DOE Fundamentals

ELECTRICAL SCIENCE

Module 12

AC Motors

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OBJECTIVES

TERMINAL OBJECTIVE

1.0 Given the type and application of an AC motor, **DESCRIBE** the operating characteristics of that motor including methods of torque production and advantages of that type.

ENABLING OBJECTIVES

1.1 **DESCRIBE** how a rotating magnetic field is produced in an AC motor.

1.2 **DESCRIBE** how torque is produced in an AC motor.

1.3 Given field speed and rotor speed, **CALCULATE** percent slip in an AC motor.

1.4 **EXPLAIN** the relationship between speed and torque in an AC induction motor.

1.5 **DESCRIBE** how torque is produced in a single-phase AC motor.

1.6 **EXPLAIN** why an AC synchronous motor does not have starting torque.

1.7 **DESCRIBE** how an AC synchronous motor is started.

1.8 **DESCRIBE** the effects of over and under-exciting an AC synchronous motor.

1.9 **STATE** the applications of the following types of AC motors:

   a. Induction
   b. Single-phase
   c. Synchronous

AC MOTOR THEORY

AC motors are widely used to drive machinery for a wide variety of applications. To understand how these motors operate, a knowledge of the basic theory of operation of AC motors is necessary.

EO 1.1	**DESCRIBE** how a rotating magnetic field is produced in an AC motor.
EO 1.2	**DESCRIBE** how torque is produced in an AC motor.
EO 1.3	Given field speed and rotor speed, **CALCULATE** percent slip in an AC motor.
EO 1.4	**EXPLAIN** the relationship between slip and torque in an AC induction motor.

Principles of Operation

The principle of operation for all AC motors relies on the interaction of a revolving magnetic field created in the stator by AC current, with an opposing magnetic field either induced on the rotor or provided by a separate DC current source. The resulting interaction produces usable torque, which can be coupled to desired loads throughout the facility in a convenient manner. Prior to the discussion of specific types of AC motors, some common terms and principles must be introduced.

Rotating Field

Before discussing how a rotating magnetic field will cause a motor rotor to turn, we must first find out how a rotating magnetic field is produced. Figure 1 illustrates a three-phase stator to which a three-phase AC current is supplied.

The windings are connected in wye. The two windings in each phase are wound in the same direction. At any instant in time, the magnetic field generated by one particular phase will depend on the current through that phase. If the current through that phase is zero, the resulting magnetic field is zero. If the current is at a maximum value, the resulting field is at a maximum value. Since the currents in the three windings are 120° out of phase, the magnetic fields produced will also be 120° out of phase. The three magnetic fields will combine to produce one field, which will act upon the rotor. In an AC induction motor, a magnetic field is induced in the rotor opposite in polarity of the magnetic field in the stator. Therefore, as the magnetic field rotates in the stator, the rotor also rotates to maintain its alignment with the stator's magnetic field. The remainder of this chapter's discussion deals with AC induction motors.

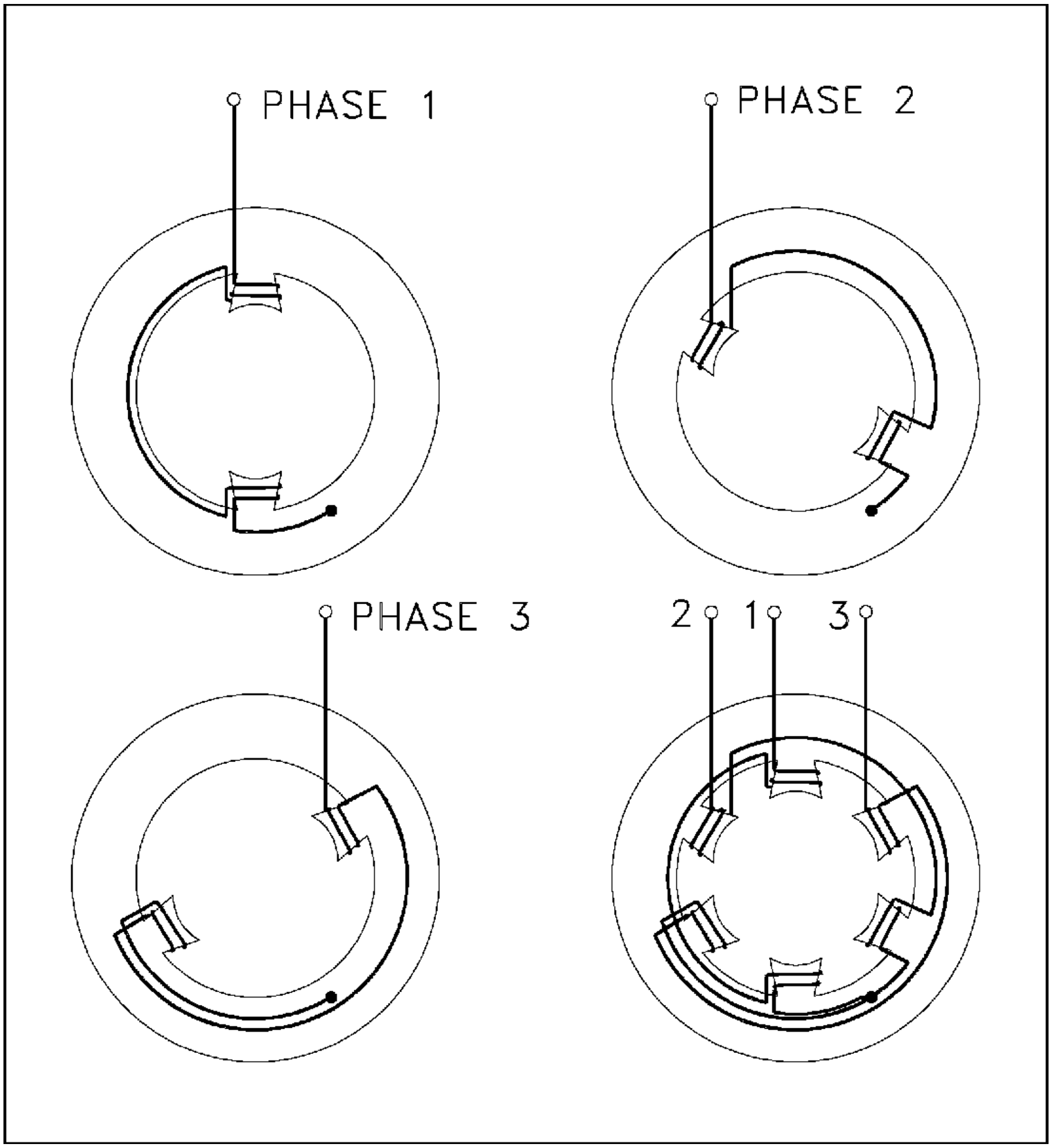


Figure 1 Three-Phase Stator

From one instant to the next, the magnetic fields of each phase combine to produce a magnetic field whose position shifts through a certain angle. At the end of one cycle of alternating current, the magnetic field will have shifted through 360°, or one revolution (Figure 2). Since the rotor has an opposing magnetic field induced upon it, it will also rotate through one revolution.

For purpose of explanation, rotation of the magnetic field is developed in Figure 2 by "stopping" the field at six selected positions, or instances. These instances are marked off at 60° intervals on the sine waves representing the current flowing in the three phases, A, B, and C. For the following discussion, when the current flow in a phase is positive, the magnetic field will develop a north pole at the poles labeled A, B, and C.

When the current flow in a phase is negative, the magnetic field will develop a north pole at the poles labeled A', B', and C'.

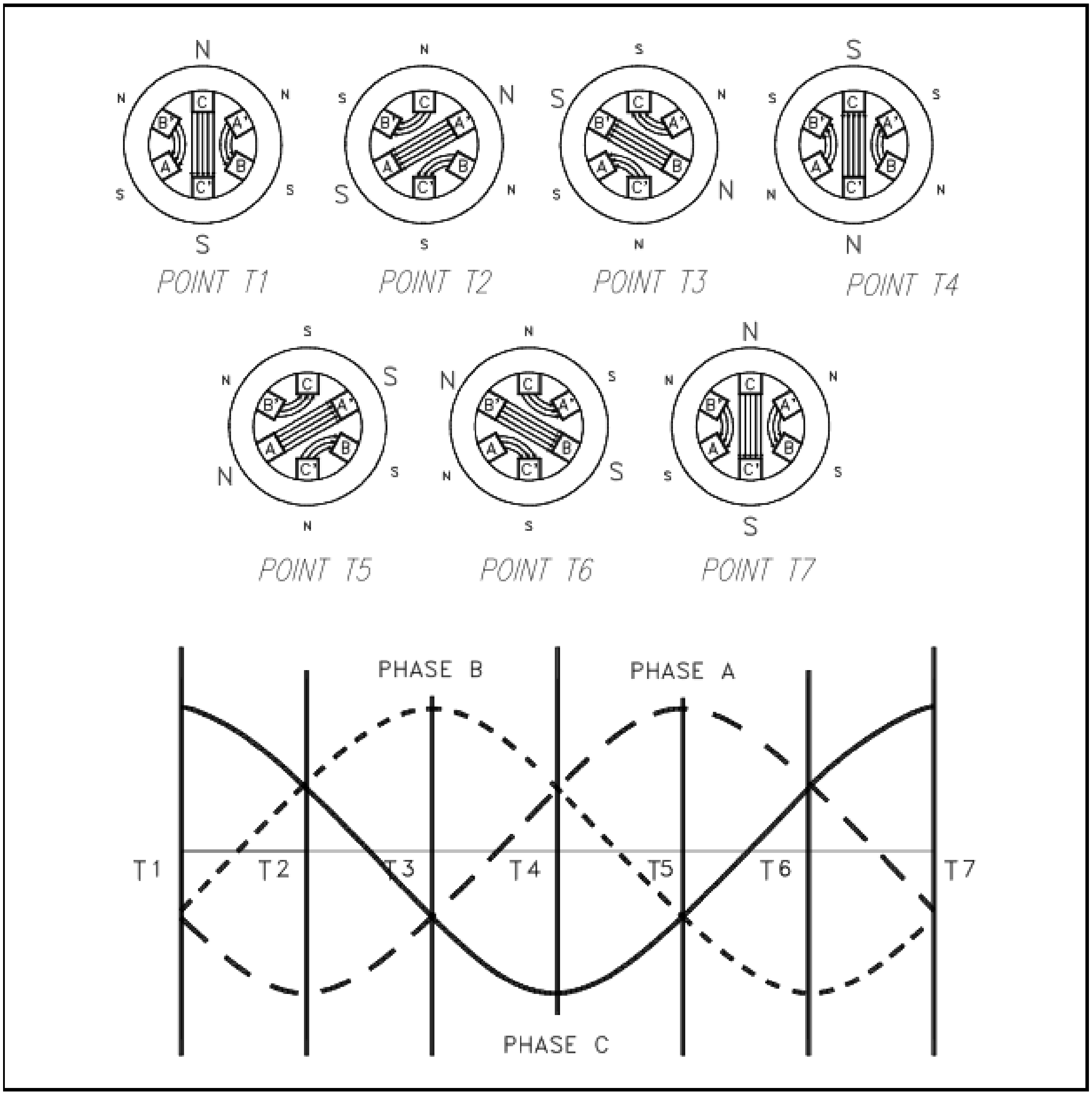


Figure 2 Rotating Magnetic Field

At point T1, the current in phase C is at its maximum positive value. At the same instance, the currents in phases A and B are at half of the maximum negative value. The resulting magnetic field is established vertically downward, with the maximum field strength developed across the C phase, between pole C (north) and pole C' (south). This magnetic field is aided by the weaker fields developed across phases A and B, with poles A' and B' being north poles and poles A and B being south poles.

At Point T2, the current sine waves have rotated through 60 electrical degrees. At this point, the current in phase A has increased to its maximum negative value. The current in phase B has reversed direction and is at half of the maximum positive value. Likewise, the current in phase

C has decreased to half of the maximum positive value. The resulting magnetic field is established downward to the left, with the maximum field strength developed across the A phase, between poles A' (north) and A (south). This magnetic field is aided by the weaker fields developed across phases B and C, with poles B and C being north poles and poles B' and C' being south poles. Thus, it can be seen that the magnetic field within the stator of the motor has physically rotated 60°.

At Point T3, the current sine waves have again rotated 60 electrical degrees from the previous point for a total rotation of 120 electrical degrees. At this point, the current in phase B has increased to its maximum positive value. The current in phase A has decreased to half of its maximum negative value, while the current in phase C has reversed direction and is at half of its maximum negative value also. The resulting magnetic field is established upward to the left, with the maximum field strength developed across phase B, between poles B (north) and B' (south). This magnetic field is aided by the weaker fields developed across phases A and C, with poles A' and C' being north poles and poles A and C being south poles. Thus, it can be seen that the magnetic field on the stator has rotated another 60° for a total rotation of 120°.

At Point T4, the current sine waves have rotated 180 electrical degrees from Point T1 so that the relationship of the phase currents is identical to Point T1 except that the polarity has reversed. Since phase C is again at a maximum value, the resulting magnetic field developed across phase C will be of maximum field strength. However, with current flow reversed in phase C the magnetic field is established vertically upward between poles C' (north) and C (south). As can be seen, the magnetic field has now physically rotated a total of 180° from the start.

At Point T5, phase A is at its maximum positive value, which establishes a magnetic field upward to the right. Again, the magnetic field has physically rotated 60° from the previous point for a total rotation of 240°. At Point T6, phase B is at its maximum negative value, which will establish a magnetic field downward to the right. The magnetic field has again rotated 60° from Point T5 for a total rotation of 300°.

Finally, at Point T7, the current is returned to the same polarity and values as that of Point T1. Therefore, the magnetic field established at this instance will be identical to that established at Point T1. From this discussion it can be seen that for one complete revolution of the electrical sine wave (360°), the magnetic field developed in the stator of a motor has also rotated one complete revolution (360°). Thus, you can see that by applying three-phase AC to three windings symmetrically spaced around a stator, a rotating magnetic field is generated.

Torque Production

When alternating current is applied to the stator windings of an AC induction motor, a rotating magnetic field is developed. The rotating magnetic field cuts the bars of the rotor and induces a current in them due to generator action. The direction of this current flow can be found using the left-hand rule for generators. This induced current will produce a magnetic field, opposite in polarity of the stator field, around the conductors of the rotor, which will try to line up with the magnetic field of the stator. Since the stator field is rotating continuously, the rotor cannot line up with, or lock onto, the stator field and, therefore, must follow behind it (Figure 3).

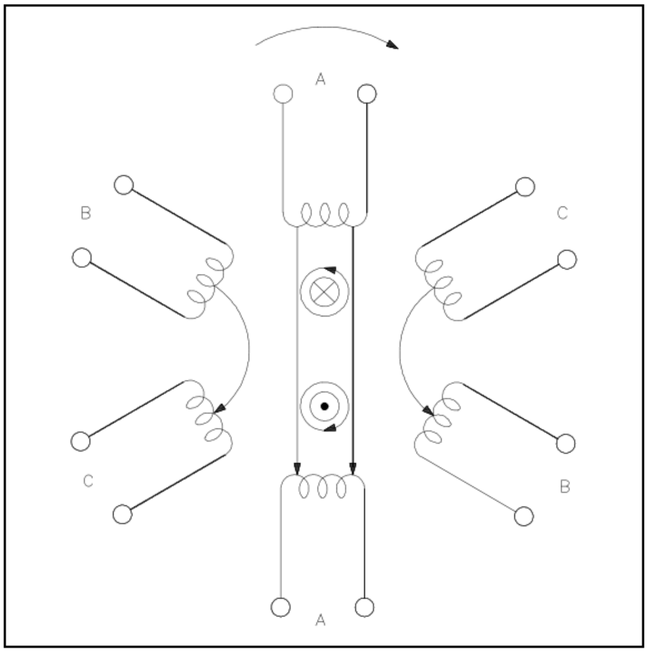


Figure 3 Induction Motor

Slip

It is virtually impossible for the rotor of an AC induction motor to turn at the same speed as that of the rotating magnetic field. If the speed of the rotor were the same as that of the stator, no relative motion between them would exist, and there would be no induced EMF in the rotor. (Recall from earlier modules that relative motion between a conductor and a magnetic field is needed to induce a current.) Without this induced EMF, there would be no interaction of fields to produce motion. The rotor must, therefore, rotate at some speed less than that of the stator if relative motion is to exist between the two.

The percentage difference between the speed of the rotor and the speed of the rotating magnetic field is called *slip.* The smaller the percentage, the closer the rotor speed is to the rotating magnetic field speed. Percent slip can be found by using Equation (12-1).

$$\text{SLIP} = \frac{N_S - N_R}{N_S} \times 100\% \qquad (12\text{-}1)$$

where

N_S = synchronous speed (rpm)

N_R = rotor speed (rpm)

The speed of the rotating magnetic field or synchronous speed of a motor can be found by using Equation (12-2).

$$N_S = \frac{120\ f}{P} \tag{12-2}$$

where

N_s = speed of rotating field (rpm)

f = frequency of rotor current (Hz)

P = total number of poles

Example: A two pole, 60 Hz AC induction motor has a full load speed of 3554 rpm. What is the percent slip at full load?

Solution:

Synchronous speed:

$$N_S = \frac{120\ f}{P}$$

$$N_S = \frac{120\ (60)}{2}$$

$$N_S = 3600\ \text{rpm}$$

Slip:

$$\text{SLIP} = \frac{N_S - N_R}{N_S}\ \text{x}\ 100\%$$

$$\text{SLIP} = \frac{3600 - 3554}{3600}\ \text{x}\ 100\% = 1.3\%$$

Torque

The torque of an AC induction motor is dependent upon the strength of the interacting rotor and stator fields and the phase relationship between them. Torque can be calculated by using Equation (12-3).

$$T = K\ \Phi\ I_R \cos \Theta_R \tag{12-3}$$

where

T = torque (lb-ft)

K = constant

Φ = stator magnetic flux

I_R = rotor current (A)

$\cos \Theta_R$ = power factor of rotor

During normal operation, K, Φ, and $\cos \Theta_R$ are, for all intents and purposes, constant, so that torque is directly proportional to the rotor current. Rotor current increases in almost direct proportion to slip. The change in torque with respect to slip (Figure 4) shows that, as slip increases from zero to ~10%, the torque increases linearly. As the load and slip are increased beyond full-load torque, the torque will reach a maximum value at about 25% slip. The maximum value of torque is called the *breakdown torque* of the motor. If load is increased beyond this point, the motor will stall and come to a rapid stop. The typical induction motor breakdown torque varies from 200 to 300% of full load torque. Starting torque is the value of torque at 100% slip and is normally 150 to 200% of full-load torque. As the rotor accelerates, torque will increase to breakdown torque and then decrease to the value required to carry the load on the motor at a constant speed, usually between 0-10%.

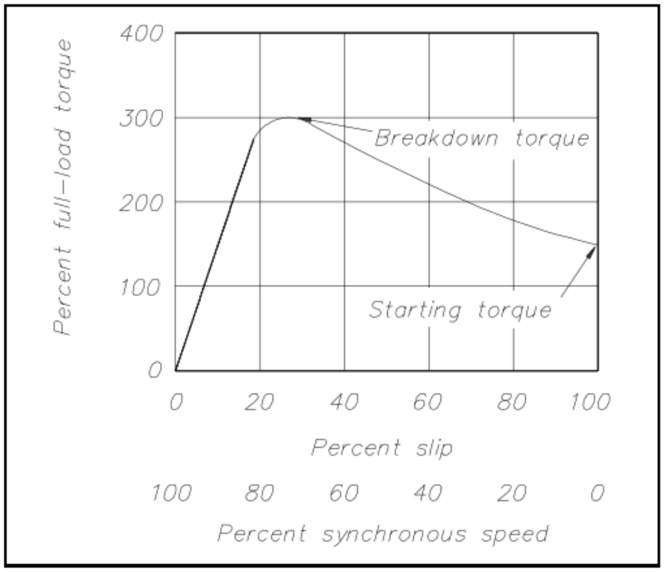


Figure 4 Torque vs Slip

Summary

The important information covered in this chapter is summarized below.

AC Motor Theory Summary

- A magnetic field is produced in an AC motor through the action of the three-phase voltage that is applied. Each of the three phases is 120° from the other phases. From one instant to the next, the magnetic fields combine to produce a magnetic field whose position shifts through a certain angle. At the end of one cycle of alternating current, the magnetic field will have shifted through 360°, or one revolution.
- Torque in an AC motor is developed through interactions with the rotor and the rotating magnetic field. The rotating magnetic field cuts the bars of the rotor and induces a current in them due to generator action. This induced current will produce a magnetic field around the conductors of the rotor, which will try to line up with the magnetic field of the stator.
- Slip is the percentage difference between the speed of the rotor and the speed of the rotating magnetic field.
- In an AC induction motor, as slip increases from zero to ~10%, the torque increases linearly. As the load and slip are increased beyond full-load torque, the torque will reach a maximum value at about 25% slip. If load is increased beyond this point, the motor will stall and come to a rapid stop. The typical induction motor breakdown torque varies from 200 to 300% of full-load torque. Starting torque is the value of torque at 100% slip and is normally 150 to 200% of full-load torque.

AC MOTOR TYPES

Various types of AC motors are used for specific applications. By matching the type of motor to the appropriate application, increased equipment performance can be obtained.

EO 1.5 DESCRIBE how torque is produced in a single-phase AC motor.

EO 1.6 EXPLAIN why an AC synchronous motor does not have starting torque.

EO 1.7 DESCRIBE how an AC synchronous motor is started.

EO 1.8 DESCRIBE the effects of over and under-exciting an AC synchronous motor.

EO 1.9 STATE the applications of the following types of AC motors:

a. Induction

b. Single-phase

c. Synchronous

Induction Motor

Previous explanations of the operation of an AC motor dealt with induction motors. The induction motor is the most commonly used AC motor in industrial applications because of its simplicity, rugged construction, and relatively low manufacturing costs. The reason that the induction motor has these characteristics is because the rotor is a self-contained unit, with no external connections. This type of motor derives its name from the fact that AC currents are induced into the rotor by a rotating magnetic field.

The induction motor rotor (Figure 5) is made of a laminated cylinder with slots in its surface. The windings in the slots are one of two types. The most commonly used is the "squirrel-cage" rotor. This rotor is made of heavy copper bars that are connected at each end by a metal ring made of copper or brass. No insulation is required between the core and the bars because of the low voltages induced into the rotor bars. The size of the air gap between the rotor bars and stator windings necessary to obtain the maximum field strength is small.

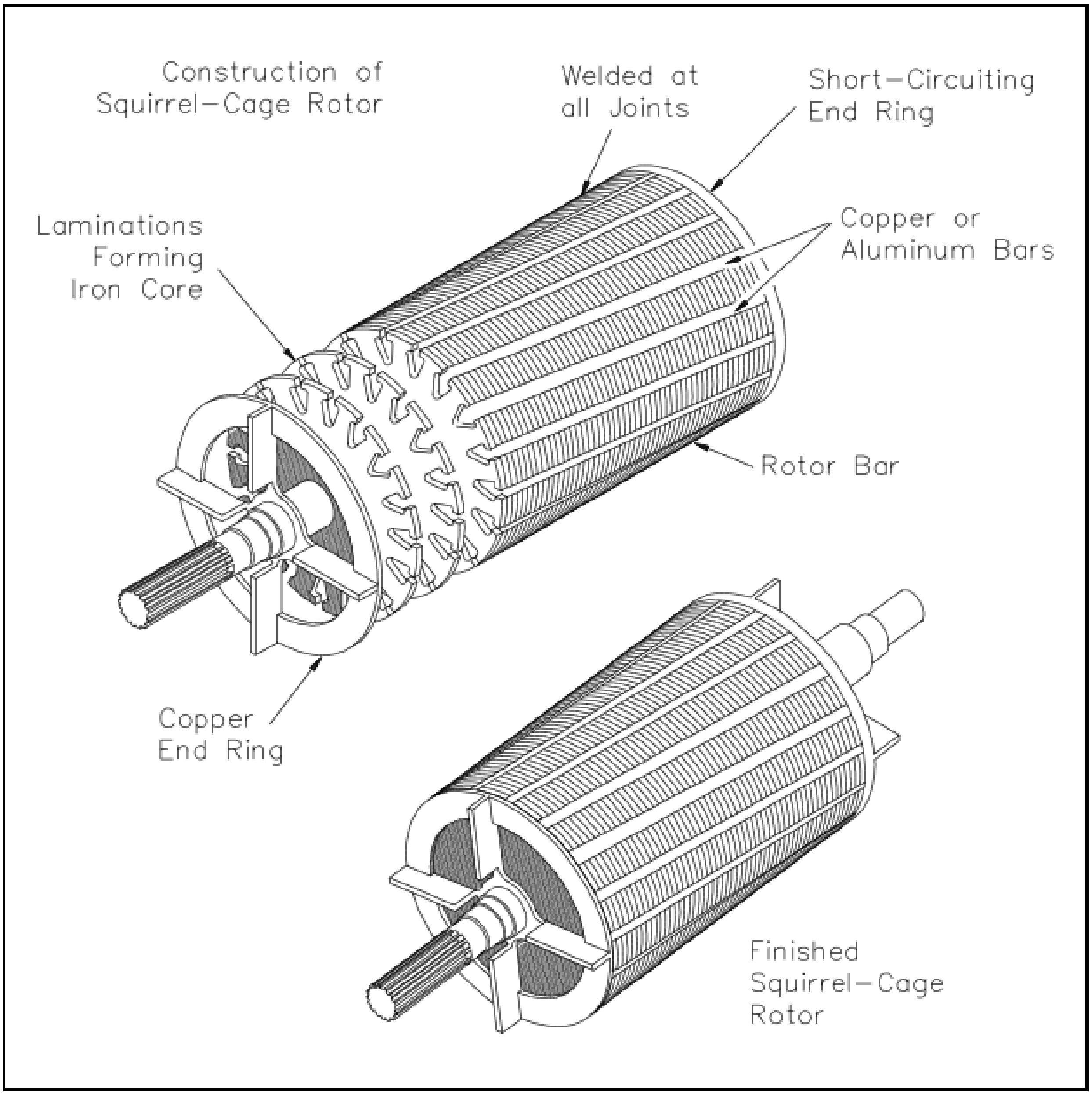


Figure 5 Squirrel-Cage Induction Rotor

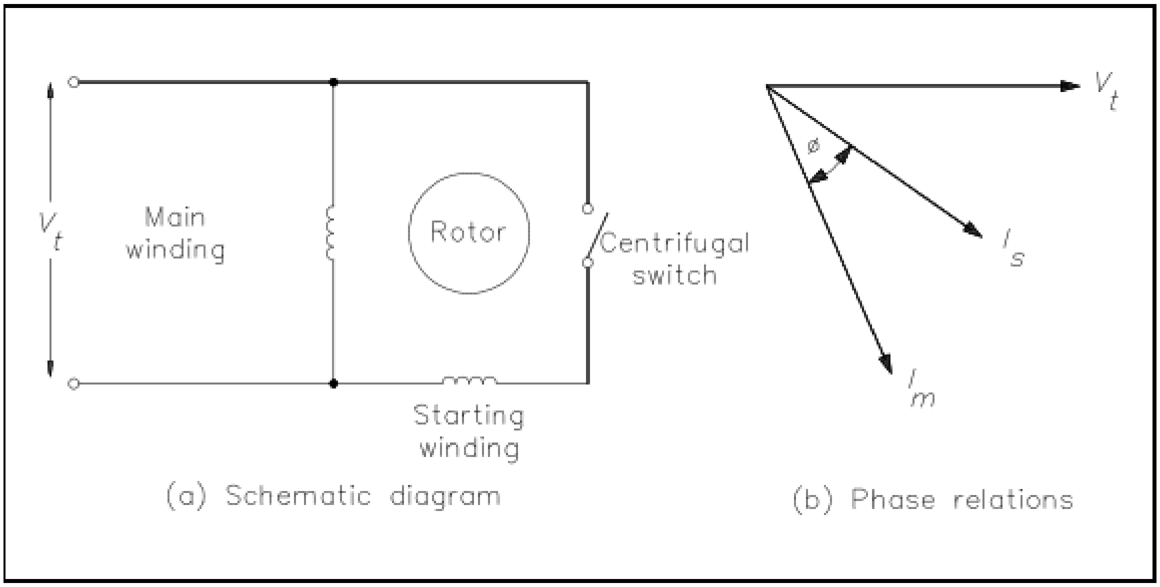


Figure 6 Split-Phase Motor

Single-Phase AC Induction Motors

If two stator windings of unequal impedance are spaced 90 electrical degrees apart and connected in parallel to a single-phase source, the field produced will appear to rotate. This is called phase splitting.

In a split-phase motor, a starting winding is utilized. This winding has a higher resistance and lower reactance than the main winding (Figure 6). When the same voltage V, is applied to the starting and main windings, the current in the main winding (I_M) lags behind the current of the starting winding I_s (Figure 6). The angle between the two windings is enough phase difference to provide a rotating magnetic field to produce a starting torque. When the motor reaches 70 to 80% of synchronous speed, a centrifugal switch on the motor shaft opens and disconnects the starting winding.

Single-phase motors are used for very small commercial applications such as household appliances and buffers.

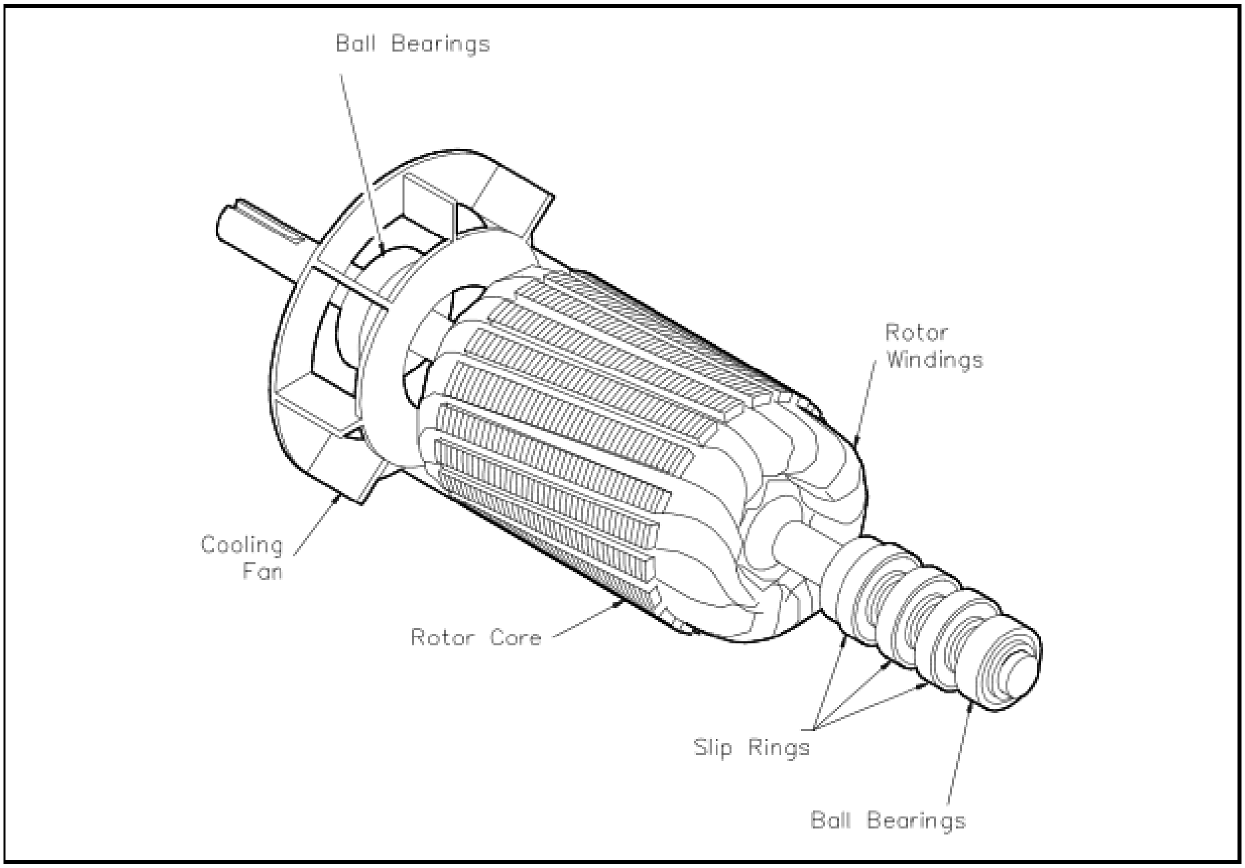


Figure 7 Wound Rotor

Synchronous Motors

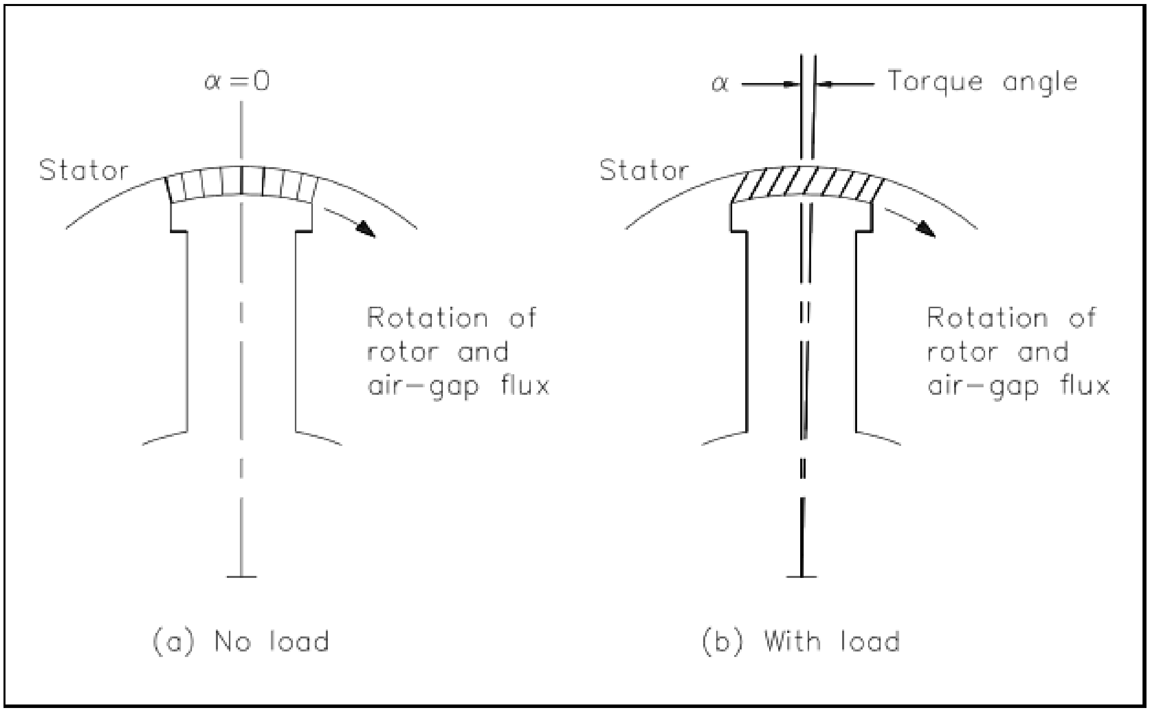
Synchronous motors are like induction motors in that they both have stator windings that produce a rotating magnetic field. Unlike an induction motor, the synchronous motor is excited by an external DC source and, therefore, requires slip rings and brushes to provide current to the rotor. In the synchronous motor, the rotor locks into step with the rotating magnetic field and rotates at synchronous speed. If the synchronous motor is loaded to the point where the rotor is pulled out of step with the rotating magnetic field, no torque is developed, and the motor will stop. A synchronous motor is not a self-starting motor because torque is only developed when running at synchronous speed; therefore, the motor needs some type of device to bring the rotor to synchronous speed.

Synchronous motors use a wound rotor. This type of rotor contains coils of wire placed in the rotor slots. Slip rings and brushes are used to supply current to the rotor. (Figure 7).

Starting a Synchronous Motor

A synchronous motor may be started by a DC motor on a common shaft. When the motor is brought to synchronous speed, AC current is applied to the stator windings. The DC motor now acts as a DC generator and supplies DC field excitation to the rotor of the synchronous motor. The load may now be placed on the synchronous motor. Synchronous motors are more often started by means of a squirrel-cage winding embedded in the face of the rotor poles. The motor is then started as an induction motor and brought to ~95% of synchronous speed, at which time direct current is applied, and the motor begins to pull into synchronism. The torque required to pull the motor into synchronism is called the pull-in torque.

As we already know, the synchronous motor rotor is locked into step with the rotating magnetic field and must continue to operate at synchronous speed for all loads. During no-load conditions, the center lines of a pole of the rotating magnetic field and the DC field pole coincide (Figure 8a). As load is applied to the motor, there is a backward shift of the rotor pole, relative to the stator pole (Figure 8b). There is no change in speed. The angle between the rotor and stator poles is called the *torque angle* (α).



(a) No load (b) With load

Figure 8 Torque Angle

If the mechanical load on the motor is increased to the point where the rotor is pulled out of synchronism (cE90°), the motor will stop. The maximum value of torque that a motor can develop without losing synchronism is called its pull-out torque.

Field Excitation

For a constant load, the power factor of a synchronous motor can be varied from a leading value to a lagging value by adjusting the DC field excitation (Figure 9). Field excitation can be adjusted so that PF = 1 (Figure 9a). With a constant load on the motor, when the field excitation is increased, the counter EMF (V_G) increases. The result is a change in phase between stator current (I) and terminal voltage (V_i), so that the motor operates at a leading power factor (Figure 9b). V_p in Figure 9 is the voltage drop in the stator winding's due to the impedance of the windings and is 90° out of phase with the stator current. If we reduce field excitation, the motor will operate at a lagging power factor (Figure 9c). Note that torque angle, a, also varies as field excitation is adjusted to change power factor.

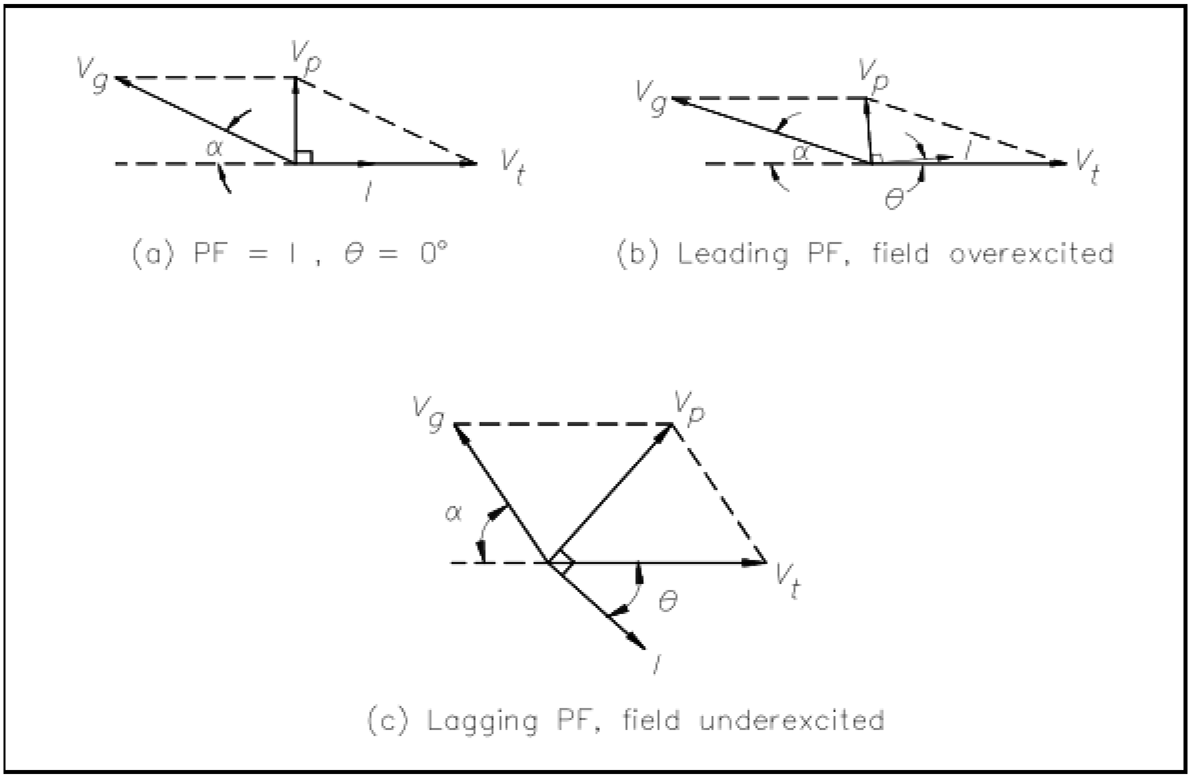


Figure 9 Synchronous Motor Field Excitation

Synchronous motors are used to accommodate large loads and to improve the power factor of transformers in large industrial complexes.

Summary

The important information in this chapter is summarized below.

AC Motor Types Summary

- In a split-phase motor, a starting winding is utilized. This winding has a higher resistance and lower reactance than the main winding. When the same voltage (V_T) is applied to the starting and main windings, the current in the main winding lags behind the current of the starting winding. The angle between the two windings is enough phase difference to provide a rotating magnetic field to produce a starting torque.
- A synchronous motor is not a self-starting motor because torque is only developed when running at synchronous speed.
- A synchronous motor may be started by a DC motor on a common shaft or by a squirrel-cage winding imbedded in the face of the rotor poles.
- Keeping the same load, when the field excitation is increased on a synchronous motor, the motor operates at a leading power factor. If we reduce field excitation, the motor will operate at a lagging power factor.
- The induction motor is the most commonly used AC motor in industrial applications because of its simplicity, rugged construction, and relatively low manufacturing costs.
- Single-phase motors are used for very small commercial applications such as household appliances and buffers.
- Synchronous motors are used to accommodate large loads and to improve the power factor of transformers in large industrial complexes.