Motors: Theory and Application

26202-05

Lake House Spa & Pool Barn
at Lake Austin Spa Resort
Austin, Texas
Commercial $5–10 Million Award Winner
Spaw Glass Contractors, Inc.

26202-05

Motors: Theory and Application

Topics to be presented in this module include:

Overview

Motor windings are electromagnets in which like polarities repel one another and unlike polarities attract each other. The rotor in any motor is the part that turns and is used to drive the load. The stationary windings are typically mounted in a doughnut-like arrangement into which the rotor is installed.

Windings are built into the rotor, and current flows through these windings. Likewise, a current flow is created through the stationary windings. Any time current flows through a conductor, a magnetic field is created around that conductor. Since both windings have current flowing through them at the same time, magnetic fields are generated around both windings. As these magnetic fields interact, they either repel or attract each other. Manipulating the current flow through the rotor and the secondary windings enables the rotor to turn at controlled speeds or in different directions. This is the basic operation of any motor. Motors can be designed to supply high speed, high torque, or both, depending on the demands of the load.

Objectives

Upon completion of this module, you will be able to do the following:

1. Define the following terms:
   - Ampacity
   - Branch circuit
   - Circuit breaker
   - Controller
   - Duty
   - Equipment
   - Full-load amps
   - Ground fault circuit interrupter
   - Interrupting rating
   - Motor circuit switch
   - Thermal protector
   - NEMA design letter
   - Nonautomatic
   - Overcurrent
   - Overload
   - Power factor
   - Rated full-load speed
   - Rated horsepower
   - Remote control circuit
   - Service factor
   - Thermal cutout
2. Describe the various types of motor enclosures.
3. Describe how the rated voltage of a motor differs from the system voltage.
4. Describe the basic construction and components of a three-phase squirrel cage induction motor.
5. Explain the relationships among speed, frequency, and the number of poles in a three-phase induction motor.
6. Describe how torque is developed in an induction motor.
7. Explain how and why torque varies with rotor reactance and slip.
8. Define percent slip and speed regulation.
9. Explain how the direction of a three-phase motor is reversed.
10. Describe the component parts and operating characteristics of a three-phase wound-rotor induction motor.
11. Describe the component parts and operating characteristics of a three-phase synchronous motor.
12. Define torque, starting current, and armature reaction as they apply to DC motors.
13. Explain how the direction of rotation of a DC motor is changed.
14. Describe the design and characteristics of a DC shunt, series, and compound motor.
15. Describe dual-voltage motors and their applications.
16. Describe the methods for determining various motor connections.
17. Describe general motor protection requirements as delineated in the *NEC*®.

202CMAP.EPS

Prerequisites

Before you begin this module, it is recommended that you successfully complete *Core Curriculum; Electrical Level One;* and *Electrical Level Two,* Module 26201-05.

This course map shows all of the modules in *Electrical Level Two.* The suggested training order begins at the bottom and proceeds up. Skill levels increase as you advance on the course map. The local Training Program Sponsor may adjust the training order.

Required Trainee Materials

1. Pencil and paper
2. Appropriate personal protective equipment
3. Copy of the latest edition of the *National Electrical Code®*

Trade Terms

Armature	Hours
Branch circuit	Intermittent duty
Brush	Overcurrent
Circuit breaker	Overload
Commutator	Periodic duty
Continuous duty	Revolutions per minute (rpm)
Controller	Rotation
Duty	Synchronous speed
Equipment	Thermal protector
Field poles	Varying duty
Horsepower	

1.0.0 ◆ INTRODUCTION

The electric motor is the workhorse of modern industry. Its functions are almost unlimited. To control the motors that drive machinery and **equipment,** we must have electrical supply circuits that perform certain functions. They must provide electrical current to cause the motor to operate in the manner needed to make it perform its intended function. They must also provide protection for the motor from adverse mechanical and electrical conditions. These functions are frequently combined within electrical equipment that we classify as motor control centers.

A thorough understanding of the functions of the various components of a motor control center is desirable from both a maintenance and a troubleshooting standpoint. Properly-maintained motor control centers ensure a minimum of downtime for unscheduled repairs, increase productivity, and contribute to a safer working environment.

2.0.0 ◆ DC MOTOR PRINCIPLES

When a bar of magnetic material is given an induced magnetic charge, a field of magnetic force is developed around the bar. We picture this field as consisting of lines of force that exist in the space surrounding the bar. These lines of force appear to leave one end of the bar and extend outside the bar to the opposite end.

The end of the bar magnet where magnetic lines appear to start is called the north pole of the magnet, while the end where these lines reenter the magnet is called the south pole. Actually, the lines extend inside the magnet from the south pole to the north pole, completing a closed loop. This principle is shown in *Figure 1*.

There are several characteristics of these magnetic lines of force that must be remembered when dealing with electric motors. They are:

- Magnetic lines of force are continuous and always form closed loops.
- Magnetic lines of force do not cross.
- Magnetic lines of force with polarities in the same direction repel each other. In other words, a north pole will repel a north pole and a south pole will repel a south pole.

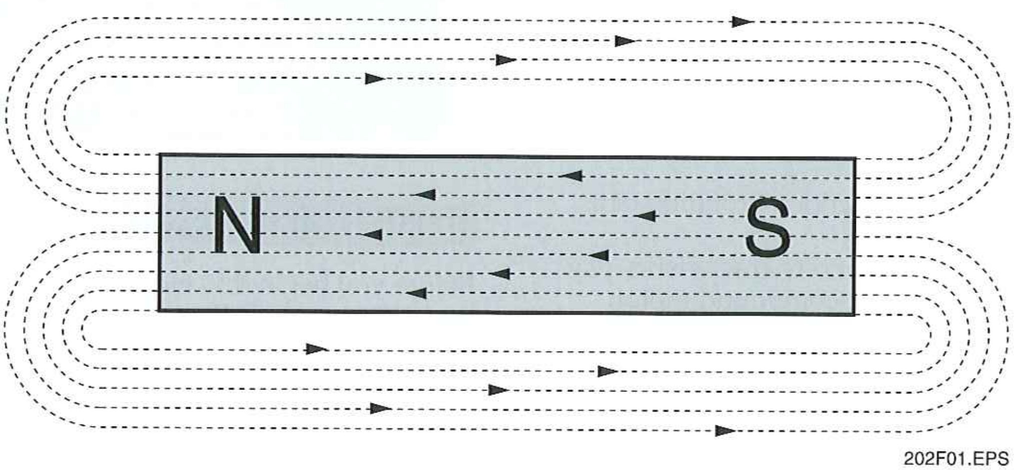


Figure 1 ◆ Magnetic field.

INSIDE TRACK

Early Electric Motors

The first U.S. patent for a motor was issued to Thomas Davenport in 1837. He reported that he used silk from his wife's wedding gown as insulation for the conductors, but despite this sacrifice, his motor was not commercially successful. Practical electric motors, like the practical light bulb, did not appear until the late 19th century.

- Magnetic lines of force having polarities in opposite directions tend to attract each other and combine. In other words, a south pole will be attracted by a north pole and vice versa.
- Magnetic lines of force tend to shorten themselves. Therefore, the magnetic lines of force existing between two unlike poles cause the poles to tend to pull together.
- Magnetic lines of force pass through all known materials, magnetic or nonmagnetic. Some materials provide a much easier path for these lines than others. These materials have high permeability and low reluctance. (Reluctance is discussed later in this module.)

2.1.0 Hand Rules

When a current is passed through the wire, circular lines of force are produced around the wire. These flux lines go in a direction described by the left-hand rule. This rule is shown in *Figure 2*.

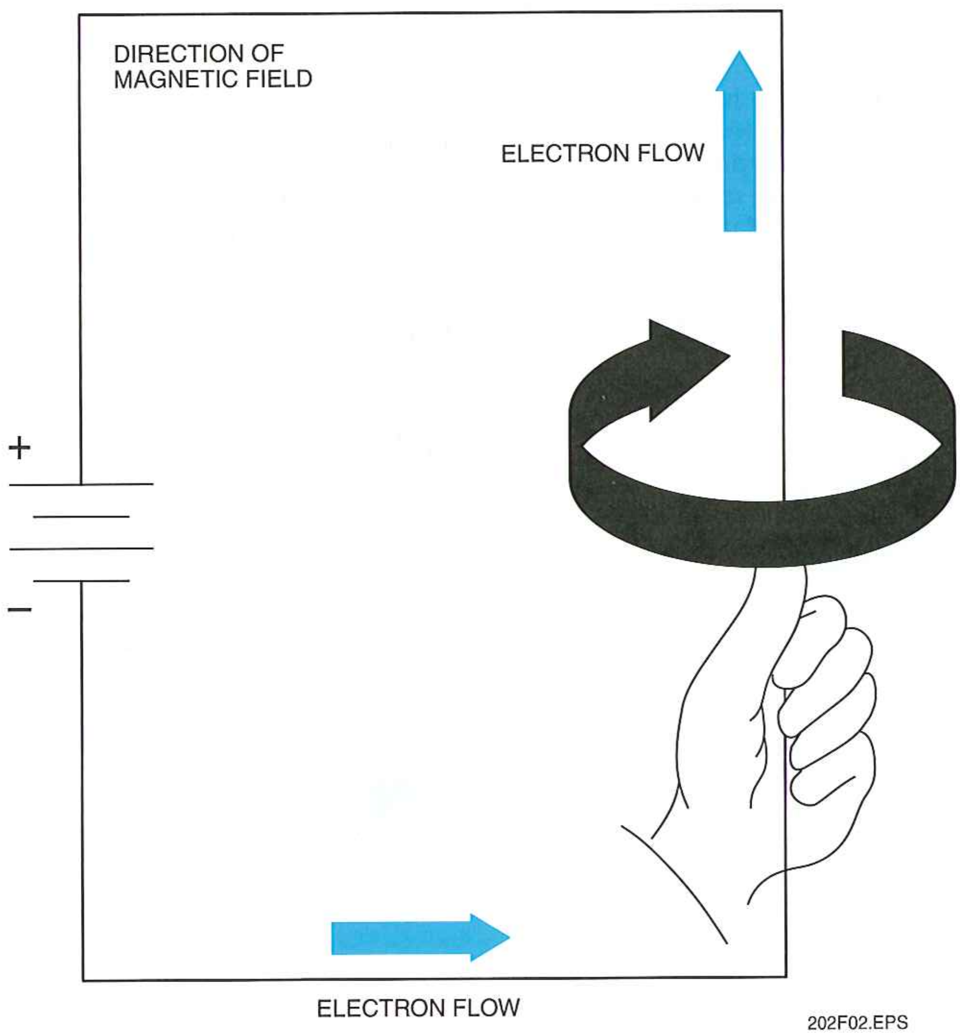


Figure 2 ◆ Left-hand rule for conductors.

The left-hand rule shows the direction of the flux lines around a wire that is carrying current. When the thumb points in the direction of the electron current, the fingers will point in the direction of the magnetic lines of force.

The right-hand rule for motors shows the direction that a current-carrying wire will be moved in a magnetic field (see *Figure 3*). When the forefinger is pointed in the direction of the magnetic field lines, and the center finger is pointed in the direction of the current in the wire, the thumb will point in the direction that the wire will be moved.

2.2.0 DC Motor Components

A DC motor consists of a few major components, each with a specific purpose in the motor's operation.

The **armature** is a movable electromagnet located between the poles of another fixed permanent (field) magnet, as shown in *Figure 4*.

The magnetic field from the armature conductors interacts with the magnetic field from the field magnet. The result of the field interaction is motor action.

Current in a conductor also has its associated magnetic field. When a conductor is placed in another magnetic field from a separate source, the two fields can react to produce motor action. The conductor must be perpendicular to the magnetic field, as illustrated in *Figure 5*. This way, the perpendicular magnetic field of the current is in the same plane as the external magnetic field.

Unless the two fields are in the same plane, they cannot affect each other. In the same plane, however, lines of force in the same direction reinforce to make a stronger field, while lines in the opposite direction cancel and result in a weaker field. The stronger field tends to move the conductor toward the weaker field, as illustrated in *Figure 5*.

These directions are summarized as follows:

- With the conductor at 90°, or perpendicular to the external field, the reaction between the two magnetic fields is at its maximum.
- With the conductor at 0°, or parallel to the external field, there is no effect between them.
- When the conductor rise is at an angle between 0° and 90°, only the perpendicular component is effective.

In motor action, the wire only moves in a straight line, and it stops moving once out of the field, even though current still exists. A practical motor must develop continuous rotary motion. To produce this, a twisting force called torque must be developed.

Torque is produced by mounting a loop in a fixed magnetic field. Current is applied and the flux lines along both sides of the loop interact, causing the loop to act like a lever with a force pushing on its two sides in opposite directions. This is shown in *Figure 6*.

The combined forces result in a turning force or torque, because the rotor or armature is arranged to pivot on its axis. The overall turning force on the armature depends on several factors, including field strength, armature current strength, and the physical construction of the armature, especially the distance from the loop sides to the axis lines.

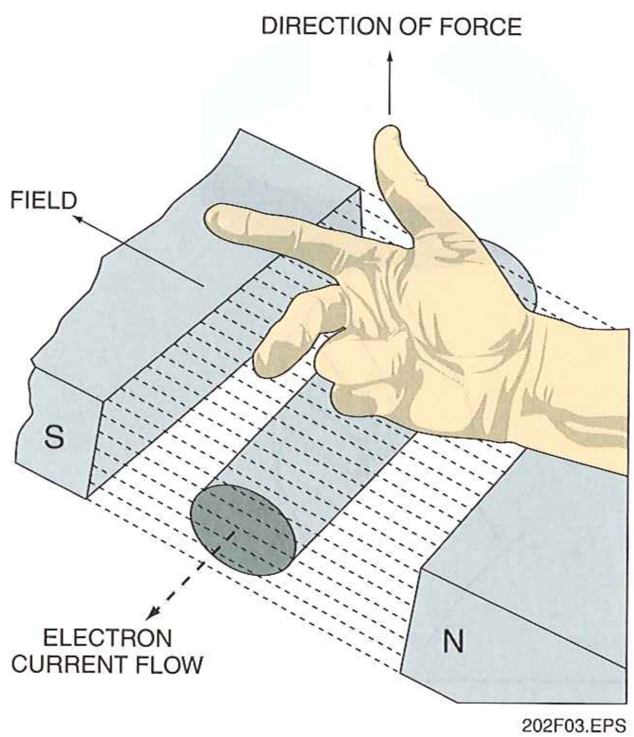


Figure 3 ◆ Right-hand rule for motors.

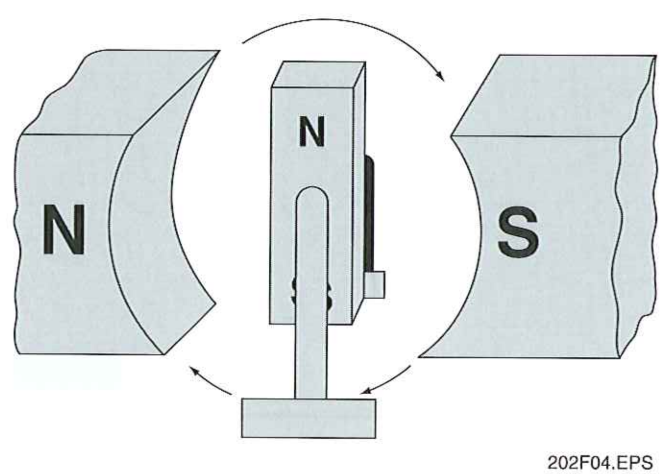


Figure 4 ◆ Basic motor action.

Hand Rules for Motors

THINK ABOUT IT

Use the left-hand conductor rule and the right-hand motor rule to explain the motor action pictured in *Figure 5*.

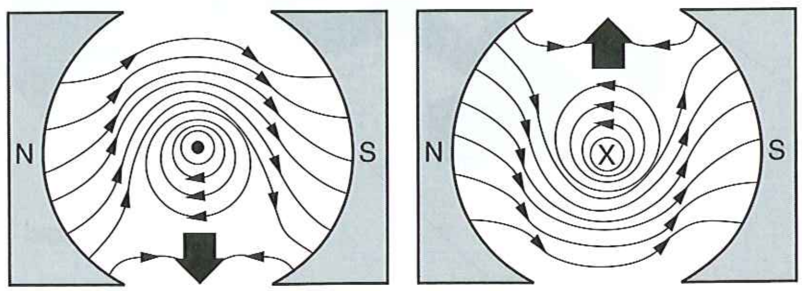


Figure 5 ◆ Motor action.

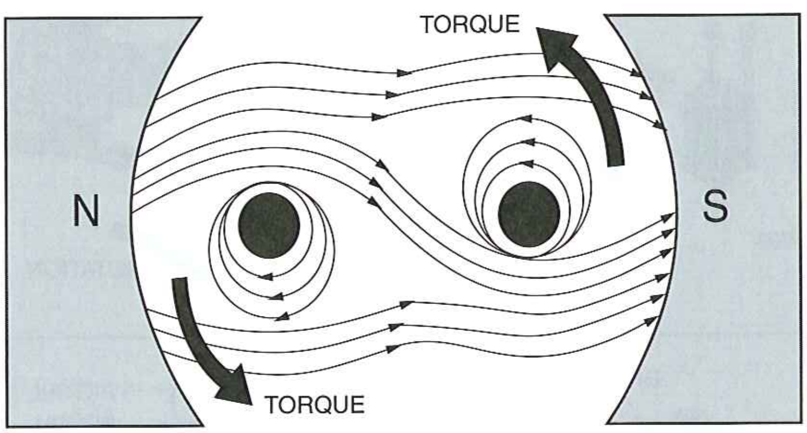


Figure 6 ◆ Torque.

Because of the lever action, the forces on the sides of the armature loop will increase as the loop sides are farther from the axis; therefore, larger armatures will produce greater torques.

In the practical motor, the torque determines the energy available for doing useful work. The greater the torque, the greater the energy. If a motor does not develop enough torque to turn its load, it stalls.

To get continuous **rotation,** the armature must be kept moving in the same direction. This requires reversing the direction of current through the armature for every 180° of revolution. A **commutator** is used to provide this switching action. This is shown in *Figure 7*.

The commutator on a DC motor is a conducting ring that is split into two segments, with each segment connected to an end of the armature loop. Current enters the side of the armature closest to the south pole of the field and leaves the side closest to the north pole of the field. The interaction of the two fields produces a torque, and the armature rotates in that direction.

A **brush** makes contact with each segment of the commutator, providing a connection between the movable commutator and the stationary DC power source. *Figure 8* shows various brushes and commutator connections used in DC motors.

The problem of switching commutator segments in a simple single-loop motor is that when

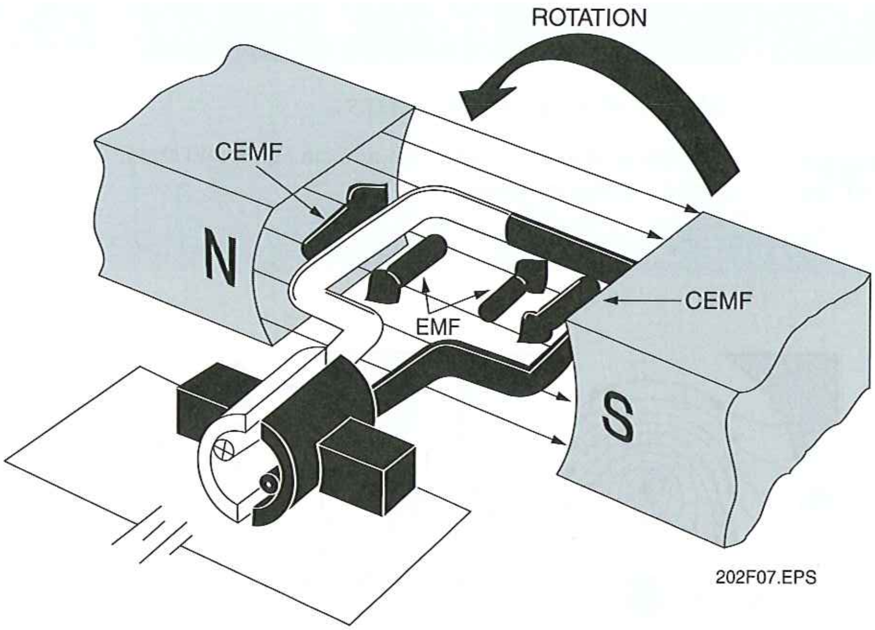


Figure 7 ◆ Single-loop armature DC motor.

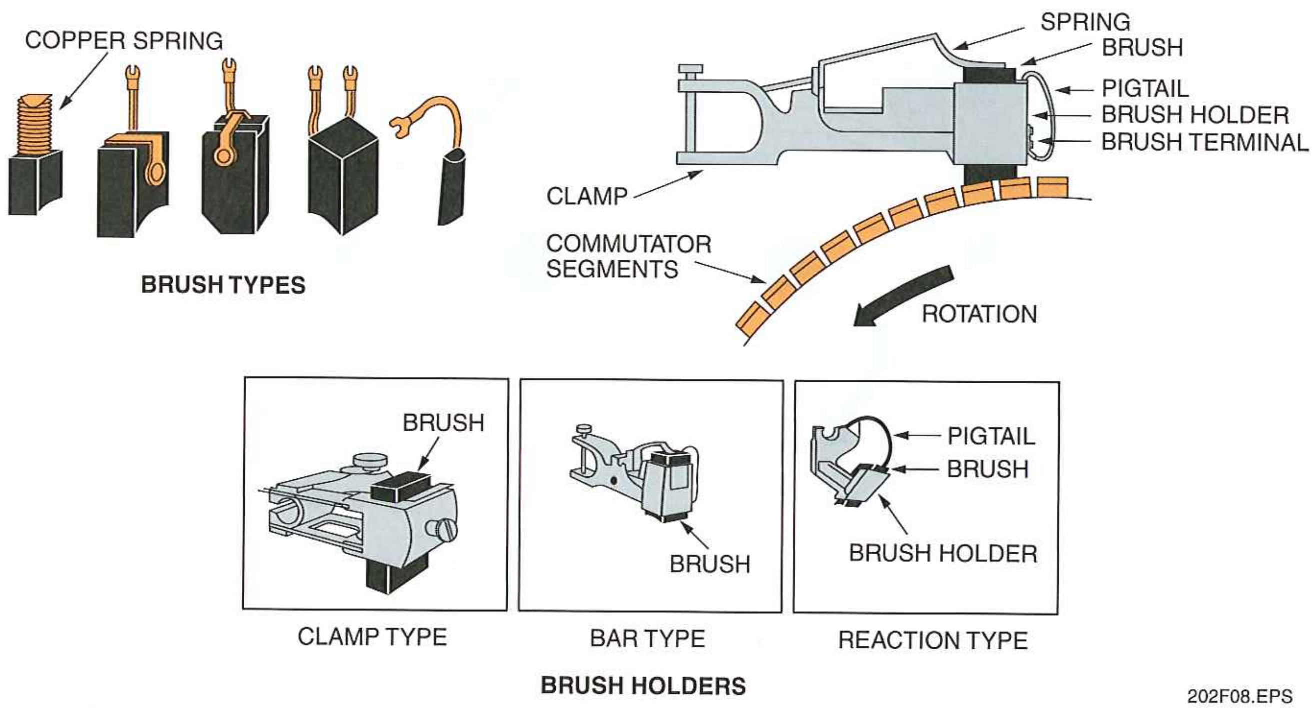


Figure 8 ◆ Brushes, brush rigging, and commutator connections.

the motor stops, there is no way of predicting the position of the armature at rest. If the armature stops in a position where the commutator is in the middle of switching, the motor will not start unless you physically turn the armature.

This problem can be overcome by winding more coils on the armature and by using more commutator segments. This will produce a self-starting motor. The motor shown in *Figure 9* uses three armature coils and three commutator segments. Regardless of where the armature comes to rest, there is always a path for current that will produce torque to rotate the armature.

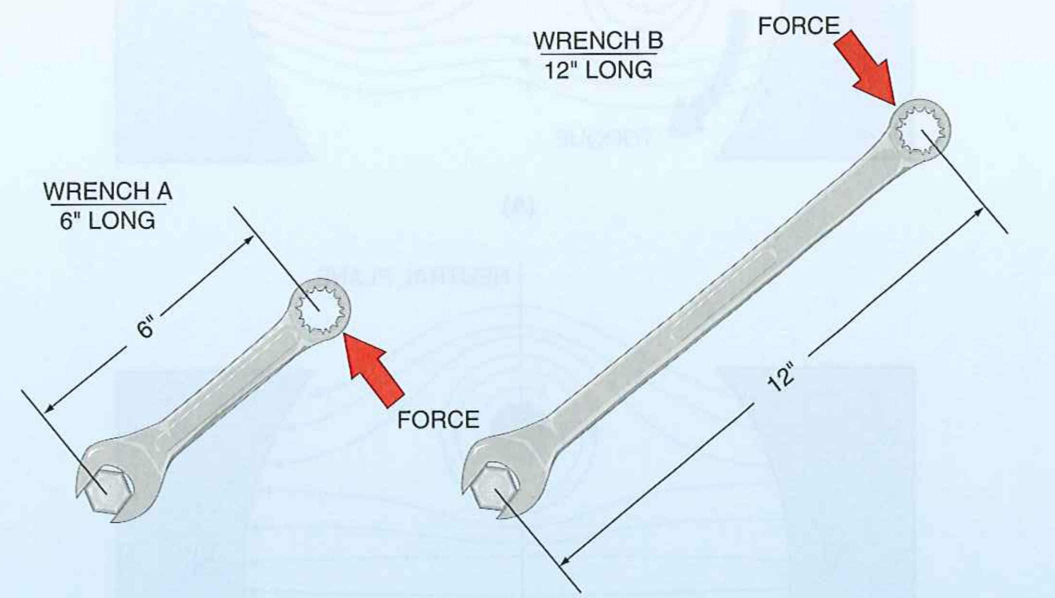
2.3.0 The Neutral Plane

The armature turns when torque is produced, and torque is produced as long as the fields of the

Understanding the Theory of Torque

THINK ABOUT IT

A motor provides torque (a turning force) similar to that needed to turn a nut. In the illustration shown here, which wrench should be able to turn the nut easier?



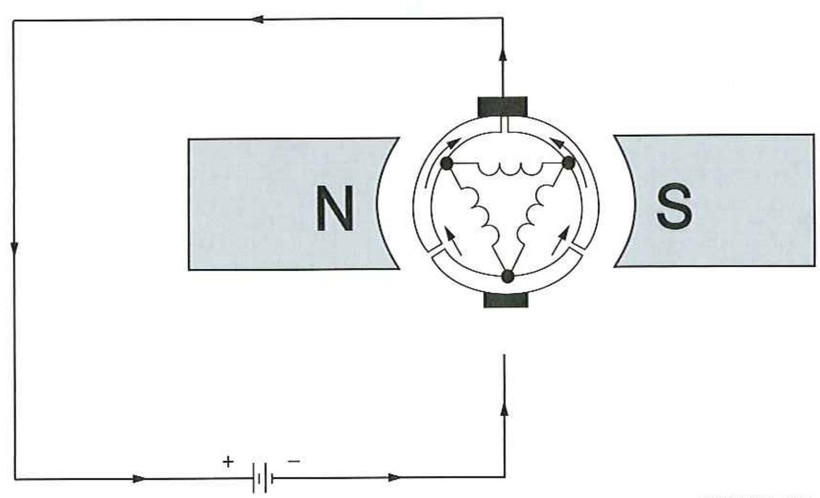


Figure 9 ◆ Self-starting motor.

magnet and armature interact. When the loop reaches a position perpendicular to the field, the interaction of the magnetic fields stops. This position is the neutral plane, shown in *Figure 10*.

In the neutral plane, no torque is produced and the rotation of the armature should stop. However, inertia tends to keep the armature in motion even after the prime moving force is removed; thus the armature tends to rotate past the neutral plane. At the neutral position, the commutator disconnects from the brushes, and once the armature goes past neutral, the sides of the loop reverse positions. The switching action of the commutator maintains the direction of current through the

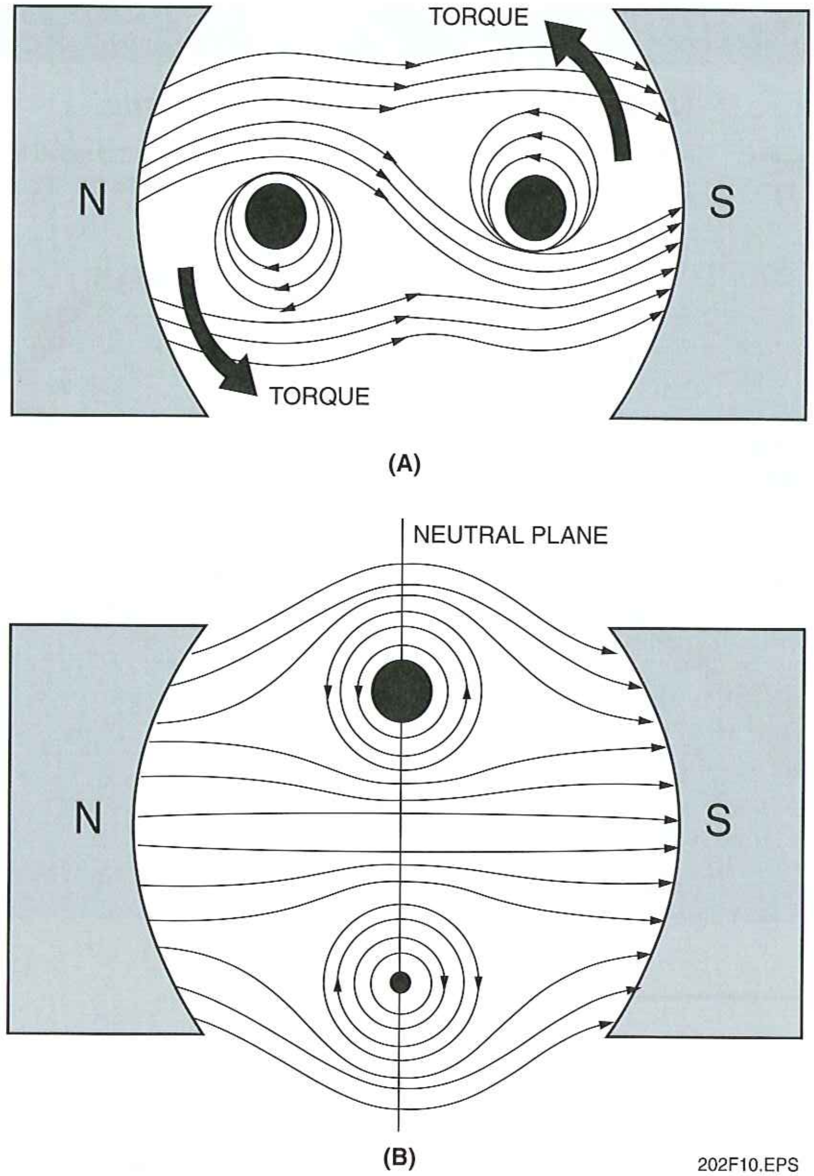


Figure 10 ◆ Neutral plane.

armature. Current still enters the armature side that is closest to the south pole.

Since the magnet's field direction remains the same throughout, the interaction of fields after commutation keeps the torque going in the original direction; thus, continuous rotation is maintained. See *Figure 11*.

Although such an elementary DC motor can be built and operated, it has two serious shortcomings that prevent it from being useful: first, such a motor cannot always start by itself; and second, once started, it operates very irregularly.

When the elementary DC motor runs, its operation is erratic because it produces torque irregularly. Maximum torque is produced only when the plane of the single-loop armature is parallel with the plane of the field. This is the position at right angles to the neutral plane. Once the armature passes this plane of maximum torque, less and less torque is developed until it arrives at the neutral plane again. Inertia carries the armature past the neutral plane and so the motor continues to turn. Its irregularity in producing torque, however, prevents the single-loop elementary DC motor from being used for practical jobs.

2.4.0 Two-Loop DC Motors

The basic DC motor is improved by building the armature with two or more loops. The loops are placed at right angles to each other; when one loop lies in the neutral plane, the other is in the plane of maximum torque. See *Figure 12*.

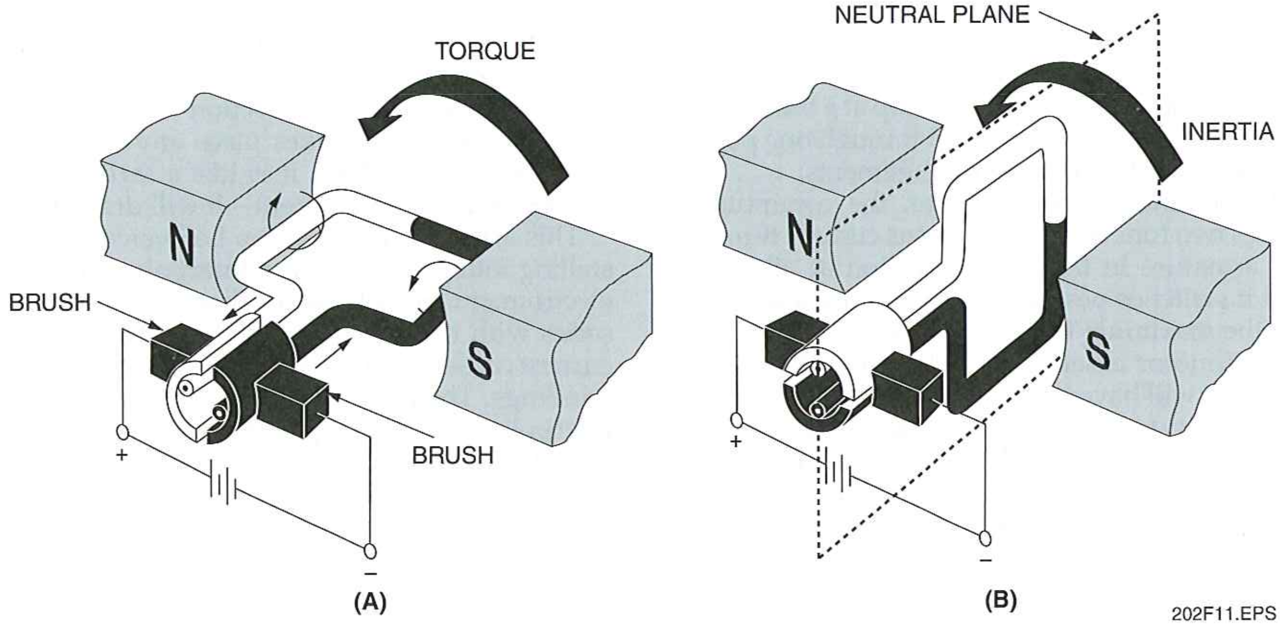


Figure 11 ◆ Neutral plane in a DC motor.

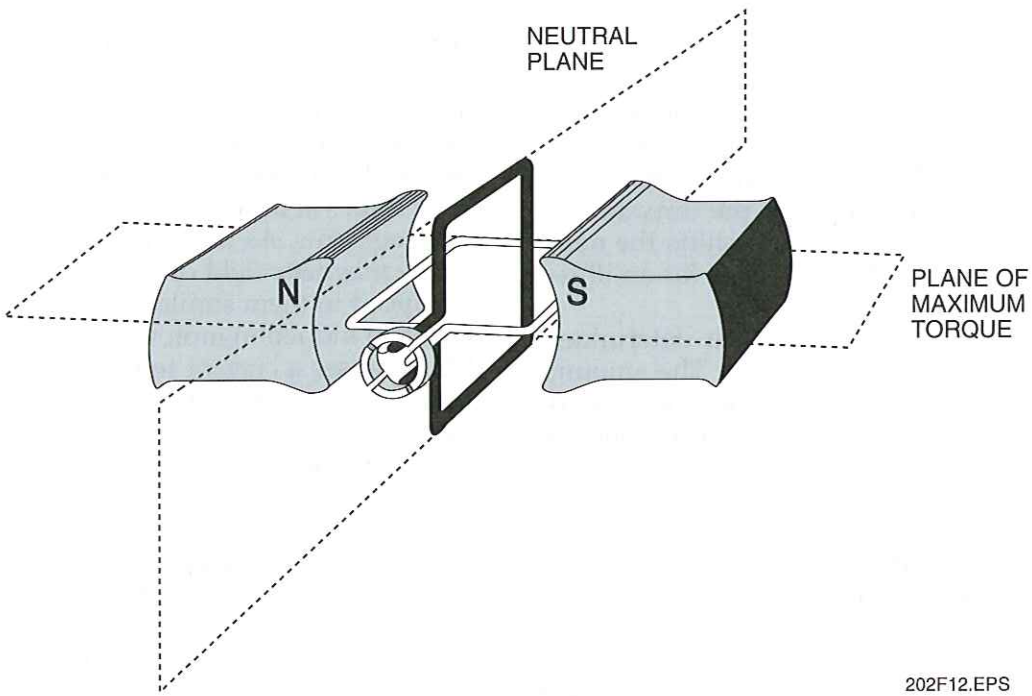


Figure 12 ◆ Two-loop armature DC motor.

THINK ABOUT IT

Two-Loop DC Motors

Using the basic principles of motor action, explain why the two-loop DC motor is self-starting and why its torque is erratic.

In this case, the commutator is split into two pairs or four segments, with one segment associated with each end of each armature loop. This sets up two parallel loop circuits. Only one loop at a time is ever connected if power is supplied through one pair of fixed brushes to one set of ring segments.

In this multi-loop armature, the commutator serves two functions: it maintains current through the armature in the same direction at all times, and it switches power to the armature loop nearing the maximum torque position.

This motor is self-starting because at least one winding will have interaction with the main field. With this two-loop system, the torque developed is steadier and stronger but still somewhat erratic, because only one loop at a time provides the torque that drives the motor.

2.5.0 Armature Reaction

When a motor armature is supplied with current, a magnetic flux is built up around the conductors of the armature windings. Armature reaction is caused by two magnetic fields: the main magnetic field from the field magnets and the magnetic field produced by the armature. These two fields combine to produce a new resultant magnetic field.

The resultant field is distorted and shifts opposite the main field and opposite the direction of armature rotation. This distortion shifts the neutral plane of the motor. See *Figure 13* for an illustration of armature reaction.

The amount of armature reaction determines how far the neutral plane is shifted. The amount of armature reaction depends on the amount and direction of the armature current. The concern over the neutral plane shift occurs because of the need for commutation.

Commutation, or the switching of the armature polarity, must take place at the neutral plane in order to allow the output current from the machine to remain in the same direction without arcing. When commutation takes place anywhere other than the neutral plane, it is like a switch that is opened during high current—it will draw an arc.

This armature reaction can be overcome by installing interpole windings. Interpoles are special electromagnetic pole pieces that are connected in series with the armature winding. The armature current causes a magnetic field to form around the windings. Their action is self-regulating, and the interpole field will apply the proper amount of cancellation field for any set of conditions. For a high armature reaction, the canceling field is strong. For a low armature reaction, the canceling field is weaker. See *Figure 14*.

2.6.0 Counter-Electromotive Force (CEMF)

When a DC motor is in operation, it acts much like a DC generator. A magnetic field is produced by the **field poles,** and a loop of wire in the armature turns and cuts this magnetic field. To understand counter-electromotive force (CEMF), first disregard the fact that external current is being applied to the rotor via the carbon brushes on the commutator segments. As the armature wires rotate and cut the magnetic field of the field poles, a voltage is induced in them similar to that which was discussed in induction motors. This induced voltage (EMF) causes a current to flow in them and a resulting magnetic field is created.

Before analyzing the relative direction between the current induced in the armature windings and the current that caused it in the field poles, first

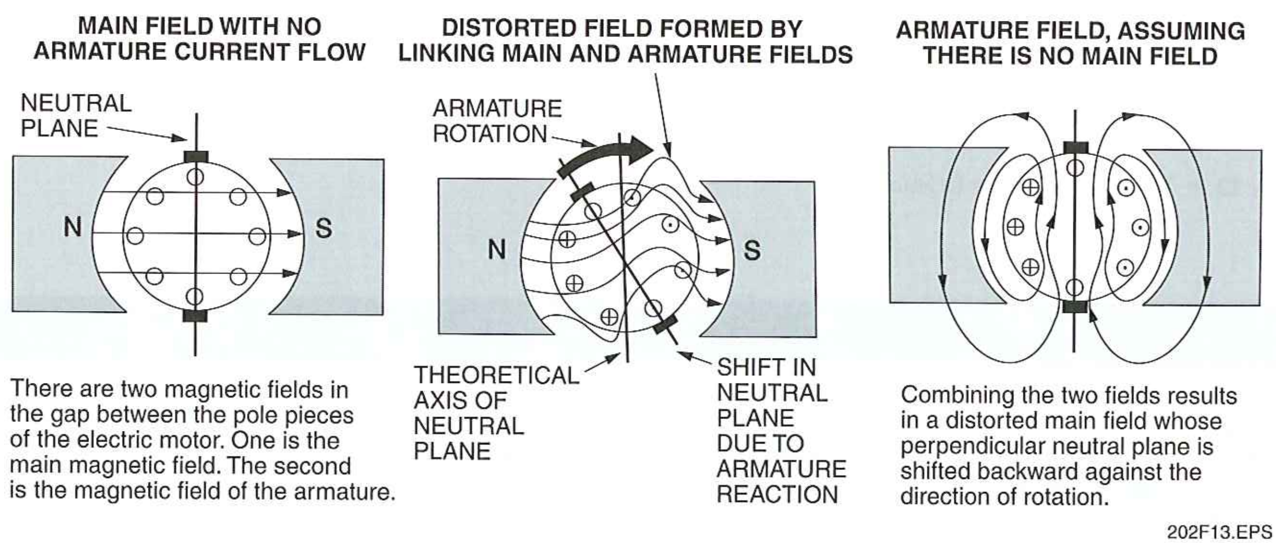


Figure 13 ◆ Armature reaction.

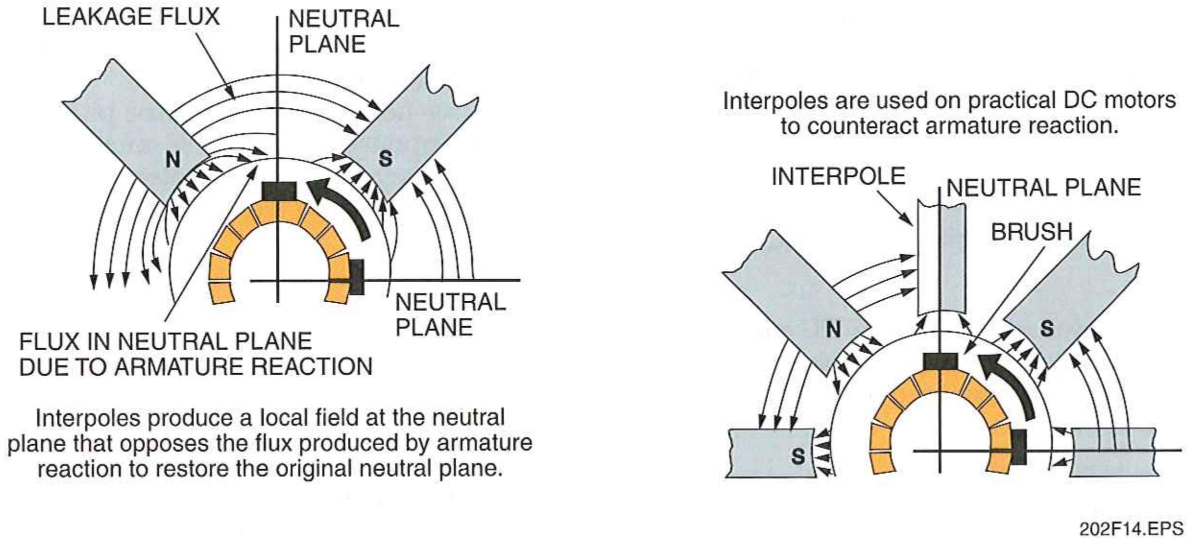


Figure 14 ◆ Interpoles.

remember the left-hand rule. Using your left hand, hold it such that your index finger points in the direction of the magnetic field (north to south) and your thumb points in the direction of rotational force on a given conductor. Your middle finger will now point in the direction of current flow for that conductor. This current would be in opposition to the current that is flowing from the battery. Since this induced voltage and induced current are opposite to those of the battery, they are called CEMF. The two currents are flowing in opposite directions. This would mean that the battery voltage and the CEMF are opposite in polarity. See *Figure 15*.

When first discussing CEMF, we disregarded the fact that external DC was being applied to the armature via the brushes. The induced voltage and resulting current flow was then shown to flow opposite to the externally applied current. This was an oversimplification, since only one current flows. Since the CEMF can never become as large as the external applied voltage, and since they are opposite in polarity, the CEMF works to cancel only a part of the applied voltage. The single current that flows is smaller due to the CEMF.

Since the CEMF of a motor is generated by the action of the armature windings cutting the lines of force set up by the field poles, the value of it will

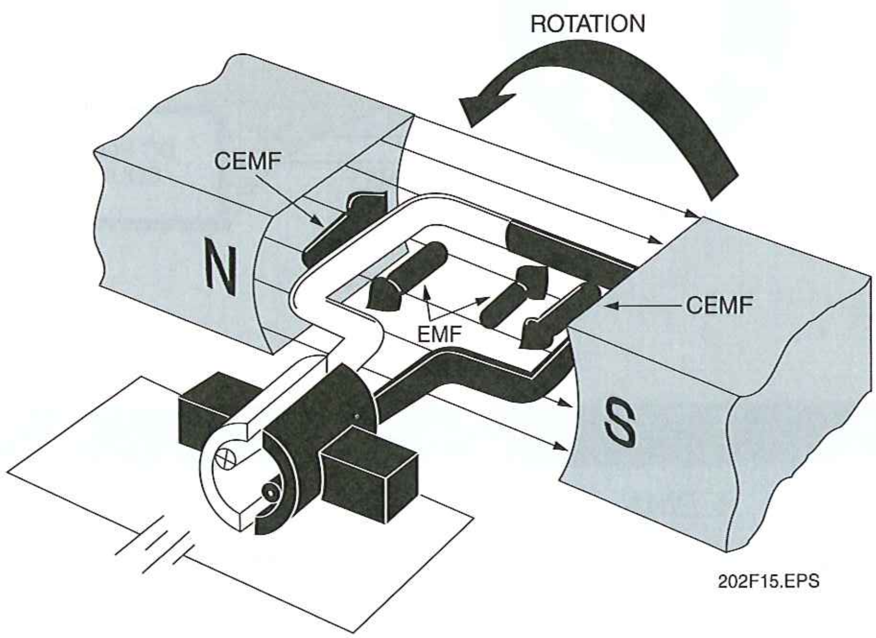


Figure 15 ◆ Counter-electromotive force (CEMF).

depend on the field strength and the armature speed. The effective voltage acting in the armature is the terminal voltage minus the CEMF. Ohm's law gives the value of armature current by:

$$\text{Armature } (I_A) = \frac{\text{terminal voltage} - \text{CEMF}}{\text{armature resistance } (R_A)}$$

$$\text{Where CEMF} = \text{terminal voltage} - (I_A \times R_A)$$

Example:

Find the value of CEMF of a DC motor when the terminal voltage is 240V and the armature current is 60 amps. The armature resistance has been measured at 0.08 ohm.

$$\text{CEMF} = \text{terminal voltage} - (I_A \times R_A)$$

$$\text{CEMF} = 240 - (60 \times 0.08) = 240 - 4.8 = 235.2\text{V}$$

CEMF acts as an automatic current limiter that reduces armature current to a level adequate to drive the motor but not great enough to heat the armature to where it is in danger of burning out. CEMF acts as a load for the DC power supply feeding the motor, so that the low-resistance motor windings do not draw excessive amounts of current.

If we stalled the armature so that no CEMF was produced, we would find that the motor draws so much current it heats up. This reaction is shown in *Figure 16*. CEMF is present in all motors and is necessary for a motor's operation.

We have now covered the basic principles and major components of the DC motor. However, there are many types of DC motors, and several of them will be covered later in this module.

2.7.0 Starting Resistance

Large DC motors require that a starting resistance be inserted in series with the motor armature. The current drawn by the armature is governed by CEMF and the armature resistance. When starting, CEMF will be zero because the rotor is at a standstill. There is also no inductive reactance, as in AC induction motors. This means that the starting current will be abnormally high unless limited by external starting resistance.

Figure 17 shows a shunt motor that is connected directly across a 250V line. The armature resistance is known to be 0.5 ohm. The full-load current of the motor is known to be 25 amps and the shunt field current is one amp. The resulting armature current under full-load conditions would therefore be 24 amps.

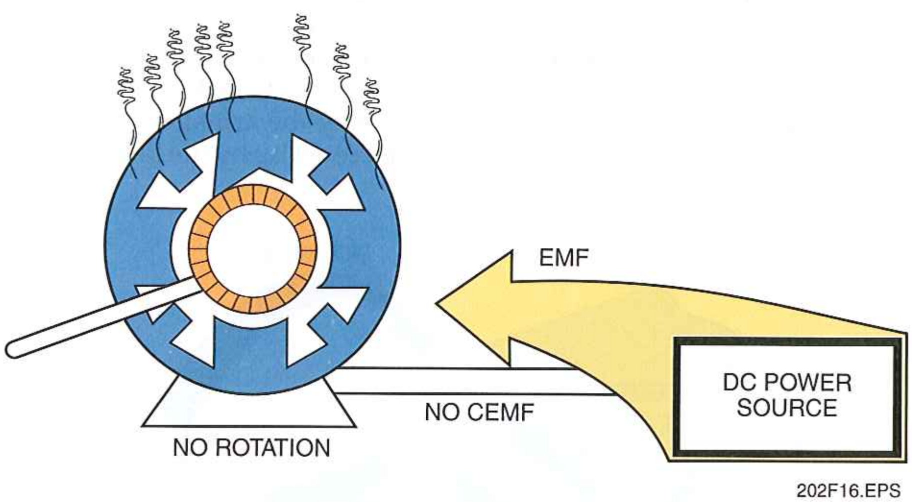


Figure 16 ◆ No CEMF.

THINK ABOUT IT

CEMF

Can a motor's CEMF equal the applied terminal voltage? If not, why not?

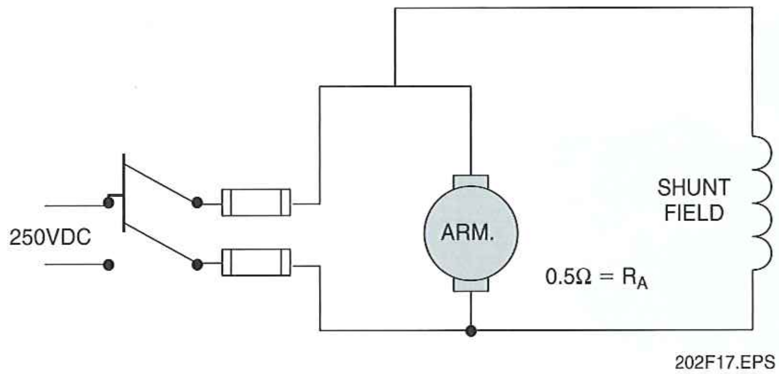


Figure 17 ◆ Shunt motor.

If starting resistance is not used, the value of the armature current (I_A) can be found using the following equation:

$$I_A = \frac{\text{terminal voltage} - \text{CEMF}}{R_A}$$

$$I_A = \frac{250V - 0V}{0.5\text{ ohm}}$$

$$I_A = 500\text{ amps}$$

This amount of starting current is too high and may result in excessive torque and heat that may cause damage to the motor. When starting resistance is added in series with the armature, the starting current can be limited to 1.5 times the full-load current value. After starting, this external resistance can be removed from service.

If we want to limit the starting armature current to 1.5 times the full-load value, we can solve for the size of resistance that would be required using the previous equations.

$$R_{starting} = \frac{(\text{terminal voltage} - \text{CEMF}) - (I_A \times R_A)}{I_A}$$

Where:

$$\text{Starting } I_A = 1.5 \times \text{steady state}$$
$$= 1.5 \times 24\text{ amps}$$
$$= 36\text{ amps}$$

At the moment of motor start, when the rotor is at a standstill and the CEMF is zero, the series resistance will be:

$$R_{starting} = \frac{(250V - 0V) - (36A)(0.5\Omega)}{36A} = 6.44\Omega$$

To find the wattage required in the starting resistance, take the square of the current multiplied by the resistance, where watt loss is calculated by the I^2R method.

Example:

Find the power developed in both watts and **horsepower** in a DC motor that has a terminal voltage of 240V and an armature current of 60A. The armature resistance is known to be 0.08Ω.

$$\text{CEMF} = V_T - (I_A \times R_A)$$
$$\text{CEMF} = 240 - (60 \times 0.08) = 235.2V$$
$$\text{Power} = EI$$
$$\text{Power} = 235.2V \times 60A = 14{,}112\text{ watts}$$
$$\text{Horsepower} = \frac{\text{watts}}{746}$$
$$= \frac{14{,}112\text{ watts}}{746}$$
$$= 18.92\text{hp}$$

3.0.0 ◆ TYPES OF DC MOTORS

There are two basic types of motor connections that are in common use. They are the series motor and the shunt motor. The series motor is so called because the field is connected in series with the armature winding. The shunt motor has the field coils connected in parallel with the armature (rotor) winding. One additional type of motor is a compound motor. This motor has both a series- and a shunt-connected field. *Figure 18* shows a typical DC motor.

3.1.0 Shunt Motors

The field circuit of a shunt motor is connected across the supply line and is in parallel with the armature. A shunt motor connection is shown in *Figure 19*.

When an external load is applied to the shunt motor, it tends to slow down. The slight decrease in

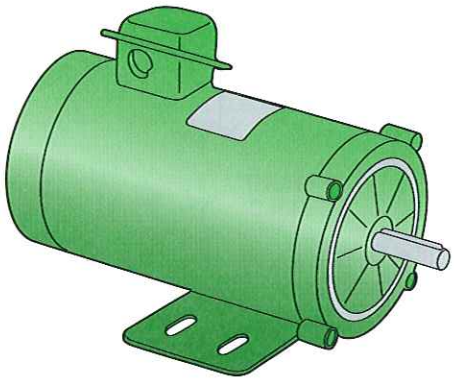
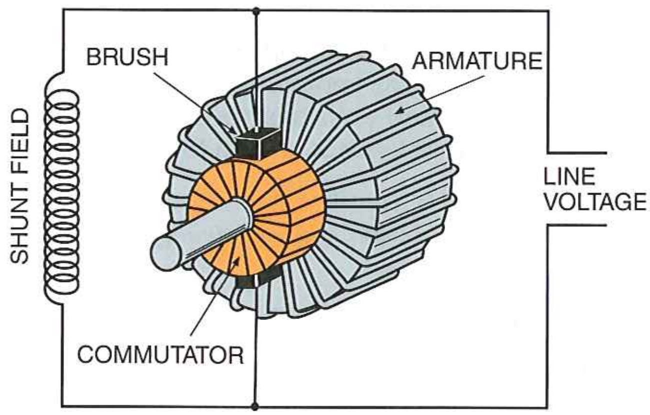

202F18.EPS

Figure 18 ◆ Typical DC motor.



202F19.EPS

Figure 19 ◆ Shunt DC motor.

speed causes a corresponding decrease in CEMF. Since the armature resistance is low, the resulting increases in armature current and torque are relatively large. Therefore, the torque is increased until it matches the opposing torque of the load. The speed of the motor then remains constant at the new value as long as the load is constant.

If the load on the shunt motor is reduced, the motor tends to speed up. The increased speed causes a corresponding increase in CEMF and a relatively large decrease in armature current and torque.

Thus, it may be seen that the amount of current through the armature of a shunt motor depends largely upon the load on the motor. The larger the load, the larger the armature current; the smaller the load, the smaller the armature current. The change in speed causes a change in CEMF and armature current in each case.

The main advantage of a shunt-wound motor is that its speed is fairly constant, changing only a few **revolutions per minute (rpm)** when the amount of load changes. The main disadvantage of this connection is that the motor does not develop much torque when it is first started. If a motor is to be started with a large load, it is generally series connected.

It is important to note that the shunt field circuit of a DC motor should never be opened when the motor is operating, especially when unloaded. This is because an open field may cause the motor to rotate at dangerously high speeds. Large DC shunt motors have a field rheostat with a no-field release feature that disconnects the motor from the power source if the field circuit opens.

3.1.1 Torque

A DC shunt motor has high torque at any rated speed. At startup, a DC shunt motor can develop up to 150% of its normal running torque as long as the resistors in the starting circuit can withstand the heating effect of the current.

3.1.2 Speed Control

DC motors have excellent speed control. To operate the motor above rated speed, a field rheostat is used to reduce the field current and field flux. To operate below rated speed, resistors are used to reduce the armature voltage.

3.1.3 Speed Regulation

The speed regulation of a shunt motor drops from 5% to 10% from no-load to full-load. As a result, a shunt motor is superior to the series DC motor but is inferior to a differential compound-wound DC motor.

INSIDE TRACK

DC Motor Applications

DC motors were developed before AC motors and one of their first uses was in electric trolleys. The DC motor is still widely used in applications that require accurate speed control or high starting torque. For example, in an elevator, the motor must start under a heavy load and accelerate smoothly. It must also stop precisely and reverse direction easily. A DC motor is a good choice for this application.

3.2.0 Series Motors

The field coils of a series motor are connected in series with the armature (*Figure 20*). The value of current through the armature and the field is the same. Hence, if the armature current changes, the field current must also change.

As the motor speeds up, the armature current and field current decrease. With a weaker field, the armature speed will increase still more. The limiting factor on the speed is the load.

If there is no load on the motor, the armature will speed up to such an extent that the windings might be thrown from the slots and the commutator destroyed by the excessive centrifugal forces. For this reason, series motors are seldom belt-connected to their loads. The belt might break, allowing the motor to overspeed and destroy itself. Series motors are usually connected to their loads directly or through gears.

The series motor is used where there is a wide variation in both torque and speed requirements, such as traction equipment, blowers, hoists, cranes, and so forth.

3.2.1 Torque

The DC series motor develops 500% of its full-load torque at starting. Therefore, this type of motor is used in applications where large amounts of starting torque are needed, such as cranes, railway applications, and other equipment with high starting torque demands. With a series motor, any increase in load causes an increase in both the armature current and the field current. Since torque depends on the interaction of these two flux fields, the torque increases as the square of the value of the current increases. Therefore, series motors produce greater torque than shunt motors for the same increase in current. The series motor shows a greater reduction in speed for an equal change in load.

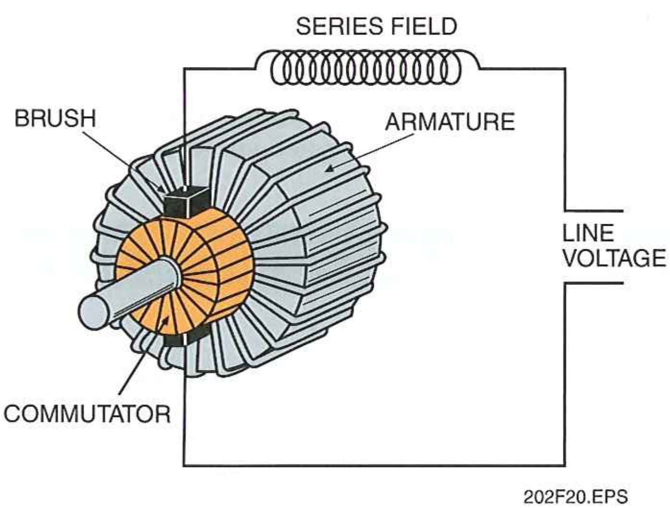


Figure 20 ◆ Series DC motor.

3.2.2 Speed Control and Speed Regulation

The speed control of a series motor is poorer than that of a shunt motor because if the load is reduced, a simultaneous reduction of current occurs in both the armature and field windings, and therefore, there is a greater increase in speed than there would be in a shunt-wound motor.

If the mechanical load were to be disconnected completely from a series motor, the motor would continue to accelerate until the motor armature self-destructed. For this reason, series-wound motors are always permanently connected to their loads.

The speed of a series DC motor is controlled by varying the applied voltage. A series motor **controller** is usually designed to start, stop, reverse, and regulate speed. The direction of rotation of a series motor is changed by reversing either the armature or field winding current flow.

3.3.0 Compound Motors

Compound DC motors are used whenever it is necessary to obtain speed regulation characteristics not obtainable with either the shunt- or series-wound motor. Because many applications require high starting torque and constant speed under load, the compound motor is used. Some industrial applications include drives for elevators, stamping presses, rolling mills, and metal shears. The compound motor has a normal shunt winding and a series winding on each field pole. They may be connected as a long shunt, as shown in *Figure 21(A)*, or a short shunt, as shown in *Figure 21(B)*. When the series winding is connected to aid the shunt winding, the machine is known as a cumulative compound motor. When the series field opposes the shunt field, the machine is known as a differential compound motor.

3.3.1 Torque

The operating characteristics of a cumulative compound-wound motor are a combination of the series motor and the shunt motor. A cumulative compound-wound motor develops high torque for sudden increases in load.

3.3.2 Speed

Unlike the series motor, the cumulative compound-wound motor has definite no-load speeds and will not build up self-destructive speeds if the

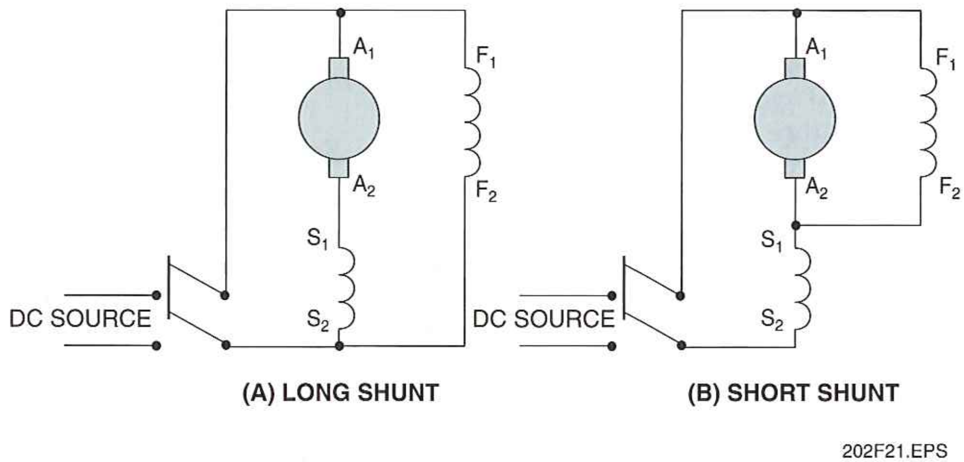


Figure 21 ◆ Long and short shunts.

INSIDE TRACK

Compound DC Motors

The compound motor avoids some of the limitations of the series-wound and shunt-wound motors. The shunt field has a constant current, so the motor will not self-destruct like a series motor. The series winding, on the other hand, provides strong torque.

load is removed. Speed control of a cumulative compound-wound motor can be controlled by inserting resistors in the armature circuit to reduce the applied voltage. When the motor is to be used for installations where the rotation must be reversed frequently, such as in elevators, hoists, and railways, the controller should have voltage dropping resistors and switching arrangements to accomplish reversal.

3.3.3 Speed Regulation

The speed regulation of a cumulative compound-wound motor is inferior to that of a shunt motor and superior to that of a series motor.

3.4.0 Operating Characteristics

Different types of motors have different operating characteristics. Therefore, the proper type of DC motor should be selected when the load to be driven is known. *Figure 22* shows the operating characteristics of a typical DC shunt motor.

Notice that the motor speed is relatively independent of the torque (load applied) from 0 to 150% of the rated capacity of the motor. Such motors find application where relatively constant speed over a wide load range is required. *Figure 23* shows the operating characteristics of a typical DC series motor.

Notice that the motor speed varies greatly with respect to the torque (load applied). With less than half of its rated load applied, the motor operates at more than 150% of its rated speed. When 150%

INSIDE TRACK

Permanent Magnet DC Motors

Many ¼hp to 3hp variable-speed DC motors available for constant or diminishing torque applications use permanent magnets for the field poles instead of shunt or series windings. They employ variable DC armature voltages up to 90V or 180V for speed control. However, they are inefficient if they use only rheostat control of the armature voltage.

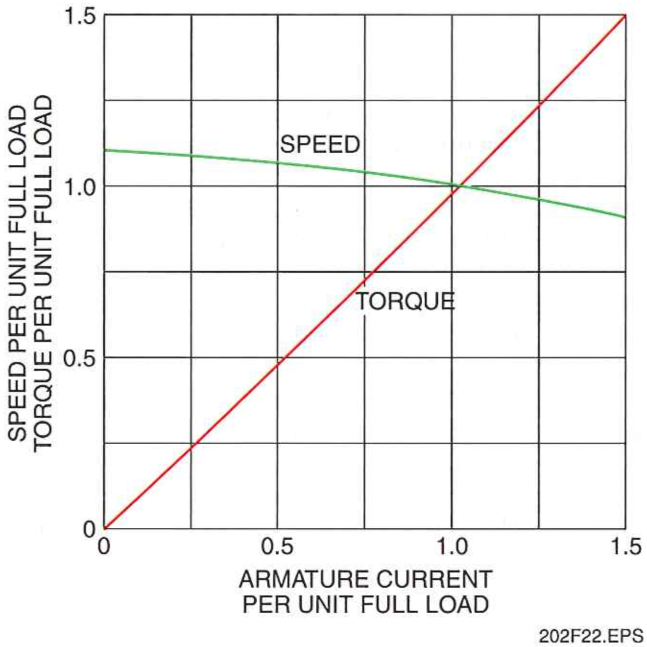


Figure 22 ◆ Operating characteristics of a typical DC shunt motor.

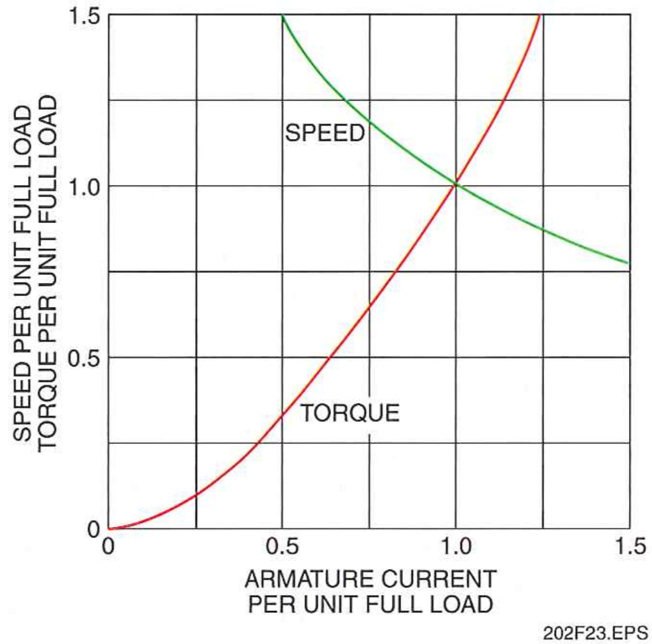


Figure 23 ◆ Operating characteristics of a typical series motor.

THINK ABOUT IT

DC Motors

Given the speed and torque characteristics of shunt and DC motors, which one would be better suited to the varying loads of an escalator?

of the rated load is applied to the motor, it drops to 75% of its rated speed. Such motors find application where a constant heavy load exists or where great speed variations are tolerable.

Figure 24 shows the operating characteristics of a DC compound motor. Notice that the motor speed is relatively constant over the operating range. Its speed does vary with the torque somewhat more than the shunt motor, but will not run away or markedly decrease, as with the series motor. Such motors find application where the load is not known exactly or where some speed variation is tolerable with load variation.

3.5.0 Brushless DC Motors

The brushless DC motor was developed to eliminate commutator problems in missiles and spacecraft operating above the Earth's atmosphere. Two general types of brushless motors are in use: the inverter-induction motor and a DC motor with an electronic commutator.

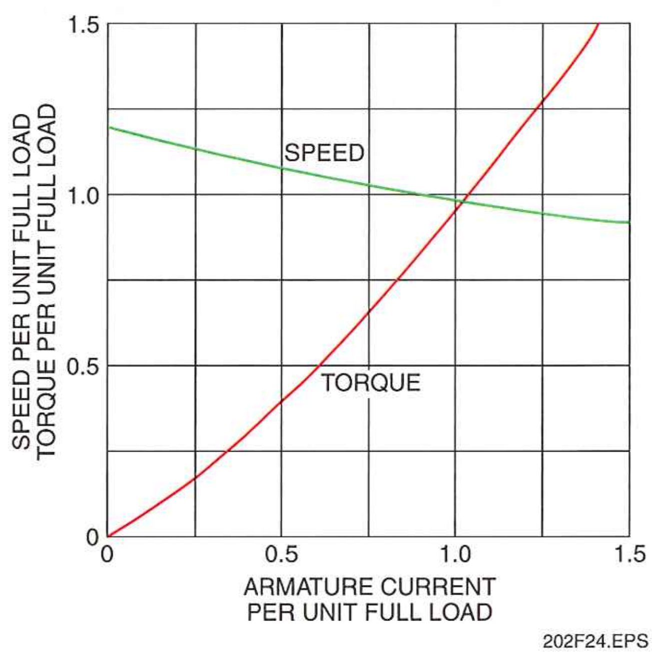


Figure 24 ◆ Operating characteristics of a typical DC compound motor.

4.0.0 ◆ ALTERNATING CURRENT MOTORS

Alternating current motors can be divided into two major types: single-phase motors and polyphase motors. The single-phase motor is normally limited to fractional horsepower ratings up to about five horsepower. They are commonly used to power such things as fans, small pumps, appliances, and other devices not requiring a great amount of power. Single-phase motors are not likely to be connected to complicated motor control circuitry.

Polyphase motors make up the majority of motors needed to drive large machinery such as pumps, large fans, and compressors. These motors have several advantages over single-phase motors in that they do not require a separate winding or other device to start the motor. They have relatively high starting torque and good speed regulation for most applications.

There are two classes of polyphase motors: induction and synchronous. The rotor of a synchronous motor revolves at **synchronous speed,** or the speed of the revolving magnetic field in the stator. The rotor of an induction motor revolves at a speed somewhat less than synchronous speed. The differences in rotor speed are due to differences in construction and operation. Both will be discussed in depth after a review of motor theory.

4.1.0 Polyphase Motor Theory

AC motors consist of two parts: the stator, or stationary part; and the rotor, or revolving part. The stator is connected to the incoming three-phase AC power. The rotor in an induction motor is not connected to the power supply, whereas the rotor of a synchronous motor is connected to external power. Both induction and synchronous motors operate on the principle of a rotating magnetic field.

4.1.1 Rotating Fields

This section shows how the stator windings can be connected to a three-phase AC input to create a magnetic field that rotates. 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.

Polyphase AC is brought into the stator and connected to windings that are physically displaced 120° apart. These windings are connected to form north and south magnetic poles, as shown in *Figure 25.* An analysis of the electromagnetic polarity of the poles at points 1 through 7 in *Figure 25* shows how the three-phase AC creates magnetic fields that rotate.

At point 1, the magnetic field in coil (pole) 1–1A is at its maximum. Negative voltages are shown in 1–2A and 3–3A. The negative voltages in these windings create smaller magnetic fields that will tend to aid the field set up in 1–1A.

At point 2, phase 3 creates a maximum negative flux in 3–3A windings. This strong negative field is aided by the weaker magnetic fields in 1–1A and 1–2A.

The three-phase AC input rises and falls with each cycle. Analyzing each point on the voltage graph shows that the resultant magnetic field rotates clockwise. When the three-phase input completes a full cycle at point 7, the magnetic field has completed an entire revolution of 360°.

4.1.2 Rotor Behavior in a Rotating Field

An oversimplification of rotor behavior shows how the magnetic field of the stator influences the rotor. Assume that a simple bar magnet is placed in the center of the stator diagrams shown in *Figure 25.* Also assume that the bar magnet is free to rotate. It has been aligned such that at point 1, its south pole is opposite the large north of the stator field.

Unlike poles attract and like poles repel. As the AC completes a cycle, going from point 1 to point 7, the stator field rotates and pulls the bar magnet with it because of the attraction of unlike poles and the repulsion of like poles. The bar magnet is rotating at the same speed as the revolving flux of the stator. This speed is known as synchronous speed. The synchronous speed of a motor is given by the equation:

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

Where:

N = speed in rpm
f = frequency in cycles per second
P = number of magnetic poles

4.1.3 Induction

Current flowing through a conductor sets up a magnetic field around the length of the conductor. Conversely, a conductor in a magnetic field will produce a current when the magnetic lines of flux cut across the conductor. This action is called induction because there is no physical connection between the magnetic field and the conductor. Current is induced in the conductor.

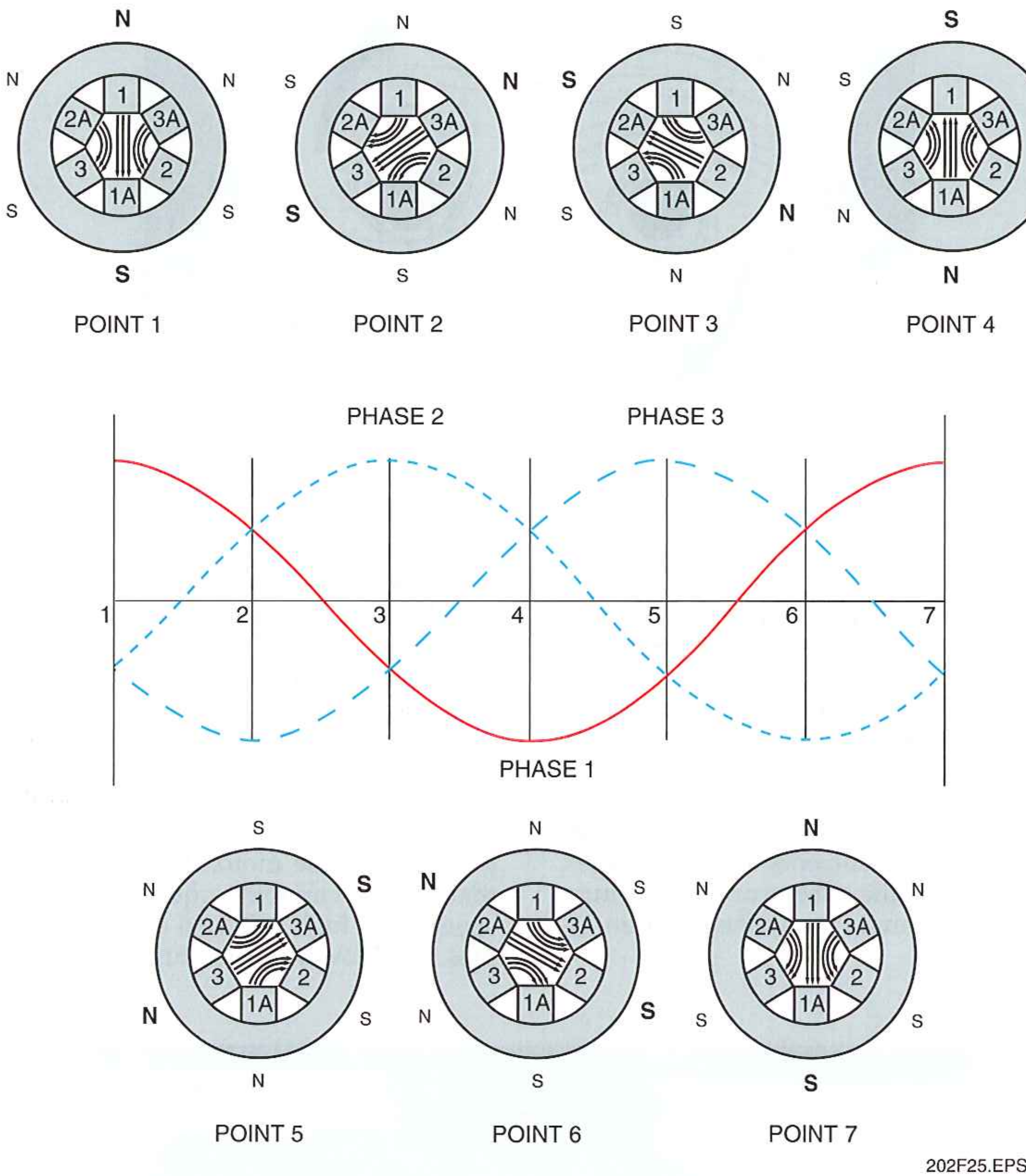


Figure 25 ◆ AC generation.

4.2.0 Three-Phase Induction Motors

In a three-phase induction motor, the driving torque is caused by the reaction of a current-carrying conductor in a magnetic field. In induction motors, the rotor currents are supplied by electromagnetic induction. The stator windings are supplied with three-phase power and produce a rotating magnetic field.

The rotor is not electrically connected to the power supply. The induction motor derives its name from the mutual inductance taking place between the stator and the rotor under operating conditions. The rotating field produced by the stator cuts the rotor conductors, inducing a voltage into the conductors. The induced voltage causes rotor current. This develops motor torque due to the reaction of a current-carrying conductor in a magnetic field. This torque causes the rotor to rotate. This principle is shown in *Figure 26*.

The three-phase (3ϕ) induction motor has a frame, or stationary part, which is the stator. The stator is made of laminated steel rings with slots on the inside circumference. The motor stator windings are the phase windings. They are symmetrically placed on the stator and may be either wye- or delta-connected. Depending on how the stator is wound, it may have two, four, or any even number of poles.

There are two varieties of three-phase induction motors: the squirrel cage rotor motor and the wound rotor motor.

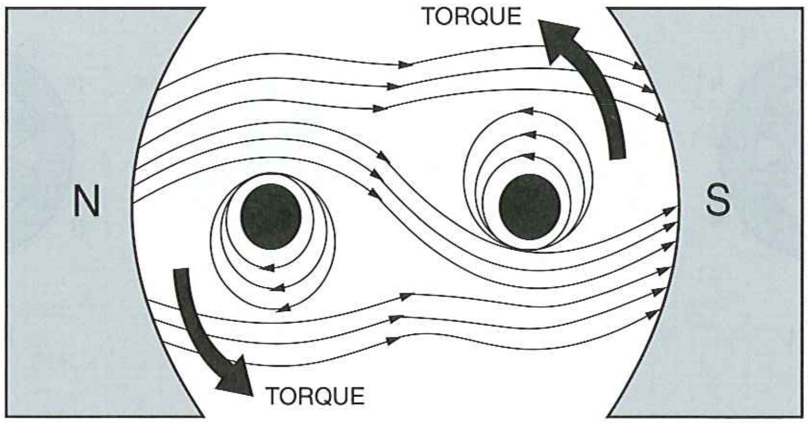


Figure 26 ◆ Producing torque.

4.2.1 Squirrel Cage Induction Motor

The squirrel cage is probably the most popular rotor in use. Three-phase squirrel cage induction motors consist of a stator, a rotor, and two end shields that house the bearings that support the rotor shaft. The frame is usually made of cast steel. The stator core is pressed into the frame. In this rotor, the bars are connected together at the ends by shorting rings made of similar material. The conductor bars carry large currents at low voltages. The bearings can be either sleeve or ball bearings. *Figure 27* shows the main components of an induction motor.

It is not necessary to insulate the bars from the core because the current will follow the path of least resistance and is confined to the cage windings. *Figure 28* shows how a squirrel cage rotor is constructed.

The squirrel cage rotor induction motor has a fixed rotor circuit. The resistance and reactance of the windings are determined when the motor is designed. The standard cage rotor motor is a general-purpose motor. It is used to drive loads that require variable torque at relatively constant speed with high full-load efficiency. Some examples are blowers, centrifugal pumps, and fans.

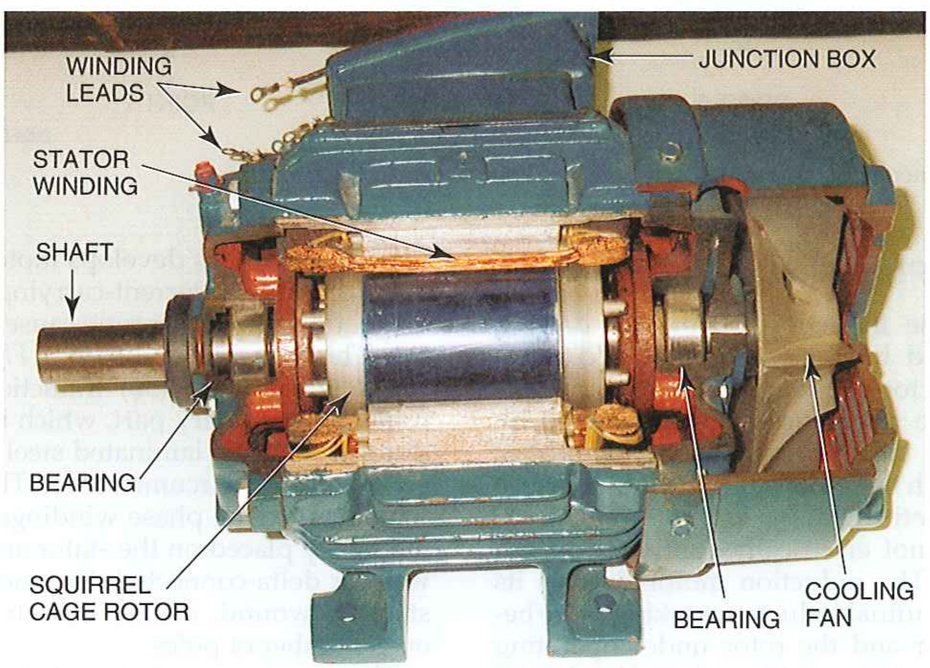


Figure 27 ◆ Main components of an induction motor.

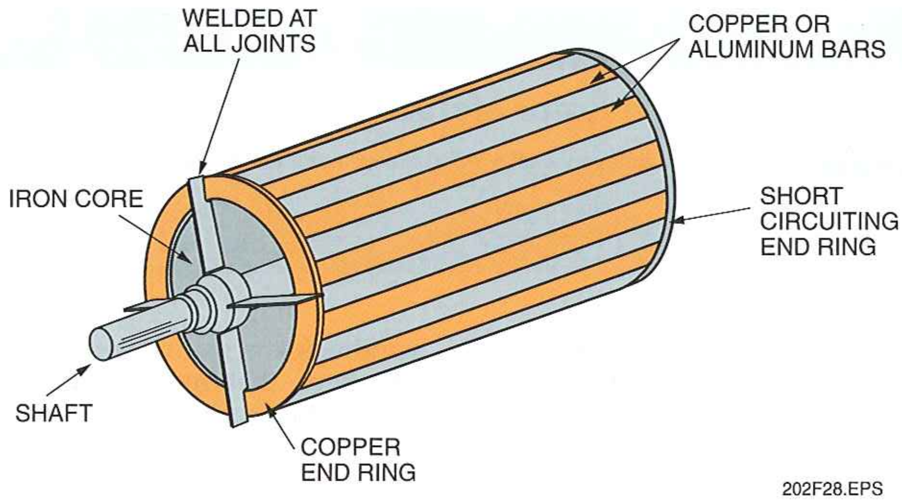


Figure 28 ◆ Squirrel cage rotor.

INSIDE TRACK

Squirrel Cage Motor Applications

Squirrel cage induction motors offer many advantages. For example, maintenance costs are low because these motors have no brushes or slip rings, but work entirely through induction. They also have a high starting torque, so they are useful in common applications such as overhead doors, large compressors, fans, and printing presses.

Due to the absence of any moving electrical contacts, they are suitable for use where they are exposed to flammable dust or gas.

If the load requires special operating characteristics, such as high starting torque, the squirrel cage rotor can be designed to have high resistance bars for a starting circuit and low resistance bars for running operation. A rotor of this type is called a double squirrel cage rotor.

4.2.2 Wound Rotor Induction Motor

A wound rotor (*Figure 29*) has a winding that is similar to the three-phase stator windings. The rotor windings are usually wye-connected with the free ends of the windings connected to three slip rings mounted on the rotor shaft. The slip rings are shown physically mounted on the end of the rotor shaft in *Figure 29*. They are used with brushes to form an electromechanical connection to the rotor.

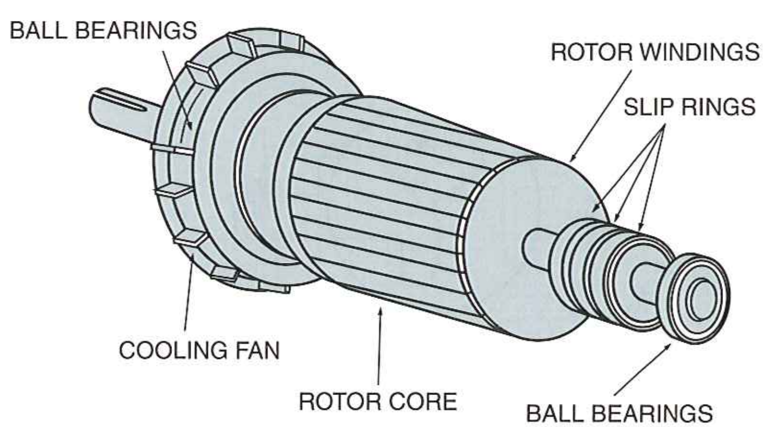


Figure 29 ◆ Wound rotor.

THINK ABOUT IT

Wound Rotor Motors

When might you want a wound rotor motor to run like a squirrel cage motor at full speed?

Slip rings are contact surfaces mounted on the shaft of a motor or generator to which the rotor windings are connected and against which the brushes ride. The brushes are sliding contacts, usually made of carbon, that make continuous electrical connection to the rotating part of a motor or generator.

The wound rotor motor often uses an external wye-connected resistor connected to the rotor through slip rings. The resistor provides a means of varying the rotor resistance. This can be used when the motor is started to produce a high starting torque. As the motor accelerates, the resistance is reduced. When the motor has reached full speed, the slip rings are short circuited, and the operation is similar to that of a squirrel cage rotor induction motor. A schematic representation of this is shown in *Figure 30*.

The wound rotor induction motor is used when it is necessary to vary the rotor resistance, to limit starting current, or to vary the motor speed. Speed can be varied by as much as 50% to 75%; the greater the resistance inserted in the rotor circuit, the lower the speed will be below synchronous speed. When the motor is operating below full speed, the percent slip is increased and the motor is operating at reduced efficiency and horsepower. When all resistance is cut completely out, the speed is somewhat less than that obtained with squirrel cage rotors. Because the rotor circuit heat generation is largely external to the rotor windings, the wound rotor motor is used for applications that require frequent starts without overheating the motor.

4.2.3 Wound Rotor Speed Control

The insertion of resistance in the rotor circuit not only limits the starting surge of current, but also produces a high starting torque and provides a means of adjusting the speed. If the full resistance of the speed controller is cut into the rotor circuit when the motor is running, the rotor current decreases and the motor slows down. As the rotor speed decreases, more voltage is induced in the rotor windings and more rotor current is developed to create the necessary torque at the reduced rotor speed.

If all the resistance is removed from the rotor circuit, both the current and motor speed will increase. However, the rotor speed will always be less than the synchronous speed of the field developed by the stator windings. Recall that this is also true of the squirrel cage induction motor. The speed of a wound rotor motor can be controlled manually or automatically with timing relays, contactors, and pushbutton speed selection.

The advantages of the wound rotor motor are high starting torque with moderate starting current, smooth acceleration under heavy load, no excessive heating during starting, good running characteristics, and adjustable speed control. The

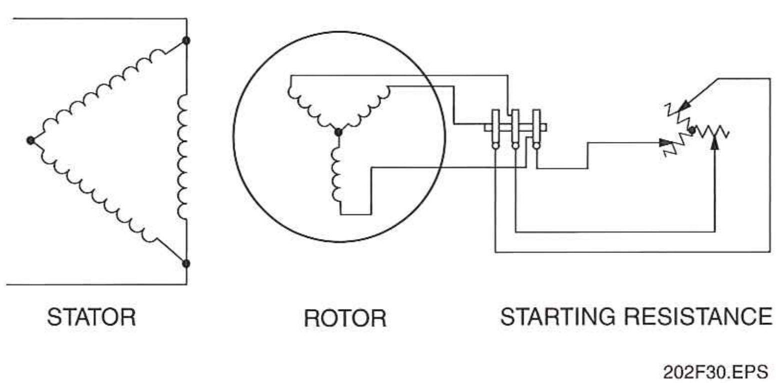


Figure 30 ◆ Wound rotor motor circuit.

INSIDE TRACK

Wound Rotor Motor Applications

Like DC motors, wound rotor motors are used where high inertia loads must be started easily or often. Wound rotor motors have starting torques in the range of 225% of full-load torque. They are used for hoists, hydraulic gates, yard locomotives, and cranes.

chief disadvantage is that both initial and maintenance costs are greater than those of the squirrel cage rotor motor.

4.2.4 Torque

The torque on the rotor of an induction motor tends to turn the rotor in the same direction as the rotating field. If the motor is not driving a load, it will accelerate to nearly the same speed as the rotating field. As the rotor accelerates, the magnitude of the induced voltage in the rotor decreases. This is because the relative motion between the rotating field and the rotor conductors is reduced. It is impossible for an induction motor to operate at synchronous speed because there would be no relative motion between the rotating field and the rotor. Thus, there would be no induced voltage, no rotor current, no rotor magnetic field, and no torque.

4.2.5 Slip

In an induction motor, the rotor always rotates at a speed less than the synchronous speed. The rotor speed is such that sufficient torque is produced to balance the restraining torque caused by motor friction and mechanical load. The difference between the synchronous speed and the rotor speed is known as slip. Slip is expressed mathematically as follows:

$$S = \frac{N - N_R}{N} \times 100\%$$

Where:

S = slip

N = synchronous speed

N_R = rotor speed

To express the quantity as a percent, multiply by 100.

Example:

A four-pole, 208V, 2hp, 60Hz, three-phase induction motor has a no-load speed of 1,790 rpm and a full-load speed of 1,650 rpm.

Find the percent slip for each case below:

- No-load condition
- Full-load condition
- Locked-rotor condition (standstill)

Before any calculations can be made, we must first calculate synchronous speed.

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

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

$$N = 1{,}800\text{rpm}$$

- At no-load condition:

$$S = \frac{N - N_R}{N} \times 100\%$$

$$S = \frac{1{,}800 - 1{,}790}{1{,}800} \times 100\%$$

$$S = 0.556\%$$

- At full-load condition:

$$S = \frac{N - N_R}{N} \times 100\%$$

$$S = \frac{1{,}800 - 1{,}650}{1{,}800} \times 100\%$$

$$S = 8.33\%$$

- At locked-rotor condition:

$$S = \frac{N - N_R}{N} \times 100\%$$

$$S = \frac{1{,}800 - 0}{1{,}800} \times 100\%$$

$$S = 100\%$$

Figure 31 shows how torque relates to speed over the operating range of a motor. Note that speed is proportional to torque on the left side up to pullout torque. Beyond this point, however, torque decreases as speed increases.

Slip is the difference between the synchronous speed and the actual speed of the rotor in an induction motor. Slip is necessary to permit motor action to occur. Under increasing load, the rotor torque increases. Since percent slip is proportional

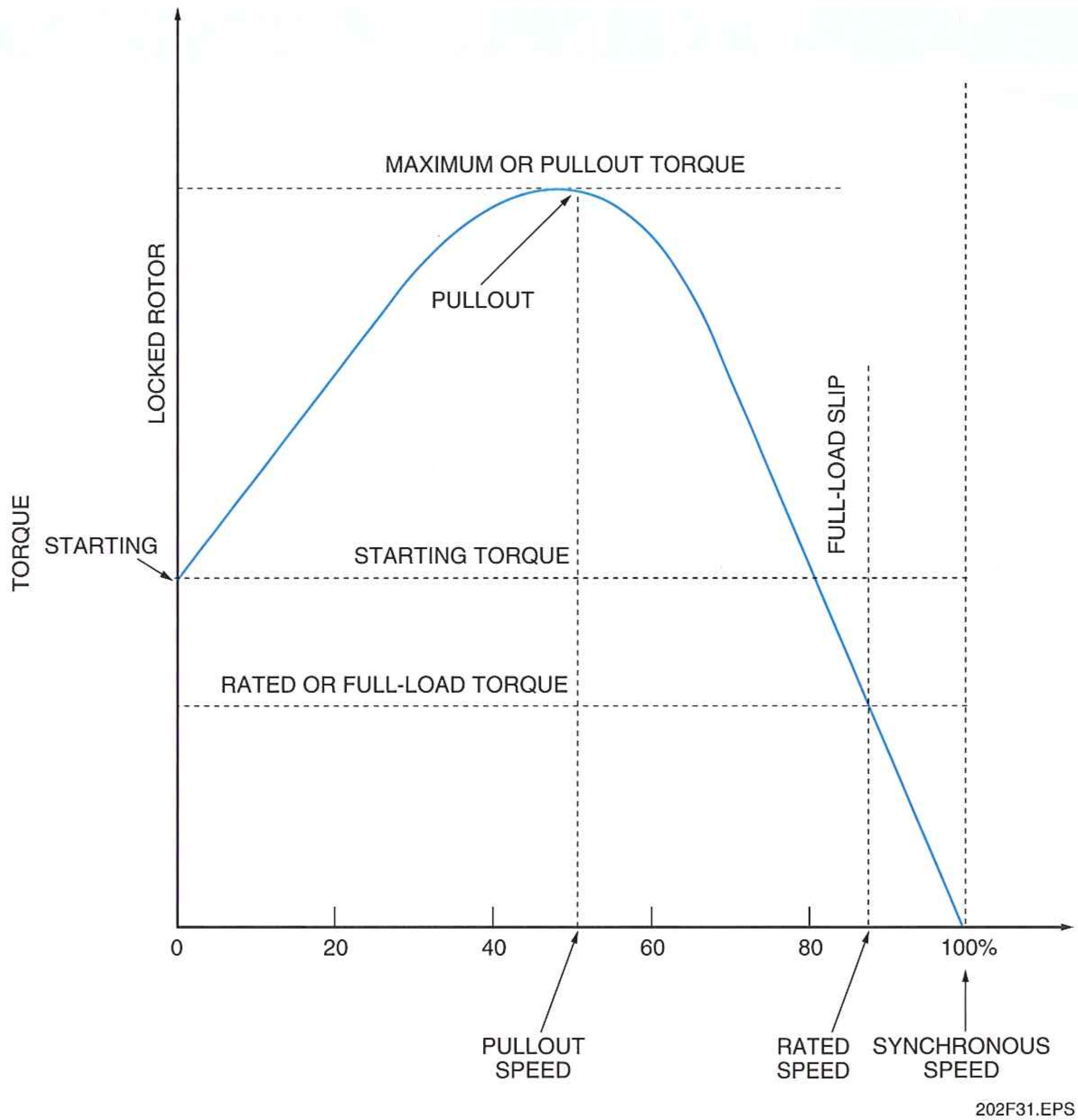


Figure 31 ◆ Typical torque-speed curve.

to torque, the amount of slip will increase. This increase means a higher current draw by the motor due to the greater difference between the rotor and the magnetic field. Motor supply voltages, current, torque, speed, and rotor impedance are closely related. By changing the resistance and reactance of the rotor, the characteristics of the motor can be changed; however, for any one rotor design these characteristics are fixed.

4.2.6 Starting Current

At the moment a three-phase induction motor is started, the current supplied to the motor stator terminals may be as high as six times the motor full-load current. This is because at starting, the rotor is at rest; therefore, the rotating magnetic field of the stator cuts the squirrel cage rotor at the maximum rate, inducing large amounts of EMF in the rotor.

This results in proportionally high currents at the input terminals of the motor as was previously discussed. Because of this high inrush, current starting protection as high as 300% of full-load current must be provided to allow the motor to start and come up to speed.

Because 100% slip exists at the instant the motor is energized (see *Figure 31*), the rotor current lags the rotor EMF by a large angle. This means that the maximum current flow occurs in a rotor conductor at a time after the maximum amount of stator flux has passed by. This results in a high starting current at a low power factor, which results in a low value of starting torque.

As the rotor speeds up, the rotor frequency and reactance decrease, causing the torque to increase up to its maximum value, then decrease to the value needed to carry the load.

4.2.7 Loaded Torque

If a load is now placed on the shaft, the rotor will tend to slow down. As it slows down, more flux lines are cut until enough torque is developed to overcome the load placed on the shaft.

The motor now runs under load at a slower speed than before the load was placed on the shaft. This normal range of operation is shown in the lower right corner of *Figure 31* as the rated or full-load torque.

In this range, the slip will vary from 2% to 10%, depending on the load applied and the motor. Rated slip will occur at the point where 100% rated load is applied. Increased load means increased slip, which means the rotor is now rotating slower. An induction motor is considered to be a constant speed motor. We will now examine how much speed fluctuates from no-load speed to full-load speed.

Example:

A two-pole induction motor has a no-load slip of 2% and a full-load slip of 8%. What are the no-load speed, full-load speed, and percent speed change?

$$\text{Nominal} = \frac{120 \times 60}{2} = 3{,}600 \text{ rpm}$$

$$\text{No-load speed} = \frac{100\% - 2\%}{100\%} \times 3{,}600 \text{ rpm} = 3{,}528 \text{ rpm}$$

$$\text{Full-load speed} = \frac{100\% - 8\%}{100\%} \times 3{,}600 \text{ rpm} = 3{,}312 \text{ rpm}$$

Percent speed change

$$= \frac{\text{no-load speed} - \text{full-load speed}}{\text{no-load speed}} \times 100\%$$

$$= \frac{3{,}528 - 3{,}312}{3{,}528} \times 100\%$$

$$= 6.12\%$$

4.2.8 Overload Condition

If the load is increased above full-rated load, everything happens as stated before to increase torque up to a certain point. *Figure 32* shows typical torque and current curves.

In *Figure 32*, note how the torque climbs as the load is increased.

This will continue as load is increased until the pullout torque point is reached. Beyond this point, the torque decreases and the motor will quickly

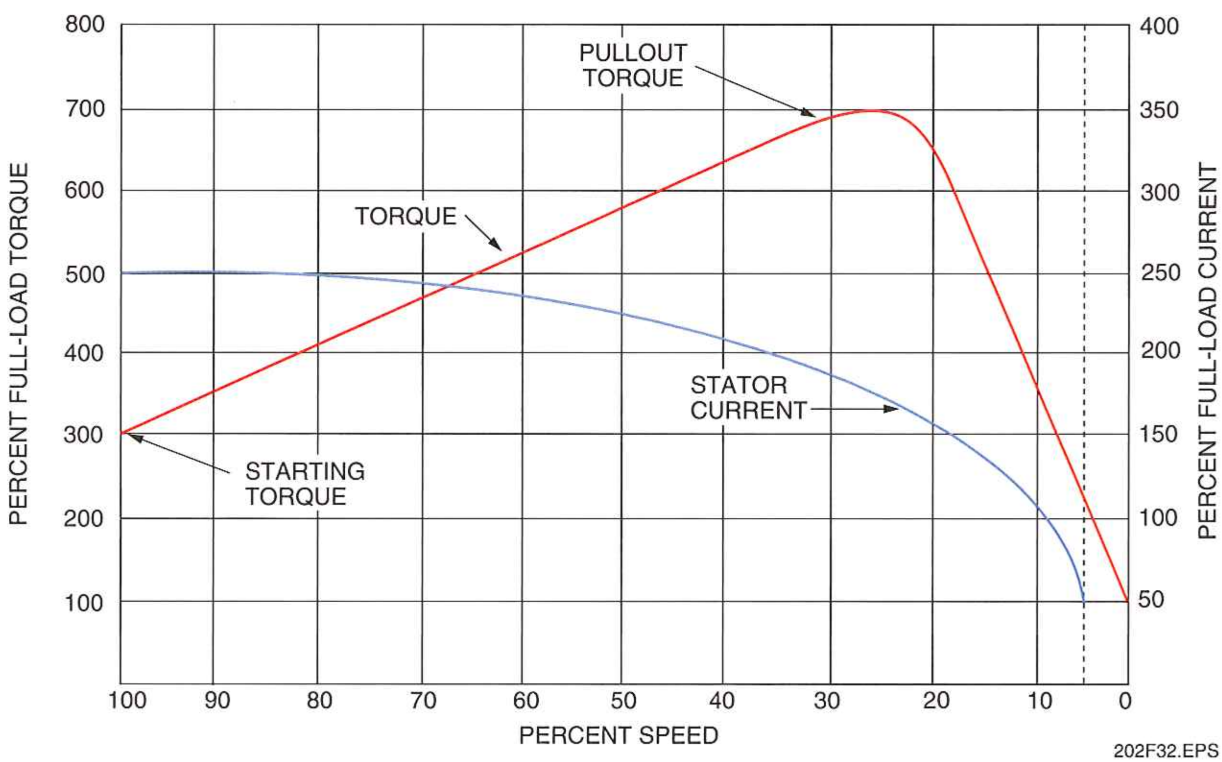


Figure 32 ◆ Torque and current curves.

stall. A typical situation is when a bench circular saw or a lathe stalls on a heavy cut. The machine will slow down as its cutting load is increased until it suddenly stalls and hums or growls loudly. The condition will persist until the load is relieved or a fuse blows or a breaker trips. The motor has simply reached a point where it cannot continue to increase its torque. Any further increase in load will cause a stall.

4.2.9 Power Factor

The power factor of a squirrel cage induction motor is poor at no-load and low-load conditions. At no-load conditions, the power factor can be as low as 15% lagging. However, as load is increased, the power factor increases. At high-rated load, the power factor may be as high as 85% to 90% lagging.

The power factor at no-load speed is low because the magnetizing component of input current is a large part of the total input current of the motor. When the load on the motor is increased, the in-phase current supplied to the motor increases, but the magnetizing component of current remains practically the same. This means that the resultant line current is more nearly in phase with the voltage, and the power factor is improved when the motor is loaded compared with an unloaded motor, which chiefly draws its magnetizing current.

Figure 33 shows the increase in power factor from no-load conditions to full-load conditions. In the no-load diagram, the in-phase current (I_{ENERGY}) is small when compared to the magnetizing current (I_M); thus, the power factor is poor at no-load conditions. In the full-load diagram, the in-phase current has increased, while the magnetizing current remains the same. As a result, the angle of lag of the line current decreases, and the power factor increases.

4.2.10 Speed Control

The speed of a three-phase squirrel cage induction motor depends on the frequency of the applied voltage and the number of poles. As a result, these motors are used in applications where speed remains constant or where it can be controlled by other means such as variable frequency drives.

4.2.11 Reversing Rotation

The direction of rotation of a three-phase induction motor can be readily reversed. The motor will

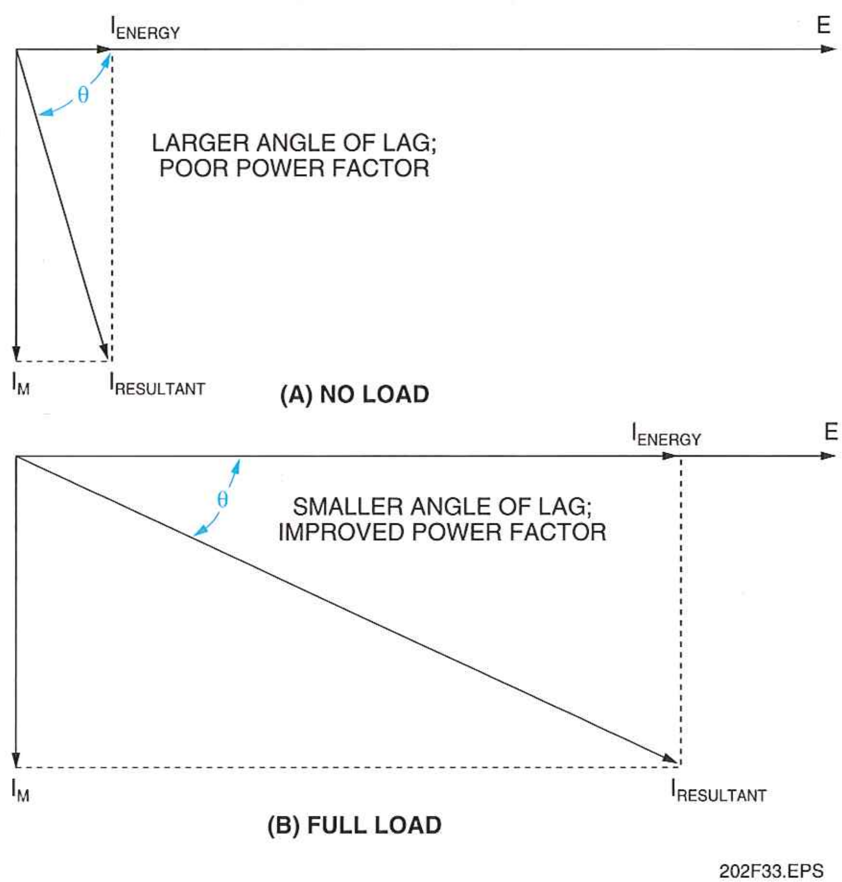


Figure 33 ◆ Power factor versus load for an induction motor.

INSIDE TRACK

Variable-Speed Drives

Variable-speed drives, known as VSDs or ASDs (adjustable-speed drives), are powerful electronic devices that are available for virtually any size motor in all types of applications. Of the various types of VSDs available, the most efficient versions for AC motors are VFDs (variable-frequency drives), which control both the frequency and the voltage applied to the motor. By changing the frequency of the rotating stator field, you change the speed of the rotor, thus changing the speed of the motor. VSDs are often used in energy management systems to conserve energy by supporting variable loads such as those that occur in heating, ventilating, and air conditioning systems. In addition to controlling the speed of a motor, VSDs are available to control both motor starting and stopping functions, as well as to provide controlled acceleration and deceleration.

rotate in the opposite direction if any two of the three incoming leads are reversed, as shown in *Figure 34*.

4.3.0 Synchronous Motors

The synchronous motor is a three-phase motor that operates at synchronous speed from no-load conditions to full-load conditions.

4.3.1 Characteristics

This type of motor has a revolving field that is energized from a source separate from the stator winding. The rotor is excited by a DC source. The magnetic field set up by the direct current on the rotor then locks in with the rotating magnetic field of the stator and causes the rotor to revolve at synchronous speed. By changing the magnitude of DC excitation, the power factor of the motor can be changed over a wide variety of power factors from leading to lagging. Because of the unique ability of synchronous motors to change power factors, they are often used as power-factor correctors. They are most often used in applications that require constant speed from no-load conditions to full-load conditions.

4.3.2 Construction

The construction of synchronous motors is essentially the same as the construction of three-phase

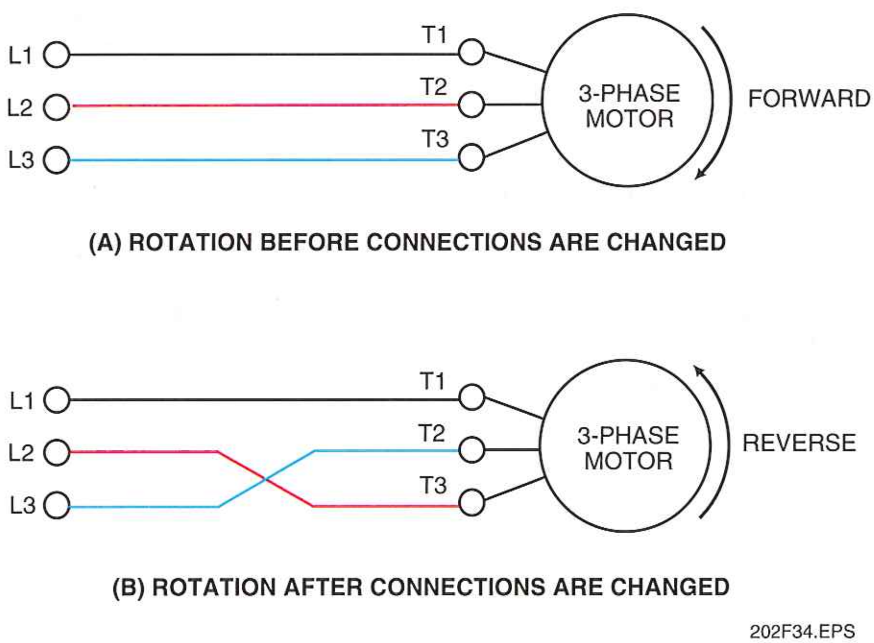


Figure 34 ◆ Three-phase induction motor rotational direction change.

Synchronous Motors

INSIDE TRACK

Three-phase synchronous motors can be used in industrial applications to correct the low power factor of a number of induction motors or other inductive devices that are operating at less than their rated load levels. Synchronous motors can accomplish power factor correction while driving their own mechanical loads. Correcting a low power factor created by inductive loads through the use of synchronous motors reduces energy costs by making efficient use of the power supplied to the industrial facility. The use of synchronous motors can eliminate the need for dedicated capacitor banks or switched capacitor banks and the surges caused by them.

generators. They have three stator windings that are 120° apart and a wound rotor that is connected to slip rings where the rotor excitation current is applied.

When three-phase AC is applied to the stator, a revolving magnetic field is created just as it is in induction motors. The rotor is energized with DC, which creates a magnetic field around the rotor. The strong rotating magnetic field of the stator attracts the rotor field. This results in a strong turning force on the rotor shaft.

This is how the synchronous motor works once it is started. However, one of the disadvantages of this type of motor is that it cannot be started just by applying AC to the stator. When AC is applied to the stator, the high-speed rotating magnetic field rushes past the rotor poles so quickly that the rotor does not have a chance to get started. The rotor is locked; it is repelled in one direction and then in another direction. In its purest form, the synchronous motor has no starting torque.

This is more easily understood using *Figure 35*. When the stator and rotor fields are energized, the poles of the rotating field approach the rotor poles of opposite polarity. The attracting force will tend to turn the rotor in a direction opposite the rotating field. As the rotor starts to move in that direction, the rotating field moves past the rotor poles and tends to pull the rotor in the same direction as the rotating field. The result is no starting torque.

To allow this type of motor to start, a squirrel cage winding is added to the rotor to cause it to start like an induction motor. This winding is called an amortisseur winding. The rotor windings are constructed so that definite north and south poles are created and these poles, when excited by DC, will lock in with the revolving field. The rotor windings are wound about the salient field poles, which are connected in series for opposite polarity.

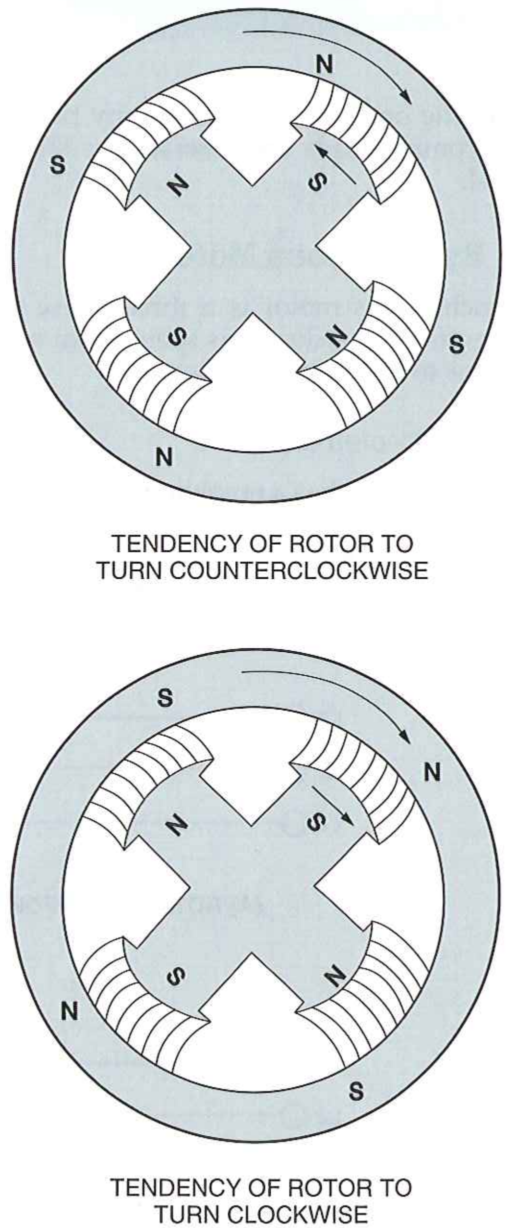


Figure 35 ◆ Synchronous motor operation at start.

The number of field poles must equal the number of stator poles. The rotor field windings are brought out to slip rings that are mounted on the rotor shaft. The field current is supplied through carbon brushes to the field windings. *Figure 36* shows a simplification of a synchronous motor. *Figure 37* shows the construction of the rotor pole assembly.

4.3.3 Principles of Operation

When a synchronous motor is started, current is first applied to the stator windings. Current is induced in the amortisseur winding and the motor starts as an induction motor. The motor then comes up to near-synchronous speed (about 5% to 10% slip). At that point, the field is excited, and the motor, turning at high speed, pulls into synchronism. When this occurs, the rotor is turning at synchronous speed, and the squirrel cage winding will not be generating any current, and therefore will not affect the synchronous motor's operation. The amortisseur windings serve an additional purpose. When the load changes frequently, the motor speed is not steady because the torque angle (discussed later) oscillates (or hunts) back and forth, trying to settle at its required value. This momentary change in speed creates a current due to induction, and there will be torque in the amortisseur winding. This momentary torque serves to dampen or stabilize the oscillating torque angle. That is why amortisseur windings are sometimes referred to as damper windings.

4.3.4 Rotor Field Excitation

The rotor must be excited from an external DC source. *Figure 38* shows a simplified synchronous motor excitation circuit. Notice that the DC field current can be varied by the rheostat; however, this does not change the speed of the motor. It only changes the power factor of the motor stator circuit. If full resistance is applied to the rotor field circuit, then the field strength of the rotor is at its minimum and the power factor is extremely lagging. As the DC field strength is increased, the power factor improves. If current is increased sufficiently, the power factor can be increased to near unity or 100%. This value of field current is referred to as normal excitation. By increasing the rotor field strength further, the power factor decreases but in a leading direction; that is, the stator circuit becomes capacitive and the motor is said to be overexcited. The synchronous motor can be used to counteract the lagging power factor in circuits by adding capacitive reactance to the circuit, thereby bringing the overall power factor closer to unity.

If the rotor DC field windings of a synchronous motor are open when the stator is energized, a high AC voltage will be induced in it because the

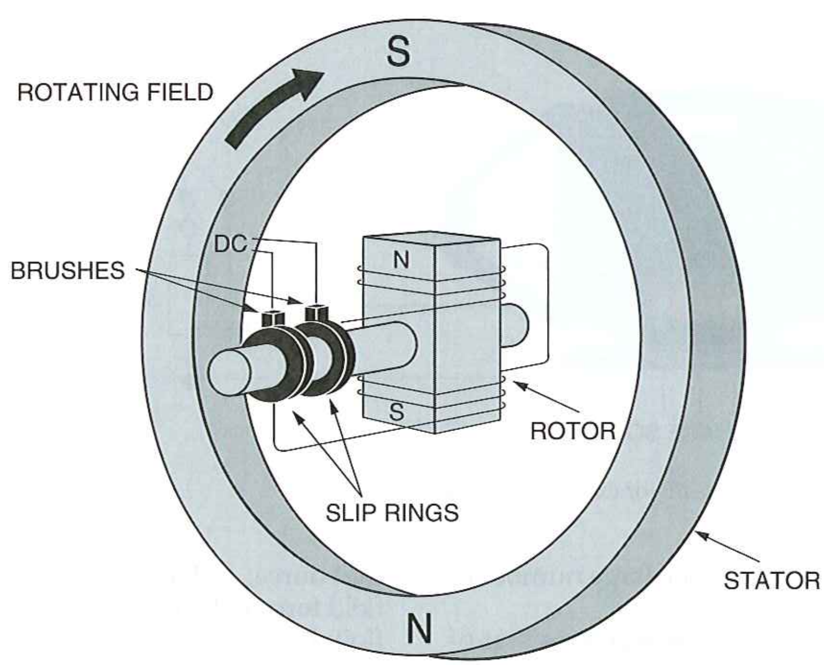


Figure 36 ◆ Simplification of a synchronous motor.

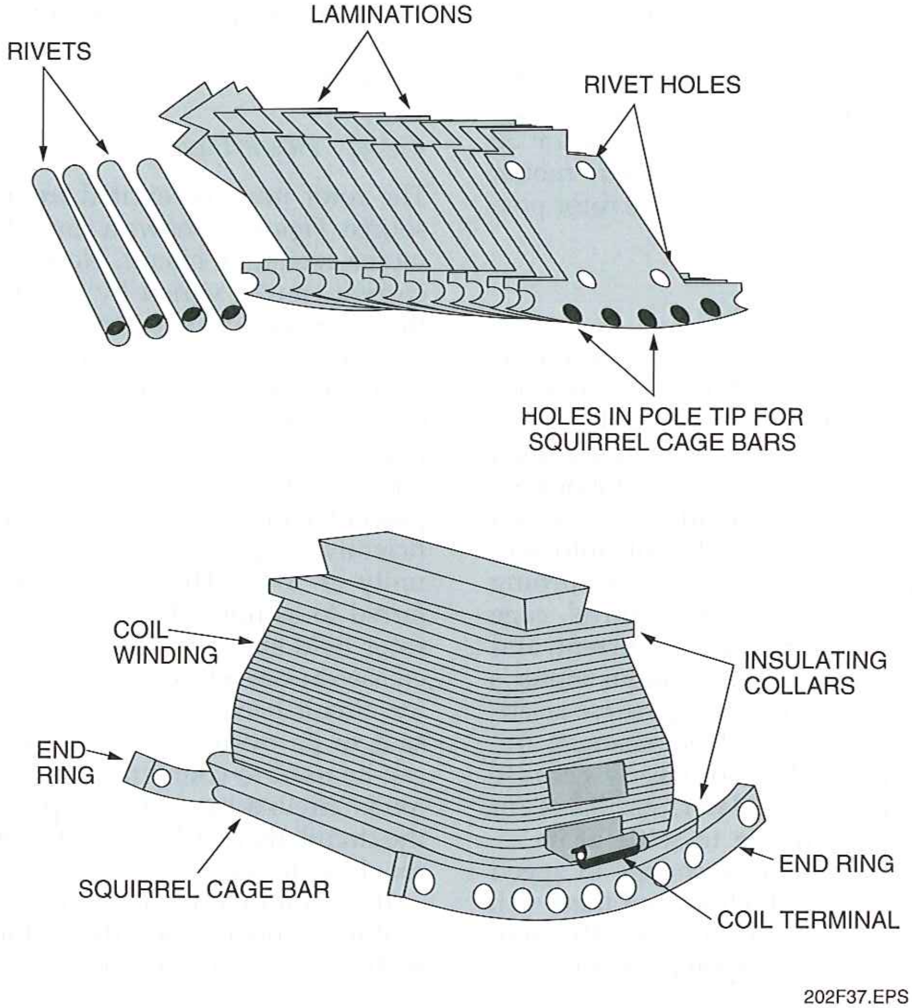


Figure 37 ◆ Pole assembly.

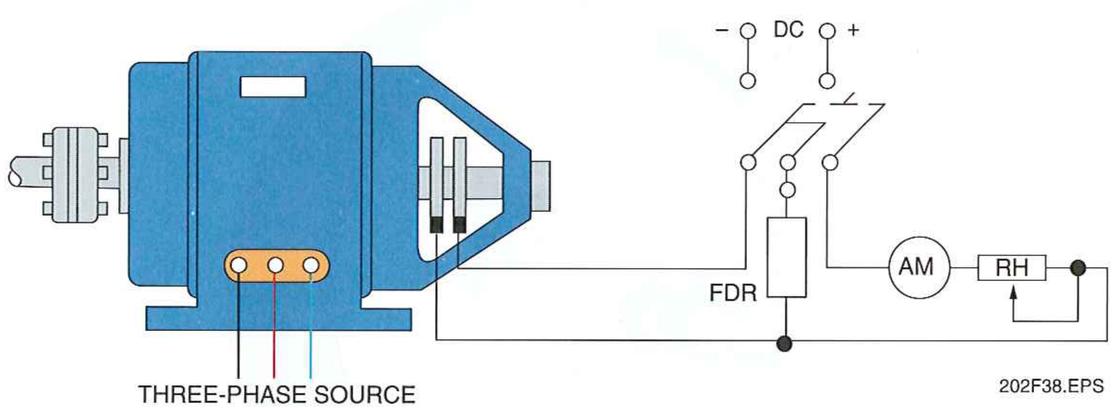


Figure 38 ◆ Simplified synchronous motor excitation circuit.

rotating field sweeps through the large number of turns at synchronous speed.

It is therefore necessary to connect a resistor of low resistance across the rotor DC field winding during the starting period. During the starting period, the DC field winding is disconnected from the source, and the resistor is connected across the field terminals. This permits alternating current to flow in the DC field winding. Because the impedance of the winding is high compared with the inserted external resistance, the internal voltage drop limits the terminal voltage to a safe value.

4.3.5 Synchronous Motor Pullout

When a synchronous motor loses synchronism with the system to which it is connected, it is said to be out of step. This occurs when the following take place singly or in combination:

- Excessive load applied to the shaft
- Supply voltage reduced excessively
- Motor excitation lost or too low

Torque pulsations applied to the shaft of a synchronous motor are also a possible cause of loss of synchronism if the pulsations occur at an unfavorable period relative to the natural frequency of the rotor with respect to the power system.

A prevalent cause of loss of synchronism is a fault occurring on the supply system. Underexcitation of the rotor is also a distinct possibility.

Synchronous motor pullout is significant in that the squirrel cage or amortisseur winding is designed for starting only. They are not as hardy as those found in induction motors. The amortisseur winding will not overheat if the motor starts, accelerates, and reaches synchronous speed within a time interval determined to be normal for the motor. However, the motor must continue to operate at synchronous speed. If the motor operates at a speed less than synchronous, the amortisseur winding may overheat and suffer damage.

Protection against a synchronous motor losing synchronism can be provided by polarized field frequency relays and out-of-step relays as well as various digital methods.

4.3.6 Synchronous Motor Torque Angle

Once the rotor is brought up to high speed (close to synchronous speed) it will lock on to the rotating magnetic field. Under these conditions, a running torque will be developed. The rotor will rotate at synchronous speed in a direction and at a speed determined by synchronous speed.

While the motor is running, the two rotating fields will line up perfectly. The rotor pole will always lag behind the stator pole by some angle. This angle is called the torque angle and is shown in *Figure 39*.

As the load on the shaft increases, the torque angle increases even though the rotor continues to turn at synchronous speed. This behavior continues until the torque angle is approximately 90°. At that point, the motor is developing a maximum torque. Any further increase in load will cause either of the following to occur:

- If the increase in load is momentary or very small, the rotor will slip a pole. In other words, the stator field will lose hold of the rotor and grab onto it again the next time around.

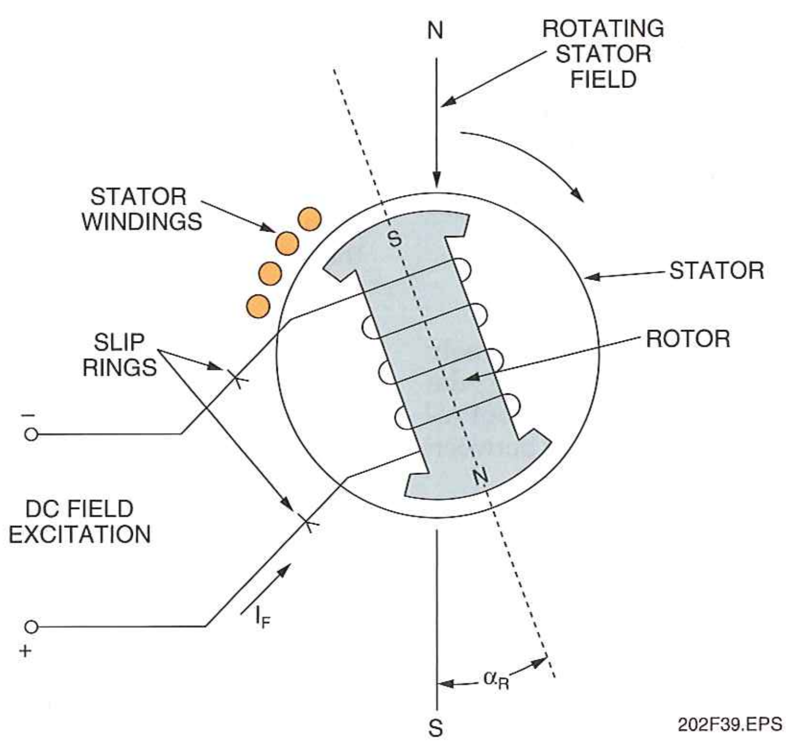


Figure 39 ◆ Torque angle.

- If the increase in load is large enough and is not momentary, the motor will lose synchronism and will either stall or cause the rotor to suffer thermal damage.

In both cases, a noticeable straining sound will be heard.

The synchronous motor should not be used where fluctuations in torque are violent. As a rule, it is also not used in small sizes (under 50hp), because it requires DC excitation. It is more difficult to start than induction motors and falls out of step quite readily when system disturbances occur. Its common applications are in motor generator sets, air compressors, and compressors in refrigerating plants.

4.4.0 Single-Phase AC Motors

Single-phase motors operate on a single-phase power supply. This is important because in the typical home or office and many areas of industrial plants, the only power source available is single-phase AC. Not only do single-phase AC motors eliminate the need for three-phase AC lines, but they are also easier to manufacture in small sizes and are, therefore, less expensive.

Examples of the many applications of single-phase AC motors today are the following: refrigerators, freezers, washers, dryers, power tools, typewriters, copying machines, heating systems, water pumps, computer peripherals, and various small appliances.

There are two basic types of single-phase motors. First, there is the single-phase induction motor. Its theory of operation is similar to that of the three-phase induction motor; hence, it runs at a speed slightly lower than synchronous speed. Second, there is the single-phase synchronous motor.

4.4.1 Single-Phase Induction Motors

Single-phase AC induction motors are extremely popular. 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, and a magnetic field is produced around the rotor. This field will always be in opposition to the stator field. However, the interaction between the rotor and stator fields will not produce rotation (see *Figure 40*). 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.

If the rotor is rotated by some outside force (a twist of your hand, for example), the push-pull

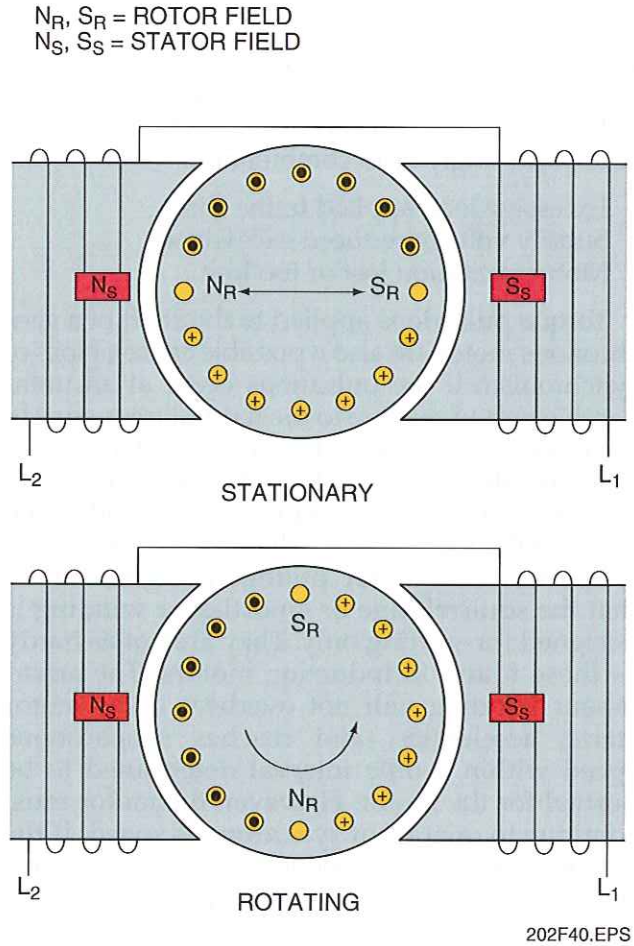


Figure 40 ◆ AC induction motor.

along the line is disturbed. Look at the fields shown in *Figure 40* as the motor begins to rotate. At this instant, the south pole on the rotor is being attracted to 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° 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.

Since a single-phase rotor will rotate if it has a rotating magnetic field present, all that remains is to find a means of generating a rotating field at the start. There are a number of practical means for generating a rotating field. All the methods used for single-phase induction motors involve the simulation of a second phase for a starting circuit. In this module, we will discuss the following types of motors: split-phase, capacitor-start, capacitor-run, shaded-pole, and repulsion-start.

Single-Phase Induction Motors

INSIDE TRACK

Outside of large industrial and commercial facilities, single-phase induction motors are the most common type of motor used. While they are initially less expensive than polyphase motors, they are also less efficient and more costly to maintain. They are typically available in small sizes from ⅛hp to 1hp (previously referred to as fractional horsepower sizes) and in sizes up to 10hp.

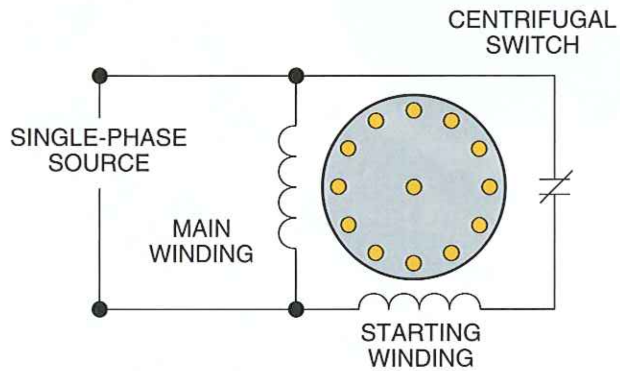
202P0201.EPS

4.4.2 Split-Phase Induction Motor

The split-phase motor, shown schematically in *Figure 41*, has a stator composed of slotted laminations that contain an auxiliary (starting) winding and a running (main) winding. The axes of these two windings are displaced by an angle of 90 electrical degrees. The starting winding has fewer turns and smaller wire than the running winding and, therefore, has different electrical characteristics. The main winding occupies the lower half of the slots and the starting winding occupies the upper half. The two windings are connected in parallel across the single-phase line supplying the motor. The motor derives its name from the action of the stator during the starting period.

When energized with single-phase AC, the two windings are physically different enough in position and construction to produce a magnetic revolving field that rotates around the stator air gap at synchronous speed. As the rotating field moves around the air gap, it cuts across the rotor conductors and induces a voltage in them. The interaction between the rotor and stator causes the rotor to accelerate in the direction in which the stator field is rotating.

When the rotor has come up to about 75% of synchronous speed, a centrifugally operated switch disconnects the starting winding from the line supply, and the motor continues to run on the main winding alone. As the motor ages, the centrifugal switch contacts pit and corrode. When this happens, they may get stuck in the closed position. To safeguard against the winding burning up, a thermal relay is also used. If the motor draws the high starting current for more than 5 or 10 seconds, the relay will de-energize.



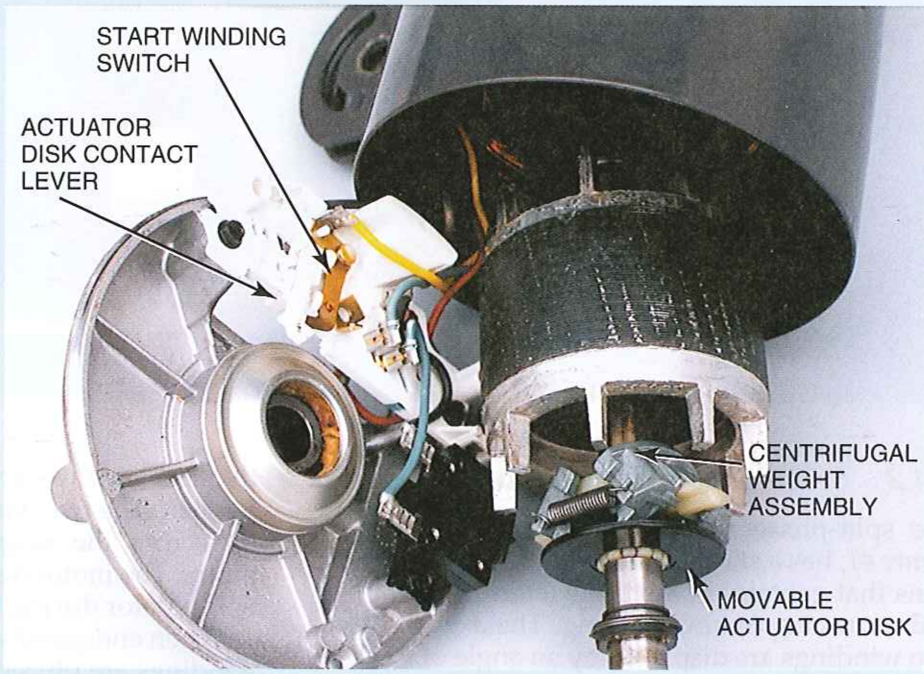
202F41.EPS

Figure 41 ◆ Split-phase motor.

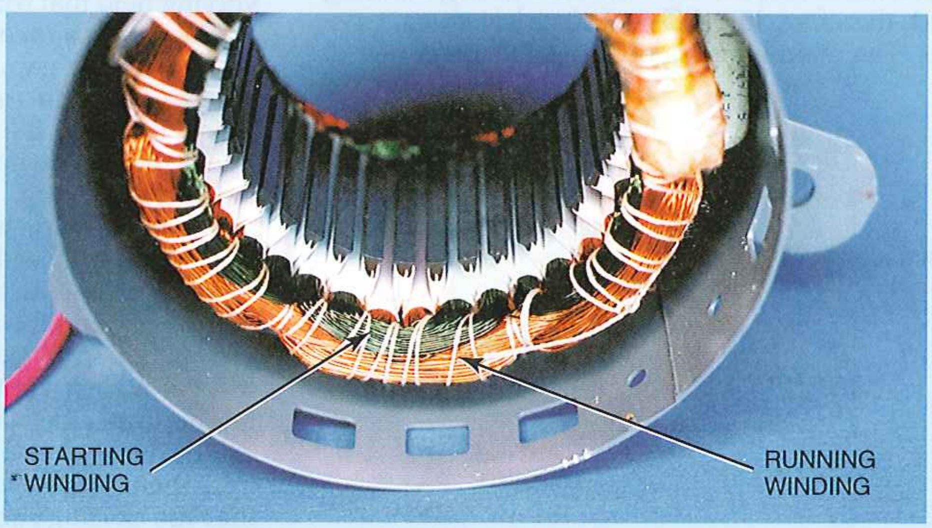
INSIDE TRACK

Modern Split-Phase Induction Motor

Photo (A) shows a centrifugally-actuated start winding switch that is closed when the motor is at rest. The start winding switch is opened and closed by the movement of an actuator disk against a contact lever. The actuator disk is moved back and forth on the rotor shaft by a centrifugal weight assembly. When the motor is at rest, springs retract the weights and cause the actuator disk to move toward the bearing at the end of the shaft. This pushes on the contact lever, closing the switch contacts. After the motor starts and reaches about 75% of its rated speed, the weights swing out against the spring tension and retract the contact disk from the contact lever. This opens the switch contacts, removing the starting winding from the circuit. If the switch does not open after starting, the motor will operate at a reduced speed until it overheats the starting winding and activates the thermal relay. Photo (B) shows the starting winding (green) and the running winding (copper).



(A) 202P0202.EPS



(B) 202P0203.EPS

In a split-phase motor, the starting torque is 150% to 200% of the full-load torque, and the starting current is six to eight times the full-load current. Fractional-horsepower split-phase motors are used in a variety of devices such as washers, oil burners, and ventilating fans. The direction of rotation of the split-phase motor can be reversed by interchanging the starting winding leads.

4.4.3 Capacitor-Type Induction Motor

The capacitor-type motor is a modified form of split-phase motor. A typical capacitor-type motor is shown in *Figure 42*. The capacitor is located on top of the motor.

To develop a larger starting torque than that available with a standard split-phase motor, a capacitor is placed in series with the auxiliary winding of a split-phase motor, as shown in *Figure 43*. This is called a capacitor-start motor. The capacitor tends to create a greater electrical phase separation of the two windings. Also, because the reactance of a capacitor is 180° out of phase with the inductive reactance of the motor windings when they are combined, they yield a lower total impedance. This allows a larger current to produce a greater magnetic field.

The net effect of the capacitor is to give its motor a starting torque of about four times its rated torque. The split-phase motor, on the other hand, produces a starting torque of about one to two times its rated torque. Once the capacitor motor has come up to speed and the starting winding has been disconnected, it will have the same running characteristics as the split-phase motor.

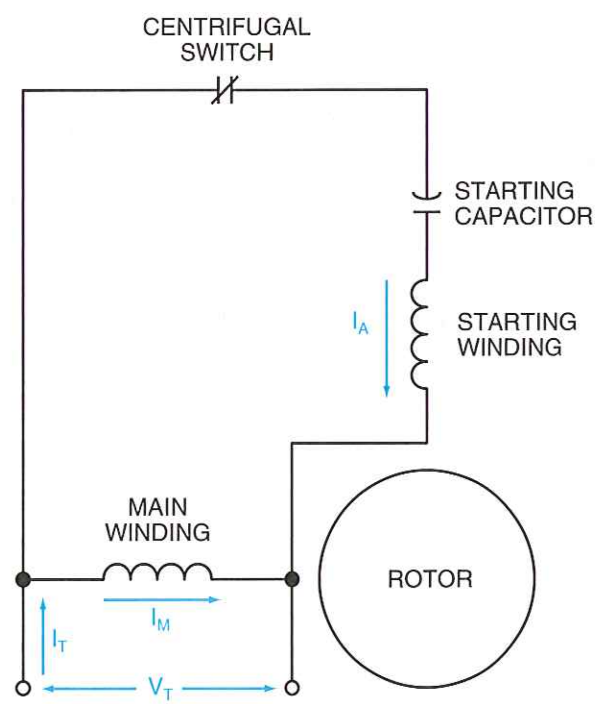
To reverse the direction of rotation of the capacitor-start motor and split-phase motor, the connection of either winding would have to be reversed. Since the starting winding is disconnected at a high speed, this reversal can be accomplished only at standstill or at low speeds when the centrifugal switch is still closed.

The capacitor-start motor is made in sizes from ¼ to 10hp (150W to 7.5kW). The starting capacitor is the dry-type electrolytic capacitor made for AC use. Typical values are from 200 to 600 microfarads (μF). *Figure 44* shows a comparison of torque slip curves for a split-phase and capacitor-start motor. It also shows the typical effect of the starting capacitor.

A variation of the capacitor-start motor is one in which the capacitor and auxiliary winding are not disconnected. The centrifugal switch in *Figure 43* is eliminated, and the auxiliary winding is left in all the time. This motor is called a capacitor-run motor.

202F42.EPS

Figure 42 ◆ Capacitor motor.



202F43.EPS

Figure 43 ◆ Capacitor-start motor schematic.

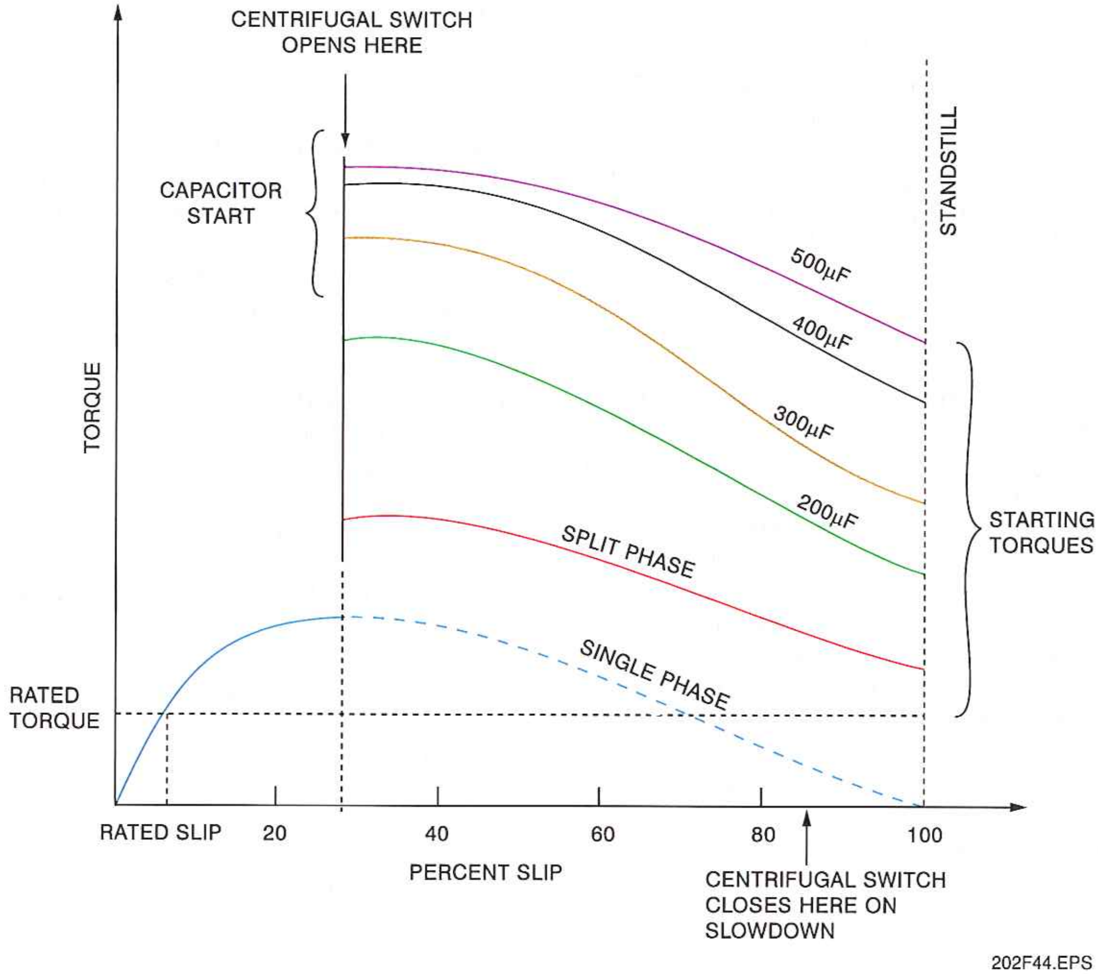


Figure 44 ◆ Torque-slip curves.

The capacity used for running under load is not the same as that needed for starting. Furthermore, the capacitors used for starting cannot be used for continuous operation. Since the capacitor used in this motor is in all the time, it must be of a different type; that is, one capable of operating continuously. The net result is that the motor has improved running characteristics; however, it does not provide a starting torque as large as that of the capacitor-start motor.

Among the improvements are higher efficiency and power factor at rated load, lower line current, and very quiet operation. It should also be pointed out that the start winding must be designed for continuous operation. This makes the motor somewhat more costly.

Another variation is the capacitor-start, capacitor-run motor. This motor combines the useful features of the capacitor-start and the capacitor-run motors by using two different capacitors, as shown in *Figure 45*.

4.4.4 Shaded-Pole Induction Motor

The shaded-pole motor employs a salient-pole stator and a cage rotor. The projecting poles on the stator resemble those of DC machines, except that the entire magnetic circuit is laminated and a portion of each pole is split to accommodate a short circuited copper strap called a shading coil. This motor is generally manufactured in very small sizes and runs up to 1⁄20hp. A four-pole motor of this type is illustrated in *Figure 46*.

The shading coils are placed around the leading pole tip, and the main pole winding is concentrated and wound around the entire pole. The four coils that make up the main winding are connected in series across the motor terminals. An inexpensive type of two-pole motor that uses shading coils is illustrated in *Figure 47*.

Referring to *Figure 47*, we see that during part of the cycle when the main pole flux (ϕ_1) is increasing, the shading coil is cut by the flux, and the resulting induced EMF and current in the

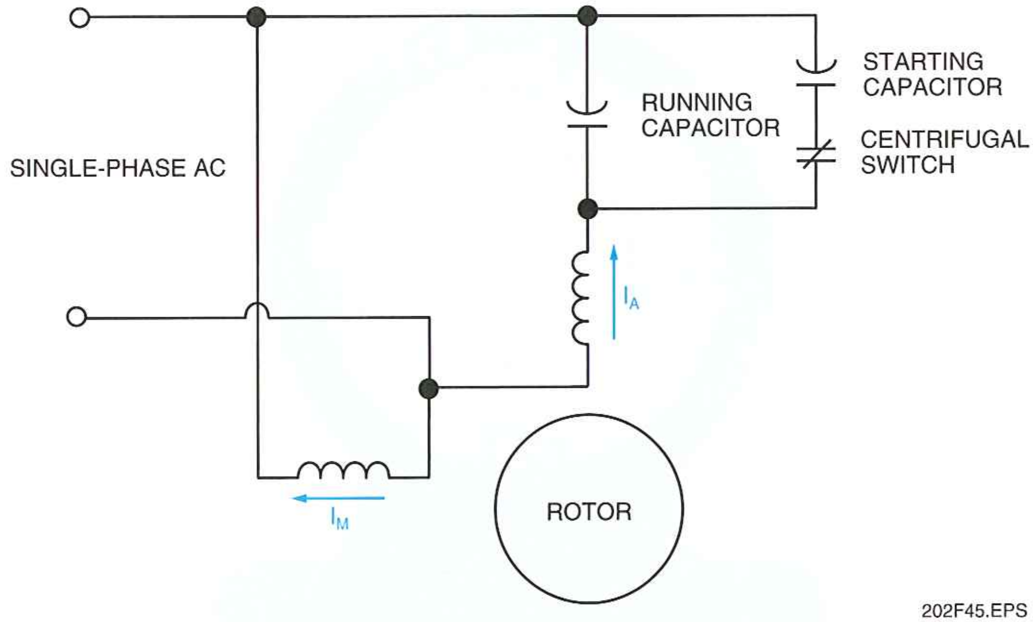
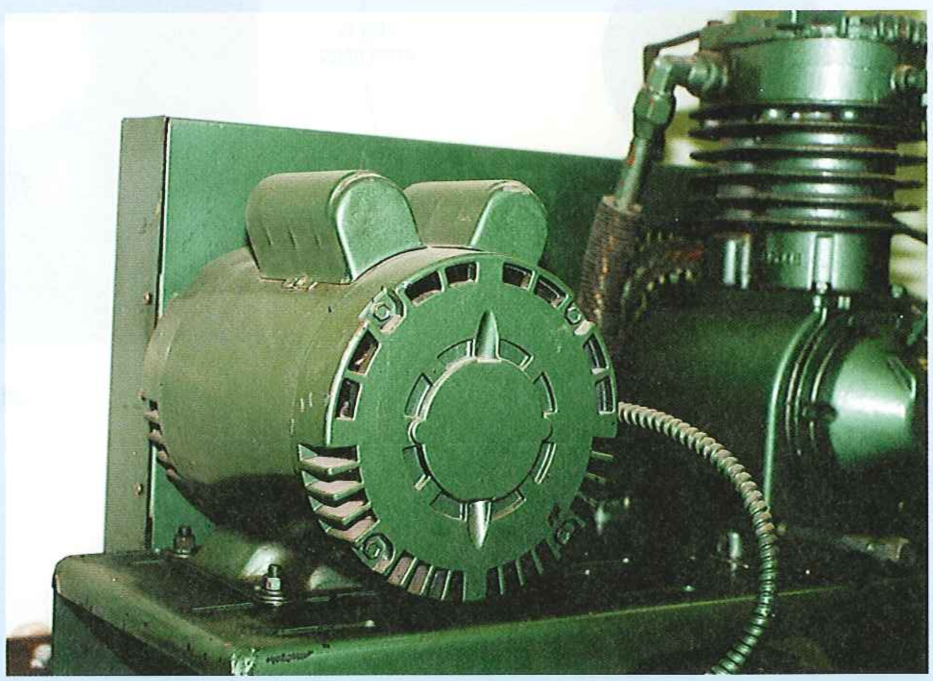


Figure 45 ◆ Capacitor-start, capacitor-run motor schematic.

INSIDE TRACK

Capacitor-Start, Capacitor-Run Motors

These motors run quietly and smoothly and have a high starting torque. Their construction is similar to a split-phase motor in that they use a centrifugal switch to remove only the start capacitor from the starting winding while leaving the run capacitor connected to the winding. These motors have a higher power factor than ordinary split-phase motors.



202P0204.EPS

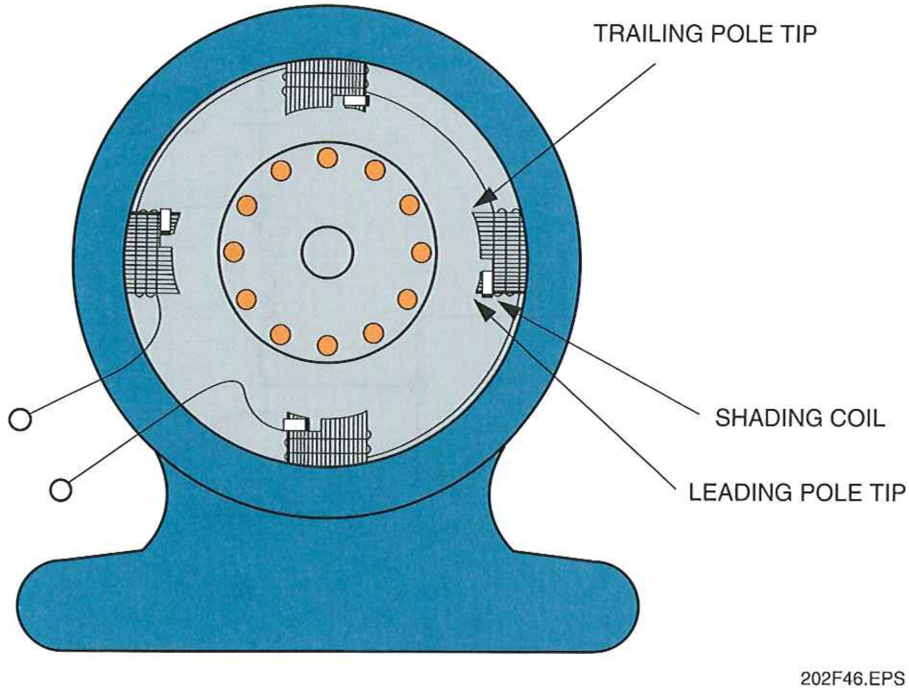


Figure 46 ◆ Four-pole shaded-pole motor.

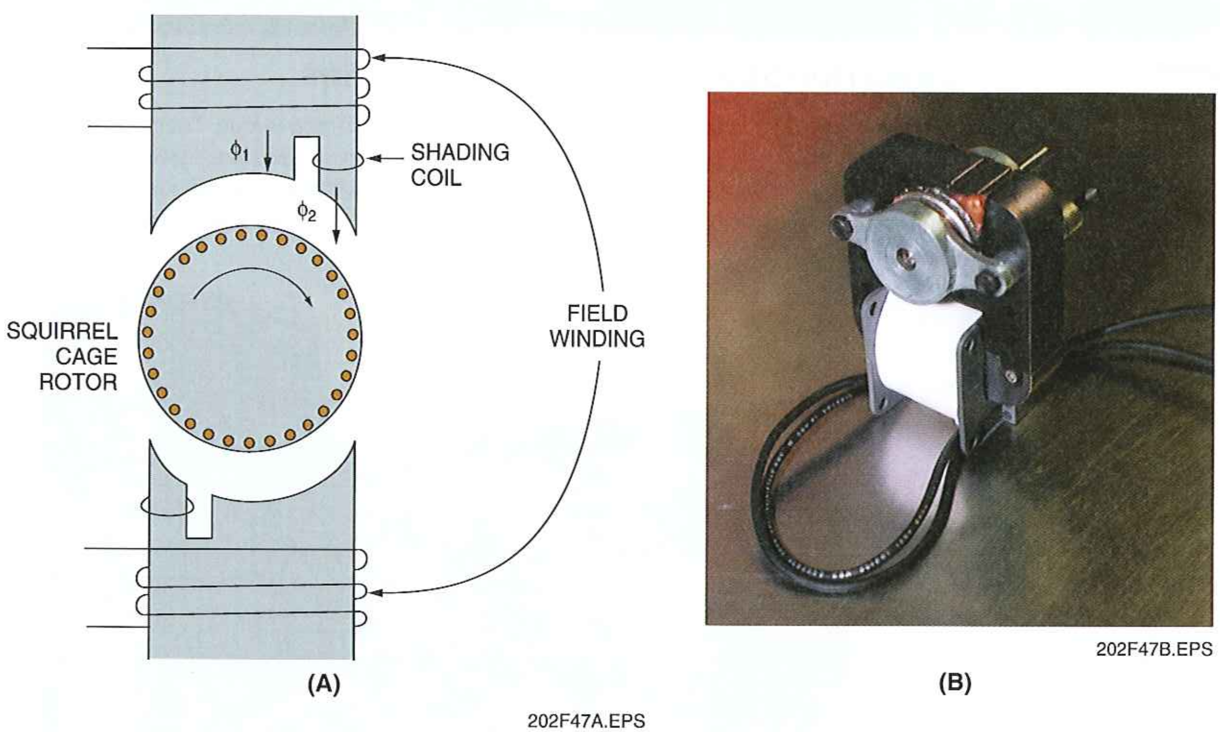


Figure 47 ◆ Two-pole shaded-pole motor.

Shaded-Pole Motors

INSIDE TRACK

The efficiency of this type of motor can be as low as 5%, but this low efficiency is rarely significant because these motors use very little power to begin with ($\frac{1}{20}$hp or less).

shading coil tend to prevent the flux from rising readily through it. Thus, the greater portion of the flux rises in that portion of the pole that is not in the vicinity of the shading coil ($\phi_1 > \phi_2$). When the flux reaches its maximum value, the rate of change of flux is zero, and the voltage and current in the shading coil are also at zero. At this time, the flux is distributed more uniformly over the entire pole face ($\phi_1 = \phi_2$).

As the main flux decreases toward zero, the induced voltage and current in the shading coil reverse their polarity, and the resulting force tends to prevent the flux from collapsing through the iron in the region of the shading coil ($\phi_2 > \phi_1$). The result is that the main flux rises first in the unshaded portion of the pole and later in the shaded portion. This action is equivalent to a sweeping movement of the field across the pole face in the direction of the shaded pole. The cage rotor conductors are cut by this moving field, and the force exerted on them causes the rotor to turn in the direction of the sweeping field.

Most shaded-pole motors have only one edge of the pole split, and therefore, the direction of rotation is not reversible. However, some shaded-pole motors have both leading and trailing pole tips split to accommodate shading coils. The leading pole tip shading coils form one series group, and the trailing pole tip shading coils form another series group. Only the shading coils in one group are simultaneously active, while those in the other group are on an open circuit.

The shaded-pole motor is similar in operating characteristics to the split-phase motor. It has the advantages of simple construction and low cost. It has no sliding electrical contacts and is reliable in operation. However, it has low starting torque, low efficiency, and a high noise level. It is normally used to operate small fans. The shading coil and split pole are also used in timers to make them self-starting.

4.4.5 Single-Phase Synchronous Motor

The single-phase synchronous motor, as its name implies, runs at synchronous speed. It finds use where a constant speed is needed, such as in turntables and clocks. It is started in the same way as any of the single-phase induction motors and therefore has a rotating field. By having a modified rotor, the motor pulls into synchronism and runs at synchronous speed.

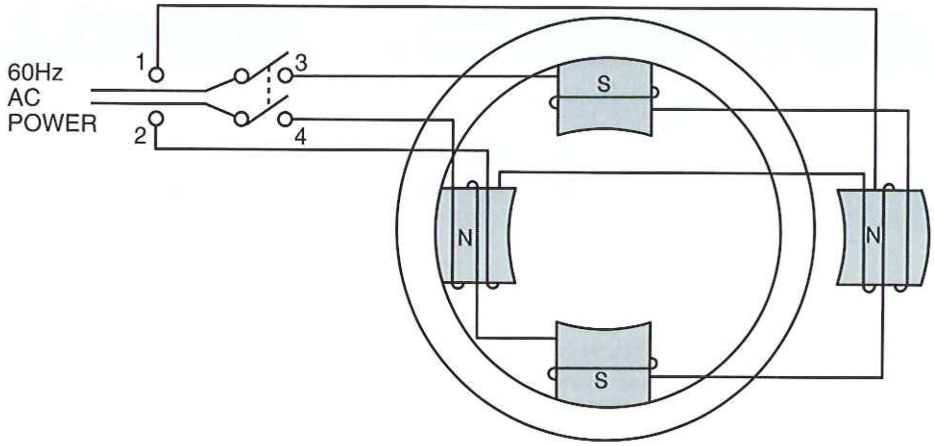
5.0.0 ◆ MULTIPLE-SPEED INDUCTION MOTORS

The speed of an induction motor depends on the power supply frequency and the number of pairs of poles used in the motor. Obviously, to alter motor speed it is merely necessary to change one of these two factors. By far the most common method used involves changing the number of poles, generally at some type of external controller.

There are two types of multiple-speed squirrel cage induction motors in common use: the multiple-winding motor and the consequent-pole motor. Both feature poles that may be changed, as required, by shifting key external connections, and in this way they provide for operating the motor at a limited number of different speeds.

5.1.0 Multiple-Winding Motor

In the multiple-winding motor, two or more separate windings are placed in the stator core slots, one over the other, as shown in *Figure 48*. For example, a four-pole winding can be positioned in the core slots and have a two-pole winding placed on top of it. The windings are insulated from each other and arranged so that only one winding at a time can be energized. Switching speeds is normally accomplished by switching contacts that are in the motor controller external to the motor itself.



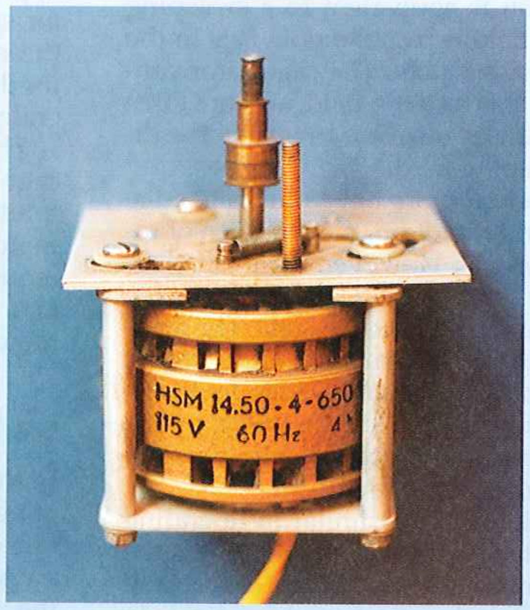
202F48.EPS

Figure 48 ◆ Two-winding, two-speed motor.

INSIDE TRACK

Hysteresis Synchronous Motor

This unusual synchronous motor has an external rotor. These motors have low noise levels, high efficiency, and constant speed, and are used for applications such as phonograph turntables.



202P0205.EPS

5.2.0 Consequent-Pole Motor

In the consequent-pole motor, there are two speeds. The motor is constructed to have a certain number of poles for high-speed operation and then, by a switching action, double this number of poles to give low-speed operation. The switching action is illustrated by the use of the two-phase motor in *Figure 49*. If you trace the wiring in *Figure 49*, you can see how the system is phased so that both magnetic north and south poles are produced at the winding projections. With two-phase power applied to the two-pole motor (two poles per phase), a rotating magnetic field of 3,600 rpm is produced.

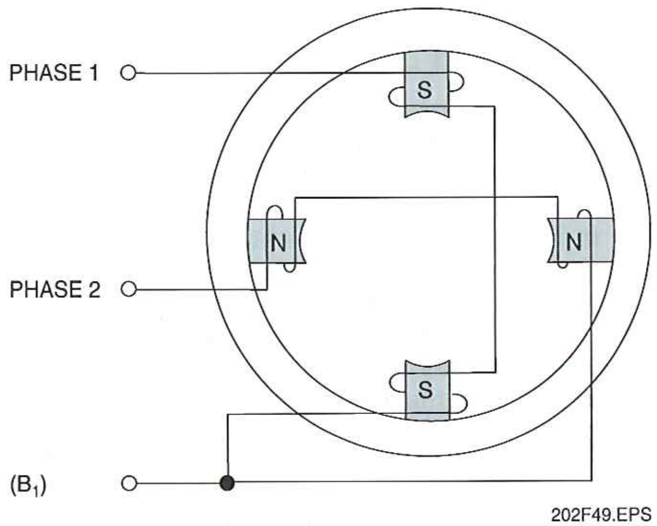


Figure 49 ◆ High-speed consequent-pole motor.

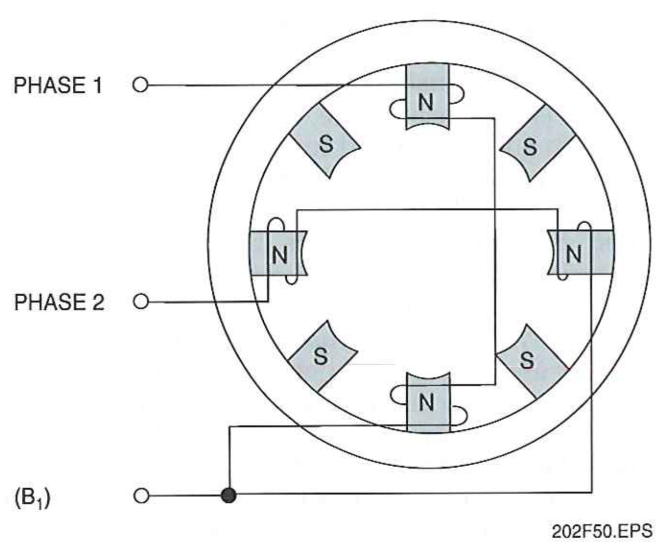


Figure 50 ◆ Low-speed consequent-pole motor.

In *Figure 50*, the connections are changed so that the system is phased to produce four magnetic north poles at the winding projections. Since every north pole must have a south pole, consequent south poles are produced between the projecting north poles as a consequence of having formed north poles. Accordingly, in *Figure 50*, there are twice as many pole groups as in *Figure 49*. Therefore, a four-pole rotating magnetic field of 1,800 rpm is produced.

Figure 51 shows the short-jumpering arrangement of the consequent-pole motor. In this, all windings are in series, and alternate north and south poles are produced. To produce consequent poles, the series connection is replaced with a parallel connection accomplished by the long-jumpering arrangement. By connecting the motor in this manner, four salient monopoles are produced and, as a result, create four opposite consequent poles. In the practical consequent-pole motor, all necessary internal connection rearrangements are accomplished at an external control panel.

Consequent-pole motor characteristics depend on the intended application. In a constant-horsepower motor, torque varies inversely with speed. It is used for driving machine tools.

In a constant-torque motor, horsepower varies directly with speed. It is used to drive pumps and air compressors, as well as in constant-pressure blowers. In a variable-torque, variable-horsepower motor, both torque and horsepower change with changes in speed. This is the type of motor found in household fans and air conditioners.

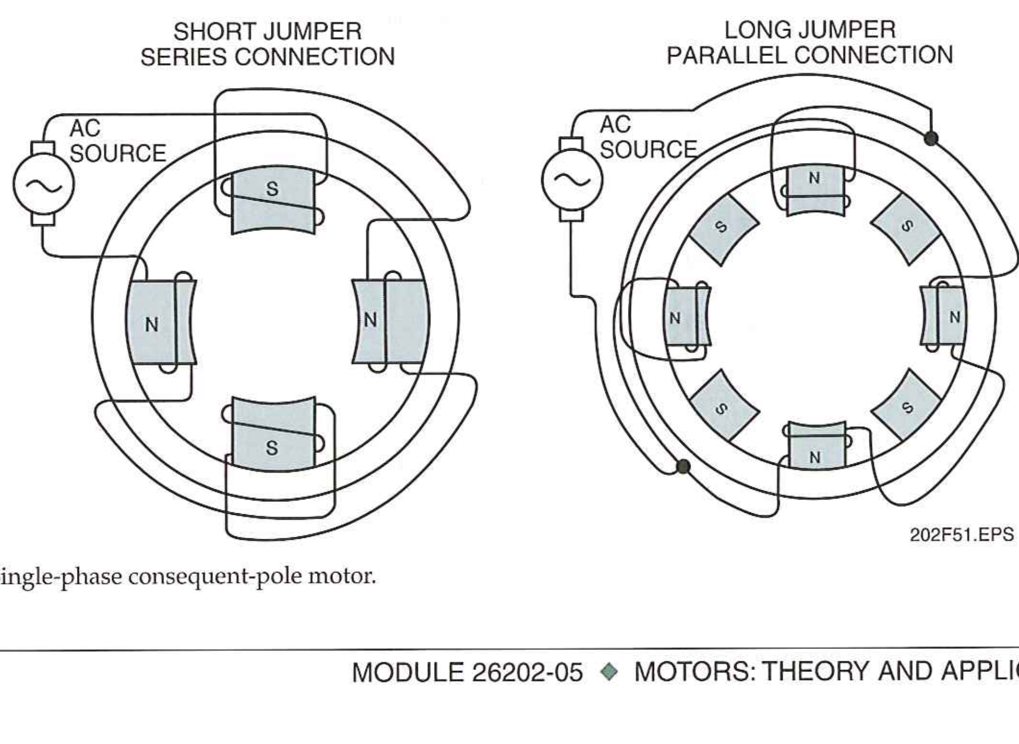


Figure 51 ◆ Single-phase consequent-pole motor.

6.0.0 ◆ VARIABLE-SPEED DRIVES

The use of adjustable speed in industrial equipment is increasing due to the need for better equipment control and for energy savings where partial power is required. AC drives compete with DC drives, eddy current drives, and mechanical and hydraulic systems as methods to control speed. Reliability, cost, and control capabilities are the major factors in system selection.

A drive system includes both the drive controller and the motor being driven. This module focuses specifically on the electronic drive components and covers various types of control for both DC and AC drives. This section provides a basic review of some fundamental principles that are important to understand when starting up, operating, or troubleshooting a variable-speed drive system.

6.1.0 Types of Adjustable Speed Loads

Most drive controllers can be adjusted or modified to optimize performance and provide the most efficient and cost-effective drive, depending on the load characteristics of the application.

It is important to understand the speed and torque characteristics as well as the maximum horsepower requirements for the type of load to be considered. Based on this, either a constant-torque controller or a variable-torque controller is selected. The most common types of loads are shown in *Figure 52*. Note that a load requires the same amount of torque at low speed as at high speed.

For a constant-torque load, the torque remains constant throughout the speed range, and the

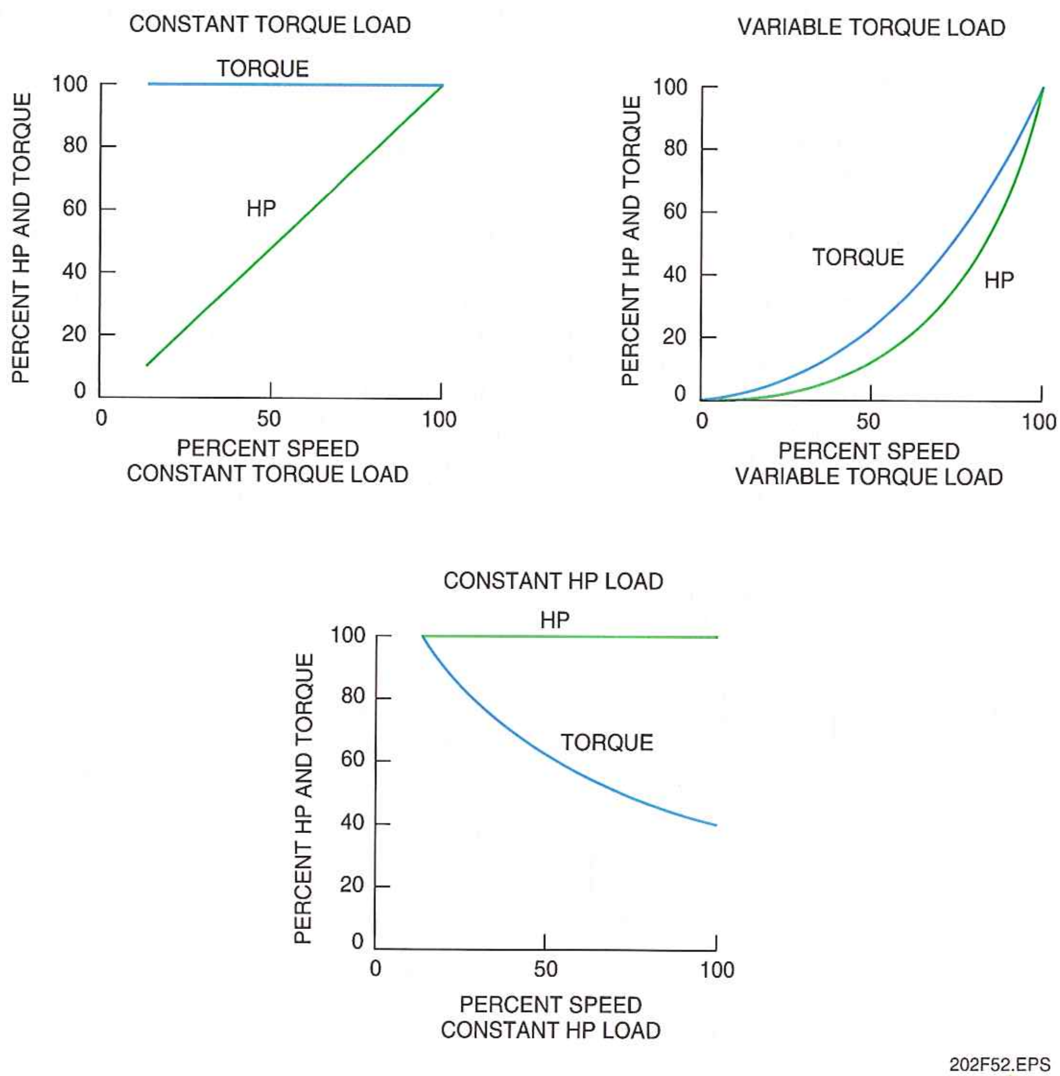


Figure 52 ◆ Types of adjustable speed loads.

horsepower increases and decreases in direct proportion to the speed. This applies to applications such as conveyors, as well as applications in which shock loads, overloads, or high inertia loads are encountered.

A variable-torque load requires much lower torque at low speeds than at high speeds. Horsepower varies approximately as the cube of the speed, and the torque varies approximately as the square of the speed. This applies to applications such as centrifugal fans, pumps, and blowers.

A constant-horsepower load requires high torque at low speeds, low torque at high speeds, and thus constant horsepower at any speed. It applies to applications such as lathes requiring slow speeds for deep cuts and high speeds for finishing. Usually, very high starting torques are required.

6.2.0 Motor Considerations

For industrial applications, motors are required to function at varying torques and speeds, and in forward and reverse directions. Besides operating as a motor, the machine may also function as a brake or a generator for short periods.

The various operating modes for industrial drives are shown in *Figure 53*. Positive and negative speed (rotation) are plotted on the horizontal axis and the torques are plotted on the vertical axis. The four quadrants of operation are labeled 1, 2, 3, and 4.

A machine operating in quadrant 1 has positive torque and speed, which means that they both act in the same direction (in this case, clockwise). A machine in this quadrant is functioning as a motor. It delivers mechanical power to a load. The machine will also act as a motor in quadrant 3, but torque and speed are reversed from quadrant 1 (counterclockwise).

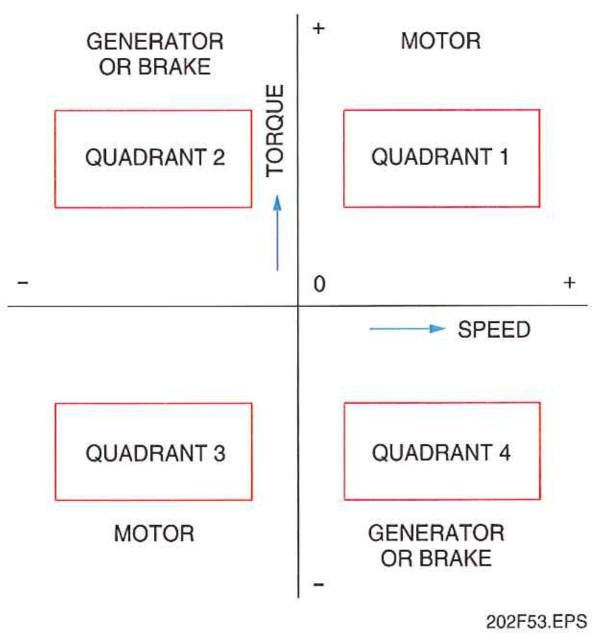


Figure 53 ◆ Electric drive operation in four quadrants.

While operating in quadrant 2, a machine will develop a positive torque and a negative speed. The torque is acting clockwise, and the speed is counterclockwise. In this quadrant, the machine is absorbing mechanical power from the load and functions as a generator. This mechanical power is converted into electric power and is generally transmitted back into the line. The electric power may also be dissipated in an external resistor, which is known as dynamic braking.

Depending on its connections, a machine may also be used as a brake while operating in quadrant 2. Absorbed mechanical power is converted to electric power, then converted into heat. If the machine absorbs electric line power as it is converting mechanical power into electric power, it functions as a brake. Both power inputs are dissipated as heat. Large power drives seldom use the brake mode of operation as it is very inefficient. The circuitry is generally chosen so that the machine will function as a generator when it is operating in quadrant 2. Quadrant 4 operation is identical to quadrant 2 except that speed and torque are reversed.

6.2.1 Typical Torque-Speed Curves

A three-phase motor has a torque-speed curve that is a good example of an electrical machine's behavior as a generator brake. The solid curve in *Figure 54* is the torque-speed curve for a machine acting as a motor in quadrant 1, a brake in quadrant 2, and a generator in quadrant 4.

If the stator leads are reversed, the torque-speed curve is shown by the dotted curve. Now the motor operates as a motor in quadrant 3, a generator in quadrant 2, and a brake in quadrant 4. The machine functions as a brake or a generator in quadrants 2 and 4, but it always runs as a motor in quadrants 1 and 3.

Figure 55 shows the torque-speed curve of a DC shunt motor. Motor, generator, and brake modes are apparent. The dotted curve represents reversed armature leads.

Variable-speed electric drives are designed to vary speed and torque in a smooth and continuous manner so as to satisfy load requirements. Typically, this is accomplished by shifting the torque-speed characteristic back and forth along the horizontal axis. The torque-speed characteristic of the motor is shifted by varying the armature

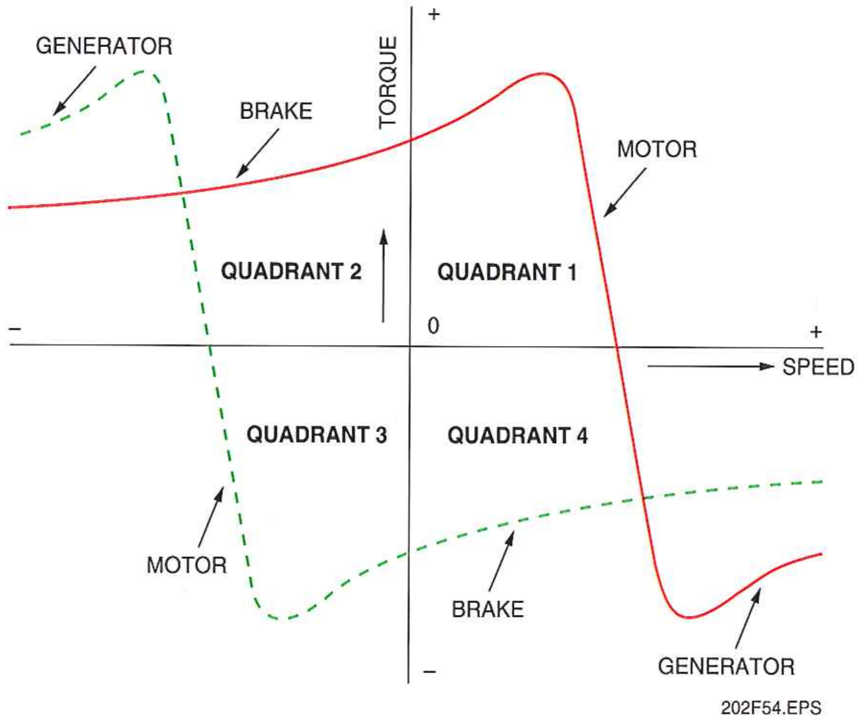


Figure 54 ◆ Four-quadrant operation for a squirrel cage motor.

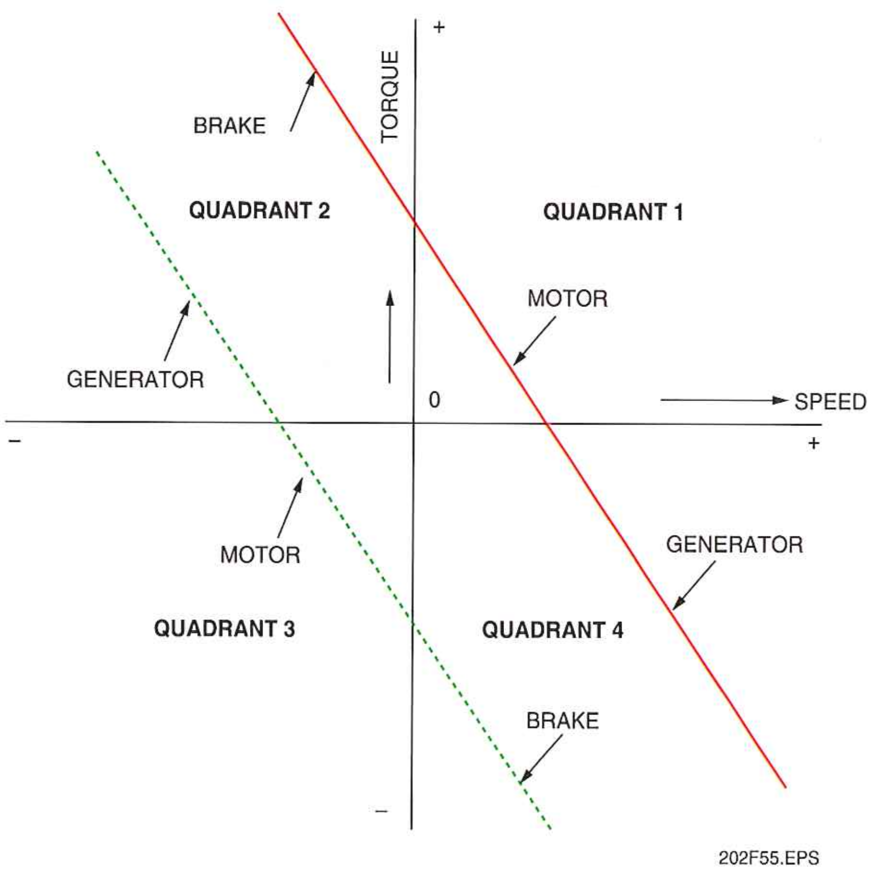


Figure 55 ◆ Four-quadrant operation for a DC motor.

voltage. Also, the curve of an induction motor can be shifted by varying the voltage and frequency applied to the stator.

In describing the various methods of motor control, only the behavior of power circuits will be discussed. The many ways of shaping and controlling triggering pulses will not be covered. They constitute a complex subject that involves sophisticated electronics, logic circuits, integrated circuits, and microprocessors.

6.2.2 Motor Heating

Since a variable-speed drive system includes both the drive controller and the motor, the design engineer should always consider the capabilities of the motor to perform acceptably under the desired operating conditions. One of the factors that you should be aware of is motor heating. When operating a motor at reduced speeds, the ability to dissipate heat is also reduced due to the slower cooling fan speed. This factor should be considered when maintaining the motor, modifying its enclosure or surrounding area, or troubleshooting the drive system.

6.3.0 Motor Speed Control

It is important to understand how DC or AC motor speed can be varied in order to understand how a drive controller accomplishes that task. This section reviews the fundamentals of DC and AC motor speed control.

6.3.1 Varying the Speed of a DC Shunt Motor

A DC shunt motor is shown in *Figure 56(A)*. Basically, there are two ways of varying the running speed of a DC shunt motor:

- Adjusting the voltage (and current) applied to the field winding. As the field voltage is increased, the motor slows down. This method is suggested by *Figure 56(B)*.
- Adjusting the voltage (and current) applied to the armature. As the armature voltage is increased, the motor speeds up. This method is suggested by *Figure 56(C)*.

6.3.2 Field Control

Here is how method 1, adjusting the field voltage, works. As the field voltage is increased, by reducing R_V in *Figure 56(B)*, for example, the field current is increased. This results in a stronger magnetic field, which induces a greater CEMF in the armature winding. The greater CEMF tends to oppose the applied DC voltage and thus reduces the armature current, I_A. Therefore, an increased field current causes the motor to slow down until the induced CEMF has returned to near its normal value.

Going in the other direction, if the field current is reduced, the magnetic field gets weaker. This causes a reduction in CEMF created by the rotating armature winding. The armature current increases, forcing the motor to spin faster, until the CEMF is once again approximately equal to what it was before. The reduction in magnetic field strength is compensated for by an increase in armature speed.

This method of speed control has certain positive features. It can be accomplished by a small, inexpensive rheostat, since the current in the field winding is fairly low. Also, because of the low value of the field current, I_F, the rheostat R_V does not dissipate very much energy. Therefore, this method is energy efficient.

However, there is one major drawback to speed control from the field winding: to increase the speed, you must reduce I_F and weaken the magnetic field, thereby lessening the motor's torque-producing ability. The ability of a motor to create torque depends on two things: the current in the armature conductors and the strength of the magnetic field. As I_F is reduced, the magnetic field is weakened, and the motor's torque-producing ability declines. Unfortunately, it is at this point

INSIDE TRACK

Using a Motor as Both a Generator and a Brake

DC motors that power subway cars are also used for regenerative braking. When driven by the train's momentum, such as when slowing down upon approaching a station, the motor acts as a generator and puts current back into the system. Thus, while the train's motors are creating a significant amount of power from the train's movement, the train makes use of the resistive torque created by the power generation to slow down the train.

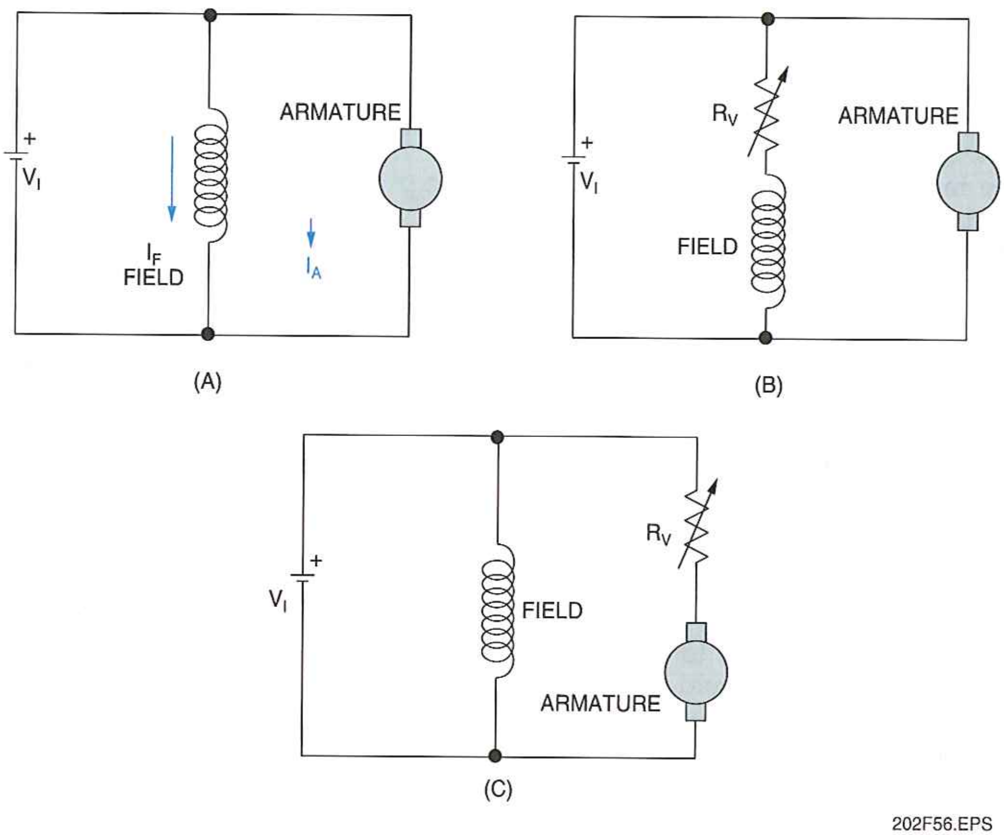


Figure 56 ◆ DC shunt motor schematic.

that the motor needs all the torque-producing ability it can get, since it probably requires greater torque to drive the load at a faster speed.

6.3.3 Armature Control

From the torque-producing point of view, method 2, armature control, is much better. As the armature voltage and current are increased by reducing R_V, the motor starts running faster, which normally requires more torque. The reason for the rise in speed is that the increased armature voltage demands an increased CEMF to limit the increase in armature current to a reasonable amount. The only way the CEMF can increase is for the armature winding to spin faster, since the magnetic field strength is fixed. In this instance, the ingredients are all present for increased torque production, since the magnetic field strength is kept constant and I_A is increased.

The problem with the armature control method of *Figure 56(C)* is that R_V, the rheostat, must handle the armature current, which is relatively large. Therefore, the rheostat must be physically large and expensive, and it will waste a considerable amount of energy.

6.3.4 Varying the Speed of an AC Motor

The principle of speed control for adjustable-frequency drives is based on the following fundamental formula for a standard AC motor:

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

Where:

N_s = synchronous speed (rpm)
f = frequency
P = number of poles

The number of poles of a particular motor is set in its design and manufacture.

The adjustable-frequency system controls the frequency (f) applied to the motor. The speed (N_s) of the motor is then proportional to this applied frequency. Control frequency is adjusted by means of a potentiometer or external signal, depending on the application.

The frequency output of the controller is adjustable over its design speed range. Therefore, the speed of the motor is adjustable over this same range. Because an electronic means of generating variable frequencies is being used, the speed range often exceeds the 60 hertz (Hz) rated speed of the motor.

When variable-frequency speed control is employed, the motor supply voltage cannot be allowed to remain at a steady value. The magnitude of the motor voltage must be increased or decreased in proportion to the frequency. That is, the voltage-to-frequency ratio, V/f, must remain approximately constant.

For instance, if the motor has a nameplate rating of 240V at 60Hz, the voltage-to-frequency ratio is 4 (240 ÷ 60 = 4). If the motor is speeded up by adjusting its variable-frequency inverter to 90Hz, the voltage magnitude must be increased to 360V, since 4 × 90 = 360. If the motor is slowed down by adjusting the inverter frequency to 45Hz, the voltage magnitude must be decreased to 180V, since 4 × 45 = 180.

The stator's magnetic field strength must remain constant under all operating conditions. If the stator field strength should happen to rise much above the design value, the motor's core material would go into magnetic saturation. This would effectively lower the core's permeability, thereby inhibiting proper induction of voltage and current in the rotor loops (or bars), thus detracting from the torque-producing capability of the motor. On the other hand, if the stator field strength should happen to fall much below the design value, the weakened magnetic field would simply induce lower values of voltage and current in the rotor loops. This would also detract from the torque-producing ability of the motor.

Therefore, the magnetic field produced by the stator windings must hold a constant rms value, regardless of frequency. The magnetizing current of an induction motor is the current that flows through the stator winding when the rotor is spinning at steady-state speed with no torque load. The magnetizing current for an induction motor is given by Ohm's law:

$$I_{mag} = \frac{V}{X_L}$$

Where:

V = rms value of the applied stator voltage

X_L = inductive reactance of the stator winding

In the equation, X_L does not remain constant as the supply frequency is adjusted; it varies in proportion to the frequency ($X_L = 2\pi fL$). Therefore V must also be varied in proportion to the frequency, so that the Ohm's law division operation yields an unvarying value of magnetizing current.

Alternatively, using $X_L = 2\pi fL$, we can rewrite the equation:

$$I_{mag} = \frac{V}{X_L}$$

$$I_{mag} = \frac{V}{2\pi fL}$$

$$I_{mag} = \frac{1}{2\pi L} \times \frac{V}{f}$$

Since 1 ÷ 2πL is a constant determined by the motor's construction, the magnetizing current is kept constant by maintaining the V/f ratio.

The controller can automatically maintain the required volts/cycle (V/Hz) ratio to the motor at any speed. This provides maximum motor capability throughout the speed range.

The V/Hz setting is typically preset at the factory. However, on many controllers it can be adjusted or changed to fine tune controller operation.

7.0.0 ◆ MOTOR ENCLOSURES

Motors are usually designed with covers over the moving parts. These covers, called enclosures, are classified by NEMA (National Electrical Manufacturers Association) according to the degree of environmental protection provided and the method of cooling. If the cover has openings, the motor is classified as an open motor; if the enclosure is complete, the motor is classified as an enclosed motor. Each of these types of motors has many modifications. *Table 1* lists the various types for both open and totally enclosed motors.

Table 1 Motor Enclosures

Open	Totally Enclosed
General purpose	Nonventilated
Drip-proof	Fan-cooled
Splash-proof	Fan-cooled guarded
Guarded	Explosion-proof
Semi-guarded	Dust- and ignition-proof
Drip-proof guarded	Pipe-ventilated
Externally ventilated	Water-cooled
Pipe-ventilated	Water-to-air-cooled
Weather-protected (Type I & Type II)	
Encapsulated windings	
Sealed windings	

The different standard types as explained and defined by NEMA are as follows:

- *General purpose* – Has ventilating openings which permit the passage of external cooling air over and around the windings of the machine.
- *Drip-proof* – Ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle from 0° to 15° downward from the vertical.
- *Splash-proof* – Ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle not greater than 100° downward from the vertical.
- *Guarded* – Openings giving direct access to live metal or rotating parts (except smooth surfaces) are limited in size by the structural parts or by screens, baffles, grills, expanded metal, or other means to prevent accidental contact with hazardous parts.
- *Semi-guarded* – Some of the ventilating openings, usually in the top half, are guarded as in the case of a guarded machine, but the others are left open.
- *Drip-proof guarded* – This type of machine has ventilating openings as in a guarded machine.
- *Externally ventilated* – Designating a machine that is ventilated by a separate motor-driven blower mounted on the machine enclosure. Mechanical protection may be as defined above. This machine is sometimes known as a blower-ventilated or force-ventilated machine.
- *Pipe-ventilated* – Openings for the admission of ventilating air are so arranged that inlet ducts or pipes can be connected to them.
- *Weather-protected* – Type I: Ventilation passages are so designed as to minimize the entrance of rain, snow, and airborne particles to the electrical parts. Type II: In addition to the enclosure described for a Type I machine, ventilating passages at both intake and discharge are so arranged that high-velocity air and airborne particles blown into the machine by storms or high winds can be discharged without entering the internal ventilating passages leading directly to the electric parts.
- *Encapsulated windings* – An AC squirrel cage machine having random windings filled with an insulating resin, which also forms a protective coating.
- *Sealed windings* – An AC squirrel cage machine making use of form-wound coils and an insulation system that, through the use of materials, processes, or a combination of materials and processes, results in a sealing of the windings and connections against contaminants.

INSIDE TRACK

Self-Cooling Motors

Conventional squirrel cage fan-cooled motors may overheat when operated at reduced speeds. Many manufacturers now offer inverter duty-rated motors with increased self-cooling capability.

7.1.0 Totally Enclosed

- *Nonventilated* – Not equipped for cooling by means external to the enclosing parts.
- *Fan-cooled* – Equipped for exterior cooling by means of a fan or fans that are integral with the machine but external to the enclosing parts.
- *Fan-cooled guarded* – All openings giving direct access to the fan are limited in size by design of the structural parts or by screens, grills, expanded metal, etc. to prevent accidental contact with the fan.
- *Explosion-proof* – Designed and constructed to withstand an explosion of a specified gas or vapor that may occur within it and to prevent the ignition of the specified gas or vapor surrounding the machine by sparks, flashes, or explosions of the specified gas or vapor that may occur within the machine casing.
- *Dust- and ignition-proof* – Designed and constructed in a manner that will exclude ignitable amounts of dust or amounts which might affect performance or rating, and that will not permit arcs, sparks, or heat otherwise generated or liberated inside the enclosure to cause ignition of exterior accumulations or atmospheric suspensions of a specific dust on or in the vicinity of the enclosure.
- *Pipe-ventilated* – Openings are so arranged that when inlet and outlet ducts or pipes are connected to them there is no free exchange of the internal air and the air outside the case.
- *Water-cooled* – Cooled by circulating water, with the water or water conductors coming in direct contact with the machine parts.
- *Water-to-air-cooled* – Cooled by circulating air, which in turn is cooled by circulating water.

7.2.0 Open Motor

The most common type of motor is the open motor. It has ventilating openings that permit the passage of external cooling air over and around its windings. If these are limited in size and shape, the motor is called a protected motor, since it is protected from any large pieces of material that may somehow enter the motor, thus damaging its internal parts. A protected motor also prevents a person from touching the rotating or electrically-energized parts of the motor. Drip-proof and splash-proof motors are constructed such that drops of liquid cannot enter the motor.

7.3.0 Enclosed Motor

The totally enclosed motor is designed to prevent the free exchange of air between the inside and outside of the actual motor housing. It is used where hostile environmental conditions and the motor application require maximum protection of the internal parts of the motor.

8.0.0 ◆ NEMA FRAME DESIGNATIONS

Frame sizes were developed by NEMA to ensure interchangeability of motors among manufacturers. They appear on motor nameplates to give information about the machine's physical dimensions. Key dimensions are:

- Distance from motor feet to shaft centerline
- Bolt-hole center-to-center distance between front and back feet
- Exposed shaft distance from shaft end to shaft shoulder

Tables are available to correlate frame size to dimensions. The system for designating the frames of motors and generators consists of a series of numbers in combination with letters.

8.1.0 Small Machines

The frame number for small machines is the D dimension in inches multiplied by 16. The following letters shall immediately follow the frame number to denote variations:

B – Carbonator pump motors

C – Type C face-mounting motors

G – Gasoline pump motors

H – A frame having an F dimension larger than that of the same frame without the suffix H

J – Jet pump motors

K – Sump pump motors

M – Oil burner motors

N – Oil burner motors

Y – Special mounting dimensions (must obtain dimensional diagram from manufacturer)

Z – All mounting dimensions are standard except the shaft extension

8.2.0 Medium Machines

The system for numbering frames of medium machines is as follows:

- The first two digits of the frame number are equal to four times the D dimension in inches. (If this product is not a whole number, the first two digits of the frame number shall be the next higher whole number.)
- The third and, when required, the fourth digit of the frame number are obtained from the value of 2F in inches.

Figure 57 shows a typical end view of a foot-mounted machine. The many different dimensions can be found on a dimension sheet for that machine (*Figure 58*). The NEMA frame designation will provide information relating to both the D and 2F dimensions.

Table 2 may be used to determine the D dimension and 2F dimension for medium-size motors. The D dimension is the distance from the centerline of the shaft to the bottom of the feet. The 2F dimension is the distance between the centerlines of the mounting holes in the feet or base of the machine.

Medium machines also use letters that denote variations. These letters follow the frame number. Since there are many more varieties of medium-size machines, the letter relates to the different aspects of mounting and shaft orientation.

For example, to understand the NEMA frame designation, we will take a typical motor frame designation and determine the D and 2F dimensions. Then we will use a different set of dimensions to determine the frame designation number.

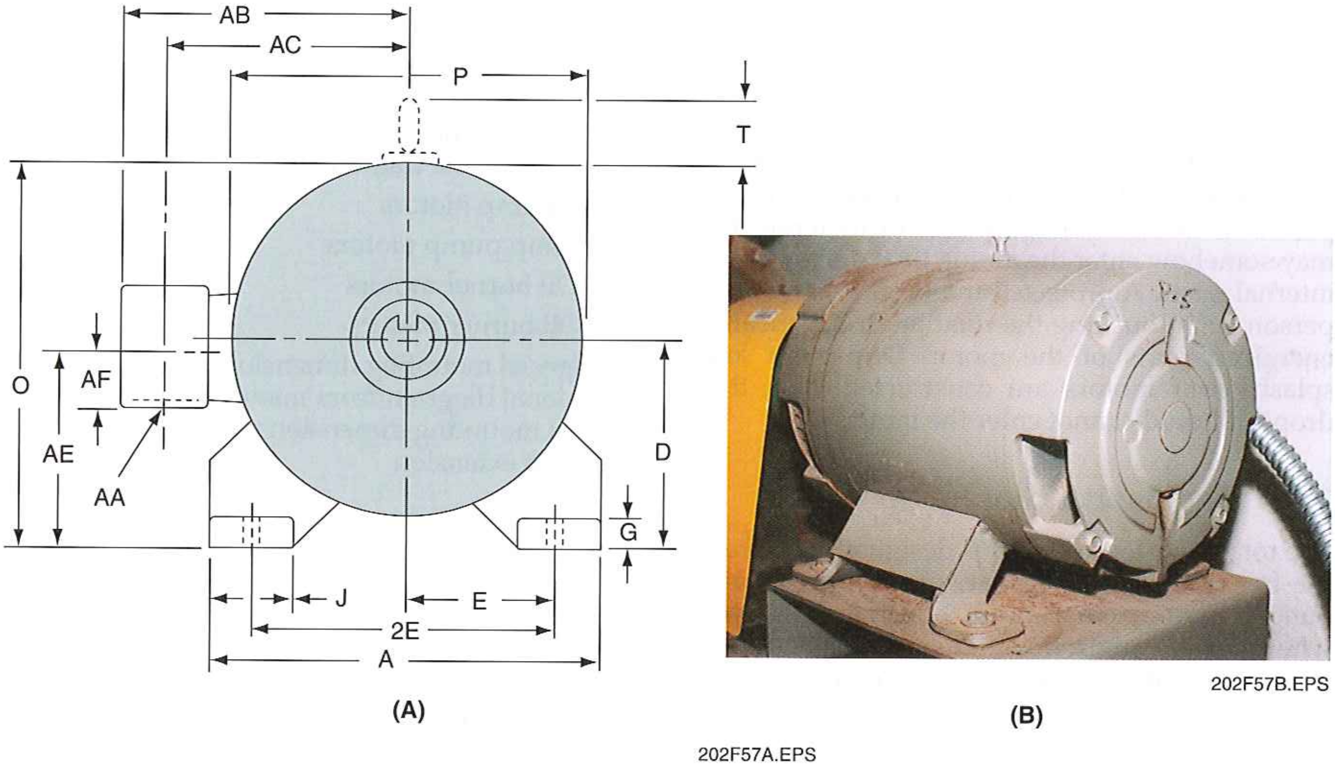


Figure 57 ◆ End view of a foot-mounted motor.

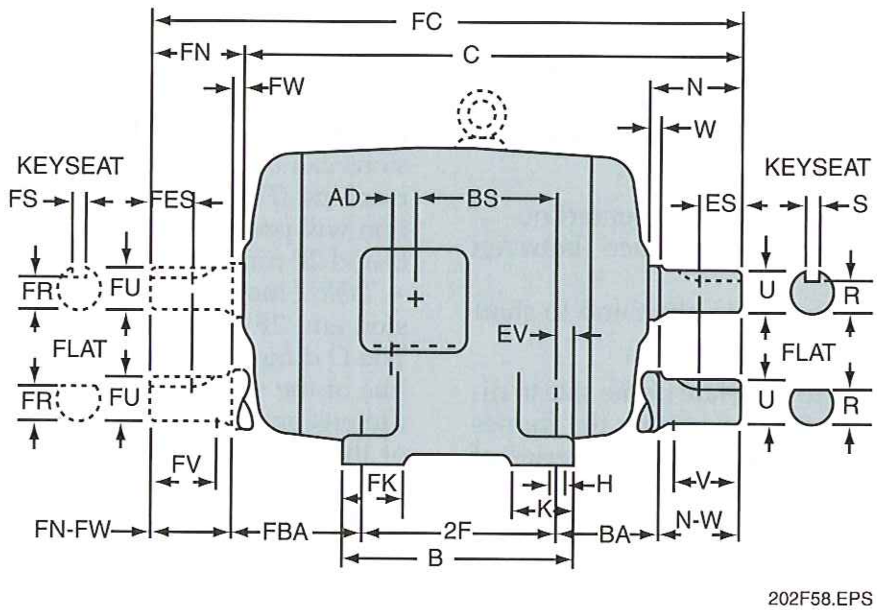


Figure 58 ◆ Lettering of dimension sheets for foot-mounted machines (side view).

Table 2 Frame Dimension Chart

Frame Number Series	D	Third/Fourth Digit in Frame Number: 1	2	3	4	5	6	7
		2F Dimensions						
140	3.50	3.00	3.50	4.00	4.50	5.00	5.50	6.25
160	4.00	3.50	4.00	4.50	5.00	5.50	6.25	7.00
180	4.50	4.00	4.50	5.00	5.50	6.25	7.00	8.00
200	4.50	4.50	5.00	5.50	6.50	7.00	8.00	9.00
210	5.00	4.50	5.00	5.50	6.50	7.00	8.00	9.00
220	5.50	5.00	5.50	6.25	6.75	7.50	9.00	10.00
250	6.25	5.50	6.25	7.00	8.25	9.00	10.00	11.00
280	7.00	6.25	7.00	8.00	9.50	10.00	11.00	12.50
320	8.00	7.00	8.00	9.00	10.50	11.00	12.00	14.00
360	9.00	8.00	9.00	10.00	11.25	12.25	14.00	16.00
400	10.00	9.00	10.00	11.00	12.25	13.75	16.00	18.00
440	11.00	10.00	11.00	12.50	14.50	16.50	18.00	20.00
500	12.50	11.00	12.50	14.00	16.00	18.00	20.00	22.00
580	14.50	12.50	14.00	16.00	18.00	20.00	22.00	25.00
680	17.00	16.00	18.00	20.00	22.00	25.00	28.00	32.00

Frame Number Series	D	Third/Fourth Digit in Frame Number: 8	9	10	11	12	13	14	15
		2F Dimensions							
140	3.50	7.00	8.00	9.00	10.00	11.00	12.50	14.00	16.00
160	4.00	8.00	9.00	10.00	11.00	12.50	14.00	16.00	18.00
180	4.50	9.00	10.00	11.00	12.50	14.00	16.00	18.00	20.00
200	5.00	10.00	11.00	…	…	…	…	…	…
210	5.25	10.00	11.00	12.50	14.00	16.00	18.00	20.00	22.00
220	5.50	11.00	12.50	…	…	…	…	…	…
250	6.25	12.50	14.00	16.00	18.00	20.00	22.00	25.00	28.00
280	7.00	14.00	16.00	18.00	20.00	22.00	25.00	28.00	32.00
320	8.00	16.00	18.00	20.00	22.00	25.00	28.00	32.00	36.00
360	9.00	18.00	20.00	22.00	25.00	28.00	32.00	36.00	40.00
400	10.00	20.00	22.00	25.00	28.00	32.00	36.00	40.00	45.00
440	11.00	22.00	25.00	28.00	32.00	36.00	40.00	45.00	50.00
500	12.50	25.00	28.00	32.00	36.00	40.00	45.00	50.00	56.00
580	14.50	28.00	32.00	36.00	40.00	45.00	50.00	56.00	63.00
680	17.00	36.00	40.00	45.00	50.00	56.00	63.00	71.00	80.00

Example 1:

A typical medium-size frame number is a 256T. Since we know this is a medium frame, we divide the first two digits by 4:

$$25 \div 4 = 6.25$$

Therefore, the D dimension is 6.25 inches.

To determine the 2F dimension, we use *Table 2* and the third digit in the frame number. The third digit is 6 and the frame is a 250 series. Using the table, the 2F dimension is 10 inches. The T in the frame number is included as part of a frame designation for which standard dimensions have been established.

Medium-size frames can have multiple letters that denote a variety of different applications and arrangements. A 256AT has the same dimensions, with the A added to denote an industrial DC machine.

Example 2:

A frame has a D dimension of 3.5 inches and a 2F dimension of 4 inches, and all standard dimensions have been established. Multiplying the

D dimension by 4 will give the first two digits of the frame designation:

$$3.5 \times 4 = 14$$

Using the table, a 140 frame series and a 2F dimension of 4 inches provides a third digit of 3. Since it is a standard dimension frame, the letter will be the suffix. This frame has a designation of 143T.

Full-load torque (rather than horsepower) determines the frame size required to house the motor. Thus, a motor developing a large amount of horsepower at high speed will have the same frame size as a machine developing less horsepower at a slower speed.

More compact design, better ventilation, and insulation systems with higher temperature ratings have enabled manufacturers to house motors in increasingly smaller frame sizes. NEMA re-rates occurred in 1952 and 1964. Motors manufactured before 1952 are generally referred to as pre-U-frame motors. Those manufactured between 1952 and 1964 are called U-frame motors; those manufactured since 1964 are called T-frame motors.

9.0.0 ◆ MOTOR RATINGS AND NAMEPLATE DATA

The ratings of an electric motor include:

- Voltage
- Full-load current
- Speed
- Number of phases and frequency
- Full-load horsepower
- Service classification

Except for full-load horsepower and service classification, these are self-explanatory units. The horsepower rating that is stamped on the motor nameplate by the manufacturer is the horsepower load the motor will carry without damaging any part of the motor.

Electric motor service classification depends on the type of service for which the motor is designed. A motor will usually fall into one of two classifications. General-purpose motors are those motors designed for use without restriction to a particular application. They meet certain specifications as standardized by NEMA. A definite-purpose motor is one that is designed in standard ratings and with standard operating characteristics for use under service conditions other than usual or for use on a particular type of application. A special-purpose motor is one with special operating characteristics or special mechanical construction, or both, that is designed for a particular application and that does not meet the definition of a general-purpose or a definite-purpose motor.

The most common machine rating is the **continuous duty** rating defining the output (in kilowatts for DC generators, kilovolt-amperes at a specified power factor for AC generators, and horsepower for motors) that can be carried indefinitely without exceeding established limitations. For **intermittent duty, periodic duty,** or **varying duty,** a machine may be given a short-time rating defining the load that can be carried for a specific time. Standard periods for short-time ratings are 5, 15, 30, and 60 minutes. Speeds, voltages, and frequencies are also specified in ratings, and provision is made for possible variations in voltage and frequency.

For example, motors must operate successfully at voltages 10% above and below rated voltage and, for AC motors, at frequencies 5% above and below rated frequency; the combined variation of voltage and frequency may not exceed 10%. Other performance conditions are so established that reasonable short-time **overloads** can be carried. Thus, the user of a motor can expect to be able to apply an overload of 25% for a short time at 90% of normal voltage with an ample margin of safety.

9.1.0 Nameplate Data

The *NEC Section 430.7* has specified information that must be listed on a motor nameplate based on its type. Requirements can also be found in *NEMA Standards MG-1* and *MG-2*. Required information plus additional information is shown on the nameplate in *Figure 59*.

9.1.1 Rated Voltage

Power plant induction motors are designed to operate with a balanced three-phase voltage source applied at the terminals. The rated voltage on the nameplate is usually lower than the voltage of the electrical system. For example, a 460V motor is designed to operate in a 480V system. Here, an assumption is made by motor manufacturers that there will be a voltage drop of 20V from the transformer down to the motor terminals (see *Table 3*). The rated or nameplate voltage is the voltage at which the motor will operate most effectively. When other than rated voltage is applied, performance will change and motor life may be reduced.

Many three-phase motors have two voltages listed on the nameplate. For example, 230/460V means the motor can be connected for either 230V or 460V operation. In these cases, a connection diagram is usually found on the nameplate, as shown in *Figure 60*. These diagrams refer to low-voltage and high-voltage connections.

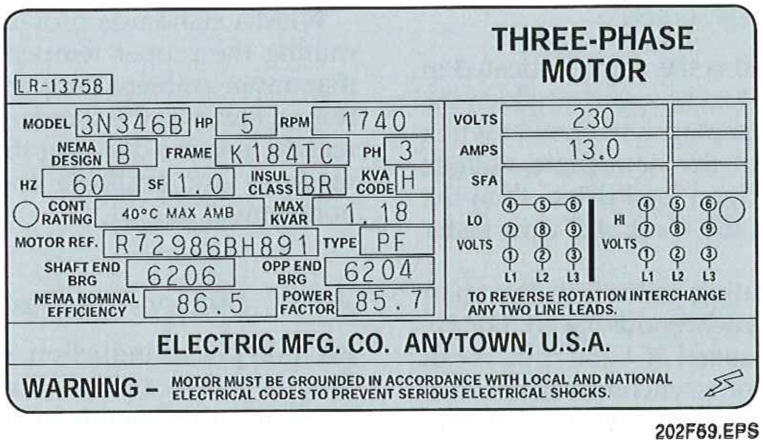


Figure 59 ◆ Nameplate data.

9.1.2 Full-Load Amps (FLA)

The FLA rating appearing on the nameplate indicates the current the motor will draw at nameplate horsepower, frequency, and voltage. Most manufacturers test to determine this value on a periodic basis during production, ensuring reasonable accuracy. The *NEC*® requires that the rated full-load current be the basis for determining the proper sizing of cable, overload protective devices, and other **overcurrent** protection in the motor circuit. Since many motors can be connected for one of two voltage ratings, they have two FLA ratings.

The FLA ratings are guaranteed if the induction motor is operating at full-load conditions and the applied voltage and frequency are the same as stated on the nameplate. When voltage or frequency are not the same, however, the current drawn by the motor at full-load conditions will be different from the nameplate indication (see *Table 4*). It is possible to damage a motor operated below its rated voltage or frequency, since the current the motor draws at full-load conditions increases in both cases. If the overload protective device is not sized properly, motor life may be shortened by this overcurrent condition.

Table 3 Induction Motor Voltages

System Voltage	Rated Voltage
216	208
240	230
480	460
600	575
2,400	2,300
4,160	4,000
4,800	4,600
6,900 and 7,200	6,600
13,200 and 13,800	13,200

Table 4 Motor Operation

Mode	Full-Load Current
110% of rated volts	7% decrease
90% of rated volts	11% increase
105% of rated frequency	5%–6% decrease
95% of rated frequency	5%–6% increase

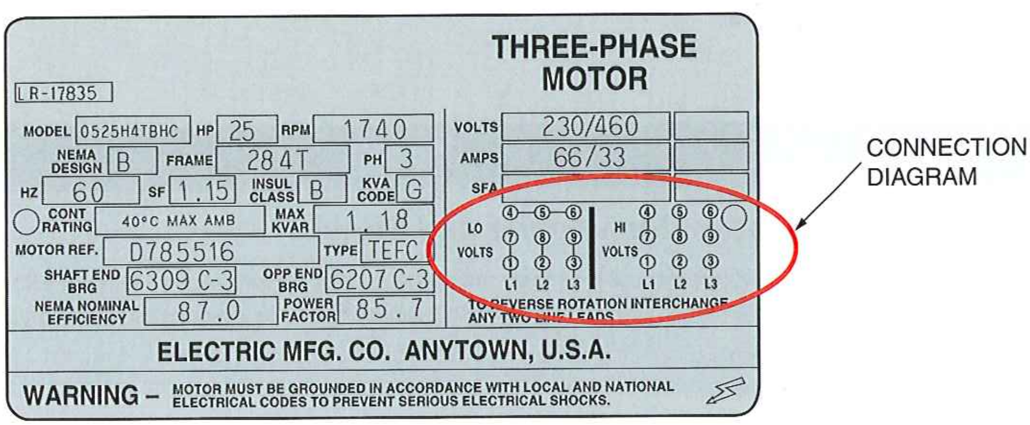


Figure 60 ◆ High-voltage and low-voltage connection diagrams shown on motor nameplate.

9.1.3 Rated Full-Load Speed

The rated full-load speed is the value indicated in rpm on the nameplate. It is the speed at which the shaft will turn at the nameplate horsepower when supplied with power at the nameplate voltage and frequency. If the driven load is less than the nameplate horsepower, the shaft will turn faster than full-load speed.

If the motor is operating unloaded, the shaft will turn very close to synchronous speed. For example, with a full-load speed of 1,750 rpm, it can be inferred that the motor's synchronous speed is 1,800 rpm. The machine will operate from close to 1,800 rpm down to 1,750 rpm, from no-load to full-load conditions.

Common synchronous speeds are 3,600, 1,800, 1,200, 900, and 600 rpm. Synchronous speed is rarely found on the motor nameplate unless the machine has been retrofitted and has not yet been tested for new full-load speed.

9.1.4 Rated Horsepower

An induction motor is really a torque generator. It delivers a needed torque to a driven machine at a certain speed. Thus:

$$\text{Horsepower} = \frac{\text{load torque in ft.-lbs} \times \text{rpm}}{5{,}250}$$

For induction motors that are built to NEMA standards, the ratings will range from ½hp to 400hp, with 24 categories in all. If horsepower requirements fall between any two ratings, the larger motor size should be selected.

Remember, an induction motor will try to deliver any amount of horsepower the load requires. If properly sized, most motors operate at something less than the motor nameplate horsepower. Standard motors are designed to operate at nameplate values from sea level up to an altitude of 3,300 feet if the ambient temperature does not exceed 104°F (40°C). Above this altitude, the nameplate horsepower no longer applies.

NEMA standards provide a method for determining the proper temperature rise, or the new maximum ambient temperature, at higher elevations. However, the standards do not provide a direct method for deriving the horsepower. Several methods are available to estimate true motor horsepower output.

9.1.5 Duty or Time Rating

All polyphase induction motors have either a **duty** or a time rating, which is the elapsed time the motor can operate at nameplate horsepower without shortening its life. The time rating of a motor is determined by operating the machine at full-load conditions and measuring the time it takes for the windings to heat up to the temperature rating of the insulation.

Standard time ratings are 5, 15, 30, and 60 minutes, and continuous or 24 **hours.** A motor with a time (or duty) rating other than continuous is a smaller motor that is given a higher horsepower rating for a shorter period of time, thus reducing size and cost. In power plant uses, most motor ratings are continuous at 104°F (40°C).

9.1.6 NEMA Design Letters

The NEMA design letter defines the starting torque characteristics of an induction motor. It is one of the most important pieces of information on the nameplate; unfortunately, when a motor is replaced, the NEMA design letter is usually ignored, often leading to misapplication of the new machine. For fans or centrifugal pumps, starting torque requirements increase with the square of the change in speed. For mixers or loaded conveyor belts, however, starting torque requirements change very little with speed.

THINK ABOUT IT

Motor Horsepower and Speed

Can you replace a fan motor rated at a specific horsepower and speed with a motor rated at the same horsepower but a higher speed to increase airflow? If not, why not?

To account for these differences, NEMA has formulated design letters A, B, C, D, and F. The difference between motors with these letters is mainly in the design of the rotor, although there are also a few external differences. Design A and B motors are intended to drive conventional loads such as fans, blowers, and centrifugal pumps. About 80% of industrial motors are NEMA Design B.

Generally, the starting current is about five to seven times the rated full-load current. From *Table 5*, it can be seen that for larger motors, the starting current can be very significant, and across-the-line starting of larger motors could result in objectionable line-voltage dips. These voltage dips could result in other control equipment dropping out on low voltage and could even cause lights to dim.

9.1.7 Insulation Class

The electrical insulation system in a motor determines the machine's ultimate life span more than any other component. By some estimates, over 60% of all motors brought to repair shops are there because of premature failure of the insulation system.

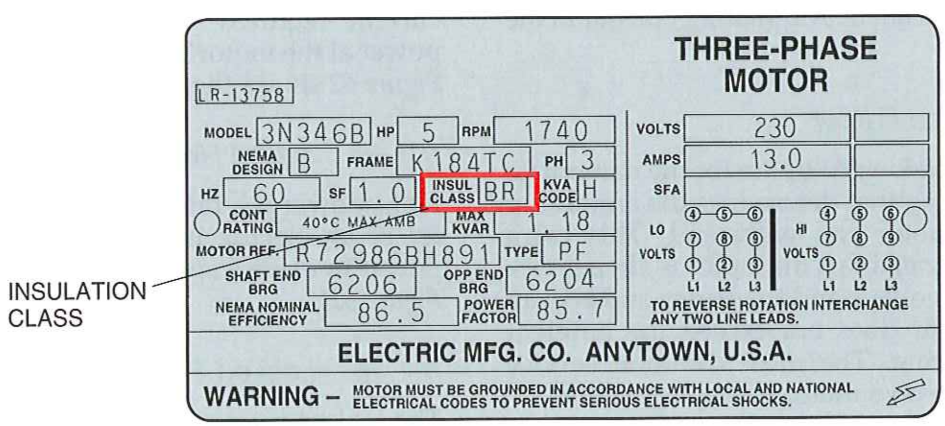
The insulation class is a NEMA designation that identifies the class of material used to insulate the windings. Four letters designate the four classifications. They are A, B, F, and H. The insulation class defines the temperature that the insulation can be subjected to without suffering damage. The insulation class is shown on the nameplate in *Figure 61*.

Class A is now obsolete insofar as industrial motors are concerned. Class A was once the most common classification for motor insulation, especially for small motors. Class A comprises materials or combinations of materials such as cotton or paper, when suitably impregnated or coated, or other materials capable of operation at the temperature rise assigned for Class A insulation for the particular machine.

Class B is the predominant class of insulation used in motor manufacturing and rewinding

Table 5 Current for 220V, 60-Cycle Squirrel Cage Motors

HP	Rated Full-Load Current	Starting (Maximum) Current: Classes B, C, D	Starting (Maximum) Current: Class F
½	2.0	12	—
1	3.5	24	—
1½	5.0	35	—
2	6.5	45	—
3	9	60	—
5	15	90	—
7½	22	120	—
10	27	150	—
15	40	220	—
20	52	290	—
25	64	365	—
30	78	435	270
40	104	580	360
50	125	725	450
60	150	870	540
75	185	1,085	675
100	246	1,450	900
125	310	1,815	1,125
150	360	2,170	1,350
200	480	2,900	1,800



202F61.EPS

Figure 61 ◆ Nameplate showing insulation class.

today. This class is the basic standard of the industry. It includes materials such as mica, glass fiber, polyester, and aramid laminates, etc., with suitable bonding substances, or other materials, not necessarily inorganic, capable of operation at the temperature rise assigned for Class B insulation for the particular machine. (The insulation class may be designated more specifically by the use of additional letters, such as the BR shown in *Figure 61*.)

Class F incorporates materials that are similar to those in Class B but are capable of operation at the temperature rise assigned for Class F for the particular machine.

Class H insulation systems comprise materials or combinations of materials such as silicone elastomer, mica, glass fiber, polyester, and aramid laminates, etc., with suitable bonding substances such as silicone resins, or other materials capable of operation at the temperature rise assigned for Class H insulation for the particular machine.

When replacing motors, ensure that the insulation class is equal to or better than that of the motor removed from service.

9.1.8 Nominal Rated Voltage

Nominal rated voltage is defined as the voltage rating at which the motor is designed to operate.

9.1.9 Minimum Starting Voltage

Minimum starting voltage may be defined as the lowest voltage at which a motor will start without drawing an excessive/trip current.

9.1.10 Frequency

Frequency is given for AC motors in hertz or cycles per second. Standard frequencies for AC motors are 50Hz and 60Hz. Alternating current in the U.S. is 60Hz.

9.1.11 Service Factor

The service factor is a multiplier for the nameplate horsepower rating that determines the amount of overload the motor can withstand. This extra horsepower is available if the motor is already operating at rated voltage and frequency and is in an environment that does not exceed the ambient temperature rating. The most common service factor appearing on a motor nameplate is 1.15.

9.1.12 NEMA Code Letters

The high current draw of the motor during the first moments of startup is called the in-rush or locked-rotor current. It can be derived from the kVA code letter on the motor nameplate. The letter corresponds to the kilovolt-amperes per rated horsepower (kVA/hp) required during the first moments of motor startup. *Table 6* provides the kVA/hp value for each kVA code—a letter from A to V, excluding I, O, and Q. The locked-rotor current is required when sizing fuses or determining a **circuit breaker** setting in an induction motor circuit.

9.1.13 Bearings

Polyphase induction motors require either anti-friction or sleeve bearings. Anti-friction bearings are standard in medium (integral) horsepower motor sizes through 125hp/1,800 rpm. They are optional in 150 to 600hp/1,800 rpm sizes. Sleeve bearings are standard in 500hp/3,600 rpm and larger sizes.

Since radial loads are higher at the drive end of the motor, the drive-end bearing has a higher load rating than the bearing at the opposite end. A typical nameplate (*Figure 62*) might depict both bearing duties as:

- Shaft end brg: 6,206
- Opp end brg: 6,204

Bearing internal clearances are: C1 and C2 (smaller-than-normal clearance); standard clearance (normal); and C3, C4, and C5 (larger-than-normal clearance). Electric motors usually require a C3 internal clearance. Some bearing manufacturers have a different designation for motor bearings that have a larger-than-normal internal clearance.

9.1.14 Rated Amperage

Rated amperage may be defined as the full-load current required to produce full-rated horsepower at the motor's rated voltage and frequency. *Figure 62* shows the amperage for a typical motor.

9.1.15 Rated Horsepower

Horsepower is a rating used to specify the capacity of an electric motor to produce mechanical power to drive a specific piece of equipment (see *Figure 62*).

9.1.16 Locked-Rotor Current

The locked-rotor current is the steady-state current of a motor with the rotor locked and with rated voltage applied at rated frequency. NEMA has designated a set of code letters (*NEC Section 430.7*) to define locked-rotor kilovolt-amperes

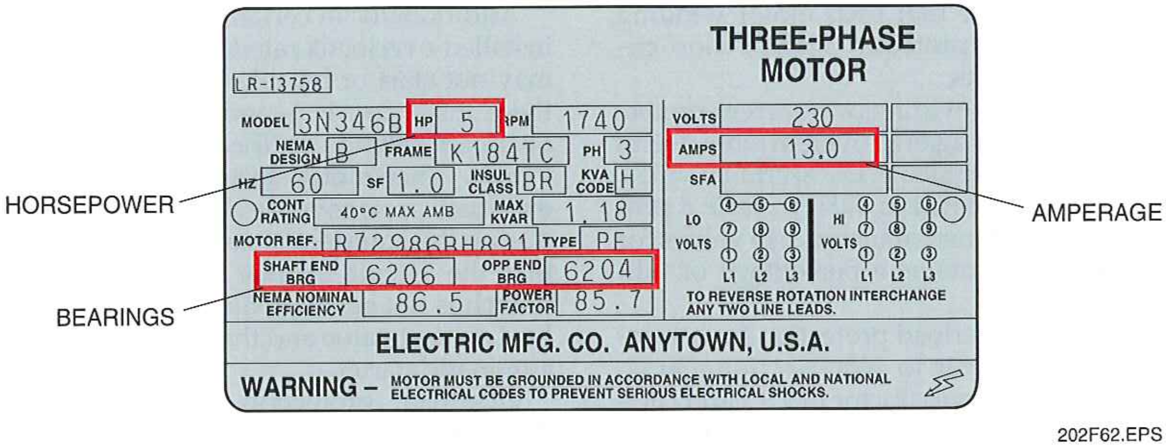


Figure 62 ◆ Nameplate showing bearings, horsepower, and amperage.

(kVA) per horsepower (*Table 6*). This code letter appears on the nameplate of all AC squirrel cage induction motors. The kVA rating is an indication of the current draw and, indirectly, the impedance of the locked rotor.

The current drawn by the motor under stall conditions can be calculated using the values given in *Table 6*. The current drawn by the motor under stalled conditions must be considered when selecting the motor protection and starting package and in coordination with the power system protective devices.

Table 6 Locked-Rotor Code Letters

Code Letter	kVA Per Horsepower with Locked Rotor
A	0–3.14
B	3.15–3.54
C	3.55–3.99
D	4.0–4.49
E	4.5–4.99
F	5.0–5.59
G	5.6–6.29
H	6.3–7.09
J	7.1–7.99
K	8.0–8.99
L	9.0–9.99
M	10.0–11.19
N	11.2–12.49
P	12.5–13.99
R	14.0–15.99
S	16.0–17.99
T	18.0–19.99
U	20.0–22.39
V	22.4–AND UP

9.1.17 Starting Current

The total instantaneous starting current comprises the locked-rotor current plus the transient in-rush that flows until the motor magnetic circuit stabilizes.

9.1.18 Temperature Rise

The temperature rise may be defined as the measure of the heat produced by the operation of the motor. Several conditions contribute to temperature rise. Examples include running current, hysteresis losses, and friction of rotating parts.

9.1.19 Power Factor

The power factor (pf) is the ratio of active power of an alternating or pulsating current (when measured with a wattmeter) to the apparent power indicated by an ammeter and voltmeter. It is also referred to as the phase factor. The power factor is the measure of the system or equipment efficiency.

9.2.0 Motor Protection

Fuses are normally used for motor overload protection. When used, fuses must be provided in each ungrounded conductor and also the grounded conductor of a three-wire, three-phase AC system with one conductor grounded. When non-fuse overload protective devices are used (*NEC Section 430.37*), follow the guidelines as stated in *Table 7*. Note that each motor winding must be individually protected against short circuits and ground faults.

In general, when providing overcurrent protection for motor circuits against overcurrents due to grounds and short circuits (*NEC Section 430.52),* follow the guidance listed in *Table 8*. *Table 8* provides time delay and instantaneous trip values for various types of motors as a percentage of full-load current.

When sizing the overload protection for continuous duty motors, refer to *NEC Section 430.32*. Motors that have a service factor of 1.15 and/or a maximum temperature rise of 40°C shall be provided with overload protection limited to 125% of the full-load current of the motor (this also applies to the secondary circuit of a wound rotor motor). All other motors shall be limited to 115% of the full-load current. Motors that are rated at less than 1hp have exceptions to this rule. Refer to *NEC Article 430* for these exceptions.

If the desired overload ratings are not available when sizing overload protection for the motor, then use the next highest available overload rating. This is allowed provided that 140% of full-load current is not exceeded by motors that have a service factor of 1.15 and/or a maximum temperature rise of 40°C. For all other motors, this maximum value would be 130% rather than 115% as stated earlier.

Additionally, in certain situations, motors with installed overloads rated as discussed previously may not start or be able to carry system load. In these instances, it is permissible to increase the overload settings to the respective 140%/130% values. When motor starting is still a problem, the overload protective device may be shorted out during the equipment startup sequence provided that the circuit breaker or fuse protecting the branch is not set at greater than 400% of the full-load current value and the motor does not have an automatic starter.

Overload protection for adjustable speed drives is based on the rated input to the power conversion equipment. If overload protection is supplied with the equipment, then no further overload protection is required. The rating of this disconnecting means shall be no less than 115% of the power conversion equipment rated input current and it shall be physically located in the incoming line. Overload protection, if not shunted, should allow a sufficient time delay for the motor to start and accelerate.

9.2.1 Thermal Protectors

Thermal protectors that are integral with the motor are often used to protect the motor from overloads and starting failures. All motors with a voltage rating greater than 600V must have a thermal

Table 7 Minimum Number of Overload Units

Type of Motor	Supply System	Number and Location of Overload Units (such as trip coils or relays)
Single-phase AC or DC	Two-wire, single-phase AC or DC, ungrounded	One in either conductor
Single-phase AC or DC	Two-wire, single-phase AC or DC, one grounded conductor	One in ungrounded conductor
Single-phase AC or DC	Three-wire, single-phase AC or DC, grounded neutral	One in either ungrounded conductor
Single-phase AC	Any three-phase supply	One in ungrounded conductor
Two-phase AC	Three-wire, two-phase AC, ungrounded	Two, one in each phase
Two-phase AC	Three-wire, two-phase AC, one grounded conductor	Two, one in each ungrounded conductor
Two-phase AC	Four-wire, two-phase AC, grounded or ungrounded	Two, one per phase in ungrounded conductors
Two-phase AC	Five-wire, two-phase AC, grounded neutral or ungrounded	Two, one per phase in any ungrounded phase wire
Three-phase AC	Any three-phase supply	Three, one in each phase*

*Exception: An overload unit in each phase shall not be required where overload protection is provided by other approved means.

Table 8 Motor Protection

Type of Motor	Nontime Delay Fuse	Dual Element (Time Delay) Fuse**	Instantaneous Trip Breaker	Inverse Time Breaker*
	Percent of Full-Load Current			
Single-phase motors	300	175	800	250
AC polyphase motors other than wound-rotor:				
Squirrel cage:				
Other than Design B, energy efficient	300	175	800	250
Design B, energy-efficient	300	175	1,100	250
Synchronous†	300	175	800	250
Wound rotor	150	150	800	150
Direct-current (constant voltage)	150	150	250	150

For certain exceptions to the values specified, see *NEC Section 430.54.*

*The values given in the last column also cover the ratings of nonadjustable inverse time types of circuit breakers that may be modified per *NEC Section 430.52.*

**The values in the Nontime Delay Fuse column apply to time delay Class CC fuses.

†Synchronous motors of the low-torque, low-speed type (usually 450 rpm or lower), such as are used to drive reciprocating compressors, pumps, etc., that start unloaded, do not require a fuse rating or circuit breaker setting in excess of 200% of the full-load current.

protector and its overload must not have an automatic reset feature. They shall trip no higher than the following percentage of full-load current:

- Motor full-load current not exceeding 9 amps—170%
- Motor full-load current between 9.1 and 20 amps—156%
- Motor full-load current greater than 20.1 amps—140%

This requirement is based on the maximum full-load motor current as listed in the tables provided in *NEC Article 430.*

Motors that are rated 1,500hp include a device that is set to de-energize the motor once the actual temperature rise of the motor equals the rated temperature rise of the motor insulation. Thermal protectors are usually sized and installed by the motor manufacturer.

9.2.2 Branch Considerations

According to *NEC Section 430.22,* when a single motor used in a continuous duty application is supplied from a branch circuit, the ampacity of the branch circuit must be not less than 125% of the motor full-load current as determined by *NEC Section 430.6(A)(1).* If a multiple-speed motor is used, then the ampacity shall be based on the highest of the full-load current ratings on the motor nameplate. Where motors have unusual duty cycle requirements, use the requirements listed in *Table 9*, as referenced in *NEC Section 430.22(E).*

Per *NEC Section 430.24*, when sizing conductors supplying several motors, the capacity shall not be less than 125% of the largest motor plus the sum of the full-load current ratings of all other motors in the group. Values for the full-load amps are taken from *NEC Tables 430.247 through 430.250.* Several motors or loads are permitted to be provided for on one branch circuit if:

- The system voltage is <600 volts.
- The branch protective device protects the smallest installed motor.
- All motors are 1hp, <20A (15A) on 120V (600V) circuits where each motor draws <6A, overloads are installed on the motor, and short circuit current and ground fault current do not exceed the branch circuit rating.
- It is part of a factory-listed assembly.

In instances where taps are used, short circuit current and ground fault current protection may not be required for the taps used. This is true provided that the tap used has the same ampacity as the branch circuit it is connected to. Additionally, the tap cannot be longer than 25' and it must also be physically protected from damage.

Table 9 Duty Cycle Service

Classification of Service	Percentages of Nameplate Current Rating			
	5-Minute Rated Motor	15-Minute Rated Motor	30- and 60-Minute Rated Motor	Continuous Rated Motor
Short-Time Duty				
Operating valves, raising or lowering rolls, etc.	110	120	150	—
Intermittent Duty				
Freight and passenger elevators, tool heads, pumps, drawbridges, turntables, etc.				
For arc welders, see *NEC Section 630.11*	85	85	90	140
Periodic Duty				
Rolls, ore- and coal-handling machines, etc.	85	90	95	140
Varying Duty	110	120	150	200

Any motor application shall be considered as continuous duty unless the nature of the apparatus it drives is such that the motor will not operate continuously with load under any condition of use.

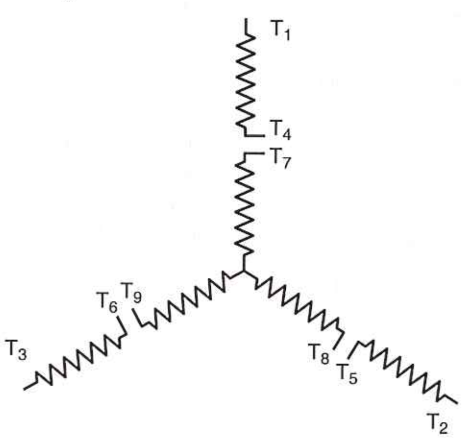
10.0.0 ◆ CONNECTIONS AND TERMINAL MARKINGS FOR AC MOTORS

The markings on the external leads of an induction motor are sometimes missing or illegible, and proper identification must be made before the motor can be connected to the line. This section describes the procedures for identifying leads in either a wye-connected or delta-connected, three-phase, nine-lead motor.

The required materials for this procedure are:

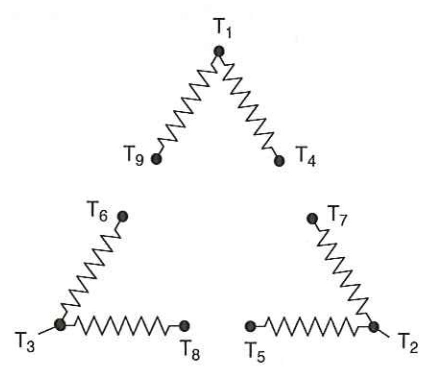
- Appropriate personal protective equipment
- 12V battery such as an automotive battery
- Analog meter with a large scale and low range (digital meters may not clearly capture the voltage kick)
- Test leads and jumpers
- Momentary contact, normally open (N.O.) pushbutton switch
- Labels to mark leads as they are identified
- Three-phase, nine-lead induction motor

Before starting, identify whether the motor to be tagged is wye-connected or delta-connected. Compare the two connection diagrams in *Figure 63* and *Figure 64*. You will see that both types of motors have nine leads and six coils. In a wye-connected motor, three coils are connected together and three coils are isolated. A delta-connected motor has three sets of two coils connected together. Using an ohmmeter, insulate all motor leads from one another and check for continuity between each lead. Start by placing one probe on one lead and check through the remaining leads. As you identify which leads show



202F63.EPS

Figure 63 ◆ Dual-voltage, three-phase wye connection.



202F64.EPS

Figure 64 ◆ Dual-voltage, three-phase delta connection.

continuity, group them together. Continue this procedure with each lead until all leads are grouped. When you have completed this procedure, you should have either three wires in one group and three sets of two wires grouped together, which would indicate a wye-connected motor, or three sets of three wires grouped together, indicating a delta-connected motor.

NOTE

If the leads are partially tied together, mark or identify them in a way that will allow you to reconnect them after the testing procedure is completed.

10.1.0 Identifying the Terminals of Wye-Connected Motors

Figure 65 shows the coil arrangement for a three-phase, wye-connected motor. To identify the terminals of a wye-connected motor, proceed as follows:

Step 1 Taking the group of three common leads, arbitrarily identify them as leads 7, 8, and 9.

Step 2 Using the diagram in *Figure 66* as a guide, connect the positive lead from the battery to lead 7. Connect the lead from the battery negative through the N.O. switch to leads 8 and 9 simultaneously.

Step 3 Connect one of the three remaining lead pairs to the voltmeter terminals.

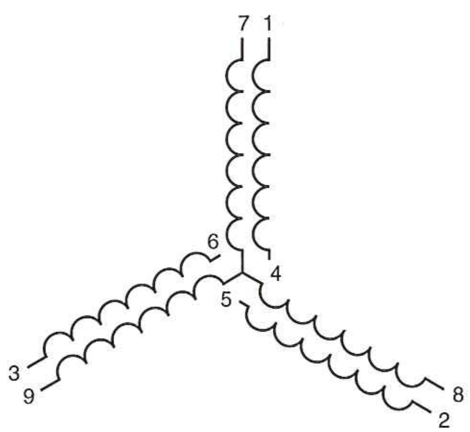
Step 4 Close the N.O. switch while observing the DC voltmeter. Use the lowest scale practical without over-ranging the meter. If the meter deflection is upward, note the voltage reading. Observe that the reading occurs only on the initial energization of the windings and then decays. Note the peak reading only and ignore the deflection in the opposite direction that occurs when the switch is opened. If the meter initially deflects downward, reverse the test lead connections.

Step 5 Continue with the remaining two lead pairs. The pair with the highest voltage reading is the winding associated with lead 7. The lead with positive polarity is identified as lead 4 and the lead with negative polarity is lead 1.

Step 6 Repeat Step 3, but apply the positive lead of the battery to lead 8 and the negative lead of the battery to leads 7 and 9. The positive lead of the pair with the highest voltage is identified as lead 5 and the lead with negative polarity is lead 2.

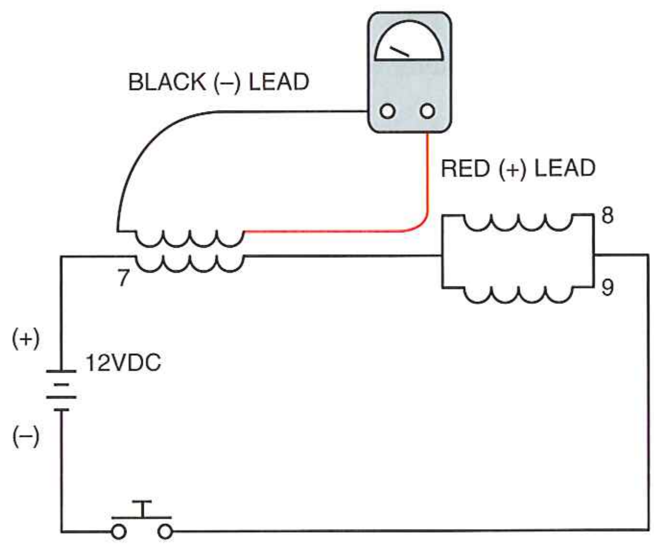
Step 7 Repeat Step 3, but apply the positive lead of the battery to lead 9 and the negative lead of the battery to leads 7 and 8. The positive lead of the pair with the highest voltage is marked lead 6 and the negative lead is lead 3.

Step 8 To confirm that all leads are correctly identified, connect the motor to the circuit. Be sure to observe proper connection procedures for the applied voltage. Once connected to the circuit, start the motor and take current readings on all three lines. If the motor starts correctly and the current readings are approximately equal, the procedure was a success.



202F65.EPS

Figure 65 ◆ Coil arrangement in a wye-connected motor.



202F66.EPS

Figure 66 ◆ Battery hookup for wye-connected motor lead identification.

Motor Lead Identification

THINK ABOUT IT

Refer to the procedure for identifying the leads in a wye-connected motor and answer the following questions:

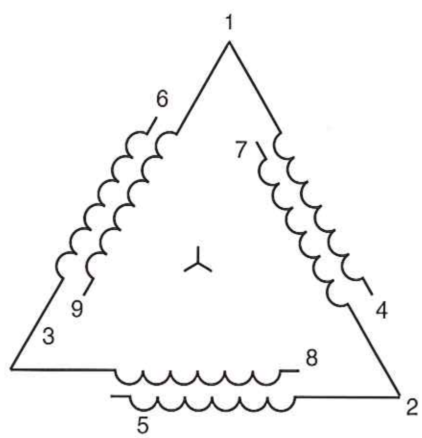
- In Step 2, what would happen if 8 and 9 were connected one at a time?
- In Step 4, why does the voltage reading decay and later deflect downward?
- In Step 5, how much larger is the high voltage reading than the lower readings? Why?

10.2.0 Identifying the Terminals of Delta-Connected Motors

A delta-connected motor has three sets of three leads. *Figure 67* shows how the coils are arranged in a delta-connected, three-phase motor. In this figure, the coils that are side by side are actually wound on the same poles on the motor. As discussed previously, this will allow some transformer interaction between adjacent coils. To identify the terminals of a delta-connected motor, proceed as follows:

Step 1 Using an ohmmeter on a low scale, measure the resistance between each of the three leads in one group. When performing this measurement, you should see that the resistance between two of the leads is about twice that between either of those two and the third. The lead that shows the least resistance to the other two will be lead 1. Refer to all three wires in this set as set 1.

Step 2 Repeat Step 1 with the second set to identify the lead with the least resistance as lead 2. Refer to all three wires in this set as set 2.



202F67.EPS

Figure 67 ◆ Coil arrangement in a delta-connected motor.

Step 3 Repeat Step 1 with the final set of leads to identify the lead with the least resistance as lead 3. Refer to all three wires in this set as set 3.

Step 4 Using the diagram in *Figure 68* as a guide, connect lead 1 to the positive terminal of a DC voltage source and one of the remaining leads in that set (set 1) to the negative terminal. Attach the red lead of the voltmeter to lead 2 and the black lead to one of the two unknown leads in set 2. Press the pushbutton and observe the meter needle. If the correct leads have been selected, a voltage will be induced into this coil. If not, connect the second lead to the voltmeter and repeat the test. If there is still no induced voltage, disconnect the unknown lead in set 1 from the DC voltage and connect the remaining unknown lead to the negative source. Repeat the test until the leads with an induced voltage have been identified. Once these leads are located, identify the lead connected to the negative terminal of the DC voltage source as lead 4 and the lead connected to the negative voltmeter probe as lead 7. Identify the other lead in set 2 as lead 5.

Step 5 The remaining lead in set 1 will be lead 9. Leaving lead 1 on the positive DC terminal, connect the negative terminal to lead 9. Attach the red lead of the voltmeter to lead 3 and the black lead to one of the two unknown leads in set 3. Press the pushbutton and observe the meter needle. If the correct leads have been selected, a voltage will be induced into this coil. If not, connect the second lead to the voltmeter and repeat the test. Once these leads are located, identify the lead connected to the negative voltmeter probe as lead 6.

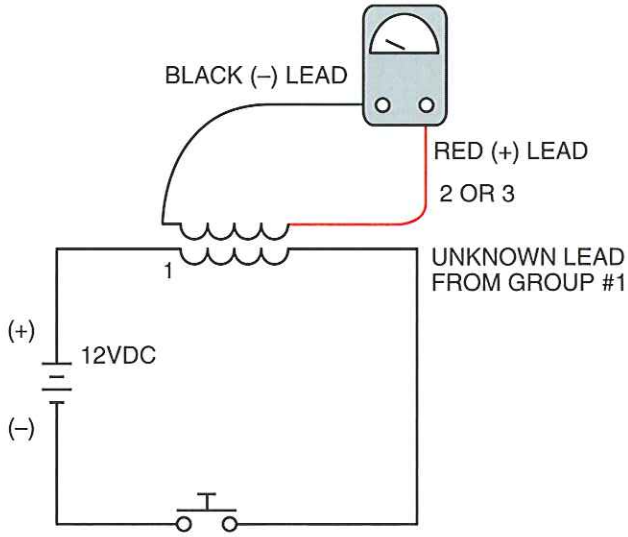


Figure 68 ◆ Battery hookup for delta-connected motor lead identification.

Step 6 The remaining lead in set 3 is lead 8. To verify this, connect lead 3 to the positive terminal of the DC voltage source and lead 8 to the negative terminal. Attach the red lead of the voltmeter to lead 2 and the black lead to lead 5. Press the pushbutton and observe the meter needle. If the results are correct, a voltage will be induced into this coil, resulting in meter needle deflection.

Step 7 To confirm that all leads are correctly identified, connect the motor to the circuit. Be sure to observe proper connection procedures for the applied voltage. Once connected to the circuit, start the motor and take current readings on all three lines. If the motor starts correctly and the current readings are approximately equal, the procedure was a success.

11.0.0 ◆ *NEC*® REQUIREMENTS

NEC Article 430 covers the application and installation of motors, motor circuits, and motor control connections, including conductors, short circuit and ground fault protection, starters, disconnects, and overload protection.

NEC Article 440 contains provisions for motor-driven equipment and for branch circuits and controllers for HVAC equipment.

All motors must be installed in a location that allows adequate ventilation to cool the motors. Furthermore, the motors should be located so that maintenance, troubleshooting, and repairs can be readily performed. Such work could consist of lubricating the motor bearings or perhaps replacing worn brushes. Testing the motor for open circuits and ground faults is also necessary from time to time.

When motors must be installed in locations where combustible material, dust, or similar material may be present, special precautions must be taken in selecting and installing the motors.

Any exposed live parts of motors operating at 50V or more between terminals must be guarded; that is, they must be installed in a room, enclosure, or location so as to allow access only by qualified persons (electrical maintenance personnel). If such a room, enclosure, or location is not feasible, an alternative is to elevate the motors not less than 8' above the floor. In all cases, adequate space must be provided around motors with exposed live parts, even when properly grounded, to allow for maintenance, troubleshooting, and repairs.

The chart in *Table 10* summarizes *NEC*® installation rules.

A summary of *NEC Article 430* is shown in *Figure 69*. Detailed information may be found in the *NEC*® under the articles or sections indicated.

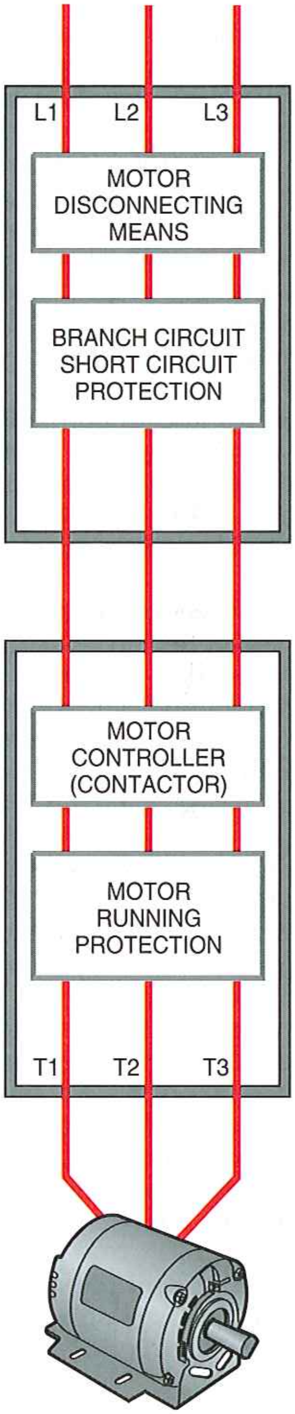
Table 10 Summary of *NEC*® Requirements for Motor Installations

Application	Requirement	*NEC*® Reference
Location	Motors must be installed in areas with adequate ventilation. They must also be arranged so that sufficient work space is provided for replacement and maintenance.	*NEC Section 430.14(A)*
	Open motors must be located or protected so that sparks cannot reach combustible materials.	*NEC Section 430.14(B)*
	In locations where dust or flying material will collect on or in motors in such quantities as to seriously interfere with the ventilation or cooling of motors and thereby cause dangerous temperatures, suitable types of enclosed motors that will not overheat under the prevailing conditions must be used.	*NEC Section 430.16*
Disconnecting means	A motor disconnecting means must be within sight from the controller location (with exceptions) and disconnect both the motor and controller. The disconnect must be readily accessible and clearly indicate the OFF/ON positions (open/closed).	*NEC Article 430, Part IX* *NEC Section 430.104*
	Motor control circuits require a disconnecting means to disconnect them from all supply sources.	*NEC Section 430.74*
	The disconnecting means must be as specified in the code.	*NEC Section 430.109*
Wiring methods	Flexible connections such as Type AC cable, Greenfield, flexible metal tubing, etc., are standard for motor connections.	*NEC Articles 300 and 430*
Motor control circuits	All conductors of a remote motor control circuit outside of the control device must be installed in a raceway or otherwise protected. The circuit must be wired so that an accidental ground in the control device will not start the motor.	*NEC Section 430.73*
Guards	Exposed live parts of motors and controllers operating at 50 volts or more must be guarded by installation in a room, enclosure, or other location so as to allow access by only qualified persons, or elevated 8 feet or more above the floor.	*NEC Section 430.232*
Adjustable speed drive systems	Requirements for adjustable speed drives and their motors.	*NEC Article 430, Part X*
Motors operating over 600 volts	Special installation rules apply to motors operating at over 600 volts.	*NEC Article 430, Part XI*
Controller grounding	Motor controllers must have their enclosures grounded.	*NEC Section 430.244*

INSIDE TRACK

Motor Connections

On dual-voltage and/or multi-speed motors, always check the wiring connection diagrams given on the motor nameplate to wire the motor for the correct voltage and/or speed.



NEC Article 430, Part IX Sections 430.101 through 430.113

Disconnects motor and controllers from circuit.

1. Continuous rating of 115% or more of motor FLC. Also see *NEC Article 430, Part II*.
2. Disconnecting means shall be as listed in *NEC Section 430.109*.
3. Must be located in sight of motor location and driven machinery. The controller disconnecting means can serve as the disconnecting means if the controller disconnect is located in sight of the motor location and driven machinery.

NEC Article 430, Part IV Sections 430.51 through 430.58

Protects branch circuit from short circuits or grounds.

1. Must carry starting current of motor.
2. Rating must not exceed values in *NEC Table 430.52* unless not sufficient to carry starting current of motor.
3. Values of branch circuit protective devices shall in no case exceed exceptions listed in *NEC Section 430.52*.

NEC Article 430, Part VII Sections 430.81 through 430.91

Used to start and stop motors.

1. Must have current rating of 100% or more of motor FLC.
2. Must be able to interrupt LRC.
3. Must be rated as specified in *NEC Section 430.83*.

NEC Article 430, Part III Sections 430.31 through 430.44

Protects motor and controller against excessive heat due to motor overload.

1. Must trip at following percent or less of motor FLC for continuous motors rated more than one horsepower.
   a) 125% FLC for motors with a marked service factor of not less than 1.15 or a marked temperature rise of not over 40°C.
   b) 115% FLC for all others. (See the *NEC®* for other types of protection.)
2. Three thermal units required for any three-phase AC motor.
3. Must allow motor to start.
4. Select size from FLC on motor nameplate.

NEC Article 430, Part II Sections 430.21 through 430.29

Specifies the sizes of conductors capable of carrying the motor current without overheating.

1. To determine the ampacity of conductors, switches, branch circuit overcurrent devices, etc., the full-load current values given in *NEC Tables 430.247 thru 430.250* shall be used instead of the actual current rating marked on the motor nameplate. *(See NEC Section 430.6.)*
2. According to *NEC Section 430.22*, branch circuit conductors supplying a single motor used in a continuous duty application shall have an ampacity of not less than 125% of motor FLC, as determined by *NEC Section 430.6(A)(1)*.

202F69.EPS

Figure 69 ◆ Summary of requirements for motors, motor circuits, and controllers.

12.0.0 ◆ TROUBLESHOOTING

The useful life of an induction motor depends largely on the condition of its insulation. In general, the insulation should be suitable for the operating requirements.

12.1.0 Stator Windings

The stator (stationary) windings appear to be so simple and rugged as to cause one to frequently overlook the necessity for certain maintenance procedures. However, a glance into the average motor repair shop will make it apparent that the induction motor stator is a vulnerable piece of equipment. Most of the work going on will be involved with replacing or repairing stator windings.

Stator troubles can usually be traced to one or more of the following causes:

- Worn bearings
- Moisture
- Overloading
- Operating single phase
- Poor insulation

Dust and dirt are usually contributing factors. Some forms of dust are highly conductive and contribute materially to insulation breakdown. The effect of dust on the motor temperature through restriction of ventilation is another reason for keeping the machine clean, either by periodically blowing it out with compressed air or by dismantling and cleaning it. The compressed air must be dry and throttled down to a low pressure that will not endanger the insulation.

Moisture – One of the most subtle enemies of motor insulation is moisture. Needless to say, motor insulation must be kept reasonably dry, although many applications make this practically impossible unless the motor is totally enclosed or otherwise protected from the direct effects of moisture. If operated in a damp place, a special moisture-resistant coating should be applied to the windings.

Dipping and baking – The life of a winding depends on keeping it in its original (or new) condition for as long as possible. In a new machine, the winding is snug in the slots and the insulation is fresh and flexible, being newly treated with varnish and therefore resistant to the deteriorating effects of moisture and other foreign matter. This condition is best maintained by periodic cleaning, followed by varnish and oven treatments.

One condition that frequently hastens winding failure is movement of the coils because of vibration during operation. After insulation dries out, it loses its flexibility and the mechanical stresses caused by starting, plugging, and stopping, as well as the natural stresses in operation under load, will precipitate short circuits in the coils and possibly failures from coil to ground, usually at the point where the coil leaves the slot. The effect of periodic varnish and oven treatments that are properly carried out so as to fill all air spaces caused by drying and shrinkage of the insulation, thereby maintaining a solid winding, will also provide an effective seal against moisture.

Rotor windings – The rotors of wound rotor motors have many features in common with the stators; therefore, the same comments apply to the care of rotor windings as are given for the care of stator windings. However, the rotor introduces some additional problems because it is a rotating element.

Most wound rotors have a three-phase winding, and are, therefore, susceptible to trouble from single-phase operation. The first symptom of an open-rotor circuit is lack of torque, with a decrease in speed accompanied by a growling noise, or perhaps a complete failure to start the load. The first place to look for an open secondary circuit is in the resistance bank or the control circuit external to the rotor. Short circuiting the rotor circuit at the slip rings and then operating the motor will usually determine whether the trouble is in the control circuit or in the rotor itself. It may be one of the stud connections to the slip rings.

If the rotor is wave wound with the windings made up of copper strap coils with clips connecting the top and bottom halves of the coil, inspect these end connections for possible signs of heating, which would be an indication of a partially open circuit. Faulty or improperly made end connections are a common source of open circuits in rotor windings.

A ground in a rotor circuit will not affect the performance of the motor unless another ground should also develop, which might cause the equivalent of a short circuit, in which case it would have the effect of unbalancing the rotor electrically. In addition to reduced torque, another symptom of this condition might be excessive vibration of the motor. There might also be sparking and uneven wear of the collector rings.

Another method of checking for short circuits in the rotor windings is to raise the brushes off the slip rings and energize the stator. If the rotor winding is free from short circuits, it should have little or no tendency to rotate, even when disconnected from the load. If it does show evidence of considerable torque or the tendency to come up to speed, the rotor should be removed and the winding opened and examined for a fault. In making this test, note that some rotors having a wide tooth design may show a tendency to rotate even though the windings are in good condition.

Still another check that can be made when the rotor is in place and the stator is energized (also with the brushes raised) is to check the voltage across the rings to see if they are balanced. When making this check, be sure that any inequality in voltage measurements is not due to the relative position of the rotor and stator phases. To avoid inaccurate measurements, the rotor should be moved to several positions during the voltage test.

12.2.0 Squirrel Cage Rotors

Squirrel cage rotors are more rugged and in general require less maintenance than wound rotors, but may have trouble because of open circuits or high resistance points in the rotor circuit. The symptoms of such conditions are generally the same as with wound rotor motors: slowing down under load and reduced starting torque. Such conditions can usually be detected by looking for evidence of heating at the end ring connections, which is particularly noticeable when shutting down after operating under load.

In brazed rotors, any fractures in the rotor bars will usually be found either at the point of connection to the end ring or at the point where the bar leaves the laminations. Discolored rotor bars are also evidence of excessive heating.

Brazing broken bars or replacing bars should only be done by a qualified person. Considerable technique is required for this kind of work, and it is recommended that the manufacturer's nearest district sales office be consulted before attempting such repairs in the shop or plant, unless an experienced operator is available.

With die-case rotors, look for cracks or other imperfections that may have developed in the end rings. A faulty die-case rotor can rarely be effectively repaired and should be replaced if defective.

12.3.0 The Air Gap

A small air gap is characteristic of the induction motor. The size of the air gap has an important bearing on the power factor of the motor. Doing anything to affect it, such as grinding the rotor laminations or filing the stator teeth, results in increased magnetizing current with a resultant lower power factor.

Good maintenance procedures call for periodically checking the air gap with a feeler gauge to ensure against a worn sleeve bearing that might permit the rotor to rub the laminations. (A very light rub can produce enough heat to destroy the coil insulation.) Gap measurements should be made on the shaft end of the motor.

On large machines, it is desirable to keep a record of these checks. Four measurements should be taken approximately 90° apart, with one of these points being the load side; that is, the point on the rotor periphery that corresponds with the load side of the bearing.

A comparison of the new measurements with previously-recorded measurements will permit the early detection of bearing wear.

12.4.0 Overloading and Single-Phase Operation

Often, a motor of adequate capacity that was properly applied in the original application is later found to be overloaded or otherwise unsuited for the job. This usually happens because of one or more of the following:

- More severe duty imposed on the motor
- A change in equipment
- A change in equipment parts
- A change in operating time

Connecting measuring instruments to the motor circuit will quickly disclose the reason for motor overheating, failure to start the load, or other abnormal symptoms.

Control circuits for many older systems were not provided with relay protection, and single-phase operation of polyphase induction motors on such circuits has frequently been responsible for motor burnout. Usually this has resulted from one of the fuses blowing while the motor is up to speed and under load. Under such conditions, the portion of winding that remains in the circuit will endeavor to carry the load until it fails due to overheating.

The effect of increasing the load on the motor beyond its rated capacity is simply to increase the operating temperature, which shortens the life of the insulation. Momentary overloads usually do no damage; consequently, the tendency is to use the thermal type of overload protection in present-day controls. Obviously, the ideal place to measure the thermal effect of overload is on the motor itself.

The polyphase induction motor is the simplest and most foolproof piece of rotating electrical apparatus. The largest single cause of winding failures is probably the rotor rubbing the stator iron, usually because of a worn or failed bearing.

13.0.0 ◆ TESTING ELECTRIC MOTORS

A simple test light or continuity tester may be used to test for an open motor coil. With all power circuits shut off, connect the continuity test leads across each motor coil in turn. If the coil is operational, the light will glow or the dial of the ohmmeter will swing to full scale.

To test for a grounded coil, connect one of the test leads to the motor frame and the other lead to one of the field coil wires. If the light glows or the ohmmeter dial swings toward zero, the coil is grounded.

To prepare for an insulation resistance test, first take the equipment or circuit to be tested out of service. Check between the equipment terminals and ground using a voltmeter (at the proper range setting) to be sure there is no voltage present. If possible, disconnect all leads to the motor being tested. When a motor or circuit is not completely isolated, make sure you are aware of all the components that will be tested when the megohmmeter (megger) is connected. Should an interconnected circuit be overlooked, the instrument readings may be lower than expected.

The testing of wiring can be performed on all types of systems if two rules are kept in mind:

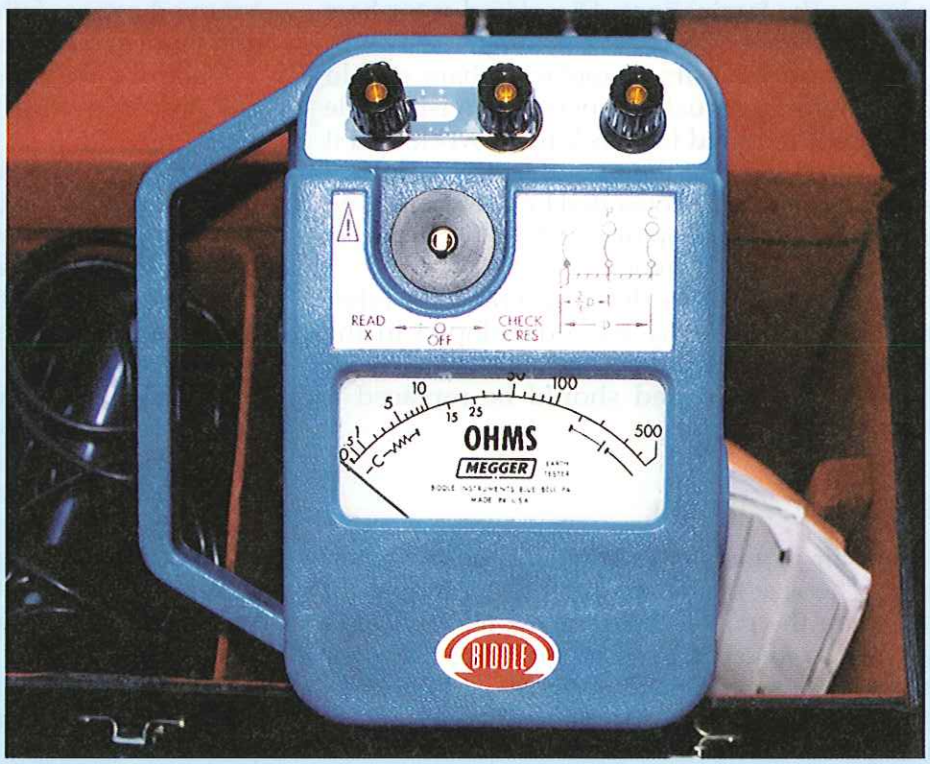
- Be sure all wiring is de-energized.
- Know what wiring is included in the test and make a record of it.

When a distribution panel is present, check the entire system to ground by attaching one megger

INSIDE TRACK

Testing with a Megohmmeter

While multimeters or ohmmeters can be used to check for open or short circuits in a motor, they can't be used to test the insulation resistance of a motor because the resistance to be measured is in the megohm range. A megohmmeter (megger) is designed to apply a high voltage to the motor to check the insulation resistance under load. Because all motor insulation degrades over time, many industrial/commercial facilities conduct a periodic maintenance program that includes checking the insulation resistance of motors on a regular schedule so that the rate of degradation can be used to predict motor failures before they occur.



202P0206.EPS

Motor Maintenance and Repair

INSIDE TRACK

Modern industrial culture has developed a "use it up, throw it away, and buy it new" mentality. Motors are often poorly maintained and quickly replaced. However, most motors are simple in construction and relatively easy to maintain and repair. Dirt and metallic particles are common causes of motor failure.

If your facility has a number of expensive motors in use, make sure that a preventive maintenance schedule is in place. Many facilities do not have such procedures. If there is no maintenance schedule, create one.

lead to the dead (de-energized) post of the open main power switch and the other lead to a grounded portion of the system such as the panel housing or an incoming conduit.

Individual circuits are tested to ground by opening distribution panel switches, fuses, or circuit breakers and testing each circuit in turn.

Once all power has been disconnected, disconnect the motor from the line, either by using the switch or by disconnecting the wiring at the motor terminals. If the switch is used, remember that the insulation resistance of the connecting wire, switch panel, and contacts will all be measured at the same time. Connect the positive megger lead to one of the motor lines and the negative test lead to the frame of the motor. If insulation resistance minimums have been established, the reading can be checked against them. Always check with your supervisor before using a megger. Since every brand of megger operates somewhat differently, always refer to the operating manual or seek assistance from your supervisor as to the proper operation of the instrument.

14.0.0 ◆ MOTOR INSTALLATION

The best motors on the market will operate improperly if they are installed incorrectly. Therefore, all personnel involved with the installation of electric motors should understand the procedures for installing the various types of motors that will be used.

WARNING!

When a motor is received at the job site, always refer to the manufacturer's instructions and follow them to the letter. Failure to do so could result in serious injury or death. Install and ground according to *NEC®* requirements and good practices. Consult qualified personnel with any questions or problems.

Keep the following in mind when installing new motors:

- *Uncrating* – Once the motor has been carefully uncrated, check to see if any damage has occurred during handling. Be sure that the motor shaft and armature turn freely. This is also a good time to check to determine if the motor has been exposed to dirt, grease, grit, or excessive moisture during shipment or storage. Motors in storage should have shafts turned over once each month to redistribute grease in the bearings. The measure of insulation resistance is a good dampness test. Clean the motor of any dirt or grit.

WARNING!

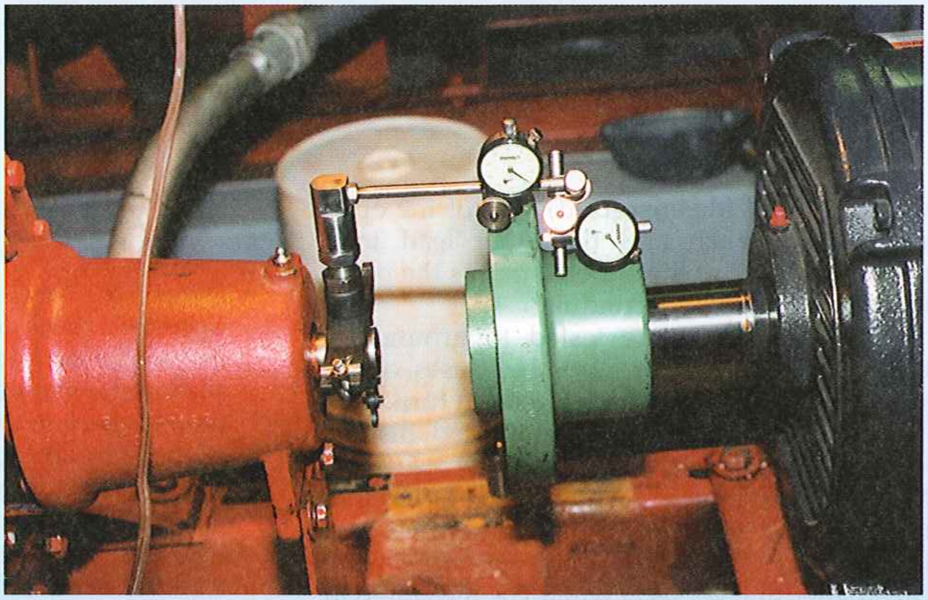
Never start a motor that has been wet until it has been completely dried and thoroughly tested.

- *Lifting* – Eyebolts or lifting lugs on motors are intended only for lifting the motor and factory motor-mounted standard accessories. These lifting provisions should never be used when lifting or handling the motor when the motor is attached to other equipment as a single unit. The eyebolt lifting capacity rating is based on a lifting alignment coincident with the eyebolt centerline. The eyebolt capacity reduces as deviation from this alignment increases.
- *Guards* – Rotating parts such as pulleys, couplings, external fans, and shaft extensions must be permanently guarded against accidental contact with clothing or body extremities.
- *Requirements* – All motors must be installed, protected, and fused in accordance with *NEC Article 430*. For general information on grounding, refer to *NEC Article 250* and *NEC Article 430, Part XIII*.
- *Thermal protector information* – The motor nameplate may or may not be stamped to indicate thermal protection.

INSIDE TRACK

Installing Motors

The shaft of this air conditioner motor must be aligned precisely with the shaft of the driven device. Note the micrometer attached to the motor and the load to achieve exact alignment.



202P0207.EPS

THINK ABOUT IT

Putting It All Together

Count the motors in your home. The typical home may easily have over 30 motors (including electronic equipment and tools). A century ago, a typical home might have had none. Determine what types of motors you have. Are they AC or DC? What identifying information can you determine by examining each motor nameplate?

Review Questions

1. The name of the motor part that rotates during operation is the _____.
   a. stator
   b. shunt/capacitor
   c. brushes/commutator
   d. armature/rotor

2. The electrical energy required to produce one horsepower of mechanical energy is _____.
   a. 476W
   b. 647W
   c. 746W
   d. 864W

3. The principal reason for developing the brushless DC motor was to _____.
   a. eliminate commutator problems
   b. improve efficiency
   c. increase horsepower
   d. improve airplanes

4. The name of the stationary motor part that produces the magnetic field during operation is the _____.
   a. stator
   b. shunt/capacitor
   c. brushes/commutator
   d. armature/rotor

5. The name of the most popular rotor in use is the _____ rotor.
   a. wound
   b. squirrel cage
   c. multiphase
   d. induction

6. The starting torque characteristics of an induction motor are defined by _____.
   a. rotor resistance
   b. starting current
   c. load
   d. stator resistance

7. The speed of an induction motor depends on the power supply frequency and _____.
   a. current
   b. voltage
   c. size
   d. number of pairs of poles

8. The NEMA frame designation for gasoline pump motors is _____.
   a. B
   b. C
   c. G
   d. H

9. The letters FLA on a motor nameplate stand for _____.
   a. fused last application
   b. fast lower arm
   c. full-load amps
   d. full-load armature

10. To determine the horsepower rating of a motor that was already installed and in place, you would _____.
    a. multiply the rated voltage times the FLA
    b. divide the nominal efficiency by the power factor
    c. check the nameplate data
    d. use a torque wrench and horsepower data

11. The multiplier to the nameplate horsepower rating is called the _____.
    a. maximum kVAR
    b. service factor
    c. power factor
    d. NEMA nominal efficiency

12. A _____ is used to protect the motor from overloads and starting failures.
    a. fuse
    b. circuit breaker
    c. centrifugal switch
    d. thermal protector

13. The code requirements for motor disconnects are covered in _____.
    a. *NEC Article 430, Part VIII*
    b. *NEC Article 430, Part IX*
    c. *NEC Article 430, Part X*
    d. *NEC Article 430, Part XI*

Review Questions

14. One of the five causes of stator problems in motors is _____.
    a. no motor protection device
    b. worn bearings
    c. torque
    d. no air circulation

15. Before starting a motor that has been wet, _____.
    a. clean it with alcohol
    b. thoroughly dry it
    c. rotate it by hand
    d. heat it

Summary

This module discussed AC and DC motor theory, construction, and various motor types and applications. This discussion included torque, speed, and speed regulations as well as the fundamental concepts associated with variable speed drive systems. Motor enclosures were described, including open and totally enclosed motors and motor frame designations. Discussions of horsepower and calculation of load under various conditions were included. *NEC*® requirements and basic troubleshooting techniques were also discussed.

Notes

Trade Terms Introduced in This Module

Armature: The rotating windings of a DC motor.

Branch circuit: The circuit conductors between the final overcurrent device protecting the circuit and the outlet(s).

Brush: A conductor between the stationary and rotating parts of a machine. It is usually made of carbon.

Circuit breaker: A device designed to open and close a circuit by nonautomatic means and to open the circuit automatically on a predetermined overcurrent without injury to itself when properly applied within its rating.

Commutator: A device used on electric motors or generators to maintain a unidirectional current.

Continuous duty: Operation at a substantially constant load for an indefinitely long time.

Controller: A device that serves to govern, in some predetermined manner, the electric power delivered to the apparatus to which it is connected.

Duty: Describes the length of operation. There are four designations for circuit duty: continuous, periodic, intermittent, and varying.

Equipment: A general term including material, fittings, devices, appliances, fixtures, apparatus, and the like used as a part of, or in connection with, an electrical installation.

Field poles: The stationary portion of a DC motor that produces the magnetic field.

Horsepower: The rated output capacity of the motor. It is based on breakdown torque, which is the maximum torque a motor will develop without an abrupt drop in speed.

Hours: The duty cycle of a motor. Most fractional horsepower motors are marked continuous for around-the-clock operation at the nameplate rating in the rated ambient conditions. Motors marked one-half are for ½-hour ratings, and those marked one are for 1-hour ratings.

Intermittent duty: Operation for alternate intervals of (1) load and no load; or (2) load and rest; or (3) load, no load, and rest.

Overcurrent: Any current in excess of the rated current of equipment or the ampacity of a conductor. It may result from an overload, short circuit, or ground fault.

Overload: Operation of equipment in excess of the normal, full-load rating, or of a conductor in excess of rated ampacity, which, after a sufficient length of time, will cause damage or dangerous overheating. A fault, such as a short circuit or ground fault, is not an overload.

Periodic duty: Intermittent operation at a substantially constant load for a short and definitely specified time.

Revolutions per minute (rpm): The approximate full-load speed at the rated power line frequency. The speed of a motor is determined by the number of poles in the winding. A four-pole, 60Hz motor runs at an approximate speed of 1,725 rpm. A six-pole, 60Hz motor runs at an approximate speed of 1,140 rpm.

Rotation: For single-phase motors, the standard rotation, unless otherwise noted, is counterclockwise facing the lead or opposite shaft end. All motors can be reconnected at the terminal board for opposite rotation unless otherwise indicated.

Synchronous speed: When the speed of the rotor is equal to the speed of the stator. The speed is determined by multiplying 120 times the frequency divided by the number of poles.

Thermal protector: A protective device for assembly as an integral part of a motor or motor compressor that, when properly applied, protects the motor against dangerous overheating due to overload or failure to start.

Varying duty: Operation at varying loads and/or intervals of time.

Additional Resources

This module is intended to present thorough resources for task training. The following reference works are suggested for further study. These are optional materials for continued education rather than for task training.

American Electricians' Handbook, Latest Edition. New York: Croft and Summers, McGraw-Hill.

National Electrical Code® Handbook, Latest Edition. Quincy, MA: National Fire Protection Association.