# UNIT 9

# Schematics and Wiring Diagrams

## OBJECTIVES

After studying this unit the student should be able to:

- Draw standard NEMA control symbols
- Define the meaning of a dashed line drawn between symbols
- Define a wiring diagram
- Define and read a schematic diagram

**Schematics** and **wiring diagrams** are the written language of control circuits. It will be impossible for a service technician to become proficient in trouble shooting electrical faults if he or she cannot read and interpret electrical diagrams. Learning to read electrical diagrams is not as difficult as many people first believe it to be. Once a few basic principles are understood, reading schematics and wiring diagrams will become no more difficult than reading a newspaper.

## TWO-WIRE CIRCUITS

Control circuits are divided into two basic types, the two-wire and the three-wire. Figure 9–1 shows a simple **two-wire control circuit**. In this circuit, a simple switch is used to control the power applied to a small motor. If the switch is open, there is no complete path for current flow, and the motor will not operate. If the switch is closed, power is supplied to the motor, and it then operates.

## THREE-WIRE CIRCUITS

**Three-wire control circuits** are used because they are more flexible than two-wire circuits. Three-wire circuits are characterized by the fact that they are operated by a magnetic relay or motor starter. These circuits are generally controlled by one or more pilot devices. Three-wire control circuits receive their name from the fact that three conductors or wires are required to make connection from a start-stop pushbutton station to a motor starter, Figure 9–2.

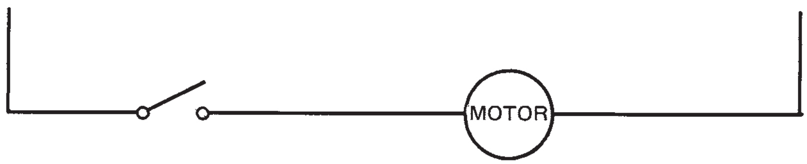


**Figure 9–1**
Two-wire control circuit.
(Source: Delmar/Cengage Learning)

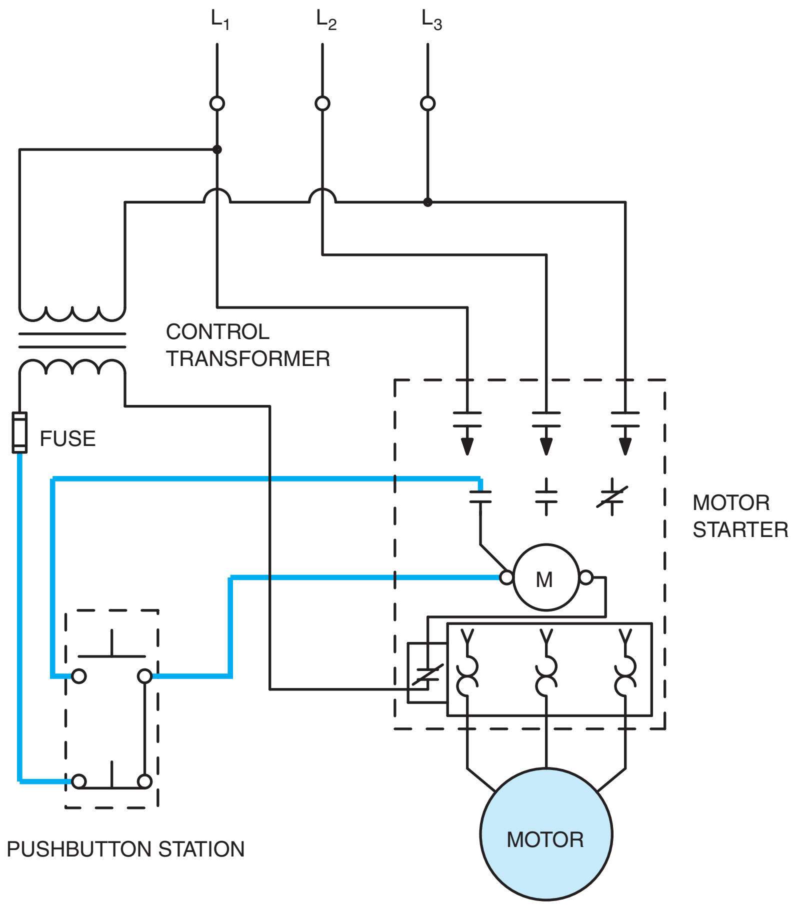


**Figure 9–2**
Basic three-wire control circuit.
(Source: Delmar/Cengage Learning)

## ELECTRICAL SYMBOLS

When a person first learns to read, he or she learns a set of symbols that are used to represent different sounds. This set of symbols is generally referred to as the alphabet. When learning to read electrical diagrams, it is necessary to learn the symbols used to represent different devices and components. The symbols shown below are commonly used on control schematics and wiring diagrams. These are not all the symbols used. Unfortunately, there is no set standard for the use of electrical symbols.

To better understand electrical symbols, it is helpful to understand some of the common terms used to describe these symbols. The terms **movable** and **stationary** contacts, for example, refer to electrical contacts located on different components. A simple switch contains both a movable and a stationary contact, Figure 9–3. Stationary contacts refer to contacts that cannot be moved or changed. Movable contacts can be moved from one position to another. The switch shown in Figure 9–3 can also be described as a **normally open** switch because:

1. The movable contact is shown not touching the stationary contact.
2. The movable contact is drawn *below* the stationary contact.

Control components are drawn in the position they should be in when the circuit is deenergized or turned off. Normally open means that there is no electrical connection or complete circuit made between the movable and stationary contacts of the switch.

The switch in Figure 9–3 can be described as a *single-pole single-throw* (SPST) switch. Single pole indicates that the switch contains only one movable contact. Single throw means that the movable contact will complete a circuit when *thrown* or moved in only one direction.

A normally closed single-pole single-throw switch is shown in Figure 9–4. The switch is **normally closed** because:

1. The movable contact is shown touching the stationary contact.
2. The movable contact is drawn above the stationary contact.

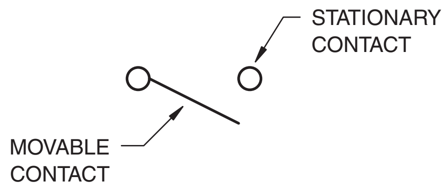


**Figure 9–3**
Normally open single-pole single-throw switch.
(Source: Delmar/Cengage Learning)

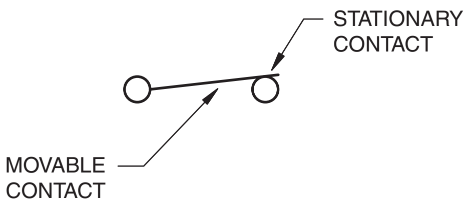


**Figure 9–4**
Normally closed single-pole single-throw switch.
(Source: Delmar/Cengage Learning)

When a component is normally closed it indicates that a complete circuit exists through the component.

Although these basic rules apply to switches, they do not necessarily apply to all control components. When possible, components are generally drawn to indicate how they function. Pushbuttons, for example, are drawn differently than switches. A normally closed pushbutton is drawn with the movable contact below instead of above the stationary contacts, Figure 9–5. It is drawn in this manner to illustrate that when pressure is applied to the spring-loaded stationary contact it will cause the movable contact to move downward, breaking the connection between the two stationary contacts. A normally open pushbutton symbol is drawn with the movable contact above instead of below the stationary contacts. Pressure forces the movable contact downward, bridging the gap between the two stationary contacts and completing a circuit.

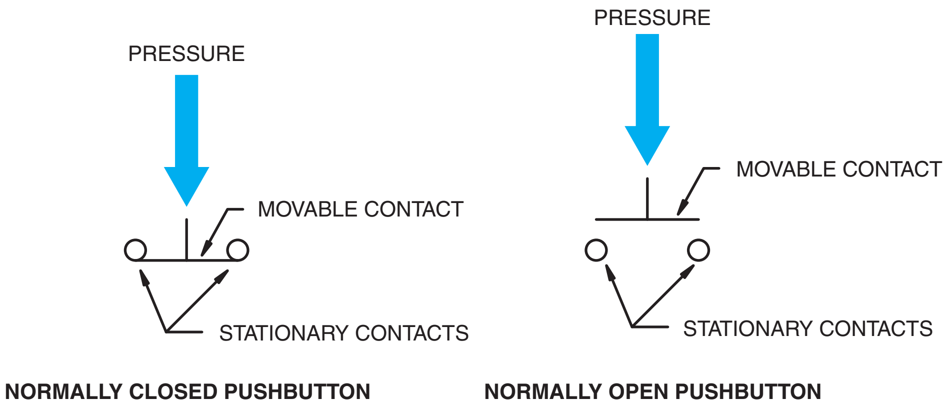


**Figure 9–5** Common pushbutton symbols. (Source: Delmar/Cengage Learning)

Most of the following symbols are approved by the **National Electrical Manufacturers Association (NEMA)**:

1. Normally closed push button. Generally used to represent a stop button.

2. Normally open push button. Generally used to represent a start button.

3. Double-acting push button. Contains both normally closed and normally open contacts on one push button.

4. Double-acting push button drawn differently but meaning the same as number 3.

5. Double-acting push button. The dashed line indicates mechanical connection. This means that when one button is pushed, the other moves at the same time.

6. Single-pole single-throw switch (SPST).

7. Single-pole double-throw switch (SPDT). Notice this switch has only one pole, the switch arm, but it has two stationary contacts. In the diagram, the switch arm makes contact with the upper stationary contact. When the switch is thrown, contact will be made between the switch arm and the lower stationary contact. The switch arm or pole of the switch is generally referred to as the common because it can make contact to either of the two stationary contacts.

8. Double-pole single-throw switch (DPST). Notice the dashed line, which indicates mechanical connection between the two switch arms.

9. Double-pole double-throw switch (DPDT).

10. Off-Automatic-Manual control switch. This switch is basically a single-pole double-throw that has a center off position.

11. Normally open relay contact.

12. Normally closed relay contact.

13. Fuse

14. Fuse


15. Transformer


16. Coil


17. Coil (Generally used to represent the coil of a relay or motor starter in a control schematic.)


18. Pilot light or lamp


19. Lamp or light bulb


20. Thermal heater element


21. Thermal heater element. (Generally used to represent the overload heater element in a motor control circuit.)


22. Solenoid coil


23. Fixed resistor


24. Variable resistor


25. Variable resistor


26. Single-pole circuit breaker


27. Double-pole circuit breaker


28. Capacitor


29. Normally closed float switch


30. Normally open float switch


31. Normally closed pressure switch


32. Normally open pressure switch


33. Normally closed temperature switch. (Normally closed thermostat)


34. Normally open temperature switch.


35. Normally closed flow switch. This symbol is used to represent both liquid- and air-sensing flow switches.


36. Normally open flow switch.


37. Normally closed limit switch.


38. Normally open limit switch.


39. Normally closed ON-DELAY timer contact. Often shown on schematics as DOE, which stands for Delay On Energize.


40. Normally open ON-DELAY timer contact.


41. Normally closed OFF-DELAY timer contact. Often shown on schematics as DODE, which stands for Delay on De-Energize.


42. Normally open OFF-DELAY timer contact


43. Battery


44. Electrical ground


45. Mechanical ground


46. Wires crossing without connection


47. Wires crossing without connection


48. Wires connecting. The dot in the center of the cross is known as a **node**. This is used to indicate connection.


49. Rotary switch

**Figure 9–6**
Normally closed pressure switch. (Source: Delmar/Cengage Learning)

**Figure 9–7**
Normally closed held-open pressure switch. (Source: Delmar/Cengage Learning)

**Figure 9–8**
Normally open pressure switch. (Source: Delmar/Cengage Learning)

**Figure 9–9**
Normally open held-closed pressure switch. (Source: Delmar/Cengage Learning)

The contact symbols shown are standard and relatively simple to understand. There can be instances, however, in which symbols can be used to show something that is not apparent. For example, the symbol for a normally closed pressure switch is shown in Figure 9–6. Notice that this symbol not only shows the movable arm making contact with the stationary contact, but it also shows the movable arm drawn above the stationary contact. In Figure 9–7, the contact arm is shown not making connection with the stationary contact. This symbol, however, is not a normally open contact symbol because the contact arm is drawn above the stationary contact. This symbol indicates a normally closed held-open pressure switch. This symbol is indicating that the switch is actually connected as a normally closed switch, but pressure is used to keep the contact open. If pressure decreases to a certain point, the switch contact will close.

Figure 9–8 shows a normally open pressure switch. Notice that the contact arm is drawn below the stationary contact. Figure 9–9 shows the same symbol except that the movable arm is making connection with the stationary contact. This symbol represents a normally open held-closed pressure switch. This switch symbol indicates that the pressure switch is wired normally open, but pressure holds the contact closed. If the pressure decreases to a certain level, the switch will open and break connection to the rest of the circuit.

## SCHEMATIC DIAGRAMS

Schematic diagrams *show components in their electrical sequence without regard for physical location.* Schematic diagrams are used to troubleshoot and install control circuits. Schematics are generally easier to read and understand than wiring diagrams.

## WIRING DIAGRAMS

Wiring diagrams *show components mounted in their general location with connecting wires.* A wiring diagram is used to represent how the circuit generally appears. To help illustrate the differences between wiring diagrams and schematics, a basic control circuit will first be explained as a schematic and then shown as a wiring diagram.

## READING SCHEMATIC DIAGRAMS

To read a schematic diagram, a few rules must first be learned. Commit the following rules to memory:

1. Reading a schematic diagram is similar to reading a book. It is read from left to right and from top to bottom.
2. Electrical symbols are always shown in their off or deenergized position.
3. Relay contact symbols are shown with the same numbers or letters that are used to designate the relay coil. All contact symbols that have the same number or letter as a coil are controlled by that coil regardless of where in the circuit they are located.
4. When a relay is energized, or turned on, all of its contacts change position. If a contact is shown as normally open, it will close when the coil is energized. If the contact is shown normally closed, it will open when the coil is turned on.
5. There must be a complete circuit before current can flow through a component.
6. Components used to provide a function of stop are generally wired normally closed and connected in series. Figure 9–10 illustrates this concept. Both switches A and B are normally closed and connected in series. If either switch is opened, connection to the lamp will be broken and current will stop flowing in the circuit.
7. Components used to provide the function of start are generally wired normally open and connected in parallel. In Figure 9–11, switches A and B are normally open and connected in parallel with each other. If either switch is closed, a current path will be provided for the lamp and it will turn on.

## DASHED LINES

Often the service technician must be able to determine what dashed lines indicate. Schematic diagrams often contain dashed lines.

In the schematic diagram shown in Figure 9–12, dashed lines indicate several different conditions.

1. Mechanical connection between two components such as those shown in electrical symbols 5, 8, and 9. Each of these symbols show a dashed line connected between different components. The dashed line indicates that when one component is changed the other one is changed, at the same time. The double-acting push buttons illustrated in number 5 will both operate when one of them is pushed.

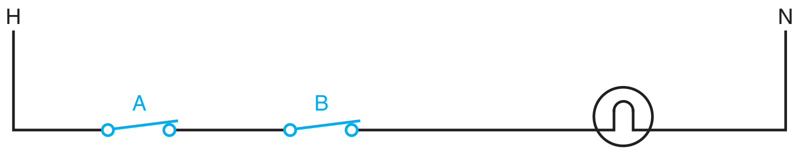


**Figure 9–10** Components used to perform the function of stop are normally closed and connected in series.
(Source: Delmar/Cengage Learning)

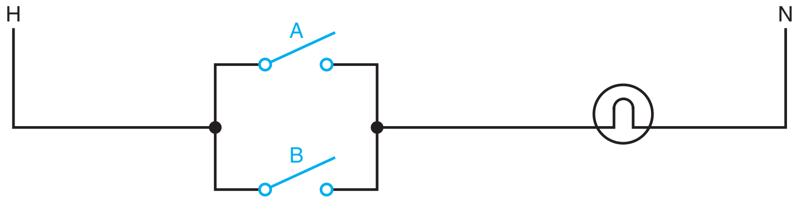


**Figure 9–11** Components used to perform the function of start are normally open and connected in parallel.
(Source: Delmar/Cengage Learning)

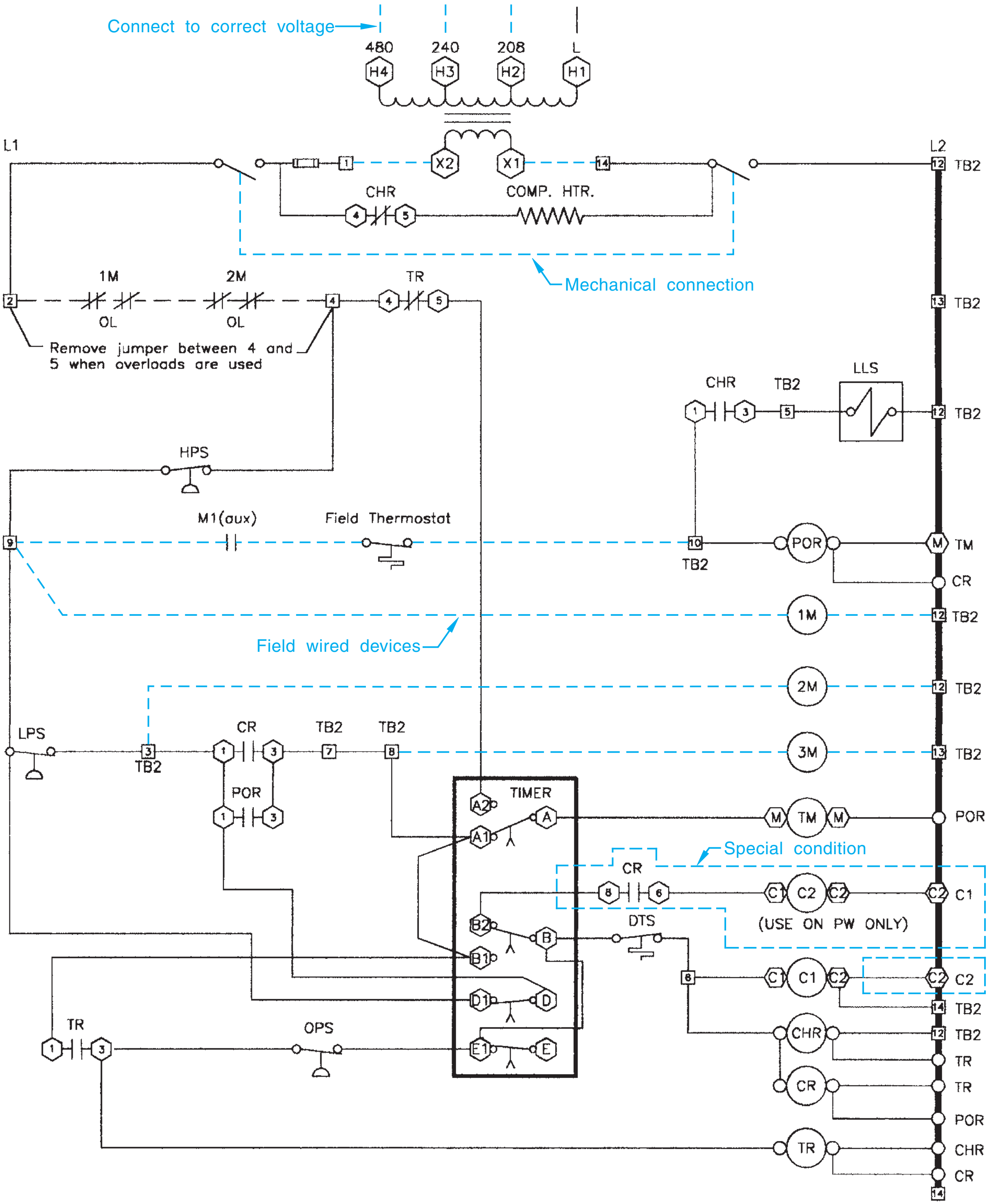


Figure 9–12
Dashed lines can represent different conditions. (Drawing courtesy of Carrier Corp.).

2. Field wired or installed components.
3. Components used only in special circumstances.
4. Factory wired or installed components.

At the top of the diagram, dashed lines indicate that only one set of the primary terminals is to be connected depending on the amount of input voltage. An input voltage of 480 volts, for example, would have one line connected to the H1 terminal and the other to the H4 terminal. An input voltage of 208 volts would have one line connected to the H1 terminal and the other connected to the H2 terminal.

Another dashed line connected between two switches indicates that these two switches are mechanically connected. In reality, this would be a double-pole single-throw switch, Figure 9–13. The dashed line indicates that when one switch is opened or closed, the other one is opened or closed also.

Several components, such as 1M, 2M, and 3M are connected with dashed lines. The dashed lines in this instance indicates that these devices are field wired and not part of the assembled unit. Wiring to these devices is connected during the installation of the equipment. It should be noted that some diagrams will use dashed lines to indicate factory-installed wiring, and solid lines illustrate field-connected devices. There is no hard rule. It is generally necessary for the service person to determine the meaning of the lines on a particular schematic.

Another set of components shown in Figure 9–12 is surrounded by dashed lines. These dashed lines mark components that are used under special circumstances. Contactor coil, C2, and contact CR are installed only if the compressor motor utilizes part winding starting. If the motor does not employ part winding starting, these components will not be present.

## EXAMPLE

The first circuit to be discussed is a basic control circuit used throughout industry. Figure 9–14 shows a start-stop push button circuit. This schematic shows both the control circuit and the motor circuit. Schematic diagrams do not always show both control and motor connections. Many schematic diagrams show only the control circuit.

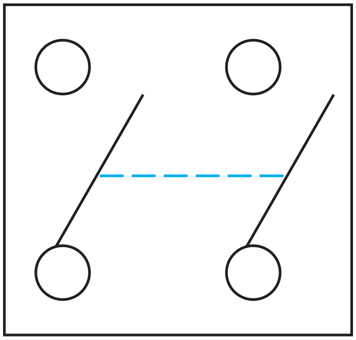

**Figure 9–13**
Double-pole single-throw switch. (Source: Delmar/Cengage Learning)

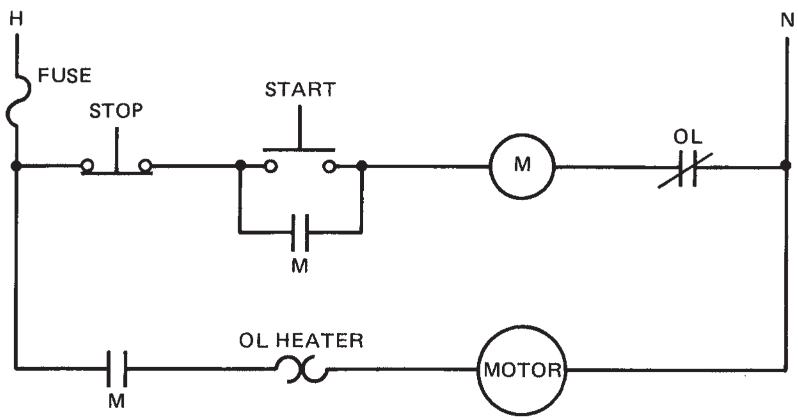


**Figure 9–14**
Start-stop pushbutton control circuit.
(Source: Delmar/Cengage Learning)

Notice in this schematic that there is no complete circuit to M motor starter coil because of the open start push button and open M auxiliary contacts. There is also no connection to the motor because of the open-M load contacts. The open-M contacts connected in parallel with the start button are small contacts intended to be used as part of the control circuit. This set of contacts is generally referred to as the holding, sealing, or maintaining contacts. These contacts are used to provide a continued circuit to the M coil when the start button is released.

The second set of M contacts is connected in series with the overload heater element and the motor, and are known as **load** contacts. These contacts are large and designed to carry the current needed to operate the load. Notice that these contacts are normally open and there is no current path to the motor.

When the start button is pushed, a path for current flow is provided to the M-motor starter coil. When the M coil energizes, both M contacts close, Figure 9–15. The small auxiliary contact provides a continued current path to the motor starter coil when the start button is released and returns to its open position. The large M load contact closes and provides a complete circuit to the motor and the motor begins to run. The motor will continue to operate in this manner as long as the M coil remains energized.

If the stop button is pushed, Figure 9–16, the current path to the M coil is broken and the coil de-energizes. This causes both M contacts to return to their normally open position. When M holding contacts open, there is no longer a complete circuit provided to the coil when the stop button is returned to its normal position. The circuit remains in the off position until the start button is again pushed.

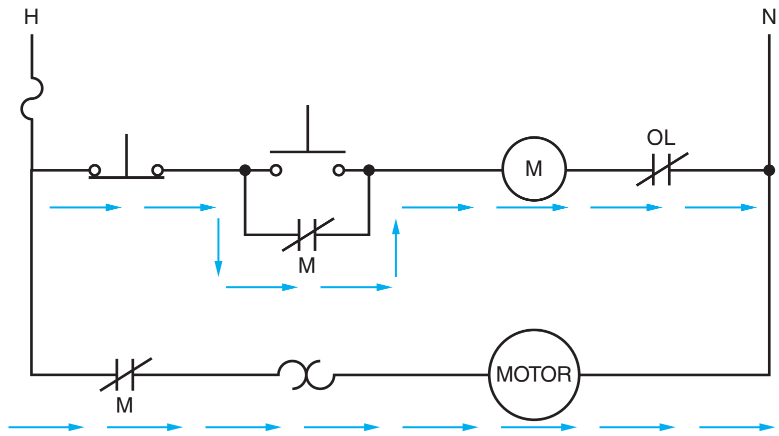


**Figure 9–15**
Current path through the circuit.
(Source: Delmar/Cengage Learning)

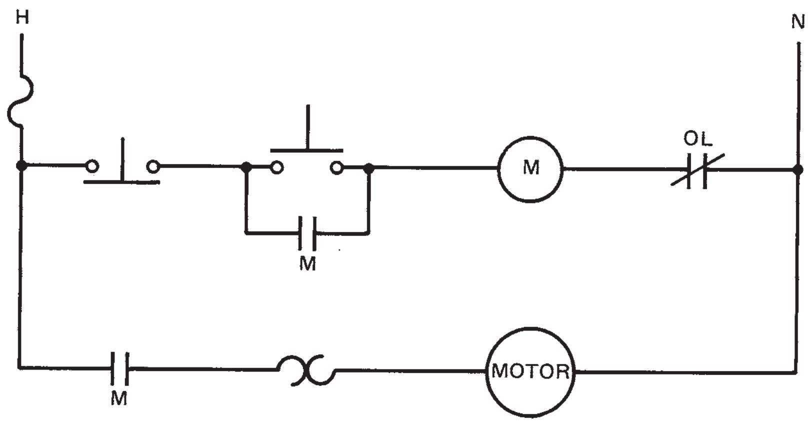


**Figure 9–16**
The stop button breaks the circuit.
(Source: Delmar/Cengage Learning)

Notice that the overload contact is connected in series with the motor starter coil. If the overload contact should open, it has the same effect as pressing the stop button. The fuse is connected in series with both the control circuit and the motor. If the fuse should open, it has the effect of disconnecting power from the line.

A wiring diagram for the start-stop pushbutton circuit is shown in Figure 9–17. Although this diagram looks completely different, it is electrically the same as the schematic diagram. Notice the push button symbols indicate double-acting push buttons. The stop button, however, uses only the normally closed section and the start button uses only the normally open section. The motor starter shows three load contacts and two auxiliary contacts. One auxiliary contact is open and one is closed. Notice that only the open contact has been used.

The overload unit shows two different sections. One section contains the thermal heater element connected in series with the motor, and the normally closed contact is connected in series with the coil of the M-motor starter.

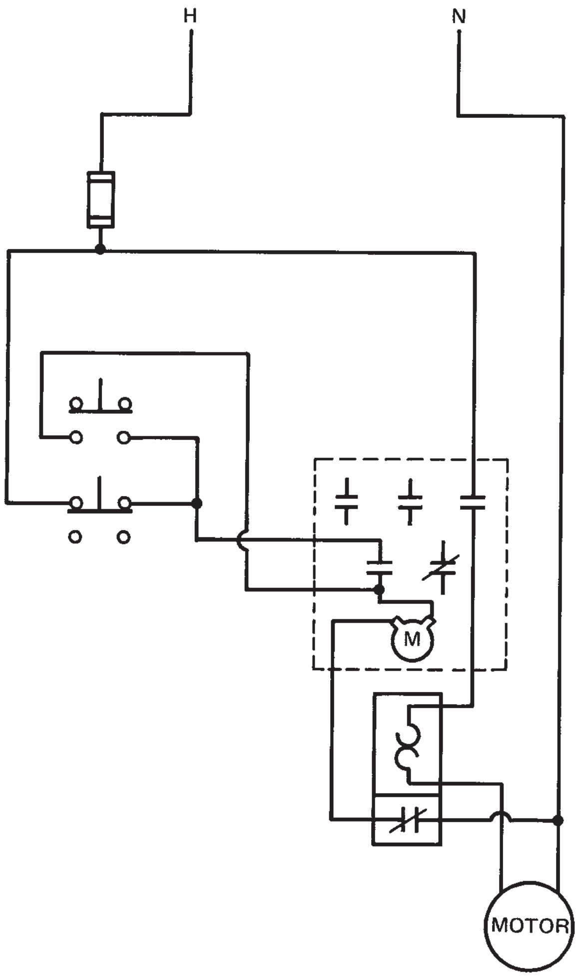


**Figure 9–17**
Wiring diagram of start-stop pushbutton control circuit.
(Source: Delmar/Cengage Learning)

## EXAMPLE

The circuit shown in Figure 9–18 controls the operation of an oil-fired boiler. A high pressure pump motor is used to inject fuel oil into a combustion chamber where it is burned. A blower motor is used to supply combustion air to the chamber. The circuit will not permit fuel oil to be injected into the chamber unless the blower motor is operating. The circuit also permits the blower motor to continue operation for a period of one minute after the thermostat is satisfied. This permits any residual smoke or fumes to be removed from the combustion chamber.

The first step in understanding the operation of the circuit is to examine the components and determine what they control. The thermostat is a normally closed held open switch. It is normally closed because the movable contact is drawn above the stationary contact. The movable contact is not making connection to the stationary contact, however. This indicates that the contact is being held open. The thermal symbol indicates that the contact is controlled by temperature. The thermal symbol represents a bimetal helix. An increase in temperature causes the helix to expand and push upward on the contact. A decrease in temperature causes the helix to contract. If the helix contracts enough, the movable contact will make connection with the stationary contact and close the switch. This thermostat symbol indicates that an increase of temperature will open the switch and a decrease of temperature will close the switch. This is the normal operation of a heating thermostat.

The high temperature switch is a thermally activated switch also. The switch is shown normally closed. If the temperature should increase high enough, the switch will open and break connection to the high pressure pump motor relay and time delay relay.

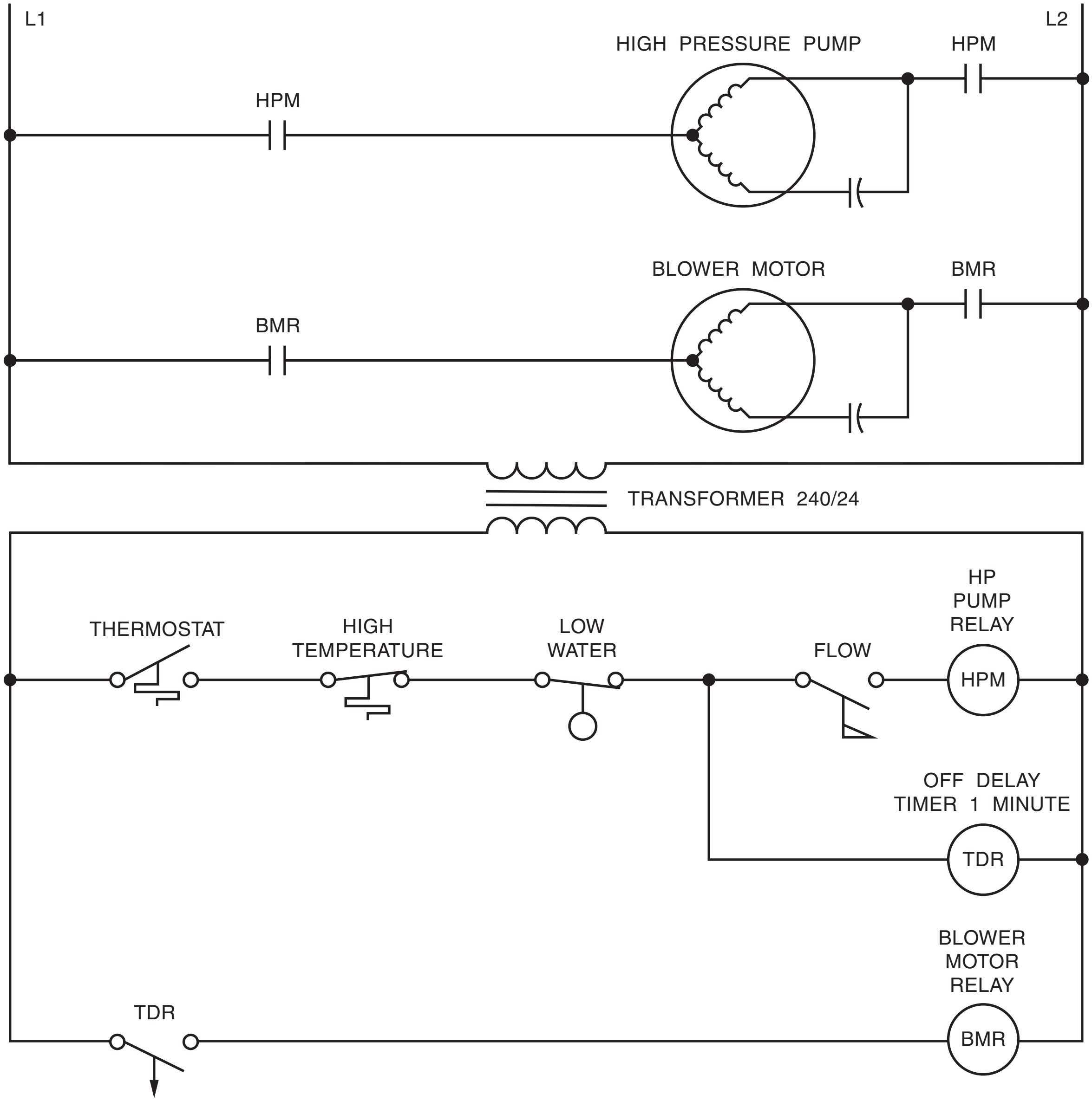


**Figure 9–18**
Boiler control circuit. (Source: Delmar/Cengage Learning)

The low water switch is a normally open held closed switch. The switch is normally open because the movable contact is drawn below the stationary contact. Because the movable contact is touching the station contact it is being held closed. This switch is drawn to indicate that a drop in liquid level will cause the switch contacts to open and break the circuit to the high pressure pump motor relay and time delay relay. One of the most dangerous conditions for a boiler is a low water level. If the water level should drop below a preset point, the switch will open.

The flow switch is normally open. A flow of air causes the switch contacts to close. The flow switch is used to insure that there is a flow of combustion air into the combustion chamber before fuel oil is injected into the chamber.

The time delay contact (TDR) is connected in series with the blower motor relay coil. The symbol indicates that the timer is an off delay timer. The arrow always points in the direction the contacts will move after the delay period. The arrow indicates that the contacts will delay reopening after they have changed position.

## CIRCUIT OPERATION

When the thermostat contact closes, a circuit is completed through the closed high temperature switch, low water switch, and coil of the time delay relay. Since the timer is an off delay timer, TDR contacts close immediately and energize the blower motor relay, Figure 9–19. This causes the BMR

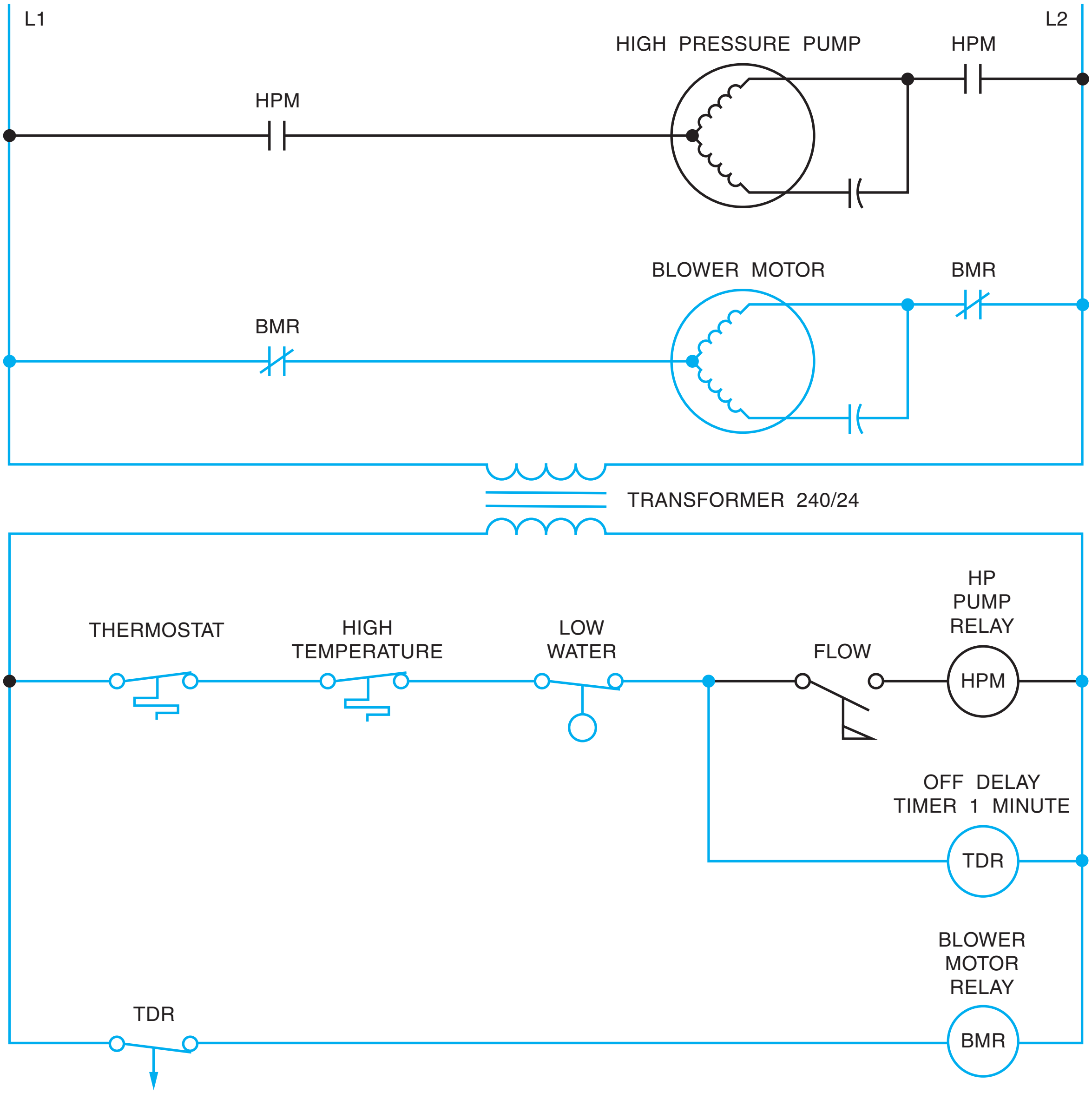


**Figure 9–19**
The thermostat contacts close. (Source: Delmar/Cengage Learning)

contacts to close and connect the blower motor to the power line.

The air flow produced by the blower motor causes the flow switch to close and energize the coil of the high pressure pump motor relay, Figure 9–20. This causes the HPM contacts to close and connect the high pressure pump to the line. The circuit is now in full operation. The circuit will continue to operate in this manner until the thermostat contacts reopen, Figure 9–21. When the thermostat contacts reopen, power is disconnected from the high pressure pump motor relay and the time delay relay. Because the

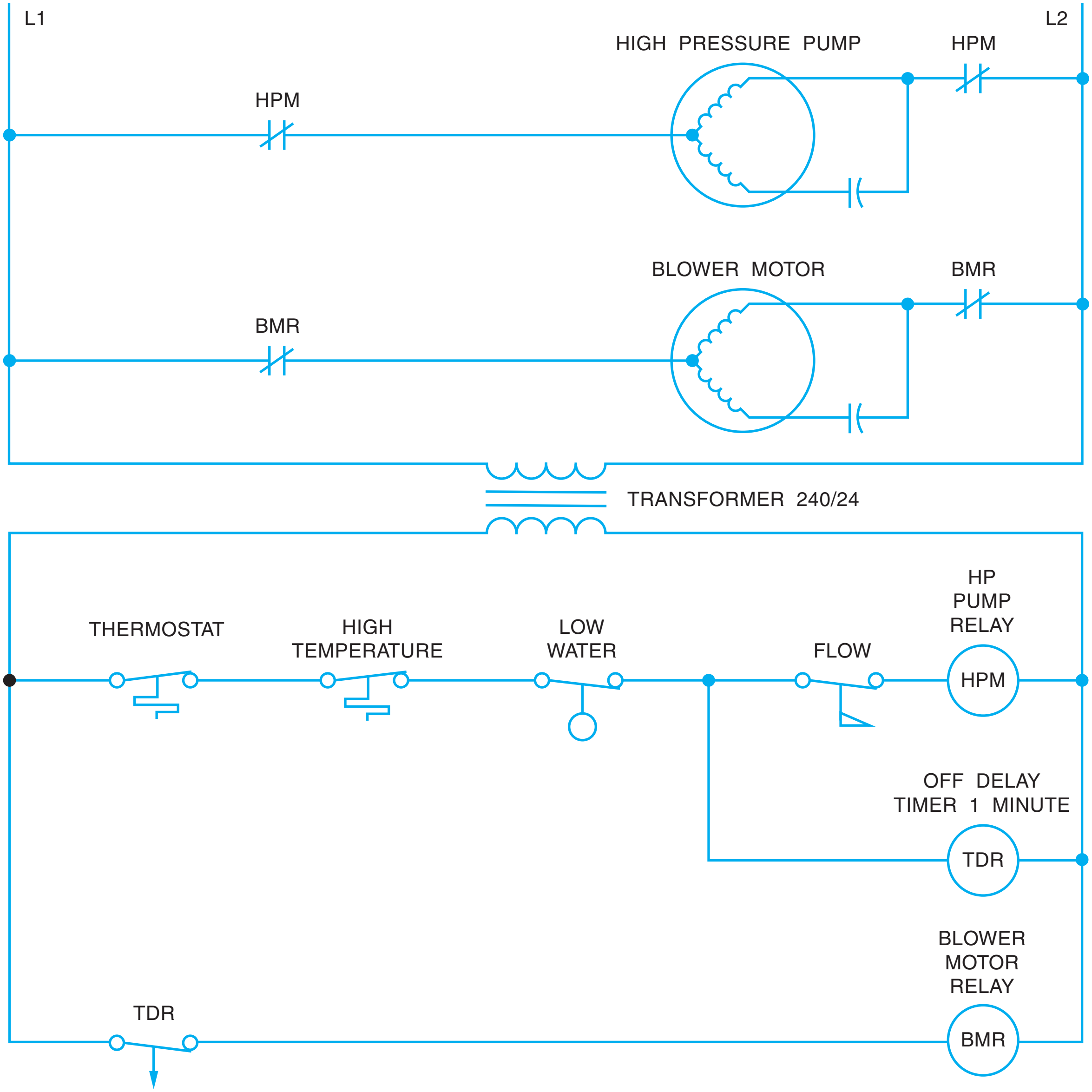


**Figure 9–20**
The circuit is in full operation. (Source: Delmar/Cengage Learning)

time delay relay is an off delay timer, it does not start timing until the coil is deenergized. The TDR contacts will remain closed for a period of 1 minute before reopening. This permits the blower motor to remove any smoke and fumes from the combustion chamber. When the TDR contacts open, the circuit is back in its original state as shown in Figure 9–18. If the high temperature switch or low water switch should open, it would have the same effect as opening the thermostat.

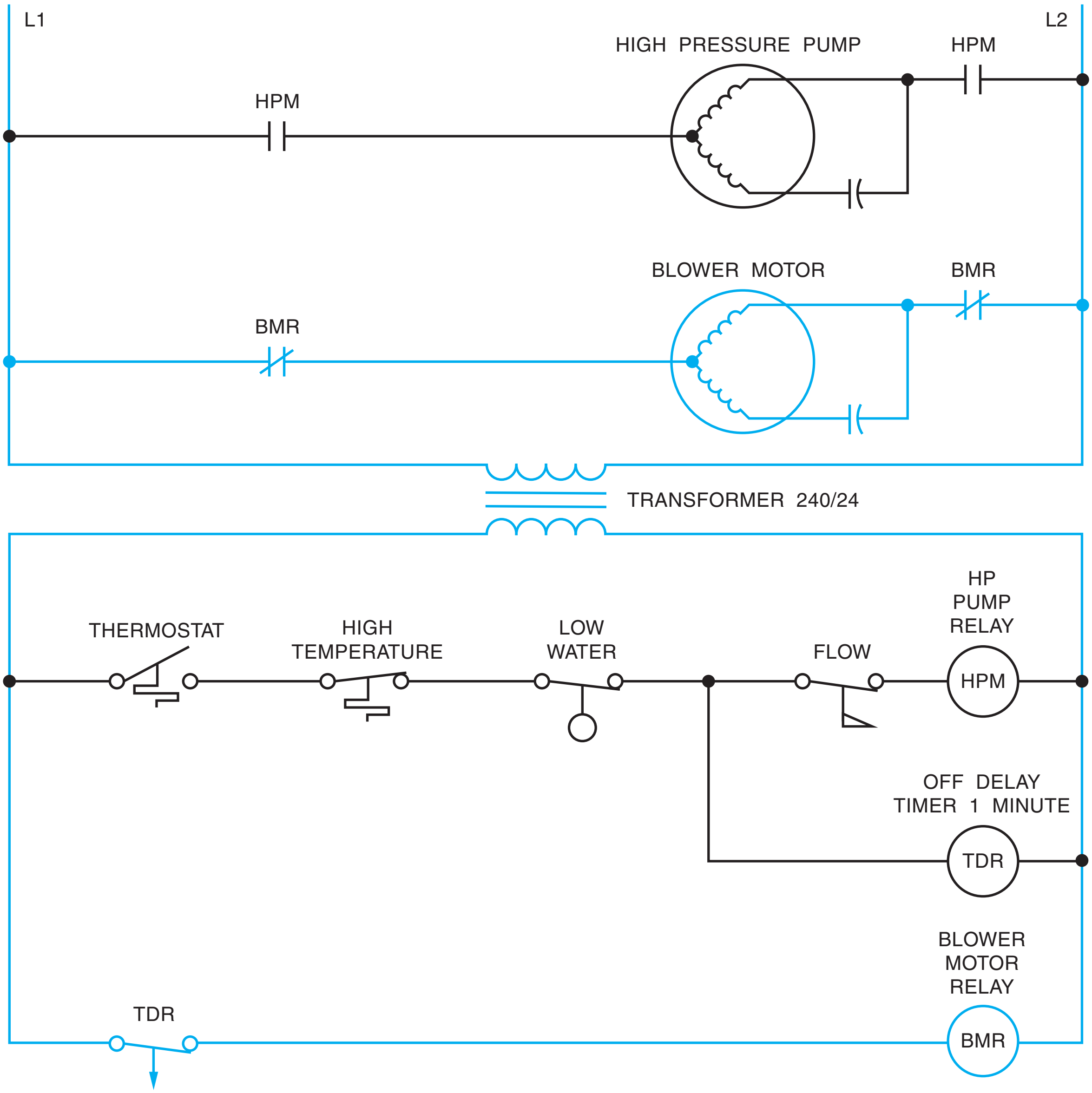


**Figure 9–21**
The thermostat contacts open. (Source: Delmar/Cengage Learning)

## SUMMARY

- Schematics and wiring diagrams are the written language of control systems.
- Motor control symbols are generally drawn to pictorially represent their function.
- The way a motor control symbol is drawn indicates how it is to be connected in a circuit.
- Schematic diagrams show components in their electrical sequence without regard for physical location.
- Wiring diagrams show a pictorial representation of the circuit with connecting wires.
- Schematics and wiring diagrams always show the circuit in its deenergized or off position.

## KEY TERMS

**load**
**movable contact**
**National Electrical Manufacturers Association (NEMA)**
**node**
**normally closed**
**normally open**
**schematics**
**stationary contact**
**three-wire control circuits**
**two-wire control circuit**
**wiring diagrams**

## REVIEW QUESTIONS

1. What are the two basic types of motor controls?
2. Define a schematic diagram.
3. Define a wiring diagram.
4. Components used for the function of stop are generally wired ________________ and connected in ________________.
5. Components used for the function of start are generally wired ________________ and connected in ________________.
6. When reading a schematic diagram, are the components shown in their energized or deenergized position?
7. What does this symbol represent?

8. What does this symbol represent?

9. What does a dashed line drawn between components represent?

10. What is an auxiliary contact?
11. Make a schematic drawing of a cooling thermostat that turns on the coil of a contactor. Label the contactor CC, which stands for compressor contactor. Make sure that the circuit is drawn so that an increase in temperature will cause the contact to close.
12. Draw a schematic that controls the operation of a sump pump. A float switch is used to turn the pump on when the water rises to a high enough level. It is assumed that the float switch has contacts rated high enough to control the motor without the use of a relay.
13. Draw a schematic diagram for a low water level alarm. A float switch is used to detect the level of water in a tank. If it should fall below a predetermined level, a warning light will come on and an alarm will sound.
14. Draw a circuit for a low pressure cutoff switch. If the pressure falls below a certain level, it will cause a contactor coil to be disconnected. Label the contactor CC.
15. Add a thermal switch to the circuit in question 14. The switch is to be installed so that a rise in temperature will disconnect the contactor coil.

# UNIT 10

# Developing Wiring Diagrams

## OBJECTIVES

After studying this unit the student should be able to:

- Discuss the operation of an electric circuit by interpreting a schematic diagram
- Place wire numbers on a schematic diagram and develop a wiring diagram from the schematic

In this unit, two schematic diagrams are discussed, including their operation and development into wiring diagrams. Developing a wiring diagram from a schematic is the same basic procedure that is followed when installing a control system. Understanding this process is also a great advantage when troubleshooting existing circuits.

## DEVELOPING CIRCUIT 1

The first circuit discussed is shown in Figure 10–1. In this circuit, a fan motor is controlled by relay **FR (fan relay)**. The circuit is so designed that a switch can be used to turn the circuit completely off, operate the fan manually, or permit the fan to be operated by a thermostat. If the control switch is moved to the “MAN” position as shown in Figure 10–2, a complete circuit is provided to the

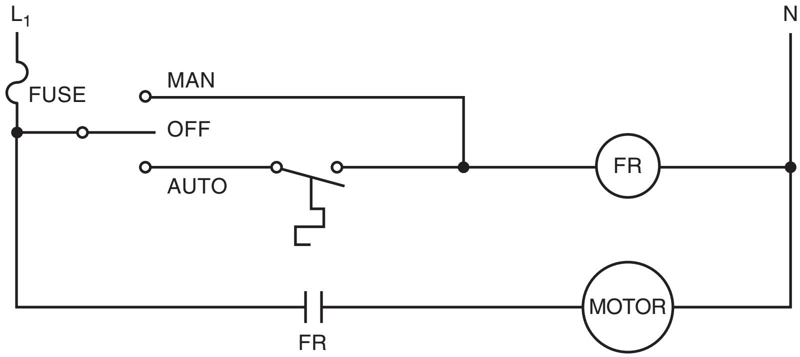


**Figure 10–1**
Fan control circuit. (Source: Delmar/Cengage Learning)

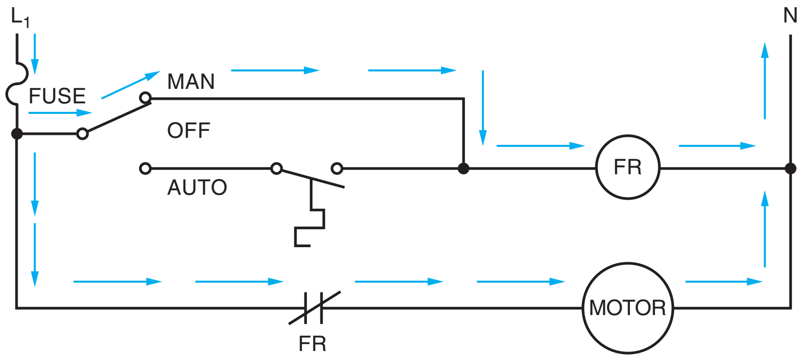


**Figure 10–2**
Fan relay coil is energized by control switch. (Source: Delmar/Cengage Learning)

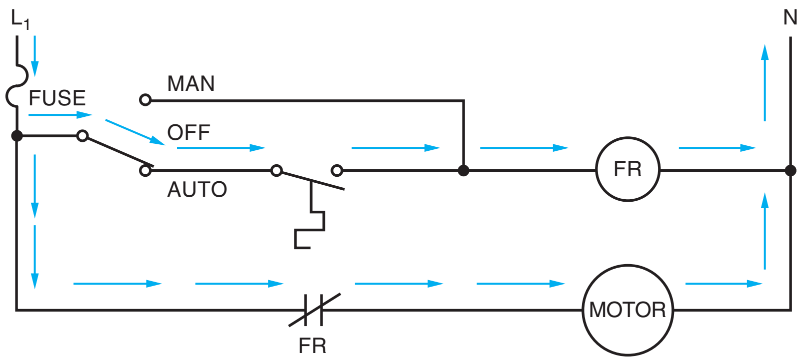


**Figure 10–3**
Fan relay is controlled by the thermostat. (Source: Delmar/Cengage Learning)

fan relay coil. Then the relay energizes, FR contact closes and connects the motor to the line. This setting permits the fan to be operated at any time, regardless of the condition of the thermostat.

If the control switch is moved to the "AUTO" position as shown in Figure 10–3, the fan will be controlled by the action of the thermostat. When the temperature increases to a predetermined level, the thermostat contact will close. This completes a circuit to FR coil. When FR coil energizes, the FR contact closes and connects the fan motor to the line. When the temperature decreases sufficiently, the thermostat contact opens and breaks the circuit to FR coil. When FR coil deenergizes, FR contact opens and disconnects the motor from the line.

This schematic will now be developed into a wiring diagram. To aid in the connection of this circuit, a simple numbering system will be used. To use

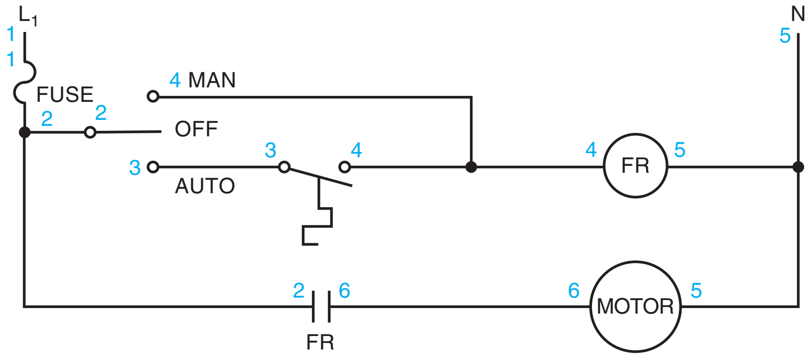


**Figure 10–4** Schematic is numbered to aid in connection of the circuit. (Source: Delmar/Cengage Learning)

this numbering system, the following rules will be followed:

1. All components connected to the same line will receive the same number.
2. Any time a component is gone through, the number will change.
3. A set of numbers can be used only once.

Figure 10–4 shows the numbers placed on the schematic. Notice that a 1 is placed at the incoming power line and a 1 is also placed at one side of the fuse. Because the fuse is a component, the number must change on the other side of it. Therefore, the fuse has a 2 on the other side. There is also a 2 placed beside the common terminal of the OFF-MANUAL-AUTOMATIC switch, and a 2 placed beside one side of FR contact. Notice that all of these components have the same number because there is no break between them.

The AUTO side of the switch has been numbered 3, and one side of the thermostat has also been numbered 3. The other side of the thermostat is numbered 4, the MAN side of the switch is number 4, and one side of FR coil is numbered 4. The other side of the coil has been numbered 5, the neutral line is numbered 5, and one side of the motor is numbered 5. The other side of the motor is numbered 6, and the other side of FR contact is numbered 6.

Notice that all the points that are electrically connected together have the same number. Notice also that no set of numbers was used more than once.

The components of the system are shown in Figure 10–5. Notice that numbers have been placed beside certain components. These numbers

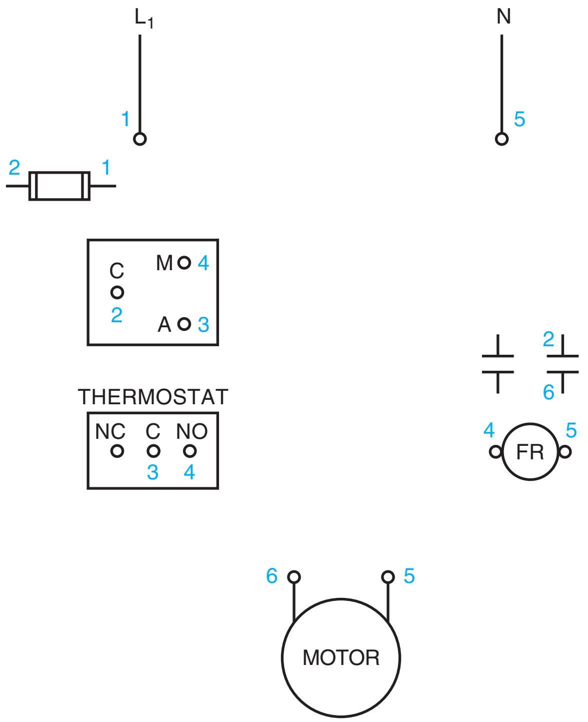


**Figure 10–5** Circuit components are numbered with the same numbers that appear on the schematic. (Source: Delmar/Cengage Learning)

correspond to the numbers in the schematic. For example, the fuse in the schematic is shown with a 1 on one side and a 2 on the other side. The fuse in the wiring diagram is shown with a 1 on one side and a 2 on the other side. Notice the OFF-MANUAL-AUTOMATIC switch shown on the schematic. The common terminal is numbered 2, the

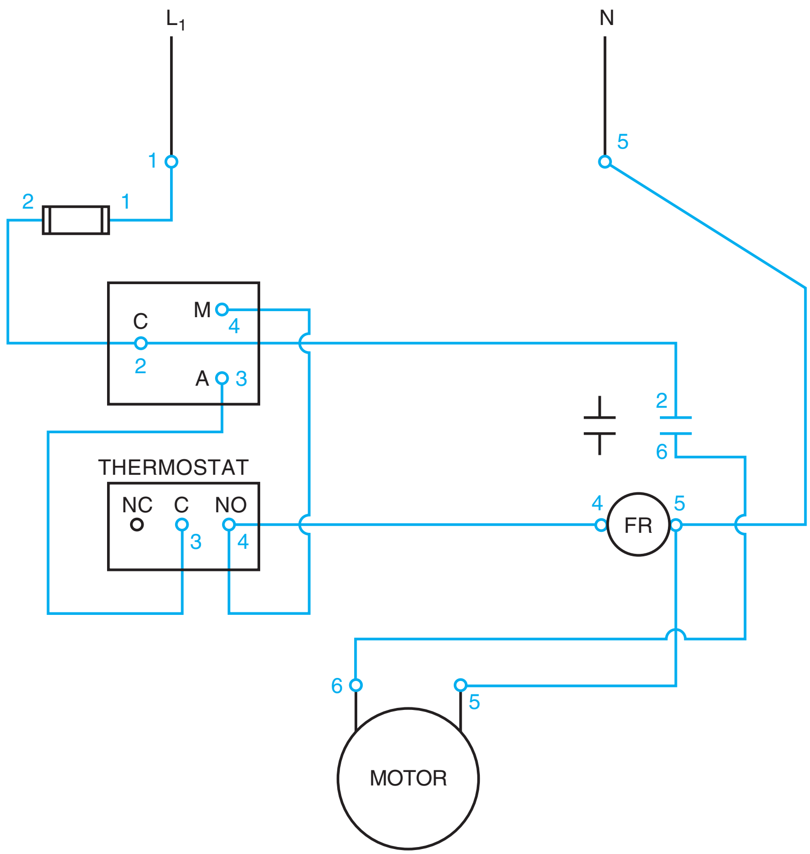


**Figure 10–6**
Like numbers are connected.
(Source: Delmar/Cengage Learning)

MAN terminal is numbered 4, and the AUTO terminal is numbered 3. Now notice the same switch on the wiring diagram. The common terminal is numbered 2, the MAN terminal is numbered 4, and the AUTO terminal is numbered 3. The thermostat in the schematic has been numbered 3 on one terminal and 4 on the other terminal. The thermostat shown in the wiring diagram has three terminals. One terminal is common, one terminal is marked NC, and the other terminal is marked NO. This is a common arrangement for many control components. This shows that the thermostat is a single-pole double-throw switch. Because the thermostat shown in the schematic is normally open, the 3 will be placed beside the common terminal, and the 4 will be placed beside the NO contact. Notice that one of the contacts on FR relay is numbered 2 on one side and 6 on the other side. FR coil is numbered 4 on one side and 5 on the other. One motor terminal is numbered 5 and the other is numbered 6.

Now that the component parts have been numbered with the same numbers as those used on the schematic, connection can be made easily and quickly. To connect the circuit, connect all the like numbers. For example, all the number 1s will connect together, all the number 2s will connect together, and so forth. The connected circuit is shown in Figure 10–6.

## DEVELOPMENT OF CIRCUIT 2

The schematic diagram for circuit 2 is shown in Figure 10–7. Notice this schematic shows both the control circuit and the motor connection. This circuit is designed to turn off a compressor if the pressure in the system reaches a predetermined

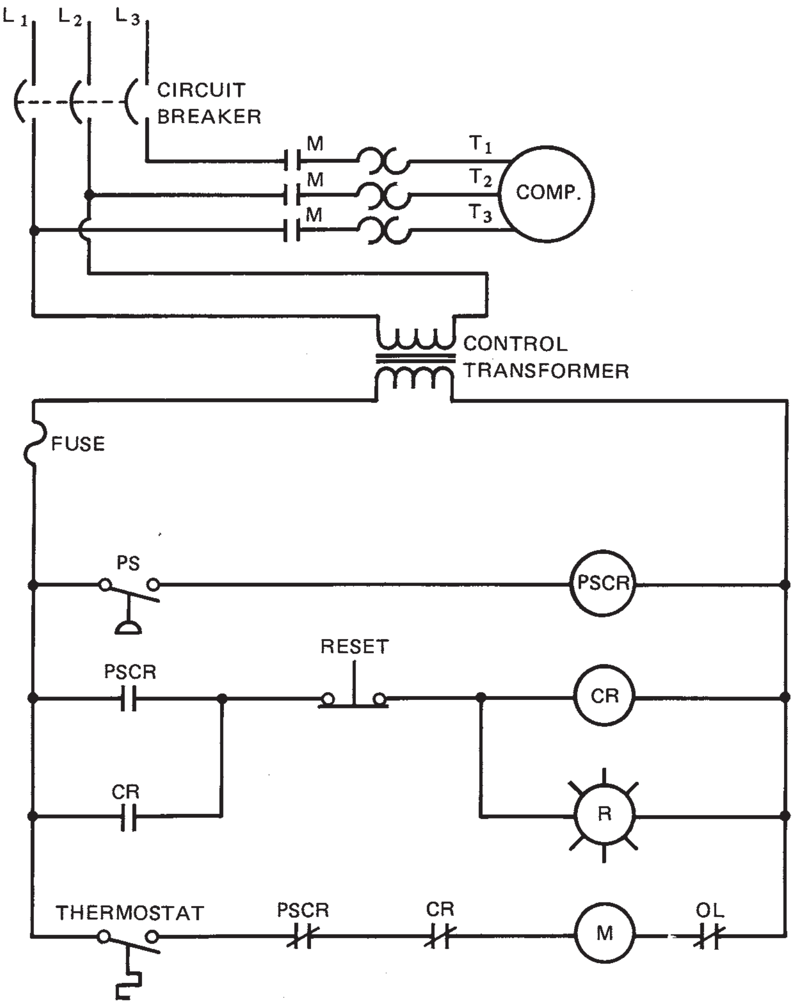


**Figure 10–7** High pressure locks compressor off. (Source: Delmar/Cengage Learning)

level. If the pressure becomes high enough to cause the pressure switch contacts to close, the compressor motor will not only be disconnected from the power line, but a warning light will also be turned on. Once the warning light has been turned on, the system must be manually reset by the service technician before the compressor can be restarted by the thermostat. The operation of the circuit is as follows:

When the thermostat contact closes, a circuit is completed to M motor starter coil. When M coil energizes, M contacts close and connect the compressor to the three-phase power line. When the temperature decreases, the thermostat contacts open and deenergize M coil. When M coil deenergizes, M contacts open and disconnect the compressor from the power line. Notice that in the normal action of this circuit, the compressor is controlled by the thermostat.

Now assume that the thermostat contacts are closed and that the compressor is connected to the power line. Also assume that the pressure in the system becomes too great and that the contacts of the pressure switch close. When the pressure switch contacts close, **PSCR (pressure switch control relay)** coil energizes. This causes both

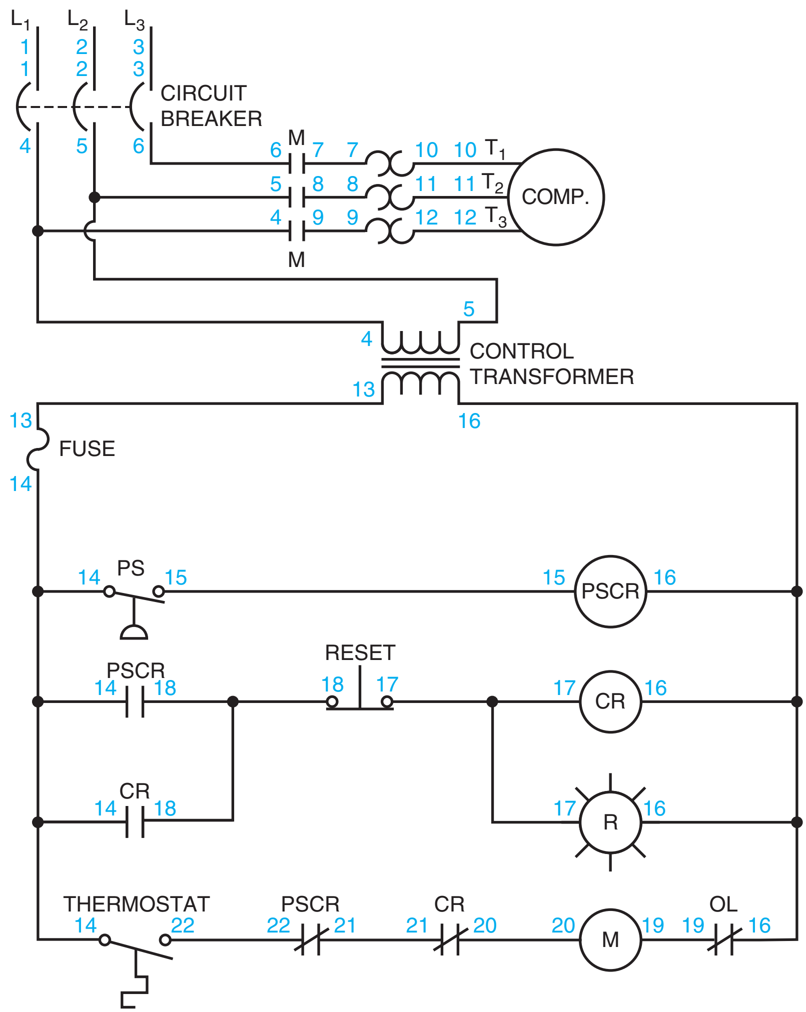


**Figure 10–8**
Schematic is numbered to aid in circuit connection. (Source: Delmar/Cengage Learning)

PSCR contacts to change position. When the normally closed PSCR contact opens, the circuit to M coil is broken. This causes the compressor to be disconnected from the line. When the normally open PSCR contact closes, a circuit is completed to CR (control relay) coil. When CR coil energizes, both CR contacts change position. The normally open CR contact closes to maintain a circuit to CR coil in the event that the pressure in the system decreases and opens the pressure switch contacts. This would cause PSCR relay to deenergize and return both PSCR contacts to their normal position. The normally closed CR contact will open. This prevents M coil from being energized by the thermostat if PSCR contact should reclose. Notice that the warning light is connected in parallel with the coil of CR relay. The warning light will be turned on as long as CR relay coil is turned on. As long as CR relay is energized, the compressor cannot be restarted by the thermostat.

Now assume that the pressure in the system has returned to normal and the problem that caused the excessive pressure has been corrected. When the pressure switch contact reopened, PSCR coil deenergized and reset both PSCR contacts to their normal position. When the service technician presses the reset button, CR coil deenergizes and both CR contacts return to their normal positions.

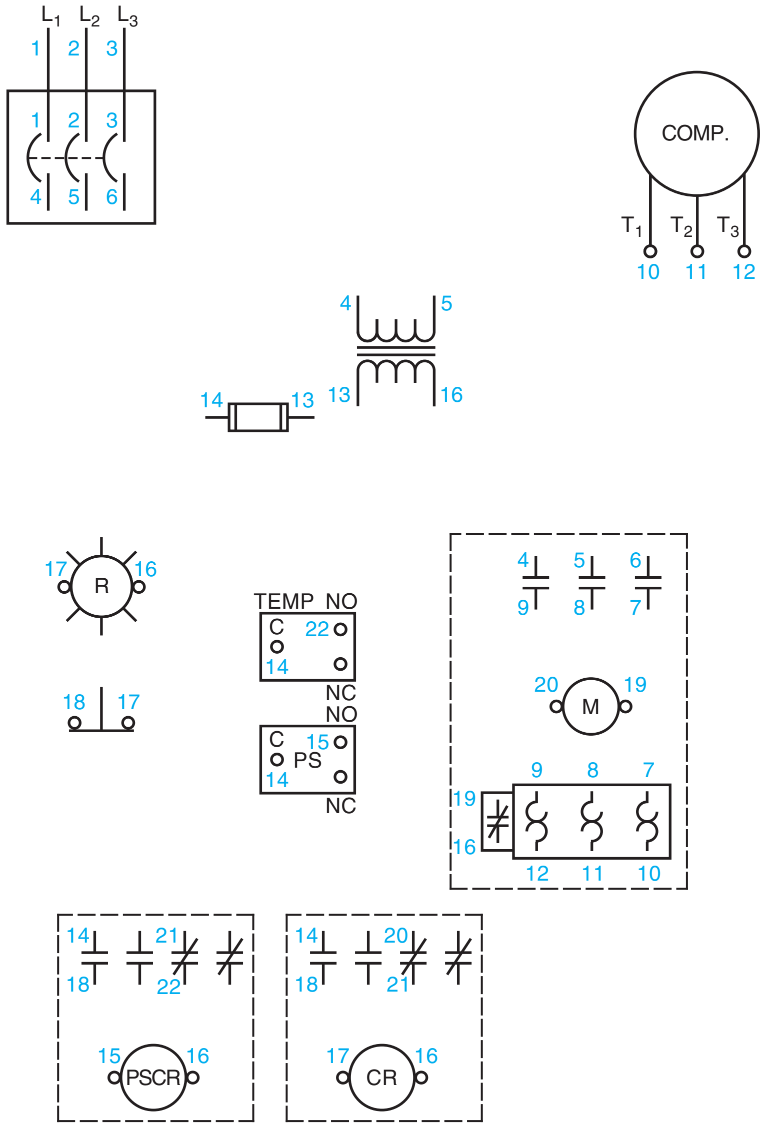


**Figure 10–9**
Components are numbered the same in the schematic. (Source: Delmar/Cengage Learning)

The circuit is now back in its original position and ready for normal operation.

This schematic diagram is now being developed into a wiring diagram. As before, the schematic is numbered in the same manner as the first example. The numbered schematic is shown in Figure 10–8. Notice that all components that are electrically tied together have the same number. Also notice that no number set has been used more than once.

The control components are shown in Figure 10–9. Notice that the numbers on the components correspond with like numbers on the schematic diagram. For example, on the schematic diagram the primary of the control transformer is numbered 4 and 5. The secondary leads are numbered 13 and 16. Notice the same is true on the wiring diagram. Note the number of each component on the schematic and then

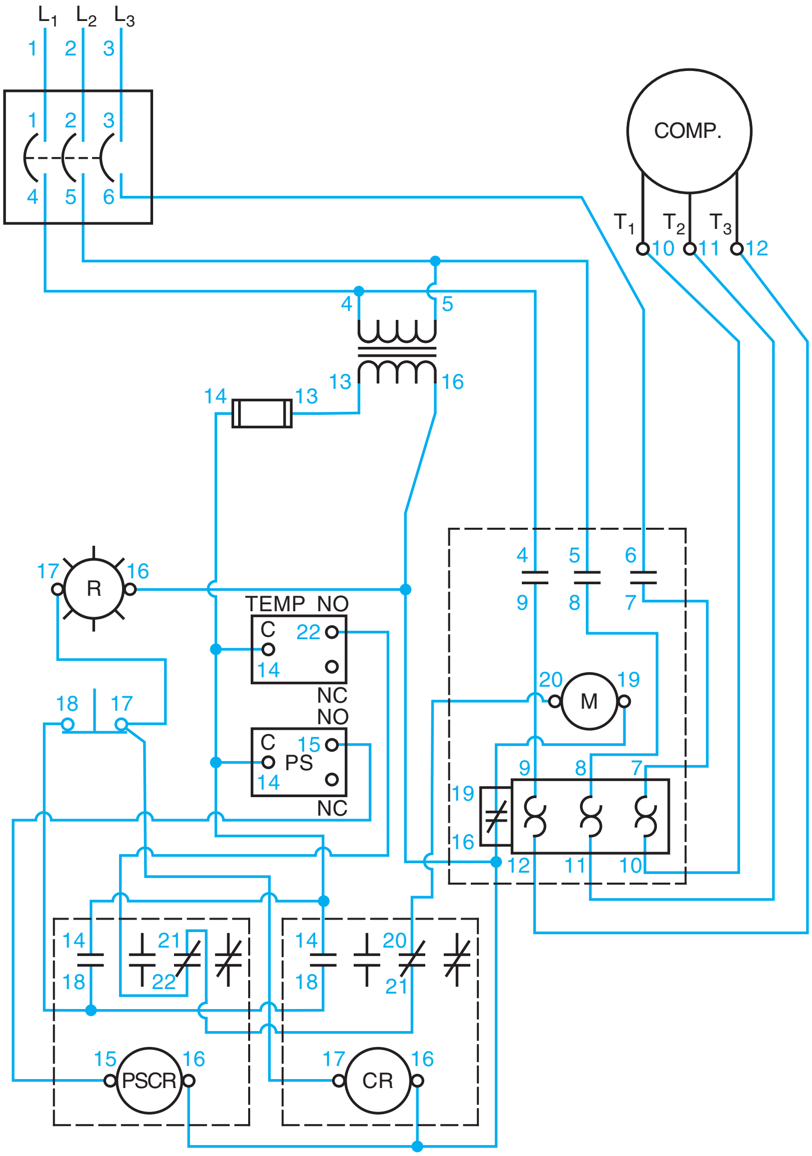


**Figure 10–10** Connection is made by connecting like numbers. (Source: Delmar/Cengage Learning)

find the corresponding number beside the proper component used on the wiring diagram.

Once the components of the wiring diagram have been numbered with the same numbers as those on the schematic, the circuit can be connected by connecting like numbers. The circuit connection is shown in Figure 10–10. Again, notice that the wiring diagram appears to be completely different from the schematic, but both are the same electrically.

## SUMMARY

- Wiring diagrams are generally developed from a schematic diagram.
- All components in a schematic diagram are shown in their deenergized or off position.
- Wire numbers are often placed on schematic diagrams to aid in connecting a wiring diagram.
- Three basic rules for placing wire numbers on a schematic diagram are:
  A. All components connected to the same line will receive the same number.
  B. Any time a component is gone through, the number will change.
  C. A set of numbers can be used only once.

## KEY TERMS

**FR (fan relay)**
**PSCR (pressure switch control relay)**

## REVIEW QUESTIONS

Refer to Figure 10–1 for the following questions.

1. Explain the action of the circuit if the thermostat should fail to operate.
2. Explain the action of the circuit if FR contacts should become shorted together.

Refer to Figure 10–7 for the following questions.

3. Explain the action of the circuit if the overload (OL) contact should open.
4. Explain the action of the circuit if the pressure switch contacts should become shorted.
5. Explain the action of the circuit if the CR coil should open.

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# SECTION 3

# Motors

# UNIT 11

# Split-Phase Motors

## OBJECTIVES

After studying this unit the student should be able to:

- List the basic types of split-phase motors
- Discuss two-phase power
- Discuss the operation of a resistance-start induction run motor
- Discuss the operation of a capacitor-start induction run motor
- Discuss the operation of a permanent-split capacitor motor
- Reverse the direction of rotation of a split-phase motor
- Connect dual voltage motors for 120- or 240-volt operation
- Identify the terminal markings of an oil-filled capacitor and discuss the proper connection to a permanent split-capacitor motor

Because three-phase power is not available to small business and residential locations, the air conditioning equipment for these areas is powered by single-phase electric motors. The single-phase motors used in air conditioning systems are generally one of two types. These are the split-phase and the shaded-pole induction motor.

## SPLIT-PHASE MOTORS

**Split-phase motors** fall into three general classifications. These are:

1. The **resistance-start induction-run motor**,
2. The **capacitor-start induction-run motor**,

3. The **permanent-split capacitor motor (PSC)**. It should be noted that although all permanent-split capacitor motors contain a run capacitor, some are equipped with a separate starting capacitor to improve starting torque. The motors with the separate starting capacitor are often referred to as **capacitor-start capacitor-run motors**.

Although all of these motors have different operating characteristics, they are similar in construction. Split-phase motors get their name from the manner in which they operate. These motors operate on the principle of a *rotating magnetic field*. A rotating magnetic field, however, cannot be produced with only one phase. Split-phase motors literally split single-phase power in order to imitate a two-phase power system. A rotating magnetic field can be produced with two separate phases.

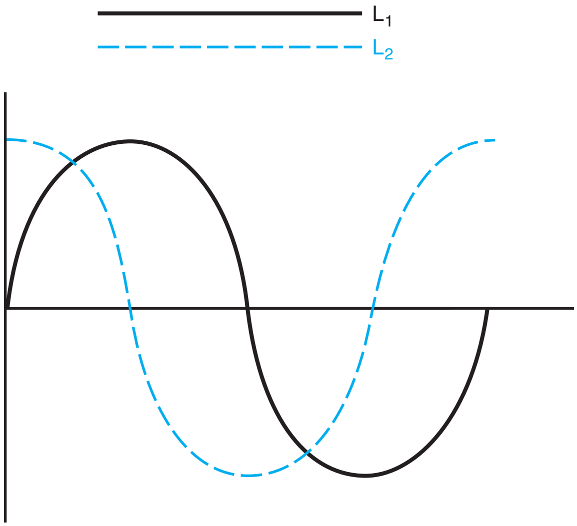



**Figure 11–2**
Two-phase voltages are 90° out of phase with each other. (Source: Delmar/Cengage Learning)

## THE TWO-PHASE SYSTEM

In some parts of the world, **two-phase power** is produced. A two-phase system is produced by having an alternator with two sets of coils wound 90° out of phase with each other, Figure 11–1. The voltages of a two-phase system are, therefore, 90° out of phase with each other, Figure 11–2. The two out-of-phase voltages can be used to produce a rotating magnetic field. Because there have to be two voltages or currents out of phase with each other to produce a rotating magnetic field, single-phase motors use two separate windings and create a phase difference between the currents in each of these windings. These motors literally "split" one phase and produce a second phase, hence the name split-phase motor.

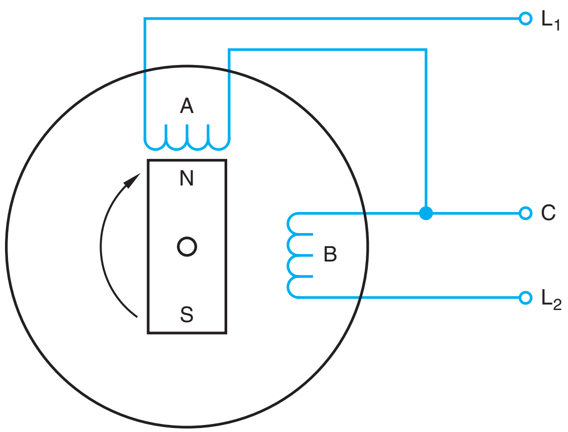



**Figure 11–1**
Two-phase alternator. (Source: Delmar/Cengage Learning)

## RESISTANCE-START INDUCTION-RUN AND CAPACITOR-START INDUCTION-RUN MOTORS

Resistance-start induction-run and capacitor-start induction-run motors are very similar in construction. The stator winding of both motors contains both a **start winding** and a **run winding**. The start winding is made of smaller wire and placed higher in the metal core material than the run winding, as shown in Figure 11–3. Since the start winding is made with smaller wire than the run winding, it will exhibit a higher resistance than the run winding. Placing the run winding deeper in the metal core material causes it to exhibit a greater amount of inductance that the start winding. Electrically, the winding appears similar to the circuit shown in Figure 11–4. The stator is constructed in this

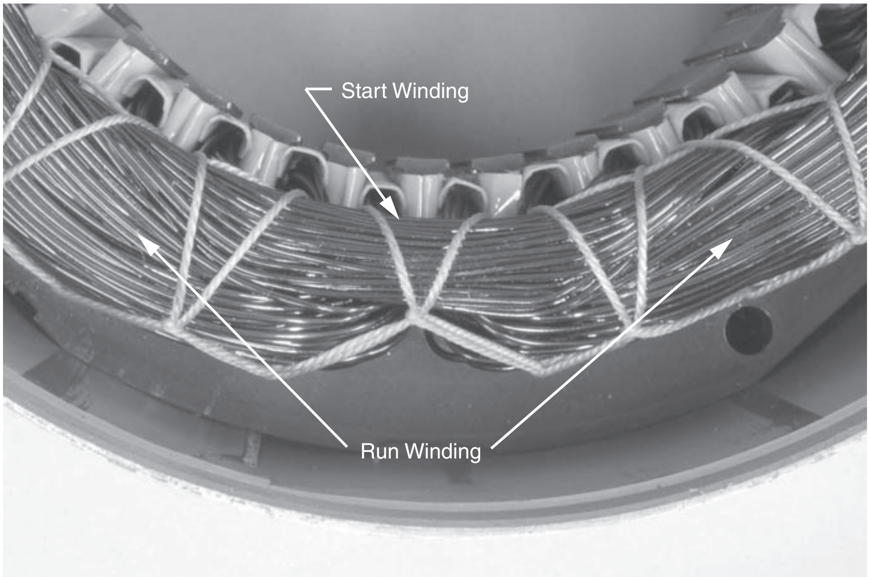



Figure 11–3
Stator winding of a resistance-start induction-run or capacitor-start induction-run motor. (Source: Delmar/Cengage Learning)

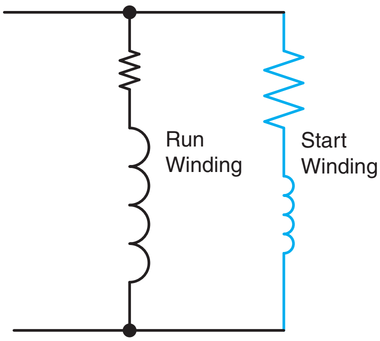



Figure 11–4
The run winding has more inductance and less resistance than the start winding. The start winding has more resistance and less inductance than the run winding. (Source: Delmar/Cengage Learning)

manner to produce a phase shift between the current flowing through the run winding and the current flowing through the start winding. Both the resistance-start and capacitor-start induction-run motors start rotation by producing a rotating magnetic field in the stator winding. Recall that a rotating magnetic field cannot be produced with a single phase.

## Resistance-Start Induction-Run Motor

The rotating magnetic field of the resistance-start induction-run motor is produced by the out-of-phase currents in the run and start windings. Since the run winding appears more inductive and less resistive than the start winding, the current flow in the run winding will be close to 90 degrees out-of-phase with the applied voltage. The start winding appears more resistive and less inductive than the run winding, causing the start winding's current to be less out-of-phase with the applied voltage, as shown in Figure 11–5. The phase-angle difference between current in the run winding and current in the start winding of a resistance-start induction-run motor is generally 35 to 40 degrees. This is enough phase-angle difference to produce a weak rotating field, and consequently a weak torque, to start the motor. Once the motor reaches about 75% of its rated speed, the start winding is disconnected from the circuit and the motor continues to operate on the run winding. In nonhermetically sealed motors, the start winding is generally disconnected with a centrifugal switch. A centrifugal switch is shown in Figure 11–6. The contacts of the centrifugal switch are connected in series with the start winding, as

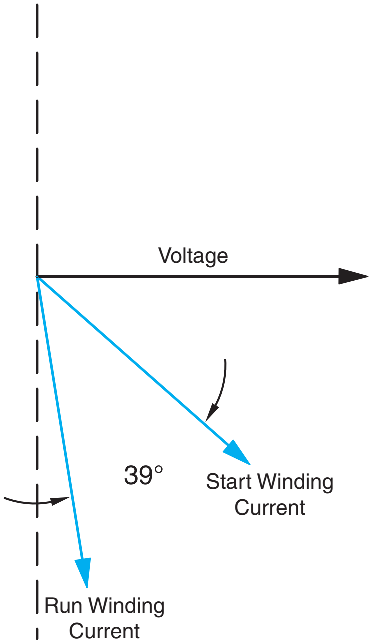



**Figure 11–5**
The run winding current and start winding current of a resistance-start induction-run motor will generally be between 35 and 40 degrees out-of-phase with each other. (Source: Delmar/Cengage Learning)

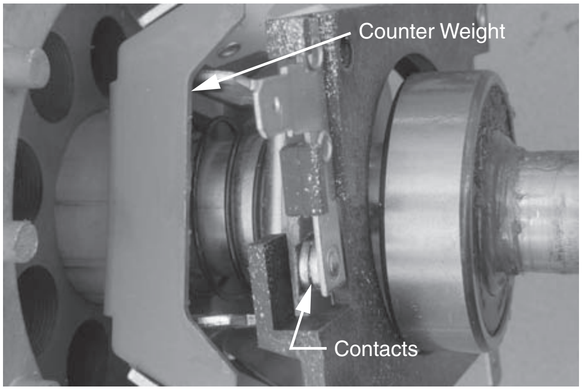



**Figure 11–6**
A centrifugal switch is used to disconnect the start windings when the motor reaches about 75% of rated speed. (Source: Delmar/Cengage Learning)

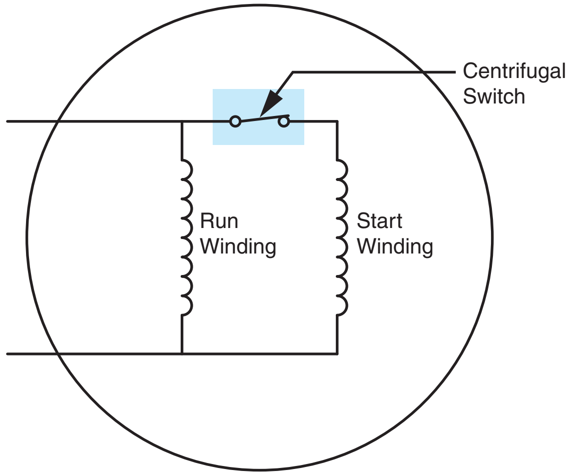



**Figure 11–7**
The centrifugal switch contacts are connected in series with the start winding. (Source: Delmar/Cengage Learning)

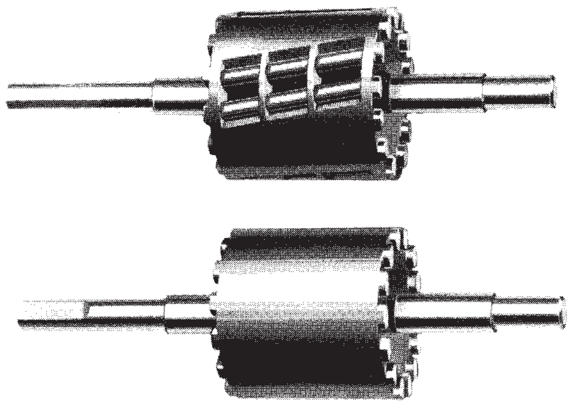


**Figure 11–8**
Squirrel cage rotor. (Courtesy of Bodine Electric Co.).

shown in Figure 11–7. When the motor is at rest or not running, the contacts of the centrifugal switch are closed and provide a circuit to the start winding. When the motor is started and reaches about 75% of its rated speed, a counterweight on the centrifugal switch moves outward because of centrifugal force, causing the contacts to open and disconnect the start winding from power. The motor continues to operate on the run winding.

When the start winding is disconnected from the circuit, a rotating magnetic field is no longer produced in the stator. This type of motor continues to operate because of current inducted in the squirrel cage windings in the rotor. Squirrel cage rotors are so named because they contain bars inside the rotor that would resemble a squirrel cage if the laminations were removed, as shown in Figure 11–8.

A squirrel cage is a device that is often placed inside the cage of small pets such as hamsters to permit them to exercise by running inside the squirrel cage. A squirrel cage rotor that has been cut in half clearly shows the bars and motor shaft, as shown in Figure 11–9. The bars of the turning squirrel cage rotor winding cut through lines of magnetic flux, causing an induced voltage in the rotor. Since the rotor bars are shorted together at each end, current flow through the rotor bars produces a magnetic field in the rotor. Alternate magnetic fields are produced in the rotor, causing the motor to continue operating, as shown in Figure 11–10. This is the same principle that permits a three-phase motor to continue operating if one phase is lost and the motor is connected to single-phase power. The main difference is that the split-phase motor is designed to operate in this condition and the three-phase motor is not. Resistance-start and capacitor-start induction-run motors are rugged and will provide years of service with little maintenance. Their operating characteristics, however, are not as desirable as those of other types of single-phase motors. Due to the way they operate, they have a low power factor. They will draw almost as much current when the motor is running at no load as they will when the motor is running at full load. Typically, if the motor has a full-load current draw of 8 amperes, the no-load current may be 6.5 to 7 amperes.

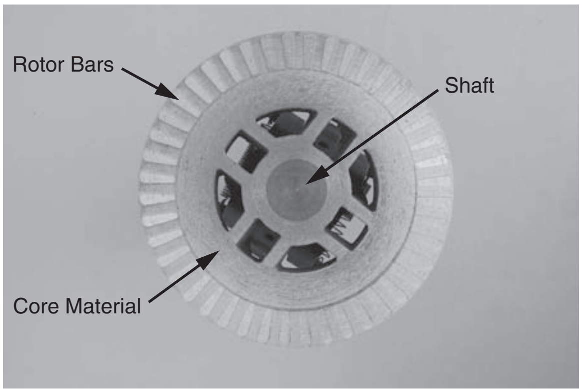



**Figure 11–9**
Bars and shaft of a squirrel cage rotor. (Source: Delmar/Cengage Learning)

## Capacitor-Start Induction-Run Motors

Capacitor-start induction-run motors are very similar to resistance-start induction-run motors. The design of the stator winding is basically the same. The main difference is that a capacitor is connected in series with the start winding, as shown in Figure 11–11. Inductive loads cause the current to lag the applied voltage. Capacitors, however, cause the current to lead the applied voltage. If the starting capacitor is sized correctly, the start winding current will lead the applied voltage by an amount that will result in a 90-degree phase shift between the run winding current and the start winding current, producing an increase in the amount of starting torque, as shown in Figure 11–12. If the capacitance of the start capacitor is too great, it will cause the start winding current to shift more than 90 degrees out-of-phase with the run winding current and starting torque will be reduced. When replacing the start capacitor for this type

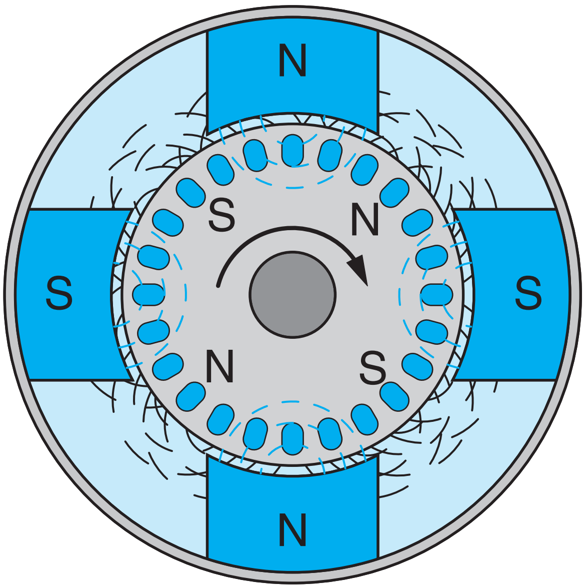



**Figure 11–10**
The rotor continues to turn because of magnetic fields produced by the current induced in the rotor of the motor. (Source: Delmar/Cengage Learning)

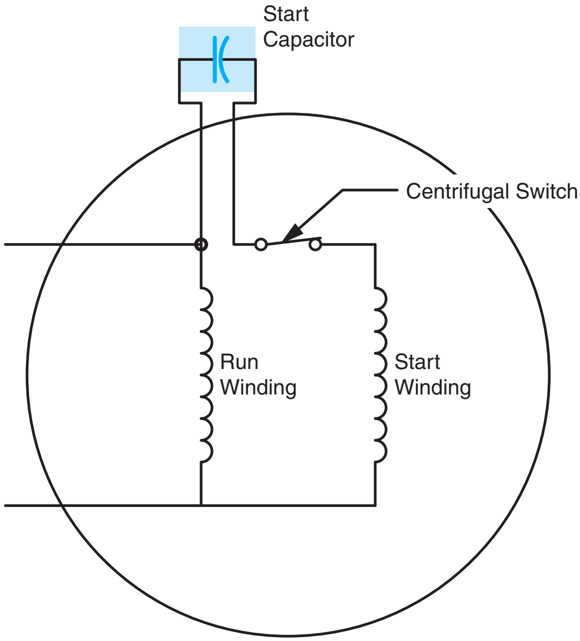



Figure 11–11
A capacitor is connected in series with the start winding. (Source: Delmar/Cengage Learning)

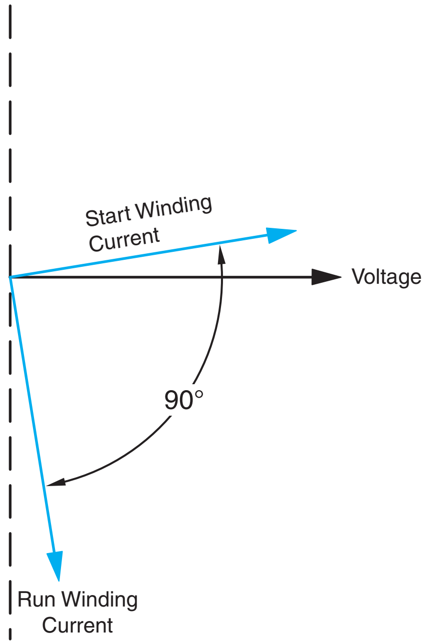



Figure 11–12
The capacitor causes a 90-degree phase shift between run winding current and start winding current.
(Source: Delmar/Cengage Learning)


Figure 11–13
A capacitor-start induction-run motor. (Source: Delmar/Cengage Learning)


Figure 11–14
Typical starting capacitor. (Source: Delmar/Cengage Learning)

of motor, the micro-farad rating recommended by the manufacturer should be followed. It is permissible to use a capacitor with a higher voltage rating, but never install a capacitor with a lower voltage rating. A capacitor-start induction-run motor is shown in Figure 11–13. A typical starting capacitor is shown in Figure 11–14.

## TESTING THE STATOR WINDING

The stator winding of a single-phase motor is generally tested with an ohmmeter. The ohmmeter test can be used to determine if a winding is open or grounded. Many single-phase motors have one lead of the run and start windings connected as shown in Figure 11–15. To test the windings for an open, connect one ohmmeter lead to the common motor terminal, and the other meter lead to the run winding. The ohmmeter should indicate continuity through the winding. The resistance of the run winding of a single-phase motor can vary greatly from one motor to another. The winding resistance of a single-speed motor may be only one or two ohms, while the resistance of a multi-speed fan motor may be 10 to 15 ohms.

To test the start winding for an open, connect the ohmmeter leads to the common terminal and the S terminal. The start winding should indicate continuity, and should have a higher resistance than the run winding. This difference of resistance may not be great, but the start winding should have a higher resistance than the run winding.

To test the stator winding for a ground, connect one of the ohmmeter leads to the case of the motor, Figure 11–16. Alternately check each motor terminal with the other ohmmeter lead. The ohmmeter should indicate no continuity between either winding and the case of the motor.

A shorted start winding can sometimes be detected by the fact that the motor will not start, but will run if the shaft is turned by hand. The motor will produce a humming sound but will not turn when power is first applied to it. The shaft can be turned in either direction by hand and the motor will continue to run in that direction.

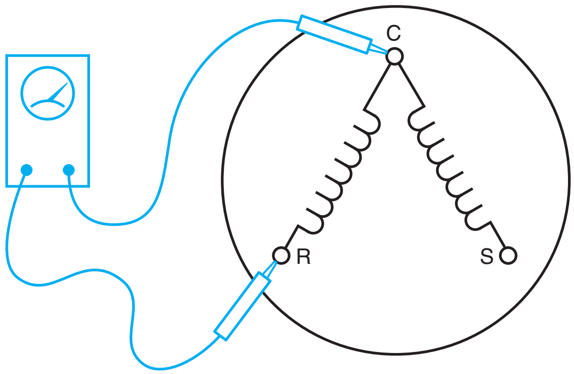



**Figure 11–15**
Testing the split-phase motor for an open winding.
(Source: Delmar/Cengage Learning)

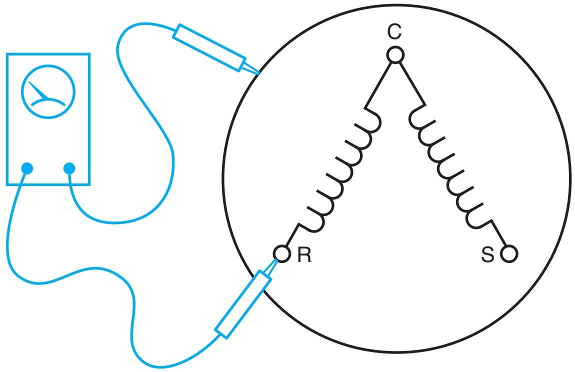



**Figure 11–16**
Testing a split-phase motor for a grounded winding.
(Source: Delmar/Cengage Learning)

## REVERSING DIRECTION OF ROTATION

The direction of rotation of a split-phase motor can be reversed by changing the start winding leads or the run winding leads, but not both. The rotation is generally reversed by changing the start winding leads with respect to the run winding. Some motor manufacturers bring both start winding leads to the outside of the motor. This permits the service technician to decide the direction of rotation the motor is to turn when it is installed on the unit.

## DUAL-VOLTAGE MOTORS

Single-phase motors can also be constructed to operate on two separate voltages. These motors are designed to be connected to 120 or 240 volts. A common connection for this type of motor contains two run windings and one start winding, Figure 11–17. The run windings are labeled T1–T2, and T3–T4. The start winding is labeled T5 and T6. In the circuit shown in Figure 11–17, the windings have been connected for operation on a 240-volt line. Each winding is rated at 120 volts. The two run windings are connected in series, which causes each to have a voltage drop of 120 volts when connected to 240 volts. Notice that the start winding has been connected in parallel with one of the run windings. This causes the start winding to have an

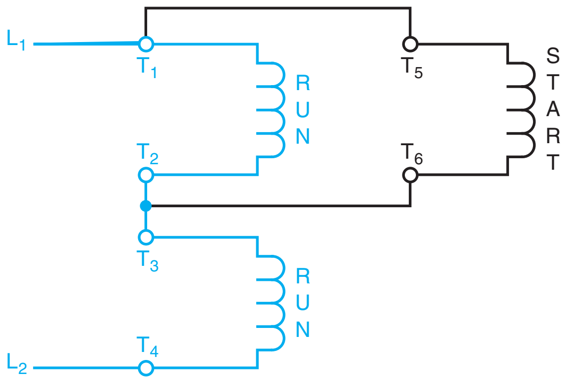



**Figure 11–17**
The run windings are connected in series for a high-voltage connection. (Source: Delmar/Cengage Learning)

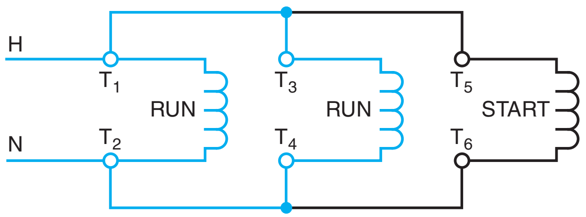



**Figure 11–18**
Because these windings are connected in parallel, each will have 120 volts applied to it. (Source: Delmar/Cengage Learning)

applied voltage of 120 volts also. Notice that each of the windings has 120 volts connected to it, which is the rating of the windings.

If the motor is to be operated on a 120 volt line, the windings are connected in parallel as shown in Figure 11–18. Because these windings are connected in parallel, each will have 120 volts applied to it.

Some dual-voltage motors will contain two start windings as well as two run windings, as shown in Figure 11–19. The run windings are labeled $T_1$ through $T_4$, the same as dual-voltage motors that contain only one start winding. One of the start windings is labeled $T_5$ and $T_6$. The second start winding is labeled $T_7$ and $T_8$. If the motor is to be connected for operation on 240 volts, the run windings are connected in series by connecting $T_2$ and $T_3$ together, and the start windings are connected in series by connecting $T_6$ and $T_7$ together. The

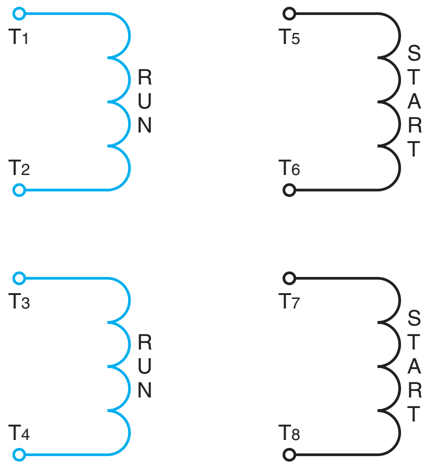



**Figure 11–19**
Some dual-voltage single-phase motors contain two start windings as well as two run windings. (Source: Delmar/Cengage Learning)

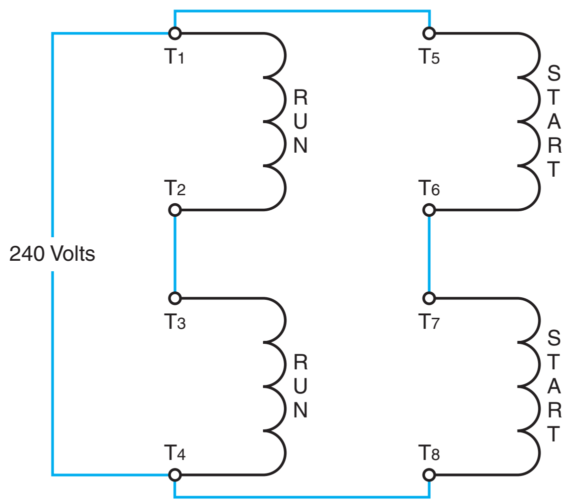



**Figure 11–20**
The motor is connected for operation on 240 volts. (Source: Delmar/Cengage Learning)

start windings are then connected in parallel with the run windings, as shown in Figure 11–20. The direction of rotation can be changed by reversing $T_5$ and $T_8$.

If the motor is operated on 120 volts, the run and start windings are connected in parallel as shown in Figure 11–21. If the motor is to be reversed, leads $T_5$ and $T_7$ are changed with leads $T_6$ and $T_8$. Some

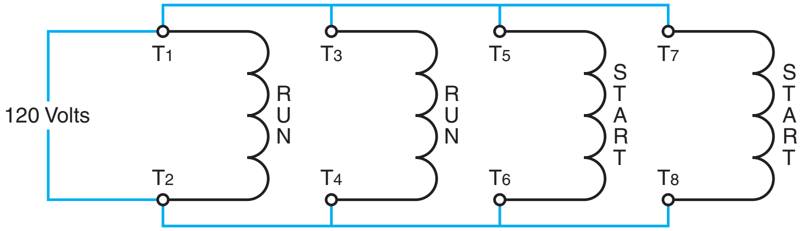



**Figure 11–21**
The motor is connected for operation on 120 volts. (Source: Delmar/Cengage Learning)

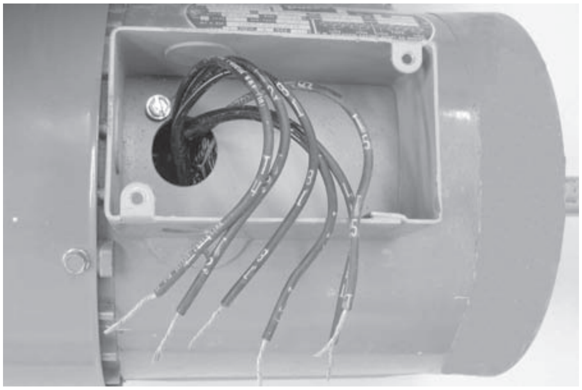


**Figure 11–22**
Connection leads of a dual-voltage single-phase motor. (Source: Delmar/Cengage Learning)

manufacturers label the start winding leads $T_5$ and $T_8$ even if they contain only one start winding. The connection leads of a dual-voltage single-phase motor are shown in Figure 11–22.

## MOTOR POWER CONSUMPTION

It should be noted that the motor does not use less energy when connected to 240 volts than it does when connected to 120 volts. Power is measured in watts, and the watts will be the same regardless of the connection. When the motor is connected to operate on 240 volts, it will have half the current draw as it does on a 120-volt connection. Therefore, the amount of power used is the same. For example, assume the motor has a current draw of 5 amps when connected to 240 volts and 10 amps when connected to 120 volts. Watts can be computed from multiplying volts by amps. When the motor is connected to 240 volts, the amount of power used is $240 \times 5 = 1{,}200$ watts. When the motor is connected to 120 volts, the power used is $120 \times 10 = 1{,}200$ watts.

The 240-volt connection is generally preferred, however, because the lower current draw causes less voltage drop on the line supplying power to the motor. If the motor is located a long distance from the panel, voltage drop of the wire can become very important to the operation of the unit.

## PERMANENT-SPLIT CAPACITOR MOTOR

The permanent-split capacitor motor has greatly increased in popularity for use in the air conditioning field over the past years. This type of split-phase motor does not disconnect the start windings from the circuit when it is running. This eliminates the need for a centrifugal switch or starting relay to disconnect the start windings from the circuit when the motor reaches about 75% of its full speed, Figure 11–23. This motor has good starting torque

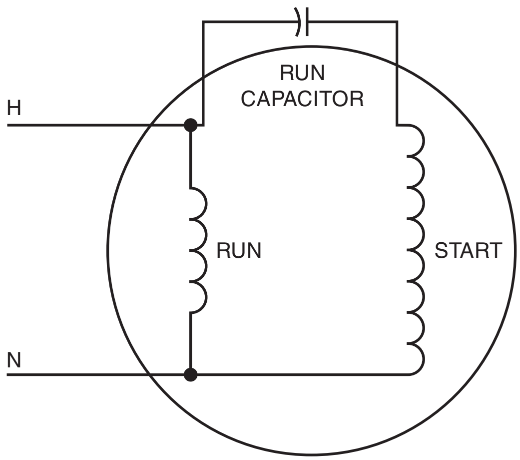



**Figure 11–23**
A schematic for a permanent-split capacitor motor. (Source: Delmar/Cengage Learning)

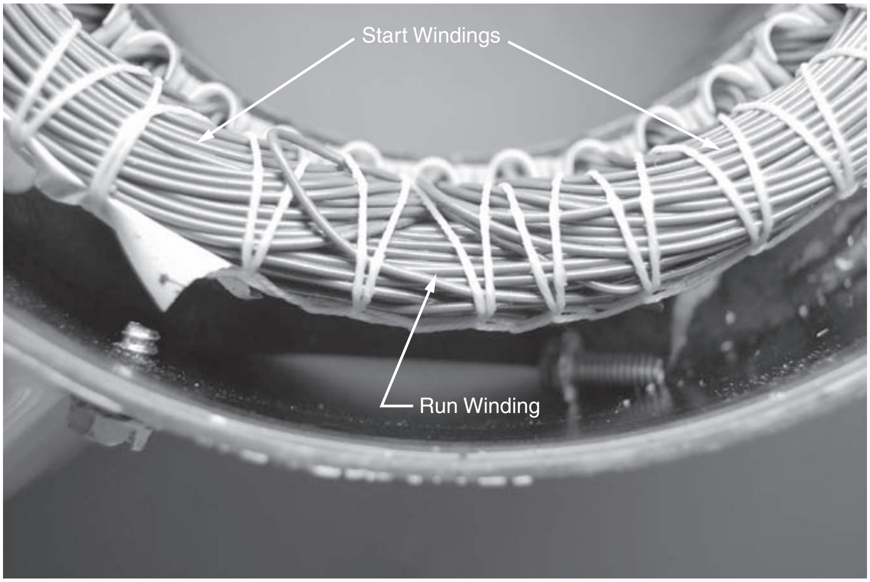



**Figure 11–24**
The run and start windings of a permanent-split capacitor motor. (Source: Delmar/Cengage Learning)

and good running torque. Because the capacitor remains in the circuit during operation, it helps correct power factor for the motor. The stator winding of the permanent-split capacitor (PSC) motor is different from the stator windings of the resistance-start induction-run or capacitor-start induction-run motors. The PSC motor stator winding still contains a run and start winding, but the start winding will generally have the same size wire and just as many turns as the run winding, as shown in Figure 11–24. The run winding is placed lower in the core material, which helps increase the inductance.

The capacitor used in this type of motor is generally the AC oil-filled type. A photograph of a permanent-split capacitor motor is shown in Figure 11–25. Because this capacitor remains connected in the circuit, an AC electrolytic capacitor cannot be used to replace the run capacitor for this type of motor.

The permanent-split capacitor motor will sometimes use an extra capacitor to aid in starting. When this is done, the start capacitor is connected in parallel with the run capacitor. During the time of starting, both of these capacitors are connected in the circuit, Figure 11–26. When the motor has accelerated to about 75% of full speed, the start capacitor is disconnected from the circuit. If the motor is an open type, the start capacitor will be disconnected by a centrifugal switch. If the motor is sealed, such as a hermetically sealed compressor, the start capacitor will be disconnected by a starting relay.

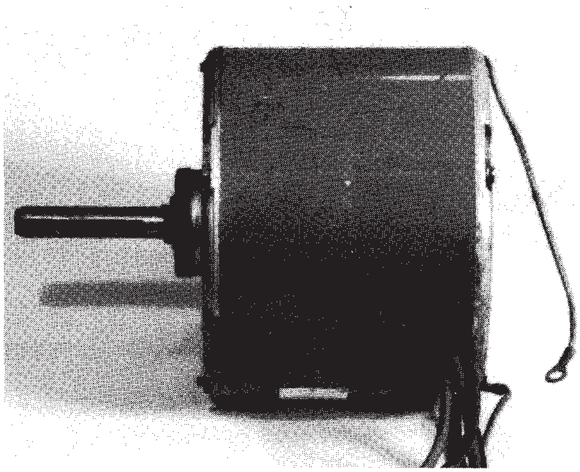


**Figure 11–25**
Permanent-split capacitor motor. (Source: Delmar/Cengage Learning)

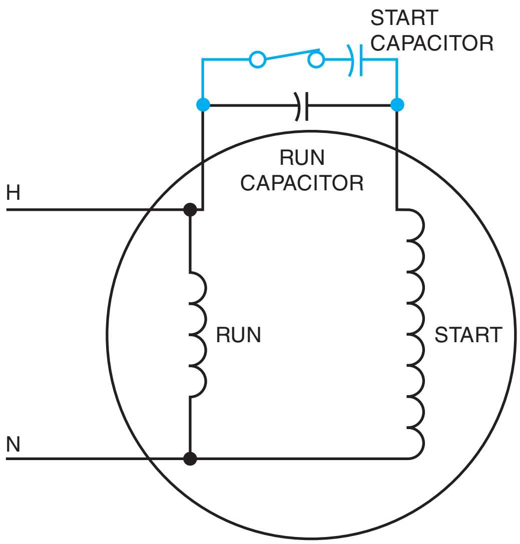



Figure 11–26
An extra starting capacitor used with a permanent-split capacitor motor. (Source: Delmar/Cengage Learning)

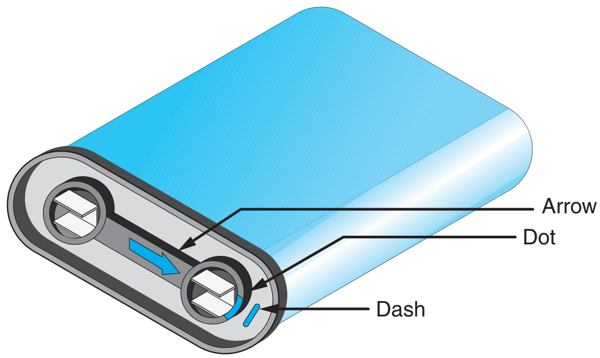



Figure 11–27
The markings indicate the terminal that connects to the plate located closest to the case of the capacitor.
(Source: Delmar/Cengage Learning)

## IDENTIFYING CAPACITOR TERMINALS

Most run capacitors and some starting capacitors are of the oil-filled type, Figure 8–15. This is especially true for high current motors such as those used to operate compressors. Many manufacturers of oil-filled capacitors will identify one terminal with an arrow, a painted dot, or by stamping a dash in the capacitor can, Figure 11–27. This identified terminal marks the connection to the plate that is located nearer to the metal container or can. It has long been known that when a capacitor's dielectric breaks down and permits a short circuit to ground, it is most often the plate nearer to the outside case that becomes grounded. For this reason, it is desirable to connect the identified capacitor terminal to the line side instead of to the motor start winding.

In Figure 11–28, the run capacitor has been connected in such a manner that the identified terminal is connected to the start winding of a compressor

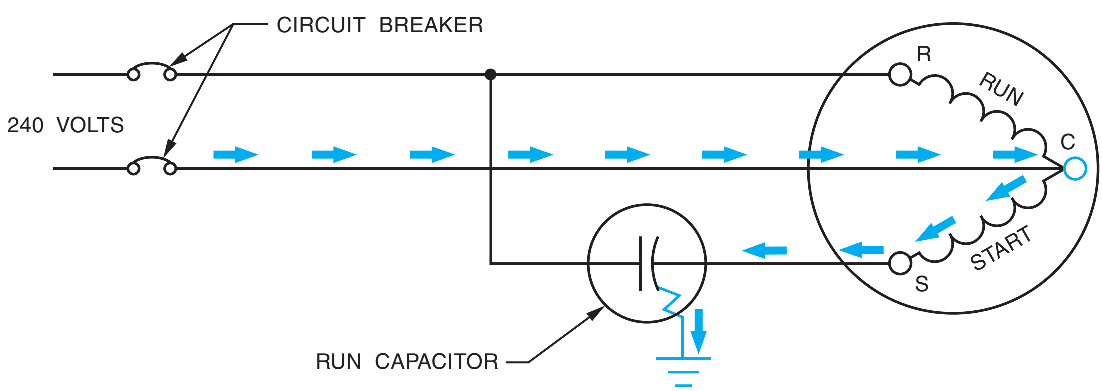



Figure 11–28
Identified capacitor terminal connected to motor start winding. (Source: Delmar/Cengage Learning)

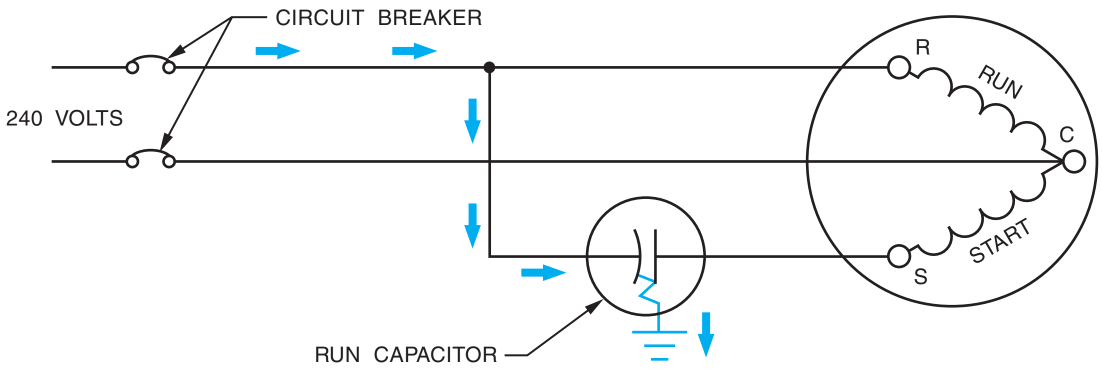



**Figure 11–29**
Identified capacitor terminal connected to the line. (Source: Delmar/Cengage Learning)

motor. If the capacitor shorts to ground, a current path would exist through the motor start winding. The start winding is an inductive-type load and inductive reactance will limit the value of current flow to ground. Since the flow of current is limited, it will take the circuit breaker or fuse time to open the circuit and disconnect the motor from the power line. This time delay can permit the start winding to overheat and become damaged.

In Figure 11–29, the run capacitor has been connected in such a manner that the identified terminal is connected to the line side. If the capacitor shorts to ground, a current path would exist directly to ground, bypassing the motor start winding. When the capacitor is connected in this manner, the start winding does not limit current flow and allows the fuse or circuit breaker to open almost immediately.

## SUMMARY

- Split-phase motors fall into three general classifications:
  A. The resistance-start induction run.
  B. The capacitor-start induction run.
  C. The permanent-split capacitor motor.
- The voltages of a two-phase system are 90° out of phase with each other.
- Split-phase motors receive their name from the fact that they split the current flow through two windings to produce an out of phase condition that produces a rotating magnetic field.
- The resistance-start induction run and capacitor-start induction run motors disconnect their start winding when they have accelerated to about 75% of their rated speed.
- Split-phase motors that are not hermetically sealed generally use a centrifugal switch to disconnect the start winding when the motor has reached about 75% of its rated speed.
- The direction of rotation of a split-phase motor can be reversed by changing the connections of the run winding or the start winding, but not both.
- Dual voltage split-phase motors can be connected to operate on 120 or 240 volts.

- The capacitor-start induction run motor develops a higher starting torque than the resistance-start induction run motor.
- The capacitor-start motor develops a higher starting torque by using the capacitor to produce a 90° phase shift between the current flow in the run winding and the current flow in the start winding.
- Maximum starting torque for the split-phase motor is produced when the run winding current and start winding current are 90° out of phase with each other.
- Permanent-split capacitor motors do not disconnect the start winding when the motor is in operation.
- Some permanent-split capacitor motors use an extra capacitor during the starting period.
- The identifying mark on an oil-filled capacitor should be connected to the line side of the circuit.

## KEY TERMS

**capacitor-start induction-run motor**
**capacitor-start capacitor-run motor**
**centrifugal switch**
**permanent-split capacitor motor (PSC)**
**resistance-start induction-run motor**
**rotating field speed**
**run winding**
**split-phase motor**
**start winding**
**torque**
**two-phase power**

## REVIEW QUESTIONS

1. What is a split-phase motor?
2. What are the three basic types of split-phase motors?
3. Explain the difference in construction of run windings and start windings.
4. How many degrees out of phase should the current in the start winding be with the current in the run winding to develop maximum starting torque?
5. What type of capacitor is generally used with a capacitor start induction-run motor?
6. Can the micro-farad value of this capacitor be increased to improve starting torque?
7. What type of capacitor is used with a permanent-split capacitor motor?
8. Does the capacitor of a capacitor start induction-run motor help correct power factor?
9. If necessary, can an AC electrolytic capacitor of higher voltage rating be used as the starting capacitor?
10. What is a centrifugal switch used for?

# UNIT 12

# The Shaded-Pole Induction Motor

## OBJECTIVES

After studying this unit the student should be able to:

- Discuss the operation of a shaded-pole induction motor
- Define a shading coil
- List common uses for the shaded-pole induction motor

The **shaded-pole induction motor** is another type of AC single-phase motor used to a large extent in the air conditioning field. This motor is popular because of its simplicity and long life. The shaded-pole motor contains no start winding or centrifugal switch. The rotating magnetic field is created by a **shading coil** wound around one side of each pole piece.

## THE SHADING COIL

The shading coil is wound around one end of the pole piece, Figure 12–1. The shading coil is actually a large loop of copper wire or a copper band. Both ends of the loop are connected together to form a complete circuit. The shading coil acts in the same manner as a transformer with a shorted secondary winding. When the voltage of the AC

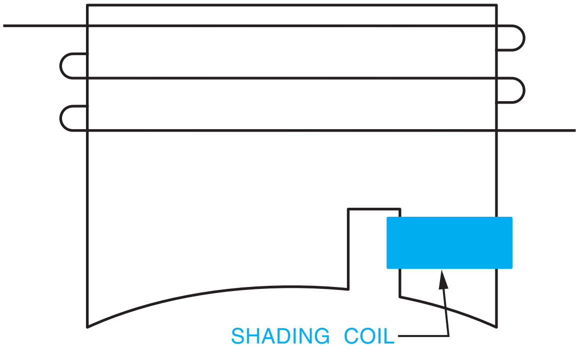



**Figure 12–1**
A shaded pole. (Source: Delmar/Cengage Learning)

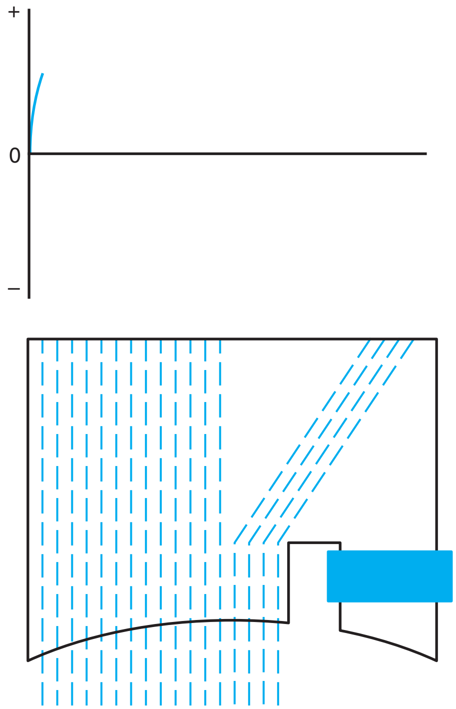



**Figure 12–2**
The shading coil opposes a change of magnetic flux as voltage increases. (Source: Delmar/Cengage Learning)

waveform increases from zero toward its positive peak, a magnetic field is created in the pole piece. As magnetic lines of flux cut through the shading coil, a voltage is induced in the coil. Because the coil is a low-resistance short circuit, a large amount of current flows in the loop. This current flow causes an **opposition** to the change of **magnetic flux**, Figure 12–2. As long as voltage is induced into the shading coil, there will be an opposition to the change of magnetic flux.

When the AC voltage reaches its peak value, it is no longer changing and there is no voltage being induced into the shaded coil. Since there is no current flow in the shading coil, there is no opposition to the magnetic flux. The magnetic flux of the pole piece is now uniform across the pole face, Figure 12–3.

When the AC voltage begins to decrease from its peak value back toward zero, the magnetic field of the pole piece begins to collapse. A current is again induced into the shading coil. The induced current opposes the change of magnetic flux, Figure 12–4. This causes the magnetic flux to be concentrated in the shaded section of the pole piece.

When the AC voltage passes through zero and begins to increase in the negative direction, the same set of events happen, except that the polarity of the magnetic field is reversed. If these events were to be

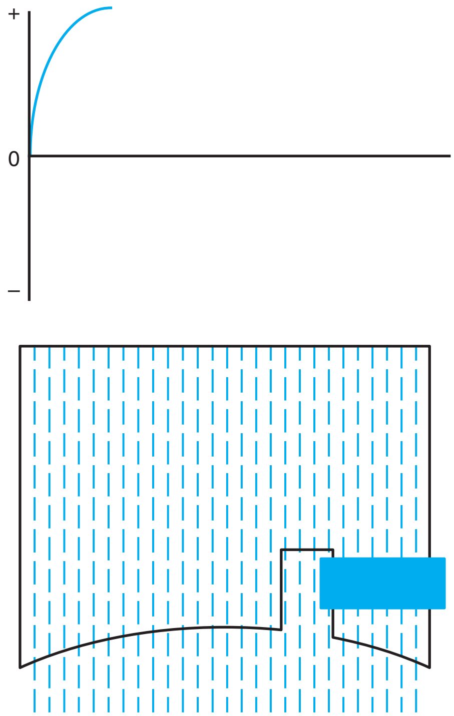



**Figure 12–3**
There is no opposition to magnetic flux when the voltage is not changing. (Source: Delmar/Cengage Learning)

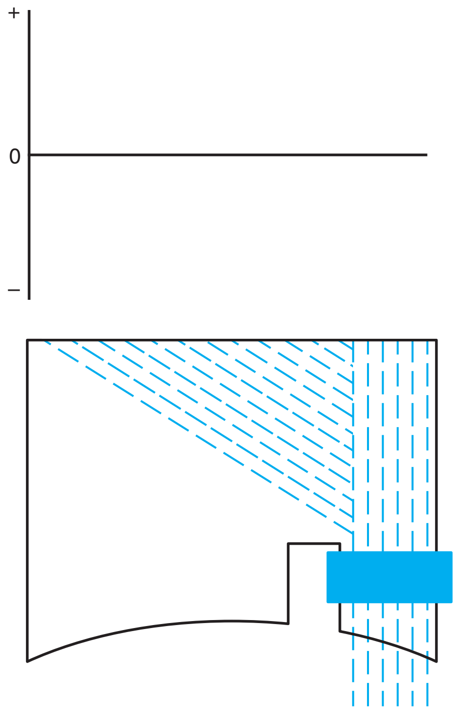



Figure 12–4
The shading coil opposes a change of flux when the voltage decreases. (Source: Delmar/Cengage Learning)

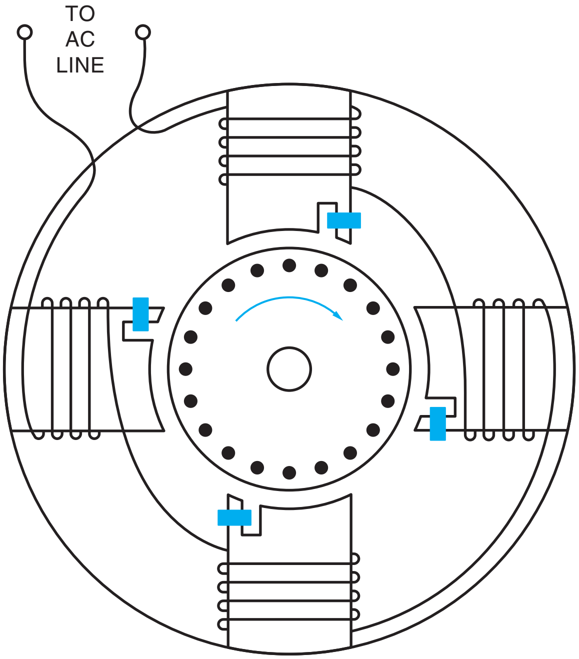



Figure 12–5
A four-pole shaded-pole induction motor. (Source: Delmar/Cengage Learning)

seen in rapid order, it could be seen that the magnetic field rotates across the face of the pole piece.

## SPEED

The speed of the shaded-pole induction motor is determined by the same factors that determine the synchronous speed of other induction motors: frequency and number of stator poles. Shaded-pole motors are commonly wound as four- or six-pole motors. Figure 12–5 shows a drawing of a four-pole motor.

## REVERSING DIRECTION OF ROTATION

The direction the magnetic field moves across the face of the pole piece is determined by the side of the pole piece that has the shaded coil. The rotor will turn in the direction of the shaded pole as shown by the arrow in Figure 12–5. If the direction of rotation must be changed, it can be done by removing the stator winding and turning it around. This is not a common practice, however. As a general rule, the shaded-pole induction motor is considered to be nonreversible.

## GENERAL OPERATING CHARACTERISTICS

The shaded-pole motor contains a standard squirrel-cage rotor. The amount of torque produced is determined by the strength of the magnetic field of the stator, the strength of the magnetic field of the rotor, and the phase-angle difference between rotor current and stator current. The shaded-pole motor has a low starting torque and running torque. This motor is generally used in applications that do not require a large amount of starting torque, such as fans and blowers. Figure 12–6 shows a photograph of a shaded-pole induction motor.

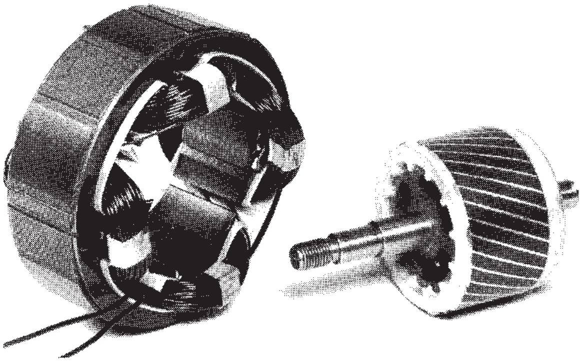


**Figure 12–6**
Stator winding and rotor of a shaded-pole induction motor. (Courtesy of Westinghouse Electric Corp.).

## SUMMARY

- The shaded-pole induction motor is popular because of its simplicity and long life.
- Shaded-pole induction motors do not contain a start winding or centrifugal switch.
- Shaded-pole induction motors operate on the principle of a rotating magnetic field.
- A shading coil or loop is used to produce an out of phase flux across the face of the pole piece, thus producing a rotating magnetic field.
- The speed of a shaded-pole induction motor is determined by the number of stator poles and the frequency of the applied voltage.
- Shaded-pole induction motors are generally considered to be nonreversible.

## KEY TERMS

**magnetic flux**
**opposition**
**shaded-pole induction motor**
**shading coil**

## REVIEW QUESTIONS

1. What is a shading coil?
2. What determines the synchronous speed of a shaded-pole motor?
3. In general, how is the direction of a shaded-pole induction motor reversed?
4. What type of rotor does the shaded-pole motor contain?
5. Name two advantages of the shaded-pole motor over the split-phase induction motor.

# UNIT 13

# Multispeed Motors

## OBJECTIVES

After studying this unit the student should be able to:

- Discuss the operation of a consequent pole motor
- List the factors that determine the synchronous field speed of an AC motor
- Discuss the operation of multispeed fan motors
- Connect a multispeed fan motor for operation at different speeds

**Multispeed AC motors** have been used to a great extent in the air conditioning field for many years. There are two basic types of multispeed motors used. One type is known as the **consequent pole motor**. The other type is generally a permanent-split capacitor motor.

## THE CONSEQUENT POLE MOTOR

The speed of the rotating magnetic field of an AC induction motor can be changed in either of two ways. These are:

1. Change the frequency of the AC voltage.
2. Change the number of stator poles.

The consequent pole motor changes the motor speed by changing the number of its stator poles. The run winding in Figure 13–1 has been **tapped**

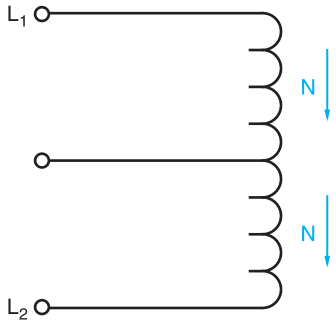



**Figure 13–1**
Center-tapped run winding. (Source: Delmar/Cengage Learning)

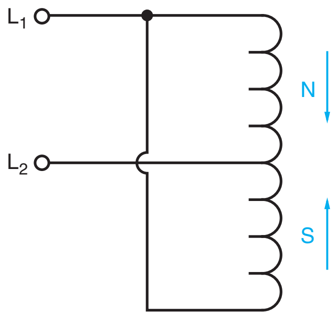



**Figure 13–2**
Two magnetic poles are produced. (Source: Delmar/Cengage Learning)

in the center. If the AC line is connected to each end of the winding as shown, current flows through the winding in only one direction. Therefore, only one magnetic **polarity** is produced in the winding. If the winding is connected as shown in Figure 13–2, current flows in opposite directions in each half of the winding. Because current flows through each half of the winding in opposite directions, the polarity of the magnetic field is different in each half of the winding. The run winding now has two polarities instead of one. There are now two magnetic poles instead of one. If the windings of a two-pole motor were to be tapped in this manner, the motor could become a four-pole motor. The synchronous speed of a two-pole motor is 3,600 RPM, and the synchronous speed of a four-pole motor is 1,800 RPM.

The consequent pole motor has the disadvantage of having a wide variation in speed. When the speed is changed, it changes from a synchronous speed of 3,600 RPM to 1,800 RPM. The speed cannot be changed by a small amount. This wide variation in speed makes the consequent pole motor unsuitable for some loads, such as fans and blowers.

The consequent pole motor, however, does have some advantages over the other type of multispeed motor. When the speed of the consequent pole motor is reduced, its torque increases. For this reason, the consequent pole motor can be used to operate heavy loads, such as **two-speed compressors**.

## MULTISPEED FAN MOTORS

Multispeed fan motors have been used in the air conditioning industry for many years. These motors are generally wound for two to five steps of speed, and are used to operate fans and squirrel-cage blowers. A schematic drawing of a three-speed motor is shown in Figure 13–3. Notice that the run winding has been tapped to produce low, medium, and high speed. The start winding is connected in parallel with the run winding section. The other end of the start lead is connected to an external oil-filled run capacitor. This motor obtains a change in speed by inserting inductance in series with the run winding. The actual run winding for this motor is between the terminals marked High and C. The windings shown between High and Medium are connected in series with the main run winding. When the rotary switch is connected to the medium-speed position, the inductive reactance of this coil limits the amount

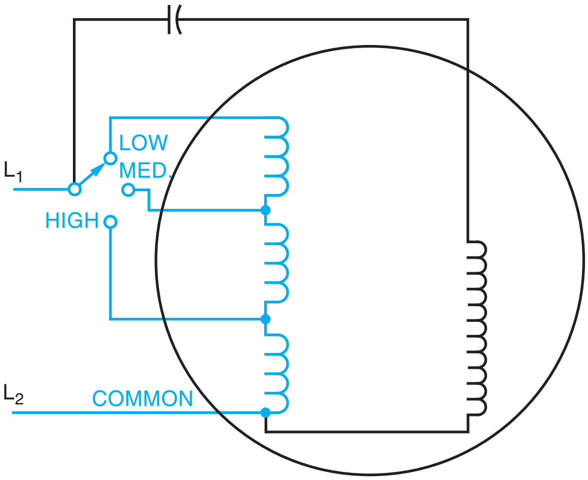


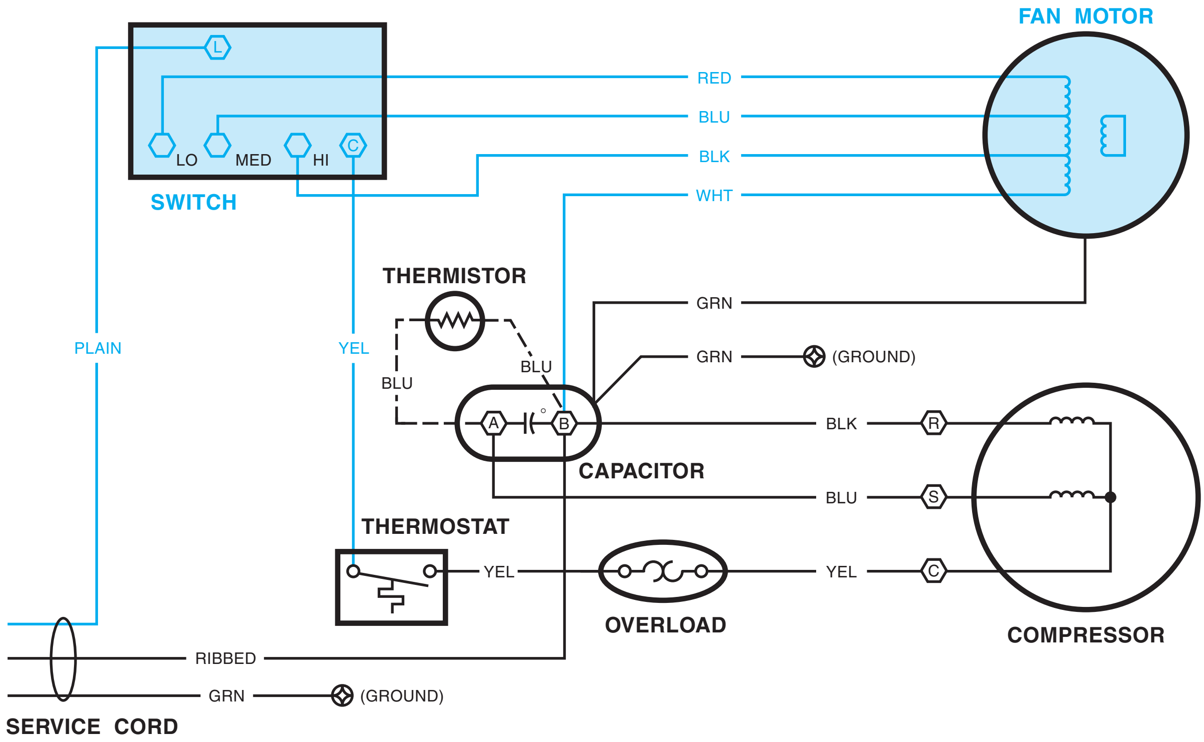

**Figure 13–3**
Three-speed fan motor. (Source: Delmar/Cengage Learning)

of current flow through the run winding. When the current of the run winding is reduced, the strength of the magnetic field of the run winding is reduced and the motor produces less torque. This causes the motor speed to decrease.

If the rotary switch is changed to the low position, more inductance is connected in series with the run winding. This causes less current to flow through the winding and another reduction in torque. When the torque is reduced, the motor speed decreases again.

Common speeds for a four-pole motor of this type are 1,625, 1,500, and 1,350 RPM. Notice that this motor does not have the wide range between speeds as the consequent pole motor does. Most induction motors would overheat and damage the motor windings if the speed were to be reduced to this extent. This motor, however, has much higher impedance in its windings than most motors. The run windings of most split-phase motors has a wire resistance of 1 to 4 ohms. This motor will generally have a resistance of 10 to 15 ohms in its run winding. It is the high impedance of the windings that permits the motor to be operated in this manner without damage.

Because this motor is designed to slow down when load is added, it is not used to operate high-torque loads. This type of motor is generally used to operate only low-torque loads, such as fans and blowers. The schematic in Figure 13–4 shows a multispeed fan motor and switch.




| SWITCH POSITION | CONTACTS MADE |
|---|---|
| LO | L to C, L to LO |
| MED | L to C, L to MED |
| HI | L to C, L to HI |
| OFF | NONE |

**Figure 13–4**
A multispeed fan motor and switch. (Source: Delmar/Cengage Learning)

## VARIABLE FREQUENCY DRIVES

One of the factors that determines the speed of the rotating magnetic field of an AC induction motor is the frequency of the applied voltage. If the frequency is changed, the speed of the rotating magnetic field changes also. A four-pole stator will have a synchronous speed (speed of the rotating magnetic field) of 1,800 RPM when connected to a 60-Hz line. If the frequency is lowered to 30 Hz, the synchronous speed decreases to 900 RPM.

When the frequency is lowered, care must be taken not to damage the stator windings. The current flow through the winding is limited to a great extent by inductive reactance. When the frequency is lowered, inductive reactance is lowered also ($X_L = 2\pi FL$). For this reason, **variable frequency** drives must employ some method of lowering the applied voltage to the stator as frequency is reduced.

In the air conditioning field, variable frequency drive is often used to control the speed of blower motors. This method of controlling air flow can be more efficient than inserting dampers into the duct system. Variable frequency drives are very popular in zone controlled systems.

Most variable frequency drives operate by first changing the AC voltage into DC and then changing it back to AC at the desired frequency. A variable frequency drive is shown in Figure 13–5. There are several methods used to change the DC voltage back into AC. The method employed is generally determined by the manufacturer, age of the equipment, and the size motor the drive must control. Variable frequency drives intended to control the speed of motors up to 500 horsepower generally use transistors. In the circuit shown in Figure 13–6, a three-phase bridge changes the three-phase alternating-current into direct current. The bridge rectifier uses **SCRs (silicon controlled rectifiers)** instead of diodes. The SCRs permit the output voltage of the rectifier to be controlled. As the frequency decreases, the SCRs fire later in the cycle and lower the output voltage to the transistors. A choke coil and capacitor bank are used to filter the output voltage before transistors Q1 through Q6 change the DC voltage back into AC. An electronic control unit is connected to the bases of transistor Q1 through Q6. The control unit converts the DC voltage back into three-phase alternating current by turning transistors on or off at the proper time and in the proper sequence. Assume, for example, that transistors Q1 and Q4 are switched on at the same time. This permits stator winding $T_1$ to be connected to a positive voltage and $T_2$ to be connected to a negative voltage. Current can flow through Q4 to $T_2$, through the motor stator winding and through $T_1$ to Q1.


**Figure 13–5**
Variable frequency drive. (Courtesy of Toshiba Corp.).

Now assume that transistors Q1 and Q4 are switched off and transistors Q3 and Q6 are switched on. Current will now flow through Q6 to stator winding $T_3$, through the motor to $T_2$, and through Q3 to the positive of the power supply.

Because the transistors are turned completely on or completely off, the waveform produced is a square wave instead of a sine wave, Figure 13–7. Induction motors will operate on a square wave

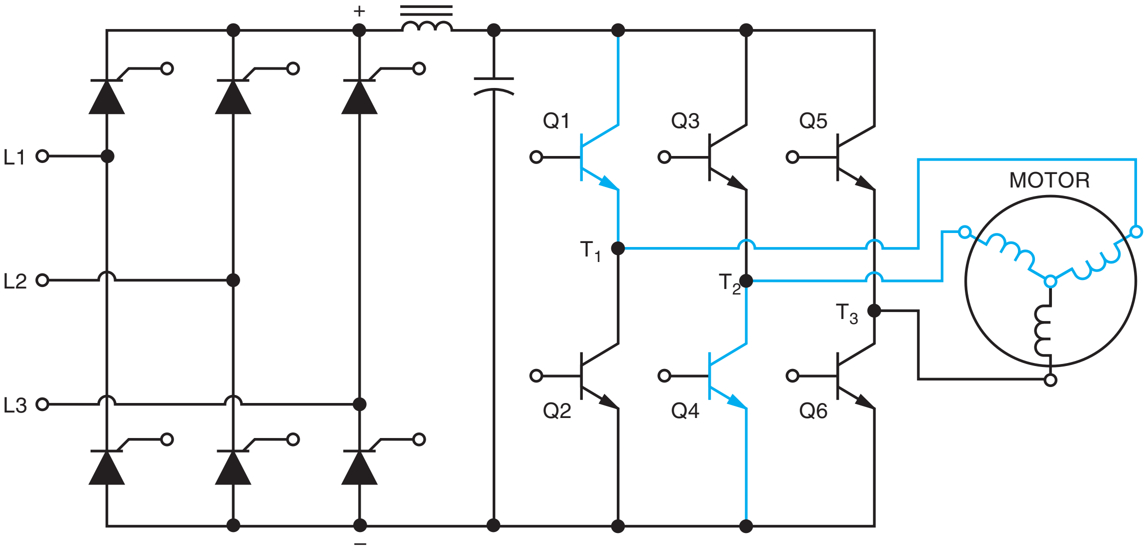



**Figure 13–6**
Variable frequency drive using bipolar transistor to change the direct current back into alternating current.
(Source: Delmar/Cengage Learning)

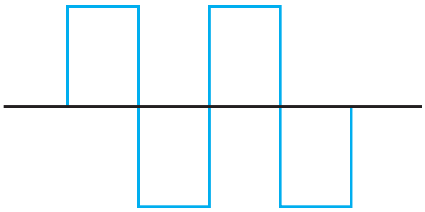


**Figure 13–7**
Square wave. (Source: Delmar/Cengage Learning)

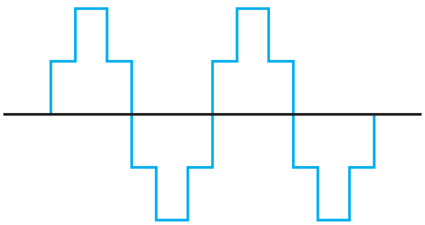


**Figure 13–8**
Stepped wave. (Source: Delmar/Cengage Learning)

without much of a problem. Some manufacturers design units that will produce a stepped waveform as shown in Figure 13–8. The stepped waveform is used because it closely approximates a sine wave.

## Some Related Problems

The circuit illustrated in Figure 13–6 employs the use of SCRs in the power supply and junction transistors in the output stage. SCR power supplies control the output voltage by chopping the incoming waveform. This can cause **harmonics** on the line that cause overheating of transformers and motors, and can cause fuses to blow and circuit breakers to trip. When bipolar junction transistors are employed as switches, they are generally driven into saturation by supplying them with an excessive amount of base-emitter current. Saturating the transistor causes the collector-emitter voltage to drop to between 0.04 and 0.03 volts. This small voltage drop allows the transistor to control large amounts of current without being destroyed. When a transistor is driven into saturation, however, it cannot recover or turn off as quickly as normal. This greatly limits the frequency response of the transistor.

## IGBTs

Many transistor-controlled variable drives now employ a special type of transistor called an **insulated gate bipolar transistor (IGBT)**. IGBTs have an insulated gate very similar to some types of field effect transistors (FETs). Because the gate is insulated, it has a very high impedance. The IGBT is a voltage controlled device, not a current controlled device. This gives it the ability to turn off very quickly. IGBTs can be driven into saturation to provide a very low voltage drop between emitter and collector, but they do not suffer from the slow recovery time of common junction transistors.

Drives using IGBTs generally use diodes to rectify the AC voltage into DC, not SCR, Figure 13–9. The three-phase rectifier supplies a constant DC voltage to the transistors. The output voltage to the motor is controlled by **pulse width modulation (PWM)**. PWM is accomplished by turning the transistor on and off several times during each half cycle, Figure 13–10. The output voltage is an average of the peak or maximum voltage and the amount of time the transistor is turned on or off. Assume that 480 volts 3 phase AC is rectified to DC and filtered. The DC voltage applied to the IGBTs is approximately 630 volts. The output voltage to the motor is controlled by the switching of the transistors. Assume that the transistor is on for 10 microseconds and off for 20 microseconds. In this example the transistor is on for one-third of the time and off for two-thirds of the time. The voltage applied to the motor would be 210 volts (630/3).

## Advantages and Disadvantages of IGBT Drives

A great advantage of drives using IGBTs is the fact that SCRs are generally not used in the power supply and this greatly reduces problems with line harmonics. The greatest disadvantage is that the fast switching rate of the transistors can cause voltage spikes in the range of 1,600 volts to be applied to the motor. These voltage spikes can destroy some motors. Line length from the drive to the motor is of great concern with drives using IGBTs. The shorter the line length the better.

## Inverter Rated Motors

Because of the problem of excessive voltage spikes caused by IGBT drives, some manufacturers produce a motor that is "inverter rated." These motors are specifically designed to be operated by variable

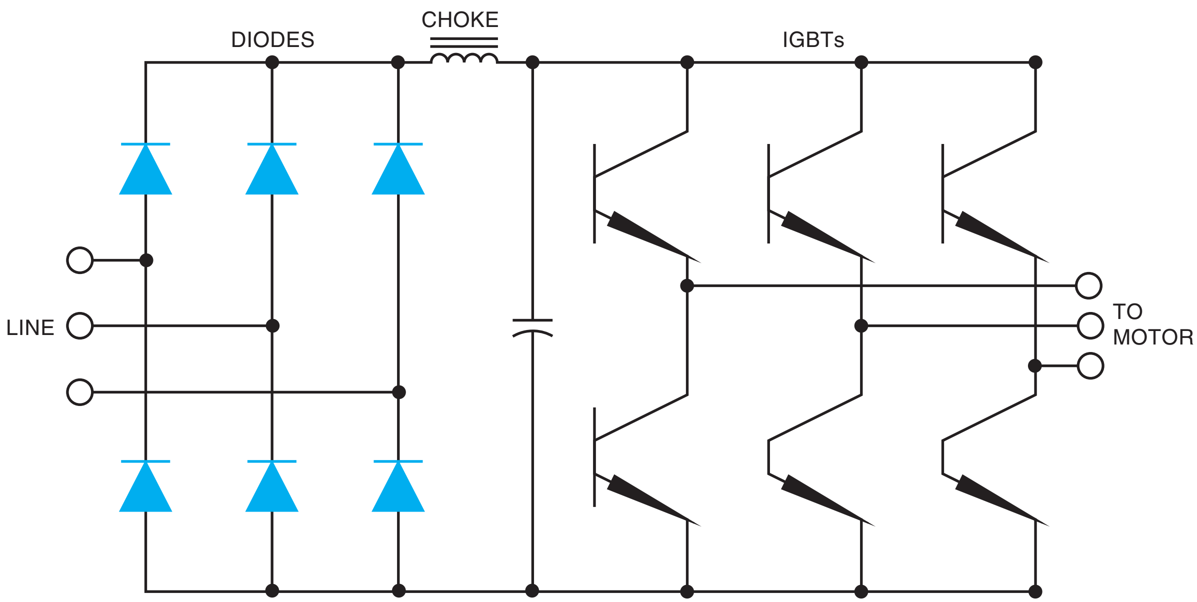



**Figure 13–9**
Variable frequency drives using IGBTs generally use diodes in the rectifier instead of SCRs. (Source: Delmar/Cengage Learning)

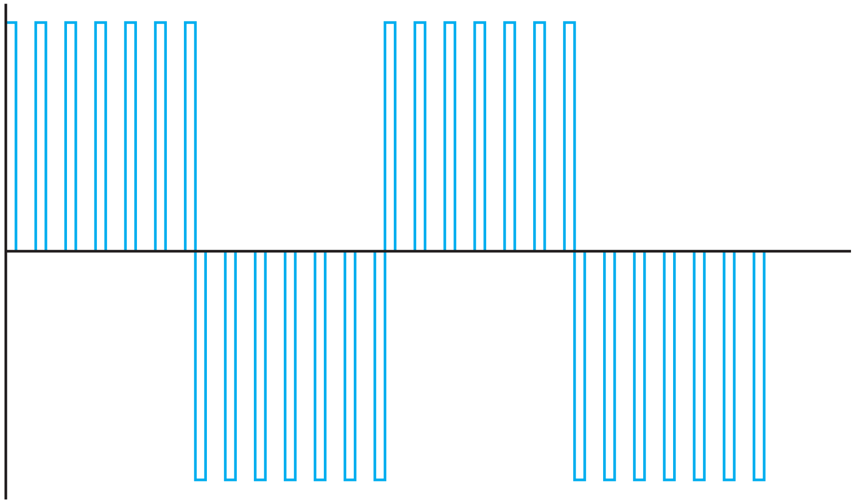


**Figure 13–10**
Pulse width modulation is accomplished by turning the voltage on and off several times during each half cycle.
(Source: Delmar/Cengage Learning)

frequency drives. They differ from standard motors in several ways:

1. Many inverter rated motors contain a separate blow to provide continuous cooling for the motor regardless of the speed. Many motors use a fan connected to the motor shaft to help draw air though the motor. When the motor speed is reduced, the fan cannot maintain sufficient air flow to cool the motor.
2. Inverter rated motors generally have insulating paper between the windings and the stator core, Figure 13–11. The high voltage spikes produce high currents that produce a high magnetic field. This increased magnetic field causes the motor windings to move. This movement can eventually cause the insulation to wear off the wire and produce a grounded motor winding.
3. Inverter rated motors generally have phase paper added to the terminal leads. Phase paper is insulating paper added to the terminal leads that exit the motor. The high voltage spikes affect the beginning lead of a coil much more than the wire inside the coil. The coil is an inductor that naturally opposes a change of current. Most of the insulation stress caused by high voltage spikes occurs at the beginning of a winding.
4. The magnet wire used in the construction of the motor windings has a higher rated insulation than other motors.

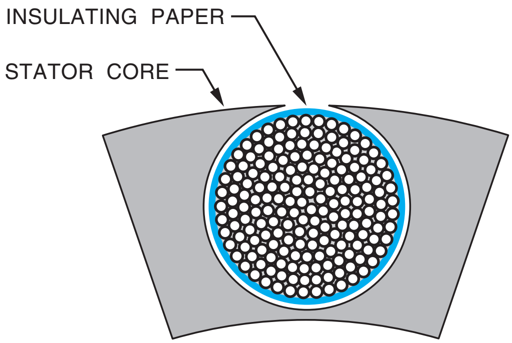



**Figure 13–11**
Insulating paper is between the windings and the stator frame. (Source: Delmar/Cengage Learning)

5. The case size is larger than most three phase motors. The case size is larger because of the added insulating paper between the windings and the stator core. Also, a larger case size helps cool the motor by providing a larger surface area for the dissipation of heat.

## Variable Frequency Drives Using SCRs and GTOs

Variable frequency drives intended to control motors over 500 horsepower generally use SCRs or GTOs (gate turn off device). GTOs are similar to SCRs except that conduction through the GTO can be stopped by applying a negative voltage, negative with respect to the cathode, to the gate. SCRs and

GTOs are thyristors and have the ability to handle a greater amount of current than transistors. An example of a single-phase circuit used to convert DC voltage to AC voltage with SCRs is shown in Figure 13–12. In this circuit, the SCRs are connected to a control unit which controls the sequence and rate at which the SCRs are gated on. The circuit is constructed so that SCRs A and A' are gated on at the same time and SCRs B and B' are gated on at the same time. Inductors $L_1$ and $L_2$ are used for filtering and wave shaping. Diodes D1 through D4 are clamping diodes and are used to prevent the output voltage from becoming excessive. Capacitor $C_1$ is used to turn one set of SCRs off when the other set is gated on. This capacitor must be a true AC capacitor because it will be charged to the alternate polarity each half cycle. In a converter intended to handle large amounts of power, capacitor $C_1$ will be a bank of capacitors. To understand the operation of the circuit, assume that SCRs A and A' are gated on at the same time. Current will flow through the circuit as shown in Figure 13–13. Notice the direction of current flow through the load, and also that capacitor $C_1$ has been charged to the polarity shown. When an SCR is gated on, it can only be turned off by permitting the current flow through the anode-cathode section to drop below a certain level called the holding current level. As long as the current continues to flow through the anode-cathode the SCR will not turn off.

Now assume that SCRs B and B' are turned on. Because SCRs A and A' are still turned on, two current paths now exist through the circuit. The positive charge on capacitor $C_1$, however, causes the negative electrons to see an easier path. The current will rush to charge the capacitor to the opposite

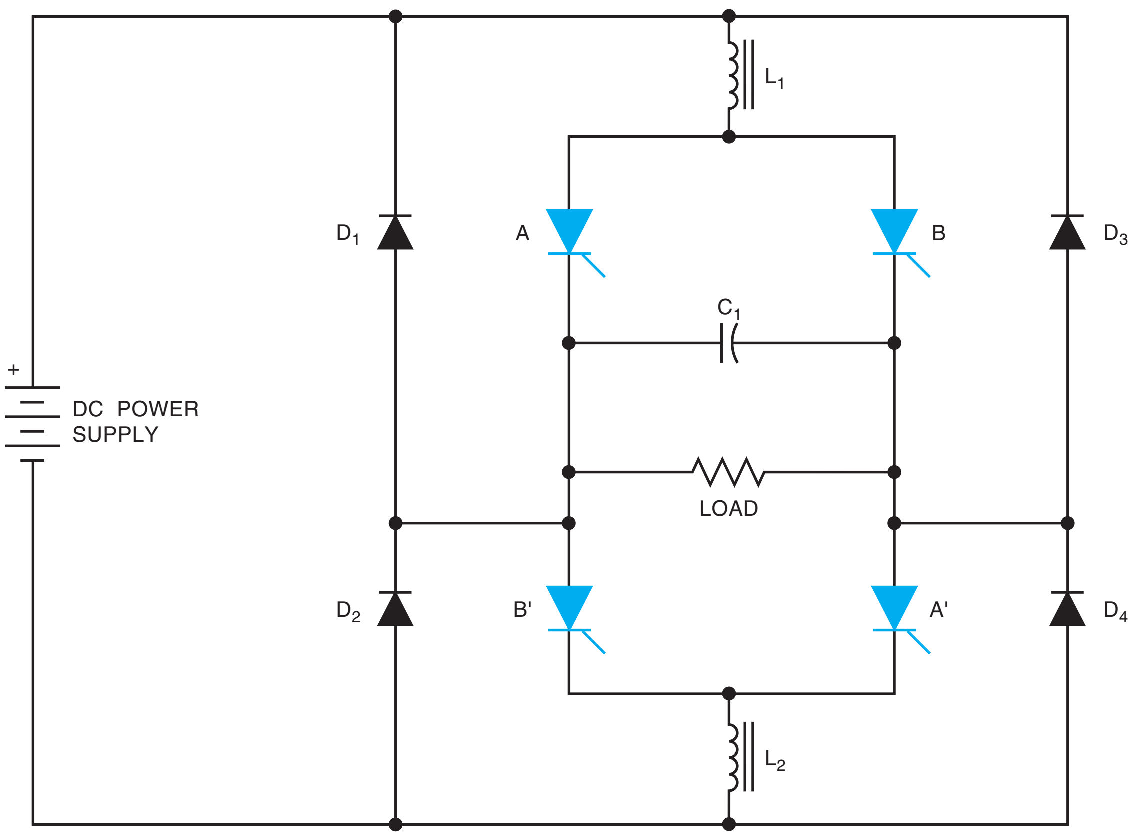



**Figure 13–12**
Changing DC to AC using SCRs. (Source: Delmar/Cengage Learning)

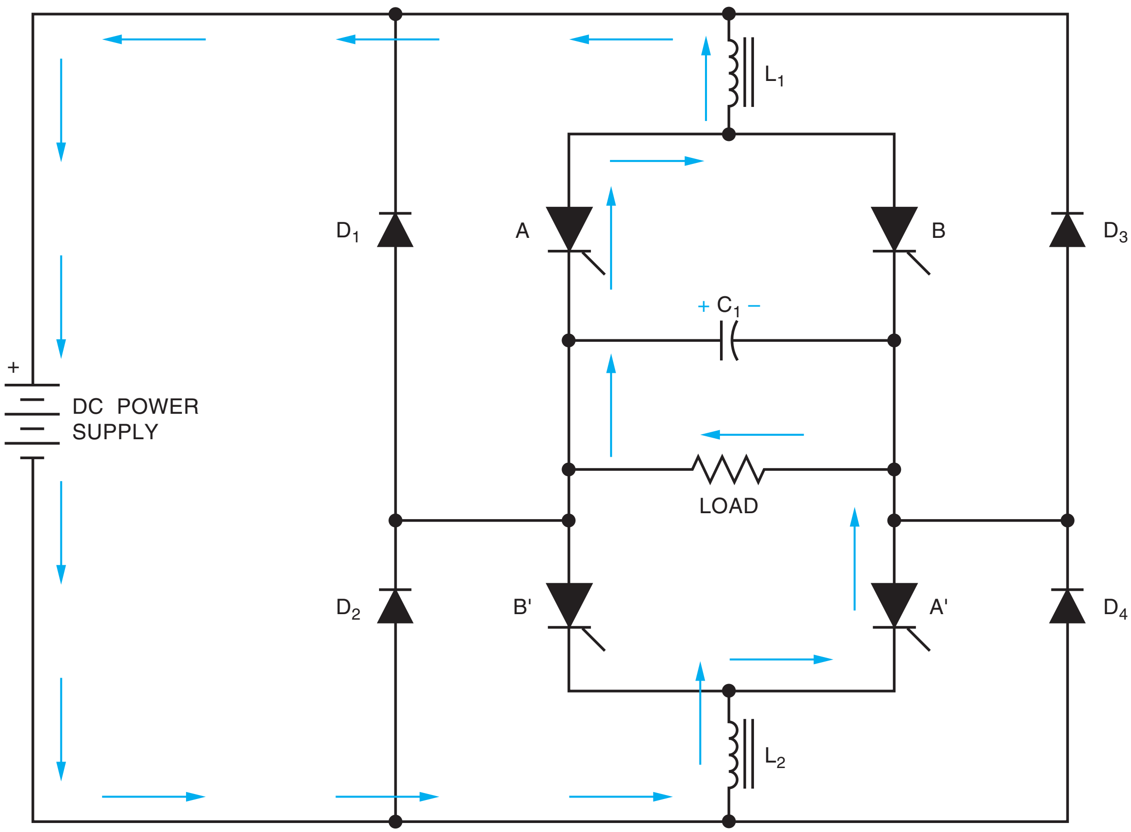



**Figure 13–13**
Current flows through SCRs A and A'. (Source: Delmar/Cengage Learning)

polarity, stopping the current flowing through SCRs A and A' permitting them to turn off. The current now flows through SCRs B and B' and charges the capacitor to the opposite polarity, Figure 13–14. Notice that the current now flows through the load in the opposite direction, which produces alternating current across the load.

To produce the next half cycle of AC current, SCRs A and A' are gated on again. The positively charged side of the capacitor will now cause the current to stop flowing through SCRs B and B' permitting them to turn off. The current again flows through the load in the direction indicated in Figure 13–14. The frequency of the circuit is determined by the rate at which the SCRs are gated on.

**FEATURES OF VARIABLE FREQUENCY CONTROL.** Although the primary purpose of a variable frequency drive is to provide speed control for an AC motor, most drives provide functions that other types of controls do not. Many variable frequency drives can provide the low speed torque characteristic that is so desirable in DC motors. It is this feature that permits AC squirrel-cage motors to replace DC motors for many applications.

Many variable frequency drives also provide current limit and automatic speed regulation for the motor. Current limit is generally accomplished by connecting current transformers to the input of the drive and sensing the increase in current as load is added. Speed regulation is accomplished by sensing the speed of the motor and feeding this information back to the drive.

Another feature of variable frequency drives is acceleration and deceleration control, sometimes

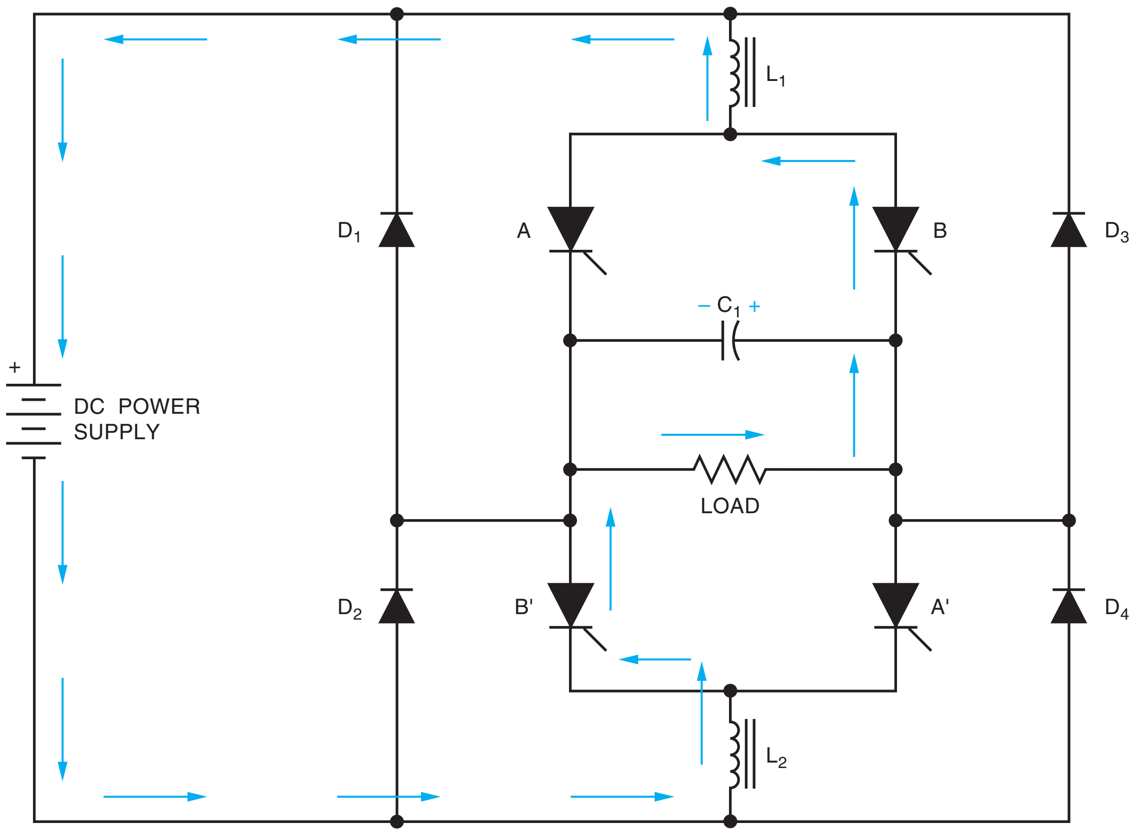



**Figure 13–14**
Current flows through SCRs B and B'. (Source: Delmar/Cengage Learning)

called "ramping." Ramping is used to accelerate or decelerate a motor over some period of time. Ramping permits the motor to bring the load up to speed slowly as opposed to simply connecting the motor directly to the line. Even if the speed control is set in the maximum position when the start button is pressed, ramping permits the motor to accelerate the load from zero to its maximum RPM over several seconds. This feature can be a real advantage for some types of loads, especially gear drive loads. In some units the amount of acceleration and deceleration time can be adjusted by setting potentiometers on the main control board. Other units are completely digitally controlled and the acceleration and deceleration times are programmed into the computer memory.

Some other adjustments that can usually be set by changing potentiometers or programming the unit are as follows:

**Current Limit:** These controls set the maximum amount of current the drive is permitted to deliver to the motor.

**Volts per Hertz:** This sets the ratio by which the voltage increases as frequency increases or decreases as frequency decreases.

**Maximum Hertz:** These controls set the maximum speed of the motor.

**Minimum Hertz:** This sets the minimum speed the motor is permitted to run.

## SUMMARY

- Consequent pole motors change speed by changing the number of stator poles.
- The disadvantage of consequent pole motors is that they have a wide range between speeds.
- The advantage of the consequent pole motor is that it maintains a high torque.
- Consequent pole motors are generally used to operate two-speed compressors because of their ability to maintain high torque.
- Multispeed fan motors insert inductance in series with the main run winding to produce a change of speed.
- The run windings of multispeed fan motors have a high resistance so they will not overheat when the motor slows down.
- Multispeed fan motors cannot be used to operate high torque loads.
- Variable frequency drives change the speed of the motor by changing the frequency of the applied voltage.
- The synchronous speed of an induction motor is the speed of the rotating magnetic field.
- Synchronous speed is determined by two factors: number of stator poles per phase, and frequency of the applied voltage.
- When the frequency to the motor is reduced, the voltage must be reduced also.
- Variable frequency drives up to 500 horsepower generally use transistors to change the DC voltage back into AC voltage.
- Variable frequency drives above 500 horsepower generally use SCRs or GTOs to change the DC voltage back into AC voltage.
- Insulated gate bipolar transistors are used in many variable frequency drives because they can be switched on or off at a faster rate.
- Units employing IGBTs can produce voltage spikes on the motor as high as 1,600 volts.
- Inverter rated motors are designed to operate with variable frequency drives.
- Some variable frequency drives use potentiometers to change settings, and others are digital and must have the setting programmed into the drive.

## KEY TERMS

**consequent pole motor**
**harmonics**
**insulated gate bipolar transistors (IGBTs)**
**multispeed AC motors**
**polarity**
**pulse width modulation (PWM)**
**silicon controlled rectifiers (SCRs)**
**tapped**
**two-speed compressors**
**variable frequency**

## REVIEW QUESTIONS

1. Name two ways of changing the speed of a rotating magnetic field.
2. How does the consequent pole motor change speed?
3. Name a disadvantage of the consequent pole motor.
4. Name an advantage of a consequent pole motor.
5. How many steps of speed are common to a multispeed fan motor?
6. Refer to Figure 13–3. Explain what would happen to motor operation if the winding between low and medium should become open.
7. What is an advantage of the multispeed fan motor over the consequent pole motor?
8. What is a disadvantage of the multispeed fan motor when compared with the consequent pole motor?
9. How much wire resistance is common for the run winding of most split-phase motors?
10. How much wire resistance is common for the multispeed fan motor?
11. What is synchronous speed?
12. What is the disadvantage of a variable frequency drive unit that uses SCRs to convert the AC voltage into DC voltage?
13. What is the disadvantage of driving a common bipolar junction transistor into saturation?
14. What is the main advantage of the insulated grate bipolar transistor over the common bipolar junction transistor?
15. What is an inverter rated motor?

## TROUBLESHOOTING QUESTIONS

Refer to the schematic shown in Figure 13–4 to answer the following questions.

1. If the switch is set in the HI position, the thermostat will control the operation of:
   A. The compressor only.
   B. The fan motor only.
   C. The speed of the fan motor.
   D. Both the compressor and the speed of the fan motor.
2. When the switch is set in the HI position, both the fan motor and compressor operate. If the switch is changed to the MED or LOW position, the compressor continues to operate, but the fan motor stops. Which of the following could cause this problem?
   A. The fan motor start winding is open.
   B. The section of run winding between the red and blue wires is open in the fan motor.
   C. The section of run winding between the blue and black wires is open in the fan motor.
   D. The section of run winding between the black and white wires is open in the fan motor.

3. The fan motor will operate in any of its three speeds, but the compressor motor will not start. Which of the following could cause this problem?
   A. The switch is not making connection between L and C.
   B. The switch is not making connection between L and LO.
   C. The switch is not making connection between L and MED.
   D. The switch is not making connection between L and HI.
4. If it is assumed that this unit operates on 120 volts AC, how is the neutral conductor identified on the schematic shown in Figure 13–4?
   A. The wire color is green.
   B. The wire color is white.
   C. The conductor is ribbed.
   D. The conductor is plain.
5. If the unit is in operation and the overload protector should open:
   A. Both the fan motor and compressor will stop operating.
   B. Only the compressor will stop operating.
   C. Only the fan motor will stop operating.
   D. Both the fan motor and compressor will continue to operate.

# UNIT 14

# Three-Phase Motor Principles

## OBJECTIVES

After studying this unit the student should be able to:

- List the three major types of three-phase motors
- Discuss the operating principle of a three-phase motor
- List the factors that determine synchronous speed
- Discuss the operation of dual-voltage motors
- Connect dual-voltage three-phase motors for operation on low voltage or high voltage

There are three basic types of **three-phase motors**. These are:

1. The squirrel-cage induction motor.
2. The wound rotor induction motor.
3. The synchronous motor.

The type of three-phase motor is determined by the rotor or rotating member. The stator windings for any of these motors is the same. In this unit, the basic principles of operation for three-phase motors will be discussed.

The principle of operation for all three-phase motors is the **rotating magnetic field**. There are three factors that cause the magnetic field to rotate. These are:

1. The voltages of a three-phase system are 120° out of phase with each other.

2. The three voltages change polarity at regular intervals.
3. The arrangement of the stator windings around the inside of the motor.

Figure 14–1A shows three AC voltages 120° out of phase with each other, and the stator winding of a three-phase motor. The stator illustrates a two-pole, three-phase motor. Two-pole means that there are two poles per phase. AC motors do not generally have actual pole pieces as shown in Figure 14–1A, but they will be used here to aid in understanding how the rotating magnetic field is created in a three-phase motor. Notice that pole pieces 1A and 1B are located opposite each other. The same is true for poles 2A and 2B, and 3A and 3B. The pole pieces 1A and 1B are wound with wire that is connected to phase one of the three-phase system. Notice also that the pole pieces are wound in such a manner that they will always have opposite magnetic polarities. If pole piece 1A has a north magnetic polarity, pole piece 1B will have a south magnetic polarity at the same time.

The windings of pole pieces 2A and 2B are connected to line 2 of the three-phase system. The windings of pole pieces 3A and 3B are connected to line 3 of the three-phase system. These pole pieces are also wound in such a manner as to have the opposite polarity of magnetism.

To understand how the magnetic field rotates around the inside of the motor, refer to Figure 14–1B. Notice a line, labeled "A," has been drawn through the three voltages of the system. This line is used to illustrate the condition of the three voltages at this point in time. The arrow drawn inside the motor indicates the greatest strength of the magnetic field at the same point in time. It is to be assumed that the arrow is pointing in the direction of the north magnetic field. Notice in Figure 14–1B, that phase 1 is at its maximum positive peak, and that phases 2 and 3 are less than maximum. The magnetic field is, therefore, strongest between pole pieces 1A and 1B.

In Figure 14–1C, line B indicates that the voltage of line 3 is zero. The voltage of line 1 is less than maximum positive; and line 2 is less than maximum negative. The magnetic field at this point is concentrated between the pole pieces of phase 1 and phase 2.

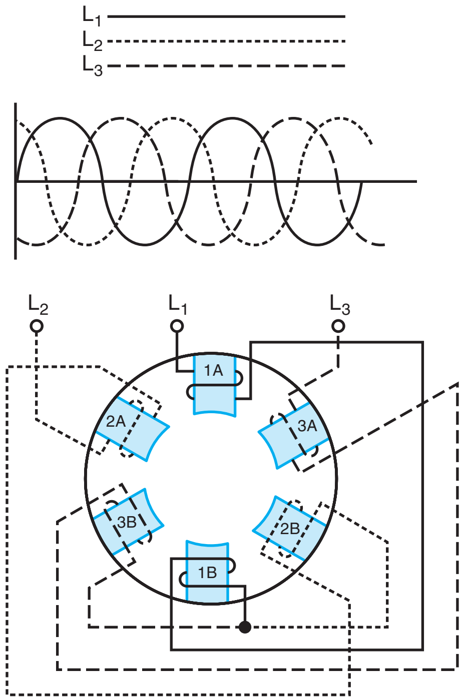



**Figure 14–1A**
Basic stator winding. (Source: Delmar/Cengage Learning)

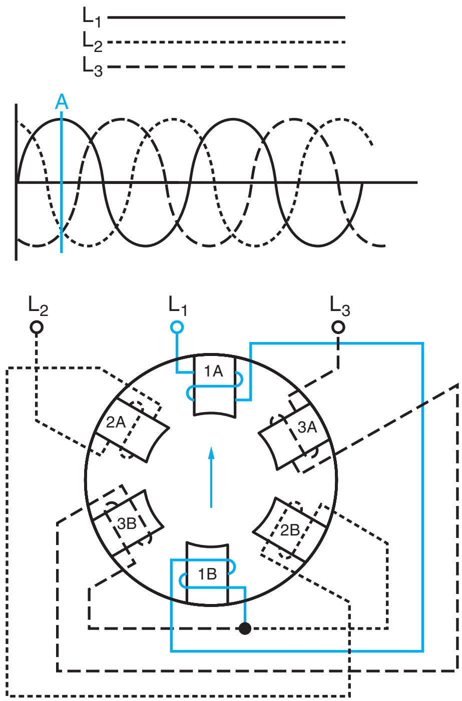



**Figure 14–1B**
The magnetic field is concentrated between the poles of phase 1. (Source: Delmar/Cengage Learning)

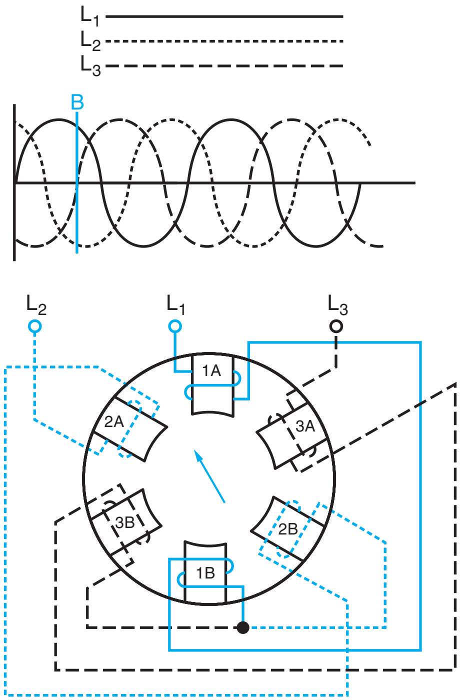



**Figure 14–1C**
The magnetic field is concentrated between phases 1 and 2. (Source: Delmar/Cengage Learning)

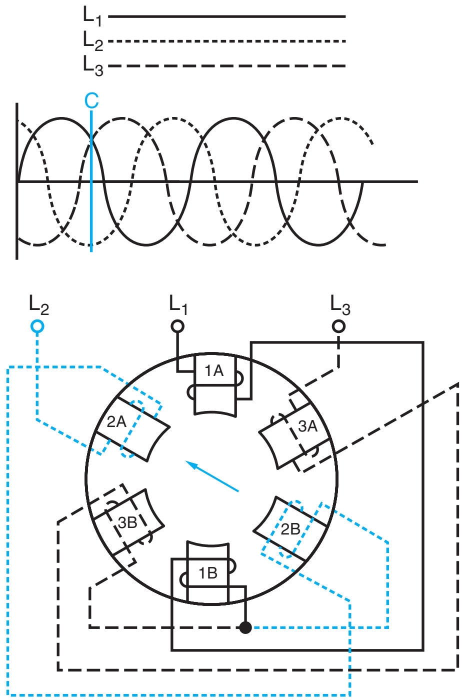



**Figure 14–1D**
The magnetic field is concentrated between the poles of phase 1. (Source: Delmar/Cengage Learning)

In Figure 14–1D, line C indicates that line 2 is at its maximum negative peak and that lines 1 and 3 are less than maximum positive. The magnetic field at this point is concentrated between pole pieces 2A and 2B.

In Figure 14–1E, line D indicates that line 1 is zero. Lines 2 and 3 are less than maximum and in opposite directions. At this point, the magnetic field is concentrated between the pole pieces of phase 2 and phase 3.

In Figure 14–1F, line E indicates that phase 3 is at its maximum positive peak and lines 1 and 2 are less than maximum and in the opposite direction. The magnetic field at this point is concentrated between pole pieces 3A and 3B.

In Figure 14–1G, line F indicates that phase 2 is 0. Line 3 is less than maximum positive; and line 1 is less than maximum negative. The magnetic field at this time is concentrated between the pole pieces of phase 1 and phase 3.

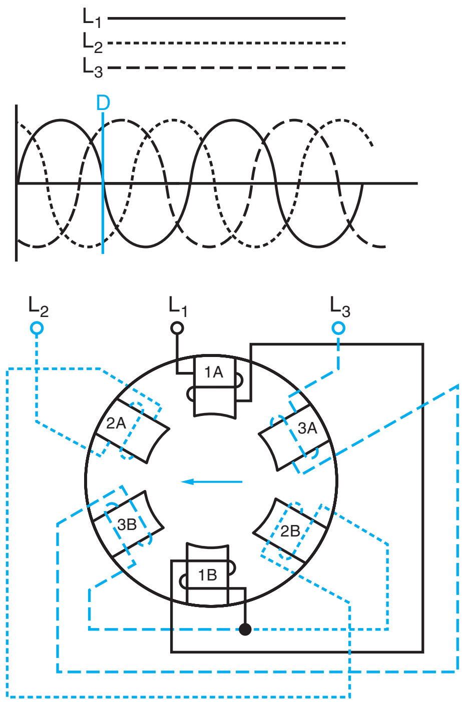



**Figure 14–1E**
The magnetic field is concentrated between phases 2 and 3. (Source: Delmar/Cengage Learning)

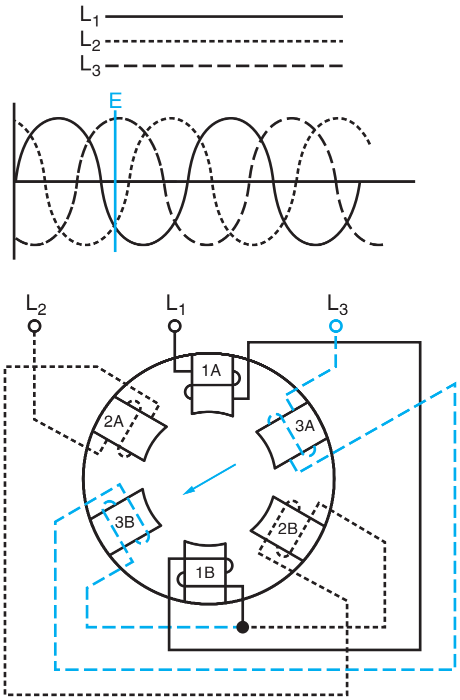



**Figure 14–1F**
The magnetic field is concentrated between the poles of phase 3. (Source: Delmar/Cengage Learning)

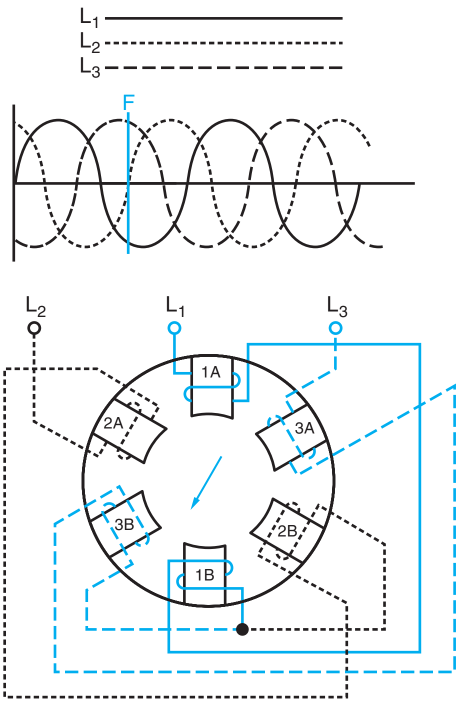



**Figure 14–1G**
The magnetic field is concentrated between phases 1 and 3.
(Source: Delmar/Cengage Learning)

In Figure 14–1H, line G indicates that phase 1 is at its maximum negative peak; and phase 2 and 3 are less than maximum and in the opposite direction. Notice that the magnetic field is again concentrated between pole pieces 1A and 1B. This time, however, the magnetic polarity is reversed because the current has reversed in the stator winding.

In Figure 14–1I, line H indicates phase 2 is at its maximum positive peak and phases 1 and 3 are less than maximum and in the negative direction. The magnetic field is concentrated between pole pieces 2A and 2B.

In Figure 14–1J, line 1 indicates that phase 3 is maximum negative; and phases 1 and 2 are less than maximum in the positive direction. The magnetic field at this point is concentrated between pole pieces 3A and 3B.

In Figure 14–1K, line J indicates that phase 1 is at its positive peak; and phases 2 and 3 are less than maximum and in the opposite direction. The

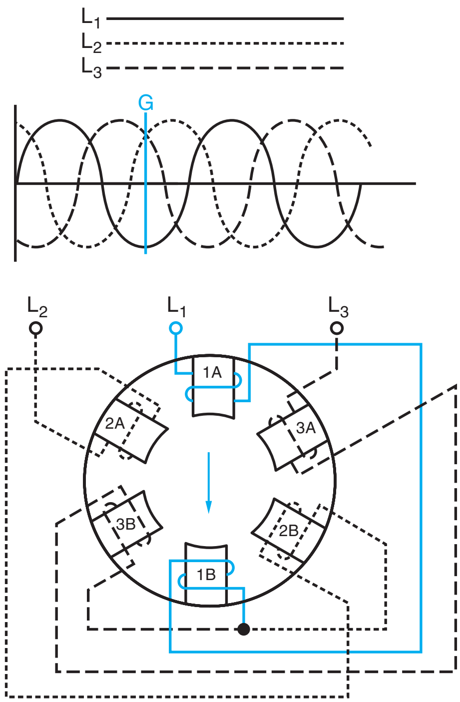



**Figure 14–1H**
The magnetic field is concentrated between the poles of phase 1. (Source: Delmar/Cengage Learning)

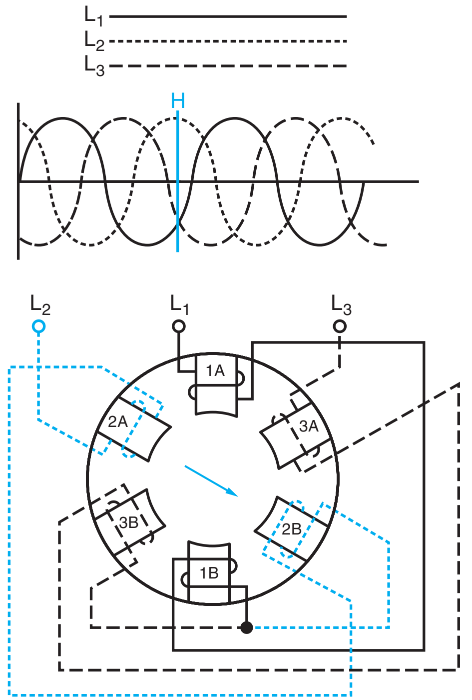



Figure 14–1I
The magnetic field is concentrated between the poles of phase 2. (Source: Delmar/Cengage Learning)

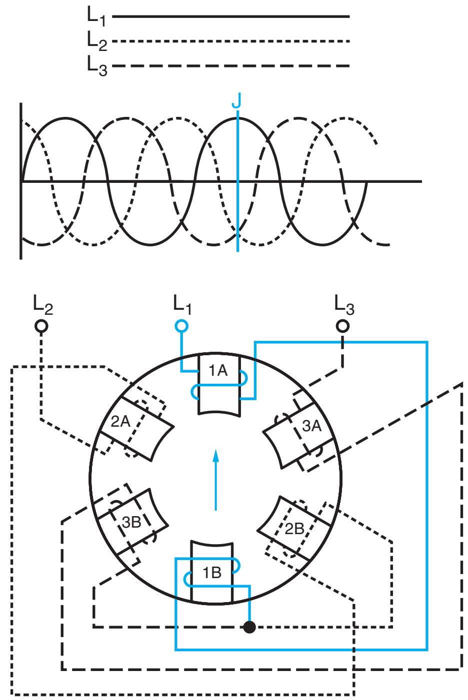



Figure 14–1K
The magnetic field has rotated 360°.
(Source: Delmar/Cengage Learning)

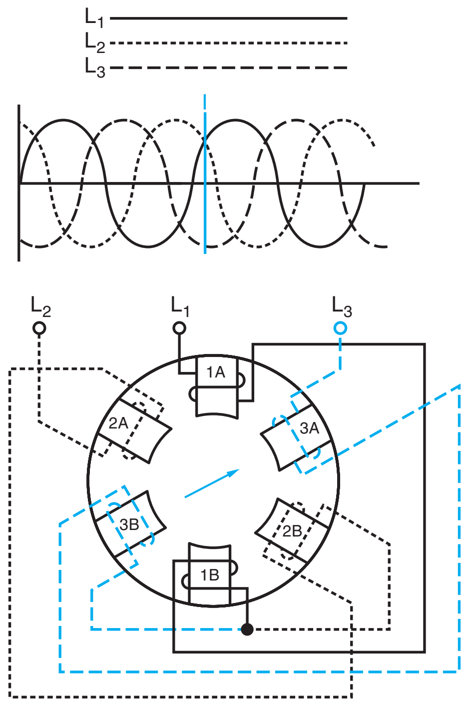



Figure 14–1J
The magnetic field is concentrated between the poles of phase 3. (Source: Delmar/Cengage Learning)

magnetic field is again concentrated between pole pieces 1A and 1B. Notice that in one complete cycle of three-phase voltage, the magnetic field has rotated 360° around the inside of the stator winding.

If any two of the stator leads is connected to a different line, the relationship of the voltages will change and the magnetic field will rotate in the opposite direction. The direction of rotation of a three-phase motor can be reversed by changing any two stator leads.

## SYNCHRONOUS SPEED

The speed at which the magnetic field rotates is known as the **synchronous speed**. The synchronous speed of a three-phase motor is determined by two factors. These are:

1. The number of stator poles.
2. The frequency of the AC line.

Because 60 Hz is a standard frequency throughout the United States and Canada, the following gives the synchronous speeds for motors with different numbers of poles.

| | |
|---|---|
| 2 Poles | 3,600 RPM |
| 4 Poles | 1,800 RPM |
| 6 Poles | 1,200 RPM |
| 8 Poles | 900 RPM |

## STATOR WINDINGS

The stator windings of three-phase motors are connected in either a wye or delta. Some stators are designed in such a manner as to be connected in either wye or delta, depending on the operation of the motor. Some motors, for example, are started as a wye-connected stator to help reduce starting current, and then changed to a delta connection for running.

Many three-phase motors have dual-voltage stators. These stators are designed to be connected to 240 volts or 480 volts. The leads of a dual-voltage stator use a standard numbering system. Figure 14–2 shows a dual-voltage wye-connected stator. Notice the stator leads have been numbered in a spiral. This diagram shows that numbers 1 and 4 are opposite ends of the same coil. Lead number 7 begins another coil, and this coil is to be connected to the same phase as 1 and 4. Leads 2 and 5 are opposite ends of the same coil. Coil number 8 must be connected with the same phase as leads 2 and 5. Leads 3 and 6 are opposite ends of a coil and must be connected with lead number 9. Keep in mind that Figure 14–2 is a schematic diagram, and that when connecting a three-phase motor for operation at the proper voltage, the leads will look more like Figure 14–3. This figure illustrates the leads coming out of the terminal connection box on the motor. Some leads are numbered with metal or plastic bands on the wires, and some leads have numbers printed on the insulation of the wire.

Figure 14–4 shows the stator connection for operation on a 480-volt line. Figure 14–5 shows

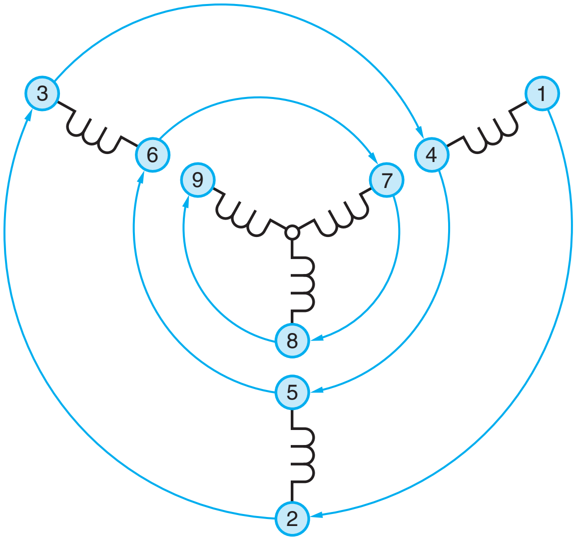



**Figure 14–2**
Numbering a dual-voltage stator. (Source: Delmar/Cengage Learning)

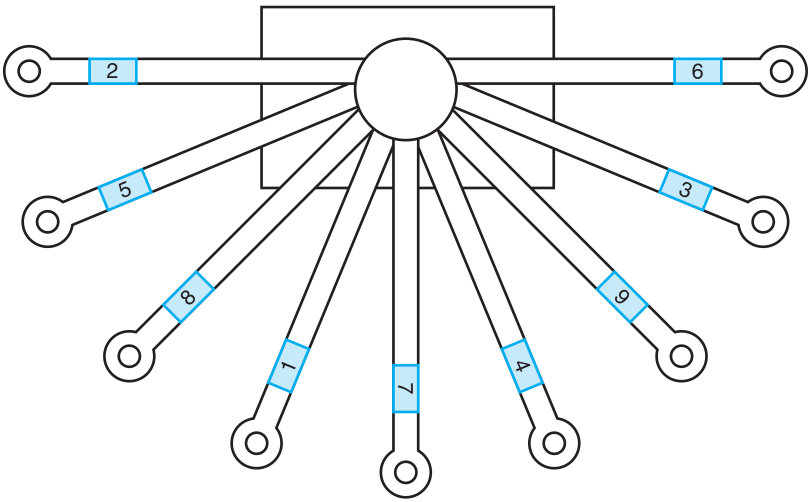



**Figure 14–3**
Leads of a dual-voltage motor.
(Source: Delmar/Cengage Learning)

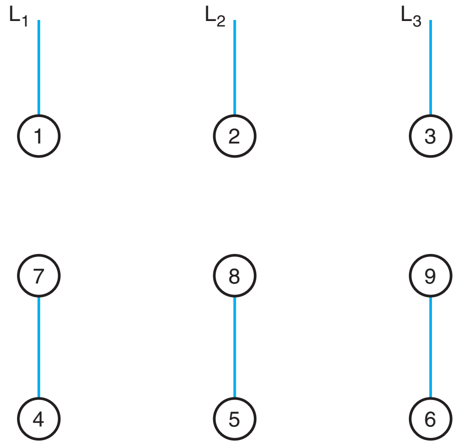



Figure 14–4
High-voltage connection. (Source: Delmar/Cengage Learning)

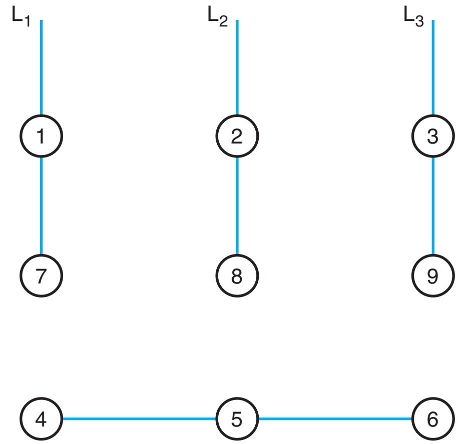



Figure 14–6
Low-voltage connection. (Source: Delmar/Cengage Learning)

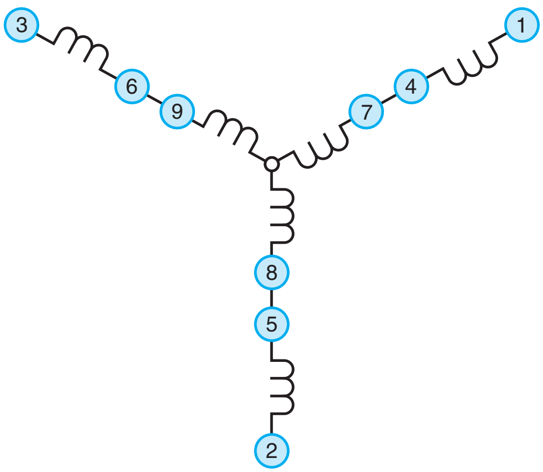



Figure 14–5
Windings connected in series. (Source: Delmar/Cengage Learning)

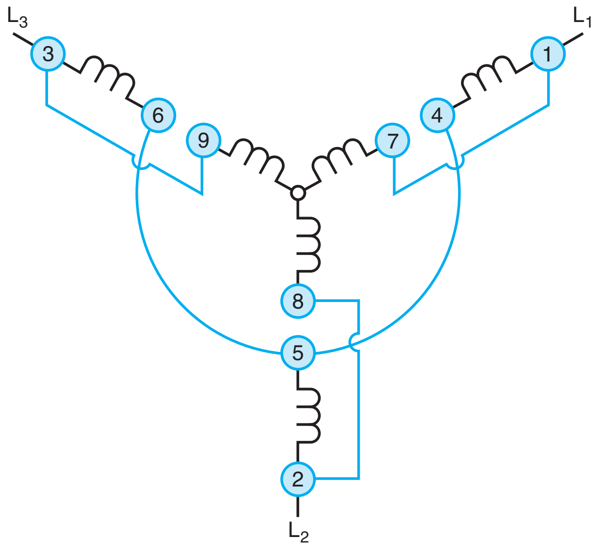



Figure 14–7
Windings connected in parallel. (Source: Delmar/Cengage Learning)

the schematic equivalent of this connection. Notice that the windings have been connected in series. Figure 14–6 shows the stator connection for operation on a 240-volt line. Figure 14–7 shows the schematic equivalent of this connection. When the motor is to be operated on 240 volts, the stator windings are connected in parallel. Notice that leads 4, 5, and 6 are connected together to form another center point. This centerpoint is electrically the same as the point where leads 7, 8, and 9 join together. Figure 14–8 shows the equivalent circuit.

When a motor is operated on a 240-volt line, the current draw of the motor is double the current draw of a 480-volt connection. For example, if a motor draws 10 amps of current when connected to 240 volts, it will draw 5 amps when connected to 480 volts. The reason for this is the difference of impedance in the windings between a 240-volt connection and a 480-volt connection. For instance, assume the stator windings of a motor have an

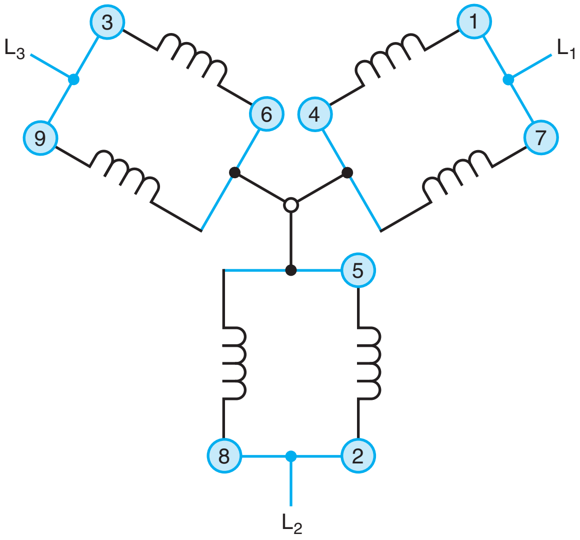



**Figure 14–8**
Equivalent parallel circuit. (Source: Delmar/Cengage Learning)

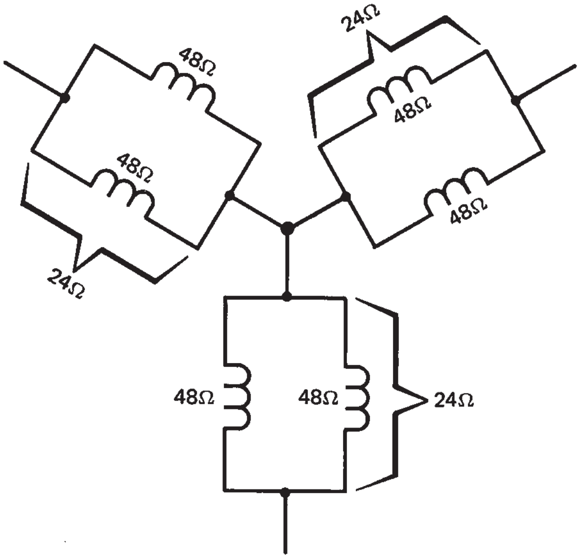



**Figure 14–9**
Total impedance of a parallel connection. (Source: Delmar/Cengage Learning)

impedance of 48 ohms. If the stator windings are connected in parallel as shown in Figure 14–9, the total impedance of the windings is 24 ohms.

$$Rt = \frac{R1 \times R2}{R1 + R2}$$

$$Rt = \frac{48 \times 48}{48 + 48}$$

$$Rt = \frac{2304}{96}$$

$$Rt = 24 \text{ ohms}$$

If 240 volts is applied to this connection, 10 amps of current will flow.

$$I = \frac{E}{R}$$

$$I = \frac{240}{24}$$

$$I = 10 \text{ amps}$$

If the windings are connected in series for operation on a 480-volt line as shown in Figure 14–10, the total impedance of the winding is 96 ohms.

$$Rt = R1 + R2$$

$$Rt = 48 + 48$$

$$Rt = 96 \text{ ohms}$$

If 480 volts is applied to this winding, 5 amps of current will flow.

$$I = \frac{E}{R}$$

$$I = \frac{480}{96}$$

$$I = 5 \text{ amps}$$

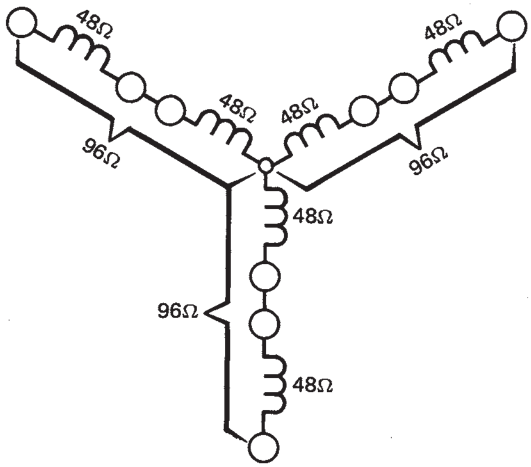



**Figure 14–10**
Impedance adds in series. (Source: Delmar/Cengage Learning)

## DELTA CONNECTIONS

Three-phase motors are also connected in delta. The same standard numbering system is used for delta-connected motors. If a dual-voltage motor is to be connected in delta, there must be 12 leads instead of 9 leads brought out at the terminal box.

Figure 14–11 shows the schematic diagram of a motor connected for operation as a high-voltage delta. Notice that the stator windings for each phase have been connected in series for operation on high voltage. If the motor is to be connected for operation on a low voltage, the windings will be connected in parallel as shown in Figure 14–12. Figure 14–13 shows an equivalent parallel connection.

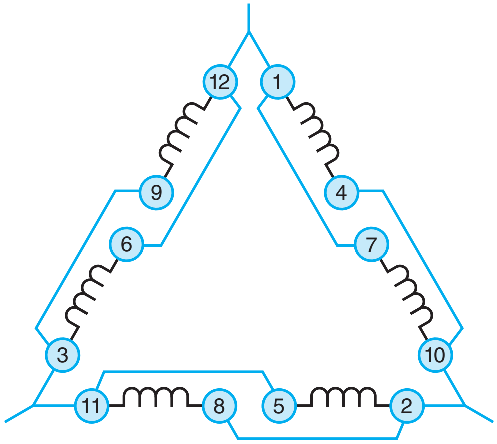



**Figure 14–12**
Low-voltage delta connection. (Source: Delmar/Cengage Learning)

## SPECIAL CONNECTIONS

Some three-phase motors designed for operation on voltages higher than 600 volts may have more than 9 or 12 leads brought out at the terminal box. A motor with 15 or 18 leads can be found in high-voltage installations. A 15-lead motor has 3 coils per phase instead of 2. Figure 14–14 shows the proper number sequence for a 15-lead motor. Notice the leads are numbered in the same spiral as a 9-lead motor.

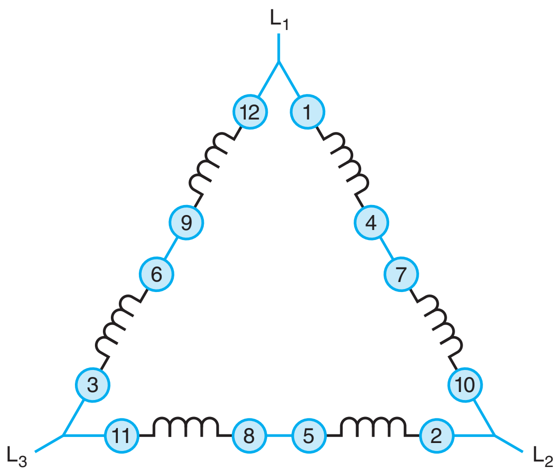



**Figure 14–11**
High-voltage delta connection. (Source: Delmar/Cengage Learning)

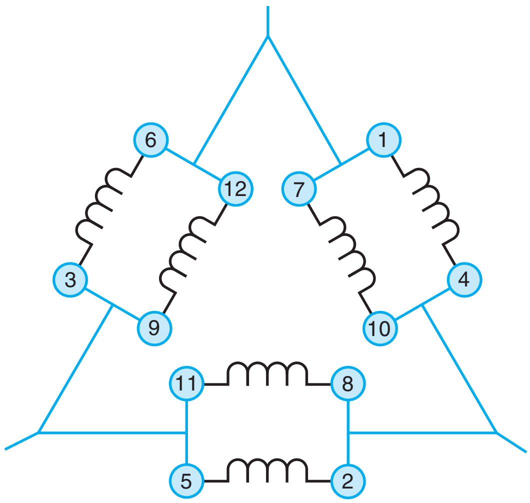



**Figure 14–13**
Equivalent parallel delta connection. (Source: Delmar/Cengage Learning)

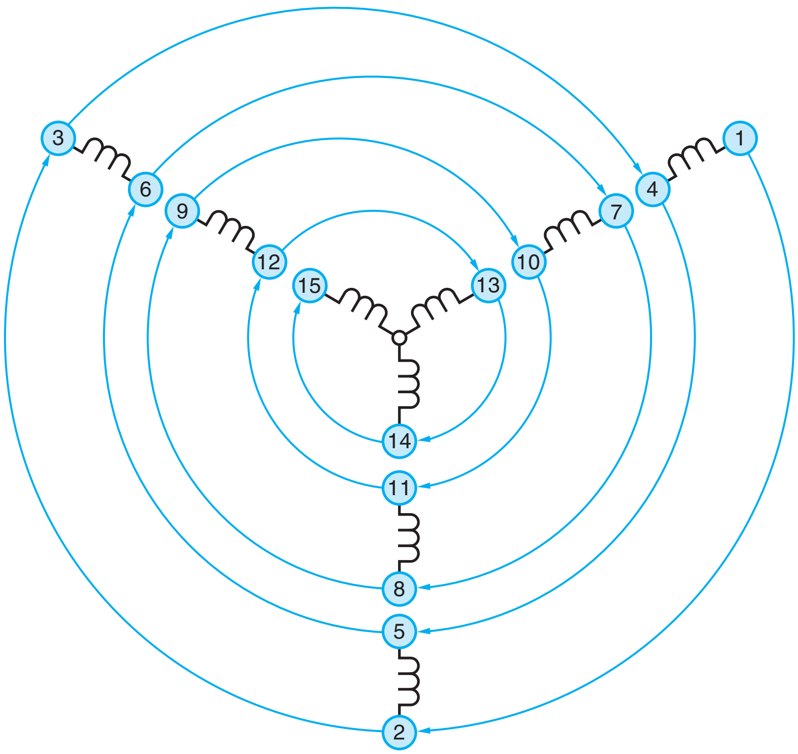



**Figure 14–14**
Fifteen-lead motor.
(Source: Delmar/Cengage Learning)

## SUMMARY

- The three basic types of three-phase motors are:
  A. Squirrel-cage induction.
  B. Wound rotor induction.
  C. Synchronous.
- All three-phase motors operate on the principle of a rotating magnetic field.
- Three factors that cause a magnetic field to rotate are:
  A. The voltages of a three-phase system are 120° out of phase with each other.
  B. The three voltages change polarity at regular intervals.
  C. The arrangement of the stator winding around the inside of the motor.
- The speed of the rotating magnetic field is determined by two factors:
  A. The number of stator poles.
  B. The frequency of the applied voltage.
- The ends of the stator windings are numbered in a standard manner.
- The stator windings of some three-phase motors are connected in a wye configuration and some are connected in a delta configuration.

- When a dual-voltage motor is to be connected for operation at low voltage, the stator windings will be connected in parallel.
- When a dual-voltage motor is to be connected for operation on high voltage, the stator windings will be connected in series.

## KEY TERMS

**rotating magnetic field**
**synchronous speed**
**three-phase motors**

## REVIEW QUESTIONS

1. What are the three basic types of three-phase motors?
2. Name three factors that produce a rotating magnetic field.
3. What is synchronous speed?
4. What two factors determine the synchronous speed of a three-phase motor?
5. How is the direction of rotation of a three-phase motor changed?
6. What is the synchronous speed of a four-pole motor when connected to a 60-Hz line?
7. A dual-voltage three-phase motor has a current draw of 50 amps when connected to a 240-volt line. How much current will flow if the motor is connected for operation on 480 volts?
8. If the stator windings of a three-phase motor are connected for operation on high voltage, will the windings be connected in series or parallel?
9. If a dual-voltage motor is connected for operation on low voltage, and the motor is then connected to high voltage, will the motor operate at a faster speed?
10. Why does a dual-voltage motor draw more current when connected to low voltage than it does when connected to high voltage?

# UNIT 15

# The Squirrel-Cage Induction Motor

## OBJECTIVES

After studying this unit the student should be able to:

- Discuss the principle of operation of a squirrel-cage three-phase motor
- List the factors that determine the amount of torque developed by a squirrel-cage motor
- Discuss code letters and their meaning
- Perform an ohmmeter test on a three-phase squirrel-cage motor

The **squirrel-cage induction motor** receives its name from the fact that the rotor contains a set of bars that resemble a squirrel cage. If the soft-iron laminations were to be removed from the rotor, it would be seen that the rotor contains a set of metal bars joined together at each end by a metal ring, Figure 15–1. Figure 15–2 shows a complete squirrel-cage rotor and stator winding.

## PRINCIPLE OF OPERATION

The squirrel-cage motor is an induction motor. This means that the current flow in the rotor is produced by induced voltage from the rotating magnetic field of the stator. In Figure 15–3, a squirrel-cage rotor is shown inside the stator winding of a three-phase motor. It will be assumed that the motor shown in Figure 15–3 contains four poles per phase, which

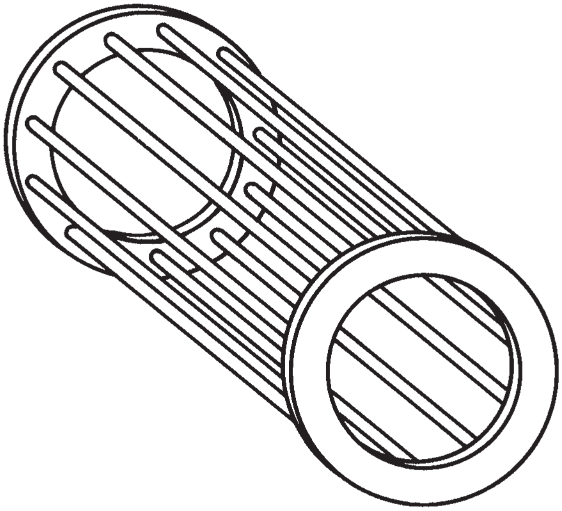


**Figure 15–1**
Squirrel-cage bars. (Source: Delmar/Cengage Learning)

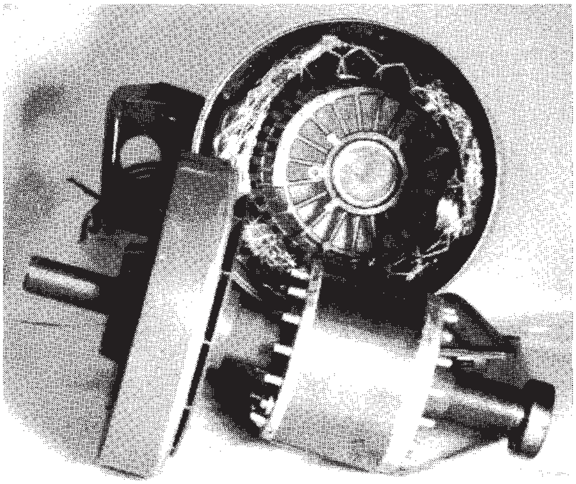


**Figure 15–2**
Rotor and stator of a three-phase squirrel-cage motor. (Source: Delmar/Cengage Learning)

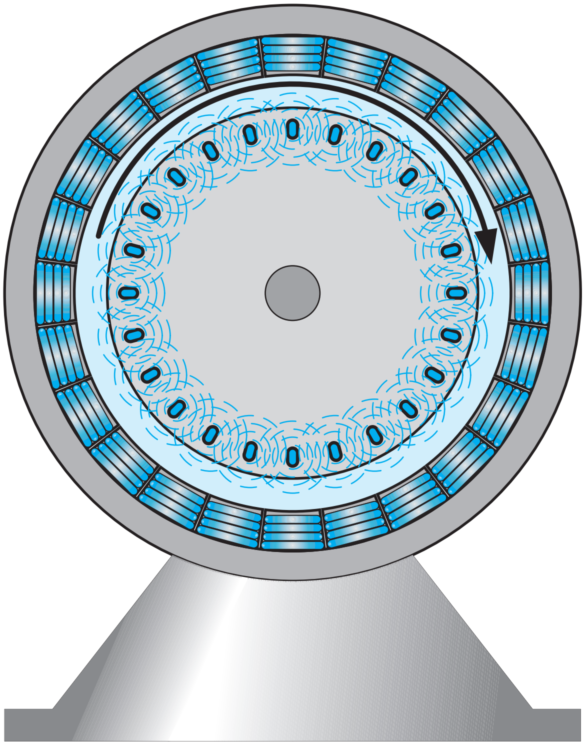


**Figure 15–3**
Voltage is induced into the rotor by the rotating magnetic field. (Source: Delmar/Cengage Learning)

produces a synchronous speed of 1,800 RPM (revolutions per minute) when the stator is connected to a 60-Hz line. When power is first connected to the stator, the rotor is not turning. The magnetic field of the stator cuts the **rotor bars** at a rate of 1,800 RPM. Three factors that determine the amount of induced voltage follow:

1. The strength of the magnetic field.
2. The number of turns of wire cut by the magnetic field. (This is sometimes stated as length of conductor.)
3. Speed of the cutting action.

Because the rotor is stationary at this time, maximum voltage is induced into the rotor. The induced voltage causes current to flow through the rotor bars. As current flows through the rotor, a magnetic field is produced around each rotor bar. The magnetic field of the rotor is attracted to the magnetic field of the stator, and the rotor begins to turn in the same direction as the rotating magnetic field.

As the speed of the rotor increases, the rotating magnetic field cuts the rotor bars at a slower rate. For example, assume the rotor has accelerated to a speed of 600 RPM. The synchronous speed of the rotating magnetic field is 1,800 RPM. Therefore, the rotor is being cut at a rate of 1,200 RPM.

(1,800 RPM – 600 RPM = 1,200 RPM). Because the rotor is being cut at a slower rate, less voltage is induced into the rotor. This produces less current flow through the rotor. When the current flow in the rotor is reduced, the current flow in the stator is reduced also.

As the rotor continues to accelerate, the rotating magnetic field cuts the rotor bars at a slower rate. This causes less voltage to be induced into the rotor, and therefore, less current flow in the rotor. Notice that the maximum amount of induced voltage and current occurs when the rotor is not turning at the instant of start. This is the reason that AC induction motors require more current to start than to run.

## TORQUE

Torque is the amount of turning or twisting force developed by a motor. It is generally measured in pound-inches or pound-feet depending on the application. Imagine a bar one foot in length attached to the shaft of a motor. A torque of one pound-foot would be the force exerted by applying a pressure of one pound on the end of the bar.

The amount of torque produced by an AC induction motor is determined by three factors. These are:

1. The strength of the magnetic field of the stator.
2. The strength of the magnetic field of the rotor.
3. The phase angle difference between stator and rotor flux.

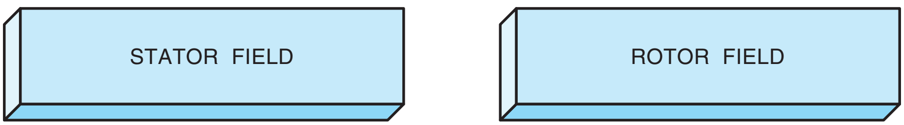
Notice that one of the factors that determines the amount of torque produced by an induction motor is the strength of the magnetic field of the rotor. *An induction motor cannot run at synchronous speed.* If the rotor was to accelerate to the speed of the rotating magnetic field, there would be no cutting action of the squirrel-cage bars and, therefore, no current flow in the rotor. If there was no current flow in the rotor, there could be no rotor magnetic field and, therefore, no torque.

When an induction motor is operating with no load connected to it, it will run close to the synchronous speed. For example, a four-pole motor that has a synchronous speed of 1,800 RPM could run at 1,795 RPM at no load. The speed of an AC induction motor is determined by the amount of torque needed. When the motor is operating at no load, it will produce only the amount of torque needed to overcome its own friction and windage losses. This low torque requirement permits the motor to operate at a speed close to that of the rotating magnetic field.

If a load is connected to the motor, it must furnish more torque to operate the load. This causes the motor to slow down. When the motor speed decreases, the rotating magnetic field cuts the rotor bars at a faster rate. This causes more voltage to be induced in the rotor and, therefore, more current. The increased current flow produces a stronger magnetic field in the rotor, which causes more torque to be produced by the motor. As the current flow increases in the rotor, it causes more current flow to be produced in the stator. This is why motor current will increase as load is added to the motor.

Another factor that determines the amount of torque produced by an induction motor is the phase angle difference between rotor and stator flux. Motor torque is basically the attracting force of two magnetic fields. Imagine two bar magnets representing the magnetic fields of the stator and rotor, Figure 15–4. If the north end of one magnetic is placed close to the south end of the other, they will be attracted to each other, Figure 15–5. Torque can be compared to the amount of force necessary to separate the two magnets. When the magnets are in line with each other, as shown in Figure 15–5, the attraction is strongest and the amount of force necessary to separate them is the greatest. This compares to the stator flux and rotor flux being in phase with each other.

**Figure 15–4** Stator and rotor magnetic fields are compared to two bar magnets. (Source: Delmar/Cengage Learning)



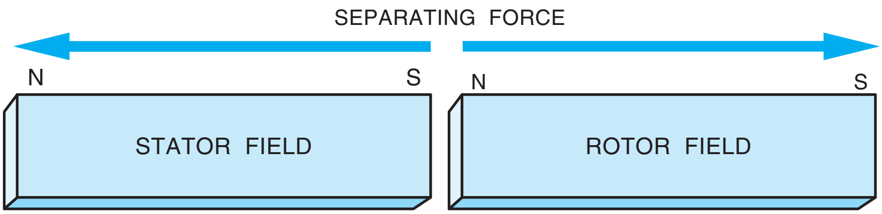



**Figure 15–5**
Torque is the force attracting the two magnets.
(Source: Delmar/Cengage Learning)

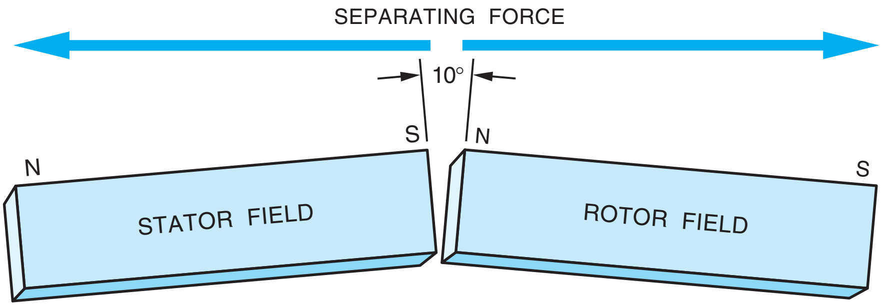



**Figure 15–6**
Magnets are separated by an angle of 10°.
(Source: Delmar/Cengage Learning)

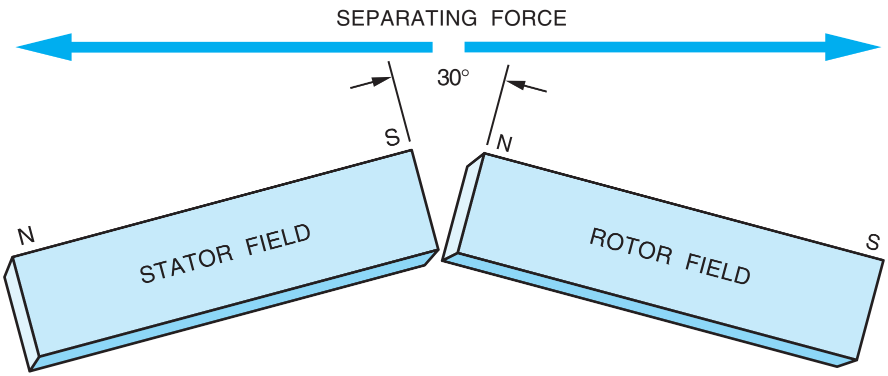



**Figure 15–7**
Magnets are separated by an angle of 30°.
(Source: Delmar/Cengage Learning)

Now assume that the two magnets are placed at an angle of 10° to each other, Figure 15–6. The 10-degree angle produces a greater amount of separation between the two magnetic fields. The magnets can now be separated with less force. Now assume that the magnets are placed at a 30° angle to each other, Figure 15–7. The amount of force necessary to separate the two magnets is less than it was at a 10° angle. The greater the angle between the two magnets, the less force required to separate them. This corresponds to the phase angle difference between rotor and stator flux. The greater the phase angle between rotor and stator flux, the less torque that is developed by the motor.

## CODE LETTERS

Squirrel-cage rotors are not all the same. Rotors are made with different types of bars. The type of rotor bars used in the construction of the rotor determines the operating characteristics of the motor. AC motors are given a **code letter** on their nameplate. The code letter indicates the type of bars used in the rotor. Figure 15–8 shows a rotor with type "A" bars. A type "A" rotor has the highest resistance of any squirrel-cage rotor. This means that the starting torque is high since the rotor current is closer to being 90° out of phase with the stator current than the other types of rotors. The high resistance of the

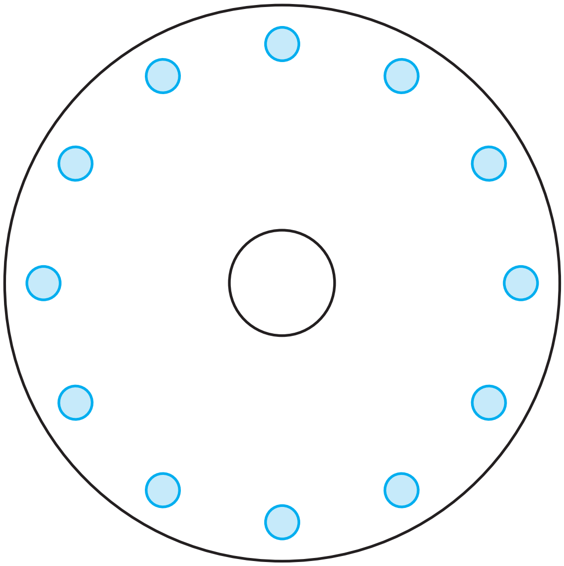


**Figure 15–8**
Type "A" rotor. (Source: Delmar/Cengage Learning)

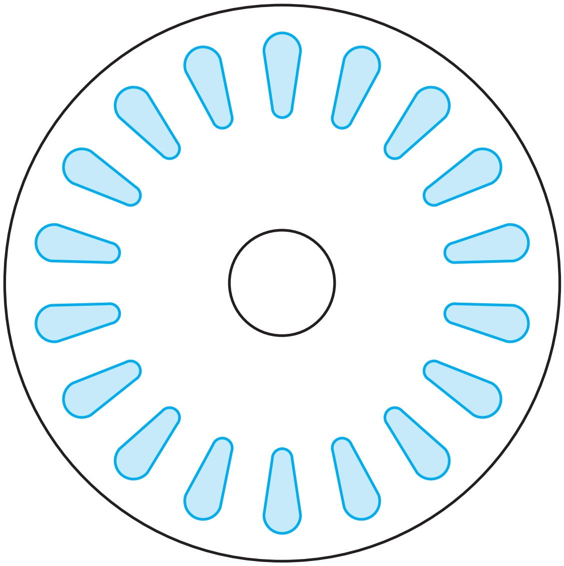


**Figure 15–9**
Type "B-E" rotor. (Source: Delmar/Cengage Learning)

rotor bars limits the amount of current flow in the rotor when starting. This produces a low starting current for the motor. A rotor with type "A" bars has very poor running characteristics, however. Because the bars are resistive, a large amount of voltage will have to be induced into the rotor to produce an increase in rotor current and, therefore, an increase in the rotor magnetic field. This means that when load is added to the motor, the rotor must slow down a great amount to produce enough current in the rotor to increase the torque.

Figure 15–9 shows a rotor with bars similar to those found in rotors with code letters B through E. These rotor bars have lower resistance than the type "A" rotor. This rotor has fair starting torque, low starting current, and fair speed regulation.

Figure 15–10 shows a rotor with bars similar to those found in rotors with code letters F through V. This rotor has low starting torque, high starting current, and good running torque. This type of rotor also has good speed regulation.

The code letter found on the nameplate is also used to determine the amount of **locked rotor current** for the motor. Locked rotor current is the amount of current the motor will draw at the moment of starting. Figure 15–11 shows *Table 430.7(B)* of the *National Electrical Code.*® This table is used to determine the locked rotor current for a squirrel-cage rotor. To use the table, the horsepower, code letter, and voltage of the motor must be known. For this example, assume

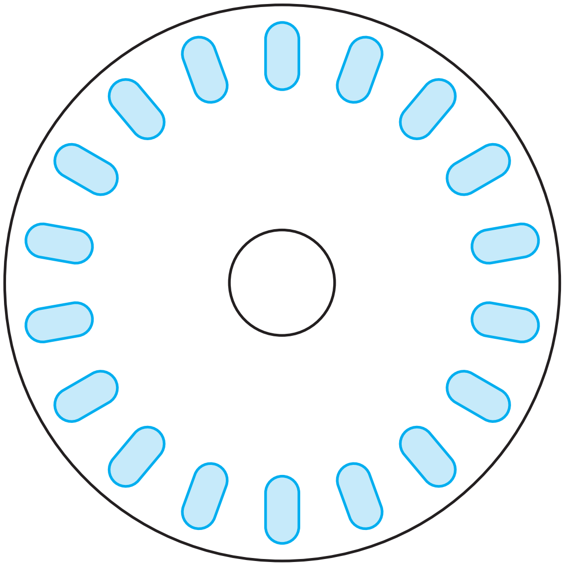


**Figure 15–10**
Type "F-V" rotor. (Source: Delmar/Cengage Learning)

**Table 430.7(B) Locked-Rotor Indicating Code Letters**

| Code Letter | Kilovolt-Amperes 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 |

**Figure 15–11**
(Reprinted with permission from NFPA 70-2008, *National Electrical Code®*, Copyright © 2008, National Fire Protection Association, Quincy, MA 02169. This reprinted material is not the complete and official position of the National Fire Protection Association on the referenced subject, which is represented only by the standard in its entirety.)

the motor is 10 horsepower, has a code letter J, and is operated on a 480-volt line. The table lists the locked rotor currents in kilovolt-amperes per horsepower. The table shows that code letter J is 7.1 to 7.99. For this calculation, a midvalue of 7.5 will be used. Because the values are listed in kilovolt-amperes, 7.5 is actually 7,500 volt-amperes. To find the locked rotor current, multiply the kVA rating by the horsepower, and then divide by the voltage.

$$I = 7500 \text{ VA} \times 10 \text{ hp}$$

$$I = \frac{75000}{480}$$

$$I = 156.25 \text{ amps}$$

## THE NAMEPLATE

Electric motors have **nameplates** that give a great deal of information about the motor. Figure 15–12 illustrates the nameplate of a three-phase induction motor. The nameplate shows that the motor is 10 horsepower, it is a three-phase motor and operates on 240 or 480 volts. The full-load running current of the motor is 28 amps when operated on 240 volts, or 14 amps when operated on 480 volts.

| MOTOR NAMEPLATE | |
|---|---|
| HP | Phase |
| 10 | 3 |
| Volts | Amps |
| 240/480 | 28/14 |
| Hz | FL Speed |
| 60 | 1,745 RPM |
| Code | SF |
| J | 1.25 |
| Frame | Model No. |
| XXXX | XXXX |

**Figure 15–12**
Motor nameplate. (Source: Delmar/Cengage Learning)

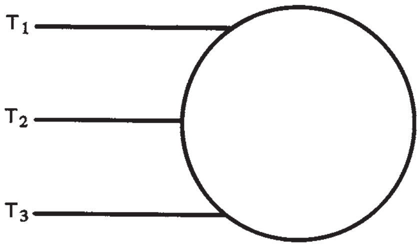



**Figure 15–13**
Schematic symbol of a three-phase squirrel-cage induction motor. (Source: Delmar/Cengage Learning)

The motor is designed to be operated on a 60-Hz AC voltage, and has a full-load speed of 1,745 RPM. The speed indicates that this motor has four poles per phase. Since the full-load speed is 1,745 RPM, the synchronous speed would be 1,800 RPM. The motor contains a type J squirrel-cage rotor, and has a service factor of 1.25. The service factor is used to determine the amperage rating of the overload protection for the motor. The frame indicates the type of mounting the motor has. Figure 15–13 shows the schematic symbol for a three-phase squirrel-cage induction motor.

## TESTING THE MOTOR

Most service technicians test a three-phase motor with an ohmmeter. The ohmmeter can be used to check the stator winding for an open condition or

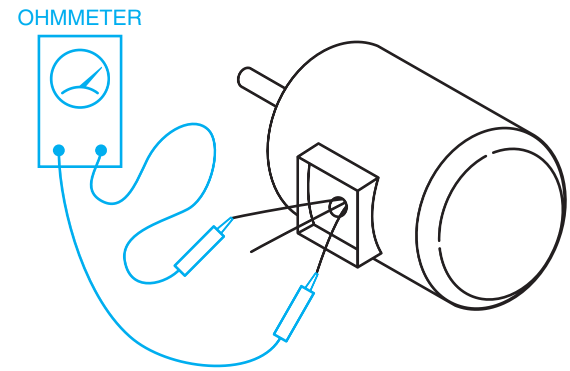



**Figure 15–14**
Testing the stator winding for opens. (Source: Delmar/Cengage Learning)

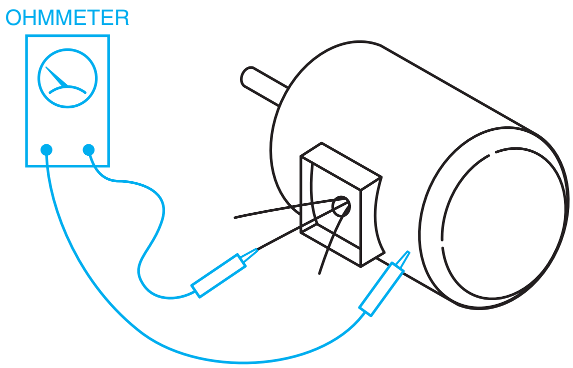



**Figure 15–15**
Testing the stator winding for grounds. (Source: Delmar/Cengage Learning)

a grounded condition. To test the stator winding for an open condition, check the continuity of each winding by measuring the resistance between each of the three windings as shown in Figure 15–14. The resistance of each pair of windings should be the same. To test for a grounded motor, connect one ohmmeter lead to the case of the motor, and the other lead to one of the motor leads. There should be no continuity between any of the leads and the case of the motor, Figure 15–15. The ohmmeter, however, will not generally detect a shorted winding. The resistance of the stator windings of most large horsepower motors is so low that they appear under normal conditions to be a short circuit to the ohmmeter. To test for a shorted winding, some method must be used to measure the reactance of the windings instead of their resistance. If the motor will run, an ammeter can be used to measure the current draw of the motor. The current of each line should be equal and within the full-load current rating of the motor. If one line has a higher current reading than the others, it is an indication of a shorted stator winding. If it is not possible to operate the motor, an instrument that measures the actual inductance of the winding can be used. If one winding has a lower inductance than the others, it is shorted.

## STARTING METHODS FOR SQUIRREL-CAGE MOTORS

There are several methods that can be employed to start three-phase squirrel-cage motors. These methods include:

1. Across-the-line starting.
2. Resistor/reactor starting.
3. Autotransformer starting.
4. Wye-delta starting.
5. Part winding starting.

### Across-the-Line Starting

The simplest of these methods is across-the-line starting. Across-the-line starting is accomplished by connecting the motor directly to the power line, Figure 15–16. This method of starting is used when the inrush current, called locked rotor current, is not so great as to adversely affect the power line. Across-the-line starting is employed for all small horsepower motors, and depending on the local power base, may be used for motors of several hundred horsepower.

### Resistor/Reactor Starting

Often it is necessary to reduce the inrush current during the starting period of large motors. One method of reducing the starting current is to connect resistors or reactors (choke coils or inductors) in series with the motor during the starting period, Figure 15–17. This permits the resistance of the resistors or the inductive reactance of the reactors to limit the inrush current when the motor is first started. After the motor has accelerated to near full

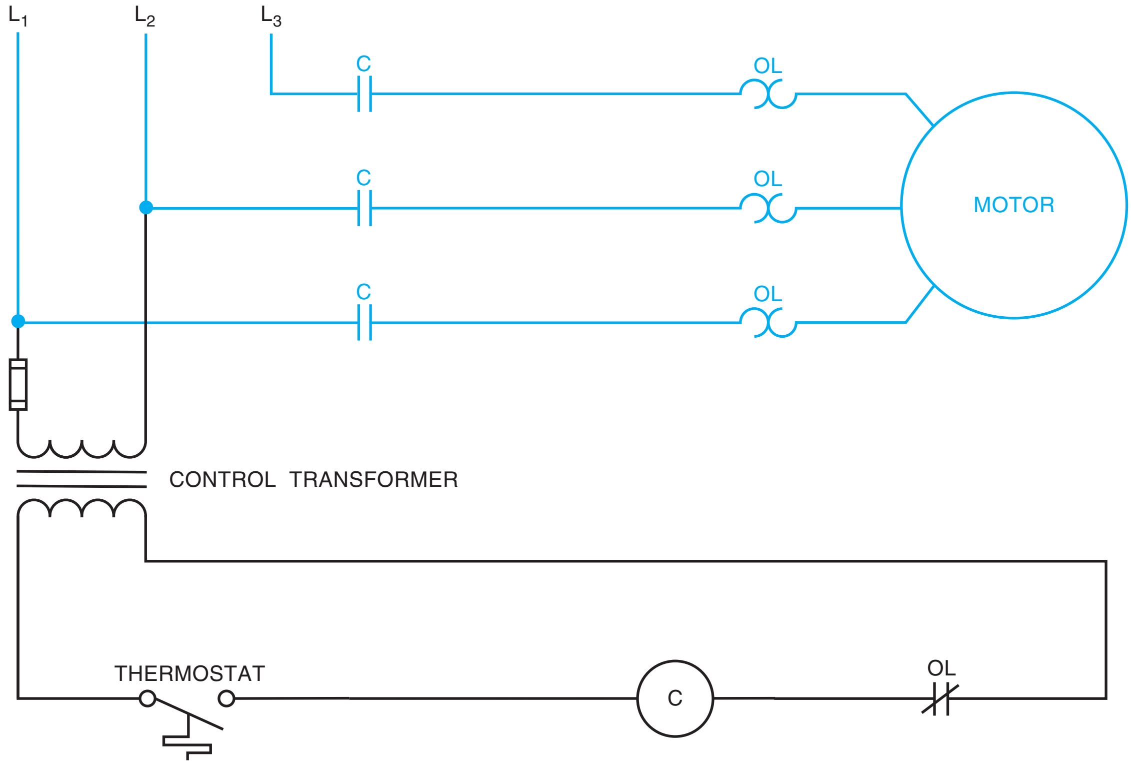



**Figure 15–16**
Across-the-line starting is accomplished by connecting the motor directly to the power line. (Source: Delmar/Cengage Learning)

load speed, the resistors or reactors are shunted out of the circuit. Several methods may be employed for shunting the resistors or reactors out of the line. The circuit shown in Figure 15–17 uses a time delay relay to energize R contactor after some period of time. The circuit operates as follows:

- When the thermostat contact closes, the coils of the compressor contactor (C) and the on-delay timer (TR) energize.
- When the compressor contactor energizes, C contacts close and connect the motor and reactors to the power line.
- After some period of time, timed contact TR closes and energizes the R contactor causing the R contacts connected in parallel with the current limiting inductors to close and shunt the inductors out of the line. The motor is now connected to full voltage.

## Autotransformer Starting

Autotransformer starting differs from resistor or reactor starting by decreasing the voltage applied to the motor during the starting period instead of inserting resistance or inductive reactance in series with the motor. It should be noted that when the voltage to the motor is reduced, the torque is reduced also. A 50% reduction of voltage will produce a 50% reduction of current also, but the torque is reduced to 25% of the value produced by full voltage starting.

Several methods can be employed when using autotransformer starting. Some starters used three transformers, but most use two transformers connected in an open delta, Figure 15–18. In this circuit, notice the addition of the normally closed R contact connected in series with S coil and the

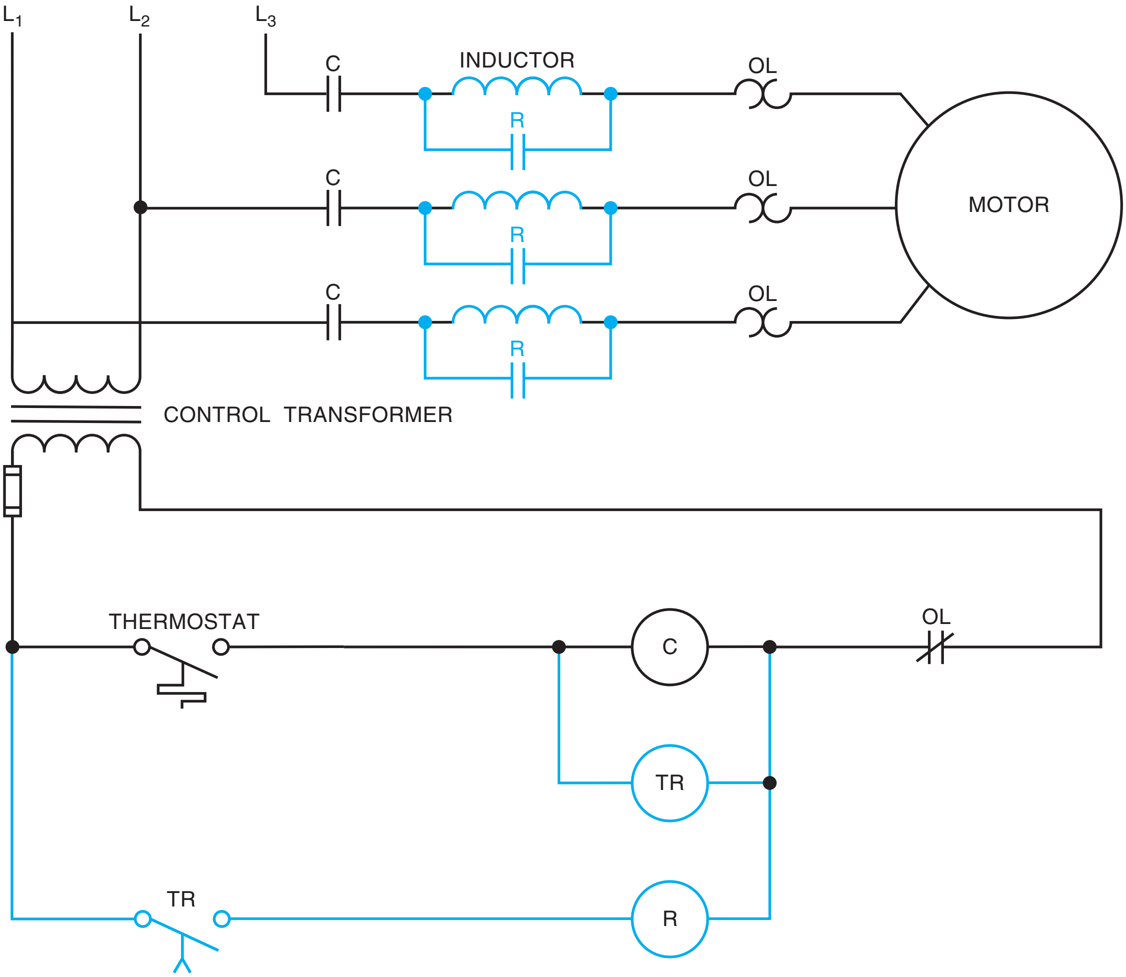



**Figure 15–17**
Reactor starter for a three-phase squirrel-cage motor. (Source: Delmar/Cengage Learning)

normally closed S contact connected in series with the R coil. This is referred to as **interlocking**. Interlocking is used to prevent one contactor being energized while some other contactor is energized. In this circuit, coils R and S can never be energized at the same time. The circuit operates as follows: (It will be assumed that timer TR is set for a delay of 3 seconds).

- When the thermostat contact closes, coils S and TR energize.
- All S contacts change position. The normally open S contacts close and connect the autotransformer to the line. The motor is now connected to reduced voltage. The normally closed S contact connected in series with the coil of the R contactor opens and prevents the possibility of the R coil being energized.
- After a delay of 3 seconds, the TR timed contacts change position.
- The normally closed TR contact connected in series with the S coil opens and disconnects it from the line.
- When the S coil deenergizes, all S contacts return to their normal position. The autotransformer is now disconnected from the line and the contact connected is series with R coil is now closed.

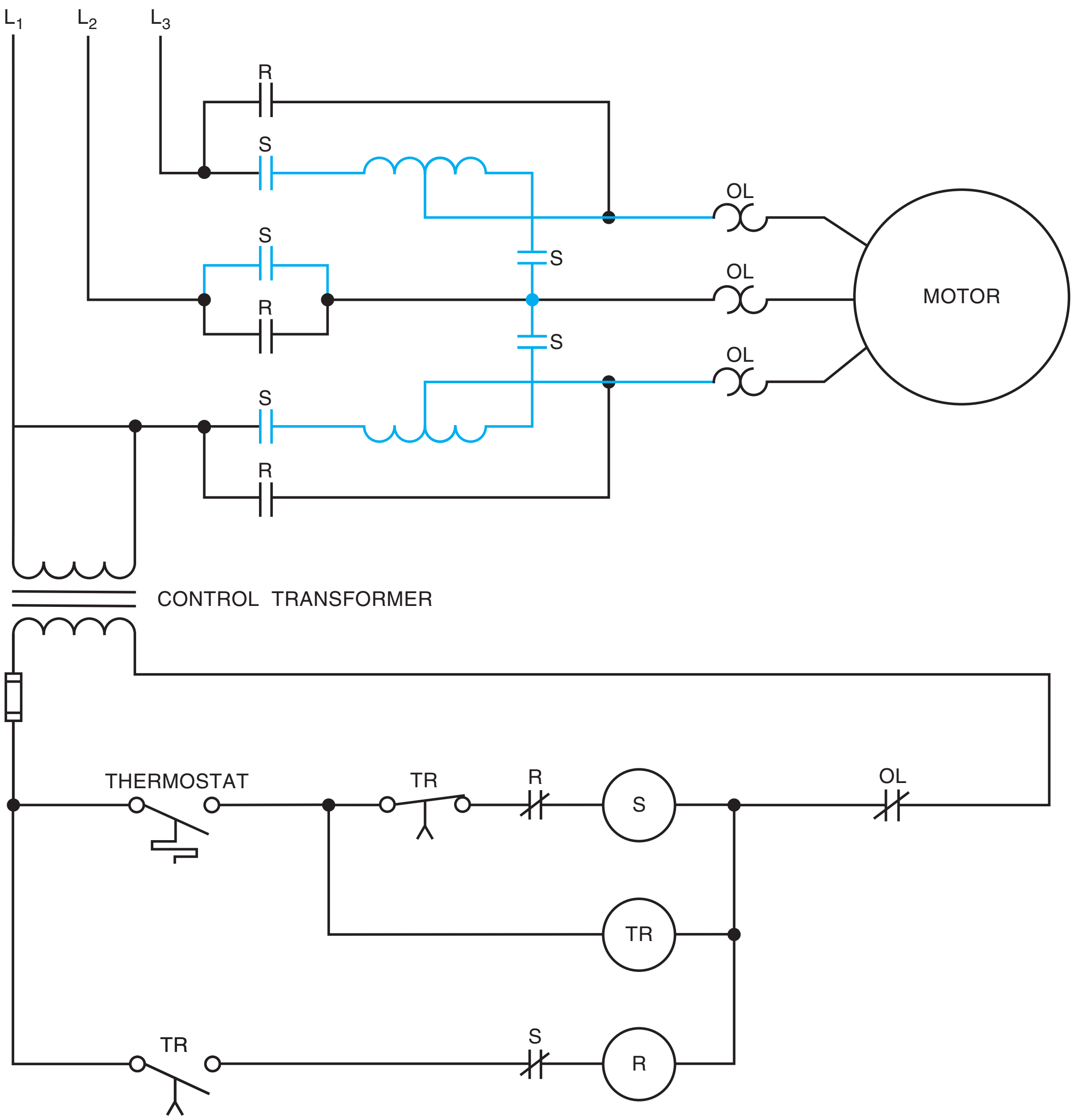



**Figure 15–18**
Autotransformer starter using an open delta connection. (Source: Delmar/Cengage Learning)

- When the normally open TR contact closes, the R coil energizes and all R contacts change position.
- The normally open R contacts close and connect the motor directly to the power line. The normally closed R contact opens and prevents the possibility of S coil being energized at the same time.

## Wye-Delta Starting

Wye-delta starting is also known as star-delta starting. Wye-delta starting is used to reduce the inrush current during the starting period by connecting the stator windings of the motor in a wye configuration during the starting period and then reconnecting them in delta during the run period. If the stator windings are connected in wye, the inrush current will be one-third the value it would be if they were connected in delta. Assume that the motor stator windings have an impedance of 2.5 ohms each. Now assume that the windings are connected in delta, Figure 15–19. It will also be assumed that the motor is connected to a line voltage of 480 volts. In a delta connection, the phase voltage is the same as the line voltage. Therefore, when the C contacts close, 480 volts will be applied across 2.5 ohms. This will produce a current in each phase of 192 amperes.

$$I_{PHASE} = \frac{480}{2.5}$$

In a delta connection, the line current is greater than the phase current by a factor of the square root of 3 (1.732). Therefore, the line current supplied to the motor is 332.5 amperes (192 × 1.732).

Now assume that the same stator windings are connected in wye, Figure 15–20. In a wye connection, the phase voltage is less than the line voltage by a factor of the square root of 3 (1.732). Therefore, 277 volts is applied across each stator winding instead of 480 volts (480/1.732). This produces a phase current of 110.8 amperes. Because the stator windings are now connected in wye instead of delta, the line current is the same as the phase current. The motor inrush current has been reduced from 332.5 amperes to 110.8 amperes by reconnecting the stator windings from delta to wye.

There are two conditions that must be met when wye-delta starting is to be used.

1. The motor must be designed to operate with its stator windings connected in delta during the normal run period.
2. All stator winding leads must be accessible at the terminal connection box. This would be leads T1 through T6 for a single voltage motor and T1 through T12 for a dual voltage motor.

Another consideration when using wye-delta starting is that the overload heaters should be sized for the phase current value and not the line current value. The basic stator connection for wye-delta starting is shown in Figure 15–21. Notice that the overload heaters are connected in the phase windings not in the line leads.

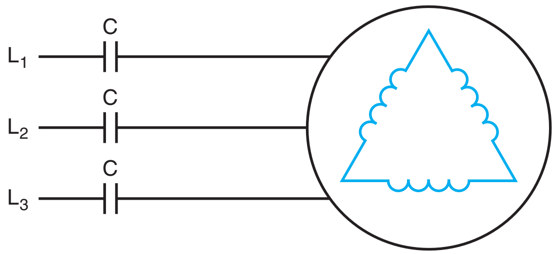



**Figure 15–19**
The stator windings are connected in delta. (Source: Delmar/Cengage Learning)

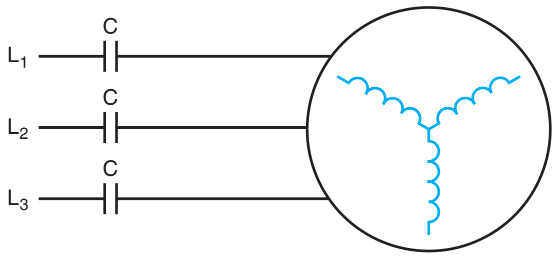



**Figure 15–20**
The stator windings are connected in wye. (Source: Delmar/Cengage Learning)

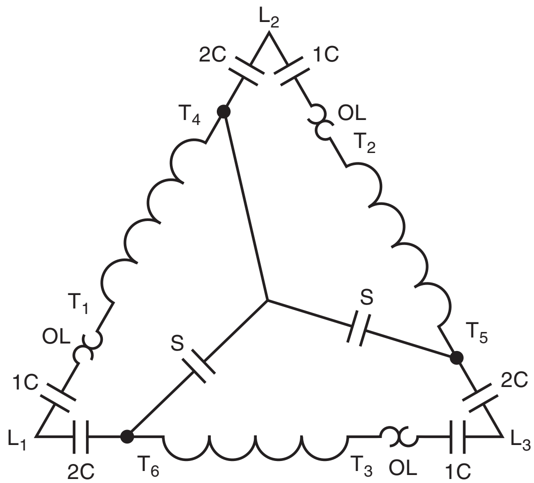



**Figure 15–21**
Stator connection for a single voltage wye-delta starter. (Source: Delmar/Cengage Learning)

A basic control schematic for a wye-delta starter is shown in Figure 15–22. To understand the operation of this circuit assume that timer TR has been set for a delay of 3 seconds.

- When the thermostat contact closes, a current path exists through coils 1C, TR, and S, Figure 15–23.
- The 1C load contacts close to supply power to the motor T leads.
- The S contacts change position also. The two S load contacts close and connect the stator winding in a wye configuration by shorting T4, T5, and T6 together. The normally open S contact connected in series with coil 2C opens to provide interlocking protection.
- After a delay of 3 seconds, both TR contacts change position, Figure 15–24.
- The normally closed TR contact connected in series with S coil opens and deenergizes S contactor causing all S contacts to return to their normal position. The normally closed S contact connected in series with coil 2C recloses to provide a current path to coil 2C.
- When the normally open TR contact connected in series with coil 2C closes, coil 2C energizes causing all 2C contacts to change position. The 2C load contacts close and reconnect the motor stator windings in a delta configuration. The normally closed 2C contact connected in series with S coil opens to provide interlocking protection.

## Part Winding Starters

Another method for reducing the starting current of large three-phase squirrel-cage motors is part winding starting. Motors intended for use with part winding starting contains two separate stator windings, Figure 15–25. Each winding is rated for

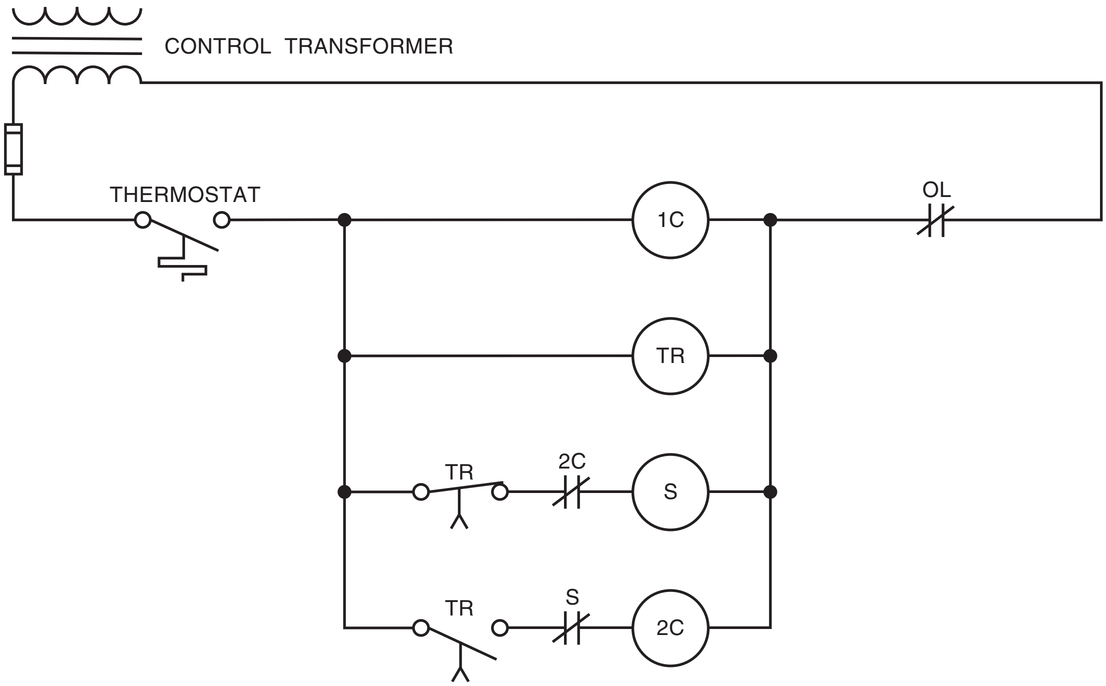



**Figure 15–22**
Basic control schematic for wye-delta starting. (Source: Delmar/Cengage Learning)

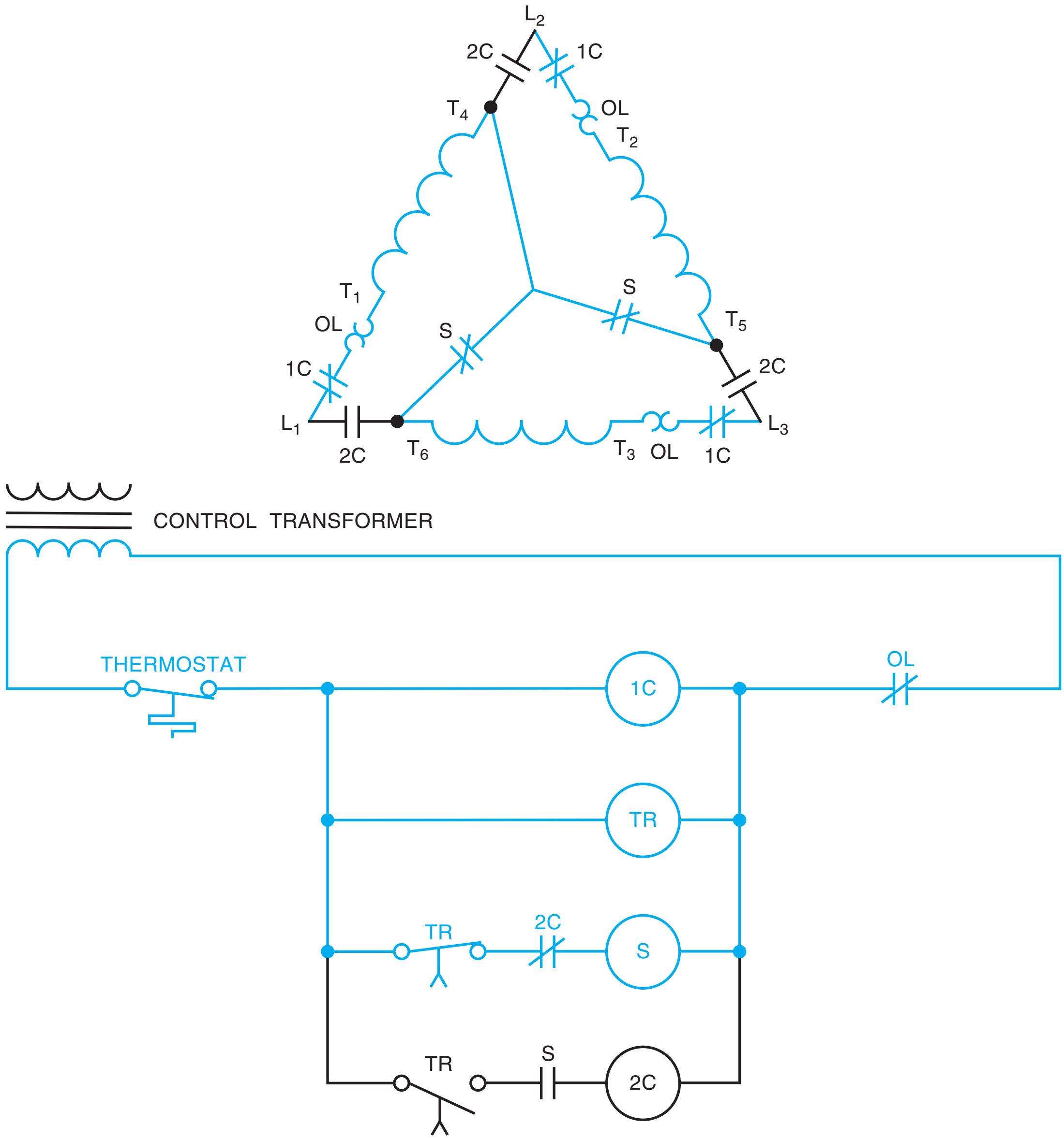



**Figure 15–23**
The stator windings are connected in wye during starting. (Source: Delmar/Cengage Learning)

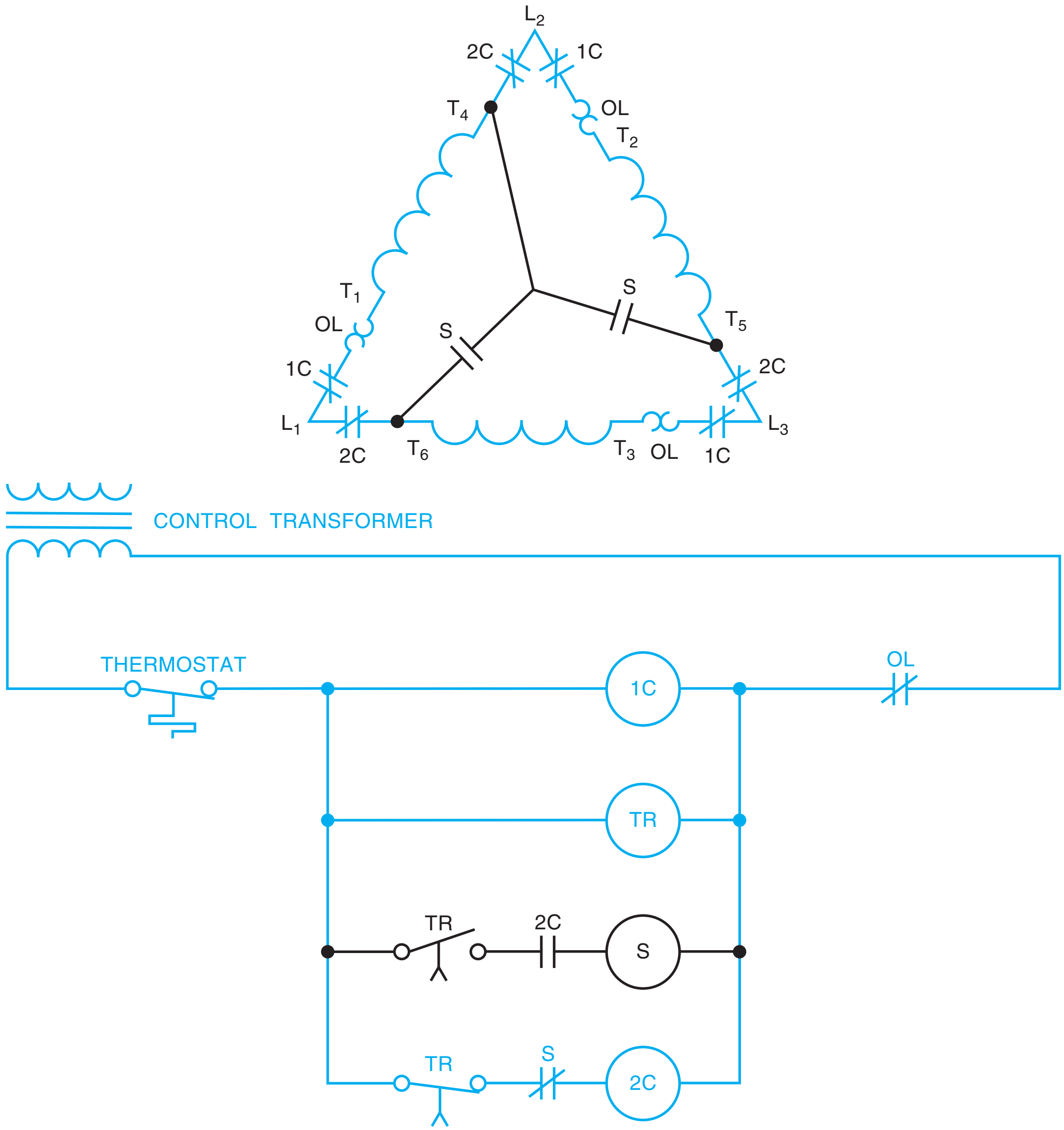



**Figure 15–24**
The stator windings are connected in delta during the run period. (Source: Delmar/Cengage Learning)

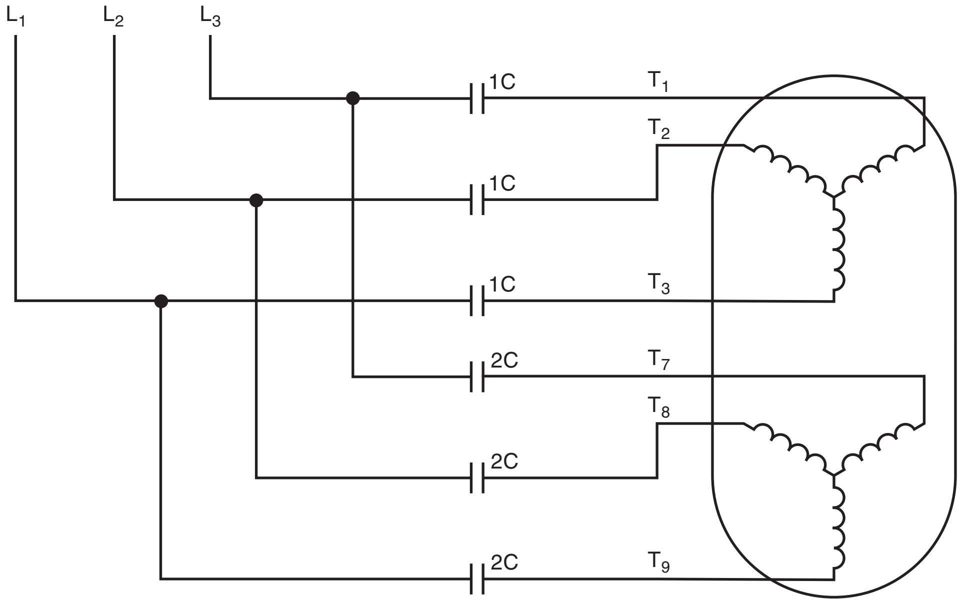



**Figure 15–25**
A motor intended for part windings starting contains two stator windings. (Source: Delmar/Cengage Learning)

the intended line voltage. The impedance of a single stator winding is double that of the two windings connected in parallel. Dual voltage motors can also be used for part winding starting provided the line voltage corresponds to the low voltage rating of the motor. A 480/240-volt motor could employ part winding starting provided the motor is connected to 240 volts and not 480 volts. In this situation T4, T5, and T6 are connected and power is connected to T1, T2, and T3 during the starting period. After some period of time, power is also connected to T7, T8, and T9. This has the same effect as connecting the stator windings in parallel.

A basic circuit for part winding starting is shown in Figure 15–26. To understand the operation of the circuit, assume that timer TR has been set for a delay of 3 seconds.

- When the thermostat contact closes power is provided to coils C1 and TR, Figure 15–27. All 1C contacts close and connect T1, T2, and T3 to the power line.
- After a delay of 3 seconds, the normally open TR contact connected in series with 2C closes and energizes coil 2C, Figure 15–28.
- When the 2C load contacts close, power is connected to T7, T8, and T9. This has the same effect as connecting the two windings in parallel.

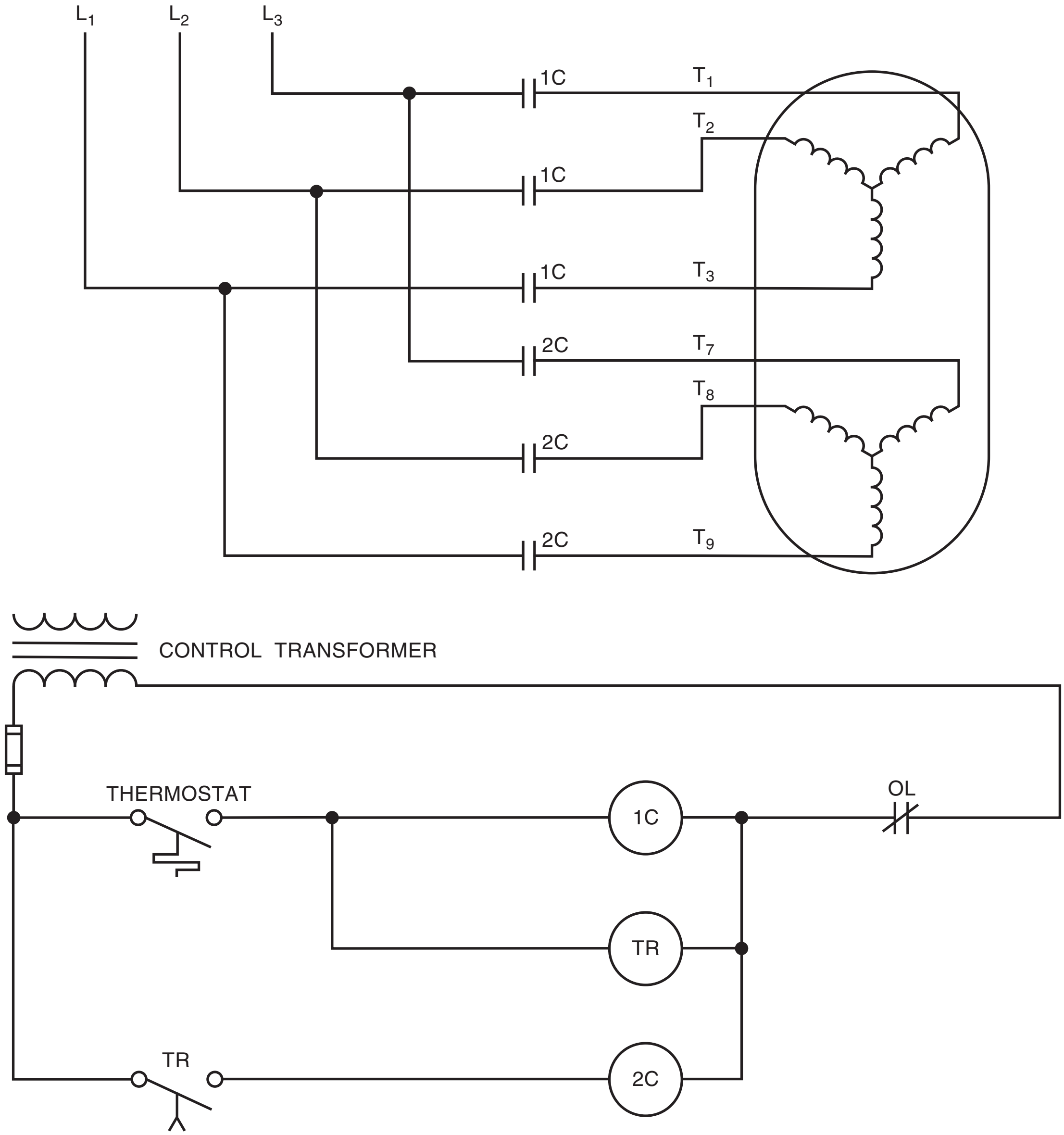



**Figure 15–26**
Basic part winding starting circuit. (Source: Delmar/Cengage Learning)

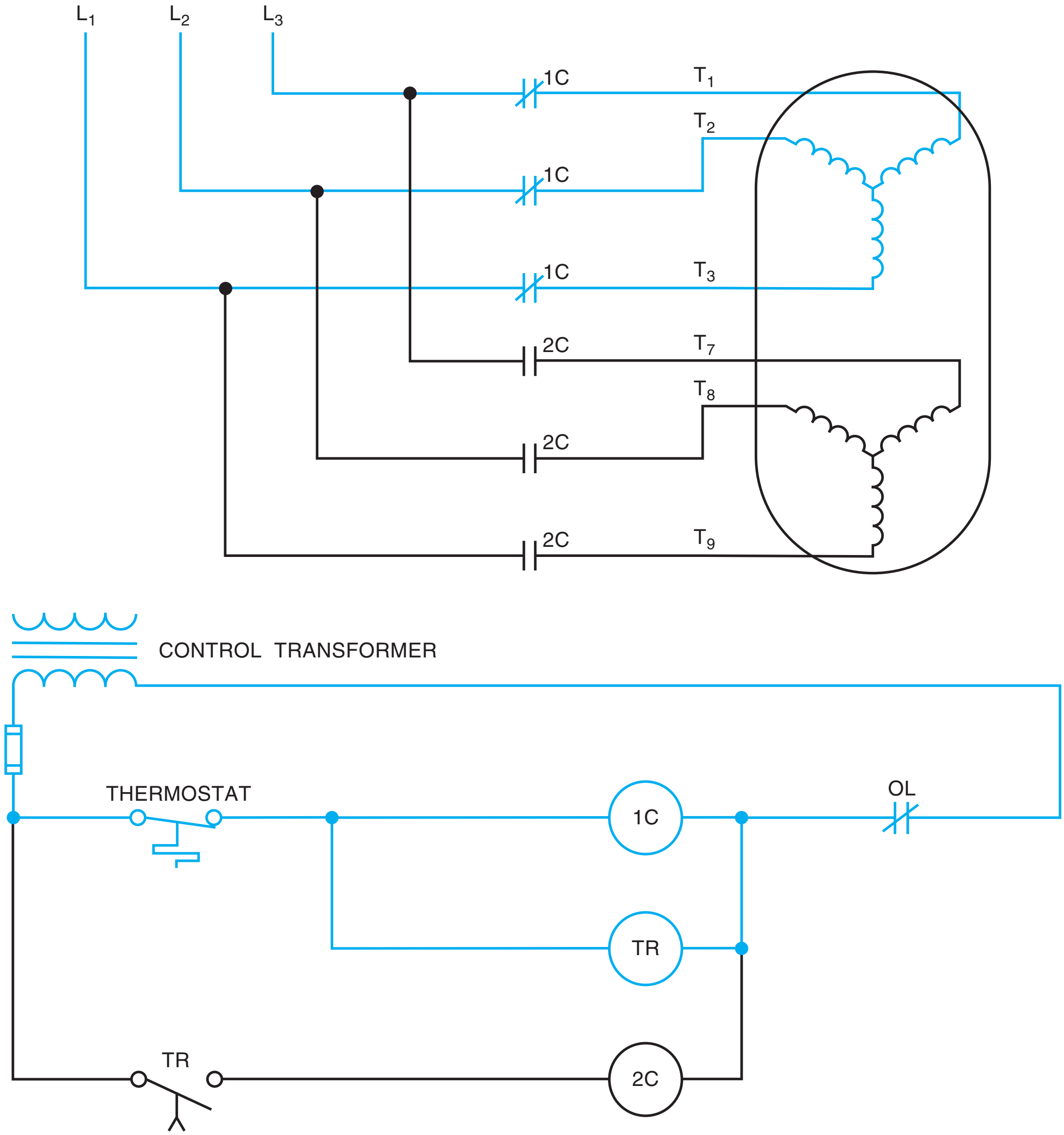



**Figure 15–27**
During the starting period only one stator winding is energized. (Source: Delmar/Cengage Learning)

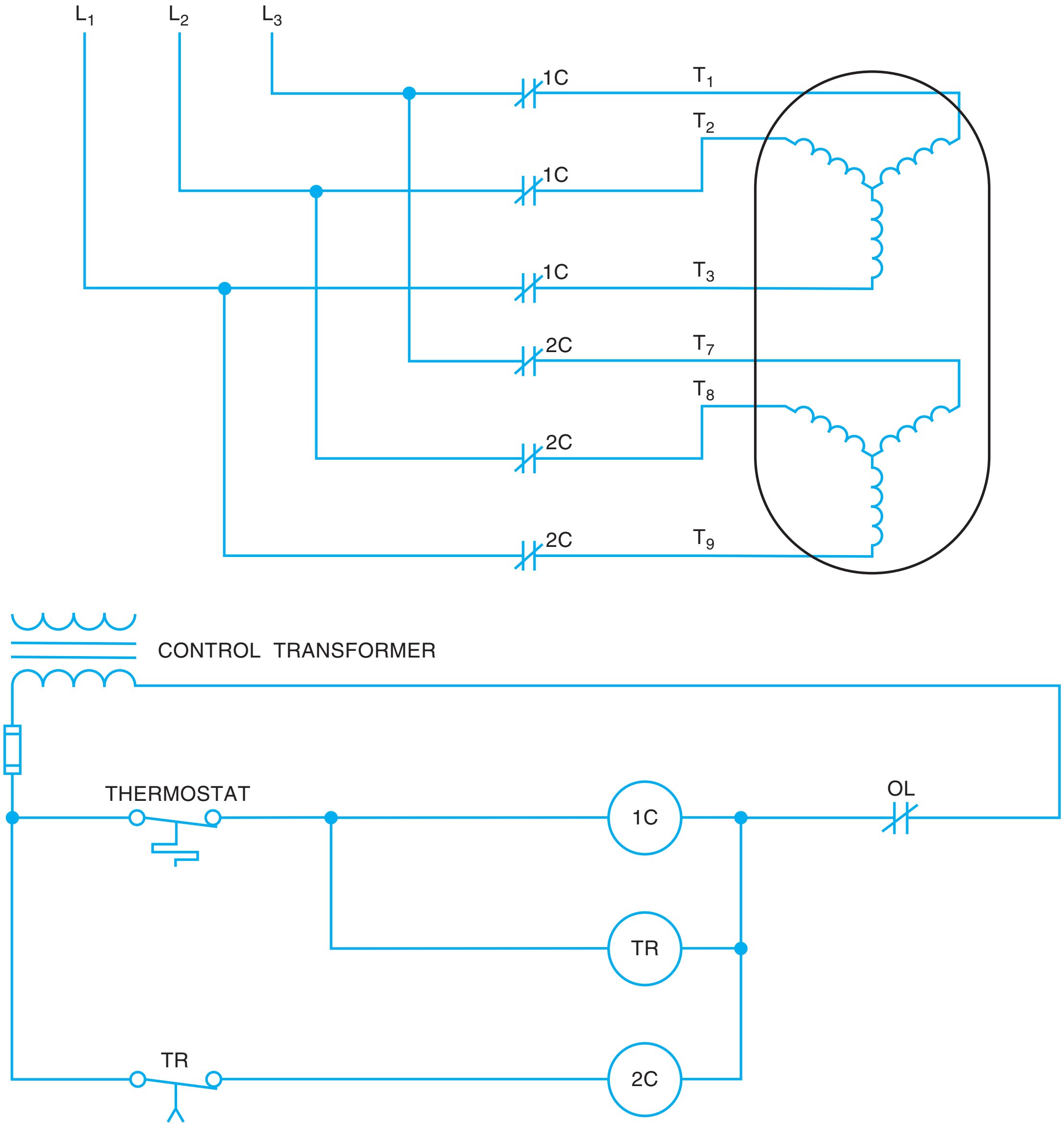



**Figure 15–28**
During the run period both stator windings are connected. (Source: Delmar/Cengage Learning)

## SUMMARY

- The squirrel-cage motor receives its name from the fact that the rotor contains a set of bars connected together at each end, and the entire assembly resembles a squirrel cage.
- Three factors that determine the amount of voltage induced into the rotor are:
  A. The strength of the magnetic field of the stator.
  B. The number of stator bars contained in the rotor.
  C. The difference in speed between the speed of the rotating magnetic field and the speed of the rotor.
- The greatest amount of current draw for a squirrel-cage motor is during the starting period.
- Three factors that determine the amount of torque produced by a squirrel-cage motor are:
  A. The strength of the magnetic field of the stator.
  B. The strength of the magnetic field of the rotor.
  C. The phase angle difference between stator current and rotor current.
- The direction of rotation of a squirrel-cage motor can be changed by reversing any two stator leads.
- The code letter found on the motor nameplate indicates the type of bars used in the construction of the rotor.
- The simplest method of starting a squirrel-cage motor is across-the-line starting.
- Resistor/reactor starting is accomplished by connecting resistors or inductors in series with the motor during the starting period.
- Autotransformer starting reduces starting current by lowering the applied voltage to the motor during the starting period.
- If the applied voltage is reduced by 50% of normal during the starting period, the starting torque is reduced to 25% of normal.
- Wye-delta starting is accomplished by connecting the stator windings in wye during the starting period and changing them to a delta connection during the normal run time.
- A motor will draw one-third as much current during the starting period with its windings connected in wye as it will if they are connected in delta.
- Two requirements for motors intended for wye-delta starting are:
  A. All stator winding leads must be brought out at the terminal connection box.
  B. The motor must be designed to run with its stator windings connected in delta.
- Motors intended to be used for part winding starting have two separate stator windings.
- Dual voltage motors can be used for part winding starting provided the motor is connected for low voltage operation.

## KEY TERMS

code letter
interlocking
locked rotor current
nameplates
rotor bars
squirrel-cage induction motor

## REVIEW QUESTIONS

1. What three factors determine the amount of torque produced by an AC induction motor?
2. When does an AC induction motor draw more current when starting than it does when running?
3. Why does the current flow to the motor increase when load is added to the motor?
4. What does the code letter found on the nameplate of the motor indicate?
5. At what degree angle between the stator current and the rotor current is the maximum torque developed?
6. What type of squirrel-cage rotor has the highest starting torque?
7. What type of squirrel-cage rotor has the best speed regulation?
8. Why can an induction motor never operate at synchronous speed?
9. What does the locked rotor current of a motor indicate?
10. The nameplate of a squirrel-cage motor indicates that the motor has a full-load speed of 875 RPM. How many poles per phase does the motor have?
11. What is the simplest of all starting methods for a squirrel-cage motor?
12. Explain interlocking.
13. How does autotransformer starting differ from resistor/reactor starting?
14. A three-phase squirrel-cage induction motor has its stator windings connected in a delta connection. During the starting period, the motor has a current draw of 360 amperes. If the stator windings were reconnected to form a wye connection during the starting period how much starting current would the motor draw?
15. What two conditions must be met before a motor can be used with a wye-delta starter?

# UNIT 16

# The Wound Rotor Induction Motor

## OBJECTIVES

After studying this unit the student should be able to:

- Describe the construction of a wound rotor induction motor
- Discuss the difference in operation between wound rotor and squirrel-cage induction motors
- Discuss the starting and running characteristics of a wound rotor induction motor
- Connect a wound rotor induction motor for operation
- Draw the standard schematic symbol for a wound rotor induction motor
- Perform an ohmmeter test on a wound rotor induction motor

Another type of three-phase induction motor used for operating large air conditioning units is the **wound rotor induction motor**. The stator winding of this motor is the same as the stator of a squirrel-cage induction motor. The rotor of the wound rotor motor, however, does not contain squirrel-cage bars. The rotor of this motor contains wound coils of wire as illustrated in Figure 16–1. The rotor will contain as many poles as there are stator poles. The motor shown in Figure 16–1 would be for a two-pole stator. Notice that there are three separate windings on the rotor. The finish end of each winding is connected together. This forms a wye connection for the rotor winding. The start end of each winding is connected to a separate **slip ring** on the rotor shaft.

The slip rings permit the connection of external resistance to the rotor windings. Figure 16–2 shows

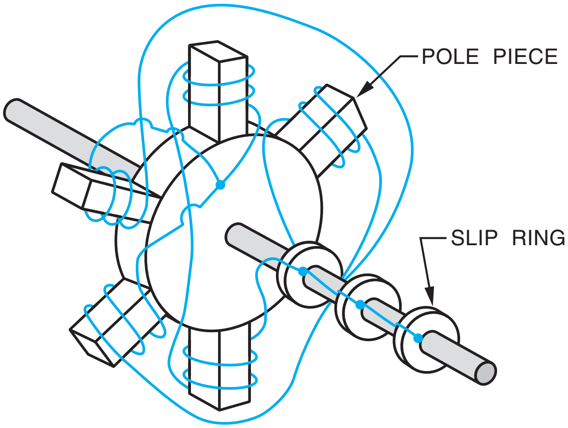



Figure 16–1
A wound rotor. (Source: Delmar/Cengage Learning)

a schematic diagram of the stator connection and rotor connection of a wound rotor motor. Notice that the wye-connected stator winding is connected directly to the incoming power. The wye-connected rotor is connected to three variable resistors. The dashed line drawn between the resistors indicates that they are mechanically connected together. If the resistance of one is changed, the resistance of the other two changes also.

Resistance is connected to the slip rings by means of **carbon brushes** as shown in Figure 16–3. Because the resistance connection to the rotor is external, the amount of resistance used in the circuit can be controlled. This permits the amount of current flow in the rotor to be controlled. If the current flow in the rotor is limited by the amount of resistance connected in the circuit, the stator current is limited also. A great advantage of the wound rotor motor is that it limits the amount of inrush current when the motor is first started. This eliminates the need for reduced voltage starters or wye-delta starting.

Another advantage of the wound rotor motor is its high starting torque. Because resistors are used to limit current flow in the rotor, the phase angle between the stator current and the rotor current is close to 90°. The schematic symbol for a wound rotor motor is shown in Figure 16–4.

## MOTOR OPERATION

When power is applied to the stator winding, a rotating magnetic field is created in the motor. This magnetic field cuts through the windings of the rotor and induces a voltage into them. The amount of voltage induced in the rotor windings is determined by the same three factors that determined the amount of voltage induced in the squirrel-cage rotor. The amount of current flow in the rotor is determined by the amount of induced voltage and the amount of resistance connected to the rotor ($I = E/R$). When current flows through the rotor, a magnetic field is produced. This magnetic field is attracted to the rotating magnetic field of the stator.

As the rotor speed increases, the induced voltage decreases because of less cutting action between the rotor windings and rotating magnetic field. This produces less current flow in the rotor and, therefore, less torque. If resistance is reduced, more current can flow, which will increase motor torque, and the rotor will increase in speed. This action continues until the rotor is operating at maximum speed and all resistance has been shorted out of the rotor circuit. When all of the resistance has been

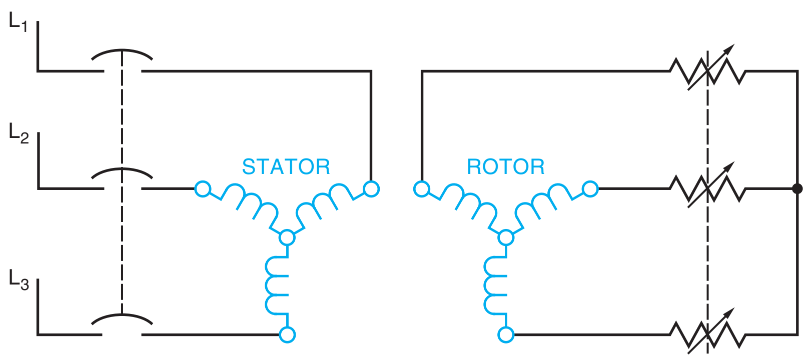



Figure 16–2
A wye-connected stator and wye-connected rotor.
(Source: Delmar/Cengage Learning)

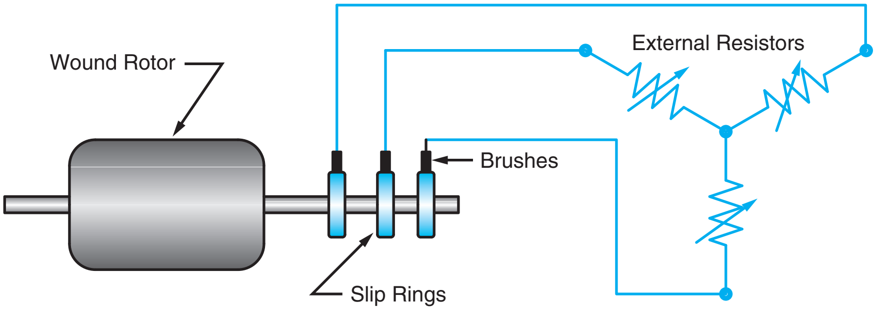



**Figure 16–3**
External resistance is connected to the rotor circuit with brushes and slip rings.
(Source: Delmar/Cengage Learning)

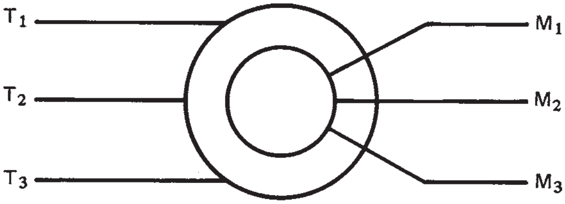



**Figure 16–4**
Schematic symbol of a wound rotor induction motor.
(Source: Delmar/Cengage Learning)

shorted out, the motor operates like a squirrel-cage induction motor.

## STARTING

Most large wound rotor motors use a method of **step starting** as opposed to actual variable resistors. Step starting is similar to shifting the gears in the transmission of an automobile. The transmission is placed in first gear when the car is first started. As the car gains speed, the transmission is shifted to second gear, then third gear, and so on until the car is operating in its highest gear. When a wound rotor motor is step started, it begins with maximum resistance connected in the rotor circuit. As the motor speed increases, resistance is shorted out of the circuit until the windings of the rotor are shorted together. The number of steps can vary from one motor to another, depending on the size of the motor and how smooth a starting action is desired.

There are different control methods used to short out the steps of resistance when starting a wound rotor motor. Some controllers sense the amount of current flow to the stator. This method is known as current limit control. Another method detects the speed of the rotor. This method is known as slip frequency control. One of the most common methods uses time relays to control when resistance is shorted out of the circuit. This method is known as **definite time control**. Figure 16–5 shows a schematic diagram of a time-controlled starter for a wound rotor motor. In this schematic, the motor circuit is shown at the top of the diagram. A control transformer is used to step the line voltage down to the value of voltage used in the control circuit. The operation of the circuit is as follows:

1. When the start button is pressed, a circuit is completed through M motor starter coil, TR1 coil, and the overload contact. When M coil energizes, all M contacts close. The three large load contacts located at the top of the diagram close and connect the stator winding to the line. The M contact located beneath the start button is known as the **holding, sealing, or maintaining contact**. Its job is to provide a continued circuit to the M coil when the start button is released. The motor now begins to run in its lowest speed. Maximum resistance is connected in the rotor circuit.
2. TR1 relay is a timer. For this example, it shall be assumed that all timers are set for a delay of 3 seconds. When TR1 coil energizes, it begins a time operation. After 3 seconds, TR1 contact closes. This completes a circuit to S1 coil and TR2 coil.

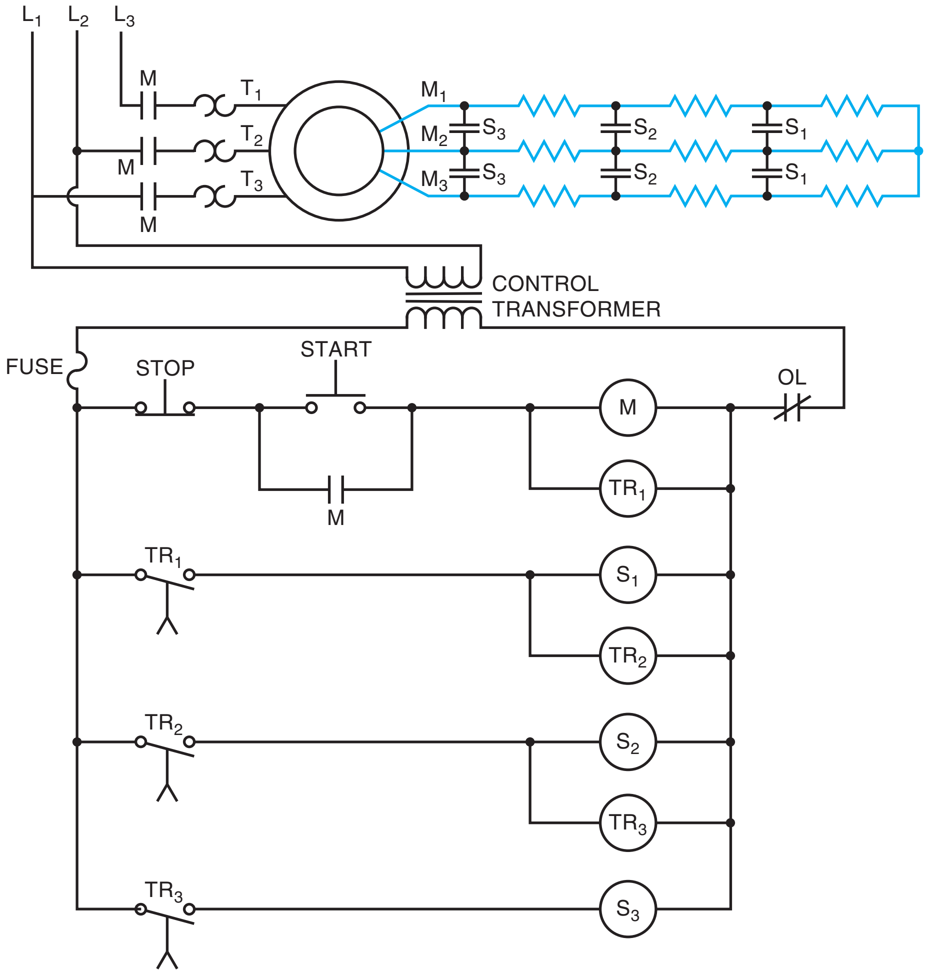



**Figure 16–5**
Definite time starting for a wound rotor motor. (Source: Delmar/Cengage Learning)

3. When S1 coil energizes, both S1 contacts close and short out the last three resistors in the rotor circuit. This causes the motor to accelerate to the next higher speed. When TR2 coil energizes, it begins timing.
4. At the end of a 3-second time period, TR2 contact closes and completes a circuit to coil S2 and TR3.
5. When S2 coil energizes, both S2 contacts close and short out the next set of resistors. This permits the motor to accelerate to a higher speed. When TR3 coil energizes, it begins its timing sequence.
6. After a 3-second time period, contact TR3 closes and provides a complete circuit for coil S3. This causes both S3 contacts to close and short out the last set of resistors. The motor now accelerates to its highest speed.
7. When the stop button is pressed, the circuit to coil M and coil TR1 is broken. When coil M deenergizes, all M contacts open. This disconnects the stator winding from the line. When TR1 coil deenergizes, contact TR1 opens immediately. This deenergizes coil S1 and coil TR2. When coil S1 deenergizes, both S1 contacts return to their open position.

When coil TR1 deenergizes, contact TR2 opens immediately. When contact TR2 opens, it breaks the circuit to coil S2 and coil TR3. When coil S2 deenergizes, both S2 contacts reopen. Contact TR3 opens immediately when coil TR3 deenergizes. This causes coil S3 to deenergize and open both S3 contacts.

8. If the fuse should blow, or the overload contact open, it has the same effect as pressing the stop button.

## TESTING A WOUND ROTOR MOTOR

Because the stator winding of the wound rotor motor is the same as the squirrel-cage motor, the same test procedure can be followed. Testing the rotor of a wound rotor motor is very similar to testing the stator. The rotor can be tested for an open winding with an ohmmeter by checking the continuity between each of the slip rings, Figure 16–6. The resistance readings should be the same between each pair of slip rings. To test the rotor for a ground, connect one ohmmeter lead to the shaft, and connect the other lead to each one of the slip rings, Figure 16–7. The ohmmeter should show no continuity between the rotor windings and ground. Like the stator winding, the rotor is difficult to test for a shorted winding. To test the rotor for a shorted winding it is generally necessary to use equipment that will measure the inductance of the winding instead of its resistance.

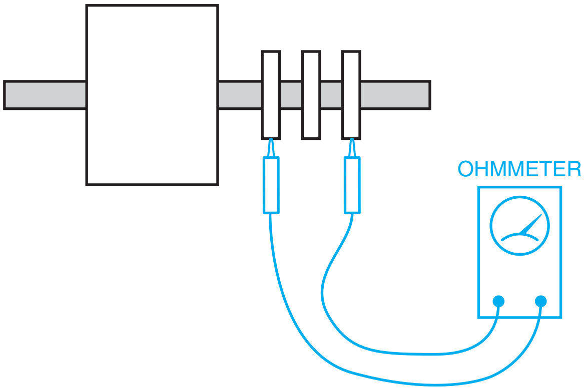



**Figure 16–6**
Testing a rotor for an open winding. (Source: Delmar/Cengage Learning)

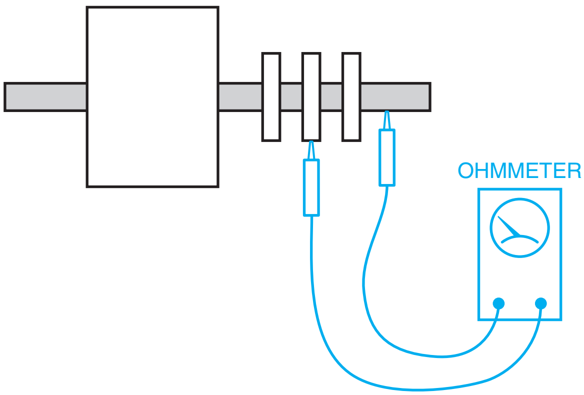



**Figure 16–7**
Testing a rotor for a grounded winding. (Source: Delmar/Cengage Learning)

## SUMMARY

- The stator winding of a wound rotor induction motor is the same as the stator winding of a squirrel-cage induction motor.
- The rotor of a wound rotor induction motor contains windings instead of squirrel-cage bars.
- The rotor of a wound rotor induction motor will contain as many poles per phase as the stator winding.

- The finish ends of each winding of a wound rotor are connected together to form a wye connection and the other ends of each winding are connected to a slip ring on the shaft.
- Wound rotor induction motors are sometimes called slip ring motors because they contain three slip rings on their shaft.
- Wound rotor induction motors have a higher starting torque per amp of starting current than any other type of three-phase motor.
- The speed of a wound rotor induction motor can be controlled by permitting resistance to remain in the rotor circuit during operation.
- The brushes of a wound rotor induction motor are used to provide connection of the rotor windings to external resistors.
- The stator winding leads of a wound rotor induction motor are labeled $T_1$, $T_2$, and $T_3$.
- The rotor leads of a wound rotor induction motor are labeled $M_1$, $M_2$, and $M_3$.

## KEY TERMS

**carbon brushes**
**definite time control**
**holding, sealing, or maintaining contact**
**slip ring**
**step starting**
**wound rotor induction motor**

## REVIEW QUESTIONS

1. How many slip rings are located on the shaft of the rotor of a wound rotor induction motor?
2. What is the purpose of the slip rings?
3. Name two advantages of the wound rotor motor over the squirrel-cage motor.
4. What two factors determine the amount of current flow in the rotor of a wound rotor motor?
5. What does the dashed line drawn between the three resistors shown in Figure 16–2 indicate?
6. Why is the starting torque of a wound rotor induction motor higher than the starting torque of a squirrel-cage induction motor?
7. The stator of a wound rotor motor has a synchronous speed of 1,200 RPM when connected to a 60-Hz line. How many poles per phase are there in the rotor?
8. Refer to Figure 16–5. Describe what would happen in this circuit if coil S1 should be open when the motor started.
9. Refer to Figure 16–5. Describe what would happen in this circuit if coil TR2 should be open when the motor is started.
10. Refer to Figure 16–5. Describe what would happen in this circuit if holding contact M should become stuck together when the motor is started and not open.

## TROUBLESHOOTING QUESTIONS

Refer to the schematic shown in Figure 16–5 to answer the following questions. It is to be assumed that all timers are set for a delay of 3 seconds.

1. When the start button is pressed, the motor starts in its lowest speed. After a delay of 6 seconds, the motor accelerates to third speed and 3 seconds later accelerates to the fourth or highest speed. Which of the following could cause this problem?

   A. Coil $TR_1$ is open.

   B. Timed contact $TR_1$ did not close.

   C. Coil $S_1$ is open.

   D. Coil $TR_2$ is open.

2. When the start button is pressed, the motor starts and accelerates through all speeds normally. When the stop button is pressed, the motor continues to operate normally. Which of the following could cause this condition?

   A. The start button is shorted. (Shorted means contacts welded together.)

   B. The stop button is shorted.

   C. M auxiliary contact is shorted.

   D. Any of the above.

3. When the start button is pressed, the motor accelerates through the first three steps of speed normally. When the motor tries to accelerate to the fourth speed, however, the motor stops. It is found that the control circuit fuse has blown. Which of the following conditions could cause this problem?

   A. The overload (OL) contact has shorted.

   B. Coil $S_2$ is shorted.

   C. Coil $TR_3$ is shorted.

   D. Coil $S_3$ is shorted.

4. When the start button is pressed, the motor immediately starts operating in third speed. Three seconds later, the motor accelerates to fourth speed. Which of the following could cause this condition?

   A. $TR_2$ timed contact is shorted.

   B. $TR_3$ timed contact is shorted.

   C. $S_2$ load contacts are shorted.

   D. None of the above.

5. When the start button is pressed, the motor will not start. Which of the following could cause this condition?

   A. The control transformer is defective.

   B. The control circuit fuse is blown.

   C. The overload contact is open.

   D. All of the above.

# UNIT 17

# The Synchronous Motor

## OBJECTIVES

After studying this unit the student should be able to:

- Describe the construction of a synchronous motor
- Compare the operating characteristics of a synchronous motor with those of a squirrel-cage induction motor and a wound rotor induction motor
- Discuss the starting and running characteristics of a synchronous motor
- Describe the function of the field discharge resistor
- Discuss power factor correction using the synchronous motor
- Perform an ohmmeter test of a synchronous motor

The third type of three-phase motor to be discussed is the **synchronous motor**. This motor has several characteristics that no other type of motor has. Some of the characteristics of a synchronous motor are:

1. The synchronous motor is not an induction motor. This means that it does not depend on induced voltage from the stator to produce a magnetic field in the rotor.
2. The synchronous motor will run at a constant speed from no load to full load.
3. The synchronous motor has the ability to not only correct its own power factor, but can also correct the power factor of other motors connected to the same line.

The synchronous motor has the same type of stator windings as the other two three-phase motors. The rotor of a synchronous motor has

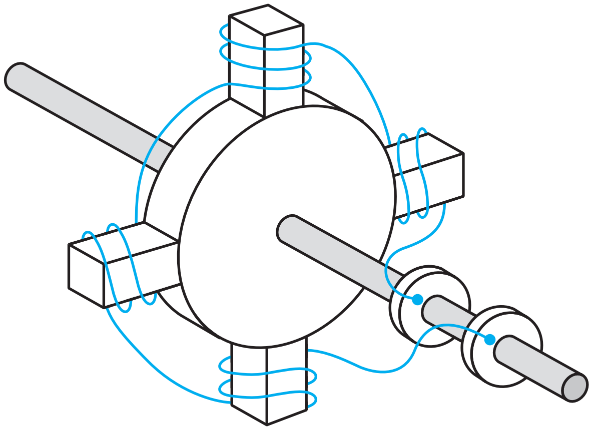


**Figure 17–1**
Rotor. (Source: Delmar/Cengage Learning)

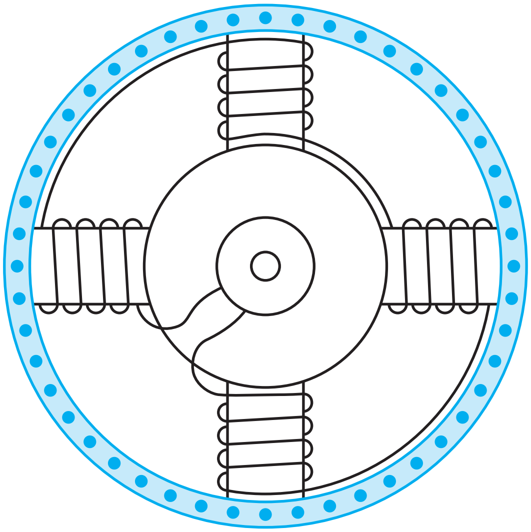


**Figure 17–2**
Amortisseur winding. (Source: Delmar/Cengage Learning)

windings similar to the wound rotor induction motor, Figure 17–1. Notice that the winding in the rotor of a synchronous motor is different, however. The winding of a synchronous motor is one continuous set of coils instead of three different sets as is the case with the wound rotor motor. Notice also that the synchronous motor has only two slip rings on its shaft as opposed to three on the shaft of a wound rotor motor.

## STARTING A SYNCHRONOUS MOTOR

The rotor of a synchronous motor also contains a set of type "A" squirrel-cage bars. This set of squirrel-cage bars is used to start the motor and is known as the **amortisseur** winding, Figure 17–2. When power is first connected to the stator, the rotating magnetic field cuts through the type "A" squirrel-cage bars. The cutting action of the field induces a current into the squirrel-cage bars. The current flow through the amortisseur winding produces a rotor magnetic field that is attracted to the rotating magnetic field of the stator. This causes the rotor to begin turning in the direction of rotation of the stator field. When the rotor has accelerated to a speed that is close to the synchronous speed of the field, DC is connected to the rotor through the slip rings on the rotor shaft, Figure 17–3. When DC is applied to the rotor, the windings on the rotor become electromagnets. The **electromagnetic field** of the rotor locks in step with the rotating magnetic field of the stator. The rotor will now turn at the same speed as the rotating magnetic field. When the rotor begins to turn at the synchronous speed of the field, there is no more cutting action between the field and the amortisseur winding. This causes the current flow in the amortisseur winding to cease.

Notice that the synchronous motor starts as a squirrel-cage induction motor. Because the rotor bars used are type "A," they have a relatively high resistance, which gives the motor good starting torque and low starting current. A synchronous motor must never be started with DC connected to the rotor. If DC is applied to the rotor, the field poles of the rotor become electromagnets. When the stator is energized, the rotating magnetic field begins turning at synchronous speed. The electromagnets of the rotor are attracted to the rotating magnetic field of the stator and are alternately attracted and repelled 60 times a second. As a result, the rotor does not turn.

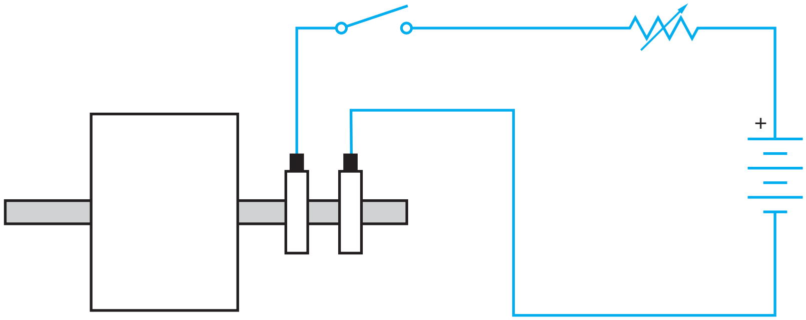


**Figure 17–3** Direct current is applied to the rotor through the slip rings. (Source: Delmar/Cengage Learning)

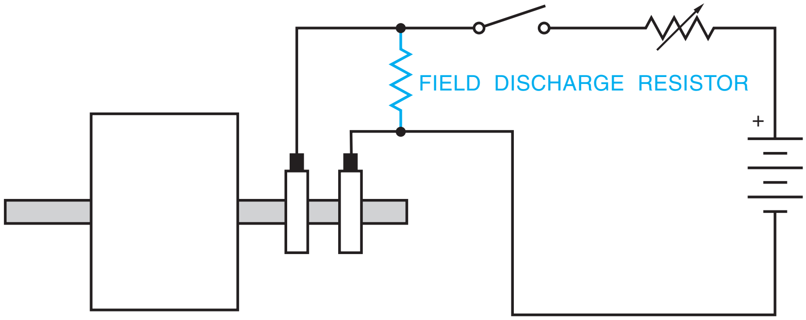



**Figure 17–4** A field discharge resistor protects the rotor circuit. (Source: Delmar/Cengage Learning)

## THE FIELD DISCHARGE RESISTOR

When the stator winding is first energized, the rotating magnetic field cuts through the rotor winding at a fast rate of speed. This causes a large amount of voltage to be induced into the winding of the rotor. To prevent this voltage from becoming excessive, a resistor is connected across the winding. This resistor is known as the **field discharge resistor**, Figure 17–4. It also helps to reduce the voltage induced into the rotor by the collapsing magnetic field when the DC is disconnected from the rotor.

## CONSTANT SPEED OPERATION

Although the synchronous motor starts as an induction motor, it does not operate as one. After the amortisseur winding has been used to accelerate the rotor to about 95% of the speed of the rotating magnetic field, direct current is connected to the rotor and the electromagnets lock in step with the rotating field. Notice that the synchronous motor does not depend on induced voltage from the stator field to produce a magnetic field in the rotor. The magnetic field of the rotor is produced by external DC applied to the rotor. This is the reason that the synchronous motor has the ability to operate at the speed of the rotating magnetic field. As load is added to the motor, the magnetic field of the rotor remains locked with the rotating magnetic field and the rotor continues to turn at the same speed.

## POWER FACTOR CORRECTION

The power factor of the synchronous motor can be changed by adjusting the **DC excitation current** to the rotor. When the DC is adjusted to the point that the motor current is in phase with the voltage, the motor has a power factor of 100%. This is considered to be normal excitation for the motor. For this example, assume this current to be 10 amps. If the DC power supply is adjusted to a point that the excitation current is less than 10 amps, the rotor is under excited. This causes the motor to have a lagging power factor like an induction motor. If the excitation current is adjusted above 10 amps, the rotor is overexcited. This causes the motor to have a leading power factor like a capacitor. When a synchronous motor is operated at no load and used for power factor correction, it is generally referred to as a **synchronous condenser**. Utility companies generally charge industries extra for poor power factor in the plant. For this reason, synchronous motors are often used when a large horsepower motor must be used. Commercial and industrial air conditioning systems are often the largest single load in a plant or building. It is not uncommon to find synchronous motors being used to operate the compressors of large air-conditioning systems.

## THE POWER SUPPLY

DC power supply of a synchronous motor can be provided by several methods. The most common of these methods is either a small DC generator mounted to the shaft of the motor, or an electronic power supply that converts the AC line voltage to DC voltage.

## TESTING THE SYNCHRONOUS MOTOR

The procedure for testing the stator winding of a synchronous motor is the same as that described for testing the stator of a squirrel-cage induction motor. The rotor can be tested with an ohmmeter for an open winding or a grounded winding. To test the rotor for an open winding, connect one of the ohmmeter leads to each of the slip rings on the rotor shaft, Figure 17–5. Since the rotor winding of a synchronous motor is intended for DC current, the resistance of the wire will be high as compared with the wire resistance of a wound rotor motor. Owing to the fact that alternating current flows in the rotor of a wound rotor motor, the current is limited by the inductance of the coil and not its resistance.

To test the rotor for a grounded winding, connect one ohmmeter lead to the shaft of the motor, and the other lead to one of the slip rings. There should be no continuity between the winding and the motor shaft, Figure 17–6.

Because the resistance of the rotor is relatively high, a shorted winding can often be found with the ohmmeter. In coils designed for DC current, the resistance of the wire is used to limit the flow of current. For example, assume the specifications of a synchronous motor indicate that the DC excitation voltage should be 125 volts, and that maximum rotor current should be 10 amps. The resistance of the rotor can now be calculated by using Ohm's law:

$$R = \frac{E}{I}$$

$$R = \frac{125}{10}$$

$$R = 12.5 \text{ ohms}$$

If the ohmmeter measures a rotor resistance close to 12.5 ohms, the rotor is good. If the ohmmeter measures a much lower resistance, however, the rotor is shorted.

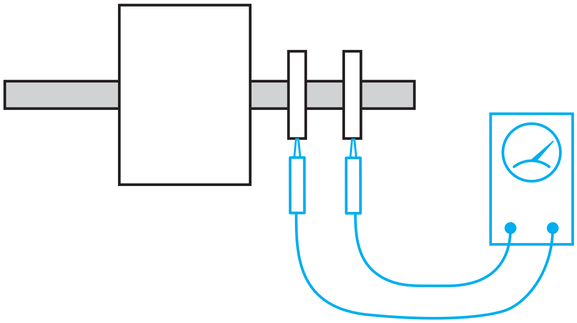


**Figure 17–5**
Testing the rotor for an open winding. (Source: Delmar/Cengage Learning)

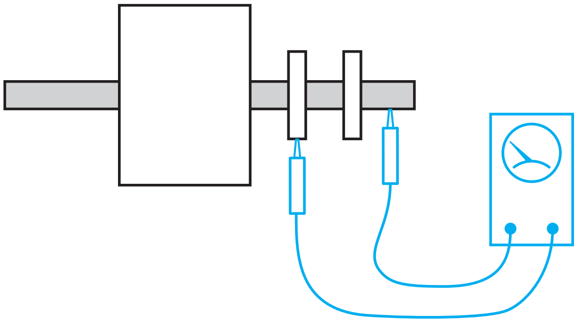


**Figure 17–6**
Testing the rotor for a grounded winding. (Source: Delmar/Cengage Learning)

## THE BRUSHLESS EXCITER

Many large synchronous motors use a brushless exciter instead of slip rings and brushes. The **brushless exciter** is constructed by incorporating a small three-phase alternator winding on the shaft of the motor, Figure 17–7. The three-phase winding is placed inside the field of electromagnets, Figure 17–8. A variable source of direct current is used to control the strength of the electromagnets. The amount of voltage induced into the armature winding is determined by three factors:

1. The number of turns of wire in the armature winding.
2. The speed of the armature.
3. The strength of the electromagnets.

Because the amount of DC current that flows through the windings of the electromagnets determines their strength, the output voltage of the three-phase armature can be controlled by the DC excitation current.

The output voltage of the alternator winding is then rectified to direct current with a three-phase bridge rectifier, Figure 17–9. The bridge rectifier and all protective devices such as fuses are mounted on the motor shaft with the armature winding. The output of the bridge rectifier is connected to the

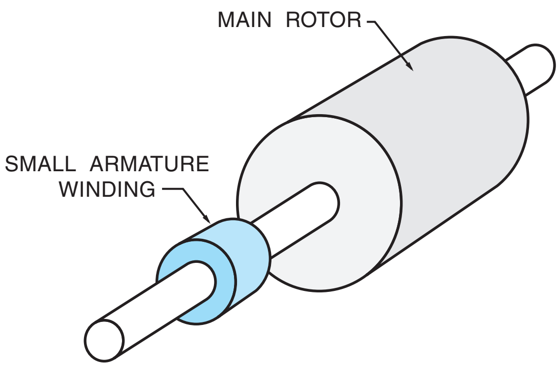



**Figure 17–7**
A brushless exciter contains a small three-phase winding on the motor shaft. (Source: Delmar/Cengage Learning)

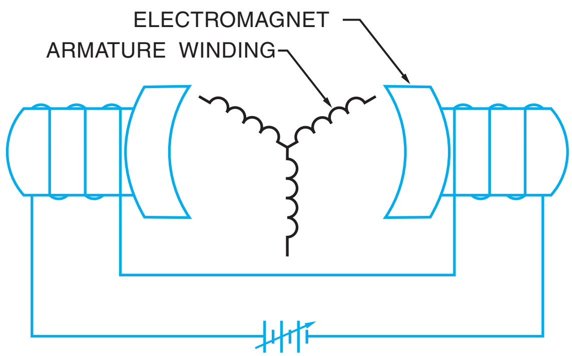



**Figure 17–8**
The armature winding is between two electromagnets. (Source: Delmar/Cengage Learning)

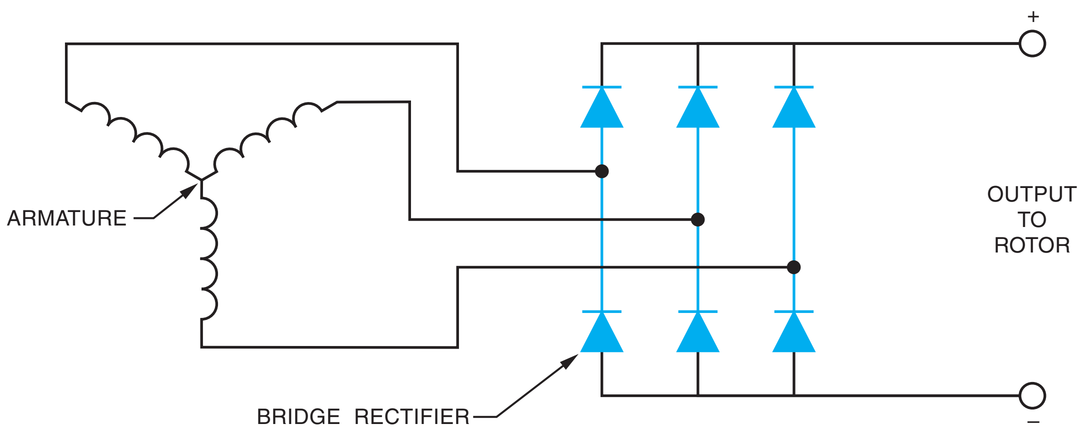



**Figure 17–9**
The output of the armature winding is connected to a three-phase bridge rectifier. (Source: Delmar/Cengage Learning)

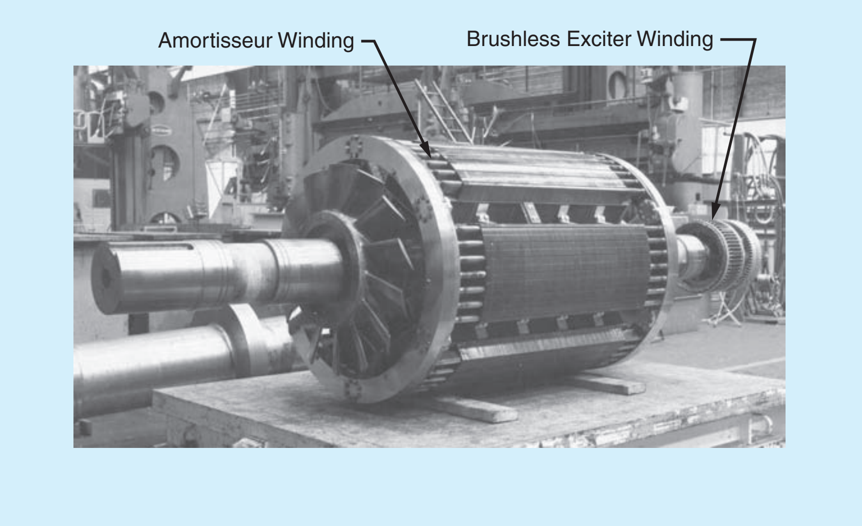



**Figure 17–10**
Rotor of a large synchronous motor. (Courtesy of Electric Machinery Corp.)

winding of the main rotor. The amount of DC excitation in the rotor of the synchronous motor is now controlled by the amount of DC excitation current supplied to the windings of the electromagnets.

The rotor of a large synchronous motor is shown in Figure 17–10. The amortisseur winding and the brushless exciter winding can be seen in the photograph.

## SUMMARY

- The synchronous motor is not an induction motor.
- The synchronous motor must have an external source of direct current supplied to the rotor during normal operation.
- The DC current supplied to the rotor is known as the excitation current.
- Synchronous motors operate at a constant speed from no load to full load.
- Synchronous motors run at the speed of the rotating magnetic field.
- The two factors that determine the speed of a synchronous motor are:
  A. Number of stator poles per phase.
  B. Frequency of the applied voltage.
- Synchronous motors use a special squirrel-cage winding called the amortisseur winding for starting.
- A synchronous motor can be made to have a leading power factor by over excitation of the rotor current.

## KEY TERMS

amortisseur
brushless exciter
DC excitation current
electromagnetic field
field discharge resistor
synchronous condenser
synchronous motor

## QUESTIONS

1. Name three characteristics of a synchronous motor that the squirrel-cage induction motor and the wound rotor motor do not have.
2. What is an amortisseur winding?
3. How many slip rings are located on the shaft of a synchronous motor?
4. How many slip rings are located on the shaft of a wound rotor induction motor?
5. Is a synchronous motor started with DC excitation voltage applied to the rotor?
6. What is the field discharge resistor used for?
7. A synchronous motor has an eight-pole stator. What will be the speed of the rotor when it is under full load?
8. How is it possible to know when a synchronous motor has normal excitation applied to its rotor?
9. How can a synchronous motor be made to have a leading power factor?
10. What is a synchronous condenser?

# UNIT 18

# Brushless DC Motors

## OBJECTIVES

After studying this unit the student should be able to:

- Describe the operation of a brushless DC motor
- Discuss applications for brushless DC motors
- List differences in construction between brushless DC motors and other types of motors
- Discuss the operation and advantages of variable speed air handlers

**Brushless** direct current motors have become very popular for operating variable speed air handlers found in many residential central heating and cooling systems. The typical air handler is powered by a multispeed motor that can generally operate at three speeds. When the fan motor is started, however, it operates at its set speed until it is turned off. Basically, the blower motor is either full on or completely off. **Variable speed** air handlers permit the motor to operate at different speeds in accord with the demands of the system. Many variable speed air handlers are operated at a low speed continuously to maintain air circulation throughout the dwelling at all times. When the heating or cooling system turns on, the fan speed can be increased gradually and in steps instead of all at once.

Variable speed air handlers exhibit several advantages over air handlers that operate at a single speed. Some of these advantages are:

**Dust collection.** Single speed air handlers pull dust through the filter at a high rate of speed. This lessens the filter's ability to trap dust particles. Variable speed air handlers operate at a very low speed most of the time, causing more dust particles to be collected by the filter.

**Less temperature variation.** Typically, the inside temperature will vary from three to five degrees before the heating or cooling system turns on. The variable speed air handler can be operated at different speeds between the cycling of the heating or cooling system to provide more or less air flow as needed. This can greatly reduce the temperature variation and permits the temperature to remain closer to the comfort zone setting.

**Better humidity control during cooling.** When the air-conditioning compressor starts, the speed of the air handler is increased gradually instead of all at once. This permits the warm air to flow across the evaporator coil at a slower rate, permitting the coil to rapidly cool down. This **rapid cooldown** results in increased moisture removal.

## THE BRUSHLESS DC MOTOR

The brushless DC motor operates by converting direct current into three-phase alternating current at different frequencies. The motor contains a **permanent magnet rotor**, a stator, and the electronics necessary to change direct current into three-phase alternating current, Figure 18–1. The speed of the motor is determined by the frequency of the three-phase current. The motor operates on the principle of a rotating magnetic field very similar to that of a three-phase induction motor. The brushless DC motor, however, is *not* an induction motor. It does not depend on current being induced into the rotor to produce a rotor magnetic field. Because permanent magnets supply the rotor magnetic field, the brushless DC motor does not exhibit the high inrush current during starting that is a characteristic of induction type motors. The starting current and the running current of the motor are basically the same. This feature greatly reduces the current-handling requirement of the electronic components needed to change direct current into three-phase alternating current.

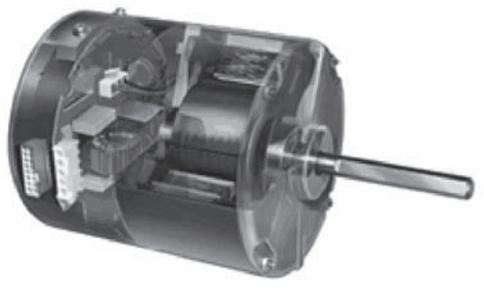


**Figure 18–1**
Brushless DC motor. (Courtesy of GE ECM™ Technologies).

The factors that determine the amount of torque produced by the brushless DC motor are the same as those for any other electric motor:

1. Strength of the magnetic field of the stator.
2. Strength of the magnetic field of the rotor.
3. Phase angle difference between rotor and stator flux.

Because the rotor magnetic field is supplied by permanent magnets, the flux of the rotor and stator are always in phase with each other. This produces a strong torque for this type of motor.

The electronic components necessary to change single-phase alternating current into direct current and then into three-phase alternating current are located inside the motor housing, Figure 18–2. Most variable frequency type controls first change alternating current into direct current because it is a simpler process to produce multiphase alternating current from direct current than to change the frequency and number of phases of an existing alternating current source.

Brushless DC motors are operated in one of two modes, the thermostat mode or the variable speed mode. When used in the thermostat mode, the motor is controlled by a 24-VAC signal from the thermostat. When used in the variable speed mode, the motor is controlled by a pulse width modulating signal.

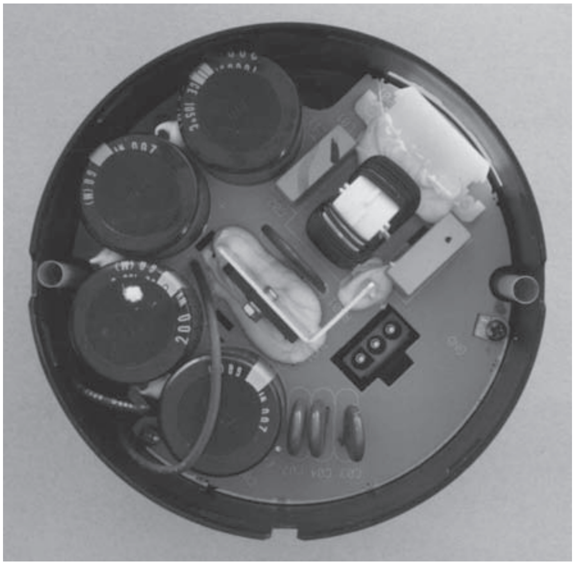
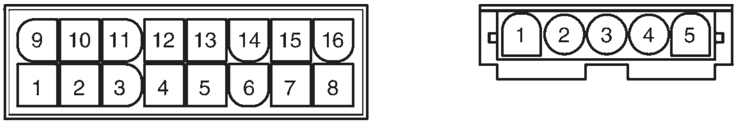


**Figure 18–2**
Electronic control unit for a brushless DC motor. (Courtesy of GE ECM™ Technologies).

The motor is provided with two terminal connections. One is a 16-pin connector and is called the **control connector**. This connector receives the information necessary to control the operation of the motor. The other connection is a 5-pin connector and is called the **power connector**. This connector provides the power to operate the motor. A pin connection diagram is shown in Figure 18–3.

Brushless DC motors can generally be obtained in 1/3, 1/2, 3/4, or 1 horsepower ratings. They can exhibit efficiency as high as 82% and can operate on 120/240 and 277 VAC at 50 or 60 Hz. The speed range is from 300 to 1,200 RPM. Although the motor can be operated at 1,200 RPM, it is generally recommended not to operate the motor above 1,050 RPM when used for continuous operation.




| CONTROL CONNECTOR | |
|---|---|
| PIN | DESCRIPTION |
| 1 | C1 |
| 2 | W/W1 |
| 3 | C2 |
| 4 | DELAY |
| 5 | COOL |
| 6 | Y1 |
| 7 | ADJUST |
| 8 | OUT - |
| 9 | O |
| 10 | BK/PWM |
| 11 | HEAT |
| 12 | R |
| 13 | EM/W2 |
| 14 | Y/Y2 |
| 15 | G |
| 16 | OUT + |

| POWER CONNECTOR | |
|---|---|
| PIN | DESCRIPTION |
| 1 | JUMPER PIN 1 TO PIN 2 FOR 120 VAC INPUT ONLY |
| 2 | |
| 3 | CHASSIS GRD. |
| 4 | AC LINE |
| 5 | AC LINE |

**WARNING**—APPLYING 240 VAC LINE INPUT WITH PINS 1 AND 2 JUMPERED WILL PERMANENTLY DAMAGE THE UNIT.

**Figure 18–3**
Pin connection diagram for a brushless DC motor. (Source: Delmar/Cengage Learning)

## Electronic Control

The brushless DC motor is controlled by a circuit board located in the air handler. The board supplies both direct current to the motor and the signals that determine motor speed. Some boards are preset at the factory for the specific type of air handler unit. Other boards contain DIP (Dual Inline Package) switches that permit the air handler to be set for different operating conditions. Typical DIP switch configurations for some systems are:

Switches 1 and 2. Set for system tonnage.
Switches 3 and 4. Set for 300, 400, or 450 cfm/ton.
Switches 5 and 6. Set for time delay or mode.
Switches 7 and 8. Set for desired heating flow.

## SUMMARY

- Brushless DC motors are generally used to power the blower in variable speed air handlers.
- The circuitry necessary to change single-phase alternating current into three-phase alternating current is located inside the motor housing.
- Brushless DC motors operate on the principle of a rotating magnetic field.
- Brushless DC motors are not induction motors. They do not depend on an inducted current to produce a magnetic field in the rotor.
- Brushless DC motors are operated in one of two modes.
- Brushless DC motors can have efficiencies as high as 82%.
- Because brushless DC motors are not induction motors, they do not exhibit the high starting current associated with induction-type motors.

## KEY TERMS

**brushless**
**control connector**
**frequency**
**permanent magnet rotor**
**power connector**
**rapid cooldown**
**rotating magnetic field**
**variable speed**

## REVIEW QUESTIONS

1. What is the operating voltage of a brushless DC motor?
2. What is the recommended maximum operating speed for a brushless DC motor when used for continuous operation?
3. If the motor is to be operated on 120 VAC, what must be done to permit the motor to operate on this voltage?
4. Referring to the power connector, which pins are used to connect AC line voltage to the motor?
5. When the brushless DC motor is used in the thermostat mode, what controls the operation of the motor?

6. Name three factors that determine the amount of torque produced by a brushless DC motor.
7. Referring to the control connector, to which pin would Y/Y2 be connected?
8. Name three advantages of a variable speed air handler over a single speed air handler.

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# SECTION 4

# Transformers

# UNIT 19 Isolation Transformers

## OBJECTIVES

After studying this unit the student should be able to:

- Discuss the different types of transformers
- Calculate values of voltage, current, and turns for single-phase transformers using formulas
- Calculate values of voltage, current, and turns for a single-phase transformer using the turns ratio
- Connect a transformer and test the voltage output of different windings

Transformers are one of the most common devices found in the HVAC field. They range in size from occupying a space of less than 1 cubic inch to requiring rail cars to move them after they have been broken into sections. Their ratings can range from mVA (millivolt amps) to GVA (gigavolt amps).

A transformer is a magnetically operated machine that can change values of voltage, current, and impedance without a change of frequency.

Transformers are the most efficient machines known. Their efficiencies commonly range from 90% to 99% at full load. Transformers can be divided into several classifications such as:

A. Isolation.

B. Auto.

C. Current.

A basic law concerning transformers is that *all values of a transformer are proportional to its turns ratio*. This does not mean that the exact number of turns of wire on each winding must be known to determine different values of voltage and current for a transformer. What must be known is the *ratio* of turns. For example, assume a transformer has two windings. One winding, the primary, has 1,000 turns of wire and the other, the secondary, has 250 turns of wire, Figure 19–1. The turns ratio of this transformer is 4 to 1 or 4:1 (1,000/250 = 4). This indicates there are four turns of wire on the primary for every one turn of wire on the secondary.

## TRANSFORMER FORMULAS

There are different formulas that can be used to find the values of voltage and current for a transformer. The following is a list of standard formulas:

Where:

$N_P$ = Number of turns in the primary

$N_S$ = Number of turns in the secondary

$E_P$ = Voltage of the primary

$E_S$ = Voltage of the secondary

$I_P$ = Current in the primary

$I_S$ = Current in the secondary

$$\frac{E_P}{E_S} = \frac{N_P}{N_S} \quad \frac{E_P}{E_S} = \frac{I_S}{I_P} \quad \frac{N_P}{N_S} = \frac{I_S}{I_P}$$

or

$$E_P \times N_S = E_S \times N_P$$

$$E_P \times I_P = E_S \times I_S$$

$$N_P \times I_P = N_S \times I_S$$

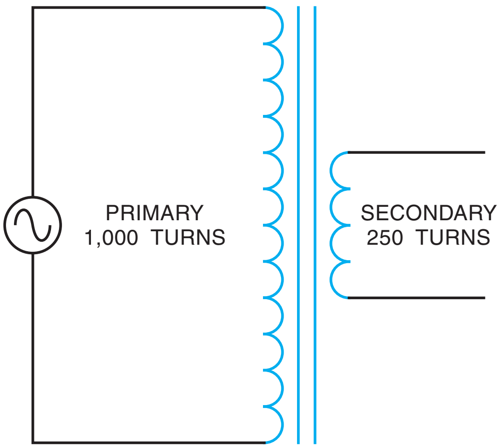



**Figure 19–1**
All values of a transformer are proportional to its turns ratio. (Source: Delmar/Cengage Learning)

The primary winding of a transformer is the power input winding. It is the winding that is connected to the incoming power supply. The secondary winding is the load winding or output winding. It is the side of the transformer that is connected to the driven load, Figure 19–2. Any winding of a transformer can be used as a primary or secondary winding provided its voltage or current rating is not exceeded. Transformers can also be operated at a lower voltage than their rating indicates, but they cannot be connected to a higher voltage. Assume the transformer shown in Figure 19–2, for example, has a primary voltage rating of 480 volts and the secondary has a voltage rating of 240 volts. Now assume that the primary winding is connected to a 120-volt source. No damage would occur to the transformer, but the secondary winding would produce only 60 volts.

## ISOLATION TRANSFORMERS

The transformers shown in Figures 19–1 and 19–2 are **isolation transformers**. This means that the secondary winding is physically and electrically isolated from the primary winding. There is

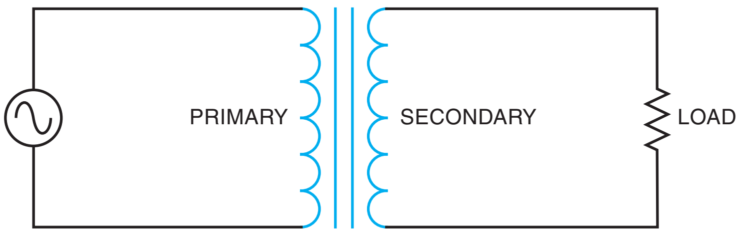



**Figure 19–2**
Isolation transformer.
(Source: Delmar/Cengage Learning)

no electrical connection between the primary and secondary winding. This transformer is magnetically coupled, not electrically coupled. This "line isolation" is often a very desirable characteristic. Because there is no electrical connection between the load and power supply, the transformer becomes a filter between the two. The isolation transformer will greatly reduce any voltage spikes that originate on the supply side before they are transferred to the load side. Some isolation transformers are built with a turns ratio of 1:1. A transformer of this type will have the same input and output voltage and is used for the purpose of isolation only.

The reason that the transformer can greatly reduce any voltage spikes before they reach the secondary is because of the rise time of current through an inductor. The current in an inductor rises at an exponential rate, Figure 19–3. As the current increases in value, the expanding magnetic field cuts through the conductors of the coil and induces a voltage that is opposed to the applied voltage. The amount of induced voltage is proportional to the rate of change of current. This simply means that the faster the current attempts to increase, the greater the opposition to that increase will be. Spike voltages and currents are generally of very short duration, which means that they increase in value very rapidly, Figure 19–4. This rapid change of value causes the opposition to the change to increase just as rapidly. By the time the spike has been transferred to the secondary winding of the transformer, it has been eliminated or greatly reduced, Figure 19–5.

Another purpose of isolation transformers is to remove some piece of electrical equipment from ground. It is sometimes desirable that a piece of electrical equipment not be connected directly to ground. This is often done as a safety precaution to eliminate the hazard of an accidental contact between a person at ground potential and the ungrounded conductor. If the case of the equipment should come in contact with the ungrounded conductor, the isolation transformer would prevent a circuit being completed to ground through someone touching the case of the equipment. Many alternating current circuits have one side connected to ground. A familiar example of this is the common

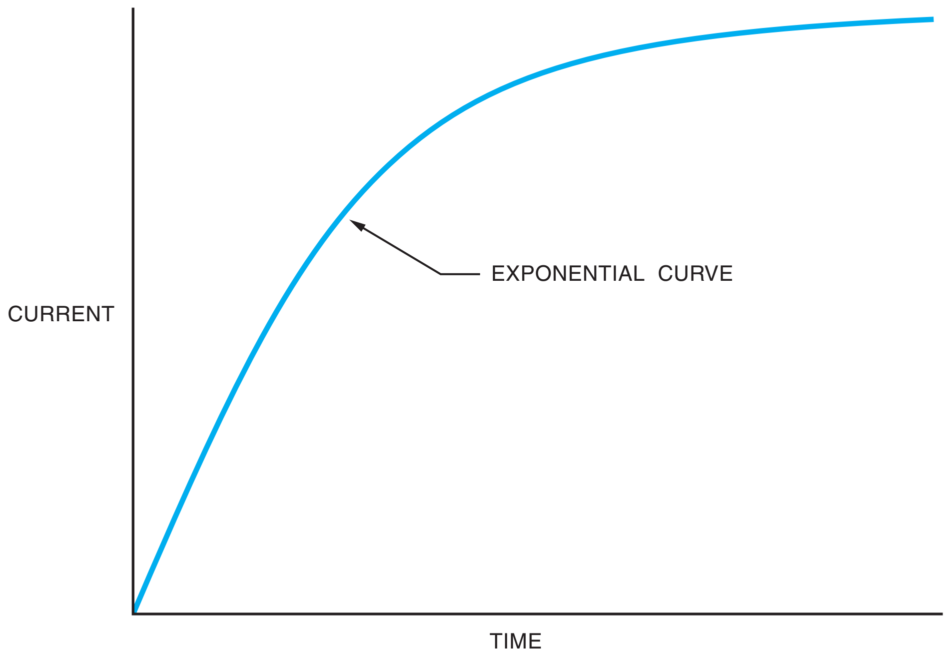



**Figure 19–3** The current through an inductor rises at an exponential rate. (Source: Delmar/Cengage Learning)

120-volt circuit with a grounded neutral conductor, Figure 19–6. An isolation transformer can be used to remove a piece of equipment from circuit ground.

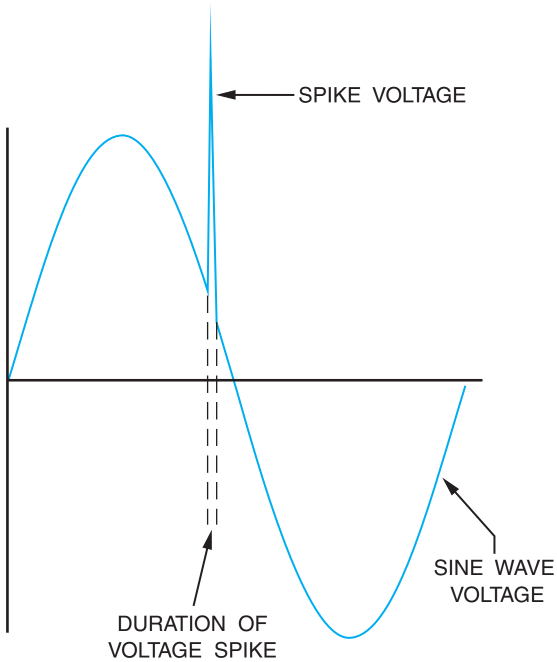



**Figure 19–4**
Voltage spikes are generally of short duration.
(Source: Delmar/Cengage Learning)

## TRANSFORMER CONSTRUCTION

The basic construction of an isolation transformer is shown in Figure 19–7. A metal core is used to provide good magnetic coupling between the two windings. The core is generally made of laminations stacked together. Laminating the core helps reduce power losses due to eddy current induction. Figure 19–7 shows the basic design of electrically separated winding.

## TRANSFORMER CORE TYPES

There are several different types of cores used in the construction of transformers. Most cores are made from thin steel punchings laminated together to form a solid metal core. Laminated cores are preferred because a thin layer of oxide forms on the surface of each lamination, which acts as an insulator to reduce the formation of eddy currents inside the core material. The amount of core material needed for a particular transformer is determined by the power rating of the transformer. The amount of core material must be sufficient to prevent saturation at full load. The type and shape of the core generally determines the amount of magnetic coupling between the windings and to some extent the efficiency of the transformer.

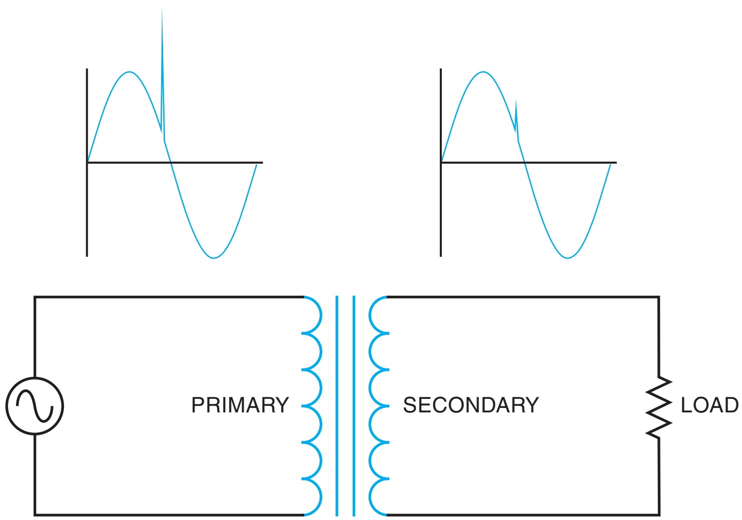



**Figure 19–5**
The isolation transformer greatly reduces the voltage spike. (Source: Delmar/Cengage Learning)

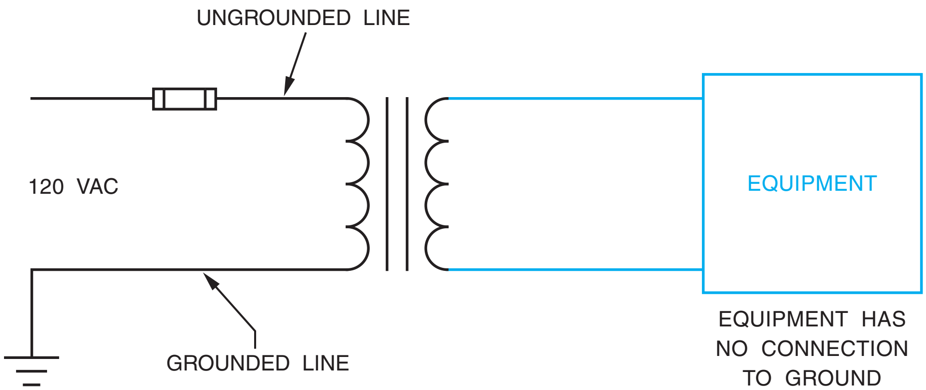



**Figure 19–6** Isolation transformer used to remove a piece of electrical equipment from ground. (Source: Delmar/Cengage Learning)

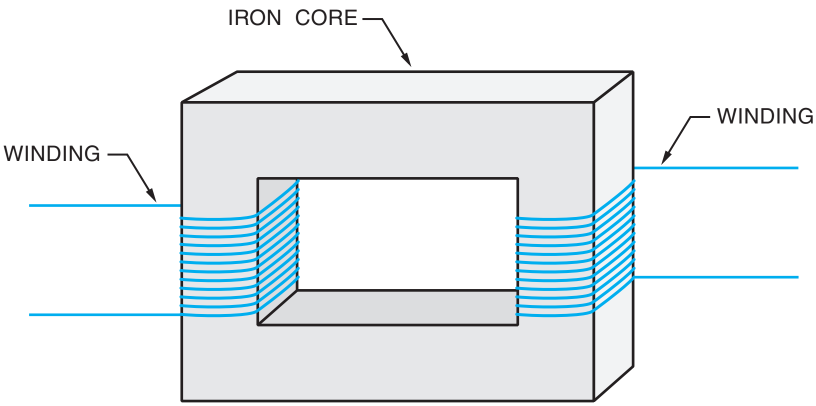



**Figure 19–7** Basic construction of an isolation transformer. (Source: Delmar/Cengage Learning)

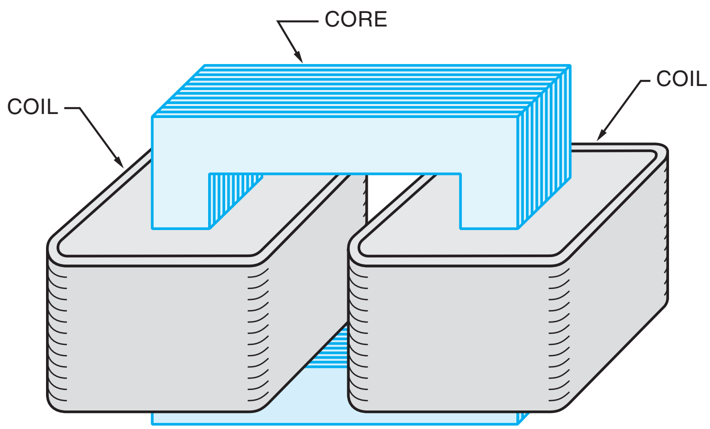



**Figure 19–8** Core-type transformer. (Source: Delmar/Cengage Learning)

The transformer illustrated in Figure 19–8 is known as a **core transformer**. The windings are placed around each end of the core material. The metal core provides a good magnetic path between the two windings.

The **shell transformer** is constructed in a similar manner as the core type, except that the shell type has a metal core piece through the middle of the window, Figure 19–9. The primary and secondary windings are wound around the center core piece with the low voltage winding being closest to the metal core. This arrangement permits the transformer to be surrounded by the core, which provides

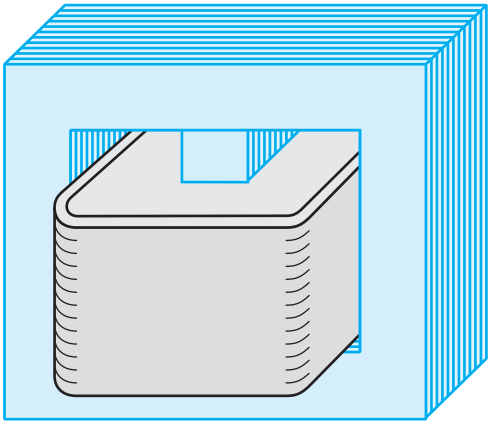


**Figure 19–9**
Shell-type transformer. (Source: Delmar/Cengage Learning)

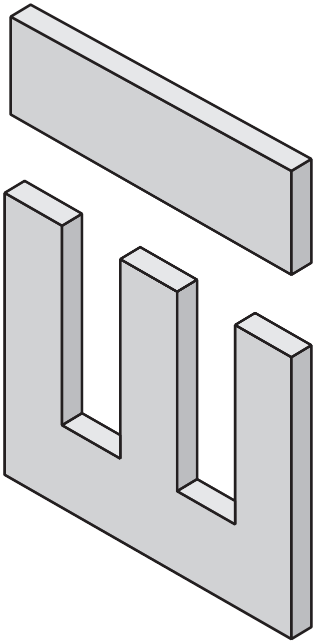



**Figure 19–10**
Shell-type cores are made of E and I laminations.
(Source: Delmar/Cengage Learning)

excellent magnetic coupling. When the transformer is in operation, all the magnetic flux must pass through the center core piece. It then divides through the two outer core pieces. Shell type cores are sometimes referred to as **E-I cores** because the steel punchings used to construct the core are in the shape of an E and an I, Figure 19–10.

The H-type core shown in Figure 19–11 is similar to the shell type core in that it has an iron core through its center around which the primary and secondary windings are wound. The H core, however, surrounds the windings on four sides instead of two. This extra metal helps reduce stray leakage flux and improve the efficiency of the transformer. The H-type core is often found on high voltage distribution transformers.

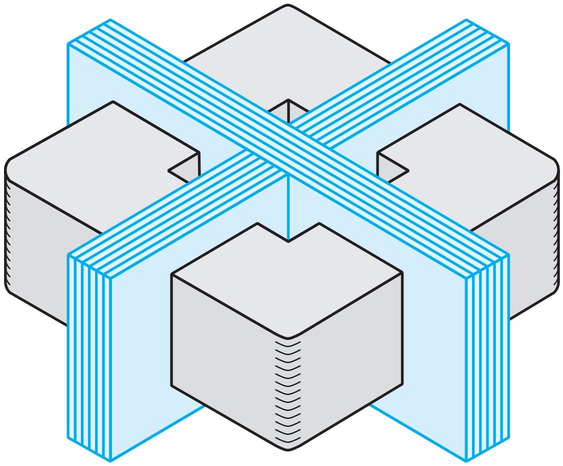


**Figure 19–11**
Transformer with H-type core. (Source: Delmar/Cengage Learning)

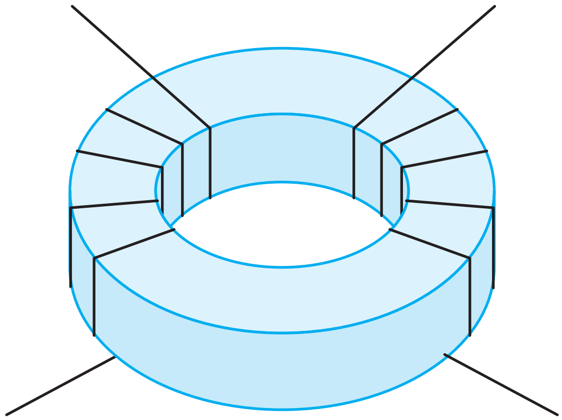


**Figure 19–12**
Toroid transformer. (Source: Delmar/Cengage Learning)

The **tape wound** or **toroid core**, Figure 19–12, is constructed by tightly winding one long continuous silicon steel tape into a spiral. The tape may or may not be housed in a plastic container depending on the application. This type core does not require steel punchings that are then laminated together. Because the core is one continuous length of metal, flux leakage is kept to a minimum. The tape wound core is one of the most efficient core designs available.

## BASIC OPERATING PRINCIPLES

In Figure 19–13, one winding of the transformer has been connected to an alternating current supply, and the other winding has been connected to a load. As current increases from zero to its peak positive point, a magnetic field expands outward around the coil. When the current decreases from its peak positive point toward zero, the magnetic field collapses. When the current increases toward its negative peak, the magnetic field again expands, but with an opposite polarity of that previously. The field again collapses when the current decreases from its negative peak toward zero. This continually expanding and collapsing magnetic field cuts the windings of the primary and induces a voltage into it. This induced voltage opposes the applied voltage and limits the current flow of the primary. When a coil induces a voltage into itself, it is known as **self-induction**. It is this induced voltage, inductive reactance, that limits the flow of current in the primary winding. If the resistance of the primary winding is measured with an ohmmeter, it will indicate only the resistance of the wire used to construct the winding and will not give an indication of the actual current limiting effect of the winding. Most transformers with a large kVA rating will appear to be almost a short circuit when measured with an ohmmeter. When connected to power, however, the actual no load current is generally relatively small.

## EXCITATION CURRENT

There will always be some amount of current flow in the primary of a transformer even if there is no load connected to the secondary. This is called the **excitation current** of the transformer. The excitation current is the amount of current required to magnetize the core of the transformer. The excitation current remains constant from no load to full load. As a general rule, the excitation current is such a small part of the full load current, it is often omitted when making calculations.

## MUTUAL INDUCTION

Because the secondary windings are wound on the same core as the primary, the magnetic field produced by the primary winding cuts the windings of the secondary also, Figure 19–14. This continually changing magnetic field induces a voltage into the secondary winding. The ability of one coil to induce a voltage into another coil is called **mutual induction**. The amount of voltage induced in the secondary is determined by the number of turns of wire in the secondary as compared with

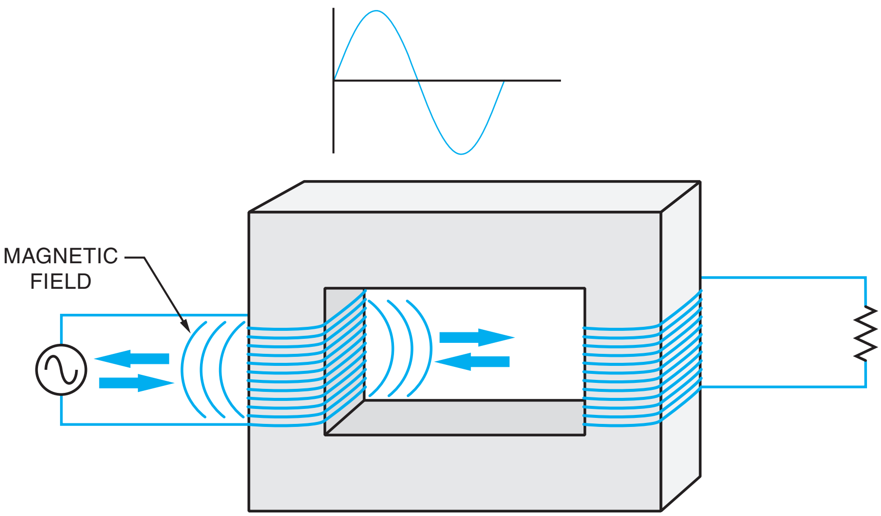



**Figure 19–13** Magnetic field produced by alternating current.
(Source: Delmar/Cengage Learning)

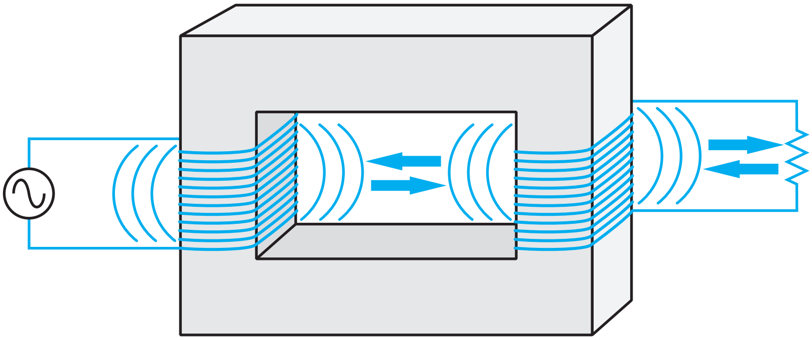


**Figure 19–14** The magnetic field of the primary induces a voltage into the secondary. (Source: Delmar/Cengage Learning)

the primary. For example, assume the primary has 240 turns of wire and is connected to 120 volts AC. This gives the transformer a volts-per-turn ratio of 0.5 (120 volts per 240 turns = 0.5 volt per turn). Now assume the secondary winding contains 100 turns of wire. Because the transformer has a volts-per-turn ratio of 0.5, the secondary voltage will be 50 volts (100 × 0.5 × 50).

## TRANSFORMER CALCULATIONS

In the following examples, values of voltage, current, and turns for different transformers will be computed.

## EXAMPLE

Assume the isolation transformer shown in Figure 19–2 has 240 turns of wire on the primary and 60 turns of wire on the secondary. This is a ratio of 4:1 (240/60 = 4). Now assume that 120 volts is connected to the primary winding. What is the voltage of the secondary winding?

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{240}{60}$$

$$E_S = 30 \text{ volts}$$

The transformer in this example is known as a **step-down transformer** because it has a lower secondary voltage than primary voltage.

Now assume that the load connected to the secondary winding has an impedance of 5 Ω. The next problem is to calculate the current flow in the secondary and primary windings. The current flow of the secondary can be computed using Ohm's law since the voltage and impedance are known.

$$I = \frac{E}{Z}$$

$$I = \frac{30}{5}$$

$$I = 6 \text{ amps}$$

Now that the amount of current flow in the secondary is known, the primary current can be computed using the formula:

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{30} = \frac{6}{I_P}$$

$$120\, I_P = 180$$

$$I_P = 1.5 \text{ amps}$$

Notice that the primary voltage is higher than the secondary voltage, but the primary current is much less than the secondary current. A good rule for transformers is that *power in must equal power out*. If the primary voltage and current are multiplied together, it should equal the product of the voltage and current of the secondary:

*Primary*

$$120 \times 1.5 = 180 \text{ volt amps}$$

*Secondary*

$$30 \times 6 = 180 \text{ volt amps}$$

## EXAMPLE

In the next example, assume that the primary winding contains 240 turns of wire and the secondary contains 1,200 turns of wire. This is a turns ratio of 1:5 (1,200/240 = 5). Now assume that 120 volts is connected to the primary winding. Compute the voltage output of the secondary winding.

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{240}{1200}$$

$$240\ E_S = 144{,}000$$

$$E_S = 600 \text{ volts}$$

Notice that the secondary voltage of this transformer is higher than the primary voltage. This type of transformer is known as a **step-up transformer**.

Now assume that the load connected to the secondary has an impedance of 2,400 Ω. Find the amount of current flow in the primary and secondary windings. The current flow in the secondary winding can be computed using Ohm's law.

$$I = \frac{E}{Z}$$

$$I = \frac{600}{2400}$$

$$I = 0.25 \text{ amp}$$

Now that the amount of current flow in the secondary is known, the primary current can be computed using the formula:

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{600} = \frac{0.25}{I_P}$$

$$120\ I_P = 150$$

$$I_P = 1.25 \text{ amps}$$

Notice that the amount of power input equals the amount of power output.

*Primary*

$$120 \times 1.25 = 150 \text{ volt amps}$$

*Secondary*

$$600 \times 0.25 = 150 \text{ volt amps}$$

## CALCULATING TRANSFORMER VALUES USING THE TURNS RATIO

As illustrated in the previous examples, transformer values of voltage, current, and turns can be computed using formulas. It is also possible to compute these same values using the turns ratio. There are several ways in which turns ratios can be expressed. One method is to use a whole number value such as 13:5 or 6:21. The first ratio indicates that one winding has 13 turns of wire for every 5 turns of wire in the other winding. The second ratio indicates that there are 6 turns of wire in one winding for every 21 turns in the other.

A second method is to use the number 1 as a base. When using this method, the number 1 is always assigned to the winding with the lowest voltage rating. The ratio is found by dividing the higher voltage by the lower voltage. The number on the left side of the ratio represents the primary winding, and the number on the right of the ratio represents the secondary winding. For example, assume a transformer has a primary rated at 240 volts and a secondary rated at 96 volts, Figure 19–15. The

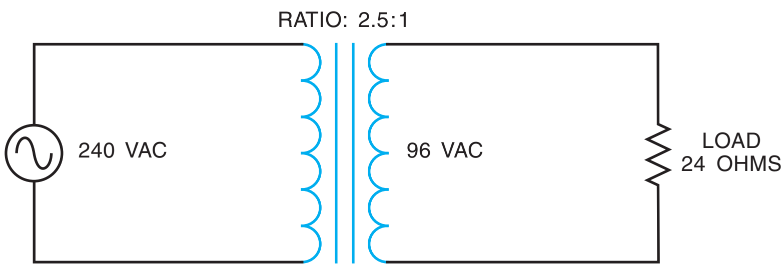



**Figure 19–15** Computing transformer values using the turns ratio. (Source: Delmar/Cengage Learning)

turns ratio can be computed by dividing the higher voltage by the lower voltage.

$$\text{Ratio} = \frac{240}{96}$$

$$\text{Ratio} = 2.5{:}1$$

Notice in this example that the primary winding has the higher voltage rating and the secondary has the lower. Therefore, the 2.5 is placed on the left and the base unit, 1, is placed on the right. This ratio indicates that there are 2.5 turns of wire in the primary winding for every 1 turn of wire in the secondary.

Now assume that there is a resistance of 24 Ω connected to the secondary winding. The amount of secondary current can be found using Ohm's law.

$$I_S = \frac{96}{24}$$

$$I_S = 4 \text{ amps}$$

The primary current can be found using the turns ratio. Recall that the volt amps of the primary must equal the volt amps of the secondary. Because the primary voltage is greater, the primary current will have to be less than the secondary current. Therefore, the secondary current will be divided by the turns ratio.

$$I_P = \frac{I_S}{\text{Turns Ratio}}$$

$$I_P = \frac{4}{25}$$

$$I_P = 1.6 \text{ amps}$$

To check the answer, find the volt amps of the primary and secondary.

*Primary*

$$240 \times 1.6 = 384$$

*Secondary*

$$96 \times 4 = 384$$

Now assume that the secondary winding contains 150 turns of wire. The primary turns can also be found by using the turns ratio. Because the primary voltage is higher than the secondary voltage, the primary must have more turns of wire. Because the primary must contain more turns of wire, the secondary turns will be multiplied by the turns ratio.

$$N_P = N_S \times \text{Turns Ratio}$$

$$N_P = 150 \times 2.5$$

$$N_P = 375 \text{ turns}$$

In the next example, assume a transformer has a primary voltage of 120 volts and a secondary voltage of 500 volts. The secondary has a load impedance of 1,200 Ω. The secondary contains 800 turns of wire, Figure 19–16. The turns ratio can be found by dividing the higher voltage by the lower voltage.

$$\text{Ratio} = \frac{500}{120}$$

$$\text{Ratio} = 1{:}4.17$$

The secondary current can be found using Ohm's law.

$$I_S = \frac{500}{1200}$$

$$I_S = 0.417 \text{ amp}$$

In this example, the primary voltage is lower than the secondary voltage. Therefore, the primary current must be higher. To find the primary current, multiply the secondary current by the turns ratio.

$$I_P = I_S \times \text{Turns Ratio}$$

$$I_P = 0.417 \times 4.17$$

$$I_P = 1.74 \text{ amps}$$

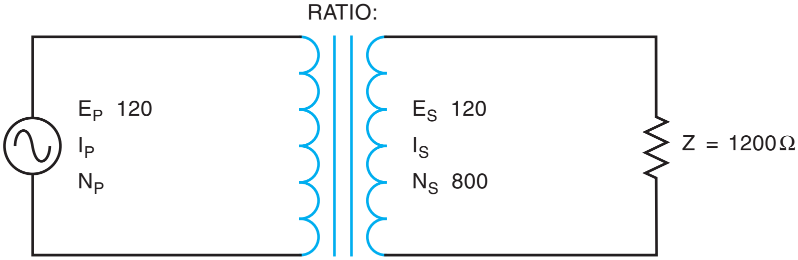



**Figure 19–16**
Calculating transformer values.
(Source: Delmar/Cengage Learning)

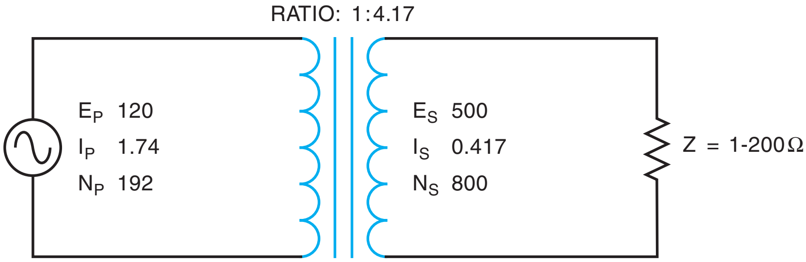



**Figure 19–17** Transformer with completed values. (Source: Delmar/Cengage Learning)

To check this answer, compute the volt amps of both windings.

*Primary*

$120 \times 1.74 = 208.8$

*Secondary*

$500 \times 0.417 = 208.8$

The slight difference in answers is caused by rounding off the values.

Because the primary voltage is less than the secondary voltage, the turns of wire in the primary will be less also. The primary turns will be found by dividing the turns of wire in the secondary by the turns ratio.

$$N_P = \frac{N_S}{\text{Turns Ratio}}$$

$$N_P = \frac{800}{4.17}$$

$$N_P = 192 \text{ turns}$$

Figure 19–17 shows the transformer with all completed values.

## MULTIPLE TAPPED WINDINGS

It is not uncommon for transformers to be designed with windings that have more than one set of lead wires connected to the primary or secondary. The transformer shown in Figure 19–18 contains a secondary winding rated at 24 volts. The primary winding contains several taps, however. One of the primary lead wires is labeled C and is the common for the other leads. The other leads are labeled 120, 208, and 240, respectively. This transformer is designed in such a manner that it can be connected to different primary voltages without changing the value of the secondary voltage. In this example, it is assumed that the secondary winding has a total of 120 turns of wire. To maintain the proper turns ratio, the primary would have 600 turns of wire between C and 120; 1,040 turns between C and 208; and 1,200 turns between C and 240.

The transformer shown in Figure 19–19 contains a single primary winding. The secondary winding, however, has been tapped at several points. One of the secondary lead wires is labeled C and is common to the other lead wires. When rated voltage is applied to the primary, voltages of 12, 24, and 48 volts can be obtained at the secondary. It should also be noted that this arrangement of taps permits the transformer to be used as a center tapped transformer for two of the voltages. If a load is placed across the lead wires labeled C and 24, the lead wire labeled 12 becomes a center tap. If a load is placed across the C and 48 lead wires, the 24-lead wire becomes a center tap.

In this example, it is assumed the primary winding has 300 turns of wire. In order to produce the proper turns ratio, it would require 30 turns of wire between C and 12, 60 turns of wire between C and 24, and 120 turns of wire between C and 48.

The transformer shown in Figure 19–20 is similar to the transformer in Figure 19–19. The transformer in Figure 19–20, however, has multiple secondary windings instead of a single secondary winding with multiple taps. The advantage of the transformer in Figure 19–20 is that the secondary windings are electrically isolated from each other. These secondary windings can be either step-up or step-down depending on the application of the transformer.

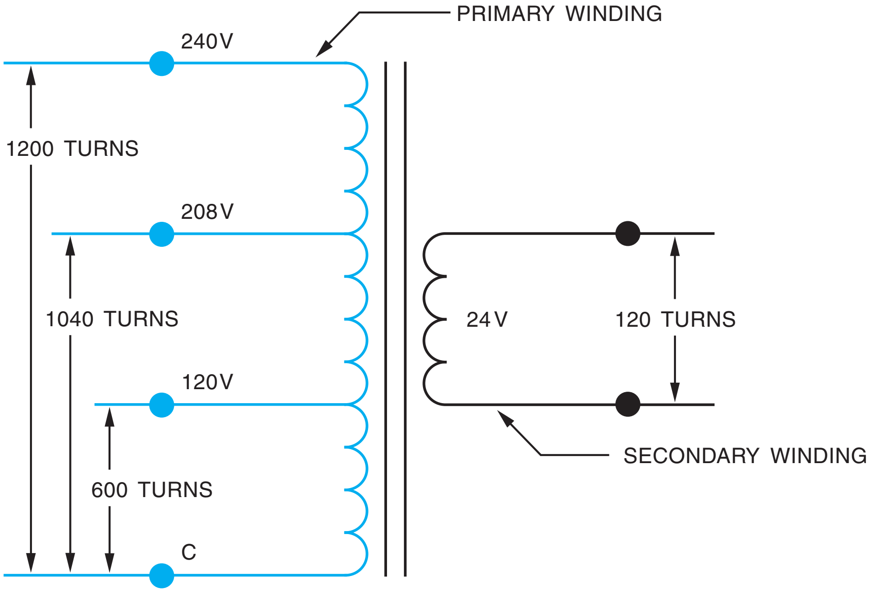



**Figure 19–18**
Transformer with multiple tap primary winding. (Source: Delmar/Cengage Learning)

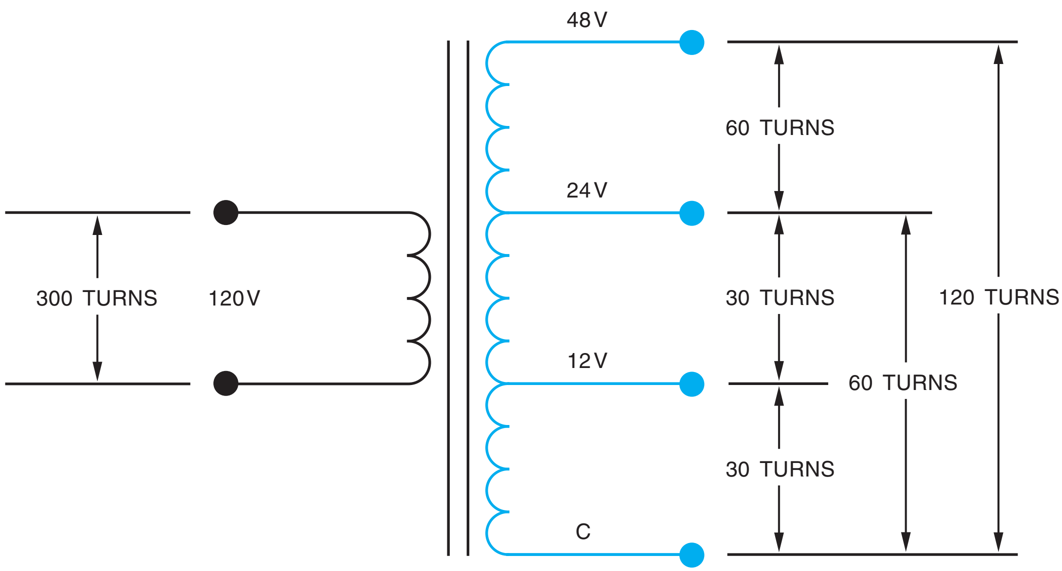



**Figure 19–19**
Transformer secondary with multiple taps. (Source: Delmar/Cengage Learning)

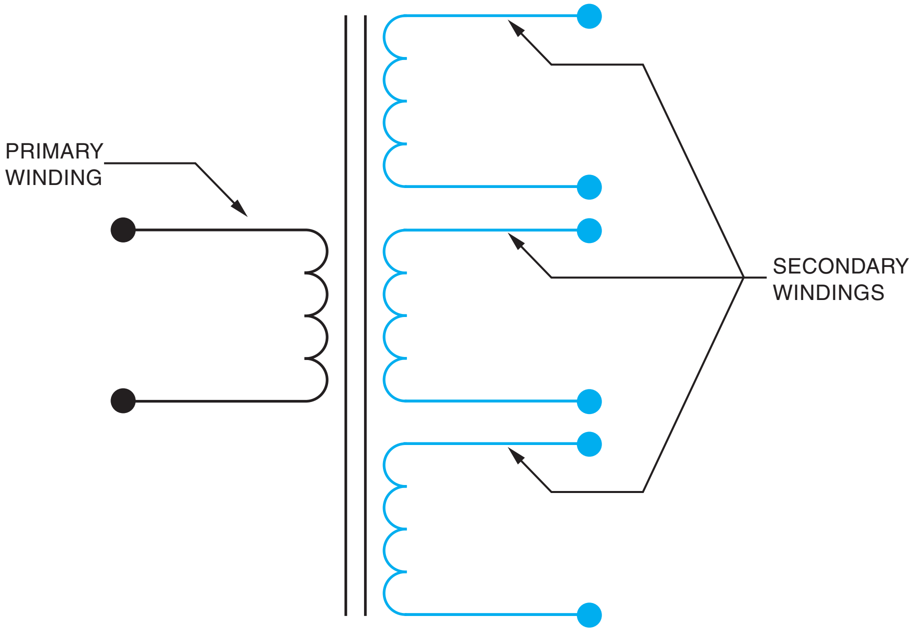



**Figure 19–20** Transformer with multiple secondary windings. (Source: Delmar/Cengage Learning)

## COMPUTING VALUES FOR TRANSFORMERS WITH MULTIPLE SECONDARIES

When computing the values of a transformer with multiple secondary windings, each secondary must be treated as a different transformer. For example, the transformer in Figure 19–21 contains one primary winding and three secondary windings. The primary is connected to 120 volts AC and contains 300 turns of wire. One secondary has an output voltage of 560 volts and a load impedance of 1,000 Ω. The second secondary has an output voltage of 208 volts and a load impedance of 400 Ω, and the third secondary has an output voltage of 24 volts and a load impedance of 6 Ω. The current, turns of wire, and ratio for each secondary and the current of the primary will be found.

**SOLUTION:** The first step will be to compute the turns ratio of the first secondary. The turns ratio can be found by dividing the smaller voltage into the larger.

$$\text{Ratio} = \frac{E_{S1}}{E_P}$$

$$\text{Ratio} = \frac{560}{120}$$

$$\text{Ratio} = 1{:}4.67$$

The current flow in the first secondary can be computed using Ohm's law.

$$I_{S1} = \frac{560}{1000}$$

$$I_{S1} = 0.56 \text{ amps}$$

The number of turns of wire in the first secondary winding will be found using the turns ratio. Because this secondary has a higher voltage than the primary, it must have more turns of wire. The number of primary turns will be multiplied by the turns ratio.

$$N_{S1} = N_P \times \text{Turns Ratio}$$

$$N_{S1} = 300 \times 4.67$$

$$N_{S1} = 1{,}401 \text{ turns}$$

The amount of primary current needed to supply this secondary winding can be found using the turns ratio also. Because the primary has less voltage, it will require more current. The primary current can be determined by multiplying the secondary current by the turns ratio.

$$I_{P(FIRST\ SECONDARY)} = I_{S1} \times \text{Turns Ratio}$$

$$I_{P(FIRST\ SECONDARY)} = 0.56 \times 4.67$$

$$I_{P(FIRST\ SECONDARY)} = 2.61 \text{ amps}$$

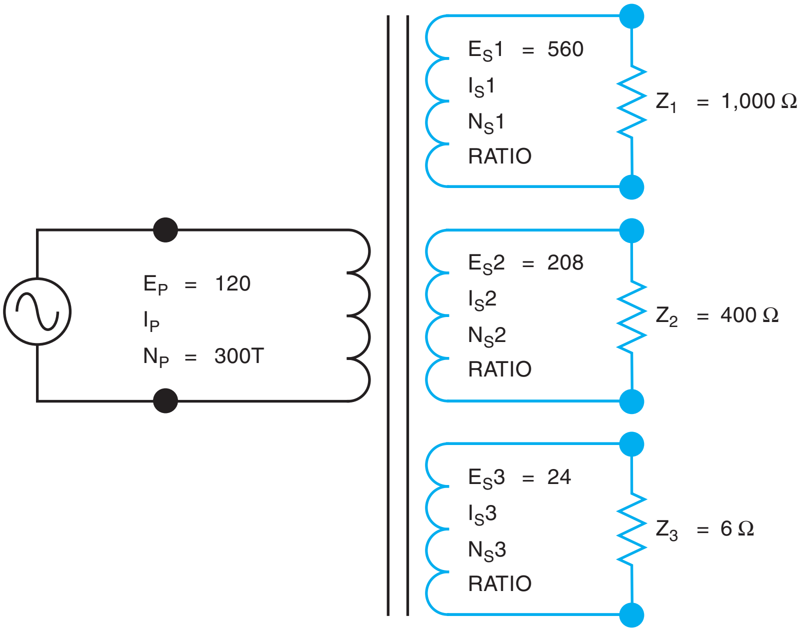



**Figure 19–21** Computing values for a transformer with multiple secondary windings. (Source: Delmar/Cengage Learning)

The turns ratio of the second secondary winding will be found by dividing the higher voltage by the lower voltage.

$$\text{Ratio} = \frac{208}{120}$$

$$\text{Ratio} = 1{:}1.73$$

The amount of current flow in this secondary can be determined using Ohm's law.

$$I_{S2} = \frac{208}{400}$$

$$I_{S2} = 0.52 \text{ amp}$$

Because the voltage of this secondary is greater than the primary, it will have more turns of wire than the primary. The turns of this secondary will be found by multiplying the turns of the primary by the turns ratio.

$$N_{S2} = N_P \times \text{Turns Ratio}$$

$$N_{S2} = 300 \times 1.73$$

$$N_{S2} = 519 \text{ turns}$$

The voltage of the primary is less than this secondary. The primary will, therefore, require a greater amount of current. The amount of primary current required to operate this secondary will be computed by multiplying the secondary current by the turns ratio.

$$I_{P(SECOND\ SECONDARY)} = I_{S2} \times \text{Turns Ratio}$$

$$I_{P(SECOND\ SECONDARY)} = 0.52 \times 1.732$$

$$I_{P(SECOND\ SECONDARY)} = 0.9 \text{ amp}$$

The turns ratio of the third secondary winding will be computed in the same way as the other two. The larger voltage will be divided by the smaller.

$$\text{Ratio} = \frac{120}{24}$$

$$\text{Ratio} = 5{:}1$$

The primary current will be found using Ohm's law.

$$I_{S3} = \frac{24}{6}$$

$$I_{S3} = 4 \text{ amps}$$

Because the output voltage of the third secondary is less than that of the primary, the number of turns of wire for this secondary will be fewer than the primary turns. To find the number of secondary turns, divide the primary turns by the turns ratio.

$$N_{S3} = \frac{N_P}{\text{Turns Ratio}}$$

$$N_{S3} = \frac{300}{5}$$

$$N_{S3} = 60 \text{ turns}$$

The primary has a higher voltage than this secondary. The primary current will, therefore, be less than the secondary current by the amount of the turns ratio.

$$I_{P(THIRD\ SECONDARY)} = \frac{I_{S3}}{\text{Turns Ratio}}$$

$$I_{P(THIRD\ SECONDARY)} = \frac{4}{5}$$

$$I_{P(THIRD\ SECONDARY)} = 0.8 \text{ amp}$$

The primary must supply current to each of the three secondary windings. Therefore, the total amount of primary current will be the sum of the currents required to supply each secondary.

$$I_{P(TOTAL)} = I_{P1} + I_{P2} + I_{P3}$$

$$I_{P(TOTAL)} = 2.61 + 0.9 + 0.8$$

$$I_{P(TOTAL)} = 4.31 \text{ amps}$$

The transformer with all computed values is shown in Figure 19–22.

## DISTRIBUTION TRANSFORMERS

A very common type of isolation transformer is the distribution transformer, Figure 19–23. This transformer is used to supply power to most homes and many businesses. In this example, it is assumed that the primary is connected to a 7,200 volt line. The secondary is 240 volts with a center tap. The center tap is grounded and becomes the neutral conductor. If voltage is measured across the entire secondary, a voltage of 240 volts will be seen. If voltage is measured from either line to the center tap, half of the secondary voltage, or 120 volts, will be seen, Figure 19–24. Loads that are intended to operate on 240 volts, such as water heaters, electric resistance heating units, and central air conditioners are connected directly across the lines of the secondary. Loads intended to operate on 120 volts connect from the center tap or neutral to one of the secondary lines. The function of the neutral is to carry the difference in current between the two secondary lines and maintain a balanced voltage. In the example shown in Figure 19–25, it is assumed that one of the secondary lines has a current flow of 30 amperes and the other has current flow of 24 amperes. The neutral will conduct the sum of the unbalanced load.

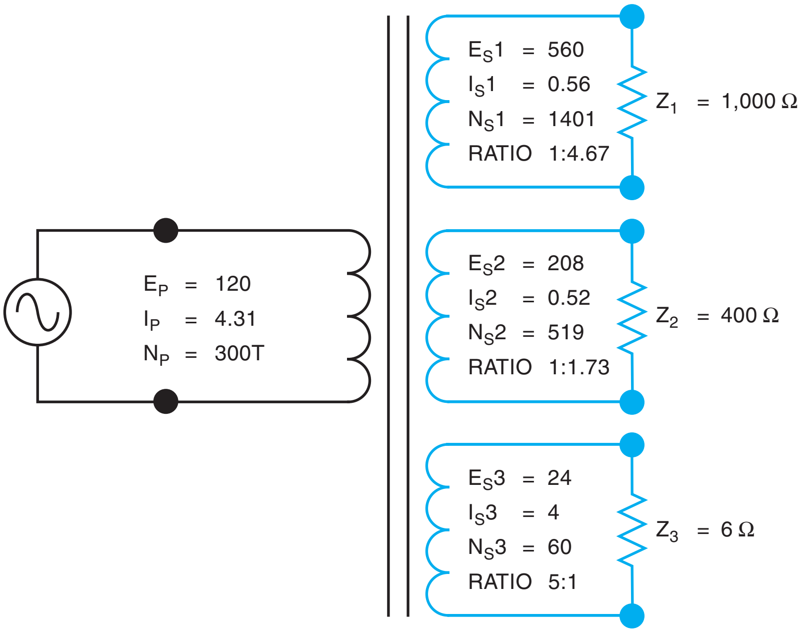



**Figure 19–22** The transformer with all computed values. (Source: Delmar/Cengage Learning)

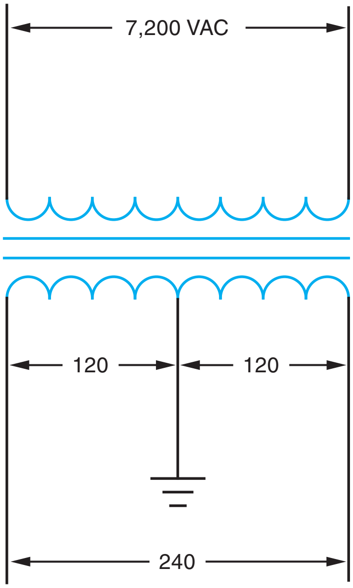



**Figure 19–23**
Distribution transformer. (Source: Delmar/Cengage Learning)

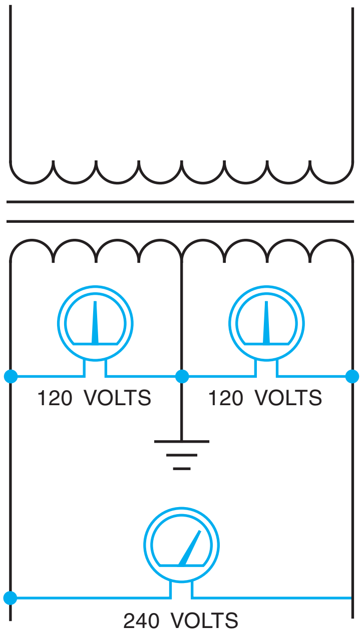



**Figure 19–24**
The voltage from either line to neutral is 120 volts. The voltage across the entire secondary winding is 240 volts. (Source: Delmar/Cengage Learning)

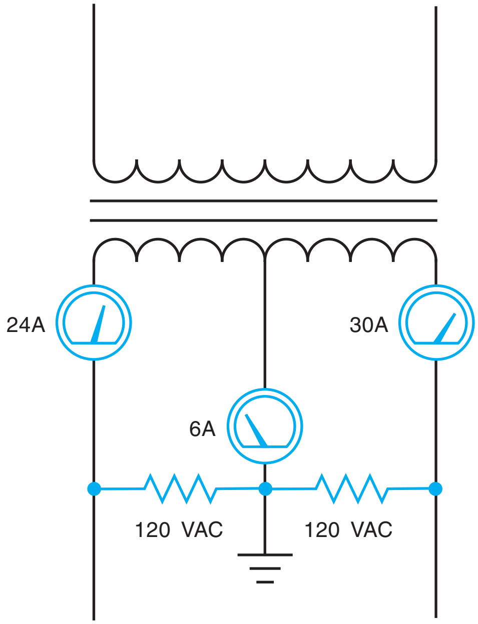



**Figure 19–25**
The neutral carries the sum of the unbalanced current. (Source: Delmar/Cengage Learning)

In this example, the neutral current will be 6 amperes (30 – 24 = 6).

## TESTING THE TRANSFORMER

There are several tests that can be made to determine the condition of the transformer. A simple test for grounds, shorts, or opens can be made with an ohmmeter, Figure 19–26. Ohmmeter A is connected to one lead of the primary and one lead of the secondary. This test checks for shorted windings between the primary and secondary. The ohmmeter should indicate infinity. If there is more than one primary or secondary winding, all isolated windings should be tested for shorts. Ohmmeter B illustrates testing the windings for grounds. One lead of the ohmmeter is connected to the case of the transformer and the other is connected to the winding. All windings should be tested for grounds and the ohmmeter should indicate infinity for each winding. Ohmmeter C illustrates testing the windings for continuity. The wire resistance of the winding should be indicated by the ohmmeter. Each winding should be tested for continuity. If the transformer appears to be in good condition after the ohmmeter

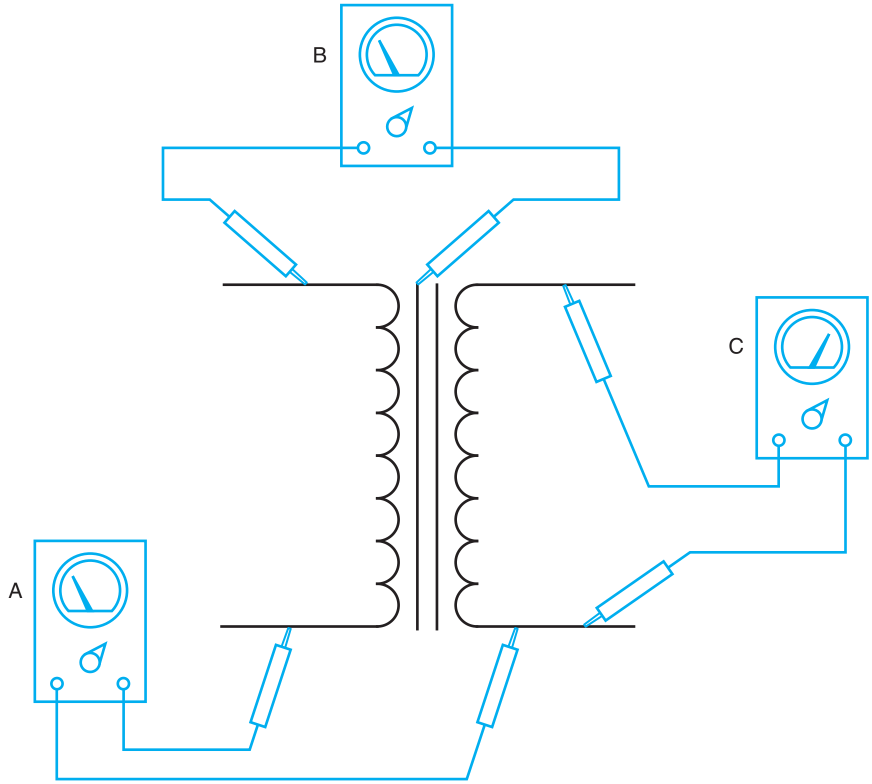



**Figure 19–26** Testing a transformer with an ohmmeter. (Source: Delmar/Cengage Learning)

test, it should then be tested for shorts and grounds with a megohmmeter or "megger." A megger will reveal problems of insulation breakdown that an ohmmeter will not.

## TRANSFORMER RATINGS

Most transformers contain a nameplate that lists information concerning the transformer. The information listed is generally determined by the size, type, and manufacturer. Almost all nameplates will list the primary voltage, secondary voltage, and kVA rating. Transformers are rated in kilovolt amps and not kilowatts because the true power is determined by the power factor of the load. Other information that may or may not be listed is frequency, temperature rise in °C, % impedance (%Z), type of insulating oil, gallon of insulating oil, serial number, type number, model number, and whether the transformer is single phase or three phase.

## DETERMINING MAXIMUM CURRENT

Notice that the nameplate does not list the current rating of the windings. Because power input must equal power output, the current rating for a winding can be determined by dividing the kVA rating by the winding voltage. For example, assume a transformer has a kVA rating of 0.5 kVA, a primary voltage of 480 volts, and a secondary voltage of 120 volts. To determine the maximum current that can be supplied by the secondary, divide the kVA rating by the secondary voltage.

$$I_S = \frac{kVA}{E_S}$$

$$I_S = \frac{500}{120}$$

$$I_S = 4.16 \text{ amps}$$

The primary current can be computed in the same way.

$$I_P = \frac{kVA}{E_P}$$

$$I_P = \frac{500}{480}$$

$$I_P = 1.04 \text{ amps}$$

Transformers with multiple secondary windings will generally have the current rating listed with the voltage rating.

## TRANSFORMER LOSSES

Although transformers are probably the most efficient machines known, they are not perfect. A transformer operating at 90% efficiency has a power loss of 10%. Some of these losses are $I^2R$ losses, eddy current losses, hysteresis losses, and magnetic flux leakage. Most of these losses result in heat production. Recall that $I^2R$ is one of the formulas for finding power or watts. In the case of a transformer, it describes the power loss associated with heat due to the resistance of the wire in both primary and secondary windings.

Eddy currents are currents that are induced into the metal core material by the changing magnetic field as alternating current produces a changing flux. Eddy currents are so named because they circulate around inside the metal in a similar manner as the swirling eddies in a river, Figure 19–27. These swirling currents produce heat, which is a power loss. Transformers are constructed with laminated cores to help reduce eddy currents. The surface of each lamination forms a layer of iron oxide, which acts as an insulator to help prevent the formation of eddy currents.

Hysteresis losses are losses due to molecular friction. As discussed previously, the reversal of the direction of current flow causes the molecules of iron in the core to realign themselves each time the current changes direction. The molecules of iron are continually rubbing against each other as they realign magnetically. The friction of the molecules rubbing together causes heat, which is a power loss. Hysteresis loss is proportional to frequency. The higher the frequency, the greater the loss. A special steel called **silicon steel** is often used in transformer cores to help reduce hysteresis loss. The power loss due to hysteresis and eddy currents is often called core loss.

Magnetic flux leakage does not produce heat, but does constitute a power loss. Flux leakage is caused by magnetic lines of flux radiating away from the transformer and not cutting the secondary windings. Flux leakage can be reduced by better core designs.

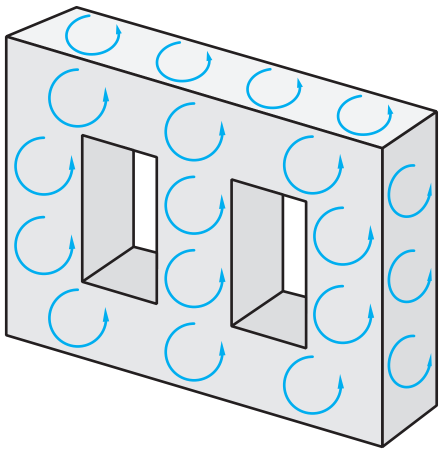


**Figure 19–27**
Eddy currents circulate inside the core material. (Source: Delmar/Cengage Learning)

## SUMMARY

- All values of voltage, current, and impedance in a transformer are proportional to the turns ratio.
- Transformers can change values of voltage, current, and impedance, but cannot change the frequency.
- The primary winding of a transformer is connected to the power line.
- The secondary winding is connected to the load.
- A transformer that has a lower secondary voltage than primary voltage is a step-down transformer.
- A transformer that has a higher secondary voltage than primary voltage is a step-up transformer.
- An isolation transformer has its primary and secondary windings electrically and mechanically separated from each other.
- When a coil induces a voltage into itself, it is known as self-induction.
- When a coil induces a voltage into another coil, it is known as mutual induction.
- Either winding of a transformer can be used as the primary or secondary as long as its voltage or current ratings are not exceeded.
- Isolation transformers help filter voltage and current spikes between the primary and secondary side.

## KEY TERMS

**core transformer**
**E-I core**
**excitation current**
**isolation transformer**
**mutual induction**
**self-induction**
**shell transformer**
**silicon steel**
**step-down transformer**
**step-up transformer**
**tape wound** or **toroid core**

## REVIEW QUESTIONS

1. What is a transformer?
2. What are common efficiencies for transformers?
3. What is an isolation transformer?
4. All values of a transformer are proportional to its ____________ ____________
5. A transformer has a primary voltage of 480 volts and a secondary voltage of 20 volts. What is the turns ratio of the transformer?
6. If the secondary of the transformer in question 5 supplies a current of 9.6 amperes to a load, what is the primary current? (Disregard excitation current.)
7. Explain the difference between a step-up and a step-down transformer.

**8.** A transformer has a primary voltage of 240 volts and a secondary voltage of 48 volts. What is the turns ratio of this transformer?

**9.** A transformer has an output of 750 volt amps. The primary voltage is 120 volts. What is the primary current?

**10.** A transformer has a turns ratio of 1:6. The primary current is 18 amperes. What is the secondary current?

## PRACTICE PROBLEMS

Refer to Figure 19–28 to answer the following questions. Find all missing values.

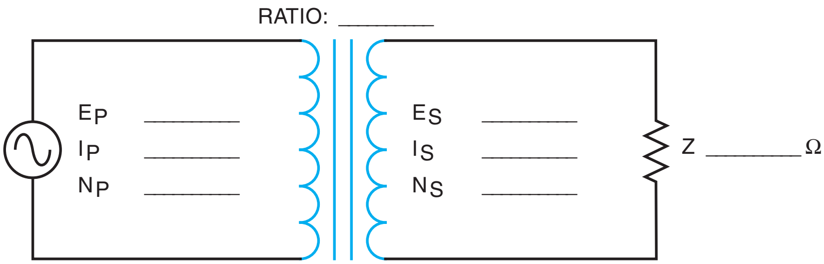



**Figure 19–28**
Practice problems 1 through 6.
(Source: Delmar/Cengage Learning)

**1.**

| | |
|---|---|
| $E_P$ = 120 | $E_S$ = 24 |
| $I_P$ = | $I_S$ = |
| $N_P$ = 300 | $N_S$ = |
| Ratio: | Z = 3 Ω |

**2.**

| | |
|---|---|
| $E_P$ = 240 | $E_S$ = 320 |
| $I_P$ = | $I_S$ = |
| $N_P$ = | $N_S$ = 280 |
| Ratio: | Z = 500 Ω |

**3.**

| | |
|---|---|
| $E_P$ = ______ | $E_S$ = 160 |
| $I_P$ = ______ | $I_S$ = ______ |
| $N_P$ = ______ | $N_S$ = 80 |
| Ratio: 1:2.5 | Z = 12 Ω |

**4.**

| | |
|---|---|
| $E_P$ = 48 | $E_S$ = 240 |
| $I_P$ = ______ | $I_S$ = ______ |
| $N_P$ = 220 | $N_S$ = ______ |
| Ratio: ______ | Z = 360 Ω |

**5.**

| | |
|---|---|
| $E_P$ = ______ | $E_S$ = ______ |
| $I_P$ = 16.5 | $I_S$ = 3.25 |
| $N_P$ = ______ | $N_S$ = 450 |
| Ratio: ______ | Z = 56 Ω |

**6.**

| | |
|---|---|
| $E_P$ = 480 | $E_S$ = ______ |
| $I_P$ = ______ | $I_S$ = ______ |
| $N_P$ = 275 | $N_S$ = 525 |
| Ratio: | Z = 1.2 kΩ |

Refer to Figure 19–29 to answer the following questions. Find all missing values.

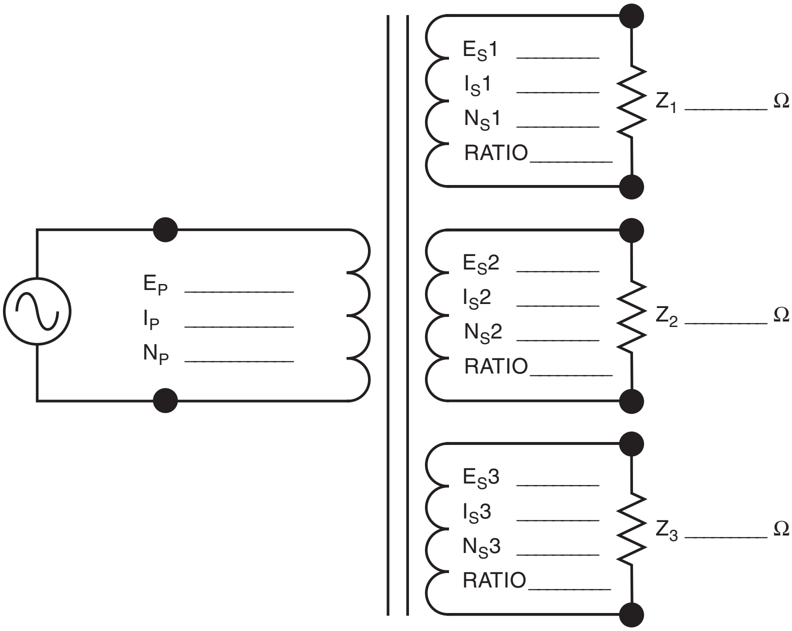



**Figure 19–29**
Practice problems 7 and 8. (Source: Delmar/Cengage Learning)

**7.**

| | | | |
|---|---|---|---|
| $E_P = 208$ | $E_{S1} = 320$ | $E_{S2} = 120$ | $E_{S3} = 24$ |
| $I_P =$ ____ | $I_{S1} =$ ____ | $I_{S2} =$ ____ | $I_{S3} =$ ____ |
| $N_P = 800$ | $N_{S1} =$ ____ | $N_{S2} =$ ____ | $N_{S3} =$ ____ |
| | $Ratio_1$ ____ | $Ratio_2$ ____ | $Ratio_3$ ____ |
| | $R_1 = 12\ k\Omega$ | $R_2 = 6\ \Omega$ | $R_3 = 8\ \Omega$ |

**8.**

| | | | |
|---|---|---|---|
| $E_P = 277$ | $E_{S1} = 480$ | $E_{S2} = 208$ | $E_{S3} = 120$ |
| $I_P =$ ____ | $I_{S1} =$ ____ | $I_{S2} =$ ____ | $I_{S3} =$ ____ |
| $N_P = 350$ | $N_{S1} =$ ____ | $N_{S2} =$ ____ | $N_{S3} =$ ____ |
| | $Ratio_1$ ____ | $Ratio_2$ ____ | $Ratio_3$ ____ |
| | $R_1 = 200\ \Omega$ | $R_2 = 60\ \Omega$ | $R_3 = 24\ \Omega$ |

# UNIT 20

# Autotransformers

## OBJECTIVES

After reading this unit the student should be able to:

- Discuss the operation of an autotransformer
- List differences between isolation transformers and autotransformers
- Compute values of voltage, current, and turns ratios for autotransformers
- Connect an autotransformer for operation

The word *auto* means self. An autotransformer is literally a **self-transformer**. It uses the same winding as both the primary and secondary. Recall that the definition of a **primary winding** is a winding that is connected to the source of power, and the definition of a **secondary winding** is a winding that is connected to a load. Autotransformers have very high efficiencies, most in the range of 95% to 98%.

In Figure 20–1, the entire winding is connected to the power source, and part of the winding is connected to the load. In this illustration, all the turns of wire form the primary and part of the turns form the secondary. Because the secondary part of the winding contains fewer turns than the primary section, the secondary will produce less voltage. This autotransformer is a **step-down** transformer.

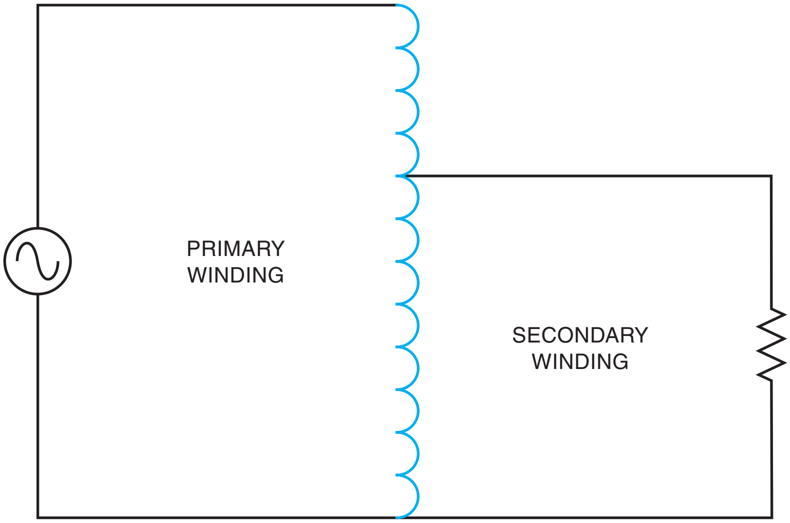



**Figure 20–1**
Autotransformer used as a step-down transformer.
(Source: Delmar/Cengage Learning)

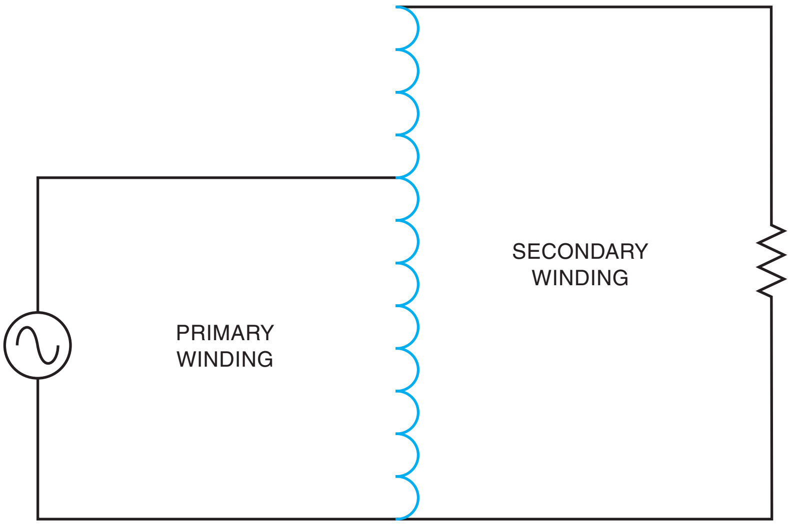



**Figure 20–2**
Autotransformer used as a step-up transformer.
(Source: Delmar/Cengage Learning)

In Figure 20–2, the primary section is connected across part of a winding and the secondary is connected across the entire winding. In this illustration the secondary section contains more windings than the primary. This autotransformer is a **step-up** transformer. Notice that autotransformers, like isolation transformers, can be used as step-up or step-down transformers.

## DETERMINING VOLTAGE VALUES

Autotransformers are not limited to a single secondary winding. Many autotransformers have **multiple taps** to provide different voltages as shown in Figure 20–3. In this example, there are 40 turns of wire between taps A and B, 80 turns of wire between taps B and C, 100 turns of wire between taps C and D,

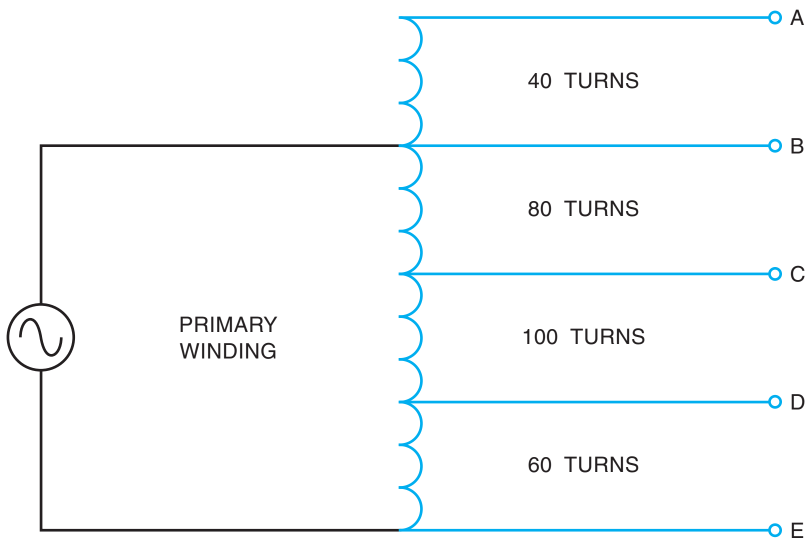



**Figure 20–3**
Autotransformer with multiple taps.
(Source: Delmar/Cengage Learning)

and 60 turns of wire between taps D and E. The primary section of the windings is connected between taps B and E. It will be assumed that the primary is connected to a source of 120 volts. The voltage across each set of taps will be determined.

There is generally more than one method that can be employed to determine values of a transformer. Because the number of turns between each tap is known, the **volts-per-turn** method will be used in this example. *The volts-per-turn for any transformer is determined by the primary winding.* In this illustration, the primary winding is connected across taps B and E. The primary turns are, therefore, the sum of the turns between taps B and E (80 + 100 + 60 = 240 turns). Because 120 volts is connected across 240 turns, this transformer will have a volts-per-turn ratio of 0.5 (240 turns/120 volts = 0.5 volts-per-turn). To determine the amount of voltage between each set of taps, it becomes a simple matter of multiplying the number of turns by the volts-per-turn.

A–B (40 turns × 0.5 = 20 volts)
A–C (120 turns × 0.5 = 60 volts)
A–D (220 turns × 0.5 = 110 volts)
A–E (280 turns × 0.5 = 140 volts)
B–C (80 turns × 0.5 = 40 volts)
B–D (180 turns × 0.5 = 90 volts)
B–E (240 turns × 0.5 = 120 volts)
C–D (100 turns × 0.5 = 50 volts)
C–E (160 turns × 0.5 = 80 volts)
D–E (60 turns × 0.5 = 30 volts)

## USING TRANSFORMER FORMULAS

The values of voltage and current for autotransformers can also be determined by using standard transformer formulas. The primary winding of the transformer shown in Figure 20–4 is between points B and N, and has a voltage of 120 volts applied to it. If the turns of wire are counted between points B and N, it can be seen that there are 120 turns of wire. Now assume that the selector switch is set to point D. The load is now connected between points D and N. The secondary of this transformer contains 40 turns of wire. If the amount of voltage applied to the load is to be computed, the following formula can be used.

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{120}{40}$$

$$120\ E_S = 4800$$

$$E_S = 40 \text{ volts}$$

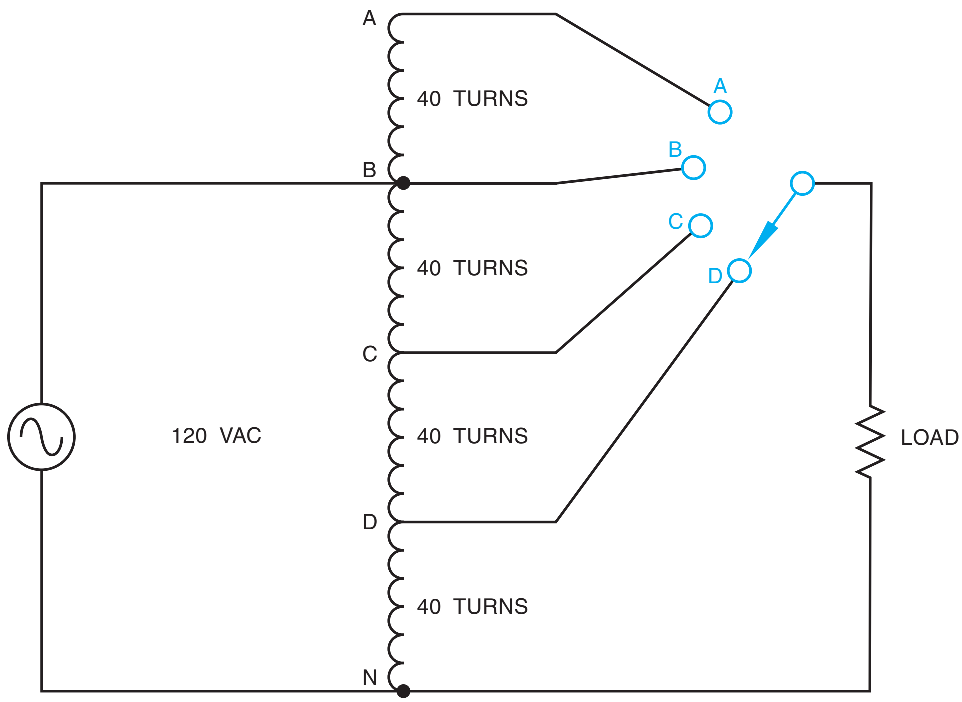



**Figure 20–4** Determining voltage and current values.
(Source: Delmar/Cengage Learning)

Assume that the load connected to the secondary has an impedance of 10 Ω. The amount of current flow in the secondary circuit can be computed using the formula:

$$I = \frac{E}{Z}$$

$$I = \frac{40}{10}$$

$$I = 4 \text{ amps}$$

The primary current can be computed by using the same formula that was used to compute primary current for an isolation type of transformer.

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$120\ I_P = 160$$

$$\frac{120}{40} = \frac{4}{I_P}$$

$$I_P = 1.333 \text{ amps}$$

The amount of power input and output for the autotransformer must also be the same.

Primary
$120 \times 1.333 = 160$ volt-amps

Secondary
$40 \times 4 = 160$ volt-amps

Now assume that the rotary switch is connected to point A. The load is now connected to 160 turns of wire. The voltage applied to the load can be computed by:

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{E_S} = \frac{120}{60}$$

$$120\ E_S = 19{,}200$$

$$E_S = 160 \text{ volts}$$

The amount of secondary current can be computed using the formula:

$$I = \frac{E}{Z}$$

$$I = \frac{160}{10}$$

$$I = 16 \text{ amps}$$

The primary current can be computed using the formula:

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{160} = \frac{16}{I_P}$$

$$120\ I_P = 2{,}560$$

$$I_P = 21.333 \text{ amps}$$

The answers can be checked by determining if the power in and power out are the same.

Primary
$120 \times 21.333 = 2{,}560$ volt-amps

Secondary
$160 \times 16 = 2{,}560$ volt-amps

## CURRENT RELATIONSHIPS

An autotransformer with a 2:1 turns ratio is shown in Figure 20–5. It is assumed that a voltage of 480 volts is connected across the entire winding. Because the transformer has a turns ratio of 2:1, a voltage of 240 volts will be supplied to the load. Ammeters connected in series with each winding indicate the current flow in the circuit. It is assumed that the load produces a current flow of 4 amperes on the secondary. Note that a current flow of 2 amperes is supplied to the primary.

$$I_{PRIMARY} = \frac{I_{SECONDARY}}{Ratio}$$

$$I_p = \frac{4}{2}$$

$$I_p = 2 \text{ amperes}$$

If the rotary switch shown in Figure 20–4 were to be removed and replaced with a sliding tap that made contact directly to the transformer winding, the turns ratio could be adjusted continuously. This type of transformer is commonly referred to as a Variac or Powerstat depending on the manufacturer. The windings are wrapped around a tape-wound toroid core inside a plastic case. The tops of the windings have been milled flat, similar to a commutator. A carbon brush makes contact with the windings. When the brush is moved across the windings, the turns ratio changes, which changes the output voltage. This type of autotransformer provides a very efficient means of controlling AC voltage.

Autotransformers are often used by power companies to provide a small increase or decrease to the line voltage. They help provide voltage regulation to large power lines.

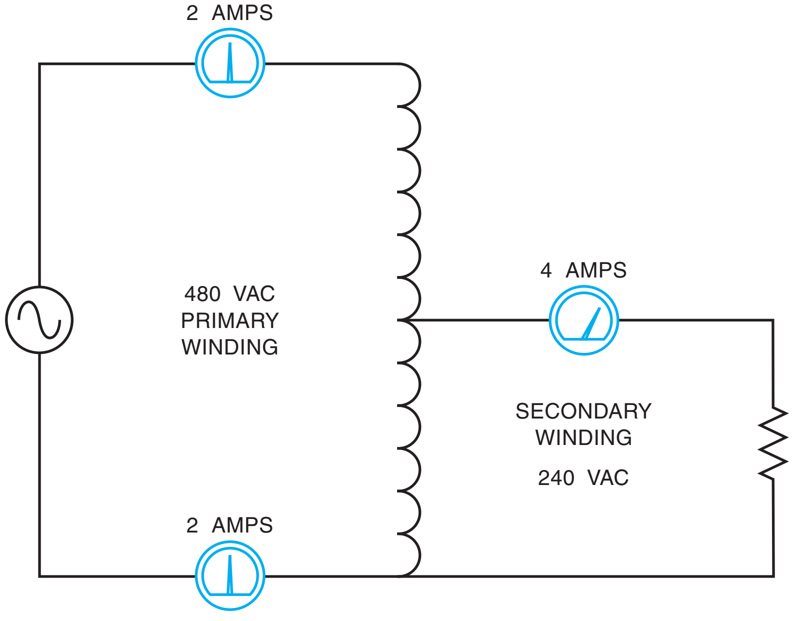



**Figure 20–5**
Current divides between primary and secondary. (Source: Delmar/Cengage Learning)

The autotransformer does have one disadvantage. Because the load is connected to one side of the power line, there is no **line isolation** between the incoming power and the load. This can cause problems with certain types of equipment and must be a consideration when designing a power system.

## SUMMARY

- The autotransformer has only one winding that is used as both the primary and secondary.
- Autotransformers have efficiencies that range from about 95% to 98%.
- Values of voltage, current, and turns can be computed in the same manner as an isolation transformer.
- Autotransformers can be step-up or step-down transformers.
- Autotransformers can be made to provide a variable output voltage by connecting a sliding tap to the windings.
- Autotransformers have the disadvantage of no line isolation between primary and secondary.
- One of the simplest ways of computing values of voltage for an autotransformer when the turns are known is to use the volts-per-turn method.

## KEY TERMS

**line isolation**
**multiple taps**
**primary winding**
**secondary winding**
**self-transformer**
**step-down**
**step-up**
**volts-per-turn**

## REVIEW QUESTIONS

1. An AC power source is connected across 325 turns of an autotransformer and the load is connected across 260 turns. What is the turns ratio of this transformer?
2. Is the transformer in question 1 a step-up or a step-down transformer?
3. An autotransformer has a turns ratio of 3.2:1. A voltage of 208 volts is connected across the primary. What is the voltage of the secondary?
4. A load impedance of 52 Ω is connected to the secondary winding of the transformer in question 3. How much current will flow in the secondary?
5. How much current will flow in the primary of the transformer in question 4?
6. The autotransformer shown in Figure 20–3 has the following number of turns between windings: A–B (120 turns), B–C (180 turns), C–D (250 turns), and D–E (300 turns). A voltage of 240 volts is connected across B and E. Find the voltages between each of the following pairs of points:

A–B ________ A–C ________ A–D ________ A–E ________

B–C ________ B–D ________ B–E ________ C–D ________

C–E ________ D–E ________

# UNIT 21

# Current Transformers

## OBJECTIVES

After studying this unit the student should be able to:

- Discuss the operation of a current transformer
- Describe how current transformers differ from voltage transformers
- Discuss safety precautions that should be observed when using current transformers
- Connect a current transformer in a circuit

Current transformers differ from voltage transformers in that the primary winding is generally part of the power line. The primary winding of a current transformer must be connected in series with the load, Figure 21–1. Current transformers are used to change the full scale range of AC ammeters. Most **in-line ammeters** (ammeters that must be connected directly into the line) that have multiple range values used a current transformer to provide the different ranges, Figure 21–2. The full scale value of the ammeter is changed by changing the turns ratio. Assume that the ammeter illustrated in Figure 21–2 is to provide range values of **5 amperes**, 2.5 amperes, 1 ampere, and 0.5 ampere. Also assume that the meter movement requires a current flow of 100 mA (0.100) to deflect the meter full scale and that the primary of the current transformer contains 5 turns of wire. Transformer formulas can

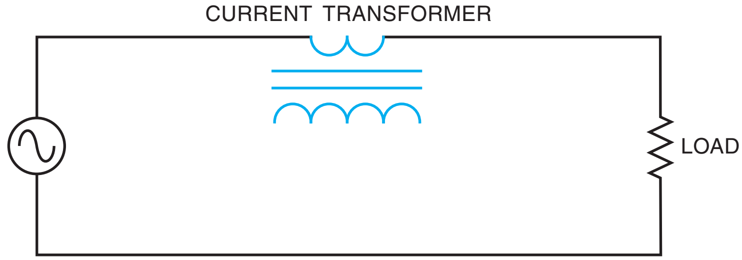



**Figure 21–1** The primary winding of a current transformer is connected in series with a load. (Source: Delmar/Cengage Learning)

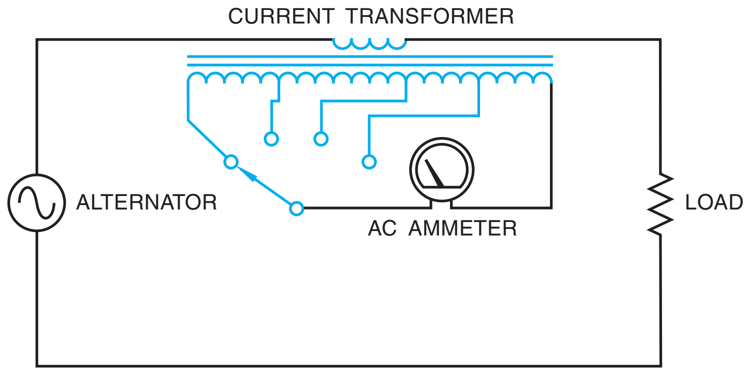



**Figure 21–2** A current transformer is used to change the range of an AC ammeter. (Source: Delmar/Cengage Learning)

be used to determine the number of secondary turns needed to produce the desired ranges. Turns needed for a full scale range of 5 amperes.

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

$$\frac{5}{N_S} = \frac{0.1}{5}$$

$$0.1N_S = 25$$

$$N_S = 250 \text{ turns}$$

Turns needed for a full scale range of 2.5 amperes.

$$\frac{5}{N_S} = \frac{0.1}{2.5}$$

$$0.1N_S = 12.5$$

$$N_S = 125 \text{ turns}$$

Turns needed for a full scale range of 1 ampere.

$$\frac{5}{N_S} = \frac{0.1}{1}$$

$$0.1N_S = 5$$

$$N_S = 50 \text{ turns}$$

Turns needed for a full scale range of 0.5 ampere.

$$\frac{5}{N_S} = \frac{0.1}{0.5}$$

$$0.1N_S = 2.5$$

$$N_S = 25 \text{ turns}$$

When a large amount of AC current must be measured, a different type of current transformer is connected in the power line. These transformers have ratios that start at 100:5 and can have ratios of several thousand to five. These **current transformers**, generally referred to in industry as **CTs**, have a standard secondary current rating of 5 amps AC. They are designed to be operated with a 5 amp AC ammeter connected directly to their secondary winding, which produces a short circuit. CTs are designed to operate with the secondary winding shorted. *The secondary winding of a CT should never be opened when there is power applied to the primary. This will cause the transformer to produce a step-up in voltage which could be high enough to kill anyone who comes in contact with it.*

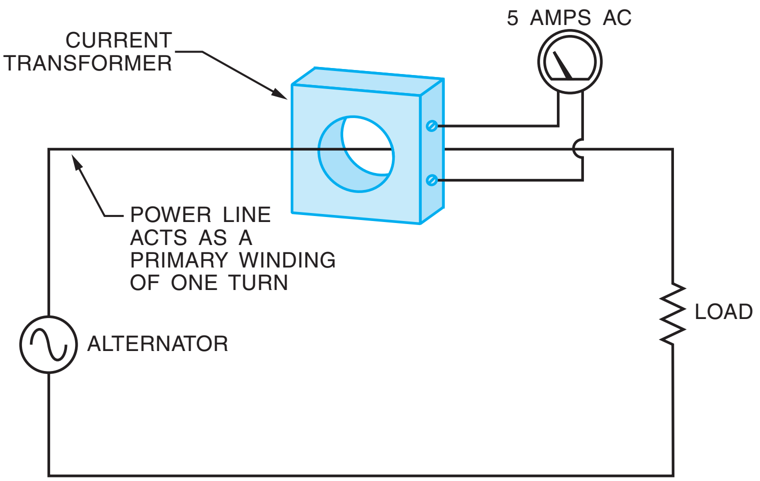



**Figure 21–3** Current transformer used to change the scale factor of an AC ammeter. (Source: Delmar/Cengage Learning)

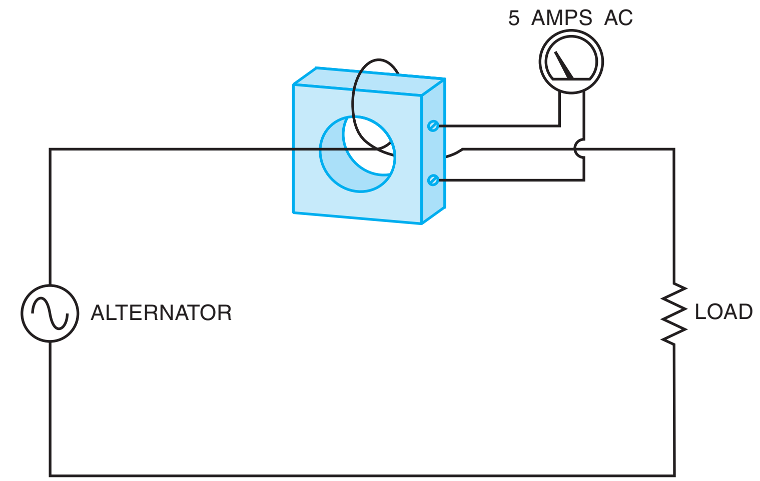



**Figure 21–4** The primary conductor loops through the CT to produce a second turn, changing the turns ratio. (Source: Delmar/Cengage Learning)

A current transformer of this type is basically a toroid transformer. A toroid transformer is constructed with a hollow core similar to a donut in that it has a hole in the middle. When current transformers are used, the main power line is inserted through the opening in the transformer, Figure 21–3. The power line acts as the primary of the transformer and is considered to be one turn.

The turns ratio of the transformer can be changed by looping the power wire through the opening in the transformer to produce a primary winding of more than one turn. For example, assume a current transformer has a ratio of 600:5. If the primary power wire is inserted through the opening, it will require a current of 600 amps to deflect the meter full scale. If the primary power conductor is looped around and inserted through the window a second time, the primary now contains two turns of wire instead of one, Figure 21–4. It now requires 300 amps of current flow in the primary to deflect the meter full scale. If the primary conductor is looped through the opening a third time, it would require only 200 amps of current flow to deflect the meter full scale.

## CLAMP-ON AMMETERS

Many service technicians use the clamp-on type of AC ammeter. To use this type of meter, the jaw of the meter is clamped around one of the conductors supplying power to the load, Figure 21–5. The meter is clamped around only one of the lines. If the meter is clamped around more than one line, the magnetic fields of the wires cancel each other and the meter indicates zero.

This type of meter uses a current transformer to operate the meter. The jaw of the meter is part of the core material of the transformer. When the meter is connected around the current carrying wire, the changing magnetic field produced by the AC current induces a voltage into the current transformer. The strength of the magnetic field and its frequency determines the amount of voltage induced in the current transformer. Because 60 Hz is a standard frequency throughout the United States and Canada, the amount of induced voltage is proportional to the strength of the magnetic field.

The **clamp-on type ammeter** can have different range settings by changing the turns ratio of the secondary of the transformer just as the in-line ammeter does. The primary of the transformer is the conductor the movable jaw is connected around. If the ammeter is connected around one wire, the primary has one turn of wire as compared to the turns of the secondary. The turn's ratio can be changed in the same manner as changing the ratio of the CT. If two turns of wire are wrapped around the jaw of the ammeter, Figure 21–6, the primary winding now contains two turns instead of one, and the turns ratio of the transformer is changed. The ammeter will now indicate double the amount of current in the circuit. The reading on the scale of the meter would have to be divided by two to get the correct reading. The ability to change the turns ratio of a clamp-on ammeter can be very useful for measuring low currents.

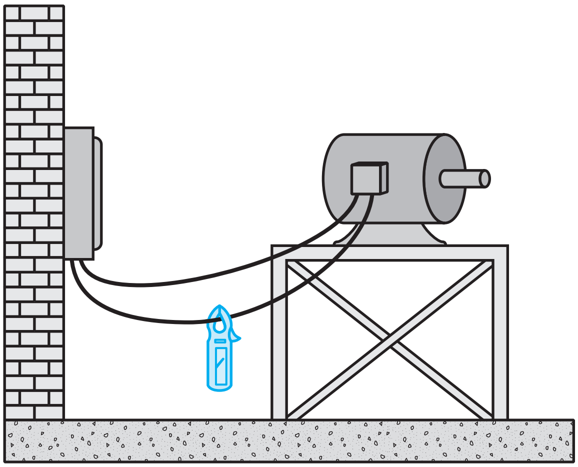


**Figure 21–5**
The clamp-on ammeter connects around one conductor. (Source: Delmar/Cengage Learning)

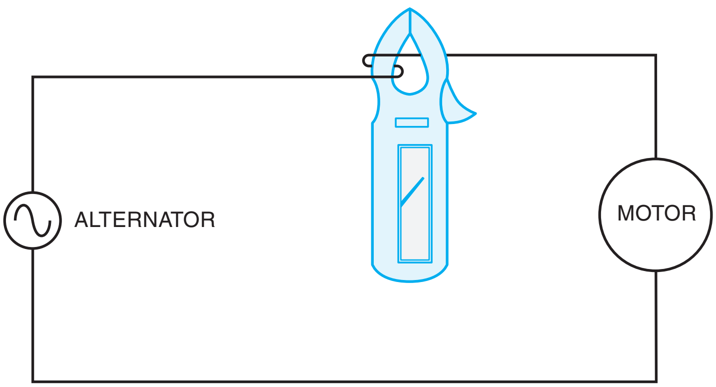



**Figure 21–6**
Looping the conductor around the jaw of the ammeter changes the ratio. (Source: Delmar/Cengage Learning)

## SUMMARY

- Current transformers have their primary winding connected in series with a load.
- Current transformers are often used to provide multiple scale values for in-line AC ammeters.
- Current transformers are often referred to as CTs.
- CTs are used to measure large amounts of AC current.
- CTs have a standard secondary current value of 5 amperes.
- CTs are designed to be operated with their secondary winding shorted.
- The short circuit connected across the secondary of the CT should never be removed when power is connected to the circuit because the secondary voltage can become very high.
- Many clamp-on AC ammeters operate on the principle of a current transformer.
- The movable jaw of the clamp-on ammeter is the core of the transformer.
- The secondary current value of a current transformer can be changed by changing the turns of wire of the primary.

## KEY TERMS

**5 amperes**
**clamp-on ammeter**
**CTs**
**current transformers**
**in-line ammeters**

## REVIEW QUESTIONS

1. Explain the difference in connection between the primary winding of a voltage transformer and the primary winding of a current transformer.
2. What is the standard current rating for the secondary winding of a CT?
3. Why should the secondary winding of a CT never be disconnected from its load when there is current flow in the primary?
4. A current transformer has a ratio of 600:5. If three loops of wire are wound through the transformer core, how much primary current is required to produce 5 amperes of current in the secondary winding?
5. Assume that a primary current of 75 amperes flows through the windings of the transformer in question 4. How much current will flow in the secondary winding?
6. What type of core is generally used in the construction of a CT?
7. A current transformer has 4 turns of wire in its primary winding. How many turns of wire are needed in the secondary winding to produce a current of 2 amperes when a current of 60 amperes flows in the primary winding?

8. A 1500:5 CT develops a voltage of 3 volts across the primary winding. If the secondary should be disconnected from its load, how much voltage would be developed across the secondary terminals?
9. A CT has a current flow of 80 amperes in its primary winding and a current of 2 amperes in its secondary winding. What is the ratio of the CT?
10. What is the most common use for a CT?

# SECTION 5

# Control Components

# UNIT 22

# Overloads

## OBJECTIVES

After studying this unit the student should be able to:

- Explain why motors should be protected from an overload condition
- List the different types of overload protectors
- Describe the operation of a solder-melting and bimetal type overload
- Connect an overload relay into a motor circuit
- Perform an ohmmeter test on an overload relay

Overload relays are designed to protect the motor circuit from damage due to **overloads**. Most overload relays are operated by heat. Since the overload unit must be sensitive to motor current, the heater of the overload relay is connected in series with the motor. In this manner, the amount of current that flows through the motor winding also flows through the overload heater. There are two basic types of overload units used in the air conditioning field, the **solder-melting type** and the **bimetal type**.

## SOLDER-MELTING TYPE OVERLOAD RELAY

The solder-melting type of overload unit is used to a large extent on commercial and industrial air conditioning units. This type of overload unit contains

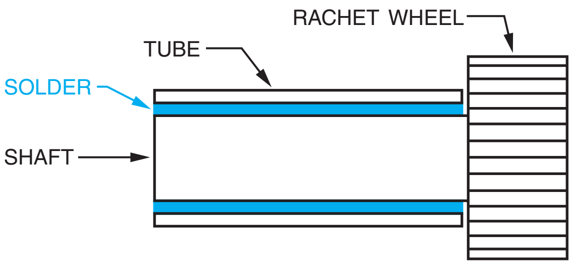



**Figure 22–1**
Shaft is held stationary by solder. (Source: Delmar/Cengage Learning)

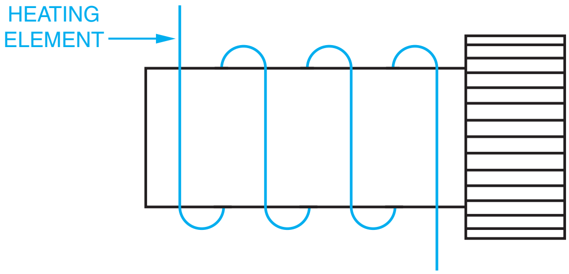



**Figure 22–2**
An electric heating element is wound around the tube. (Source: Delmar/Cengage Learning)

a ratchet wheel that is held stationary by solder. Figure 22–1 illustrates the principle of operation. A serrated wheel is attached to a shaft. The shaft is inserted in a hollow tube. The shaft would be free to rotate inside the tube except for the solder that bonds the two units together.

An electric **heating element** is wound around the tube as shown in Figure 22–2. The heating element is connected in series with the motor, Figure 22–3. The current that flows through the motor windings also flows through the heating element. The heating element is calibrated to produce a certain amount of heat when a predetermined amount of current flows through it. As long as the current flowing through it does not exceed a certain amount, there is not enough heat produced to melt the solder. If the motor should become overloaded, an excessive amount of current will flow through the heater and the solder will melt. When the solder melts, the shaft is free to turn.

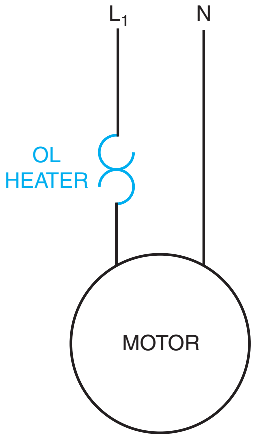



**Figure 22–3**
The overload heater is connected in series with the motor. (Source: Delmar/Cengage Learning)

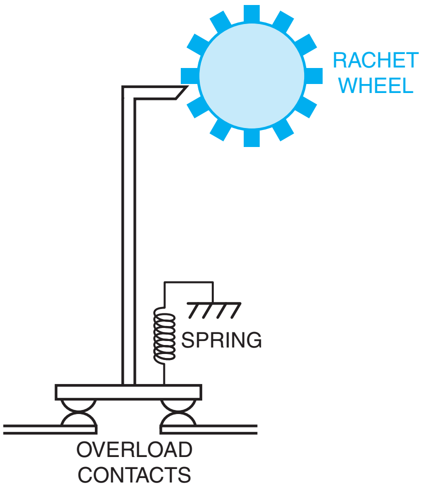



**Figure 22–4**
The ratchet wheel holds the contacts closed. (Source: Delmar/Cengage Learning)

The ratchet wheel is used to mechanically hold a set of spring-loaded contacts closed as shown in Figure 22–4. When the solder melts, the ratchet wheel is free to turn and the spring causes the contacts to open. The normally closed contacts are connected in series with the coil of the motor starter used to control the motor the overload relay is protecting, Figure 22–5. When the overload contacts open, the motor starter coil deenergizes and disconnects the motor from the line.

Notice that this overload relay has two separate sections, the **heater section** that is connected in series with the motor, and the **contact section**,

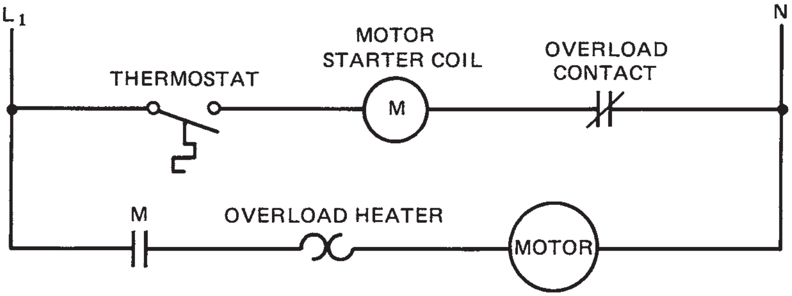



**Figure 22–5**
When the overload contact opens, the motor is disconnected from the line. (Source: Delmar/Cengage Learning)

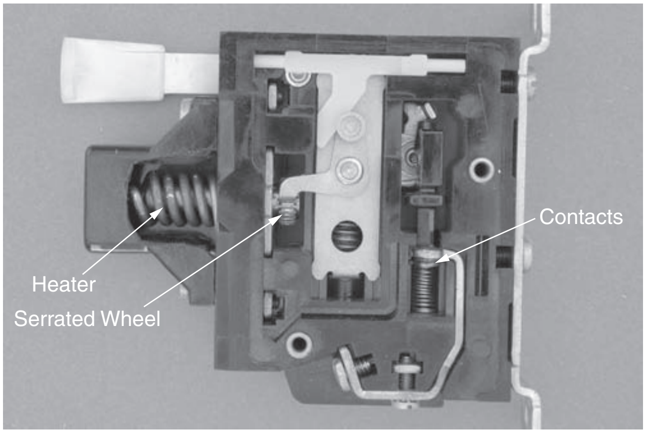



**Figure 22–6**
Solder-melting type of overload relay. (Source: Delmar/Cengage Learning)

which is connected in series with the coil of the motor starter. Notice also that the overload contacts are not used to disconnect the motor from the line. They are used to disconnect the motor starter coil from the line. This type of overload relay has a set of small auxiliary contacts that are intended to interrupt the current flow in the control circuit only. After the overload has tripped, it must be allowed to cool down enough for the solder to re-harden before it can be reset. This is generally true of any type of thermal overload. Figure 22–6 shows a photograph of this type of overload.

## BIMETAL TYPE OF OVERLOAD

The bimetal type of overload operates very similarly to the solder-melting type except a **bimetal strip** is used to cause the contacts to open, Figure 22–7. In this unit, the bimetal strip is used to mechanically

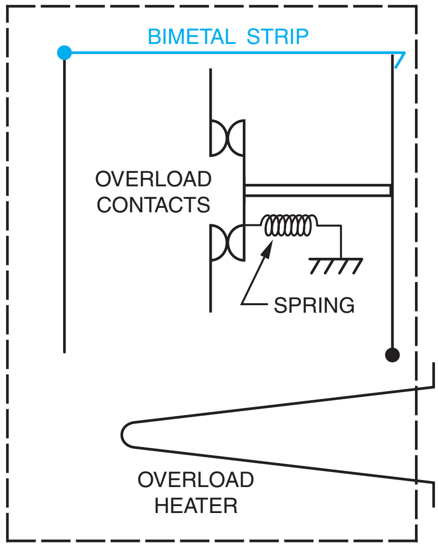



**Figure 22–7**
Bimetal type of overload. (Source: Delmar/Cengage Learning)

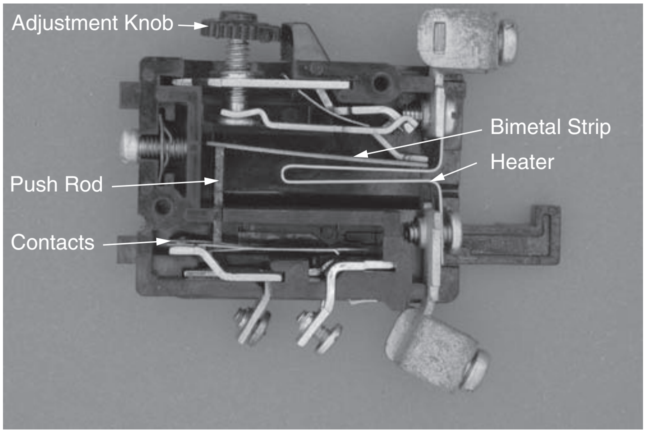



**Figure 22–8**
Bimetal-type overload relay. (Source: Delmar/Cengage Learning)

hold the spring-loaded contacts closed. If the current flow through the heater becomes excessive, the bimetal strip will warp and permit the spring to open the contacts. After the overload unit has tripped, the bimetal strip must be allowed some time to cool before it can be reset. This type of unit has an advantage over the solder-melting type in that it can be adjusted for manual reset or automatic reset, Figure 22–8. The solder-melting type of overload unit must be manually reset.

## PROTECTING THREE-PHASE MOTORS

Each phase of a three-phase motor should be protected by an overload relay. There are two methods employed to provide this protection. One method is to connect a single overload relay like those shown in Figures 22–6 and 22–8 into each phase; see Figure 22–9. When this is done, the three sets of overload contacts are connected in series with each other, as shown in Figure 22–10. Because the overload contacts are connected in series, if any one set of contacts should open, the starter coil will be disconnected, causing the load contacts to open and disconnect the motor from the line.

The second method used to protect three-phase motors is with a three-phase overload relay. This overload relay contains three separate heaters but only one set of overload contacts, Figure 22–11. If any one of the heaters should trip, it will open the set of contacts and disconnect the starter coil from the line, Figure 22–12.

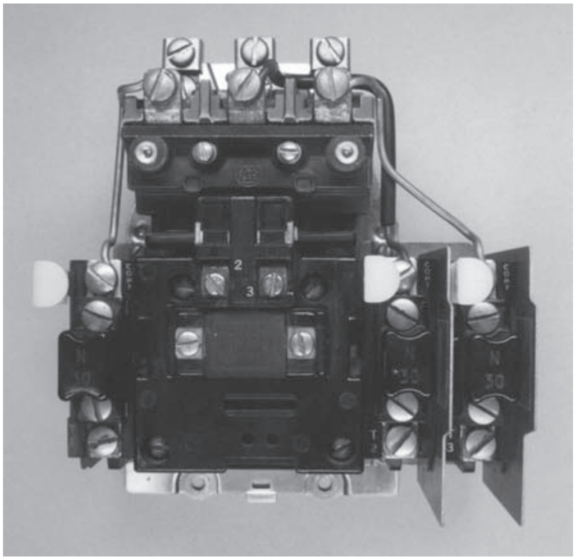


**Figure 22–9**
Three single overload relays are used to protect a three-phase motor. (Source: Delmar/Cengage Learning)

## PROTECTING SINGLE-PHASE MOTORS

Single-phase motors are generally protected with a small **automatic reset overload**, Figure 22–13. These units are constructed in one of two ways. One unit has a small heater connected in series with the motor current, Figure 22–14. In this unit the bimetal strip is constructed of a spring metal that provides a snap action when it warps. Notice that the

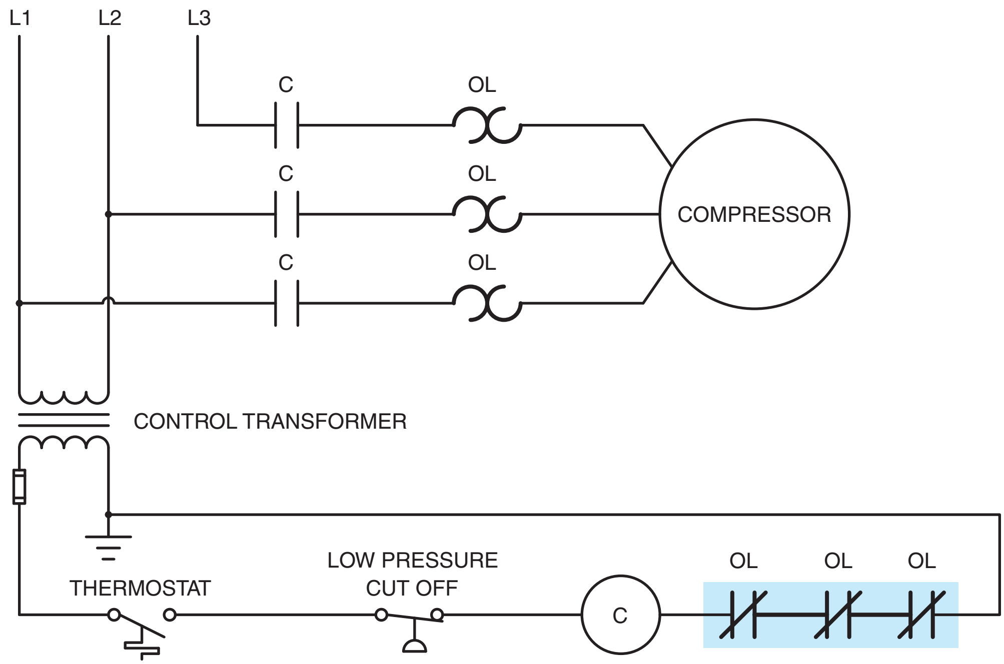



**Figure 22–10**
When three single overload relays are employed to protect a three-phase motor, all normally closed overload contacts are connected in series. (Source: Delmar/Cengage Learning)

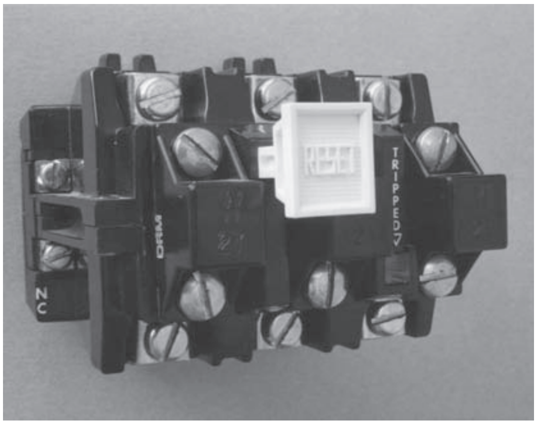



**Figure 22–11**
Three-phase overload relay. (Source: Delmar/Cengage Learning)

contacts are connected directly to the bimetal strip. This means that the motor current not only flows through the heating element, but also through the bimetal strip. If the motor current becomes excessive, the heater causes the bimetal strip to snap the contacts open and disconnect the motor from the line. Notice that the contacts of this unit are used to interrupt the motor current. When the bimetal strip has cooled enough, it snaps back to its original position and recloses the contacts.

The second type of small overload unit does not contain a heating element, Figure 22–15. In this type of unit, the bimetal strip is used as the heating element. As current flows through the bimetal strip, it begins to heat. If motor current does not become excessive, the bimetal strip does not become heated enough to cause the contacts to open. If the current does become excessive, however, the contacts snap open and disconnect the motor from the line.

These overload units can be tested with an ohmmeter for a complete circuit. If the ohmmeter indicates no continuity through them when they are cool, they are defective and must be replaced. Care must be taken to replace these units with the correct size. Overload units are designed to open their contacts when the motor current reaches 115% to 125% of full-load current. The exact rating is

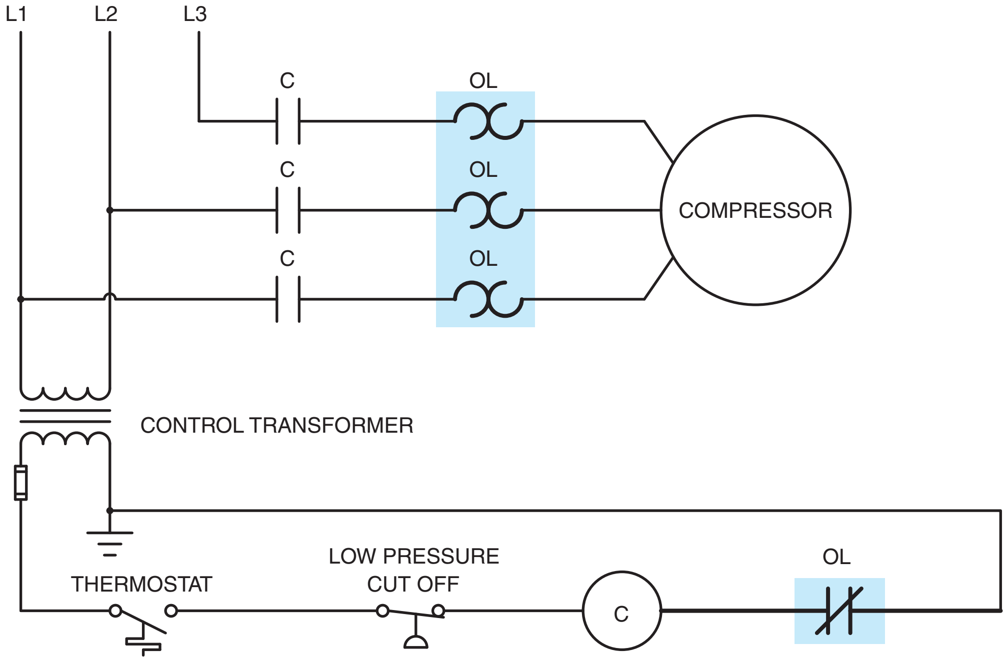



Figure 22–12
A three-phase overload relay contains three heaters and one set of contacts. (Source: Delmar/Cengage Learning)

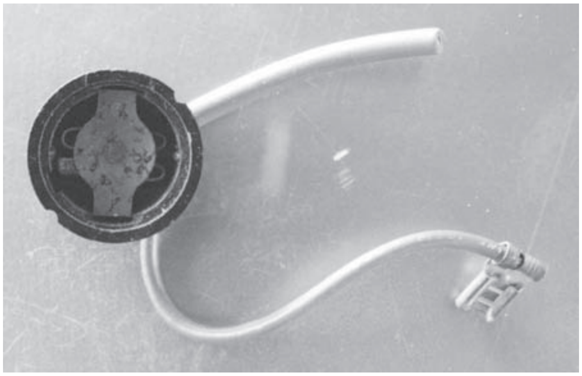


Figure 22–13
Bimetal overload often used on fractional horsepower single-phase motors. (Source: Delmar/Cengage Learning)

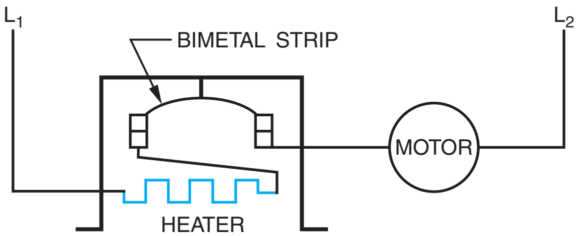



Figure 22–14
Small overload unit with heater. (Source: Delmar/Cengage Learning)

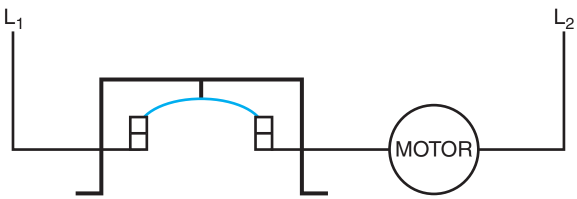



Figure 22–15
Small overload unit without heater. (Source: Delmar/Cengage Learning)

determined by the national electrical code. If an overload unit of too small a rating is installed, it will trip when there is no overload on the motor. If an overload unit of too high a value is used, the motor may be destroyed before the overload contacts open and disconnect the motor.

Notice that all of the overload units discussed are operated by sensing heat. For this reason, a heavy motor overload will cause more heat production and the unit will trip faster than it will under a light overload. Another factor that can affect these units is **ambient air temperature**. Overload relays will trip faster in hot weather than they will in cool weather. In certain parts of the country, it is often necessary to replace the heater elements of industrial-type overload units to match the season. In winter it may be desirable to use a slightly smaller heater element than normal, and in summer it may be necessary to use a slightly larger heater.

## PROTECTING LARGE MOTORS

Large horsepower motors often have current draws that are much greater than the rating of any standard overload heating element. When this is the case, current transformers are used to supply current to the overload heaters, Figure 22–16. Assume that the motor operating a large compressor has a nameplate current of 234 amperes. Now assume that three current transformers with a ratio of 300:5 are to be used to reduce the current to the overload heaters. The current rating of the overload heater can be calculated using the ratio of the current transformer.

$$\frac{300}{5} = \frac{234}{X}$$

$$300\,X = 1170$$

$$X = 3.9 \text{ amps}$$

If the overload heaters are sized for a motor with a running current of 3.9 amperes the motor will be protected. Two NEMA size 5 starters are shown in Figure 22–17. These starters contain current transformers used to reduce the current to the overload heaters.

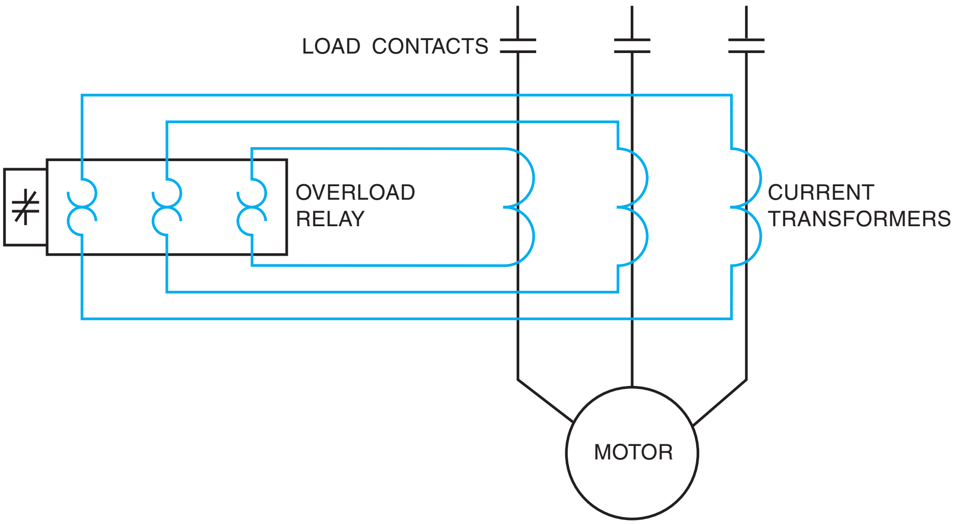



**Figure 22–16**
Current transformers reduce the motor current. (Source: Delmar/Cengage Learning)

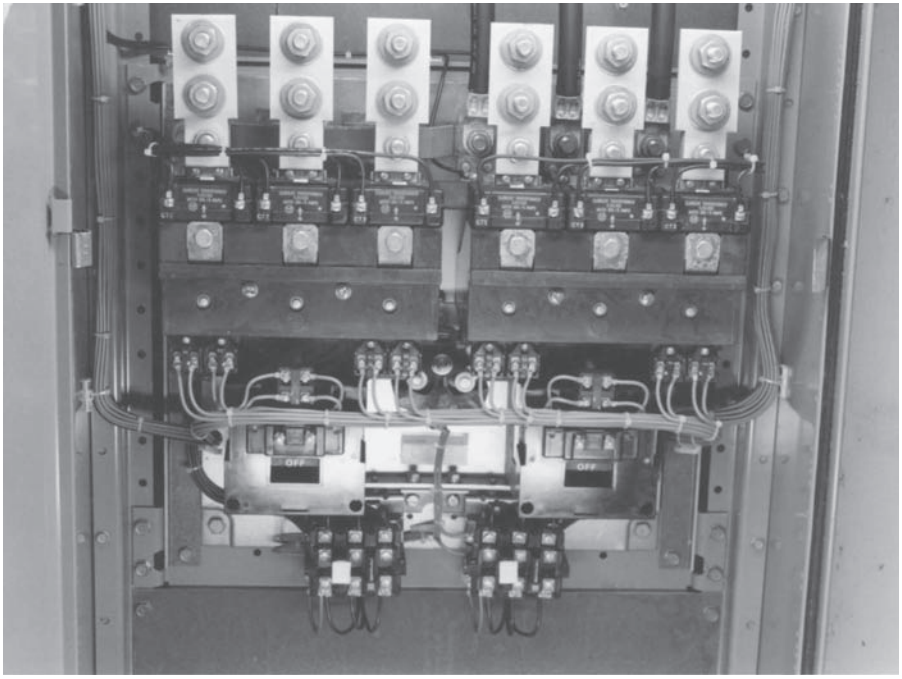


**Figure 22–17** NEMA size 5 starters with current transformers. (Source: Delmar/Cengage Learning)

## SUMMARY

- Overload relays are designed to protect the motor against an overload condition.
- Most overload relays sense motor current by connecting an electric heater in series with the motor.
- Two basic types of overload relays are:
  A. Solder-melting type.
  B. Bimetal strip type.
- Solder-melting type overload relays permit the electric heater to melt solder at a predetermined temperature and open a set of contacts.
- The bimetal strip type of overload relays open a set of contacts when the electric heating element causes a bimetal strip to warp a certain amount.
- Overload relays contain two separate sections, the heater section and the contact section.
- The contacts of an overload relay are connected in series with a motor starter coil.
- Because overload relays operate by sensing heat, they are affected by ambient temperature.

## KEY TERMS

ambient air temperature
automatic reset overload
bimetal strip
bimetal type
contact section
heater section
heating element
overloads
solder-melting type

## REVIEW QUESTIONS

1. What are the two basic types of industrial overload units?
2. What is the advantage of the bimetal type of industrial overload unit?
3. Industrial overload units are divided into two sections. What are they?
4. At what percentage of full-load motor current are overload units generally set to trip?
5. When using an industrial type of overload unit, what are the contacts connected in series with?
6. What is the difference between the two types of small overload units?
7. In the small overload unit that does not contain a heater, what is used to sense the current flow through the motor?

# UNIT 23

# Relays, Contactors, and Motor Starters

## OBJECTIVES

After studying this unit the student should be able to:

- Describe the construction of a relay
- Discuss the principle of operation of relays and contactors
- Discuss different types of relays and contactors
- Describe the difference between a contactor and a motor starter

The **relay** is a magnetically operated switch. This switch, however, can have multiple sets of contacts, and the contacts can be open or closed. The advantage of the relay is control. A single pilot device can be used to control the input or coil of the relay, and the output or contacts can control several different devices. An example of this is shown in the circuit of Figure 23–1. A flow switch is used to control the coil of a magnetic relay. When the flow switch closes, the coil of relay **FSCR (flow switch control relay)** is connected to the line. When current flows through the coil, the relay is energized, and all FSCR contacts change position. Notice that one FSCR contact is connected in series with the compressor motor. This contact does not actually start the motor, but it permits the thermostat to control the motor. This particular type of control is known as **interlocking**. Interlocking is used to prevent

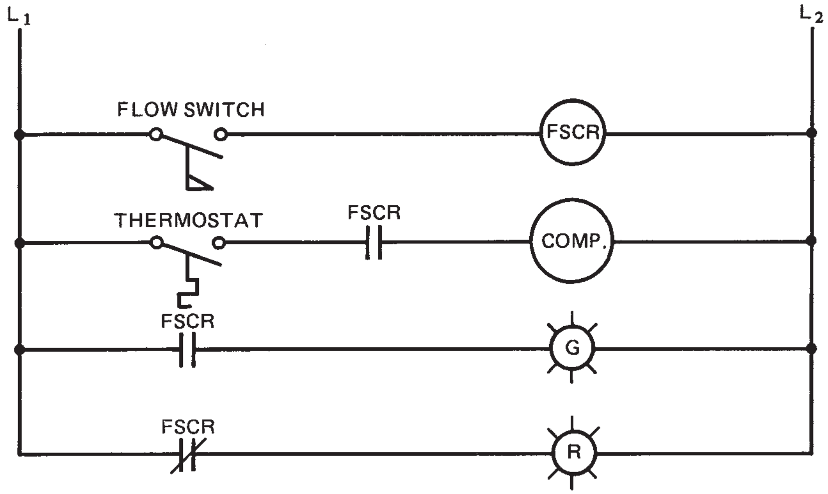



**Figure 23–1**
One relay controls several devices. (Source: Delmar/Cengage Learning)

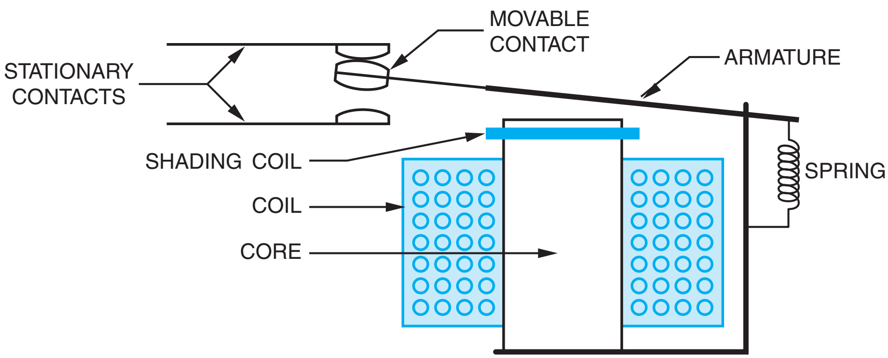



**Figure 23–2**
Simple relay. (Source: Delmar/Cengage Learning)

some function from happening until some other function has occurred. In this case, the thermostat cannot start the compressor until there is airflow in the system.

The second FSCR contact is normally open. When the FSCR coil energizes, this contact closes and turns on a green pilot light to indicate there is airflow in the system. The third FSCR contact is normally closed. It is used to turn off a red pilot light, which indicates there is no airflow in the system.

## PRINCIPLE OF OPERATION

The relay operates on the **solenoid** principle. A solenoid is an electrical device that converts electrical energy to linear motion. This principle is illustrated in Figure 23–2. A coil of wire is wound around an iron core. When current flows through the coil, a magnetic field is developed in the iron core. The magnetic field of the iron core attracts the movable arm, known as the **armature**, and overcomes the strength of the spring holding the arm away from the iron core. Notice that a movable contact is connected to the armature. In its present position, the movable contact makes connection with a stationary contact. This contact set is normally closed. When the armature is attracted to the iron core, the movable contact breaks connection with one stationary contact and makes connection with another. This relay has both a normally open and normally closed set of contacts. Notice that the movable contact is common to both of the

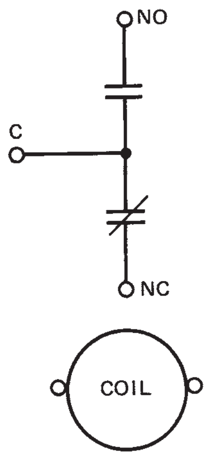



**Figure 23–3**
Schematic of a simple relay. (Source: Delmar/Cengage Learning)

stationary contacts. The movable contact would be the common and the stationary contacts would be labeled normally open and normally closed. A schematic of this type of relay is shown in Figure 23–3. This illustration shows a relay with only one set of contacts. In practice, it is common to find this type of relay with several sets of contacts.

Notice in Figure 23–2 that a shading coil has been added to the iron core. The shading coil is used with AC relays to prevent contact chatter and hum. The shading coil operates in the same way it does in the shaded-pole motor. It opposes a change of magnetic flux. The shading coil is used to provide a continuous magnetic flow to the armature when the voltage of the AC waveform is zero. DC-operated relays do not contain a shading coil since the magnetic flux is constant.

Another type of relay is shown in Figure 23–4. This relay uses a **plunger-type** of solenoid. Notice that the coil is surrounded by the iron core. There is an opening in the iron core through which the shaft of the armature can pass. When the coil is energized, the armature is attracted to both ends of the core. This creates a stronger magnetic field than the relay discussed in Figure 23–2. Notice the shading coils around both ends of the core. Notice also that the core and armature are constructed of laminated sheets. The core and armature are laminated to help prevent the induction of **eddy currents** into the core. Eddy currents are currents induced in the core material by the magnetic field of the coil. Eddy currents are generally unwanted because they heat the core and cause a power loss.

The plunger-type of solenoid is generally used with relays that use double-break contacts. A **double-break contact** is one that breaks connection at two points as shown in Figure 23–5. Notice there are two stationary contacts and one movable contact. The movable contact is used to bridge the gap between the two stationary contacts. This type of contact arrangement is preferred for relays that must control high voltage and current.

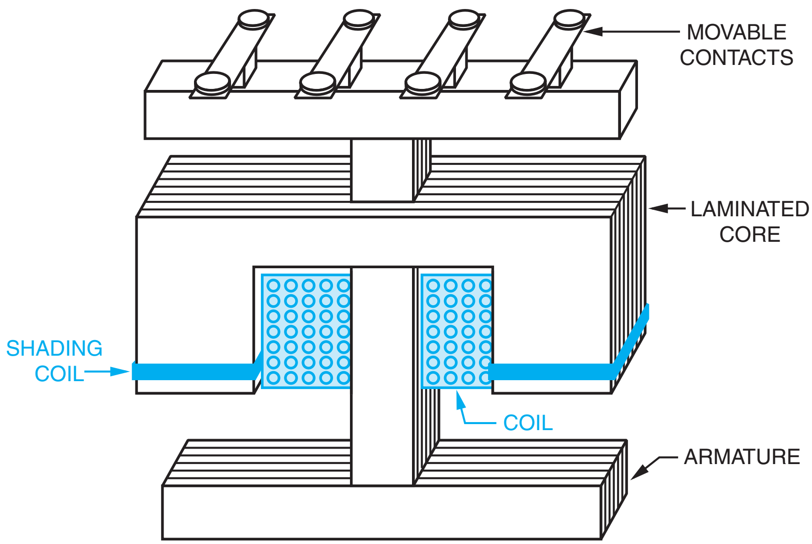



**Figure 23–4**
Plunger type of solenoid. (Source: Delmar/Cengage Learning)

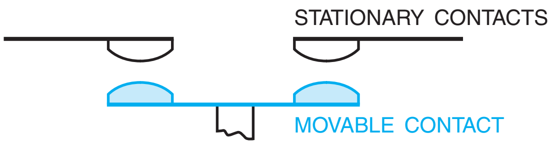



**Figure 23–5**
A set of double-beak contacts. (Source: Delmar/Cengage Learning)

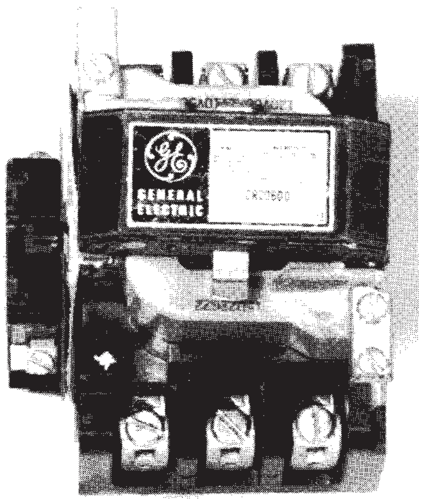


**Figure 23–6**
Contactor. (Source: Delmar/Cengage Learning)

Notice that the surface of the contact is curved. This curved surface provides a wiping action when the contacts make connection. The wiping action helps to keep contact surfaces clean. Contact surfaces should never be filed flat. This would permit oil and dirt to collect on the surface of the contact and cause poor connection.

## CONTACTORS AND MOTOR STARTERS

The term *relay* is often used to describe any type of magnetically operated switch. A relay is actually a control device that contains small auxiliary contacts designed to operate only low-current loads.

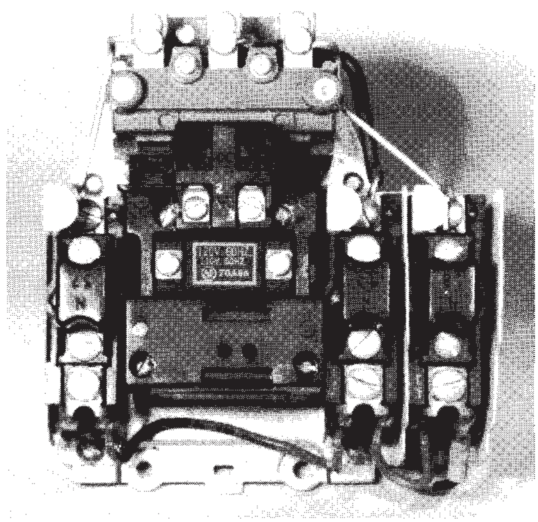


**Figure 23–7**
Motor starter with overload relays. (Source: Delmar/Cengage Learning)

A **contactor** is very similar to a relay except that a contactor contains large-load contacts designed to control large amounts of current. In the heating and airconditioning field, contactors are often used to connect power to resistance heater banks. A photograph of a contactor is shown in Figure 23–6. Contactors may contain auxiliary contacts as well as load contacts.

**Motor starters** are basically contactors with the addition of overload relays. Motor starters generally contain auxiliary contacts as well as load contacts. The auxiliary contacts are used as part of the control circuit, and the load contacts are used to connect the motor to the line. A photograph of a motor starter is shown in Figure 23–7.

## SUMMARY

- A relay is a magnetically operated switch.
- A relay is a single-input multi-output device.
- Relays can have contacts that are normally open or normally closed.
- On a schematic diagram, the contacts of a relay are always shown in the deenergized condition.
- Interlocking is used to prevent some function from happening until some other function has occurred.
- Most relays are basically electric solenoids with a set of contacts attached.
- A solenoid is a device that converts electrical energy into linear motion.
- AC relays used shading coils on the iron core to prevent contact chatter.
- Contact surfaces are generally curved to provide a wiping action.
- A relay is actually a control device that has only small auxiliary contacts that are used as part of the control circuit or to operate low current devices.
- Contactors contain large load contacts intended to connect the load to the line.
- Motor starters are contactors with the addition of overload relays.

## KEY TERMS

**armature**
**contactor**
**double-break contact**
**eddy currents**
**FSCR (flow switch control relay)**
**interlocking**
**motor starters**
**plunger-type relay**
**solenoid**

## REVIEW QUESTIONS

1. What is a solenoid?
2. What type of relays contains a shading coil?
3. What purpose does the shading coil serve?
4. What is the movable part of a relay called?
5. Why is the core material of a relay laminated?
6. What are eddy currents?
7. What effect do eddy currents have on a relay?
8. Why are contact surfaces curved?
9. What is the difference between a relay and a contactor?
10. What is the difference between a contactor and a motor starter?

# UNIT 24

# The Solid-State Relay

## OBJECTIVES

After studying this unit the student should be able to:

- Describe the construction of a solid-state relay
- Discuss the principle of opto-isolation
- Describe the internal devices used for a relay intended to control a DC and an AC load
- Describe zero switching
- Connect a solid-state relay in a circuit

The **solid-state relay** is a device that has become increasingly popular for switching applications. The solid-state relay has no moving parts, it is resistant to shock and vibration, and is sealed against dirt and moisture. The greatest advantage of the solid-state relay, however, is the fact that the control input voltage is isolated from the line device the relay is intended to control. Refer to Figure 24–1.

Solid-state relays can be used to control either a DC load or an AC load. If the relay is designed to control a DC load, a **power transistor** is used to connect the load to the line as shown in Figure 24–2. The relay shown in Figure 24–2 has a **light-emitting diode (LED)** connected to the input or control voltage. When the input voltage turns the LED on, a photo detector connected to the base of the transistor turns the transistor on and connects

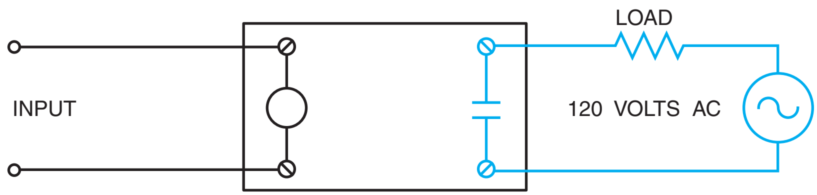



**Figure 24–1**
Solid-state relay. (Source: Delmar/Cengage Learning)

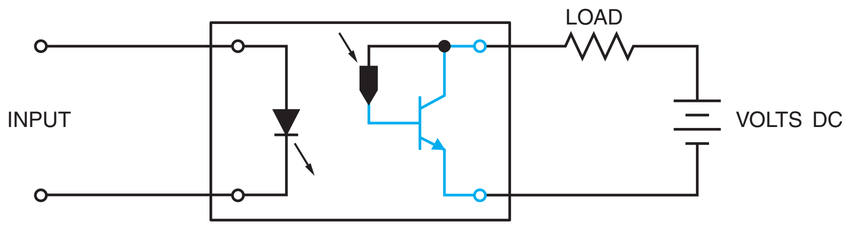



**Figure 24–2**
Power transistor used to control DC load. (Source: Delmar/Cengage Learning)

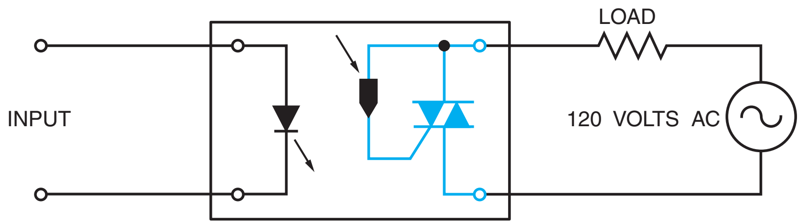



**Figure 24–3**
Triac used to control an AC load. (Source: Delmar/Cengage Learning)

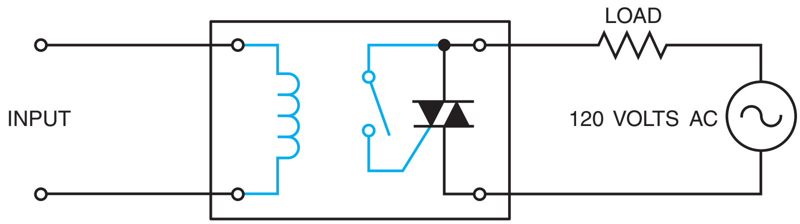



**Figure 24–4**
Reed relay controls the output. (Source: Delmar/Cengage Learning)

the load to the line. This optical coupling is a very common method used with solid-state relays. The relays that use this method of coupling are referred to as being **opto-isolated**, which means the load side of the relay is optically isolated from the control side of the relay. Because a light beam is used as the control medium, no voltage spikes or electrical noise produced on the load side of the relay can be transmitted to the control side of the relay.

Solid-state relays intended for use as AC controllers have a **triac** connected to the load circuit in place of a power transistor. Refer to Figure 24–3. In this example, an LED is used as the control device just as it was in the previous example. When the photo detector "sees" the LED, it triggers the gate of the triac and connects the load to the line.

Although opto-isolation is probably the most common method used for the control of a solid-state relay, it is not the only method used. Some relays use a small **reed relay** to control the output. Refer to Figure 24–4. A small set of reed contacts are connected to the gate of the triac. The control circuit is connected to the coil of the reed relay. When the control voltage causes a current to flow through the coil, a magnetic field is produced around the coil of the relay. This magnetic field closes the reed contacts, which causes the triac to turn on. In this type of solid-state relay, a magnetic field is used to isolate the control circuit from the load circuit instead of a light beam.

The control voltage for most solid-state relays ranges from about 3 to 32 volts and can be DC or AC. If a triac is used as the control device, load voltage ratings of 120 to 240 VAC are common and current ratings can range from 5 to 25 amps. Many solid-state relays have a feature known as **zero switching**. Zero switching means that if the relay is told to turn off when the AC voltage is in the middle of a cycle, it will continue to conduct until the AC voltage drops to a zero level and then turn off. For example, assume the AC voltage is at its positive peak value when the gate tells the triac to turn off. The triac will continue to conduct until the AC voltage drops to a zero level before actually turning off. Zero switching can be a great advantage when used with some inductive loads such as transformers. The core material of a transformer can be left saturated on one end of the flux swing if power is removed from the primary winding when the AC voltage is at its positive or negative peak. This can cause inrush currents of up to 600% of the normal operating current when power is restored to the primary.

Solid-state relays are available in different case styles and power ratings. Figure 24–5 shows a typical solid-state relay. Some solid-state relays are designed to be used as time-delay relays. One of the most common uses for the solid-state relay is the I/O (eye-oh) track of a programmable controller, which is to be covered in a later unit.

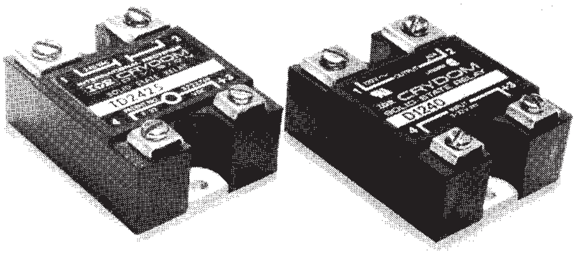


**Figure 24–5**
Solid-state relays. (Courtesy of International Rectifier).

## SUMMARY

- Solid-state relays have no moving parts.
- Solid-state relays are sealed against dirt and moisture and are resistant to mechanical shock and vibration.
- The control side of a solid-state relay is totally isolated from the load side.
- Solid-state relays used to control AC loads use a triac connected in series with the load.
- Solid-state relays used to control DC loads use a power transistor connected in series with the load.
- Many solid-state relays use a light-emitting diode (LED) as the control device.
- Opto-isolation is used to separate the load side of the circuit from the control side. This prevents any electrical noise from being transferred from the load side to the control side of the circuit.
- Solid-state relays are generally used in the I/O track of programmable controllers.

## KEY TERMS

light-emitting diode (LED)
opto-isolated
power transistor
reed relay
solid-state relay
triac
zero switching

## REVIEW QUESTIONS

1. What electronic component is used to control the output of a solid-state relay used to control a DC voltage?
2. What electronic component is used to control the output of a solid-state relay used to control an AC voltage?
3. Explain opto-isolation.
4. Explain magnetic isolation.
5. What is meant by zero switching?

# UNIT 25

# The Control Transformer

## OBJECTIVES

After studying this unit the student should be able to:

- Discuss the principle of operation of a transformer
- Define mutual induction
- Discuss the voltage and current relationships in a transformer
- Find values of voltage, current, and turns of wire using transformer formulas and Ohm's law
- Connect an industrial control transformer for operation on low and high voltage
- Perform an ohmmeter test on a control transformer

The **transformer** is a device that has the ability to change the value of AC voltage and current without a change of frequency. Most of the transformers used in the air conditioning and refrigeration field are known as **isolation transformers**. This means that the primary and secondary windings are magnetically coupled but electrically isolated from each other. Figure 25–1 illustrates the basic principle of operation of a transformer. This transformer contains two separate windings, the primary and the secondary. The primary is the winding that is connected to the power source and brings power to the transformer. The secondary winding is used to supply power to the load. Notice that there is no electrical connection between the two windings. If one lead of an ohmmeter is connected to one of the primary leads and the other ohmmeter lead is connected to one of the secondary leads, the ohmmeter

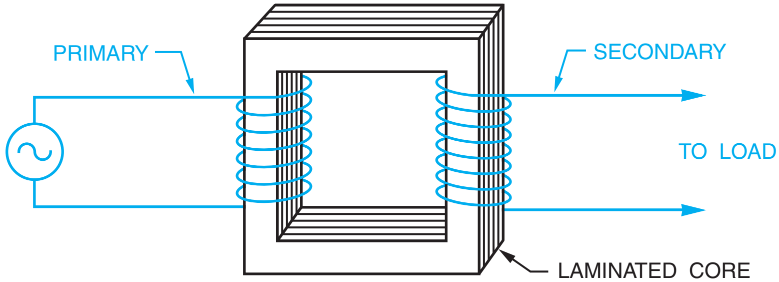



**Figure 25–1**
A basic transformer.
(Source: Delmar/Cengage Learning)

should indicate no continuity between the two windings.

## PRINCIPLE OF OPERATION

The transformer operates by magnetic induction. When current flows through the primary winding, a magnetic field is created in the winding. Because the secondary winding is wound on the same core as the primary, the magnetic field of the primary induces a voltage into the secondary. This action is known as **mutual induction**. The amount of voltage induced into the secondary is determined by the ratio of the number of turns of wire in the primary as compared with the number of turns of wire in the secondary. For example, assume that the primary winding shown in Figure 25–1 contains 120 turns of wire and is connected to 120 volts AC. This means that each turn of the primary has a voltage drop of 1 volt. If the secondary winding also has 120 turns of wire, and 1 volt is induced into each turn, then the output voltage of the secondary is 120 volts also. This transformer has a turns ratio of 1:1, which is to say that the primary contains 1 turn of wire for each turn of wire in the secondary.

Now assume that the number of turns of wire in the secondary has been changed to 60. If the number of turns in the primary has not been changed, there is still 1 volt for each turn of wire. This will produce a secondary voltage of 60 volts ($60 \times 1 = 60$).

If the number of turns of wire on the secondary is changed to 240, the output voltage of the secondary will be 240 volts ($240 \times 1 = 240$). Notice that the transformer has the ability to increase or decrease the amount of the secondary voltage. If the voltage of the secondary is less than the primary voltage, the transformer is known as a step-down transformer. If the secondary voltage is greater than the primary voltage, it is known as a step-up transformer.

## VOLTAGE AND CURRENT RELATIONSHIPS

It would first appear that the transformer has the ability to give more than it receives. This is not the case, however. Transformers are extremely efficient devices; they generally operate at 95% to 98% efficiency. For this reason, when working with transformers it is generally assumed that the power out of the transformer is equal to the power being put into the transformer.

Figure 25–2 shows the schematic symbol for a transformer. The primary has been connected to 120 volts. The secondary has a voltage of 480 volts and is connected to a load resistor of 960 ohms.

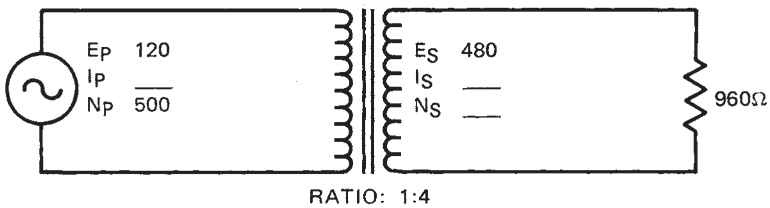



**Figure 25–2**
Schematic for transformer.
(Source: Delmar/Cengage Learning)

This transformer has a turns ratio of 1:4, which is to say that there is 1 turn of wire in the primary for every 4 turns of wire in the secondary. The amount of current in the secondary ($I_S$) can be computed by using Ohm's law.

$$I = \frac{E}{R}$$

$$I = \frac{480}{960}$$

$$I = .5 \text{ amp}$$

***Question:*** If the secondary of this transformer has a current flow of .5 amp, how much current is required in the primary? There are actually several methods that can be used to solve this problem. The most accepted method is to use the formulas shown in Figure 25–3. Because both the primary and secondary voltages are known, the formula that contains voltage and current will be used to solve the problem.

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{480} = \frac{.5}{I_P}$$

$$120\ I_P = 240$$

$$I_P = 2$$

Notice that the transformer must have a current draw of 2 amps on the primary to supply a current of .5 amps at the secondary. If the power (volts × amps) is computed for both the primary and the secondary, it will be seen that they are equal.

$$\frac{E_P}{E_S} = \frac{N_P}{N_S} \qquad \frac{E_P}{E_S} = \frac{I_P}{I_S} \qquad \frac{N_P}{N_S} = \frac{I_S}{I_P}$$

| | | |
|---|---|---|
| $E_P$ | — | Voltage of the primary |
| $E_S$ | — | Voltage of the secondary |
| $N_P$ | — | Number of turns of wire in the primary |
| $N_S$ | — | Number of turns of wire in the secondary |
| $I_P$ | — | Current flow in the primary |
| $I_S$ | — | Current flow in the secondary |

**Figure 25–3**
Transformer formulas. (Source: Delmar/Cengage Learning)

*Primary*

$$120 \times 2 = 240$$

*Secondary*

$$480 \times .5 = 240$$

The number of turns of wire can now be computed.

$$\frac{E_P}{E_S} = \frac{N_P}{N_S}$$

$$\frac{120}{480} = \frac{500}{N_S}$$

$$120\ N_S = 240{,}000$$

$$N_S = 2000$$

Notice that the secondary has 2000 turns of wire compared to 500 turns in the primary. This is consistent with the turns ratio, which states there is 1 turn of wire in the primary for every 4 turns in the secondary.

The transformer shown in Figure 25–4 is a step-down transformer that has a primary voltage of 120 volts and a secondary voltage of 24 volts. The secondary is connected to a load resistance of 6 ohms. The current flow in the secondary winding is:

$$I = \frac{E}{R}$$

$$I = \frac{24}{6}$$

$$I = 4 \text{ amps}$$

Now that the secondary current is known, the amount of primary current can be computed.

$$\frac{E_P}{E_S} = \frac{I_S}{I_P}$$

$$\frac{120}{24} = \frac{4}{I_P}$$

$$120\ I_P = 96$$

$$I_P = .8 \text{ amp}$$

If the amount of power for the primary and that for the secondary are computed, it will be seen that they are the same.

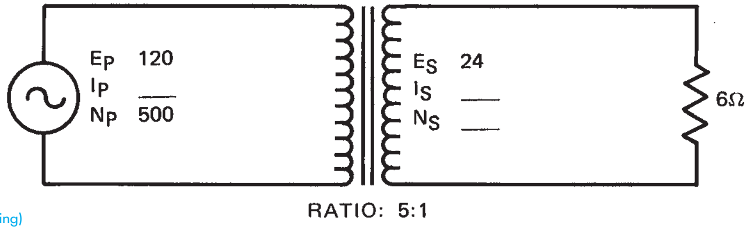



**Figure 25–4**
Step-down transformer. (Source: Delmar/Cengage Learning)

*Primary*

$120 \times .8 = 96$

*Secondary*

$24 \times 4 = 96$

The number of turns of wire in the secondary can now be computed.

$$\frac{E_p}{E_S} = \frac{N_p}{N_s}$$

$$\frac{120}{24} = \frac{500}{N_S}$$

$$120\ N_S = 12000$$

$$N_S = 100$$

Notice that the number of turns of wire in the secondary, 100, as compared with the turns of wire in the primary, 500, is consistent with the turns ratio of 5:1.

## RESIDENTIAL CONTROL TRANSFORMERS

**Control transformers** are used to change the value of line voltage to the value needed for the control circuit. Most residential air conditioning systems operate on a control voltage of 24 volts AC. The amount of current needed will vary from one system to another, but it is generally less than 1 amp. The primary voltage for residential control transformers is 120 or 240 volts. A photograph of a control transformer used in residential applications is shown in Figure 25–5. The primary lead wires for most of these transformers will be black in color. The color of the secondary leads will vary from one manufacturer to another.

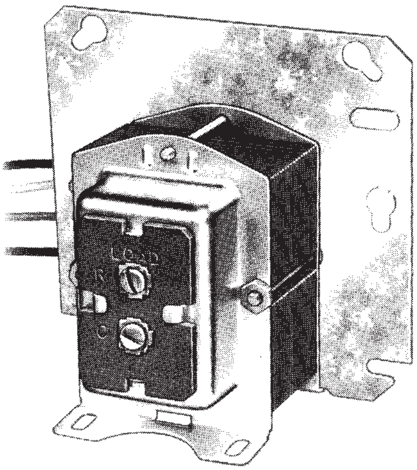


**Figure 25–5**
A 24-volt transformer. (Courtesy of Honeywell Inc.).

## INDUSTRIAL CONTROL TRANSFORMERS

Most industrial and commercial air conditioning systems operate on 240 or 480 volts. The control voltage for most of these units is 120 or 24 volts AC. Most industrial control transformers contain two primary windings and one or two secondary windings. In the following explanation, it will be assumed that the transformer has two primary windings and one secondary winding. In this type of transformer, each primary winding has a voltage rating of 240 volts, and the secondary winding has a voltage rating of 120 volts. There is a turns ratio of 2:1 between each of the primary windings and the secondary winding.

There is a standard for marking the terminals of control transformers. One of the primary windings

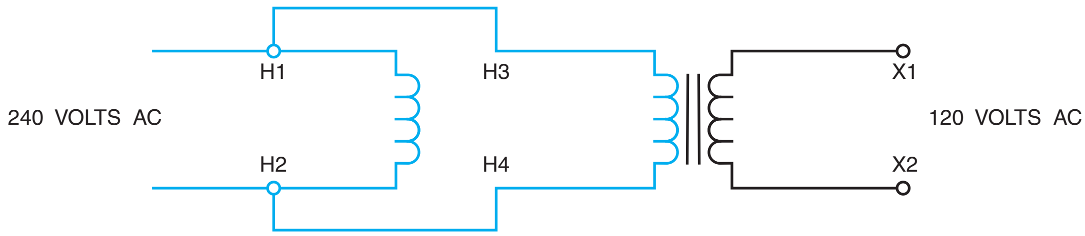



**Figure 25–6**
Primaries connected in parallel for 240-volt operation.
(Source: Delmar/Cengage Learning)

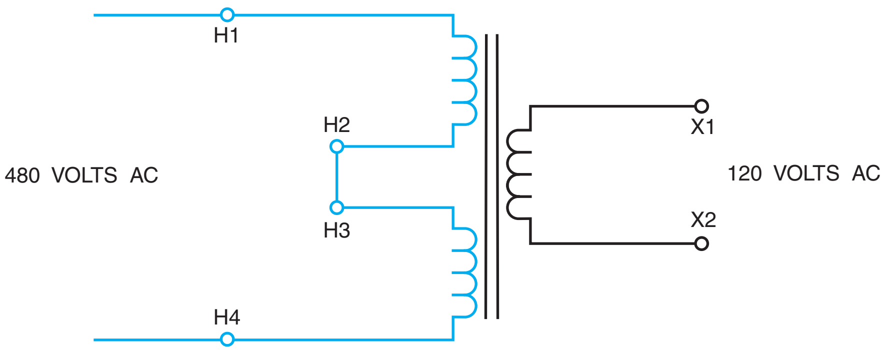



**Figure 25–7**
Primaries connected in series for 480-volt operation.
(Source: Delmar/Cengage Learning)

will be identified with terminal markings of H1 and H2. The other primary winding will be identified with terminal markings of H3 and H4. The secondary winding will be identified with terminal markings of X1 and X2.

If the transformer is to be used to change a primary voltage of 240 volts into 120 volts, the two primary windings will be connected in parallel as shown in Figure 25–6. Because the two primary windings are connected in parallel, each will receive the same voltage. This will produce a turns ratio of 2:1 between the primary windings and the secondary windings. If 240 volts is connected to the primary of a 2:1 ratio transformer, the secondary voltage will be 120 volts.

If the transformer is to be used to change 480 volts to 120 volts, the primary windings will be connected in series as shown in Figure 25–7. In this connection, H2 of one primary winding is connected to H3 of the other primary winding. This series connection of the two windings produces a turns ratio of 4:1. When 480 volts is connected to the primary, 120 volts will be produced in the secondary.

The primary windings of most control transformers have leads H2 and H3 crossed as shown in Figure 25–8. This is done to aid in the connection of the primary. For example, if it is desired to operate the transformer with the primary windings connected in parallel, a metal link is used to connect leads H1 and H3 together. Another metal link is used to connect leads H2 and H4 together,

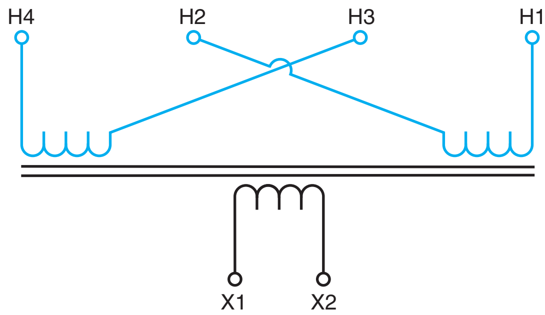



**Figure 25–8**
Primary leads are crossed. (Source: Delmar/Cengage Learning)

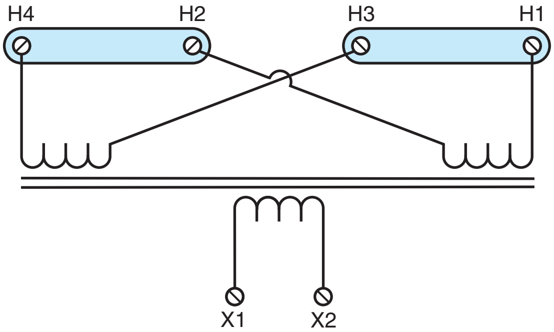



**Figure 25–9**
Metal links used to make a 240-volt connection.
(Source: Delmar/Cengage Learning)

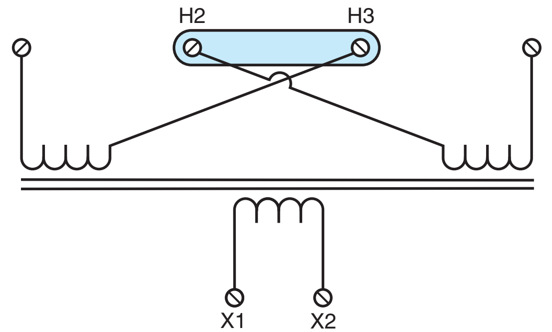



**Figure 25–10**
Metal link used to make a 480-volt connection.
(Source: Delmar/Cengage Learning)

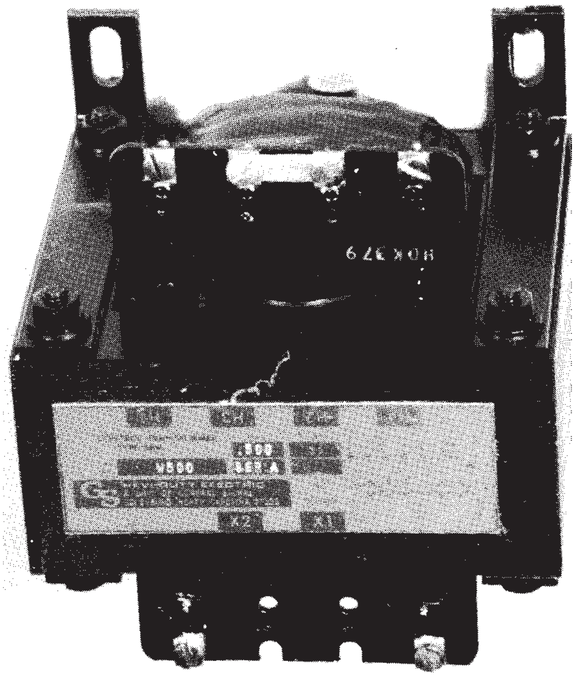


**Figure 25–11**
Industrial control transformer. (Source: Delmar/Cengage Learning)

Figure 25–9. Compare this lead connection with the schematic shown in Figure 25–6.

If it is desired to connect the primary windings for operation on 480 volts, terminals H2 and H3 are joined together with a metal link, Figure 25–10. Compare this connection with the schematic shown in Figure 25–7. A photograph of an industrial control transformer is shown in Figure 25–11.

## TESTING THE TRANSFORMER

An ohmmeter is generally used to test the windings of the transformer. To test the transformer, check for continuity through each set of windings. For example, there should be continuity between leads H1 and H2; H3 and H4; and X1 and X2. There should be no continuity between any of the windings such as H1 and H3, or H1 and X1. Also check for a grounded winding by testing to be sure there is no continuity between any of the windings and the case of the transformer.

The output voltage of the transformer should be tested with an AC voltmeter. If the output voltage is not close to the rated voltage, the transformer is probably defective. If the transformer is tested without a load connected to the secondary, it is normal for the secondary voltage to be slightly higher than the rated voltage. For example, a 24-volt transformer may have an output voltage as high as 28 volts without load connected to it. The voltage rating of the transformer assumes it is supplying full-rated current to the load. If the voltage is tested when the transformer is under full load, the rated voltage should be seen. Notice the use of the control transformer in the schematic shown in Figure 25–12.

| LEGEND | |
|---|---|
| CMT | CONDENSER MOTOR THERMOSTAT |
| CAP | CAPACITOR |
| CC | COMPRESSOR CONTACTOR |
| CCH | CRANKCASE HEATER |
| CFM | CONDENSER FAN MOTOR |
| COMP | COMPRESSOR |
| EFC | EVAPORATOR FAN CONTACTOR |
| F | FUSE |
| RR | RESET RELAY |
| T | TRANSFORMER |
| TB | TERMINAL BLOCK |
| TOP | TERMINAL OVERLOAD PROTECTOR |
| TS | TERMINAL STRIP |
| EFM | EVAPORATOR FAN MOTOR |
| LPC | LOW PRESSURE CONTROL |
| HPC | HIGH PRESSURE CONTROL |
| OL | OVERLOAD PROTECTOR |

**WARINIG**

**DISCONNECT ELECTRICAL POWER SOURCE TO PREVENT INJURY OR DEATH FROM ELECTRICAL SHOCK**

**CAUTION**

**USE COPPER CONDUCTORS ONLY TO PREVENT EQUIPMENT DAMAGE**

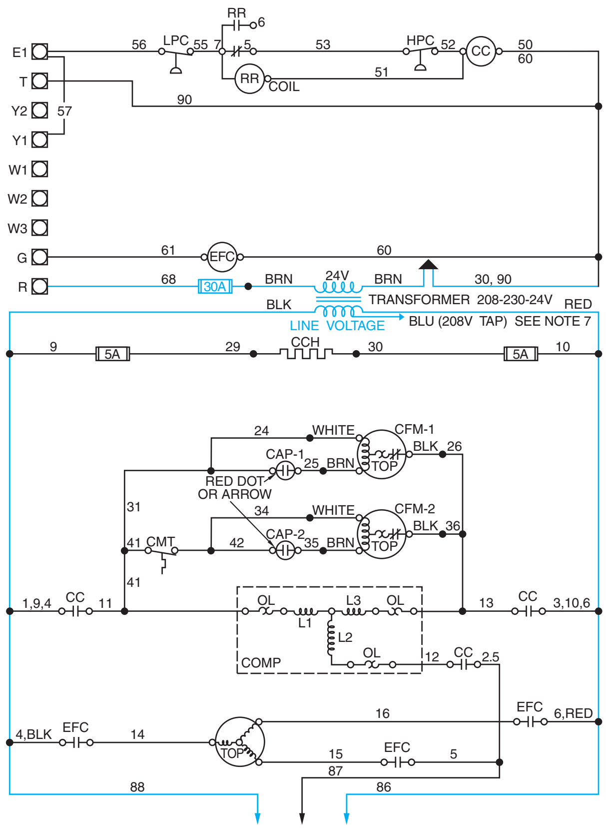



**Figure 25–12**
Control transformer used to provide low voltage for the control circuit. (Schematic courtesy of Trane Corp.).

## SUMMARY

- A transformer is a device that can change values of AC voltage and current without a change of frequency.
- Isolation transformers have their primary and secondary sides physically and electrically separated from each other.
- Isolation transformers operate on the principle of mutual induction.
- The primary is the winding of the transformer that is connected to the incoming power line.
- The secondary is the winding that is connected to the load.
- All values of voltage and current in a transformer are proportional to the turns ratio.
- A step-up transformer will have a higher secondary voltage than primary voltage.
- A step-down transformer will have a lower secondary voltage than primary voltage.

## KEY TERMS

**control transformers**
**isolation transformers**
**mutual induction**
**transformer**

## REVIEW QUESTIONS

1. What is an isolation transformer?
2. Define a step-up transformer.
3. Define a step-down transformer.
4. The primary of a transformer is connected to 120 volts AC. The secondary has a voltage of 30 volts and is connected to a resistance of 5 ohms. How much current will flow in the primary of the transformer?
5. What is the amount of control voltage used in most residential air conditioning systems?
6. What is the amount of control voltage used in most industrial air conditioning systems?
7. What is the color of the primary leads of most control transformers used for residential service?
8. How many primary windings are generally contained in an industrial control transformer?
9. What is the turns ratio of each of these primary windings as compared with the secondary winding?
10. When an industrial control transformer is to be operated on 480 volts, are the primary windings connected in parallel or in series?

# UNIT 26 Starting Relays

## OBJECTIVES

After studying this unit the student should be able to:

- List the common types of starting relays
- Describe the operation of a hot-wire relay
- Connect a hot-wire relay in a circuit
- Describe the operation of a current relay
- Connect a current relay in a circuit
- Describe the operation of a potential relay
- Connect a potential relay in a circuit
- Describe the operation of a solid-state starting relay
- Connect a solid-state starting relay in a circuit
- Describe the operation, construction, and connection of a solid-state hard starting kit

When a split-phase motor is started, it is often necessary to disconnect the start windings when the motor reaches about 75% of full speed. In an open case motor, this job is generally done by the centrifugal switch. Some single-phase motors are hermetically sealed, however, and a centrifugal switch cannot be used. When this is the case, a **starting relay** must be used. A starting relay is located away from the motor and is used to disconnect the start windings when the motor has reached about 75% of its full speed. There are four basic types of starting relays in general use:

1. The **hot-wire relay**.
2. The **current relay**.
3. The **potential relay**.
4. The **solid-state relay**.

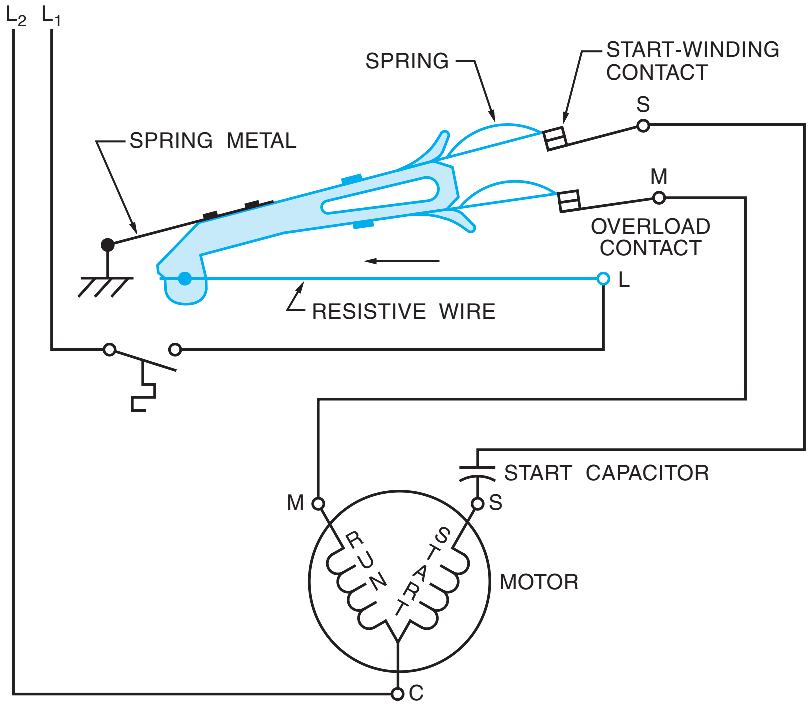



**Figure 26–1**
Hot-wire relay connection.
(Source: Delmar/Cengage Learning)

## THE HOT-WIRE RELAY

The **hot-wire relay** is so named because it uses a length of resistive wire connected in series with the motor to sense motor current. A diagram of this type of relay is shown in Figure 26–1. When the thermostat contact closes, current can flow from line 1 to terminal L of the relay. Current then flows through the resistive wire, the movable arm, and the normally closed contacts to the run and start windings. When current flows through the resistive wire, its temperature increases. This increase of temperature causes the wire to expand in length. When the length of the resistive wire increases, the movable arm is forced to move down. As the arm moves down, tension is applied to the springs of both contacts. The relay is so designed that the start contact will snap open first. When the start winding is disconnected, the current flow to the motor will decrease. If the motor current is not excessive, the resistive wire will not expand enough to cause the run contact to open. If the current flow is excessive, however, the wire will continue to expand and the contact connected in series with the run winding will open.

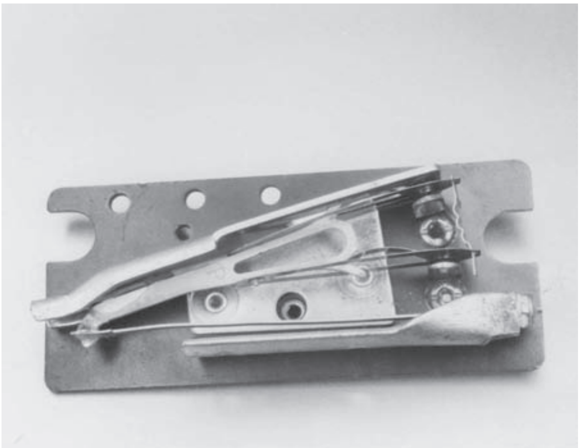


**Figure 26–2**
Hot-wire type of starting relay. (Source: Delmar/Cengage Learning)

Notice that this type of relay is used as both a starting relay and an overload relay. One disadvantage of the hot-wire relay is that it must be permitted to cool after each operation. A motor using this type of starting relay cannot be started in rapid succession. Figure 26–2 shows a photograph of the hot-wire type of starting relay.

Testing this relay is difficult. An ohmmeter can be used to check for continuity between the L terminal and the start and main winding terminals. To properly test this relay, an ammeter should be used to make certain the start contact opens and disconnects the start winding. If the relay is opening on overload, the ammeter can be used to check the current draw of the motor. This will determine if the motor is actually overloaded, or if the relay is opening when it should not. A good rule to follow concerning starting relays is to always test them if the motor has been damaged. It makes poor business sense to damage a new motor because of not checking the starting relay.

When replacing this relay, it is necessary to use the correct replacement. Because the relay is operated by motor current, it has been designed to open its contacts when a specific amount of current flows through the circuit. The relay must, therefore, be matched to the characteristics of the motor it is intended to control.

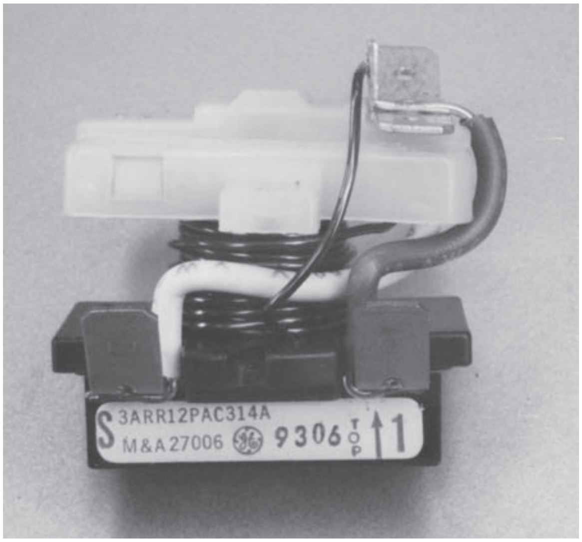



**Figure 26–3**
Current type of starting relay. (Source: Delmar/Cengage Learning)

## THE CURRENT RELAY

The **current relay** also operates by sensing the amount of current flow in the circuit. This type of relay operates on the principle of a magnetic field instead of expanding metal. The current relay contains a coil of a few turns of large wire, and a set of normally open contacts, Figure 26–3. The coil of the relay is connected in series with the run winding of the motor as shown in Figure 26–4. The contacts are connected in series with the start winding. When the thermostat contact closes and connects power to the motor, the starting contacts of the relay are open. Because no power is applied to the start winding, the motor cannot start. This causes a current of about three times the normal full-load current to flow in the run winding. The high current flow through the coil of the start relay produces a strong magnetic field. The magnetic field is strong enough to cause the solenoid to close the starting contacts. When the starting contacts close, power is applied to the start winding and the motor begins to turn. As the motor accelerates, the current flow through the run winding decreases rapidly. When the current flow through the relay coil decreases,

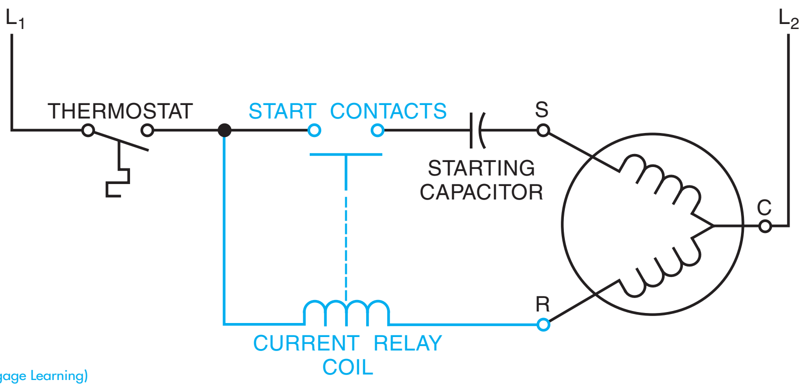



**Figure 26–4**
Current relay connection. (Source: Delmar/Cengage Learning)

the strength of the magnetic field becomes weaker. When the motor has reached about 75% of full speed, the magnetic field is weak enough to permit the solenoid to reopen the starting contacts. This disconnects the start winding from the circuit and the motor continues to operate normally.

Notice that the current relay is used to disconnect the start windings only and does not provide overload protection. A motor using this type of starting relay must be provided with separate overload protection.

If it is necessary to replace this type of relay, the correct size must be used. The current relay is matched to the characteristics of the motor it is designed to be used with. This type of relay is also sensitive to the position it is mounted in. The current relay generally uses the force of gravity to open the starting contacts. When installing a new relay, it must be mounted in the correct position. If it is installed upside down, the starting contacts will be closed instead of open.

When testing this type of relay, an ohmmeter can be used to check the continuity of the contacts. When the relay is held in the correct position, the ohmmeter should show an open circuit across the contacts. If it does not, the contacts are shorted. If the relay is held upside down, the contacts should indicate continuity. The coil of the relay is generally exposed and a visual inspection will reveal shorted windings. The best method of testing the relay is with an ammeter. If the ammeter is used to measure the current flow to the start winding, it can be seen if the motor starts and the relay contacts disconnect the start winding.

## THE POTENTIAL RELAY

The **potential** (voltage) **relay** operates by sensing an increase in the voltage developed in the start winding when the motor is operating. A potential relay is shown in Figure 26–5. A schematic diagram for a potential starting relay circuit is shown in Figure 26–6. In this circuit, the potential relay is used to disconnect the starting capacitor from the circuit when the motor reaches about 75% of its full speed. SR (starting relay) coil is connected in

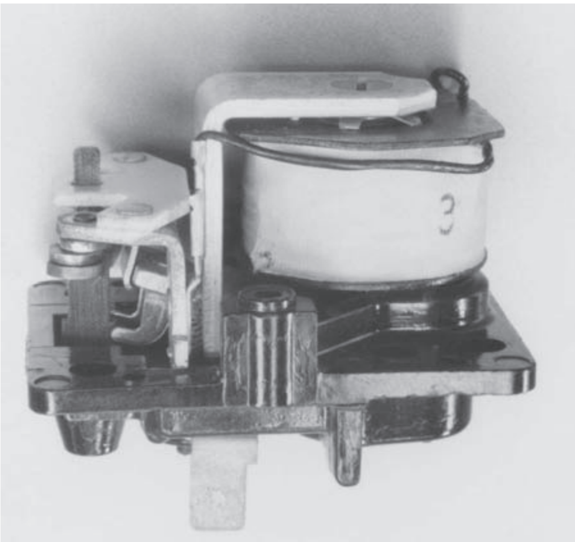


**Figure 26–5**
Potential starting relay. (Source: Delmar/Cengage Learning)

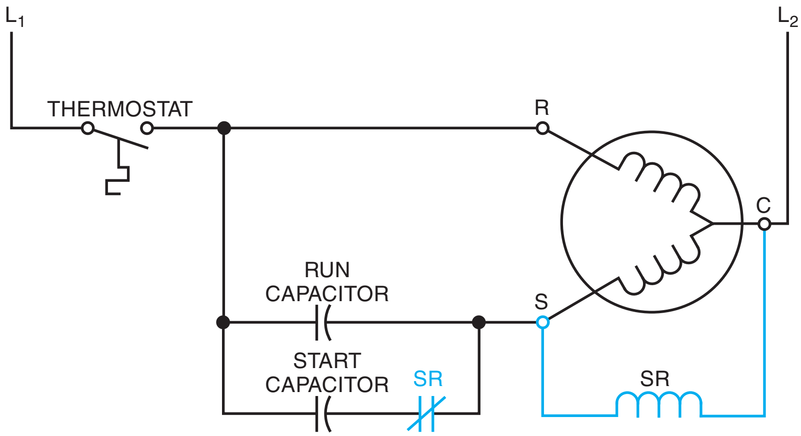



**Figure 26–6**
Potential relay connection.
(Source: Delmar/Cengage Learning)

parallel with the start winding of the motor. A normally closed SR contact is connected in series with the starting capacitor. When the thermostat contact closes, power is applied to both the run and start windings of the motor. Notice that both the run capacitor and the start capacitor are in the circuit at this time.

The rotating magnetic field of the stator cuts through the bars of the squirrel-cage rotor and induces a current into them. The current flow in the rotor produces a magnetic field around the rotor. As the rotor begins to turn, its magnetic field cuts through the start winding and induces a voltage into it. The induced voltage causes the total voltage across the start winding to be higher than the voltage applied by the line. When the motor has accelerated to about 75% of full speed, the induced voltage in the start winding is high enough to energize SR coil. When SR coil energizes, SR contact opens and disconnects the start capacitor from the circuit, Figure 26–7.

Notice that this type of relay depends on the induced voltage created in the start winding by the magnetic field of the rotor and the run winding. The start winding acts like the secondary winding of a transformer and produces a step-up in voltage. For this reason, the amount of voltage necessary to energize the coil of a potential relay is greater than line voltage. Once the relay has been energized it can be held in by less voltage than that required to energize it. The potential relay is primarily used to disconnect the starting capacitor of a permanent-split capacitor motor, as shown in Figure 26–6. Although the potential relay is still in use, it is being replaced by the solid-state relay.

The potential type of starting relay is often used with compressors that use the permanent-split capacitor start motor. The coil of the relay can be tested for an open circuit with an ohmmeter. When the ohmmeter is connected across the coil, it should indicate continuity. The actual amount of resistance can vary from one type of relay to another. The best method for testing the starting relay is with an ammeter. If an ammeter is connected to the start capacitor, it can be seen if the capacitor is energized when the motor is started, and if the relay disconnects it from the circuit.

**AUTHOR'S NOTE**: A couple of things need to be pointed out concerning the schematic in Figure 26-7. One is that there is a mistake in the terminal numbers of the potential relay. Terminal numbers 1 and 2 should be switched. The terminal shown as 2 is actually terminal 1, and the terminal shown as 1 is actually terminal 2. The second is not a mistake, but due to how the schematic was drawn it could cause confusion. Notice that the low-pressure switch has been drawn upside down. The switch appears to be a normally closed switch. In reality, it is a normally open held-closed switch. If the switch were drawn properly, it would be apparent that the switch is actually a normally open held-closed switch. Although this schematic does contain a mistake and a component not drawn properly, I chose to retain it in the text. This is an excellent example of problems that occur in the field. The service technician must be aware that mistakes like this do happen.

## SOLID-STATE STARTING RELAYS

Another type of starting relay is known as the **solid-state starting relay**, Figure 26–8. This relay is intended to replace the current-type starting relay and has several advantages over the current relay. Some of these advantages are:

1. The solid-state relay contains no moving parts and no contacts, which can become burned or pitted.
2. The solid-state relay can be used to replace almost any current relay. This interchangeability makes it possible for the service technician to stock only a few solid-state relays instead of a large number of current relays.

The solid-state starting relay is actually an electronic component known as a **thermistor**. A thermistor is a device that exhibits a change of resistance with a change of temperature. This particular thermistor has a positive coefficient of resistance, which means that the resistance of the device will increase with an increase of temperature.

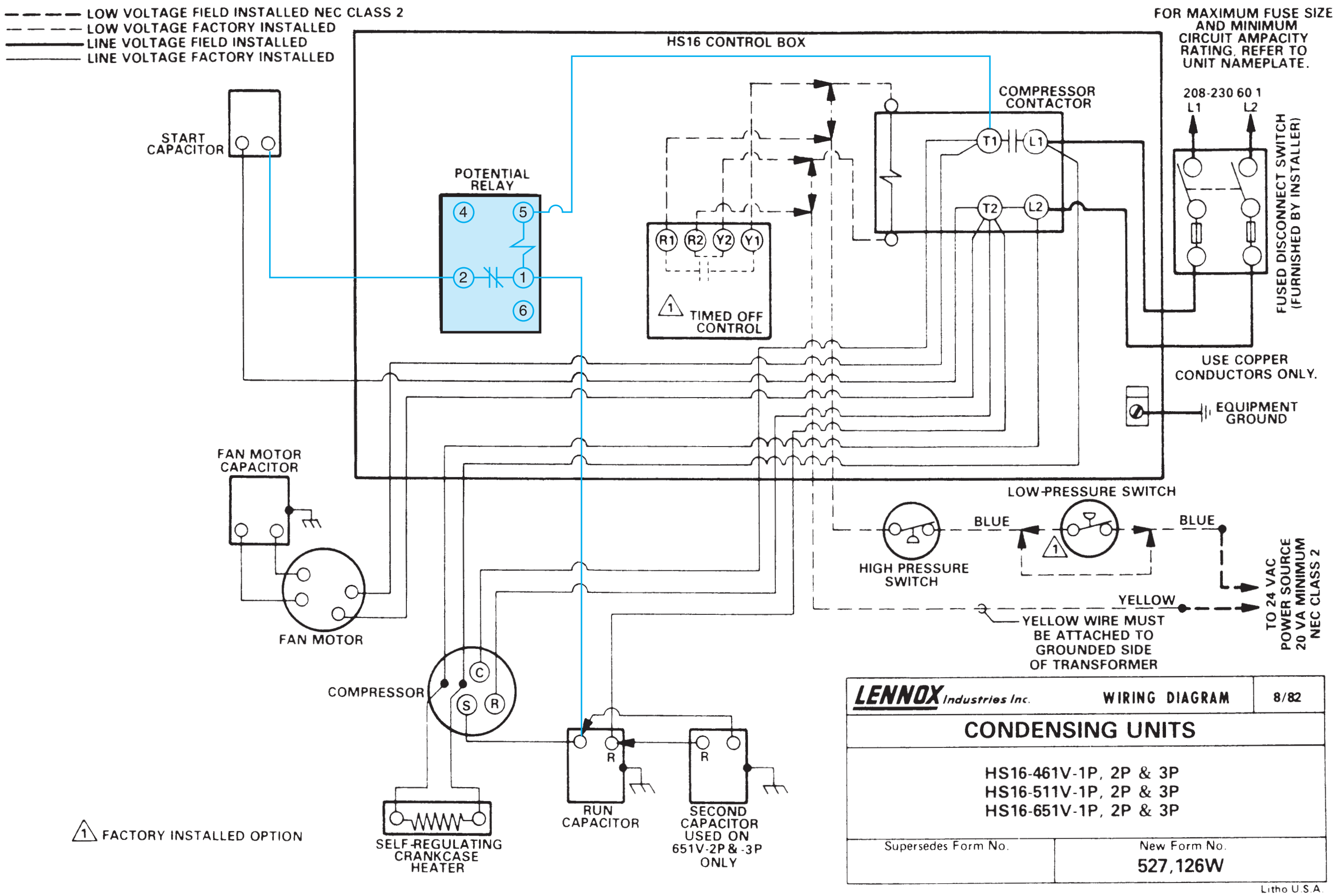



**Figure 26–7**
A potential relay is used to disconnect the start windings of the compressor when the motor reaches about 75% of full speed. (Courtesy of Lennox Industries Inc.).

The schematic diagram in Figure 26–9 illustrates the connection for a solid-state starting relay. Notice that this is the same basic connection used for the connection of a current starting relay, Figure 26–4. The solid-state relay, however, does not contain a coil or contacts. When the solid-state relay is used, a current path exists between the line connection terminal and the terminal marked M for MAIN winding. The thermistor is connected between the line connection and the terminal marked S for START winding.

When power is first applied to the circuit, the thermistor has a relatively low resistance. This permits current to flow through both the start and run windings of the motor. The temperature of the thermistor increases because of the current flowing through it. The increase of temperature causes the resistance to change from a very low value of 3 or 4 ohms to several thousand ohms. This increase of resistance is very sudden and has the effect of opening a set of contacts connected in series with the start winding. Although the start winding is never completely disconnected from the power line, the amount of current flow through it is very small, typically 0.03 to 0.05 amps, and does not affect the operation of the motor. This small amount of **leakage current** maintains the temperature of the thermistor and prevents it from returning to a low resistance. After power has been disconnected from the motor, a cool-down period of about 2 minutes should be allowed before restarting. This cool-down period is needed for the thermistor to return to a low value of resistance.

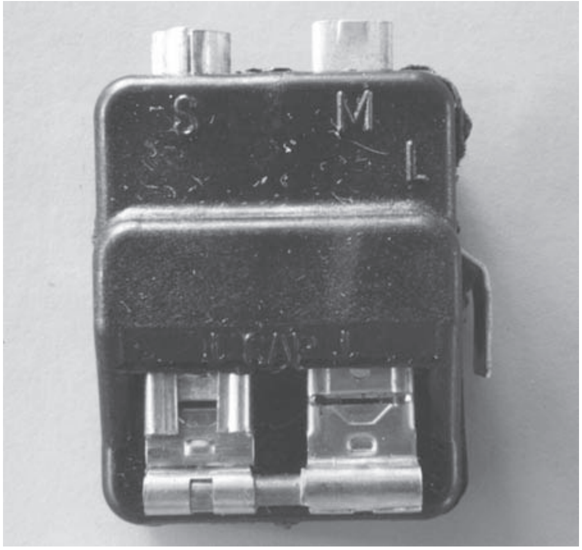



**Figure 26–8**
Solid-state starting relay. (Source: Delmar/Cengage Learning)

## TESTING THE SOLID-STATE STARTING RELAY

A continuity test can be made with an ohmmeter. If the probes of an ohmmeter are connected to the M and S terminals of the relay, a low value of resistance, typically 2 to 5 ohms, should be seen. The most accurate test is made by connecting the relay in the motor circuit. A clamp-on ammeter set to its lowest scale can be used to measure the current in the start winding. After the motor has been started, the ammeter should give an indication very close to zero amps.

## SOLID-STATE HARD STARTING KIT

Another device that uses a solid-state relay, the **solid-state hard starting kit,** is shown in Figure 26–10. This device is intended to increase

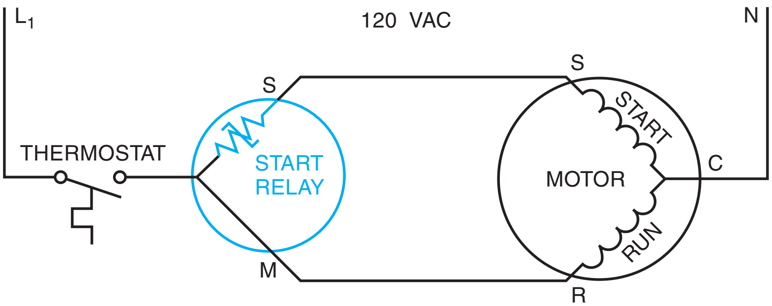



**Figure 26–9**
Solid-state starting relay connection.
(Source: Delmar/Cengage Learning)

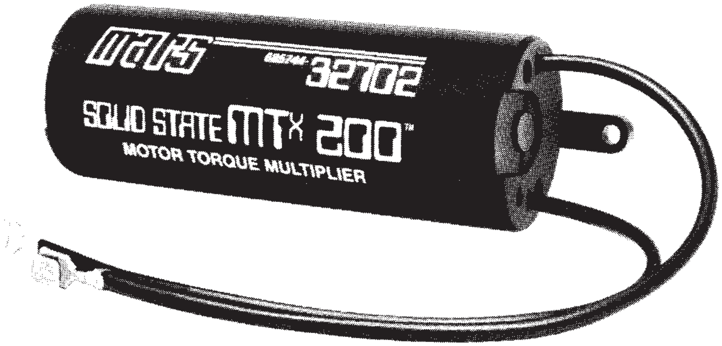



**Figure 26–10**
Hard starting kit increases starting torque of permanent-split capacitor motors. (Courtesy of Motors & Armatures, Inc.)

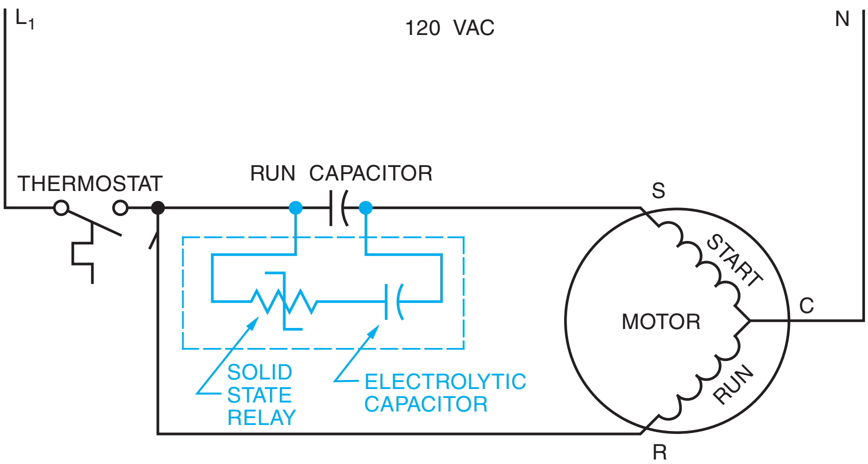



**Figure 26–11**
Hard starting kit.
(Source: Delmar/Cengage Learning)

the starting torque of a permanent-split capacitor motor. The kit contains a solid-state relay and an AC electrolytic capacitor similar to those used as the starting capacitor for a capacitor-start induction run motor. The kit connects directly across the terminals of the existing run capacitor as shown in Figure 26–11. When the thermostat contact closes and connects power to the motor circuit, the resistance of the solid-state relay is very low. A current path exists through the run winding, run capacitor, solid-state relay, electrolytic capacitor, and start winding. Because the run capacitor and electrolytic capacitor are connected in parallel, their values of capacitance add, providing extra capacitance to the motor during the starting period. The current flowing through the solid-state relay and electrolytic capacitor causes the temperature of the relay to increase, resulting in an increase in resistance. The increased resistance reduces the current flow through the electrolytic capacitor to a very low value. This has the effect of disconnecting the electrolytic capacitor from the circuit. The leakage current through the relay and electrolytic capacitor prevents the relay from returning to a low value of resistance. After power has been disconnected from the motor circuit, a cool down period of 2 to 3 minutes should be given to permit the solid-state relay to return to a low value of resistance.

## SUMMARY

- Starting relays are used to disconnect the start winding of a hermetically sealed split-phase motor.
- The four basic types of starting relays are:
  A. The hot-wire relay.
  B. The current relay.
  C. The potential relay.
  D. The solid-state relay.
- The hot-wire relay senses motor current by connecting a piece of resistive wire in series with the motor. The motor current heats the wire, causing it to expand and open a set of contacts.
- Hot-wire relays can also provide overload protection for the motor.
- Current relays use a coil connected in series with the motor run winding. The magnetic field of the coil is used to close a set of contacts connected in series with the start winding.
- The potential relay is used primarily with permanent-split capacitor motors.
- The coil of the potential relay is connected in parallel with the motor start winding.
- The contact of the potential relay is connected in series with the starting capacitor.
- Solid-state starting relays are generally used to replace current starting relays.
- Solid-state starting relays use a thermistor, which rapidly changes its resistance when heated.
- Solid-state hard starting kits generally consist of an AC electrolytic capacitor and a solid-state starting relay that connect in parallel with the existing run capacitor.

## KEY TERMS

**current relay**
**hot-wire relay**
**leakage current**
**potential relay**
**solid-state hard starting kit**
**solid-state starting relay**
**starting relay**
**thermistor**

## REVIEW QUESTIONS

1. What are the four types of starting relays?
2. On what type of motor is it necessary to use a starting relay?
3. What principle is used to operate the hot-wire relay?
4. What principle is used to operate the current relay?
5. What type of starting relay does not sense motor current to operate?
6. What type of starting relay can be used for overload protection for the motor?
7. What type of motor can the potential relay be used with?

8. Is the start contact of a hot-wire relay open or closed when power is first applied to the motor?
9. Is the start contact of a current relay open or closed when power is first applied to the motor?
10. Refer to the circuit shown in Figure 26–4. What would happen if the coil of the current relay were open when the thermostat connected power to the motor circuit?

## TROUBLESHOOTING QUESTIONS

Refer to the schematic shown in Figure 26–7 to answer the following questions.

**NOTE:** *The "TIMED OFF CONTROL" shown in the schematic is a short-cycle timer, which will be discussed in Unit 36.*

1. What voltage is used to operate the coil of the compressor contactor?
   A. 208 VAC
   B. 230 VAC
   C. 60 VAC
   D. 24 VAC
2. This schematic does not show the thermostat connection, which is relatively common with air conditioning schematics. In which wire would the thermostat contact normally be connected?
   A. L1
   B. L2
   C. The blue wire
   D. The yellow wire
3. Which of the following components is not controlled by the operation of the compressor contactor?
   A. Self-regulating crankcase heater
   B. The fan motor
   C. The compressor
   D. All circuit components are controlled by the compressor contactor.
4. To which line is the common of the compressor connected?
   A. The blue wire of the 24-volt circuit.
   B. The yellow wire of the 24-volt circuit.
   C. Line 1 of the main power.
   D. Line 2 of the main power.
5. Assume that this unit is a model 651V-3P. How many capacitors are connected to the compressor start winding during the initial starting period?
   A. 1
   B. 2
   C. 3
   D. None

# UNIT 27 Variable-Speed Motor Control

## OBJECTIVES

After studying this unit the student should be able to:

- Describe different types of variable-speed motors
- Discuss autotransformer control
- Connect an autotransformer speed controller in a circuit
- Discuss the use of a triac to control motor speed
- Connect a triac speed controller in a circuit
- Discuss the operation of a series impedance speed control
- Connect a series impedance speed controller in a circuit

The use of small **variable-speed motors** has increased greatly in the last few years. These motors are commonly used to operate light loads such as ceiling fans and blower motors. There are two types of motors used for these applications, the shaded-pole and the permanent-split capacitor motor. These motors are used because they operate without having to disconnect a set of start windings with a centrifugal switch or starting relay. Motors intended to be used in this manner are wound with high-impedance stator windings. The high impedance of the stator limits the current flow through the motor when the speed of the rotor is decreased. Speed control for these motors is accomplished by controlling the amount of voltage applied to the motor, or by inserting impedance in series with the stator winding.

## VARIABLE-VOLTAGE CONTROL

The amount of voltage applied to the motor can be controlled by several methods. One method is to use an **autotransformer** with several taps, Figure 27–1. This type of controller has several steps of speed control. Notice that the applied voltage, 120 volts in this illustration, is connected across the entire transformer winding. When the rotary switch is moved to the first tap, 30 volts is applied to the motor. This produces the lowest motor speed for this controller. When the rotary switch is moved to the second tap, 60 volts is applied to the motor. This provides an increase in motor speed. When the switch has been moved to the last position, the full 120 volts is applied to the motor operating it at the highest speed.

Another type of variable-voltage control uses a triac to control the amount of voltage applied to the motor, Figure 27–2. This type of speed control provides a more linear control since the voltage can be adjusted from 0 to the full applied voltage. At first appearance, many people assume this controller to be a **variable resistor** connected in series with the motor. A variable resistor large enough to control even a small motor would produce several hundred watts of heat and could never be mounted in a switch box. The variable resistor in this circuit is used to control the amount of phase shift for the triac. The triac controls the amount of voltage applied to the motor by turning on at different times during the AC cycle.

A triac speed control is very similar to a triac light dimmer used in many homes. A light dimmer, however, should never be used as a motor speed controller. Triac light dimmers are intended to be used with resistive loads such as incandescent lamps. Light dimmer circuits will sometimes permit one half of the triac to start conducting before the other half. The wave form shown in Figure 27–3 illustrates this condition. Notice that only part of the positive half of the waveform is being conducted to the load. Since only positive voltage is being applied to the load, it is DC. Operating a resistive load, such as an incandescent lamp with DC, will do no damage. Operating an inductive load such as the winding of a motor can do a great deal of damage, however. When direct current is applied to a motor winding, there is no inductive reactance to limit the current. The actual wire resistance of the stator is the only current limiting factor. The motor winding or the

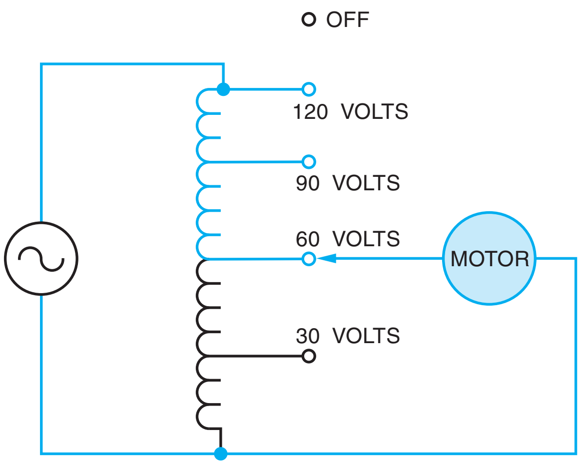



**Figure 27–1**
Autotransformer controls motor voltage. (Source: Delmar/Cengage Learning)

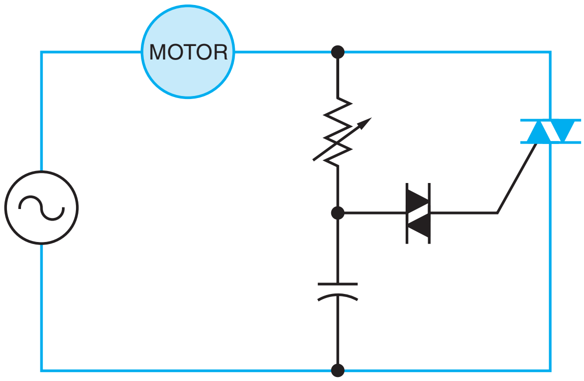



**Figure 27–2**
Triac used to control motor speed.
(Source: Delmar/Cengage Learning)

**Figure 27–3**
Triac conducts only the positive half of the waveform.
(Source: Delmar/Cengage Learning)

controller can easily be destroyed if direct current is applied to the motor. For this reason only triac controllers designed for use with inductive loads should be used for motor control. A photograph of a triac speed controller is shown in Figure 27–4.

## SERIES IMPEDANCE CONTROL

Another common method of controlling the speed of small AC motors is to connect impedance in series with the stator winding. This is the same basic method of control used with multi-speed fan motors. The circuit in Figure 27–5 shows a tapped inductor connected in series with the motor. When the motor is first started, it is connected directly to the full voltage of the circuit. As the rotary switch is moved from one position to another, steps of inductance are connected in series with the motor. As more inductance is connected in series with the stator, the amount of current flow decreases. This produces a weaker magnetic field in the stator. **Rotor slip** increases because of the weaker magnetic field and causes the motor speed to decrease. A photograph of this type of controller is shown in Figure 27–6.

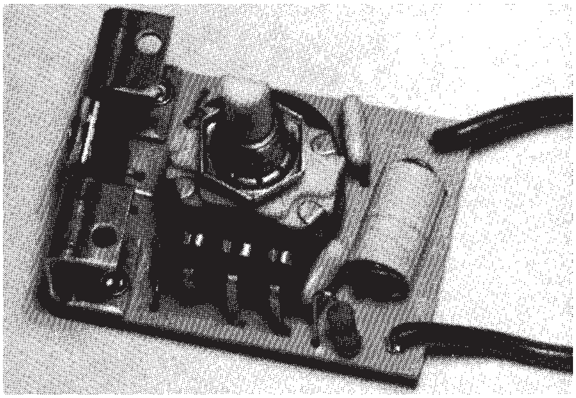


**Figure 27–4**
Triac speed control. (Source: Delmar/Cengage Learning)

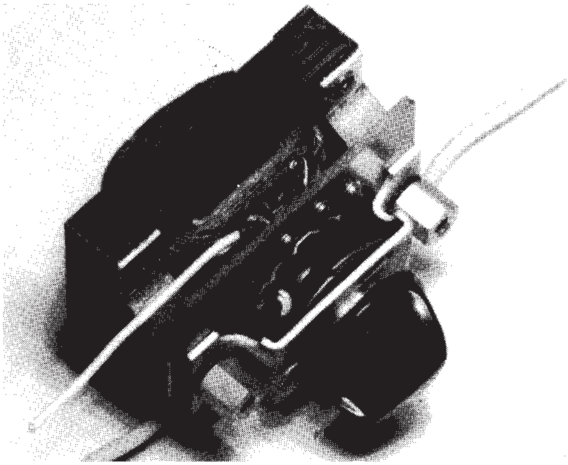


**Figure 27–6**
Fan speed control using a tapped inductor connected in series with the motor. (Source: Delmar/Cengage Learning)

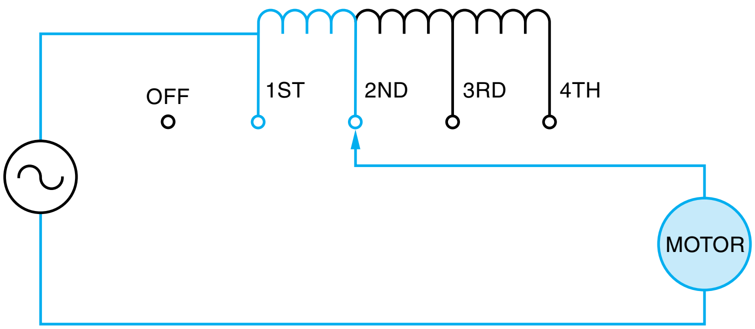



**Figure 27–5**
Series inductor changes impedance of circuit. (Source: Delmar/Cengage Learning)

## SUMMARY

- The two main types of single-phase AC motors used for variable-speed control are the permanent-split capacitor motor and the shaded-pole motor.
- Permanent-split capacitor motors and shaded-pole motors are generally used for variable-speed control because they do not have to disconnect the start windings when the motor reaches a certain speed.
- Variable-speed control for small motors is accomplished by controlling the amount of voltage applied to the motor or by inserting impedance in series with the motor.
- Two common methods used to control the voltage applied to the motor are autotransformer control and triac control.
- Only triac controllers designed for use as motor speed controllers should be used for motor speed control.
- Series impedance control is accomplished by connecting a tapped inductor in series with the motor.

## KEY TERMS

**autotransformer**
**rotor slip**
**variable resistor**
**variable-speed motors**

## REVIEW QUESTIONS

1. What two types of small AC motors are used with variable-voltage speed control?
2. Why are these two types of motors used?
3. Name two methods of variable-voltage control for small AC motors.
4. What solid-state device is used to control the voltage applied to the motor?
5. Why is it necessary to use only controllers designed for use with inductive loads?
6. Name a method other than variable voltage used to control the speed of small AC motors.

# UNIT 28

# The Defrost Timer

## OBJECTIVES

After studying this unit the student should be able to:

- Describe the construction of a defrost timer
- Discuss the operation of a continuous run and cumulative compressor run timer
- Connect a defrost timer for continuous run
- Connect a defrost timer for cumulative compressor run
- Discuss the operation of commercial defrost timers
- Perform an ohmmeter test on a defrost timer

Many of the refrigeration appliances used in the home are "frost-free." The frost-free appliance could more accurately be termed "automatic defrost." The brain of the frost-free appliance is the **defrost timer**. The job of this timer is to disconnect the compressor circuit and connect a **resistive heating element** located near the **evaporator** at regular time intervals. The defrost heater is thermostatically controlled and is used to melt any frost formation on the evaporator. The defrost heater is permitted to operate for some length of time before the timer disconnects it from the circuit and permits the compressor to operate again.

## TIMER CONSTRUCTION

The defrost timer is operated by a single-phase synchronous motor like those used to operate electric wall clocks, Figure 28–1. The contacts are operated

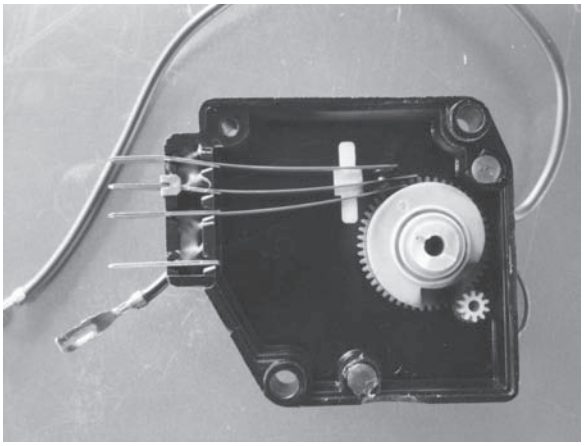


**Figure 28–1**
Defrost timer. (Source: Delmar/Cengage Learning)

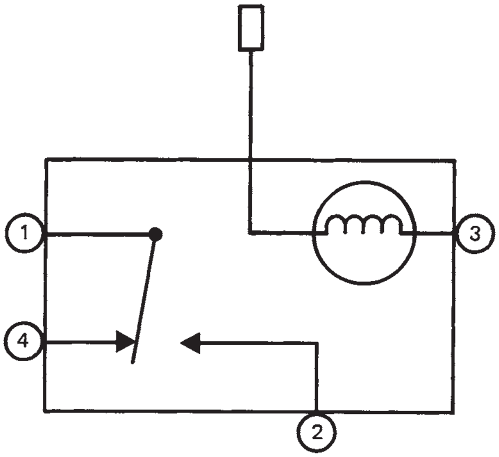



**Figure 28–2**
Schematic of a defrost timer. (Source: Delmar/Cengage Learning)

by a **cam** that is gear driven by the clock motor. A schematic drawing of the timer is shown in Figure 28–2. Notice that terminal 1 is connected to the common of a single-pole double-throw switch. Terminals 2 and 4 are connected to stationary contacts of the switch. In the normal operating mode, the switch makes connection between contacts 1 and 4. When the defrost cycle is activated, the contact will change position and make connection between terminals 1 and 2. Terminal 3 is connected to one lead of the motor. The other motor lead is brought outside the case. This permits the timer to be connected in one of two ways, which are:

1. The **continuous run timer**.
2. The **cumulative compressor run timer**.

It should be noted that the schematic drawing can be a little misleading. In the schematic shown, the timer contact can only make connection between terminals 1 and 4, or terminals 1 and 2. In actual practice, a common problem with this timer is that the movable contact becomes stuck between terminals 4 and 2. This causes the compressor and defrost heater to operate at the same time.

## THE CONTINUOUS RUN TIMER

The schematic for the continuous run timer is shown in Figure 28–3. Notice in this circuit that the pigtail lead of the motor has been connected to terminal 1, and that terminal 1 is connected directly to the power source. Terminal 3 is connected directly to the neutral. This places the timer motor directly across the power source, which permits the motor to operate on a continuous basis.

Figure 28–4 shows the operation of the timer in the compressor run cycle. Notice there is a current path through the timer motor and a path through the timer contact to the thermostat. This permits power to be applied to the compressor and evaporator motor when the thermostat closes.

Figure 28–5 shows the operation of the circuit when the timer changes the contact and activates the defrost cycle. Notice there is still a complete circuit through the timer motor. When the timer contact changes position, the circuit to the thermostat is open and the circuit to the defrost heater is closed. The heater can now melt any frost accumulation on the evaporator. At the end of the defrost cycle, the timer contact returns to its normal position and permits the compressor to be operated by the thermostat.

## THE CUMULATIVE COMPRESSOR RUN TIMER

The cumulative compressor run timer circuit gets its name from the fact that the timer motor is permitted to operate only when the compressor is in operation and the thermostat is closed. The schematic for this circuit is shown in Figure 28–6. Notice that the

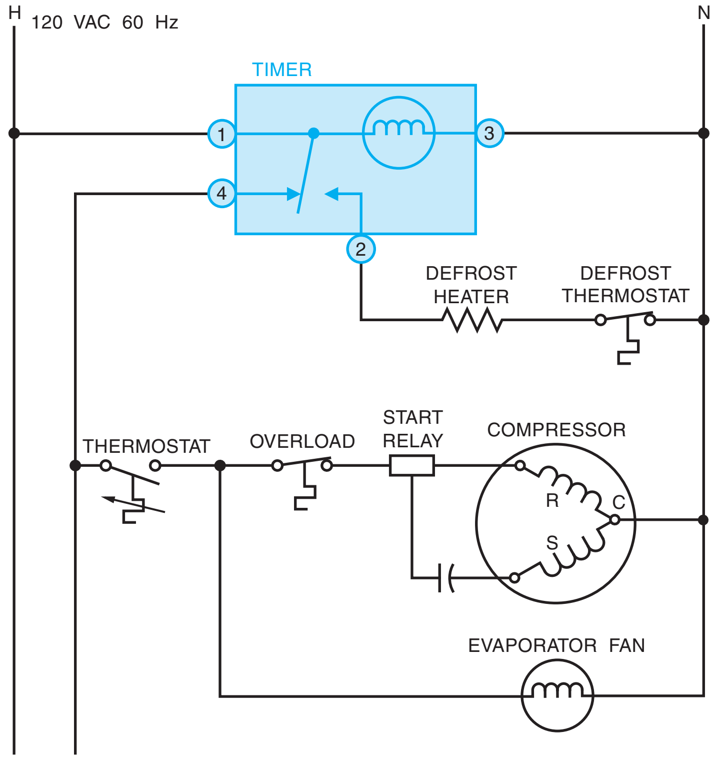



**Figure 28–3**
Schematic of a defrost timer used in a continuous run circuit.
(Source: Delmar/Cengage Learning)

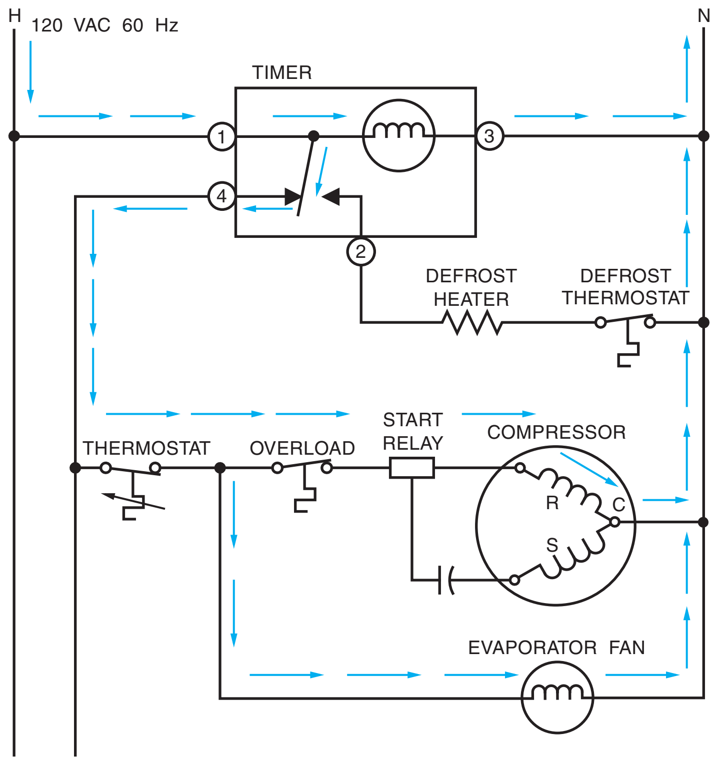



**Figure 28–4**
Current path during cooling operation.
(Source: Delmar/Cengage Learning)

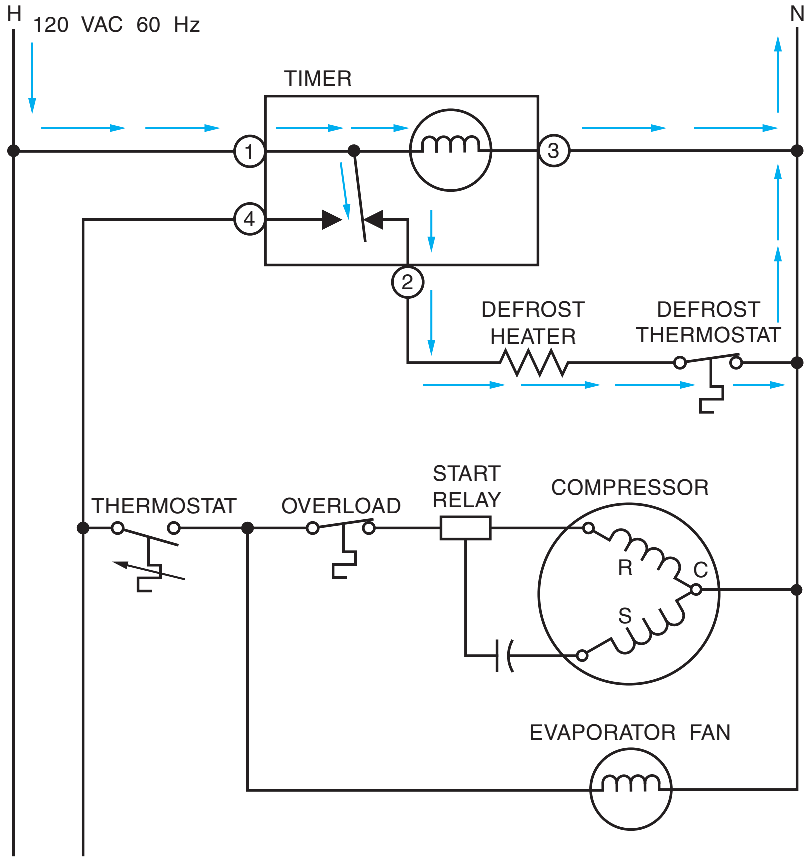



**Figure 28–5**
Current path during defrost operation. (Source: Delmar/Cengage Learning)

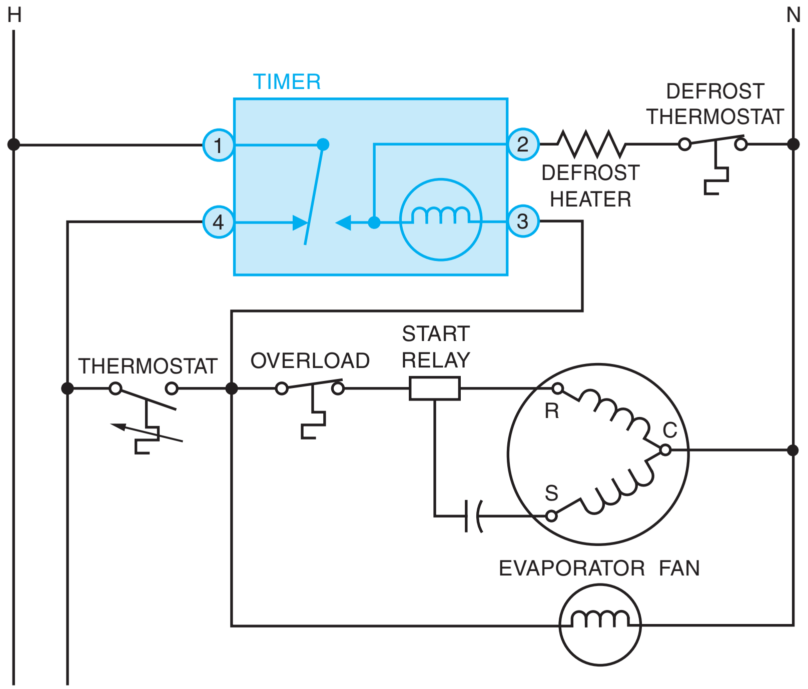



**Figure 28–6**
Defrost timer connected in a cumulative compressor run circuit.
(Source: Delmar/Cengage Learning)

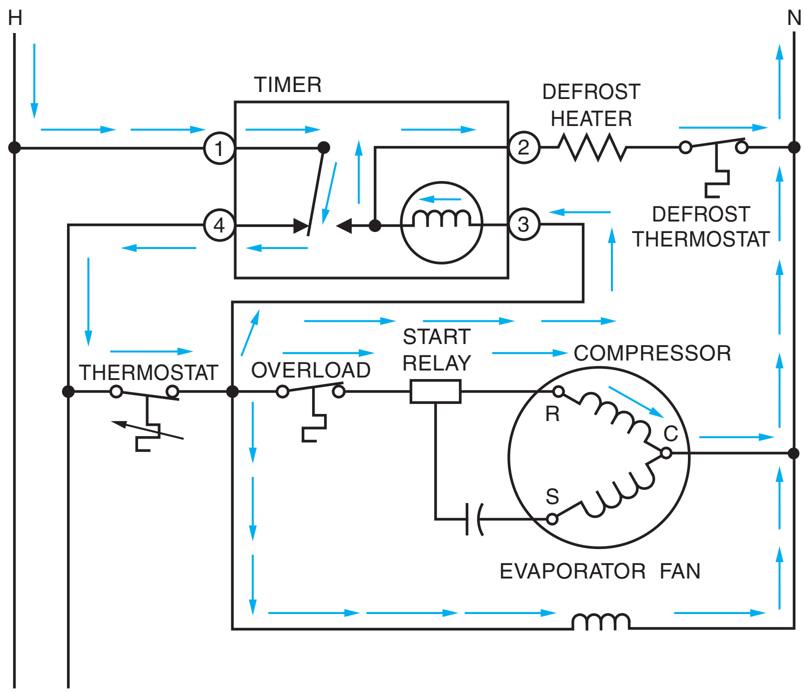



**Figure 28–7**
Current path during the cooling cycle.
(Source: Delmar/Cengage Learning)

pigtail lead of the clock motor has been connected to terminal 2 instead of terminal 1. Figure 28–7 shows the current path during compressor operation. The timer contact is making connection between terminals 1 and 4. This permits power to be applied to the thermostat. When the thermostat contact closes, current is permitted to flow through the compressor motor, the evaporator fan motor, and the defrost timer motor. In this circuit, the timer motor is connected in series with the defrost heater. The operation of the timer motor is not affected, however, because the impedance of the timer motor is much greater than the resistance of the heater. For this reason almost all the voltage of this circuit is dropped across the timer motor. The impedance of the timer motor also limits the current flow through the defrost heater to such an extent that it does not become warm.

Figure 28–8 shows the current path through the circuit when the defrost cycle has been activated. Notice in this circuit that the defrost heater is connected directly to the power line. This permits the heater to operate at full power and melt any frost accumulation on the evaporator. There is also a current path through the timer motor and run winding of the compressor motor. In this circuit, the timer motor is connected in series with the run winding of the compressor. As before, the impedance of the timer motor is much greater than the impedance of the run winding of the compressor. This permits almost all the voltage in this circuit to be applied across the timer motor. At the end of the defrost cycle, the timer contact returns to its normal position and the compressor is permitted to operate.

## TESTING THE TIMER

An ohmmeter can be used to check the continuity of the contacts and the motor winding. However, to really test the timer for operation takes time. The cam can be manually turned to the position so that the defrost cycle is turned on. This can be checked with a voltmeter to determine when full circuit voltage is applied to terminal 2. It is then necessary to

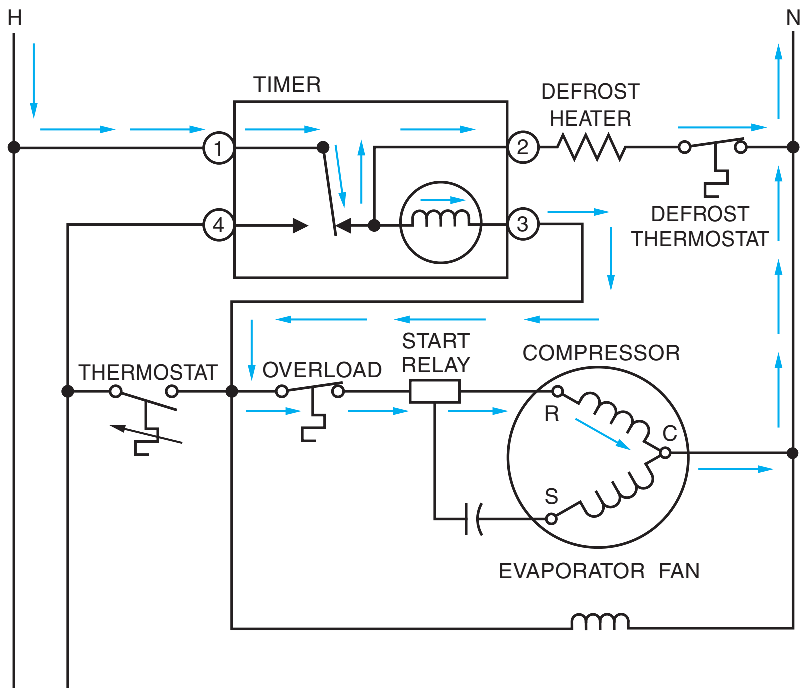



**Figure 28–8**
Current path during the defrost cycle.
(Source: Delmar/Cengage Learning)

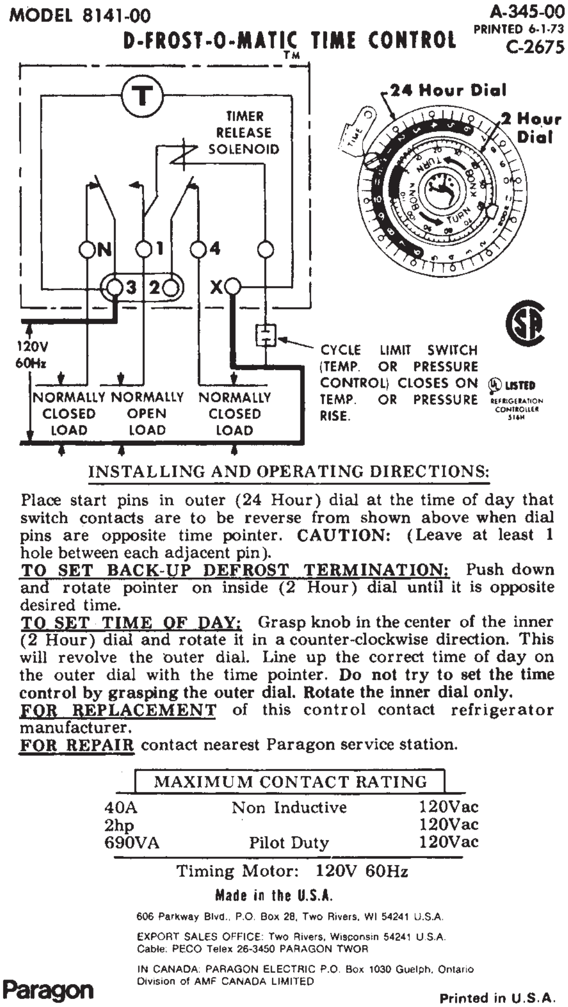
wait long enough for the timer to open the contact to the defrost heater and reconnect the compressor circuit. If the thermostat is closed, the compressor will start when the timer contact changes position. This test shows that the timer motor is operating and that the contact does change position.

## COMMERCIAL DEFROST TIMERS

Many large commercial refrigeration units often use a separate **timer clock** to control the defrost cycle. This has several advantages over the previously discussed defrost timer. When this method is used, the timer clock is connected directly across the power line as shown in Figure 28–9. This separates the operation of the timer from the operation of the compressor. In this way, the defrost cycle can be started during periods when the unit is in minimum use.

Timers of this type, Figure 28–10, generally have two timed settings. One determines the time of day or night the timer turns on. The second setting determines how long the timer is permitted to remain on. The timer shown in this example can be started on even numbered hours of the day or night. The center knob sets how long the contacts are energized before they return to their normal position. Once turned on, the contacts can be set to remain in their energized position for a minimum of two minutes to a maximum of 120 minutes.

This timer has a separate timer release solenoid incorporated into its design. When the timer release solenoid is energized, it causes the contacts to return to their normal reenergized position immediately. This permits the action of some type of external limit switch, such as a temperature or pressure switch, to terminate the defrost cycle.




INSTALLING AND OPERATING DIRECTIONS:

Place start pins in outer (24 Hour) dial at the time of day that switch contacts are to be reverse from shown above when dial pins are opposite time pointer. **CAUTION:** (Leave at least 1 hole between each adjacent pin).

**TO SET BACK-UP DEFROST TERMINATION:** Push down and rotate pointer on inside (2 Hour) dial until it is opposite desired time.

**TO SET TIME OF DAY:** Grasp knob in the center of the inner (2 Hour) dial and rotate it in a counter-clockwise direction. This will revolve the outer dial. Line up the correct time of day on the outer dial with the time pointer. **Do not try to set the time control by grasping the outer dial. Rotate the inner dial only.**

**FOR REPLACEMENT** of this control contact refrigerator manufacturer.

**FOR REPAIR** contact nearest Paragon service station.

| MAXIMUM CONTACT RATING | | |
|---|---|---|
| 40A | Non Inductive | 120Vac |
| 2hp | | 120Vac |
| 690VA | Pilot Duty | 120Vac |

Timing Motor: 120V 60Hz

**Made in the U.S.A.**

606 Parkway Blvd., P.O. Box 28, Two Rivers, WI 54241 U.S.A.

EXPORT SALES OFFICE: Two Rivers, Wisconsin 54241 U.S.A.
Cable: PECO Telex 26-3450 PARAGON TWOR

IN CANADA: PARAGON ELECTRIC P.O. Box 1030 Guelph, Ontario
Division of AMF CANADA LIMITED

Paragon

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**Figure 28–9**
Schematic diagram of a commercial defrost timer.
(Courtesy of Paragon Electric Company, Inc.).

**Figure 28–10**
Commercial defrost timer. (Courtesy of Paragon Electric Company, Inc.).

## SUMMARY

- Frost-free appliances use a defrost timer to control the operation of the defrost cycle.
- The function of the defrost timer is to disconnect the compressor from the circuit and connect a resistive heater located near the evaporator at regular intervals.
- The defrost timer is a cam-operated timer powered by a small single-phase synchronous motor similar to an electric clock motor.
- Two basic connections for a defrost timer are:

  A. The continuous run timer.

  B. The cumulative compressor run timer.
- The motor of the continuous run timer is connected directly to the power line and runs at all times.
- The motor of the cumulative compressor run timer is connected in such a manner that it runs only during the time the compressor motor is in operation.
- Commercial defrost timers often use a separate time clock to control the defrost cycle.

## KEY TERMS

**cam**
**continuous run timer**
**cumulative compressor run timer**
**defrost timer**
**evaporator**
**resistive heating element**
**timer clock**

## QUESTIONS

1. What type of motor is used to operate the timer?
2. Why is one of the motor leads brought outside the timer?
3. Name two ways of connecting the defrost timer.
4. What function does the defrost heater perform?
5. To which terminal is the pigtail lead of the timer motor connected if the timer is to operate continuously?

# UNIT 29

# The Thermostat

## OBJECTIVES

After studying this unit the student should be able to:

- Define a thermostat
- Describe the operation of bimetal thermostats
- Discuss the operation of a contact-type and mercury-contact thermostat
- Discuss the operation of heating and cooling thermostats
- Describe the operation of the fan switch
- Discuss the operation of the heat anticipator and cooling anticipator
- Discuss the operation of line voltage, programmable, staging, and differential thermostats
- Connect a thermostat in a circuit

**Thermostats** are temperature-sensitive switches. They use a variety of methods to sense temperature, and can be found with different **contact** arrangements. Some thermostats are designed to be used with low-voltage systems, generally 24 volts; and others are designed to be connected directly to line voltage and operate motors and heating units. The advantage of low-voltage thermostats is that they are more economical and safer to use inside the home.

## BIMETAL THERMOSTATS

One of the most common methods of sensing temperature is with a bimetal strip. When used as the temperature sensing element of a thermostat, the bimetal strip is generally bent in a spiral that resembles a clock spring. If a contact is attached to the end of the strip and another contact is held stationary, a thermostat is formed, Figure 29–1. A small permanent magnet is used to provide a snap action for the contacts.

This type of thermostat is inexpensive and has the advantage of not having to be mounted in a level position. The greatest enemy of an open-contact thermostat is dirt. This is especially true for thermostats designed for low-voltage operation. If poor thermostat contact is suspected, the contacts should be cleaned. This can be done with a strip of hard paper, such as typing paper, and alcohol. Soak a strip of hard paper in alcohol and place the strip between the contacts. Close the contacts and draw the strip through the closed contacts. This will generally remove any accumulation of dirt and oil. After cleaning, the contacts should be buffed to remove any alcohol residue. This can be done by drawing a piece of dry hard paper through the contacts several times. This type of thermostat is shown in Figure 29–2.

To avoid the problem of dirty contacts, the contacts of some thermostats are enclosed inside a glass tube, Figure 29–3. Because the contacts are enclosed in glass, they are stationary. The bimetal strip is attached to a permanent magnet instead of a contact. In the case of a double acting thermostat, there are two magnets attached to the bimetal strip. When the magnet is close enough to the glass tube, it is attracted to the metal contacts and causes the contacts to close with a snap action.

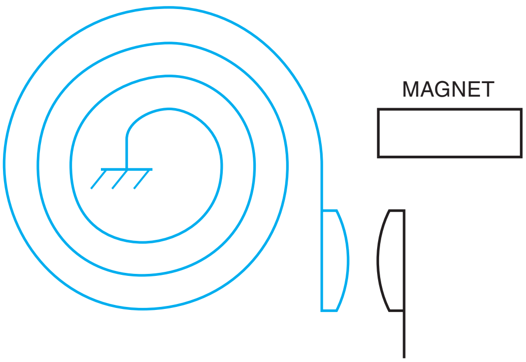


**Figure 29–1**
Contacts operated by a bimetal strip. (Source: Delmar/Cengage Learning)

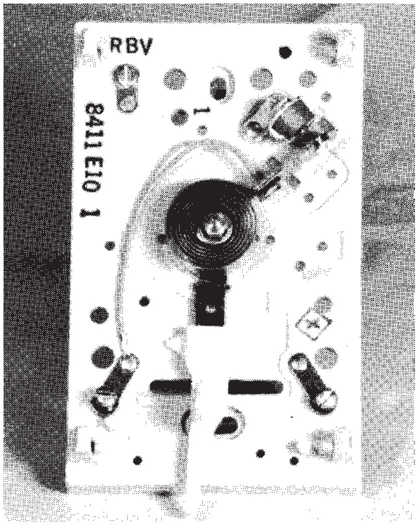


**Figure 29–2**
Open-contact thermostat. (Source: Delmar/Cengage Learning)

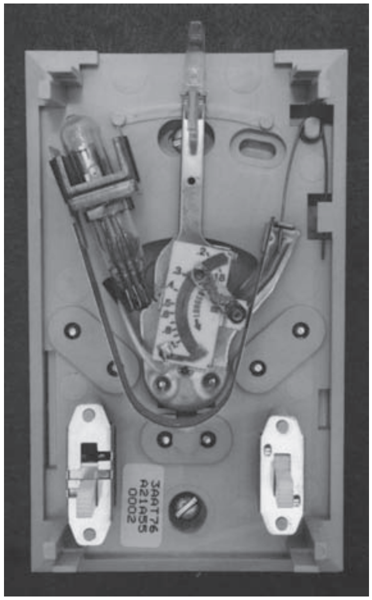


**Figure 29–3**
Contacts are enclosed inside a glass tube. (Source: Delmar/Cengage Learning)

## MERCURY CONTACT THERMOSTAT

Another type of contact used with the bimetal type of thermostat is the mercury contact. In this type of thermostat, a small pool of mercury is sealed inside

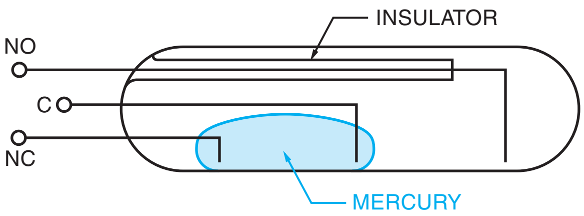


Figure 29–4
Mercury contacts. (Source: Delmar/Cengage Learning)

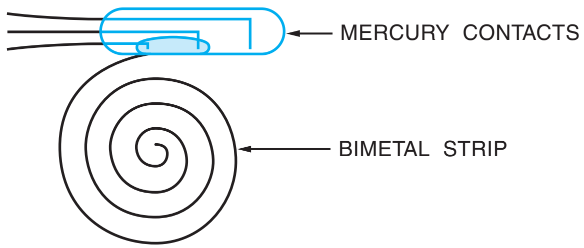


Figure 29–5
Mercury-type thermostat. (Source: Delmar/Cengage Learning)

Figure 29–6
Mercury thermostat. (Source: Delmar/Cengage Learning)

a glass container. A set of contacts is also sealed in the glass. Most mercury-type contacts are made to be single-pole double-throw, which means there are a common terminal, a normally open terminal, and a normally closed terminal. Figure 29–4 illustrates this type of contact. Notice in this example that the pool of mercury makes connection with the common terminal, located in the center, and the normally closed terminal. If the glass bulb is tilted in the other direction, the mercury will flow to the opposite end and make connection between the common terminal and the normally open contact.

The mercury contact has the advantage of being sealed in glass and not subjected to dirt and oil. When this type of contact is used with a bimetal strip, it is generally mounted as shown in Figure 29–5. This type of thermostat uses the weight of the mercury to provide a snap action for the contact instead of a magnet. When the bimetal strip has turned far enough to permit the mercury to flow from one end of the glass bulb to the other, the weight of the mercury prevents any spring action of the bimetal strip from snapping the contact open. A mercury thermostat, however, must be mounted in a level position if it is to operate properly. This can sometimes be a problem in homes that do not remain level. A mercury type thermostat is shown in Figure 29–6.

Mercury type thermostats are particularly sensitive to the way they are mounted. If they are to operate correctly, they must be mounted level. The manufacturer's instructions will generally show how the thermostat should be checked with a leveling device.

## HEATING AND COOLING THERMOSTATS

Many thermostats are designed to be used for both heating and cooling applications. This can be done with thermostats that contain both a normally open and normally closed contact. A simple schematic diagram of this type of thermostat is shown in Figure 29–7. Notice the thermostat contact is a single-pole double-throw type. The selector switch is a double-pole type. The dashed line indicates mechanical intertie. With the selector switch in the position shown, the thermostat is being used for heating. If the selector switch is changed, the

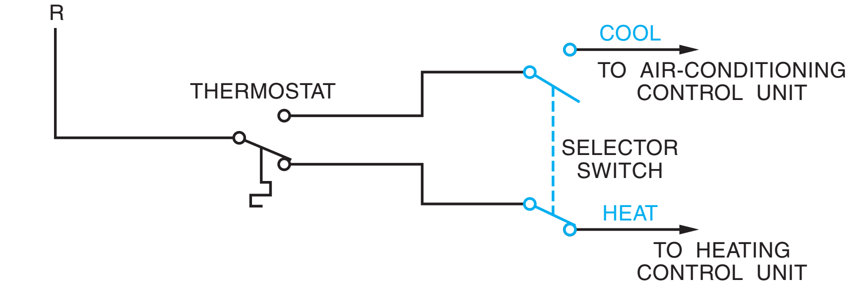


**Figure 29–7**
Dual operation of a thermostat.
(Source: Delmar/Cengage Learning)

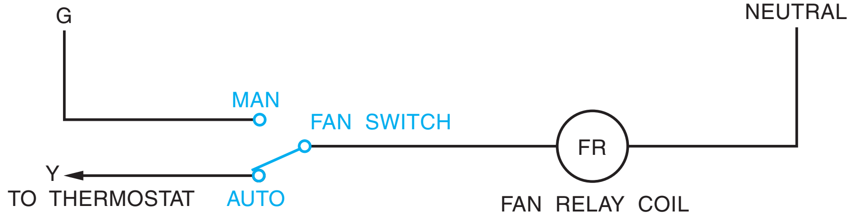


**Figure 29–8**
Fan switch. (Source: Delmar/Cengage Learning)

bottom movable contact will break connection with its stationary contact, and the top movable contact will make connection with its stationary contact. Notice that changing this switch will also change the sense of the thermostat. In the heating position, the thermostat activates the heating unit when the contact closes because of a decrease in temperature. In the cooling position, the thermostat activates the air conditioning unit when the contact makes connection because of an increase in temperature.

## THE FAN SWITCH

Many thermostats are designed to permit manual control of the blower fan. This is done to permit the blower fan to be operated separately. Some people find it desirable to operate the blower fan continuously to provide circulation of air throughout the building. This is especially true for buildings equipped with electronic air cleaners (precipitators) or for buildings that must remove undesirable elements such as smoke in an office building or night club. A schematic diagram of this type of circuit is shown in Figure 29–8. The **fan switch** is a single-pole double-throw switch. When the switch is in one position, it permits the fan relay to be controlled by the thermostat. If the switch is thrown in the opposite direction, the fan relay is connected directly to the control voltage.

## THE HEAT ANTICIPATOR

The **heat anticipator** is a small resistance heater located near the bimetal strip. The function of this heater is to slightly preheat the bimetal strip and prevent overrun of the heating system. For example, many heating systems, such as fuel oil or gas, operate by heating a metal container called a heat exchanger. When the temperature of the heat exchanger reaches a high enough level, a thermostatically controlled switch causes the blower to turn on and blow air across the heat exchanger. The moving air causes heat to be removed from the heat exchanger to the living area. When the thermostat is satisfied, the heating unit is turned off. The blower will continue to operate, however, until the excess heat has been removed from the heat exchanger.

Now assume that the thermostat has been set for a temperature of 75 degrees. If the heating unit is permitted to operate until the temperature reaches 75 degrees, the final temperature of the living area may be from 3 to 5 degrees higher than the thermostat setting by the time enough heat has been removed from the heat exchanger to cause the blower to turn off.

If the heat anticipator has been properly set, however, it will cause the thermostat to turn off several degrees before the room temperature has reached the thermostat setting. This permits the excess heat of the heat exchanger to raise the temperature to the desired level without overrunning the thermostat setting.

The setting of the heat anticipator is controlled by a sliding contact. There are markings such as .2, .25, .3, .35, and .4. The sliding contact is generally set at the number that corresponds to the current rating of the control system. The current rating can generally be located in the service information or on the control unit itself. The heat anticipator does not have to be set at that position, however. The service technician should set it to operate the unit for longer or shorter periods depending on the desires of the customer.

## THE COOLING ANTICIPATOR

A device that operates in a similar manner to the heat anticipator is the **cooling anticipator**. The cooling anticipator is a resistive heating element that operates in an opposite sense to the heat anticipator. The cooling anticipator operates while the thermostat contacts are open and the air conditioning unit is not running. The cooling anticipator heats the thermostat slightly and causes it to close its contacts before the ambient temperature increases enough to close them.

The circuit shown in Figure 29–9 displays the current path of the heat anticipator for a heating and cooling thermostat during the heating cycle. In this mode of operation, current flows through the heat anticipator while the thermostat contact is closed and the heating unit is in operation.

In Figure 29–10, the thermostat has been switched to the cooling mode. Notice that a current path exists through the cooling anticipator when

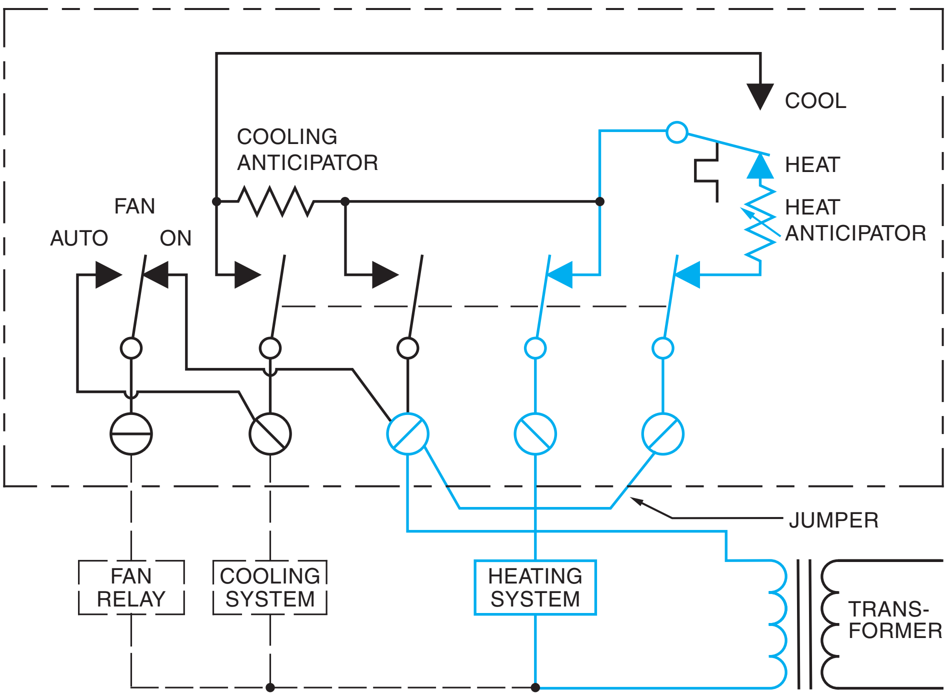


**Figure 29–9** Current path for heat anticipator. (Source: Delmar/Cengage Learning)

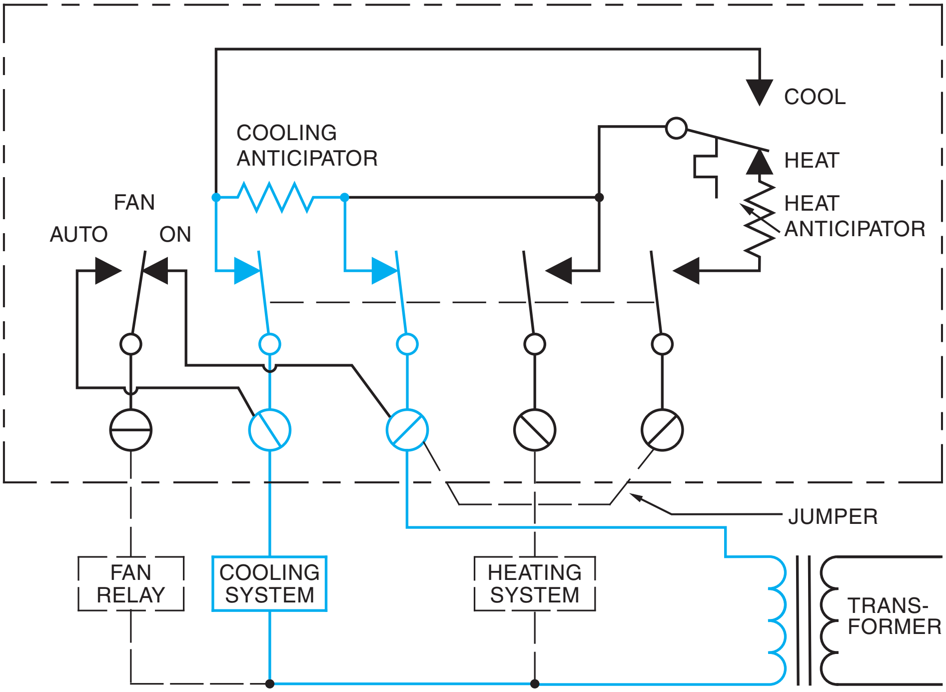


**Figure 29–10**
Current path for cooling anticipator. (Source: Delmar/Cengage Learning)

the thermostat contact is open and the air conditioning unit is not in operation. When the thermostat contact closes, a low resistance path exists around the cooling anticipator. This stops the flow of current through it while the air conditioning unit is in operation.

## LINE VOLTAGE THERMOSTATS

**Line voltage thermostats** are generally used to control loads such as blower fans and heating elements. This means that the thermostat must contain contacts that are capable of handling the current needed to operate these loads without an intervening relay. This type of thermostat is shown in Figure 29–11. Many of these thermostats use the pressure of refrigerant in a sealed system to sense temperature, Figure 29–12. When the temperature increases, the pressure in the system increases also. The increase in pressure causes the bellows to expand. When the bellows expands far enough, it activates a set of spring-loaded contacts.

Although line voltage thermostats can be used for many applications, they do not contain a heat anticipator and are not as accurate as low voltage thermostats.

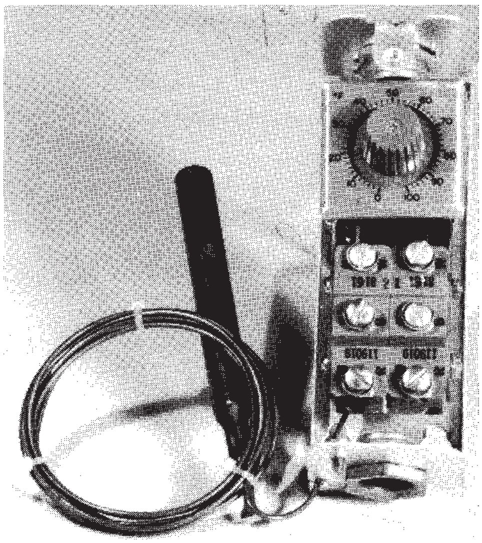

**Figure 29–11**
Line voltage thermostat. (Source: Delmar/Cengage Learning)

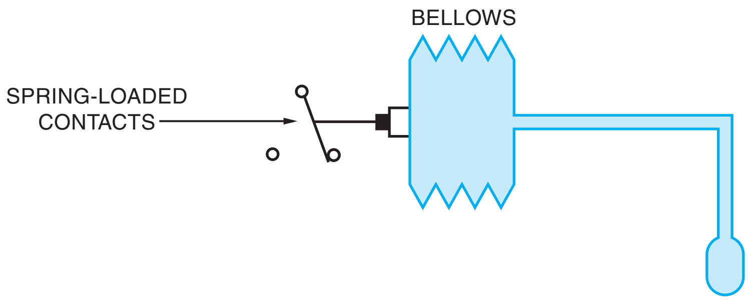


Figure 29–12
Thermostat contacts are operated by pressure. (Source: Delmar/Cengage Learning)

## PROGRAMMABLE THERMOSTATS

The term *programmable* is a catch word that has taken on many meanings. In the case of thermostats, the term *programmable* generally means that a thermostat can be set to operate at different temperature settings at different times. **Programmable thermostats** range in complexity from units that use a simple time clock to units that are operated by integrated circuits (ICS) and permit the temperature to be set to any desired level at any desired time. A programmable thermostat is shown in Figure 29–13. This thermostat uses a quartz-operated time clock and two separate thermostat units. The time clock is used to operate a switch. The setting of the clock determines the position of the switch at any particular time. A schematic for this type of circuit is shown in Figure 29–14. Notice that

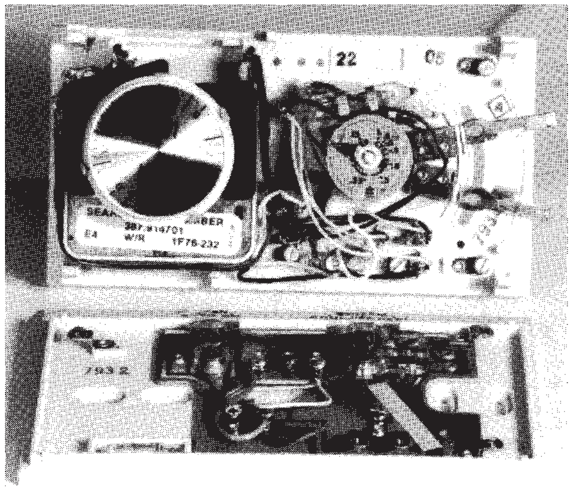

Figure 29–13
Programmable thermostat. (Source: Delmar/Cengage Learning)

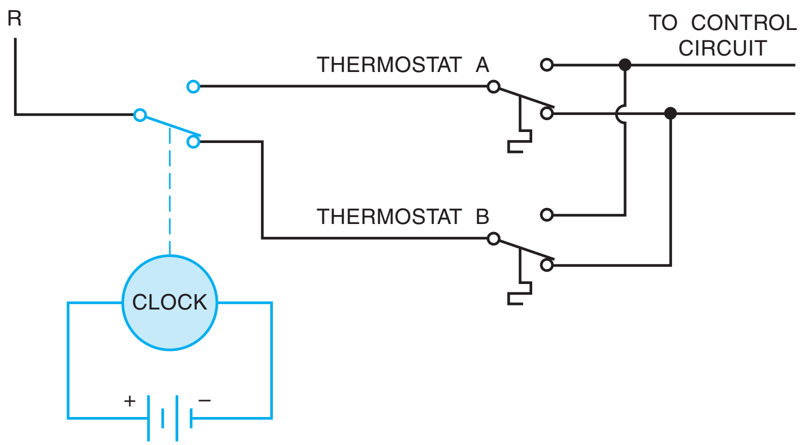


Figure 29–14
Schematic for a programmable thermostat. (Source: Delmar/Cengage Learning)

the position of the clock-operated switch determines which thermostat is used to control the system. To understand the operation of this system, assume that thermostat A has been set for a temperature of 95 degrees, and thermostat B is set for 75 degrees. The time clock has been set to permit thermostat A to control the air conditioning system when there is no one in the residence. One hour before people are to return home, the time clock changes the contact and thermostat B is used to control the system. Because thermostat B has been set for 75 degrees, the residence will have been cooled to that temperature when the people arrive.

The programmable thermostat can reduce energy consumption by maintaining a desired temperature only during the hours the dwelling is occupied. The temperature can be maintained at an uncomfortable level the rest of the time, which permits the air conditioning unit to operate much less.

## Electronic Programmable Thermostats

Many programmable thermostats are solid state and do not contain mechanical contacts. These units generally employ electronic devices such as thermistors to sense temperature. They can be programmed for several different conditions or events. Many permit the thermostat to be programmed differently for each day. The temperature can be set differently for different times of the day. Most electronic thermostats provide a variety of functions and options that are set by the homeowner. An electronic thermostat is shown in Figure 29–15.

## STAGING THERMOSTATS

**Staging thermostats** are similar to programmable thermostats in that they contain two separate sets of contacts. Unlike the programmable thermostat, however, the staging thermostat contains only one bimetal strip, which is used to control the action of both sets of contacts. One set of contacts is designed to operate slightly behind the other set. A good example of how a staging thermostat is used can be found in a heat-pump system. Assume that the first contact is used to operate the compressor relay, and the second contact is used to operate the contactor, which controls the electric resistance heating strips. When the temperature decreases, the first thermostat contact closes and connects the compressor to the line. If the compressor is able to provide enough heat to the dwelling, the second contact will never make connection. If, however,

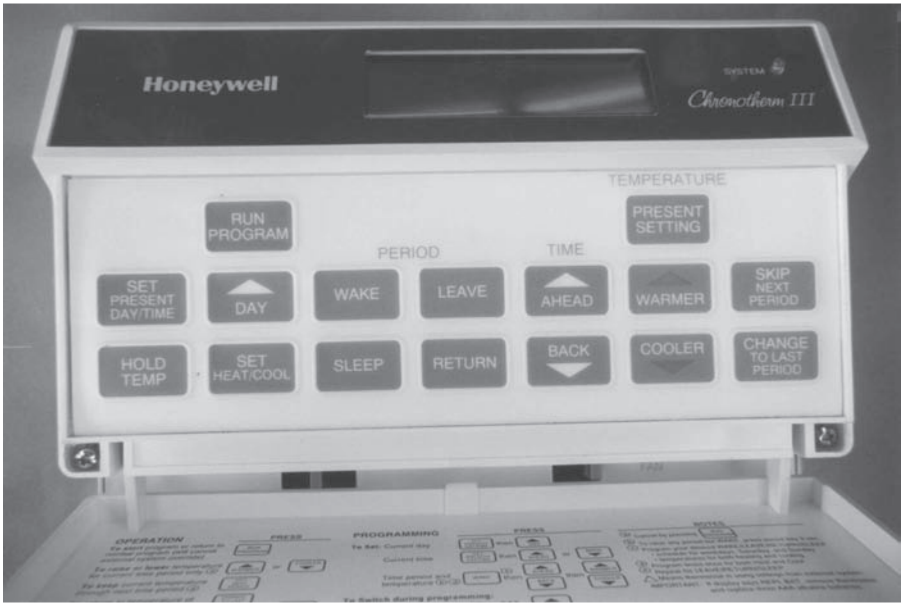


**Figure 29–15**
Electronic thermostat.
(Source: Delmar/Cengage Learning)