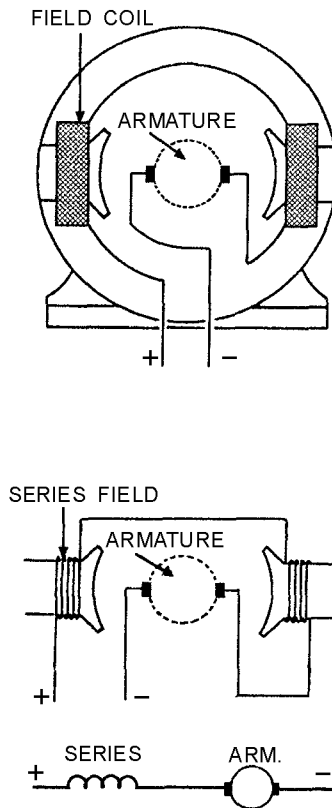
Industry builds ac motors in different sizes, shapes, and ratings for many different types of jobs. These motors are designed for use with either polyphase or single-phase power systems. It is not possible here to cover all aspects of the subject of ac motors. Only the principles of the most commonly used types are dealt with in this chapter.

In this chapter, ac motors will be divided into (1) series, (2) synchronous, and (3) induction motors. Single-phase and polyphase motors will be discussed. Synchronous motors, for purposes of this chapter, may be considered as polyphase motors, of constant speed, whose rotors are energized with dc voltage. Induction motors, single-phase or polyphase, whose rotors are energized by induction, are the most commonly used ac motor. The series ac motor, in a sense, is a familiar type of motor. It is very similar to the dc motor that was covered in chapter 2 and will serve as a bridge between the old and the new.

*Q1.* What are the three basic types of ac motors?

### SERIES AC MOTOR

A series ac motor is the same electrically as a dc series motor. Refer to figure 4-1 and use the left-hand rule for the polarity of coils. You can see that the instantaneous magnetic polarities of the armature and field oppose each other, and motor action results. Now, reverse the current by reversing the polarity of the input. Note that the field magnetic polarity still opposes the armature magnetic polarity. This is because the reversal effects both the armature and the field. The ac input causes these reversals to take place continuously.



**Figure 4-1.—Series ac motor.**

The construction of the ac series motor differs slightly from the dc series motor. Special metals, laminations, and windings are used. They reduce losses caused by eddy currents, hysteresis, and high reactance. Dc power can be used to drive an ac series motor efficiently, but the opposite is not true.

The characteristics of a series ac motor are similar to those of a series dc motor. It is a varying-speed machine. It has low speeds for large loads and high speeds for light loads. The starting torque is very

high. Series motors are used for driving fans, electric drills, and other small appliances. Since the series ac motor has the same general characteristics as the series dc motor, a series motor has been designed that can operate both on ac and dc. This ac/dc motor is called a universal motor. It finds wide use in small electric appliances. Universal motors operate at lower efficiency than either the ac or dc series motor. They are built in small sizes only. Universal motors do not operate on polyphase ac power.

*Q2. Series motors are generally used to operate what type of equipment?*

*Q3. Why are series motors sometimes called universal motors?*

### **ROTATING MAGNETIC FIELDS**

The principle of rotating magnetic fields is the key to the operation of most ac motors. Both synchronous and induction types of motors rely on rotating magnetic fields in their stators to cause their rotors to turn.

The idea is simple. A magnetic field in a stator can be made to rotate electrically, around and around. Another magnetic field in the rotor can be made to chase it by being attracted and repelled by the stator field. Because the rotor is free to turn, it follows the rotating magnetic field in the stator. Let's see how it is done.

Rotating magnetic fields may be set up in two-phase or three-phase machines. To establish a rotating magnetic field in a motor stator, the number of pole pairs must be the same as (or a multiple of) the number of phases in the applied voltage. The poles must then be displaced from each other by an angle equal to the phase angle between the individual phases of the applied voltage.

*Q4. What determines the number of field poles required to establish a rotating magnetic field in a multiphase motor stator?*

### **TWO-PHASE ROTATING MAGNETIC FIELD**

A rotating magnetic field is probably most easily seen in a two-phase stator. The stator of a two-phase induction motor is made up of two windings (or a multiple of two). They are placed at right angles to each other around the stator. The simplified drawing in figure 4-2 illustrates a two-phase stator.

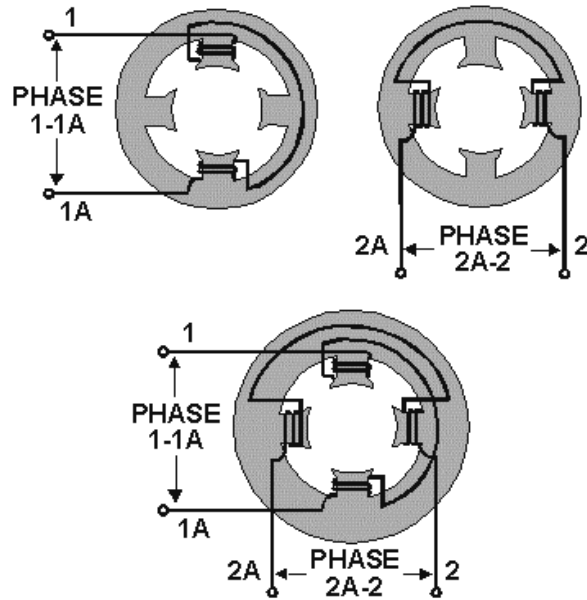


Figure 4-2.—Two-phase motor stator.

If the voltages applied to phases 1-1A and 2-2A are  $90^\circ$  out of phase, the currents that flow in the phases are displaced from each other by  $90^\circ$ . Since the magnetic fields generated in the coils are in phase with their respective currents, the magnetic fields are also  $90^\circ$  out of phase with each other. These two out-of-phase magnetic fields, whose coil axes are at right angles to each other, add together at every instant during their cycle. They produce a resultant field that rotates one revolution for each cycle of ac.

To analyze the rotating magnetic field in a two-phase stator, refer to figure 4-3. The arrow represents the rotor. For each point set up on the voltage chart, consider that current flows in a direction that will cause the magnetic polarity indicated at each pole piece. Note that from one point to the next, the polarities are rotating from one pole to the next in a clockwise manner. One complete cycle of input voltage produces a 360-degree rotation of the pole polarities. Let's see how this result is obtained.

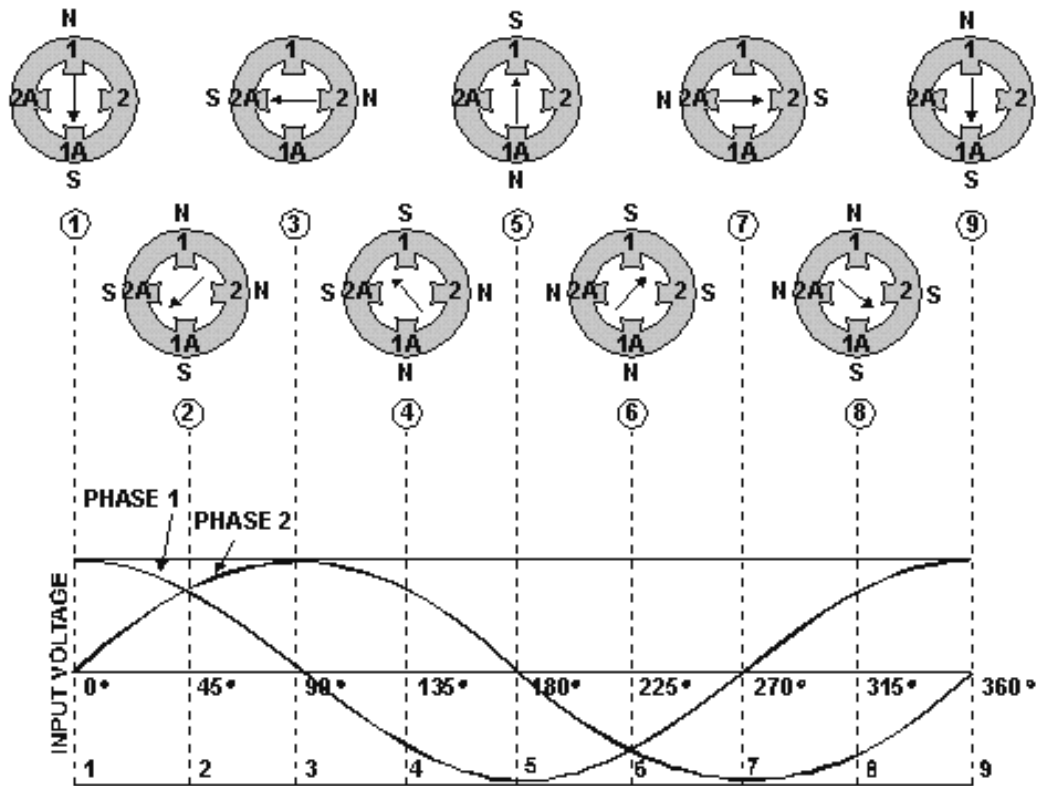


Figure 4-3.—Two-phase rotating field.

The waveforms in figure 4-3 are of the two input phases, displaced  $90^\circ$  because of the way they were generated in a two-phase alternator. The waveforms are numbered to match their associated phase. Although not shown in this figure, the windings for the poles 1-1A and 2-2A would be as shown in the previous figure. At position 1, the current flow and magnetic field in winding 1-1A is at maximum (because the phase voltage is maximum). The current flow and magnetic field in winding 2-2A is zero (because the phase voltage is zero). The resultant magnetic field is therefore in the direction of the 1-1A axis. At the 45-degree point (position 2), the resultant magnetic field lies midway between windings 1-1A and 2-2A. The coil currents and magnetic fields are equal in strength. At  $90^\circ$  (position 3), the magnetic field in winding 1-1A is zero. The magnetic field in winding 2-2A is at maximum. Now the resultant magnetic field lies along the axis of the 2-2A winding as shown. The resultant magnetic field has rotated clockwise through  $90^\circ$  to get from position 1 to position 3. When the two-phase voltages have completed one full cycle (position 9), the resultant magnetic field has rotated through  $360^\circ$ . Thus, by placing two windings at right angles to each other and exciting these windings with voltages  $90^\circ$  out of phase, a rotating magnetic field results.

Two-phase motors are rarely used except in special-purpose equipment. They are discussed here to aid in understanding rotating fields. You will, however, encounter many single-phase and three-phase motors.

*Q5. What is the angular displacement between field poles in a two-phase motor stator?*

## THREE-PHASE ROTATING FIELDS

The three-phase induction motor also operates on the principle of a rotating magnetic field. The following discussion shows how the stator windings can be connected to a three-phase ac input and have a resultant magnetic field that rotates.

Figure 4-4, views A-C show the individual windings for each phase. Figure 4-4, view D, shows how the three phases are tied together in a Y-connected stator. The dot in each diagram indicates the common point of the Y-connection. You can see that the individual phase windings are equally spaced around the stator. This places the windings  $120^\circ$  apart.

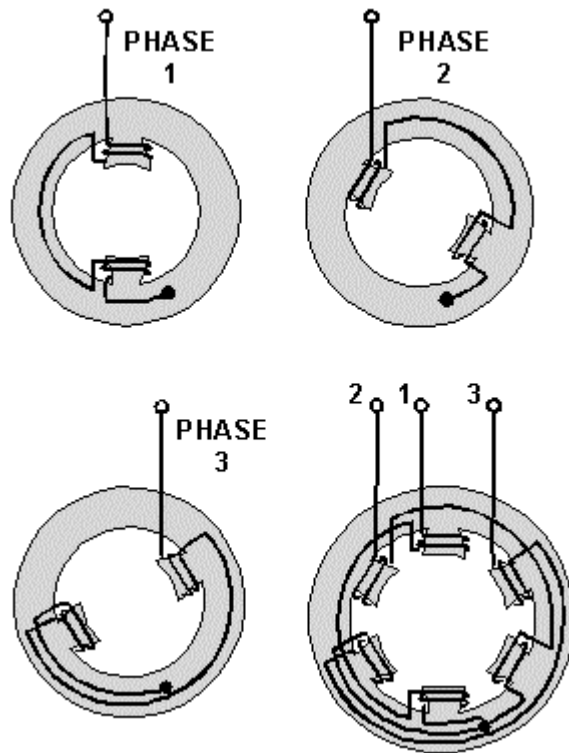


Figure 4-4.—Three-phase, Y-connected stator.

The three-phase input voltage to the stator of figure 4-4 is shown in the graph of figure 4-5. Use the left-hand rule for determining the electromagnetic polarity of the poles at any given instant. In applying the rule to the coils in figure 4-4, consider that current flows toward the terminal numbers for positive voltages, and away from the terminal numbers for negative voltages.

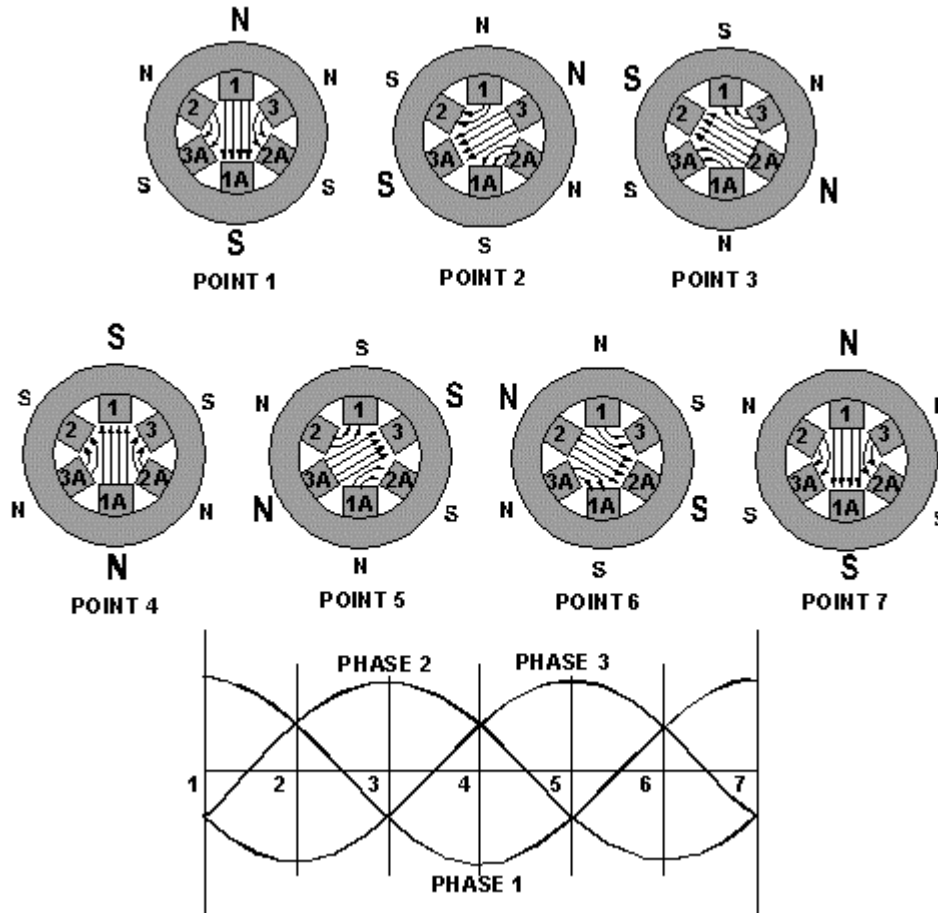


Figure 4-5.—Three-phase rotating-field polarities and input voltages.

The results of this analysis are shown for voltage points 1 through 7 in figure 4-5. At point 1, the magnetic field in coils 1-1A is maximum with polarities as shown. At the same time, negative voltages are being felt in the 2-2A and 3-3A windings. These create weaker magnetic fields, which tend to aid the 1-1A field. At point 2, maximum negative voltage is being felt in the 3-3A windings. This creates a strong magnetic field which, in turn, is aided by the weaker fields in 1-1A and 2-2A. As each point on the voltage graph is analyzed, it can be seen that the resultant magnetic field is rotating in a clockwise direction. When the three-phase voltage completes one full cycle (point 7), the magnetic field has rotated through  $360^\circ$ .

Q6. What is the major difference between a two-phase and a three-phase stator?

### ROTOR BEHAVIOR IN A ROTATING FIELD

For purposes of explaining rotor movement, let's assume that we can place a bar magnet in the center of the stator diagrams of figure 4-5. We'll mount this magnet so that it is free to rotate in this area. Let's also assume that the bar magnet is aligned so that at point 1 its south pole is opposite the large N of the stator field.

You can see that this alignment is natural. Unlike poles attract, and the two fields are aligned so that they are attracting. Now, go from point 1 through point 7. As before, the stator field rotates clockwise. The bar magnet, free to move, will follow the stator field, because the attraction between the two fields

continues to exist. A shaft running through the pivot point of the bar magnet would rotate at the same speed as the rotating field. This speed is known as synchronous speed. The shaft represents the shaft of an operating motor to which the load is attached.

Remember, this explanation is an oversimplification. It is meant to show how a rotating field can cause mechanical rotation of a shaft. Such an arrangement would work, but it is not used. There are limitations to a permanent magnet rotor. Practical motors use other methods, as we shall see in the next paragraphs.

## SYNCHRONOUS MOTORS

The construction of the synchronous motors is essentially the same as the construction of the salient-pole alternator. In fact, such an alternator may be run as an ac motor. It is similar to the drawing in figure 4-6. Synchronous motors have the characteristic of constant speed between no load and full load. They are capable of correcting the low power factor of an inductive load when they are operated under certain conditions. They are often used to drive dc generators. Synchronous motors are designed in sizes up to thousands of horsepower. They may be designed as either single-phase or multiphase machines. The discussion that follows is based on a three-phase design.

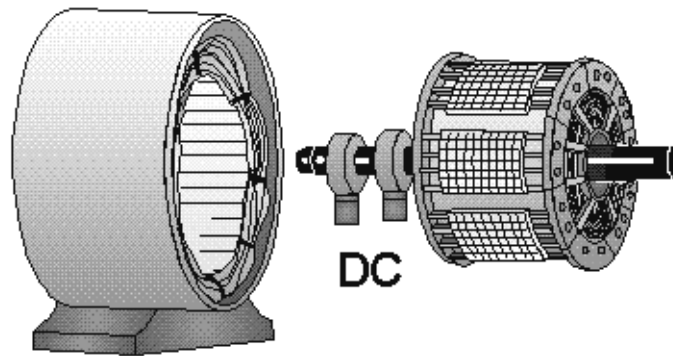


Figure 4-6.—Revolving-field synchronous motor.

To understand how the synchronous motor works, assume that the application of three-phase ac power to the stator causes a rotating magnetic field to be set up around the rotor. The rotor is energized with dc (it acts like a bar magnet). The strong rotating magnetic field attracts the strong rotor field activated by the dc. This results in a strong turning force on the rotor shaft. The rotor is therefore able to turn a load as it rotates in step with the rotating magnetic field.

It works this way once it's started. However, one of the disadvantages of a synchronous motor is that it cannot be started from a standstill by applying three-phase ac power to the stator. When ac is applied to the stator, a high-speed rotating magnetic field appears immediately. This rotating field rushes past the rotor poles so quickly that the rotor does not have a chance to get started. In effect, the rotor is repelled first in one direction and then the other. A synchronous motor in its purest form has no starting torque. It has torque only when it is running at synchronous speed.

A squirrel-cage type of winding is added to the rotor of a synchronous motor to cause it to start. The squirrel cage is shown as the outer part of the rotor in figure 4-7. It is so named because it is shaped and looks something like a turnable squirrel cage. Simply, the windings are heavy copper bars shorted



together by copper rings. A low voltage is induced in these shorted windings by the rotating three-phase stator field. Because of the short circuit, a relatively large current flows in the squirrel cage. This causes a magnetic field that interacts with the rotating field of the stator. Because of the interaction, the rotor begins to turn, following the stator field; the motor starts. We will run into squirrel cages again in other applications, where they will be covered in more detail.

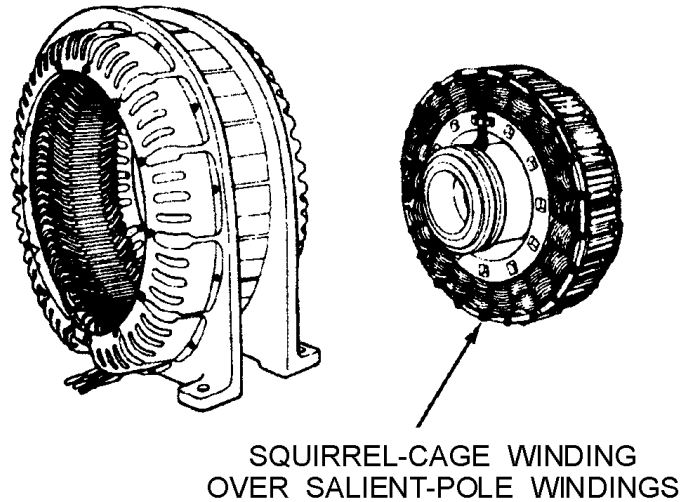


Figure 4-7.—Self-starting synchronous ac motor.

To start a practical synchronous motor, the stator is energized, but the dc supply to the rotor field is not energized. The squirrel-cage windings bring the rotor to near synchronous speed. At that point, the dc field is energized. This locks the rotor in step with the rotating stator field. Full torque is developed, and the load is driven. A mechanical switching device that operates on centrifugal force is often used to apply dc to the rotor as synchronous speed is reached.

The practical synchronous motor has the disadvantage of requiring a dc exciter voltage for the rotor. This voltage may be obtained either externally or internally, depending on the design of the motor.

*Q7. What requirement is the synchronous motor specifically designed to meet?*

## INDUCTION MOTORS

The induction motor is the most commonly used type of ac motor. Its simple, rugged construction costs relatively little to manufacture. The induction motor has a rotor that is not connected to an external source of voltage. The induction motor derives its name from the fact that ac voltages are induced in the rotor circuit by the rotating magnetic field of the stator. In many ways, induction in this motor is similar to the induction between the primary and secondary windings of a transformer.

Large motors and permanently mounted motors that drive loads at fairly constant speed are often induction motors. Examples are found in washing machines, refrigerator compressors, bench grinders, and table saws.

The stator construction of the three-phase induction motor and the three-phase synchronous motor are almost identical. However, their rotors are completely different (see fig. 4-8). The induction rotor is made of a laminated cylinder with slots in its surface. The windings in these slots are one of two types (shown in fig. 4-9). The most common is the squirrel-cage winding. This entire winding is made up of

heavy copper bars connected together at each end by a metal ring made of copper or brass. No insulation is required between the core and the bars. This is because of the very low voltages generated in the rotor bars. The other type of winding contains actual coils placed in the rotor slots. The rotor is then called a wound rotor.

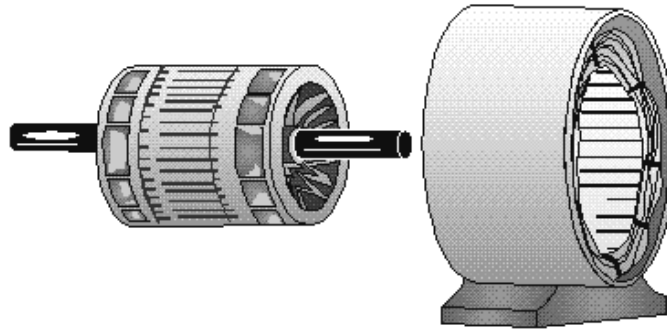


Figure 4-8.—Induction motor.

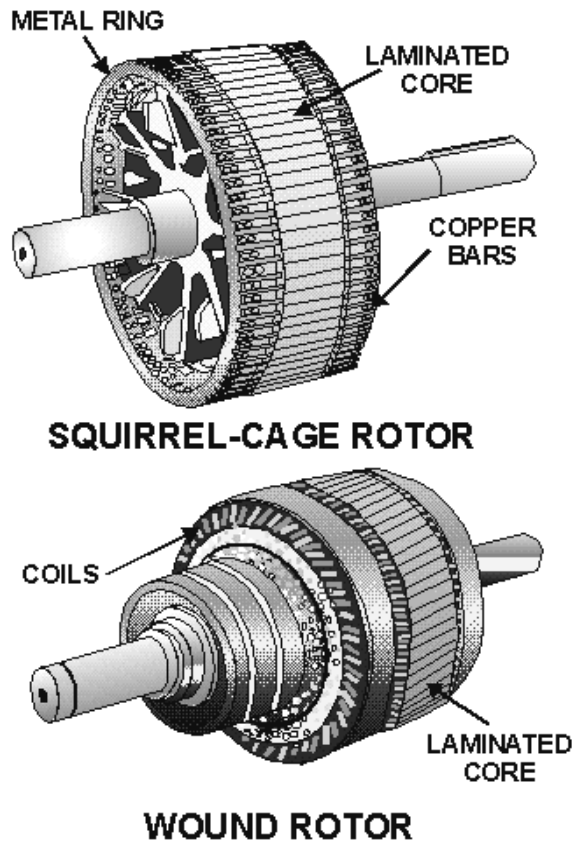


Figure 4-9.—Types of ac induction motor rotors.

Regardless of the type of rotor used, the basic principle is the same. The rotating magnetic field generated in the stator induces a magnetic field in the rotor. The two fields interact and cause the rotor to

turn. To obtain maximum interaction between the fields, the air gap between the rotor and stator is very small.

As you know from Lenz's law, any induced emf tries to oppose the changing field that induces it. In the case of an induction motor, the changing field is the motion of the resultant stator field. A force is exerted on the rotor by the induced emf and the resultant magnetic field. This force tends to cancel the relative motion between the rotor and the stator field. The rotor, as a result, moves in the same direction as the rotating stator field.

It is impossible for the rotor of an induction motor to turn at the same speed as the rotating magnetic field. If the speeds were the same, there would be no relative motion between the stator and rotor fields; without relative motion there would be no induced voltage in the rotor. In order for relative motion to exist between the two, the rotor must rotate at a speed slower than that of the rotating magnetic field. The difference between the speed of the rotating stator field and the rotor speed is called slip. The smaller the slip, the closer the rotor speed approaches the stator field speed.

The speed of the rotor depends upon the torque requirements of the load. The bigger the load, the stronger the turning force needed to rotate the rotor. The turning force can increase only if the rotor-induced emf increases. This emf can increase only if the magnetic field cuts through the rotor at a faster rate. To increase the relative speed between the field and rotor, the rotor must slow down. Therefore, for heavier loads the induction motor turns slower than for lighter loads. You can see from the previous statement that slip is directly proportional to the load on the motor. Actually only a slight change in speed is necessary to produce the usual current changes required for normal changes in load. This is because the rotor windings have such a low resistance. As a result, induction motors are called constant-speed motors.

*Q8. Why is the ac induction motor used more often than other types?*

*Q9. The speed of the rotor is always somewhat less than the speed of the rotating field. What is the difference called?*

*Q10. What determines the amount of slip in an induction motor?*

## **SINGLE-PHASE INDUCTION MOTORS**

There are probably more single-phase ac induction motors in use today than the total of all the other types put together.

It is logical that the least expensive, lowest maintenance type of ac motor should be used most often. The single-phase ac induction motor fits that description.

Unlike polyphase induction motors, the stator field in the single-phase motor does not rotate. Instead it simply alternates polarity between poles as the ac voltage changes polarity.

Voltage is induced in the rotor as a result of magnetic induction, and a magnetic field is produced around the rotor. This field will always be in opposition to the stator field (Lenz's law applies). The interaction between the rotor and stator fields will not produce rotation, however. The interaction is shown by the double-ended arrow in figure 4-10, view A. Because this force is across the rotor and through the pole pieces, there is no rotary motion, just a push and/or pull along this line.

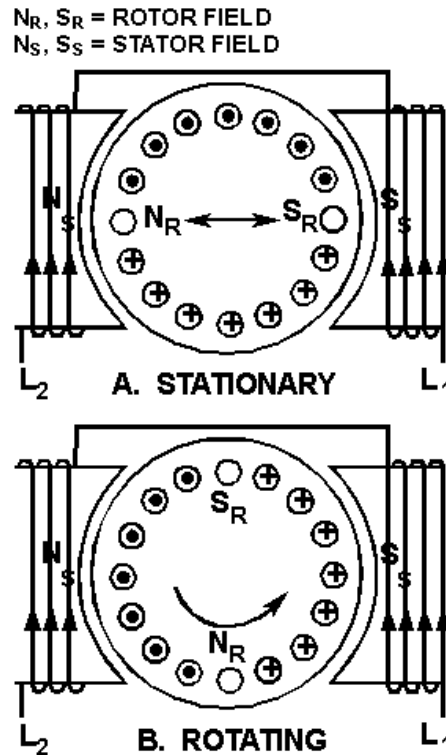


Figure 4-10.—Rotor currents in a single-phase ac induction motor.

Now, if the rotor is rotated by some outside force (a twist of your hand, or something), the push-pull along the line in figure 4-10, view A, is disturbed. Look at the fields as shown in figure 4-10, view B. At this instant the south pole on the rotor is being attracted by the left-hand pole. The north rotor pole is being attracted to the right-hand pole. All of this is a result of the rotor being rotated  $90^\circ$  by the outside force. The pull that now exists between the two fields becomes a rotary force, turning the rotor toward magnetic correspondence with the stator. Because the two fields continuously alternate, they will never actually line up, and the rotor will continue to turn once started. It remains for us to learn practical methods of getting the rotor to start.

There are several types of single-phase induction motors in use today. Basically they are identical except for the means of starting. In this chapter we will discuss the split-phase and shaded-pole motors; so named because of the methods employed to get them started. Once they are up to operating speed, all single-phase induction motors operate the same.

*Q11. What type of ac motor is most widely used?*

### Split-Phase Induction Motors

One type of induction motor, which incorporates a starting device, is called a split-phase induction motor. Split-phase motors are designed to use inductance, capacitance, or resistance to develop a starting torque. The principles are those that you learned in your study of alternating current.

**CAPACITOR-START.**—The first type of split-phase induction motor that will be covered is the capacitor-start type. Figure 4-11 shows a simplified schematic of a typical capacitor-start motor. The stator consists of the main winding and a starting winding (auxiliary). The starting winding is connected in parallel with the main winding and is placed physically at right angles to it. A 90-degree electrical

phase difference between the two windings is obtained by connecting the auxiliary winding in series with a capacitor and starting switch. When the motor is first energized, the starting switch is closed. This places the capacitor in series with the auxiliary winding. The capacitor is of such value that the auxiliary circuit is effectively a resistive-capacitive circuit (referred to as capacitive reactance and expressed as  $X_C$ ). In this circuit the current leads the line voltage by about  $45^\circ$  (because  $X_C$  about equals  $R$ ). The main winding has enough resistance-inductance (referred to as inductive reactance and expressed as  $X_L$ ) to cause the current to lag the line voltage by about  $45^\circ$  (because  $X_L$  about equals  $R$ ). The currents in each winding are therefore  $90^\circ$  out of phase - so are the magnetic fields that are generated. The effect is that the two windings act like a two-phase stator and produce the rotating field required to start the motor.

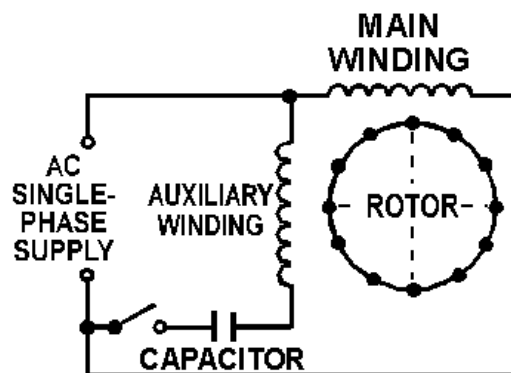


Figure 4-11.—Capacitor-start, ac induction motor.

When nearly full speed is obtained, a centrifugal device (the starting switch) cuts out the starting winding. The motor then runs as a plain single-phase induction motor. Since the auxiliary winding is only a light winding, the motor does not develop sufficient torque to start heavy loads. Split-phase motors, therefore, come only in small sizes.

**RESISTANCE-START.**—Another type of split-phase induction motor is the resistance-start motor. This motor also has a starting winding (shown in fig. 4-12) in addition to the main winding. It is switched in and out of the circuit just as it was in the capacitor-start motor. The starting winding is positioned at right angles to the main winding. The electrical phase shift between the currents in the two windings is obtained by making the impedance of the windings unequal. The main winding has a high inductance and a low resistance. The current, therefore, lags the voltage by a large angle. The starting winding is designed to have a fairly low inductance and a high resistance. Here the current lags the voltage by a smaller angle. For example, suppose the current in the main winding lags the voltage by  $70^\circ$ . The current in the auxiliary winding lags the voltage by  $40^\circ$ . The currents are, therefore, out of phase by  $30^\circ$ . The magnetic fields are out of phase by the same amount. Although the ideal angular phase difference is  $90^\circ$  for maximum starting torque, the  $30^\circ$ -degree phase difference still generates a rotating field. This supplies enough torque to start the motor. When the motor comes up to speed, a speed-controlled switch disconnects the starting winding from the line, and the motor continues to run as an induction motor. The starting torque is not as great as it is in the capacitor-start.

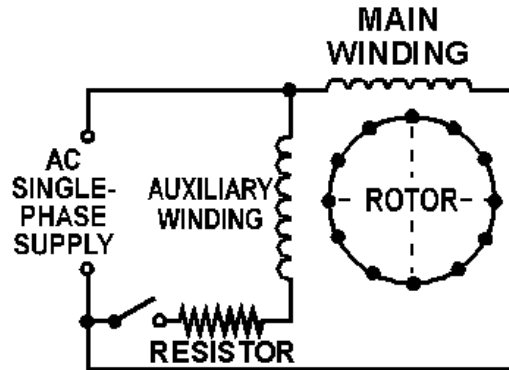


Figure 4-12.—Resistance-start ac induction motor.

Q12. How do split-phase induction motors become self-starting?

### Shaded-Pole Induction Motors

The shaded-pole induction motor is another single-phase motor. It uses a unique method to start the rotor turning. The effect of a moving magnetic field is produced by constructing the stator in a special way. This motor has projecting pole pieces just like some dc motors. In addition, portions of the pole piece surfaces are surrounded by a copper strap called a shading coil. A pole piece with the strap in place is shown in figure 4-13. The strap causes the field to move back and forth across the face of the pole piece. Note the numbered sequence and points on the magnetization curve in the figure. As the alternating stator field starts increasing from zero (1), the lines of force expand across the face of the pole piece and cut through the strap. A voltage is induced in the strap. The current that results generates a field that opposes the cutting action (and decreases the strength) of the main field. This produces the following actions: As the field increases from zero to a maximum at  $90^\circ$ , a large portion of the magnetic lines of force are concentrated in the unshaded portion of the pole (1). At  $90^\circ$  the field reaches its maximum value. Since the lines of force have stopped expanding, no emf is induced in the strap, and no opposing magnetic field is generated. As a result, the main field is uniformly distributed across the pole (2). From  $90^\circ$  to  $180^\circ$ , the main field starts decreasing or collapsing inward. The field generated in the strap opposes the collapsing field. The effect is to concentrate the lines of force in the shaded portion of the pole face (3). You can see that from  $0^\circ$  to  $180^\circ$ , the main field has shifted across the pole face from the unshaded to the shaded portion. From  $180^\circ$  to  $360^\circ$ , the main field goes through the same change as it did from  $0^\circ$  to  $180^\circ$ ; however, it is now in the opposite direction (4). The direction of the field does not affect the way the shaded pole works. The motion of the field is the same during the second half-cycle as it was during the first half of the cycle.

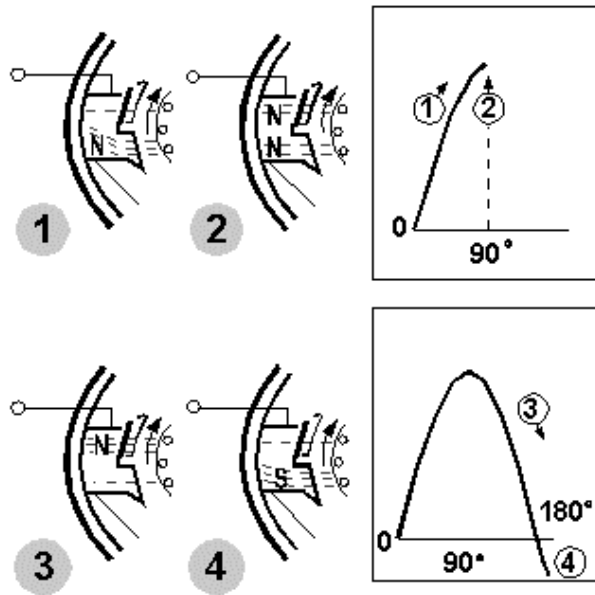


Figure 4-13.—Shaded poles as used in shaded-pole ac induction motors.

The motion of the field back and forth between shaded and unshaded portions produces a weak torque to start the motor. Because of the weak starting torque, shaded-pole motors are built only in small sizes. They drive such devices as fans, clocks, blowers, and electric razors.

*Q13. Why are shaded-pole motors used to drive only very small devices?*

### Speed of Single-Phase Induction Motors

The speed of induction motors is dependent on motor design. The synchronous speed (the speed at which the stator field rotates) is determined by the frequency of the input ac power and the number of poles in the stator. The greater the number of poles, the slower the synchronous speed. The higher the frequency of applied voltage, the higher the synchronous speed. Remember, however, that neither frequency nor number of poles are variables. They are both fixed by the manufacturer.

The relationship between poles, frequency, and synchronous speed is as follows:

$$n \text{ (rpm)} = \frac{120f}{p}$$

where  $n$  is the synchronous speed in rpm,  $f$  is the frequency of applied voltage in hertz, and  $p$  is the number of poles in the stator.

Let's use an example of a 4-pole motor, built to operate on 60 hertz. The synchronous speed is determined as follows:

$$n = \frac{120f}{p}$$

$$n = \frac{120 \times 60}{4}$$

$$n = 1800 \text{ rpm}$$

Common synchronous speeds for 60-hertz motors are 3600, 1800, 1200, and 900 rpm, depending on the number of poles in the original design.

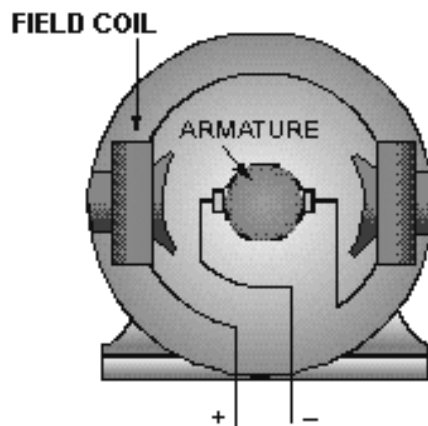
As we have seen before, the rotor is never able to reach synchronous speed. If it did, there would be no voltage induced in the rotor. No torque would be developed. The motor would not operate. The difference between rotor speed and synchronous speed is called slip. The difference between these two speeds is not great. For example, a rotor speed of 3400 to 3500 rpm can be expected from a synchronous speed of 3600 rpm.

### SUMMARY

This chapter introduced you to the basic principles concerning ac motors. While many variations of types exist, the three types presented provide you with background for further study if you require more extensive knowledge of the subject. The following information provides a summary of the major subjects of this chapter for your review.

The three **AC MOTOR TYPES** presented are the series, synchronous, and induction ac motors.

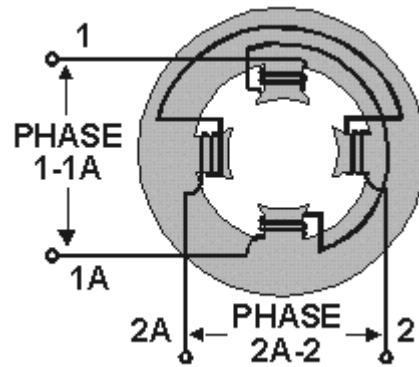
**AC SERIES MOTORS** are nearly identical to the dc series motors. Special construction techniques allow ac series motors to be used as **UNIVERSAL MOTORS**, operating on either ac or dc power.



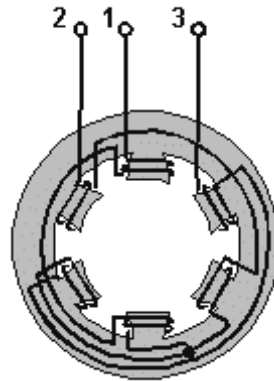
**ROTATING FIELDS** are developed by applying multiphase voltages to stator windings, which consist of multiple field coils. This rotating magnetic field causes the rotor to be pushed and pulled because of interaction between it and the rotor's own field.

**TWO-PHASE ROTATING FIELDS** require two pairs of field coils displaced by 90°. They must be energized by voltages that also have a phase displacement of 90°.

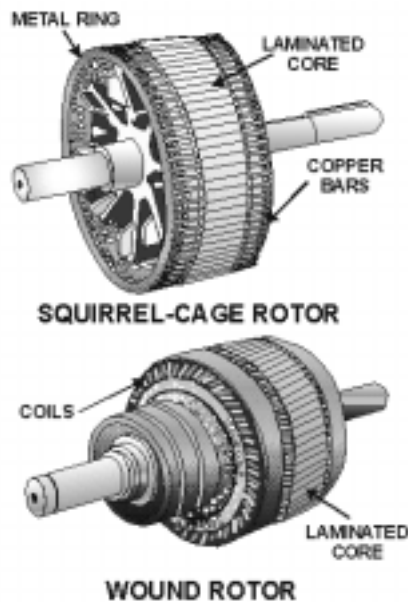




**THREE-PHASE ROTATING FIELDS** require three pairs of windings 120° apart, energized by voltages that also have a 120-degree phase displacement.



**SYNCHRONOUS MOTORS** are specifically designed to maintain constant speed, with the rotor synchronous to the rotating field. Synchronous motors require modification (such as squirrel-cage windings) to be self-starting.



**INDUCTION MOTORS** are the most commonly used of all electric motors due to their simplicity and low cost. Induction motors may be single-phase or multiphase. They do not require electrical rotor connection. Split-phase motors with special starting windings, and shaded-pole motors, are types of single-phase induction motors.

**SYNCHRONOUS SPEED** is the speed of stator field rotation. It is determined by the number of poles and the frequency of the input voltage. Thus, for a given motor, synchronous speed is constant.

**SLIP** is the difference between actual rotor speed and the synchronous speed in induction motors. Slip must exist for there to be torque at the rotor shaft.

#### ***ANSWERS TO QUESTIONS Q1. THROUGH Q13.***

- A1. *Series, synchronous, induction.*
- A2. *To power small appliances.*
- A3. *They operate on either ac or dc.*
- A4. *The number of phases in the applied voltage.*
- A5. *90°.*
- A6. *Number and location of field poles.*
- A7. *Constant speed required by some loads.*
- A8. *They are simple and inexpensive to make.*
- A9. *Slip.*
- A10. *Load.*
- A11. *Single-phase induction motor.*
- A12. *By using combinations of inductance and capacitance to apply out-of phase currents in starting windings.*
- A13. *They have very weak starting torques.*

# APPENDIX I

## Motor and Generator

### GLOSSARY

**AMPLIDYNE**—A special dc generator in which a small dc voltage applied to field windings controls a large output voltage from the generator. In effect, an amplidyne is a rotary amplifier, oftentimes producing gain in the order of 10,000.

**ARMATURE**—The windings in which the output voltage is generated in a generator or in which input current creates a magnetic field that interacts with the main field in a motor. Note: Armature is often used as being identical with ROTOR. This usage is correct only part of the time. See the text and the entries under ROTOR and STATOR in this Glossary.

**ARMATURE LOSSES**—Copper losses, eddy current losses, hysteresis losses which act to decrease the efficiency of armatures.

**ARMATURE REACTION**—The effect, in a dc generator, of current in the armature creating a magnetic field that distorts the main field and causing a shift in the neutral plane.

**BRUSHES**—Sliding contacts, usually carbon, that make electrical connection to the rotating part of a motor or generator.

**COMMUTATION**—The act of a commutator in converting generator output from an ac voltage to a dc voltage.

**COMMUTATOR**—A mechanical device that reverses armature connections in motors and generators at the proper instant so that current continues to flow in only one direction. In effect, the commutator changes ac to dc.

**COMPENSATING WINDINGS**—Windings embedded in slots in pole pieces, connected in series with the armature, whose magnetic field opposes the armature field and cancels armature reaction.

**COMPOUND-WOUND MOTORS AND GENERATORS**—Machines that have a series field in addition to a shunt field. Such machines have characteristics of both series- and shunt-wound machines.

**CAPACITOR-START MOTOR**—A type of single-phase, ac induction motor in which a starting winding and a capacitor are placed in series to start the motor. The values of  $X_c$  and  $R$  are such that the main-winding and starting-winding currents are nearly 90 degrees apart, and starting torque is produced as in a two-phase motor.

**COUNTER EMF**—The voltage generated within a coil by a moving magnetic field cutting across the coil itself. This voltage is in opposition (counter) to the moving field that created it. Counter emf is present in every motor, generator, transformer, or other inductance winding, whenever an alternating current flows.

**DELTA**—A 3-phase connection in which windings are connected end-to-end, forming a closed loop that resembles the Greek letter Delta. A separate phase wire is then connected to each of the three junctions.

**DRUM-TYPE ARMATURE**—An efficient, popular type of armature designed so that the entire length of the winding is cutting the field at all times. Most wound armatures are of this type.

**EDDY CURRENTS**—Currents induced in the body of a conducting mass by a variation in magnetic flux.

**FIELD**—The electromagnet that furnishes the magnetic field that interacts with the armature in motors and generators.

**FIELD EXCITATION**—The creation of a steady magnetic field within the field windings by applying a dc voltage either from the generator itself or from an external source.

**GENERATOR**—A machine that converts mechanical energy to electrical energy by applying the principal of magnetic induction. A machine that produces ac or dc voltage, depending on the original design.

**GRAMME-RING ARMATURE**—An inefficient type of armature winding in which many of the turns are shielded from the field by its own iron ring.

**INDUCTION MOTOR**—A simple, rugged, ac motor with desirable characteristics. The rotor is energized by transformer action (induction) from the stator. More induction motors are used than any other type.

**INTERPOLES**—Small auxiliary poles placed between main field poles, whose magnetic field opposes the armature field and cancels armature reaction. Interpoles accomplish the same thing as compensating windings.

**LAP WINDING**—An armature winding in which opposite ends of each coil are connected to adjoining segments of the commutator so that the windings overlap.

**LEFT-HAND RULE FOR GENERATORS**—A representation of the relationships between motion, magnetic force, and resultant current in the generation of a voltage. The thumb, forefinger, and middle finger of the left hand are extended at right angles to each other. The thumb should point in the direction the conductor moves. The forefinger should point in the direction of magnetic flux from north to south. The middle finger will then point in the direction the generated voltage forces current to flow. Any of three quantities may be found if the other two are known.

**MAGNETIC INDUCTION**—The generation of a voltage in a circuit by causing relative motion between a magnetic field and the circuit. The relative motion can be the result of physical movement or the rise and fall of a magnetic field created by a changing current.

**MOTOR**—A machine that converts electrical energy to mechanical energy. It is activated by ac or dc voltage, depending on the design.

**MOTOR LOAD**—Any device driven by a motor. Typical loads are drills, saws, water pumps, rotating antennas, generators, etc. The speed and power capabilities of a motor must be matched to the speed and power requirements of the motor load.

**MOTOR REACTION**—The force created by generator armature current that tends to oppose normal rotation of the armature.

**MOTOR STARTERS**—Large resistive devices placed in series with dc motor armatures to prevent the armature from drawing excessive current until armature speed develops counter emf. The resistance is gradually removed from the circuit either automatically or manually as motor speed increases.

**MULTIPHASE**—See polyphase.

**POLE PIECES**—The shaped magnetic material upon which the stator windings of motors and generators are mounted or wound.

**POLE**—The sections of a field magnet where the flux lines are concentrated; also where they enter and leave the magnet.

**POLYPHASE**—Term that describes systems or units of a system that are activated by or which generate separate out-of-phase voltages. Typical polyphase systems are 2-phase and 3-phase whose voltages are 90- and 120-degrees out of phase, respectively. This term means the same as MULTIPHASE.

**PRIME MOVER**—The source of the turning force applied to the rotor of a generator. This may be an electric motor, a gasoline engine, steam turbine, etc.

**ROTATING FIELD**—The magnetic field in a multiphase ac motor that is the result of field windings being energized by out-of-phase voltages. In effect, the magnetic field is made to rotate electrically rather than mechanically.

**ROTOR**—The revolving part of a rotating electrical machine. The rotor may be either the field or the armature, depending on the design of the machine.

**SELF-EXCITED GENERATORS**—Dc generators in which the generator output is fed to the field to produce field excitation.

**SERIES-WOUND MOTORS AND GENERATORS**—Machines in which the armature and field windings are connected in series with each other.

**SHUNT-WOUND MOTORS AND GENERATORS**—Machines in which the armature and field windings are connected in parallel (shunt) with each other.

**SLIP**—The difference between rotor speed and synchronous speed in an ac induction motor. The rotor will always be slower than the synchronous speed by the amount of slip, otherwise, no voltage would be induced in the rotor.

**SLIP RINGS**—Contacts that are mounted on the shaft of a motor or generator to which the rotor windings are connected, and against which the brushes ride.

**SQUIRREL-CAGE WINDINGS**—A type of rotor winding in which heavy conductors are imbedded in the rotor body. The conductors are shorted together at the ends by continuous rings. No insulation is required between the windings and the core. This type of winding is rugged, easily manufactured, and practically maintenance free. It is widely applied in ac induction motors. Physically, it appears as a rotating squirrel-cage, thus the name.

**STATOR**—The stationary part of a rotating electrical machine. The stator may be either the field or the armature, depending on the design of the machine.

**SYNCHRONOUS MOTOR**—An ac motor whose rotor is activated by dc. It is characterized by constant speed and requires squirrel-cage windings or some other method to be self-starting.

**SYNCHRONOUS SPEED**—The speed at which the rotating field in an ac motor revolves. This speed is a function of the number of poles in the field and the frequency of the applied voltage.

**VOLTAGE REGULATION**—A measure of the ability of a generator to maintain a constant output voltage from no-load to full-load operation. Expressed as a percentage of full-load voltage, the better the regulation, the lower the percent.

**WAVE WINDING**—An armature winding in which the two ends of each coil are connected to commutator segments separated by the distance between poles. The winding goes successively under each main pole before reaching the starting point again.

**WYE (Y)**—A 3-phase connection in which one end of each phase winding is connected to a common point. Each free end is connected to a separate phase wire. The diagram of this connection often resembles the letter Y.