CONSTRUCTION ELECTRICIAN APPRENTICESHIP PROGRAM

Level 3 — Line H: Install Electrical Equipment



LEARNING GUIDE H-5

INSTALL AC MOTORS AND ALTERNATORS

ita
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THE RIGHT SKILLS ▶ A PROVEN ADVANTAGE

BRITISH COLUMBIA

Foreword

The Industry Training Authority (ITA) is pleased to release this major update of learning resources to support the delivery of the BC Electrician Apprenticeship Program. It was made possible by the dedicated efforts of the Electrical Articulation Committee of BC (EAC).

The EAC is a working group of electrical instructors from institutions across the province and is one of the key stakeholder groups that supports and strengthens industry training in BC. It was the driving force behind the update of the Electrician Apprenticeship Program Learning Guides, supplying the specialized expertise required to incorporate technological, procedural and industry-driven changes. The EAC plays an important role in the province's post-secondary public institutions. As discipline specialists the committee's members share information and engage in discussions of curriculum matters, particularly those affecting student mobility.

ITA would also like to acknowledge the Construction Industry Training Organization (CITO) which provides direction for improving industry training in the construction sector. CITO is responsible for organizing industry and instructor representatives within BC to consult and provide changes related to the BC Construction Electrician Training Program.

We are grateful to EAC for their contributions to the ongoing development of BC Construction Electrician Training Program Learning Guides (materials whose ownership and copyright are maintained by the Province of British Columbia through ITA).

Industry Training Authority
January 2011

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LEVEL 3, LEARNING GUIDE H-5:

INSTALL AC MOTORS AND ALTERNATORS

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Learning Objectives

- The learner will be able to describe the operating principles of AC machines.
- The learner will be able to connect and maintain AC machines.

Activities

- Read and study the topics of Learning Guide H-5: Install AC Motors and Alternators.
- Complete Self-Tests 1 through 20. Check your answers with the Answer Key provided at the end of this Learning Guide.

Resources

All resources are provided in this Learning Guide.

BC Trades Modules
www.bctradesmodules.ca

We want your feedback! Please go the BC Trades Modules website to enter comments about specific section(s) that require correction or modification. All submissions will be reviewed and considered for inclusion in the next revision.

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Be advised that references to the Workers' Compensation Board of British Columbia safety regulations contained within these materials do not/may not reflect the most recent Occupational Health and Safety Regulation. The current Standards and Regulation in BC can be obtained at the following website: http://www.worksafebc.com.

Please note that it is always the responsibility of any person using these materials to inform him/herself about the Occupational Health and Safety Regulation pertaining to his/her area of work.

Industry Training Authority
January 2011

Learning Task 1:

Describe the constructional features of three-phase induction motors

The main components of the three-phase, squirrel-cage induction motor are the stator and the rotor. At each end of the stator is the housing for bearings that support and align the rotor shaft. This Learning Task describes all these parts.

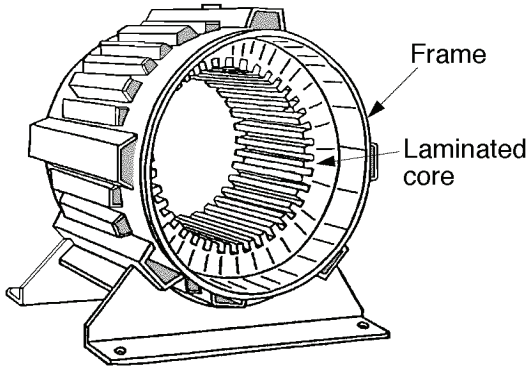


Figure 1—Stator shown without the stator windings installed

The stator

The stationary part of the motor is called the *stator* (Figure 1). It consists of a hollow, cylindrical, laminated steel core that is placed in a cast iron or steel frame. The laminations reduce the eddy-current losses. The core, which has slots for the pole windings, has two purposes:

- It supports the stator coil windings.
- It provides a low-reluctance path for the magnetic circuit.

The three-phase stator winding is made up of three single-phase windings placed 120 electrical degrees apart. They are connected either in delta or in wye.

The squirrel-cage rotor

The *rotor* is that portion of the motor that rotates (Figure 2). It consists of a cylindrical, laminated steel core. This core has evenly spaced holes from one end to the other. They are punched near the outer surface to receive the bars of the rotor winding. The motor shaft is pressed into another hole punched right through the centre of the laminations.

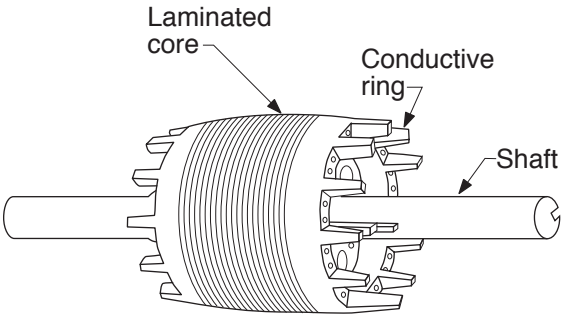


Figure 2—Typical squirrel-cage rotor from a smaller motor

The actual rotor winding is called a *squirrel cage* (Figure 3) because of its resemblance to the exercise machine a pet squirrel or hamster uses. It consists of copper or aluminum bars embedded into the core near the surface of the rotor.

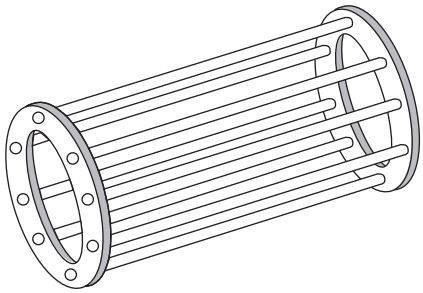


Figure 3—Squirrel-cage rotor shown without the core

The bars are connected to each other at both ends by a conductive ring made of the same material as that used for the bars. The bars are normally skewed slightly so that they are not parallel with the slots cut in the stator core. This produces a smoother and quieter motor operation.

In larger machines the rotor bars are driven into holes punched through the rotor core laminations. The end rings are then welded or brazed to the bars.

In some smaller machines the punched, laminated core is placed into a mould, and aluminum is injected into the mould to form the bars and end rings as one piece (Figure 4). The mould is so constructed that the end rings are cast complete with fan blades, which are used to help circulate the air inside the motor to cool the windings and cores.

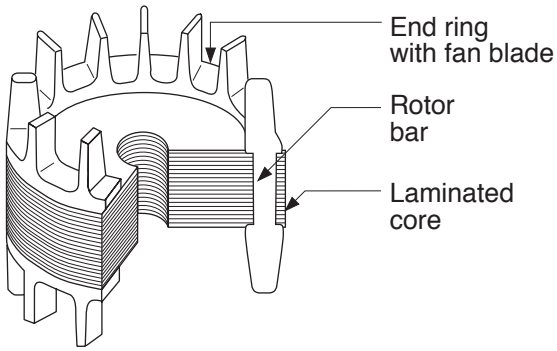


Figure 4—Cut-away section of a cast squirrel-cage rotor

End bells and bearings

A small air gap is provided between the stator and the rotor to allow the rotor to rotate freely within the stator. End bells are bolted to either end of the stator frame. Their main purpose is to house the bearings that support the rotor shaft and keep it aligned with the stator so that it can turn freely within the stator. These end bells may also provide different levels of enclosure and protection for the inner parts of the motor.

Types of enclosures

Motors are operated in many different physical environments. They may be subjected to such things as moisture, dust, corrosive chemicals and flammable gases, so each must be designed and constructed to operate safely and without damage in the environment to which it will be exposed. The National Electrical Manufacturers Association (NEMA) sets the standards for classifying motors. Two ways it classifies them are by the method used to protect them from the environment and by the method used to cool them. These classifications make it possible to select a motor with an enclosure to match the environment in which it will operate.

Open machine

An open machine has ventilation openings to permit external cooling air to pass over and around its windings. The term *open machine*, when applied to a large apparatus without qualification, is a machine with no restricted ventilation other than that required by the mechanical construction. Within this classification are the following subclassifications:

- Drip-proof machine
- Splash-proof machine
- Semi-guarded machine
- Guarded machine
- Drip-proof, guarded machine
- Open, externally ventilated machine
- Open, pipe-ventilated machine
- Weather-protected machine: Type I and Type II

Totally enclosed machine

A totally enclosed machine prevents the free exchange of air between the inside and the outside of the case, but it is not sufficiently enclosed to be airtight. Within this classification are the following subclassifications:

- Totally enclosed, non-ventilated machine
- Totally enclosed, fan-cooled machine
- Explosion-proof machine

- Dust-proof, ignition-proof machine
- Waterproof machine
- Totally enclosed, pipe-ventilated machine
- Totally enclosed, water-cooled machine
- Totally enclosed, water-cooled and air-cooled machine
- Totally enclosed, air-to-air-cooled machine
- Totally enclosed, fan-cooled, guarded machine
- Totally enclosed, air-over machine

Machines with encapsulated or sealed windings

Two types of machines are made for environmental conditions that are more severe than the usual insulation system can withstand. They are machines with:

- Encapsulated windings
- Sealed windings

The nameplate information is used to select the proper supply and control equipment for the motor. It may also be used to order suitable replacement parts or a whole replacement motor. Figure 5 shows a typical motor nameplate.

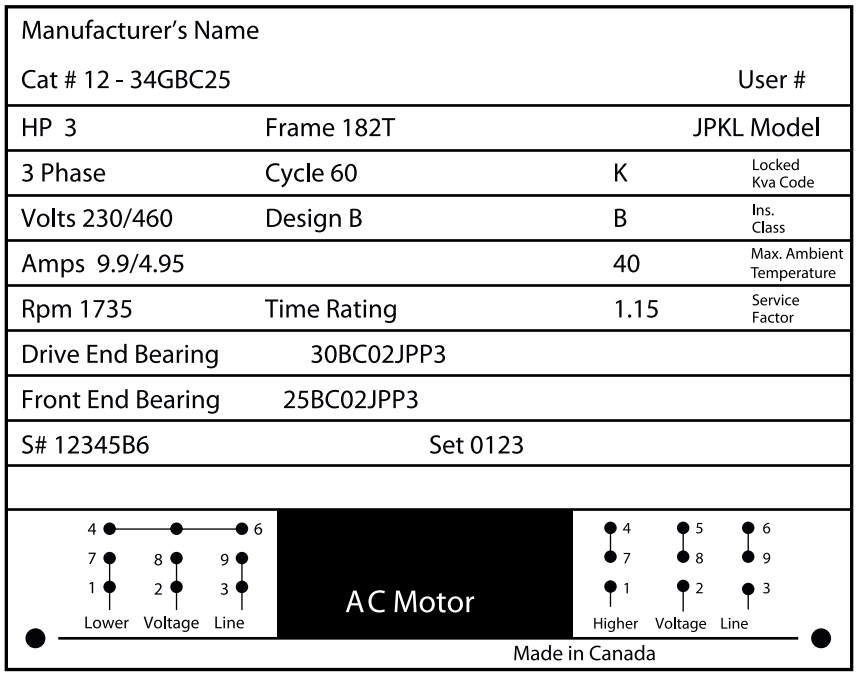


Figure 5—Typical motor nameplate

The motor nameplate typically contains the following information:

- The manufacturer's name, the type and the frame designation
- The horsepower output
- A time rating (continuous or short-time duty)
- The maximum ambient temperature for which the motor is designed
- A designation of the insulation system
- The revolutions per minute at full-rated load
- The frequency of the supply
- The number of phases
- The voltage
- The full-load amperes
- The code letter for locked-rotor kVA
- For motors equipped with thermal protection, the words "thermally protected"
- The design letter
- The designation of terminals
- Evidence of approval

Manufacturer's name and type

The nameplate would include such information as AC induction motor, DC shunt motor and AC synchronous motor. This data may be encoded in the model or identification number on the nameplate.

Frame designation

The code designating the frame can be used to look up the physical dimensions of the motor in the NEMA standards—for example, the distance from the bottom of the feet to the centre line of the shaft, or the distance between the mounting holes.

Horsepower

Horsepower (HP) is the rated output horsepower of the motor at full load, and this rating is used for several purposes:

- It is used to match the size of the motor to the load.
- CEC requires it for selecting the proper size starter and disconnect size for the motor.
- It can be used to determine the full-load current of the motor if that information is not given.

Service factor

When the service factor (SF) is multiplied by the rated horsepower, the product is the maximum horsepower the motor can supply continuously at the rated voltage and frequency without damaging the motor.

Time rating

The time rating is either continuous or "short time." *Continuous* means that the motor can go on supplying its full-load horsepower rating without interruption or change. *Short-time* ratings are established at 5, 15, 30 or 60 minutes. Motors with these ratings cannot supply the rated horsepower continuously. They start from a temperature within 5°C of the ambient temperature and may supply the rated horsepower for the time designated in the rating.

Maximum ambient temperature

Ambient temperature is the temperature of the surrounding cooling medium that comes in contact with the heated parts of the motor. Normally the ambient temperature is that of the surrounding air.

Insulation system designation

Insulation systems are classified according to their thermal endurance. There are four common classes for motors (and generators) and, in accordance with the Canadian Electrical Code (CEC), the insulation class must be known to select the appropriate supply conductors to feed the motor.

Class A or Class 105

This rating is designed for use where a rise in continuous, full-load temperature will not exceed 55°C over a 40°C ambient temperature, and the hot-spot temperature will be no more than 10°C over the normal rise. (This means a maximum conductor hot spot temperature of 105°C.)

Class B or Class 130

This rating is designed for use where a rise in continuous, full-load temperature will not exceed 80°C over a 40°C ambient temperature, and where the hot-spot temperature will be no more than 10°C over the normal rise. (This means a maximum conductor hot spot temperature of 130°C.)

Class F or Class 155

This rating is designed for use where a rise in continuous full-load temperature will not exceed 105°C over a 40°C ambient temperature, and where the hot-spot temperature will be no more than 10°C over the normal rise. (This means a maximum conductor hot-spot temperature of 155°C.)

Class H or Class 180

This rating is designed for use where a rise in continuous full-load temperature will not exceed 125°C over a 40°C ambient temperature, and where the hot-spot temperature will be no more than 15°C over the normal rise. (This means a maximum conductor hot-spot temperature of 180°C.)

Revolutions per minute

The revolutions per minute (rpm) is the speed of the motor at the rated horsepower. It is related directly to the frequency of the supply and inversely to the number of poles in the motor.

Frequency
Information on the nameplate gives the frequency (Hz) of the supply to which the motor is to be connected. If the motor is to operate successfully under running conditions at full load and with the rated voltage applied, the frequency of the supply should not vary more than 5% from the value given.

Number of phases
The number of phases the motor is designed to operate on must match the number of phases in the supply system.

Volts
This information is the required operating voltage of the motor. If the motor is to operate successfully under running conditions at full load and with the rated frequency, the supply voltage should not vary more than 10% from the value given. *Remember that the power is proportional to the square of the voltage.*

Full-load current
Full-load current (amp) is the current the motor draws when it operates at the rated voltage and supplies the rated horsepower. CEC requires the full-load current to determine the proper size and rating for supply equipment.

Code letter for locked-rotor kVA
This letter may be looked up in a table to determine the ratio of the locked-rotor kVA to the horsepower rating of the motor.

Design letter
The design letter designates the relationship between the torque and the speed of the motor. There are four design-letter ratings: A, B, C and D. There is more information on this subject later in this Learning Guide.

Designation of terminals
This designation is often given as connection diagrams, which show the interconnection of the motor terminals and the connection of the terminals to the supply.

Evidence of approval
All electrical equipment installed in accordance with the CEC must display the approval of a certified agency such as the Canadian Standards Association (CSA).

Energy-efficiency standards
In 1993, British Columbia, Ontario, Quebec, Nova Scotia and New Brunswick introduced legislation establishing efficiency standards for certain electrical products. Included in the list are electric motors rated from 1 to 200 horsepower and manufactured after April 1, 1993. If sold in the provinces named, these motors must bear CSA's energy-efficiency label (Figure 6) to verify that they meet the requirements of the standard designated as CSA C390-93.

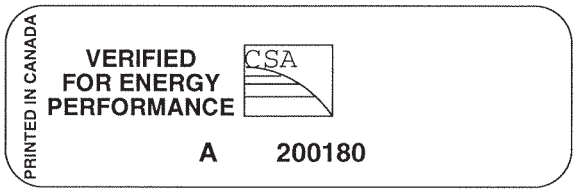


Figure 6—CSA energy-efficiency label

Now do Self-Test 1 and check your answers.

Self-Test 1

1. What name is given to the stationary part of the motor?

2. What name is given to the rotating part of the motor?

3. What is the purpose of the laminations in the cores of both of those parts of the motor?

4. Why are the bars of the squirrel cage slightly skewed so they are not parallel with the slots in the stator?

5. What is the main purpose of the end bells on a motor?

6. Name two ways motor enclosures are classified.

7. What name is given to the machine with an enclosure that does not prevent the free exchange of air between the inside and the outside of the machine?

8. What name is given to the machine with an enclosure that prevents the free exchange of air between the inside and the outside of the machine?

9. The winding of a three-phase winding is made up of three single-phase windings placed _____ electrical degrees apart from each other.

10. What are the two purposes of the stator core?

11. What does the frame designation tell about the motor?

12. Does the horsepower rating of the motor refer to input power or to output power?

13. What does the service factor of the motor tell about the motor?

14. What would an electrician use the insulation system designation for when installing a motor?

15. What does the ambient temperature rating refer to?

16. In what units is the speed of the motor rated?

17. For a motor to operate successfully under running conditions at full load, by what maximum percentage may the frequency of the supply vary?

18. For a motor to operate successfully under running conditions at full load, what is the maximum variation from rated voltage allowed?

19. What relationship is expressed by the design letter on a motor nameplate?

20. Define the term *full-load current*.

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 2:

Describe the operating principles of three-phase induction motors

For AC induction motors, there is no electrical connection between the stator circuit and the rotor circuit. Similar to transformer action, currents are induced in the rotor (secondary) by the flux produced in the stator (primary). This is achieved by producing a rotating magnetic field in the stator windings.

Development of rotating magnetic field

Figure 1 is a diagram of a two-pole, three-phase stator connected in a wye configuration. *Two-pole* means that each phase has two poles. Each winding is wound in such a way that it creates two poles, each with polarity opposite to the other. For example, when the pole marked A_1 is a north, the pole marked A_2 will be a south.

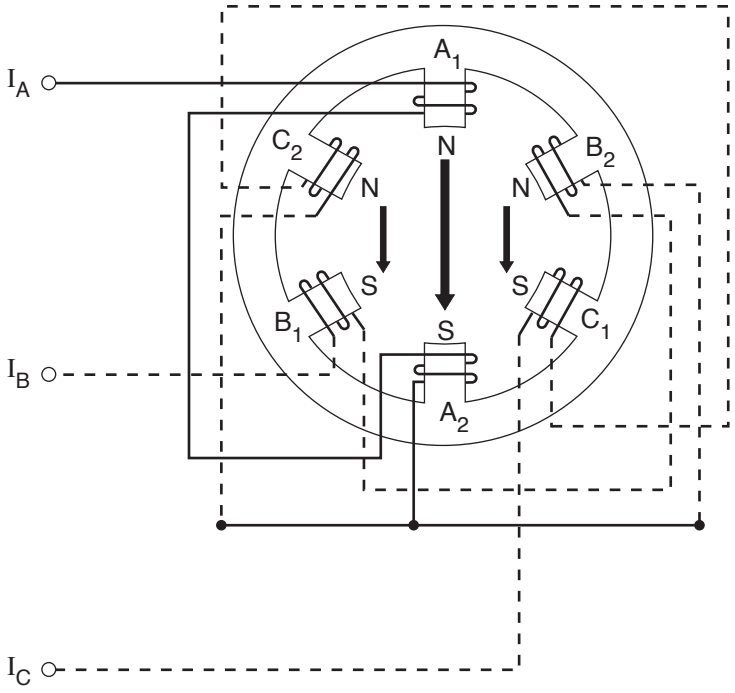


Figure 1—Simple, wye-connected, two-pole, three-phase stator

Figure 2 shows a graph of three-phase currents, each 120° apart with an ABC phase rotation. The vertical lines show where each phase will be in its cycle with respect to the other two phases.

By examining the graph at each of the seven points marked by the vertical lines, it is possible to see the current directions and magnitudes on the diagram in Figure 1. The pole polarities can then be determined and the flux lines drawn to show the direction of the magnetic field in the centre of the stator.

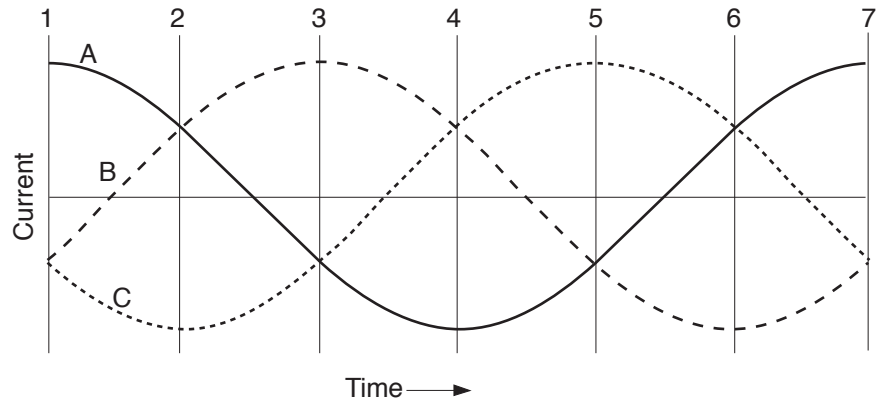


Figure 2—Graph of a three-phase current

To determine the polarities and draw the flux lines, a positive and negative direction of current must first be assumed. For the purpose of this description, a current in the positive direction is assumed to flow into the stator windings, while a current in the negative direction is assumed to flow out of the stator windings.

Direction of the field at point 1 in the cycle

You can see in the Figure 2 graph that, at point 1 in the cycle, the current in phase A is at its positive peak. This means that the current in phase A is at its maximum and flowing into the stator winding. Applying the left-hand rule for coils determines that a strong north pole is formed at pole A_1 and that a strong south pole is formed at pole A_2. This is shown in Figure 3.

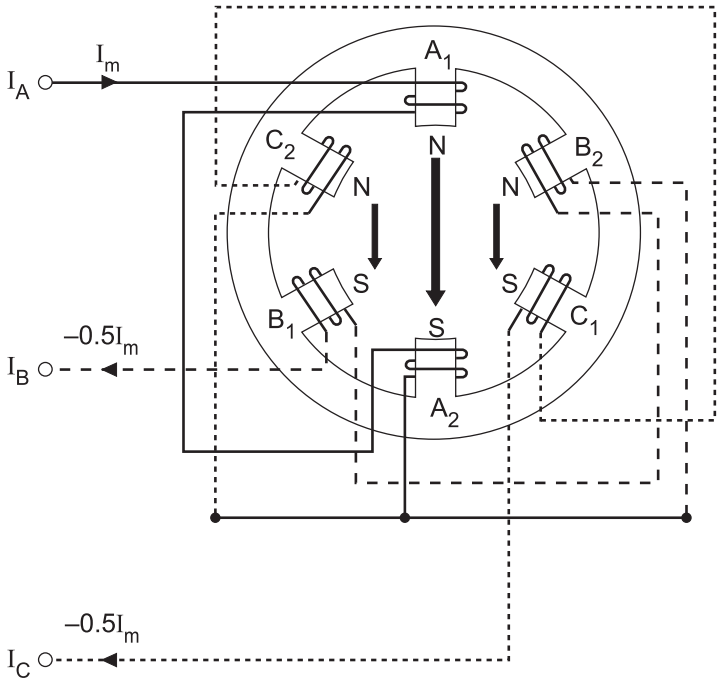


Figure 3—Point 1 in the cycle

At the same time, the currents in phases B and C are equal to one-half of their peak value and in the negative direction. The currents in these two phases are flowing out of the stator windings. Applying the left-hand rule for coils determines that a weaker north pole is formed at both B_2 and C_2 and that a weaker south pole is formed at both B_1 and C_1. This is also shown in Figure 3.

The three north poles (A_1, B_2 and C_2) together form one big north pole, which is strongest in the centre. And the three south poles (A_2, B_1 and C_1) together form one big south pole, which also is strongest in the centre. That is why this three-phase induction motor is called a *two-pole* motor rather than a *six-pole* motor.

Direction of the field at point 2 in the cycle

From the graph in Figure 2 you can see that, at point 2 in the cycle, the current in phase C is at its negative peak. It is at its maximum and flowing out of the stator winding. Applying the left-hand rule for coils determines that a strong north pole is formed at pole C_2 and that a strong south pole is formed at pole C_1. This is shown in Figure 4.

At the same time, the currents in phases A and B are equal to one-half of their peak value and in the positive direction. The currents in these two phases are flowing into the stator windings. Applying the left-hand rule for coils determines that a weaker north pole is formed at both A_1 and B_1, and that a weaker south pole is formed at both A_2 and B_2. This too is shown in Figure 4.

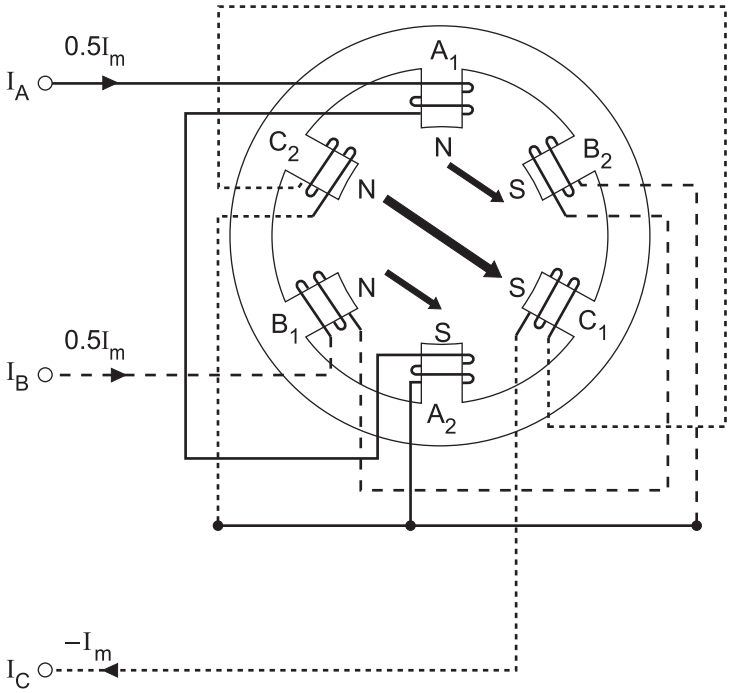


Figure 4—Point 2 in the cycle

The three north poles (A_1, B_1 and C_2) together form one big north pole, which is strongest in the centre. And the three south poles (A_2, B_2 and C_1) together form one big south pole, also strongest in the centre.

Notice that, while the currents in Figure 2 have shifted by 60 electrical degrees, the centre of the magnetic poles in Figure 4 has also shifted by 60 mechanical degrees.

Direction of the field at point 3 in the cycle

From the graph in Figure 2 you can see that, at point 3 in the cycle, the current in phase B is at its positive peak. It is at its maximum and flowing into the stator winding. Applying the left-hand rule for coils determines that a strong north pole is formed at pole B_1 and that a strong south pole is formed at pole B_2. This is shown in Figure 5.

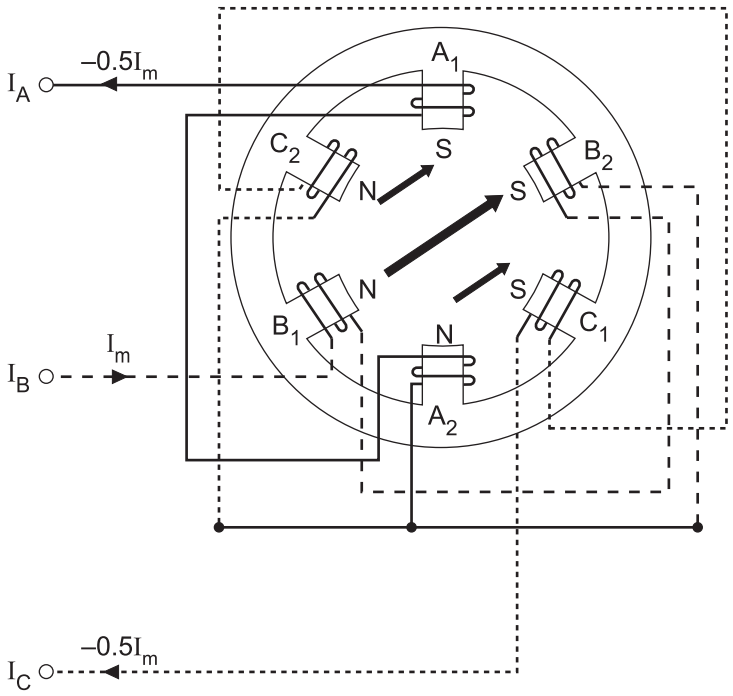


Figure 5—Point 3 in the cycle

At the same time, the currents in phases A and C are equal to one-half of their peak value and in the negative direction. The currents in these two phases are flowing out of the stator windings. Applying the left-hand rule for coils determines that a weaker north pole is formed at both A_2 and C_2, and that a weaker south pole is formed at both A_1 and C_1. This too is shown in Figure 5.

The three north poles (A_2, B_1 and C_2) together form one big north pole, which is strongest in the centre. And the three south poles (A_1, B_2 and C_1) together form one big south pole, which is strongest in the centre.

Again notice that, while the currents in Figure 2 have shifted by a further 60 electrical degrees, the centre of the magnetic poles in Figure 5 has also shifted by a further 60 mechanical degrees.

Direction of the field at point 4 in the cycle

From the graph in Figure 2 you can see that, at point 4 in the cycle, the current in phase A is at its negative peak. It is at its maximum and flowing out of the stator winding. Applying the left-hand rule for coils determines that a strong north pole is formed at pole A_2 and that a strong south pole is formed at pole A_1. This is shown in Figure 6.

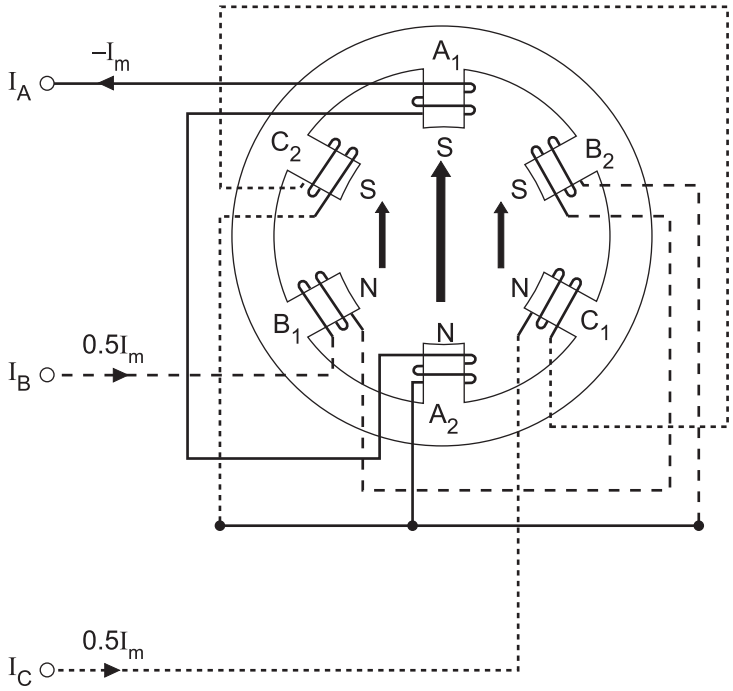


Figure 6—Point 4 in the cycle

At the same time, the currents in phases B and C are equal to one-half of their peak value and in the positive direction. The currents in these two phases are flowing into the stator windings. Applying the left-hand rule for coils determines that a weaker north pole is formed at both B_1 and C_1, and that a weaker south pole is formed at both B_2 and C_2. This too is shown in Figure 6.

The three north poles (A_2, B_1 and C_1) together form one big north pole, which is strongest in the centre. And the three south poles (A_1, B_2 and C_2) together form one big south pole, which also is strongest in the centre.

Again notice that, while the currents in Figure 2 have shifted by a further 60 electrical degrees, the centre of the magnetic poles in Figure 6 has also shifted by a further 60 mechanical degrees.

Direction of the field at point 5 in the cycle

The graph in Figure 2 shows that, at point 5 in the cycle, the current in phase C is at its positive peak. It is at its maximum and flowing into the stator winding. Applying the left-hand rule for coils determines that a strong north pole is formed at pole C_1, and that a strong south pole is formed at pole C_2. This is shown in Figure 7.

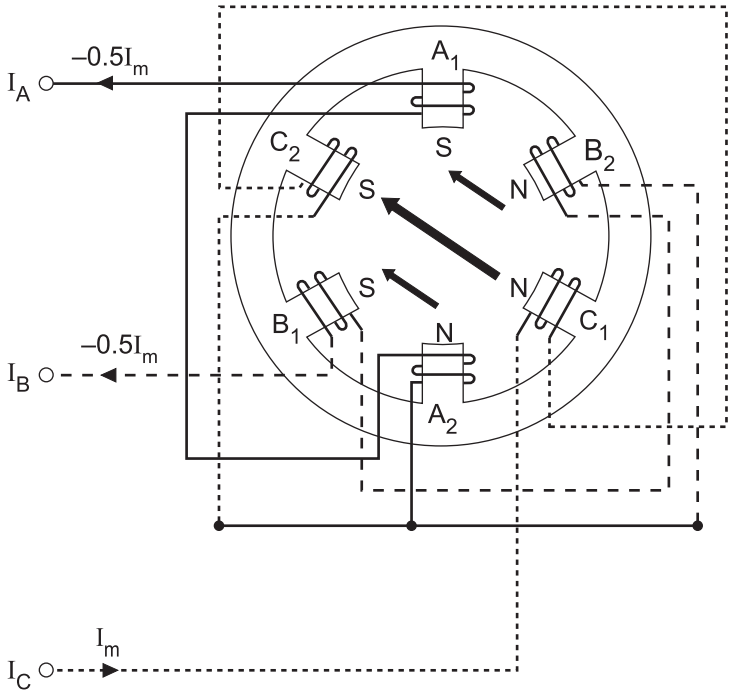


Figure 7—Point 5 in the cycle

At the same, time the currents in phases A and B are equal to one-half of their peak value and in the negative direction. The currents in these two phases are flowing out of the stator windings. Applying the left-hand rule for coils determines that a weaker north pole is formed at both A_2 and B_2, and that a weaker south pole is formed at both A_1 and B_1. This is also shown in Figure 7.

The three north poles (A_2, B_2 and C_1) together form one big north pole, which is strongest in the centre. And the three south poles (A_1, B_1 and C_2) together form one big south pole, which is strongest in the centre.

Once more notice that, while the currents in Figure 2 have shifted by a further 60 electrical degrees, the centre of the magnetic poles in Figure 7 has also shifted by a further 60 mechanical degrees.

Direction of the field at point 6 in the cycle

The graph in Figure 2 shows that, at point 6 in the cycle, the current in phase B is at its negative peak. The current in phase B is at its maximum and flowing out of the stator winding. Applying the left-hand rule for coils determines that a strong north pole is formed at pole B_2, and that a strong south pole is formed at pole B_1. This is shown in Figure 8.

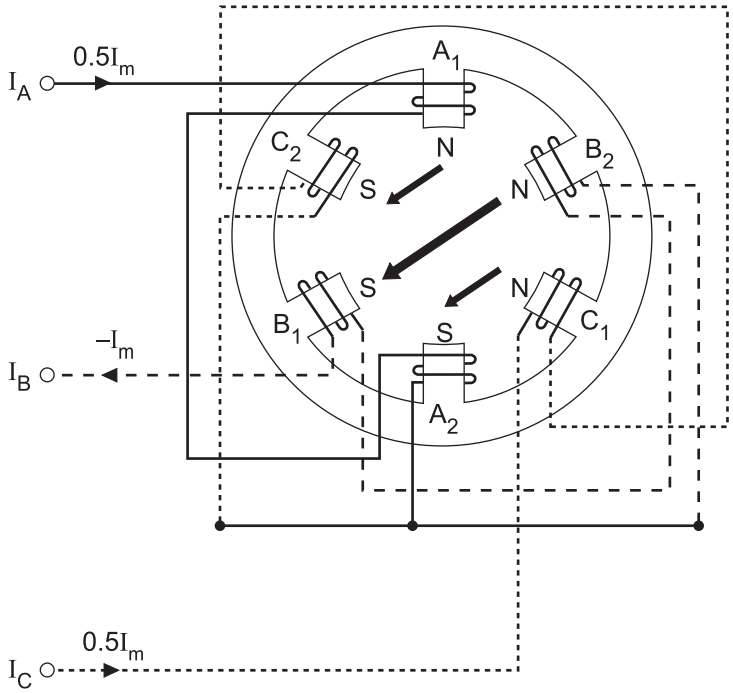


Figure 8—Point 6 in the cycle

At the same time, the currents in phases A and C are equal to one-half of their peak value and in the positive direction. The currents in these two phases are flowing into the stator windings. Applying the left-hand rule for coils determines that a weaker north pole is formed at both A_1 and C_1, and that a weaker south pole is formed at both A_2 and C_2. This is also shown in Figure 8.

The three north poles (A_1, B_2 and C_1) together form one big north pole, which is strongest in the centre. And the three south poles (A_2, B_1 and C_2) together form one big south pole, which also is strongest in the centre.

Notice that, while the currents in Figure 2 have shifted by a further 60 electrical degrees, the centre of the magnetic poles in Figure 8 has also shifted by a further 60 mechanical degrees.

Direction of the field at point 7 in the cycle

Point 7 in the cycle is the same as point 1. The direction of the field has moved by 60° six times, bringing it back to where it started. This means that at point 7 the direction of the field is back to where it started and that the cycle will begin again. If more points had been plotted, they would show that the field is not actually jumping in steps but instead is continuously revolving in the stator.

Synchronous speed

You have seen that, in one complete cycle of alternating current, the magnetic field within the stator has made one complete mechanical revolution. If the frequency of the supply is increased, the speed at which the field rotates also increases. If the frequency of the supply decreases, the speed at which the field rotates decreases. This means that the speed at which the field rotates is directly proportional to the frequency.

The speed at which the field rotates is called the *synchronous speed* of the motor and is measured in revolutions per minute rpm. In the two-pole motor example, one cycle of current was equivalent to one revolution of the field. A 60-hertz source completes 3600 cycles each minute, so a two-pole motor connected to a 60-hertz source will have a synchronous speed of 3600 rpm.

In fact, the synchronous speed of any induction motor can be determined by using the following equation:

$$n = \frac{f \times 60}{P}$$

where:

n = the synchronous speed of the motor in rpm
f = the frequency of the supply current in hertz
P = the number of pairs of poles (2) per phase in the motor

Note: The 60 is in the equation to convert from cycles per second to cycles per minute.

Example 1: Calculate the synchronous speed of a 6-pole, 60-hertz induction motor.

$$n = \frac{f \times 60}{P}$$

$$= \frac{60 \text{ hertz} \times 60}{3 \text{ pairs}}$$

$$= 1200 \text{ rpm}$$

Development of rotor torque

In a squirrel-cage induction motor the rotor bars and the end rings form the rotor windings (Figure 9). The bars and end rings form short-circuited coils. The bars are not insulated from the laminated steel core, but, because their resistance is so low compared to that of the core, the current flows mainly in the squirrel cage.

There is no electrical connection between the stator of an induction motor and the rotor. But for the motor to produce torque, a current must flow in the rotor windings. This is accomplished through electromagnetic induction in much the same way as current is induced in the secondary of a transformer.

When the motor is first energized, the rotor is stationary and the stator field rotates past the rotor at synchronous speed. As the field cuts across the bars of the rotor, it induces a voltage in the rotor bars. This voltage causes a current to flow through the rotor as shown in Figure 10.

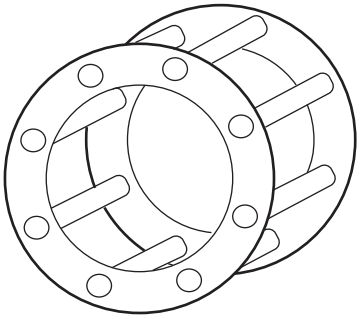


Figure 9—Squirrel cage

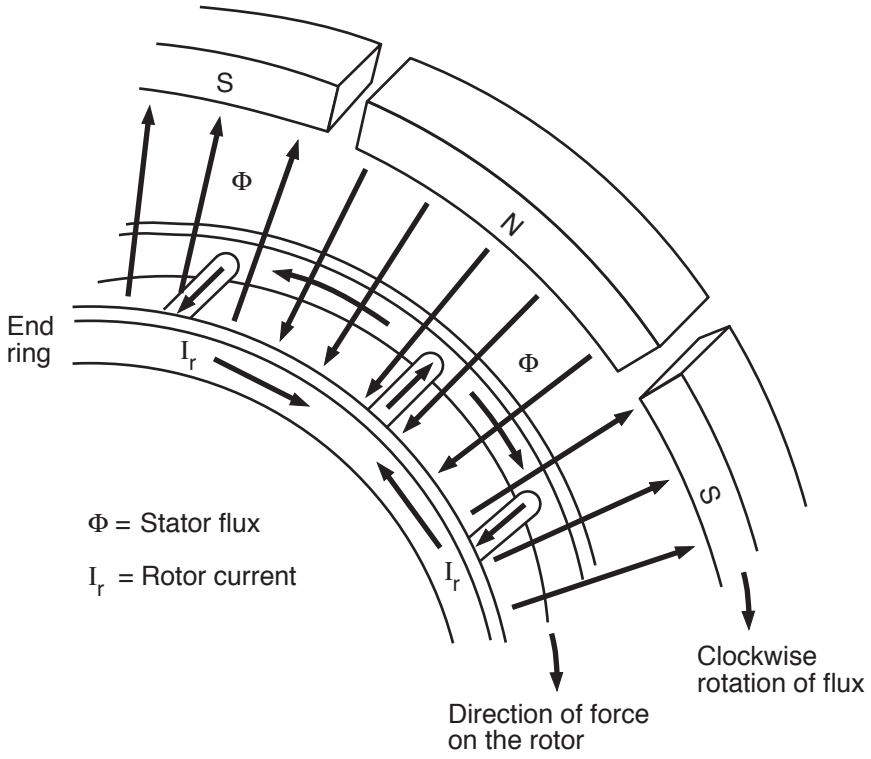


Figure 10—Torque produced in the rotor

The stator field in Figure 10 is shown rotating in a clockwise direction. The rotor bars (conductors) are stationary, but can be thought of as moving counterclockwise to the direction of the rotating stator field. By applying the left-hand generator rule, you can determine the current directions shown in the rotor of Figure 10.

With the rotor current directions known, you can then determine the direction of thrust on the rotor bars by applying the right-hand motor rule. Applying this rule shows that the rotor will produce a thrust in the same direction as the motion of the stator field. If the load on the motor is not excessive, the rotor will start to turn and accelerate.

Rotor speed and slip

The rotor of the motor accelerates but never reaches synchronous speed. To induce a voltage in the rotor, there must always be some relative motion between the stator field and the rotor. If both travelled at the same speed, no current would flow in the rotor and no torque would be created.

As the rotor speed increases, the relative speed between the rotating stator field and the rotor decreases. This difference in speed is called the *slip speed*.

Slip speed = Synchronous speed – Rotor speed

The slip speed is often expressed as a percentage of the synchronous speed. This is called the *percent slip*, and is calculated as follows:

$$\text{Percent slip} = \frac{\text{Synchronous speed} - \text{Rotor speed}}{\text{Synchronous speed}} \times 100$$

Note that the percent slip is high when the rotor speed is low, and that the percent slip is low when the rotor speed is high. Keep this in mind when you analyze the characteristics of induction motors.

Example 2: Find the rotor speed of a two-pole, 60-hertz motor running at 5% slip.

Solution:
First find the synchronous speed for this motor.

$$\text{Synchronous speed} = \frac{60 \text{ hertz} \times 60}{1 \text{ pair}}$$

$$= 3600 \text{ rpm}$$

Next transpose the percent slip formula to yield the following:

$$\text{Slip speed} = \frac{\text{Percent slip} \times \text{Synchronous speed}}{100}$$

$$= \frac{5 \times 3600 \text{ rpm}}{100}$$

$$= 180 \text{ rpm}$$

Then transpose the slip speed formula to yield the following:

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

$$= 3600 \text{ rpm} - 180 \text{ rpm}$$

$$= 3420 \text{ rpm}$$

Speed regulation

As load is added to a motor, the rotor slows down. The difference between the speed of the motor at no load and the speed of the motor at full load is called the *speed regulation* of the motor. It is calculated as follows:

$$\text{Speed regulation} = \text{No-load speed} - \text{Full-load speed}$$

For the purpose of comparing the characteristics of different motors, speed regulation is often expressed as a percentage of the rated full-load speed of the motor. It is calculated as follows:

$$\text{Percent speed regulation} = \frac{\text{No-load speed} - \text{Full-load speed}}{\text{Full-load speed}} \times 100$$

In a motor with good or low-speed regulation, the speed does not change much between no load and full load. On the other hand, in a motor with poor or high-speed regulation, the speed changes a lot between no load and full load.

Example 3: A certain four-pole, 60-hertz induction motor has a no-load speed of 1790 rpm and a full-load speed of 1740 rpm. Calculate its percent speed regulation.

$$\text{Percent speed regulation} = \frac{\text{No-load speed} - \text{Full-load speed}}{\text{Full-load speed}} \times 100$$

$$= \frac{1790 \text{ r/min} - 1740 \text{ r/min}}{1740 \text{ r/min}} \times 100$$

$$= 2.87\%$$

Reversing rotation

It has been demonstrated that the thrust produced by the rotor will be such that it attempts to turn itself in the same direction as the rotating magnetic field. To reverse the direction of the motor, just reverse the direction of the rotating magnetic field. Do this by interchanging any two of the stator leads where they connect to the source.

Interchanging any two of the stator lead connections accomplishes the same thing as reversing the phase sequence of the supply. This causes the sequence in which the stator poles reach their peaks to be reversed and the stator field rotates in the opposite direction.

Speed-torque-current characteristics

It is primarily the inductance of the stator winding that limits the flow of current into the motor. As current flows through the stator windings, it creates a magnetic flux, which induces a counter emf to limit the flow of current through the winding. When current flows in the rotor, it establishes a flux that interacts with the stator flux. This interaction upsets the balance of applied voltage and counter emf in the stator winding. The stator current changes to re-establish the stator flux, and to rebalance the applied voltage and counter emf.

Each change in rotor current must be matched by a change in stator current. The rotor current is at its maximum value when the rotor is at a standstill, because the induced voltage in the rotor is at its maximum. As a result the stator current is also at its maximum when the rotor is at a standstill.

As the rotor speed increases, the voltage induced in the rotor decreases. This results in a decrease in rotor current and a decrease in stator current. So both rotor and stator currents are at their maximum when the rotor is "locked" (stationary); and both are at their minimum when the rotor speed is at its highest.

You may think that torque is at its highest when the two currents are at their highest. This is not necessarily the case. The torque produced by the rotor is determined by using the following formula:

$$T = K\Phi_s I_r \cos\theta_r$$

where:

T = Torque in newton metres
K = A constant for the motor that takes into account the physical characteristics of the motor such as how it is wound and how the core is constructed
Φ_s = The stator flux in webers
I_r = The current flowing in the rotor in amperes
$\cos \theta_r$ = The power factor of the rotor circuit

Since K is a constant for the motor, it does not change as the motor operates. As well, the value of stator flux (Φ_s) remains relatively constant as the motor speed changes. However, the values of rotor current (I_r) and rotor power factor ($\cos \theta_r$) do change drastically as the motor speed changes.

The resistance of the rotor is independent of the speed of the rotor; however, the reactance of the rotor increases as the speed of the rotor decreases. This means that the power factor of the rotor also decreases as the rotor speed decreases.

As the rotor speed decreases, the current in the rotor increases at the same time as the power factor decreases. The increase in current tends to increase the torque while the decrease in power factor tends to decrease the torque. Whether or not the torque increases as speed decreases depends on which of these two factors experiences the greatest change.

Figure 11 shows a graph of torque, rotor power factor and rotor current plotted with respect to percent slip for a typical squirrel-cage induction motor.

Remember that, as the percent slip increases, the rotor speed is actually decreasing. So 0% slip really means synchronous speed and 100% slip means the rotor is at a standstill. Therefore, the speed of the motor is shown as decreasing as you look from left to right.

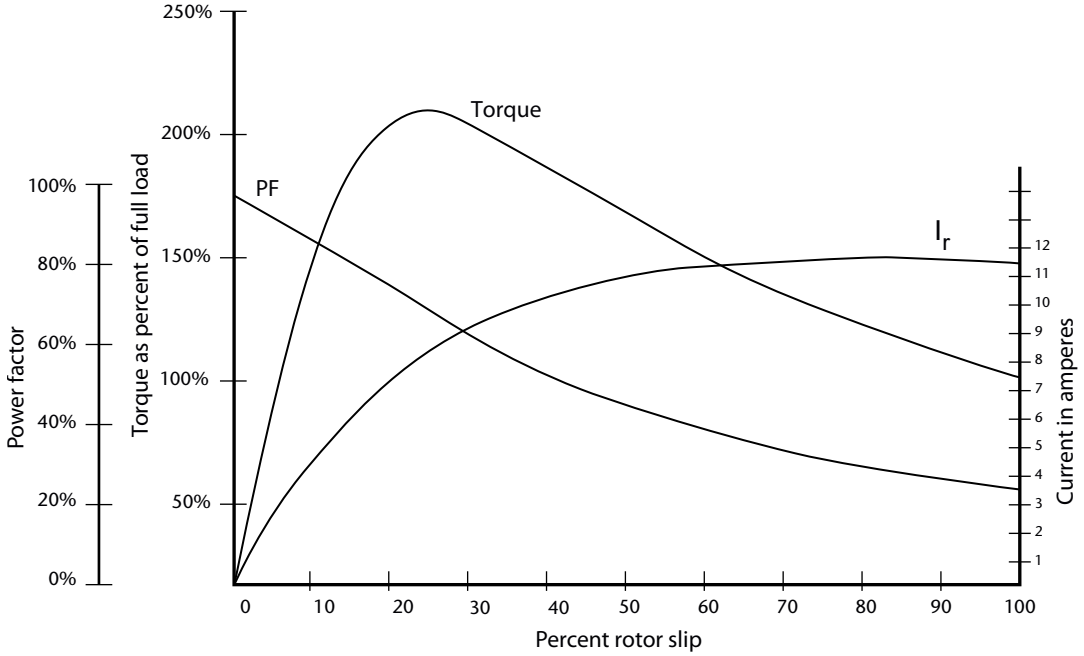


Figure 11—Torque, rotor power factor and rotor current with respect to percent slip

Notice, in Figure 11, what happens to the torque developed by the rotor as the speed of the rotor decreases from synchronous speed. From 0% slip to about 25% slip, the torque increases, but after 25% slip, the torque decreases. The reason is that from 0% slip to 25% slip, the current increases at a rate faster than the decrease in power factor. But after 25% slip, the power factor decreases at a rate faster than the increase in current.

Full-load torque

The full-load torque of a motor is the torque necessary to produce rated horsepower at rated full-load speed. AC induction motors are normally designed to develop full-load torque at about 2% to 5% slip. This ensures that the speed of the motor does not change by very much between no load and full load. In this way the motor may be considered a constant-speed motor.

Breakdown torque

The maximum torque that the motor will produce is called the *stalling torque* or the *breakdown torque*. If the motor load is increased beyond this point, it will quickly slow down and stall.

On a standard squirrel-cage induction motor, breakdown torque occurs at approximately 25% slip and has a magnitude of between 175% and 300% of the full-load torque.

Starting torque

At the moment power is applied to the stator of a squirrel-cage induction motor, the rotor is not moving. The torque that is produced at this point is referred to as the *starting torque* or *locked rotor torque*. It is defined as the maximum torque the motor will develop at rest for all angular positions of the rotor with rated voltage applied at rated frequency.

On standard squirrel-cage induction motors, the starting torque has a magnitude of between 70% and 275% of full-load torque, depending on the speed and power ratings of the motor.

NEMA design standards for the squirrel-cage induction motor

By incorporating different rotor designs in the motor, motor manufacturers can produce motors with varying torque-speed characteristics. The National Electrical Manufacturers Association (NEMA) has four standardized design classifications for motors with respect to their torque-speed characteristics. In this way, the motor can be properly matched to the load it supplies. The four classes are A, B, C and D.

Design class A

Design class A has torque characteristics similar to those in design class B, but it does not have the same restrictions on maximum starting currents imposed on design class B.

Design class B

Design class B is a general-purpose motor. Its starting torque is low compared with a class C or D motor, so it is not used to start high-inertia loads, and its starting torque is typically lower than its breakdown torque. It is used to supply such loads as fans, blowers, rotary pumps, unloaded compressors, some conveyors, metal-cutting machine tools and miscellaneous machinery.

Design class C

The design class C motor has a locked rotor torque equal to or slightly larger than its breakdown torque. It is more suitable for higher inertia starts. Motors in this class are used to supply loads such as large centrifugal blowers, flywheels, crusher drums, loaded compressors, loaded piston pumps and loaded conveyors. A double-cage rotor would have this type of torque vs speed characteristic.

Design class D

The design class D motor has a very high breakdown torque. It is suitable for loads such as punch presses, shears, forming machine tools, cranes, hoists, elevators and oil well pumping jacks. The speed regulation of this class of motors is typically higher than that of the other classes. A high-resistance rotor would have this type of torque vs speed characteristic.

Figure 12 shows typical torque vs speed characteristics for the different design classes. The curves for particular motors in the classes would vary somewhat from these. But they do show the relative breakdown torques and starting torques in comparison. Note that the breakdown torque for design class D is not specified, so the curve for this motor can be less steep near synchronous speed and, as a result, it can mean poorer speed regulation.

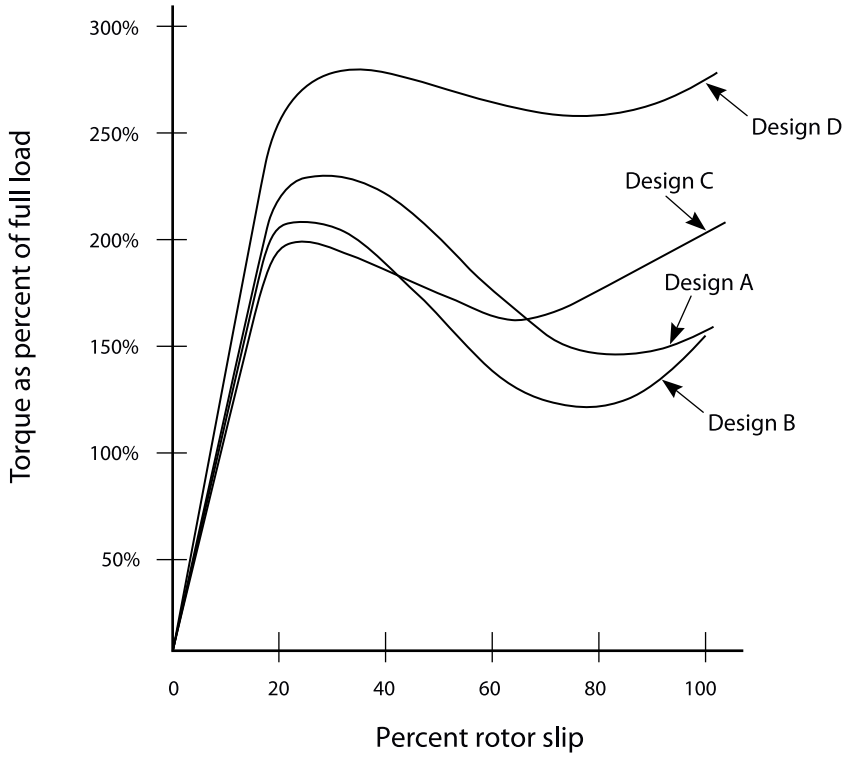


Figure 12—Torque vs speed characteristics of different rotor design classes

Motor efficiency

The efficiency of a machine is a measure of the ratio of the useful work done by a machine to the total work done on the machine. It is calculated by using the following formula:

$$\text{Percent efficiency} = \frac{\text{Power out}}{\text{Power in}} \times 100$$

The useful power out will always be less than the power in because some of the power is lost through friction, windage, heat and the like.

When people purchase a motor for a particular purpose, they are interested in the power the motor is capable of supplying to the load. For this reason, motors are rated according to their output power.

Output power is the power available at the motor shaft for the load to use.

Example 4: A 5 hp, three-phase, 575-volt motor delivers rated horsepower to the load. The motor is connected to a 600-volt, three-phase source and draws 4.75 amps at a power factor of 90% lagging. What is the efficiency of the motor?

Solution:
Find the true input power by using the following equation:

$$P_{in} = \sqrt{3} \times E_L \times I_L \times PF$$

$$= \sqrt{3} \times 600\,V \times 4.75\,A \times 0.9$$

$$= 4443 \text{ watts}$$

Convert the output power to watts by multiplying the hp by 746 watts/hp.

$$P_{out} = 5 \text{ hp} \times 746 \text{ watts/hp}$$

$$= 3730 \text{ watts}$$

Find the efficiency:

$$\text{Efficiency} = \frac{\text{Power out}}{\text{Power in}} \times 100$$

$$= \frac{3730 \text{ watts}}{4443 \text{ watts}} \times 100$$

$$= 84\%$$

Linear-induction motor

A linear-induction motor is a motor that, instead of rotating, moves in a line. It consists of a flat stator and a flat rotor. The stator looks like a normal stator that has been cut and rolled out flat. The rotor is no more than a flat bar made of a conductive material—normally aluminum

because it is relatively inexpensive and lightweight. Figure 13 shows the stator of a three-phase, two-pole linear-induction motor. Notice that it looks just like the three-phase stator discussed earlier except that it is flat instead of cylindrical.

The three phases are wye-connected, but they could be delta-connected as well. Each phase winding is wound so that it creates two poles, each with a polarity opposite to the other. For example, when the pole marked A_1 is north, the pole marked A_2 is south. The bar drawn under the stator is a conductive bar and takes the place of the conventional rotor. It is continuous for the full distance the linear-induction motor is expected to travel. As well, it is backed with iron to reduce the reluctance of the magnetic path.

One very important point you need to be aware of is the difference between the conventional motor and the linear-induction motor. In a conventional motor, the stator is stationary and the rotor moves. In a linear-induction motor, the stator moves while the rotor remains stationary.

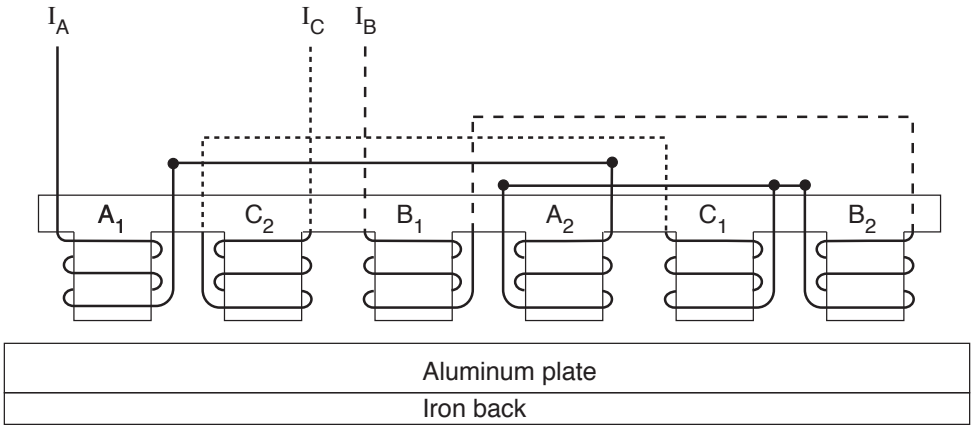


Figure 13—Stator of a three-phase, two-pole linear-induction motor

As the magnetic field of the stator passes across the rotor, it induces circulating currents in the rotor. Figure 14 shows three poles passing over the rotor. For the sake of simplicity, the rotor is shown as a horizontal ladder. This shows the path of the circulating currents in the rotor. The currents induced in a solid plate of conductor are similar to those flowing in the ladder.

The direction of the currents in the rotor may be determined by applying the left-hand rule for generators. Under the north pole, a current is induced in a direction away from the reader; under the south pole, a current is induced in a direction toward the reader. This results in circulating currents as shown in Figure 14.

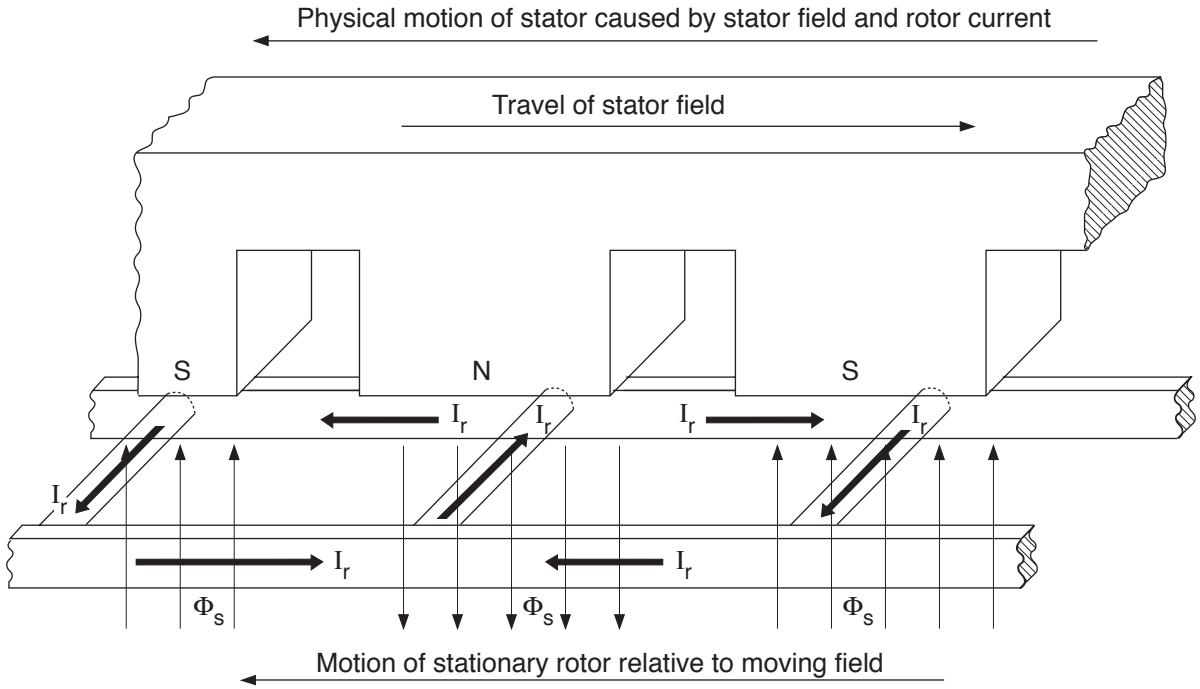


Figure 14—Rotor's production of force on the stator of linear-induction motor

If the right-hand motor rule is now applied to the stator field and the rotor currents, it is possible to determine that the stator is placing a thrust on the rotor. This thrust is in the same direction as the moving stator field. But since the rotor is fixed and cannot move, the stator moves in a direction opposite to the direction of the moving stator field.

This is much like sitting in a rowboat and trying to push the dock away. Since the dock is fixed, it stays put and the boat moves away from the dock in a direction opposite to that in which the dock was supposed to move. In the case of the linear-induction motor, the rotor is fixed and stays put, forcing the stator to move in the opposite direction.

As the stator moves, the speed at which the stator field cuts the rotor is decreased. This induces a smaller voltage at a lower frequency in the rotor, just as it did in a conventional, squirrel-cage induction motor.

The standard, squirrel-cage induction motor has a synchronous speed measured in revolutions per minute. Since the linear-induction motor does not rotate, it is not possible to measure its synchronous speed in rpm. However, since it moves in a straight line, the synchronous speed of a linear-induction motor may be measured in metres per second. The magnetic field moves by one pole each half-cycle. This means that the field moves by two poles each cycle. So if the distance between pole centres is known and if the frequency of the supply is known, it is possible to determine the synchronous speed of the linear-induction motor by applying the following formula:

Synchronous speed = 2 □ pole pitch □ frequency

where:

Synchronous speed is measured in metres per second;
Frequency is measured in hertz (cycles per second);
Pole pitch is measured in metres.



The stator can never actually attain synchronous speed. If it moved at the same speed as the field but in the opposite direction, then the field would effectively be stationary. That is, there would be no relative motion between the stator field and the rotor, so no current would be induced in the rotor. With no current flowing in the rotor, there would be no thrust between the stator and the rotor. So the stator will always move slower than the synchronous speed of the motor.



Now do Self-Test 2 and check your answers.

Self-Test 2

1. The flux created by any winding will be at a maximum when the current through that winding is at a _____ .

2. When the current through a winding reverses, the flux direction created by that winding _____ .

3. What effect does increasing the frequency of the supply have on the speed of the rotating magnetic field?

4. What effect does increasing the number of poles have on the speed of the rotating magnetic field?

5. Define the term *synchronous speed*.

6. What would be the synchronous speed of an eight-pole motor connected to a 60-hertz supply?

7. What would be the number of poles in a motor with a synchronous speed of 720 rpm when the motor is connected to a 60-hertz supply?

8. Since there is no electrical connection between the stator and the rotor, how is current made to flow in the rotor of a squirrel-cage induction motor?

9. Define the term *slip speed*.

10. Define the term *percent slip*.

11. Define the term *speed regulation*.

12. How is the direction of rotation reversed in a squirrel-cage induction motor?

13. Define the term *full-load torque*.

14. Define the term *breakdown torque*.

15. Define the term *locked rotor torque*.

16. Define the term *starting torque*.

17. At what rotor speed will the stator current be the highest?

18. What type of loads is a NEMA design class C motor suitable for?

19. Find the slip speed and percent slip of a six-pole, 60-hertz induction motor when the rotor is turning at 1158 rpm.

20. A six-pole, 60-hertz induction motor has a no-load speed of 1191 rpm and a full-load speed of 1171 rpm. Calculate the percent speed regulation.

21. A motor is rated at 55.95 kW. How much horsepower is this?

22. A 25-horsepower, three-phase, 575-volt motor delivers rated horsepower to the load. The motor is connected to a 600-volt, three-phase source and draws 24 A at a power factor of 87% lagging. What is the efficiency of the motor?

23. Which part of the linear-induction motor actually moves?

24. In what units is the synchronous speed of a linear-induction motor measured?

_____

25. Relative to the direction of the moving magnetic field, in what direction does the linear-induction motor move?

_____

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 3:

Identify common connections for squirrel-cage induction motors

For three-phase induction motors, the windings are connected in either wye or delta. Typically the motor has three, six, nine or twelve external leads, depending on what the motor was designed for.

Terminal markings for three-phase induction motors

Figure 1 is a schematic phasor diagram showing an inverted wye connection. The individual circuits in each phase are arranged for series connection with correct polarity relations in the circuit. The angles between the windings indicate their relative phase angles.

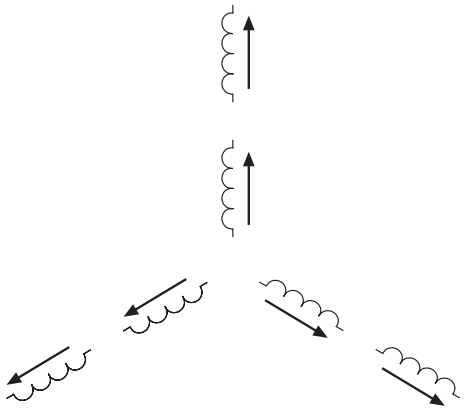


Figure 1—Schematic phasor diagram of a three-phase motor

Figure 2 shows how to properly number the terminal leads of each winding. Starting with T_1 at the outside and top of the diagram, the ends of the circuit must be numbered consecutively in a clockwise direction and proceed on a spiral toward the centre of the diagram.

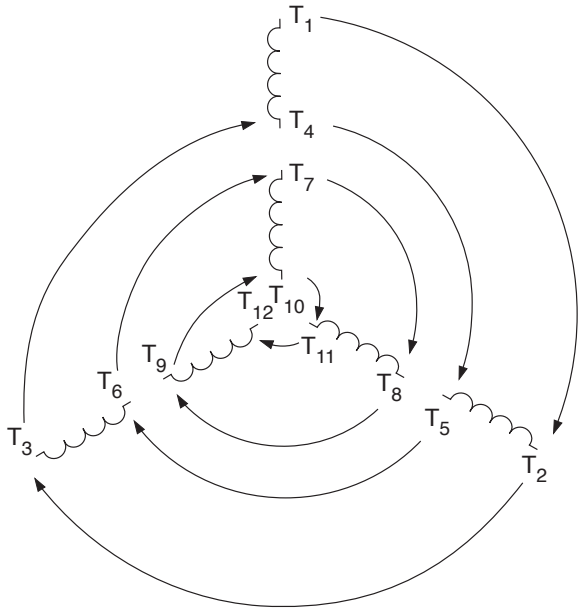


Figure 2—Convention for wye terminal markings

If the winding is to be delta-connected, the inverted wye diagram shall be rotated 30° counterclockwise, as shown in the left drawing of Figure 3. This means that T_1 becomes the top of the right-hand side of the delta, as shown in the right drawing of Figure 3.

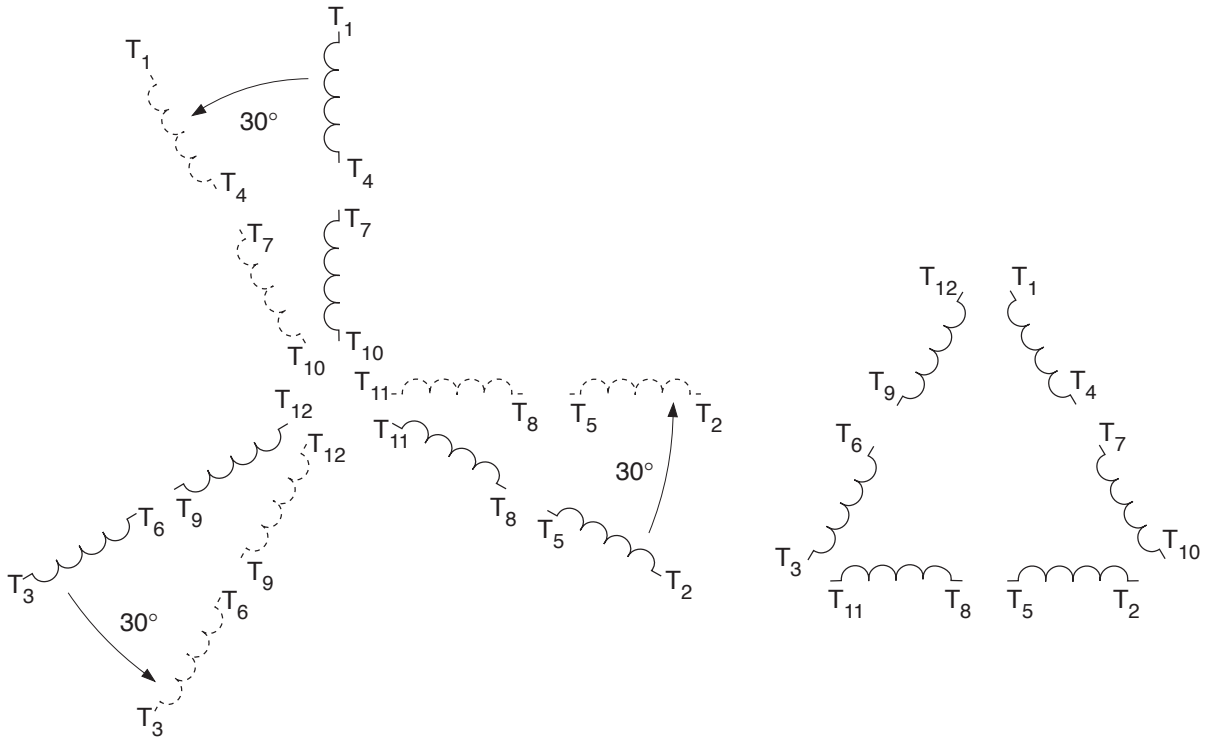


Figure 3—Convention for delta terminal markings

Whenever two or more leads are connected and one lead is brought out, the higher lead designation is dropped. Figure 4 shows an example of a nine-lead, delta-connected motor where the lead designations T_{10}, T_{11} and T_{12} are dropped.

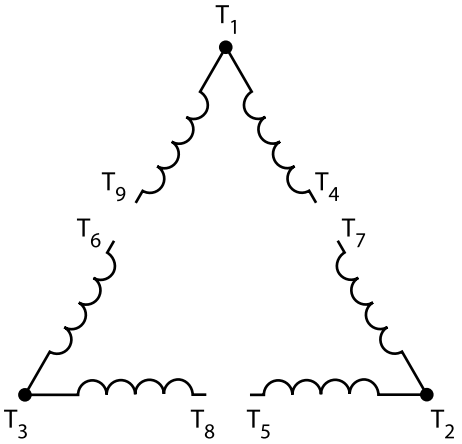


Figure 4—Internal connections for nine-lead delta motors

If no lead is brought out, all the interconnected leads have their terminal designations dropped. Figure 5 shows an example of a nine-lead, wye-connected motor where the neutral connection is not brought out. If the neutral connection were brought out, it would be designated T_0.

It should be noted that NEMA standards state that "the numbering of the terminals on polyphase induction motors does not imply standardization of the direction of rotation of the motor shaft."

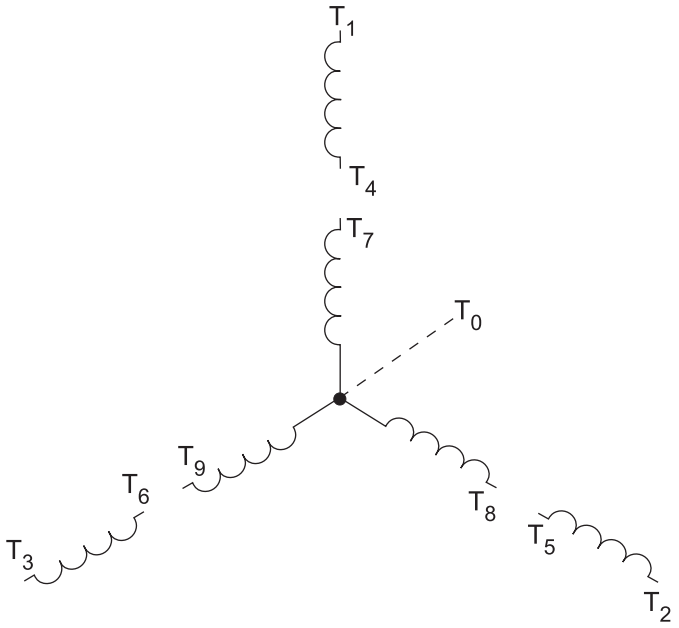


Figure 5—Internal connections for nine-lead wye motor

Three-lead motors

In a three-lead motor, only three terminal leads are brought out of the motor. This motor is single voltage. Its leads are designated T_1, T_2 and T_3, and it may be wye- or delta-connected inside. Figure 6 shows both a three-lead wye and a three-lead delta schematic. Whether it is wye- or delta-connected is not important to the installer as long as the supply voltage is suitable for the rated voltage on the nameplate. The motor can be connected L_1 to T_1, L_2 to T_2 and L_3 to T_3 for one rotation and any two line leads interchanged for the reverse rotation.

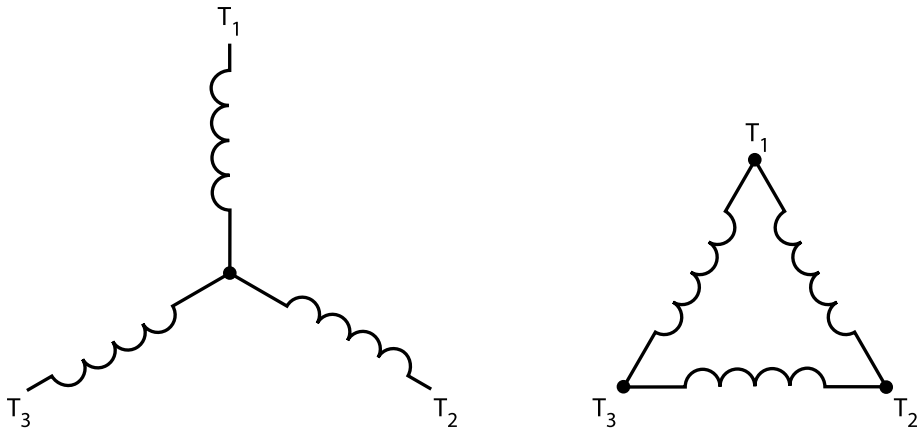


Figure 6—Three-lead motors

Six-lead motors

A six-lead motor has six terminal leads brought out of the motor, and it may be connected in wye or delta. It is a dual-voltage motor. Its leads are designated T_1, T_2, T_3, T_4, T_5 and T_6. Figure 7 shows how this motor could be both wye- and delta-connected. Below each schematic is a connection diagram. It shows only the terminals and how they are interconnected.

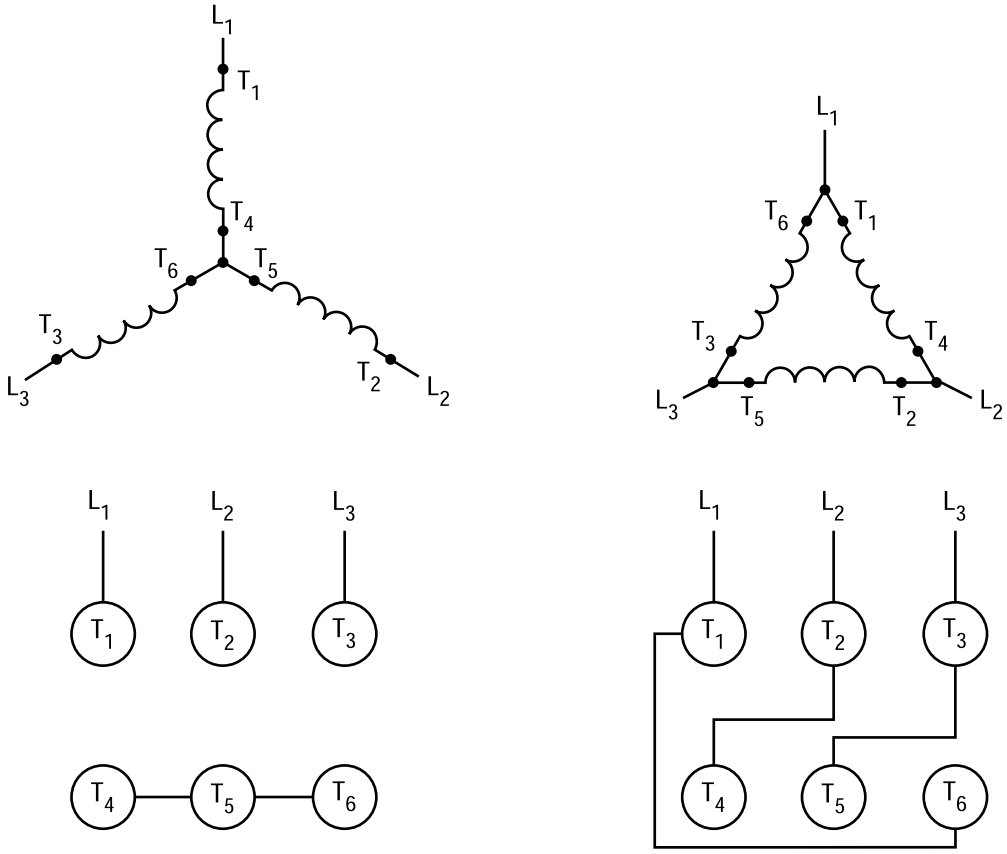


Figure 7—Six-lead motor connections

When the motor is wye-connected, the three terminals T_4, T_5 and T_6 are connected to form the wye point. The line leads are connected L_1 to T_1, L_2 to T_2 and L_3 to T_3 for one rotation, and any two line leads may be interchanged for the other rotation.

The wye connection is often used to start larger motors because only 58% of the line voltage is applied across each winding. As a result, the line current and the motor torque are reduced to 33% of what they would be if the motor were started delta-connected across the same line.

Once the motor comes up to speed, the connections are then changed to delta. L_1 is connected to both T_1 and T_6. L_2 is connected to both T_2 and T_4. And L_3 is connected to both T_3 and T_5. When used in this mode of operation, it is referred to as a *wye-delta* motor.

Nine-lead motors

Nine-lead motors are dual-voltage motors internally connected in wye or delta, with leads designated from T_1 to T_9. Notice that the terminal designations T_{10}, T_{11} and T_{12} have been dropped, because these leads are not brought out of the motor (Figure 8). The winding sets of each phase are intended for connection in series for the higher voltage, or in parallel for the lower voltage.

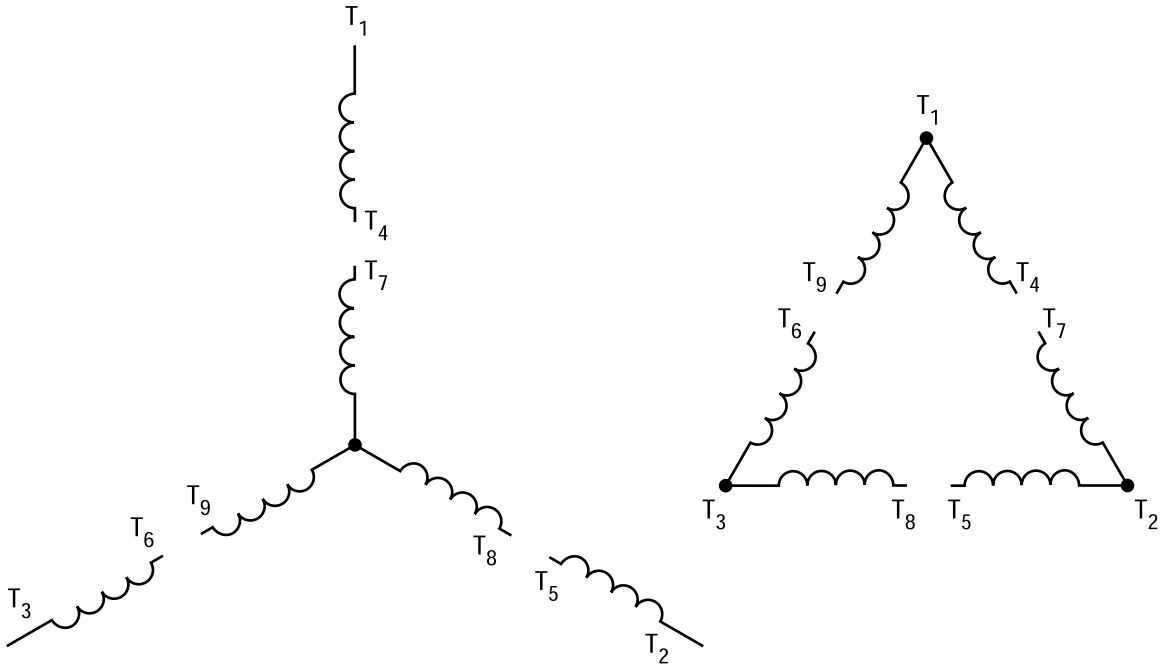


Figure 8—Nine-lead motor terminal designations

Before making the external connections for this type of motor, the electrician must know whether it is internally connected in wye or in delta. If the internal connections are wye, then the external connections must also be wye. Conversely, if the internal connections are delta, the external connections must be delta.

Figure 8 shows the internal connections of a wye motor and a delta motor. An electrician can use these diagrams to tell whether the motors are wye- or delta-connected internally. With a continuity tester it is possible to test the terminal leads. A wye-connected motor should have continuity between leads T_7, T_8 and T_9; a delta-connected motor should not. A delta-connected motor should have continuity between leads T_4 and T_9, between leads T_5 and T_7, and between leads T_6 and T_8, but a wye-connected motor should not.

The lower voltage connections for the nine-lead wye- and delta-connected motors are shown in Figure 9. Note that the two winding sets of each phase are parallel-connected. Also, note the location of terminals T_7, T_8 and T_9 with respect to the other terminals on the connection diagram. This is done to simplify the connections.

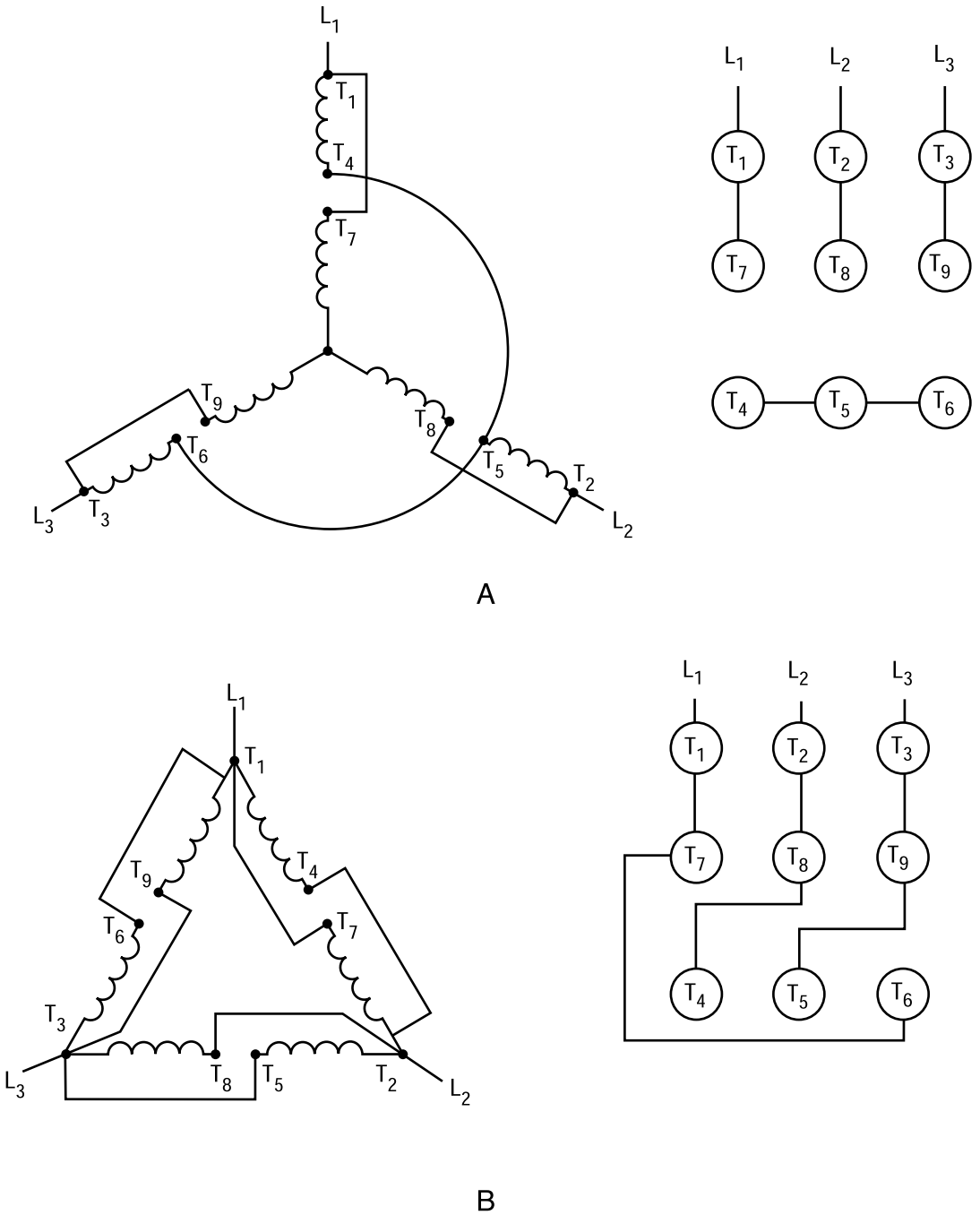


Figure 9—Lower voltage, nine-lead motor connections

The higher voltage connections for the nine-lead wye- and delta-connected motors are shown in Figure 10. Note that for each phase, the two sets of windings are series-connected.

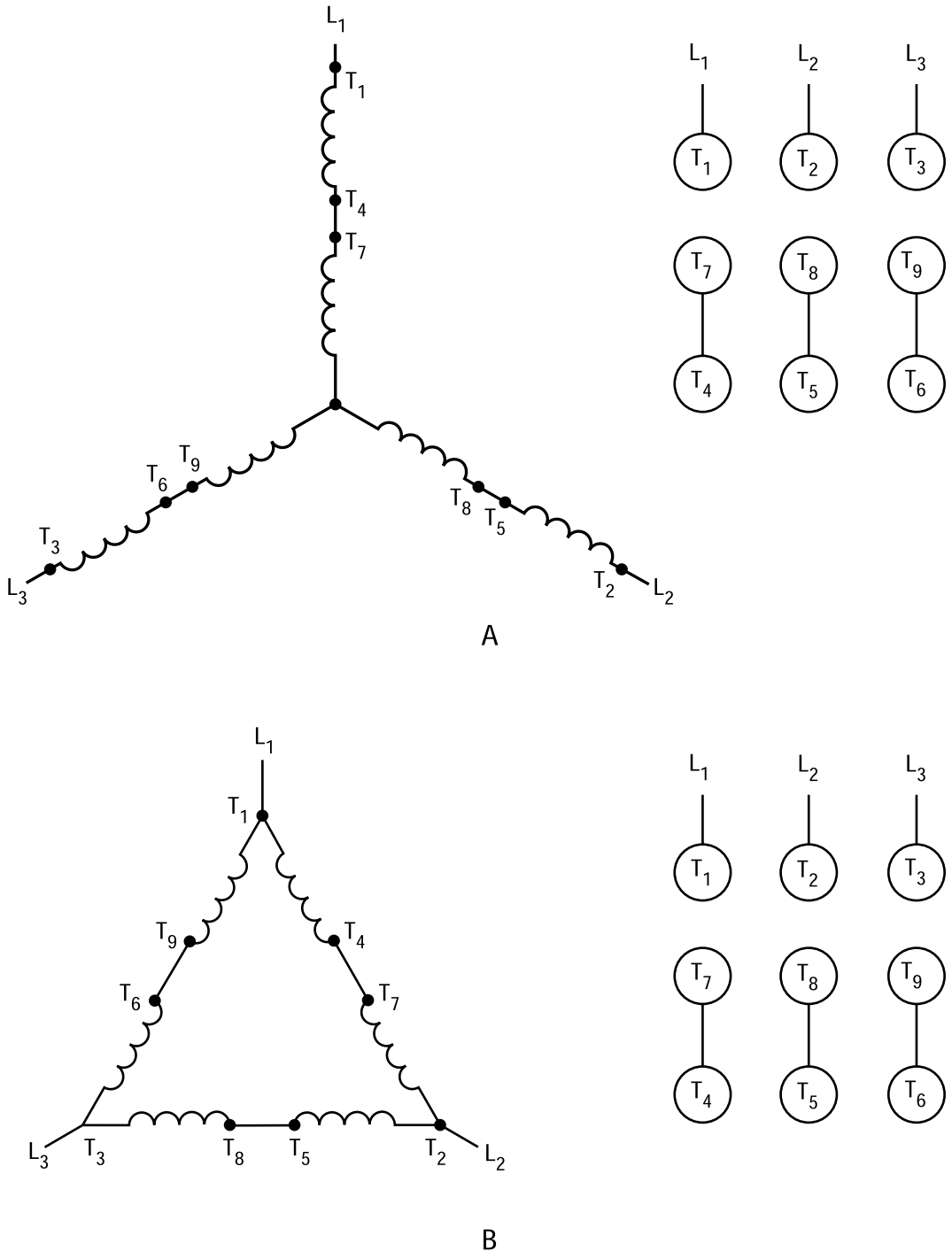
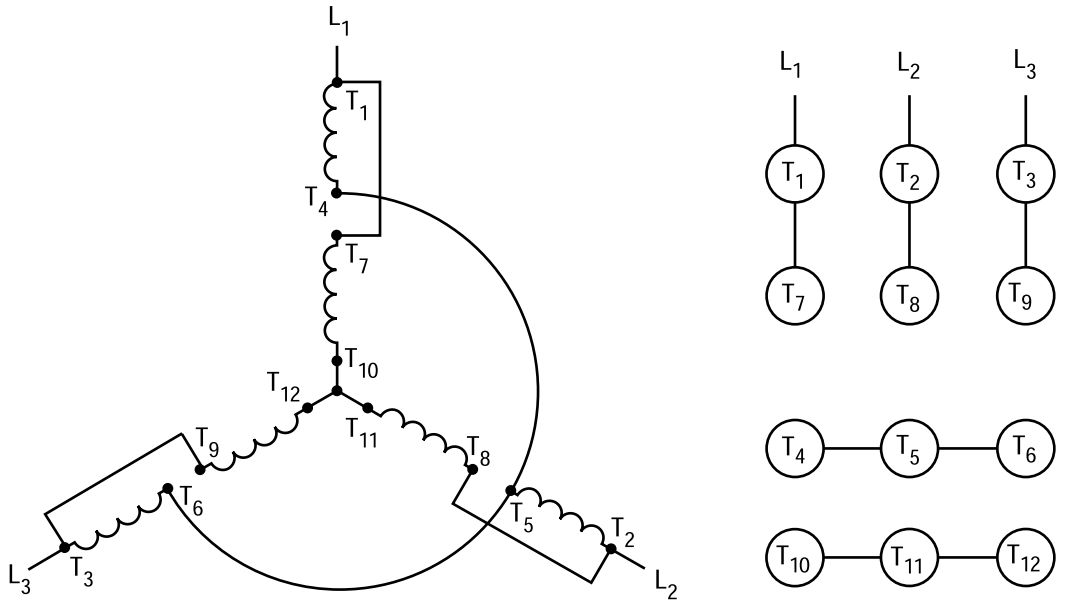


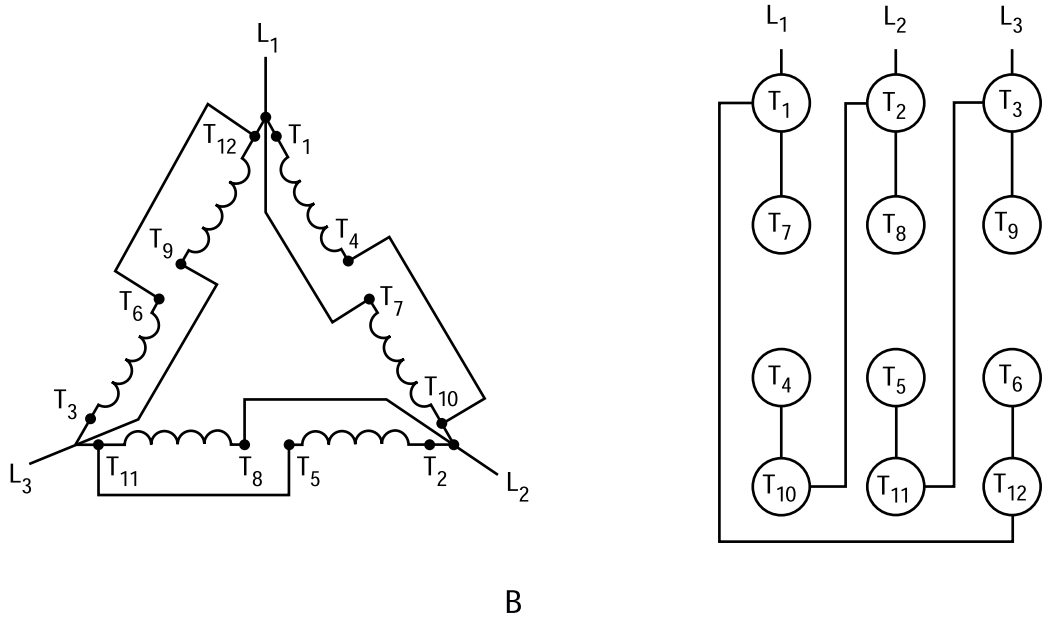
Figure 10—Higher voltage, nine-lead motor connections

Twelve-lead motors

Twelve-lead motors are typically dual-voltage and either wye- or delta-connected. Their terminals are marked T_1 to T_{12}. Each phase has four terminals, two for each winding set, and the winding sets of each phase are connected in series for the higher voltage, or in parallel for the lower. Figure 11 shows both the wye and the delta connections for the lower voltage. Notice in both diagrams that the two windings in each phase are connected in parallel.



A



B

Figure 11—Lower voltage, 12-lead motor connections

Figure 12 shows both the wye and delta connections for the higher voltage. Notice that in both diagrams the two windings in each phase are connected in series.

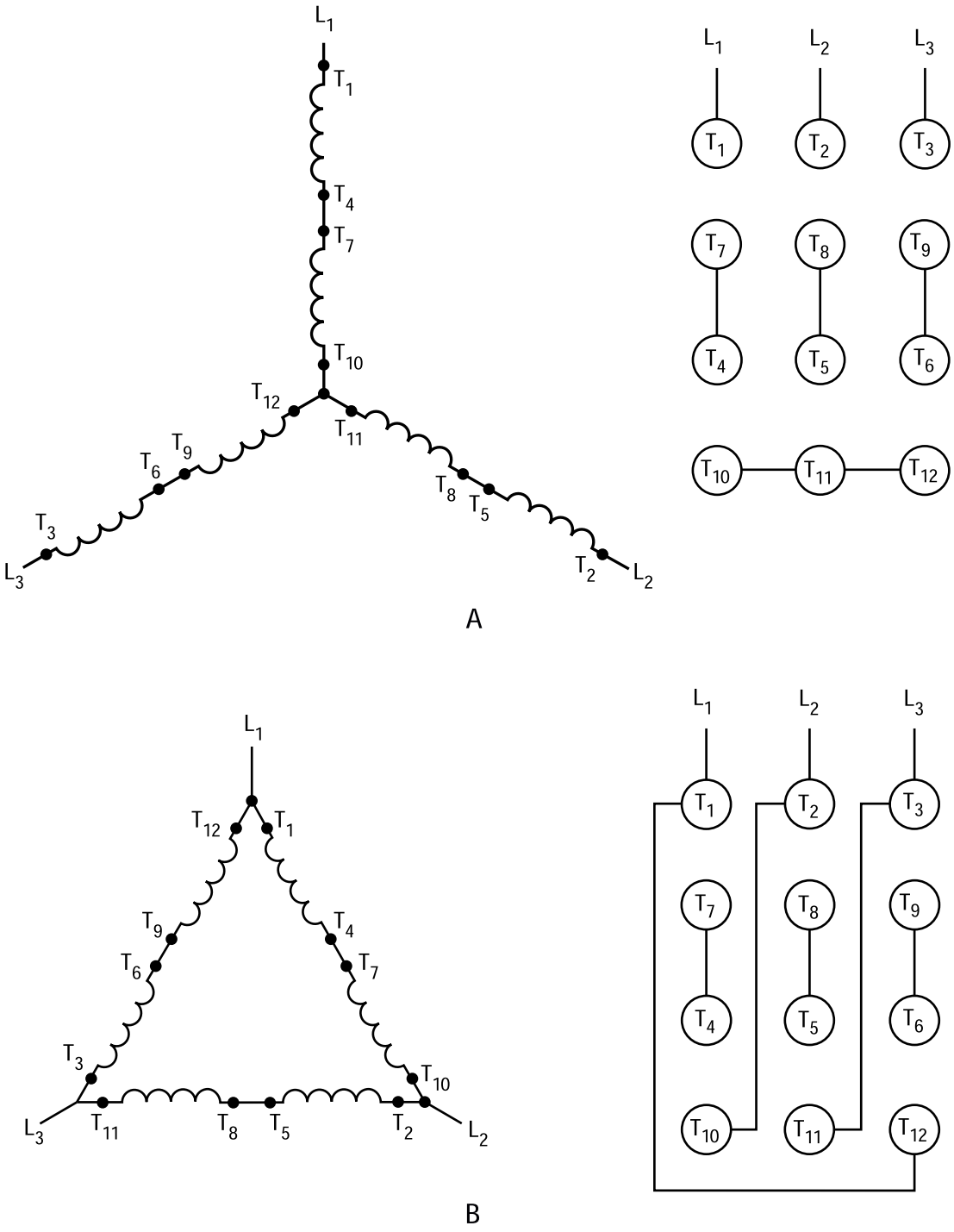


Figure 12—Higher voltage, 12-lead motor connections

Ensuring the proper motor rotation first time around

The numbering of terminals on polyphase induction motors in accordance with NEMA standards does not imply a standardized direction of rotation for the rotor shaft.

On some motors it is possible to connect the motor and momentarily energize it to see if it rotates in the desired direction. On some machines, however, even a momentary jog of the motor in the wrong direction could damage the machine. In this case, a motor-rotation indicator and a phase-sequence indicator should be used to ensure a connection that will produce the desired rotation.

Motor-rotation indicator

The motor-rotation indicator is used before any power is connected to the motor. It is not intended for live circuits. It has three leads marked A, B and C. These are attached to the three motor leads T_1, T_2 and T_3 after all the other terminal connections, except the line connections, are made in the motor.

The motor is then turned by hand in the desired direction. The indicator will read either ABC or CBA rotation. If it reads CBA, simply reverse the line leads designated A and C.

Phase-sequence indicator

The phase-sequence indicator is connected to the load terminals of the motor starter to determine the phase sequence of the supply. It too has three leads marked A, B and C.

Leads A, B and C are connected to terminals T_1, T_2 and T_3 on the motor starter, and the starter is momentarily energized. The indicator will read either ABC or CBA rotation. If it reads CBA, interchange any two of the line leads at the starter.

If the tested ABC on the motor starter is now matched to the tested ABC on the motor, the motor should rotate in the desired direction when power is applied.

 Now do Self-Test 3 and check your answers.

Self-Test 3

1. Between which terminals is continuity measured on a nine-lead motor that is delta-connected internally? List all of them.

2. Between which terminals is continuity measured on a nine-lead motor that is wye-connected internally? List all of them.

3. Draw a completed connection diagram for a nine-lead, delta-connected motor wired for the lower voltage delta.

4. Draw a completed connection diagram for a nine-lead, delta-connected motor wired for the higher voltage delta.

5. Draw a completed connection diagram for a nine-lead, wye-connected motor wired for the lower voltage wye.

6. Draw a completed connection diagram for a nine-lead, wye-connected motor wired for the higher voltage wye.

7. Draw a completed connection diagram for a 12-lead motor connected for the lower voltage delta.

8. Draw a completed connection diagram for a 12-lead motor connected for the higher voltage delta.

9. Draw a completed connection diagram for a 12-lead motor connected for the lower voltage wye.

10. Draw a completed connection diagram for a 12-lead motor connected for the higher voltage wye.

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 4:

Describe basic maintenance and troubleshooting for three-phase induction motors

A main reason why squirrel-cage induction motors are so popular is that they require less maintenance than other motors. This, however, does not mean that they should be installed and then ignored. Many motors fail early because a simple maintenance program was not established.

Basic maintenance

The following are random points on maintaining a squirrel-cage induction motor.

- Select a motor with an enclosure that is suitable for the environment to which it will be exposed. As well, since problems such as restricted cooling air flow can drastically shorten the life of a motor, keep the area around a motor clear so that air can circulate and carry excess heat away from it.
- Motors are often installed in very dusty areas or at the ends of conveyor belts where material can build up around the motor. Periodically check the motor and clean it off with dry compressed air.
- If the motor is an open type, you may also need to use dry compressed air to blow out dust from the windings. Better still, on some machines it is preferable to use a vacuum cleaner so that foreign material does not lodge deeper into the motor.
- Some motors come equipped with fittings for supplying grease to the bearings. Periodically pump grease into the bearings. Remember, however, that too much grease can do more damage than too little. Excess grease will get into the windings, where it may damage the insulation. Following the manufacturer's specifications minimizes the possibility of damage from improper greasing.
- Most mills or plants have scheduled periods of downtime. At this time you can perform a simple inspection that will reduce the risk of a failure during peak production times when downtime is extremely costly. Use all of your senses when you make these inspections: look at, listen to, feel and smell the motor and its connections.
- To begin an inspection, visually inspect the motor and surrounding area to determine whether the air flow is being impeded. The motor and the surrounding area should be clean.
- As bearings wear they become noisy. A stethoscope may be used to check the bearing for noise that would indicate wear and possible failure in the near future. Replacing a worn bearing during this scheduled downtime lessens the chances of failure during a peak production time.
- If a stethoscope is not available, use a screwdriver. Put your ear to the handle of the screwdriver and its tip on the motor near the bearing. Be very careful of the moving parts on the motor and of the machine it is driving. It takes a skilled ear and experience to detect bearing problems this way.

- Bearing manufacturers sell tools called *bearing analyzers*. They are small enough to fit in your pocket yet capable of measuring different vibration frequencies. Later readings may be compared with earlier readings to detect trends in the vibration. These subsequent readings can then be used to detect problems with bearings, couplings and alignment.
- A general motor vibration may indicate a damaged coupling or misalignment between the motor and the load. If these are suspected, check the coupling and the alignment.
- The terminal box on the motor can be opened and the connections inside checked. Look and smell for signs of overheating, which may indicate a loose or faulty connection. Visually inspect the insulation on the connections. Motor connections are subjected to a lot of vibration.
- Periodically test the motor to determine the condition of the winding insulation. On a low-voltage motor, this test can be done with a megger, or megohmmeter. If it is carried out on the line side of the starter, the motor's insulation and supply conductors can be checked together. That way, the terminal connections at the motor do not have to be opened and re-insulated.
- The megger should produce a voltage suitable for the motor being tested. Place it between the ground and each lead terminal connection in turn. Crank the megger long enough for the pointer to stabilize. This will take a few seconds. Normally the pointer will dip, indicating a low resistance as the line windings become charged. The pointer will then rise and stabilize after a period of time.
- On a low-voltage motor, any reading of 1 megohm or larger is generally considered acceptable. The following is a general rule for minimum insulation resistance:

$$R_m = kV + 1$$

where:

R_m = the minimum resistance in megohms
kV = the kilovolt rating of the machine

For example, using this rule of thumb, the minimum resistance for a 600-volt machine would be:

$$R_m = \frac{600}{1000} + 1M\Omega$$
$$= 1.6\ M\Omega$$

After testing with a megger, connect the line being tested to ground to discharge any capacitive charge that may exist between it and the ground.

Troubleshooting

Table 1 lists typical motor problems, the possible causes and the remedial measures to take.

Table 1: Troubleshooting AC motor problems

Problem	Possible cause	Remedy
Motor stalls.	Application is incorrect.	Change the type or size of the motor. Discuss the problem with the manufacturer.
	Motor is overloaded.	Either reduce the load or replace the motor with a motor of higher capacity.
	Motor voltage is low.	Restore to voltage marked on the nameplate.
	Circuit is open or fuses are blown.	Reset the overload relay; check for open leads. Replace fuses.
	Rotor is rubbing.	Replace bearings.
Motor is connected but won't start.	One phase is open.	Repair the lead connections.
	Overloaded motor.	Reduce the load.
	Defective rotor.	Check the rotor for broken bars or rings; replace the rotor.
	Bad connection to stator coil.	Find and repair the open wire.
	Fuse is blown, breaker tripped.	Replace fuse or reset breaker.
	Bearings are frozen or rotor is rubbing.	Replace bearings.
	Starting (single-phase) relay is open.	Replace or repair the relay.
Motor runs, then dies.	Motor is overloaded.	Reduce the load.
	Power failure.	Inspect the motor for loose connections to the line, to the fuses and to the control.
Motor takes a long time to accelerate.	Bad circuit.	Check for high-resistance connections, then repair.
	Too much loading.	Either reduce the load or increase the size of the motor.
	Squirrel-cage rotor is defective.	Install a new rotor.
	Not enough voltage is applied.	Apply the correct voltage.
Motor does not come up to speed.	Motor is improperly applied.	Get in touch with the supplier or manufacturer.
	There is a line drop and the voltage at the terminals has become too low.	Use a larger wire size or a higher voltage on the transformer terminals.
	Load on starting is too high.	Increase the motor size or check into unloading until motor is at full speed.

Problem	Possible cause	Remedy
	If this is a wound motor, secondary resistance may be improperly controlled.	Correct the secondary control operation.
	Primary circuit is open.	Locate the fault and repair.
	Rotor bars are broken.	Inspect for cracks near the end rings and replace the rings if they are defective.
Motor runs backwards.	Three-phase motor: Connection or phase sequence is wrong.	Reverse any two leads.
	Single-phase motor: Connection is wrong.	Reverse the starting winding leads.
Motor overheats while running under load.	Check for overload.	Reduce the load, or increase the size of the motor.
	Motor is improperly ventilated because air passages are clogged with dirt.	Clean the air passages.
	One phase of motor is open.	Check all the leads to make sure they are properly connected.
	Coil is grounded.	Find the coil and repair it.
	Unbalanced voltage at the terminals.	Check for faulty leads, wiring and connections, and repair.
	Stator coil is shorted.	Repair or replace stator.
	Connection is faulty.	Repair the connection.
	Voltage is too high or too low.	Use a voltmeter to check the motor terminals, then adjust the voltage.
	Rotor is rubbing stator bore.	Replace the worn bearings.
Motor vibrates.	Motor is misaligned.	Realign the motor.
	Motor base is weak.	Strengthen the motor base.
	Coupling is out of balance.	Balance the coupling.
	Bearing(s) are defective.	Replace the bearing(s).
	Unbalanced driven equipment.	Rebalance the driven equipment.
	Balancing weights have shifted.	Rebalance the rotor.
	Bearings are out of line.	Line up the bearings correctly.
	Polyphase motor: motor is running single-phase.	Check for an open circuit.
Bearings are hot.	Shaft is bent.	Straighten the shaft or replace it.
	Belt pull is excessive.	Reduce tension on the belt.
	Drive is misaligned.	Realign the drive.
	Not enough lubrication.	Lubricate.
	Grease has deteriorated, or lubricant is contaminated.	Remove the old grease; wash the bearings in solvent; apply new grease.
	Too much lubricant.	Reduce the amount of grease. (Bearings should not be more than half-filled.)

Problem	Possible cause	Remedy
	Motor or some other nearby source is hot and giving off heat.	Provide a shield or introduce additional cooling.
	Overloaded bearing.	Check the bearing alignment, side thrust and end thrust.
	Broken ball or rough races.	Replace the bearing and clean the housing.
During normal operation of three-phase motor, line current is unbalanced.	Voltage at terminals are unequal.	Check leads and connections.
	Motor operating single-phase.	Check for open contacts or wiring.
	Poor contact between rotor brush and wound rotor resistance.	Renew and reseat the brushes.
	Turns in stator coil are shorted.	Repair or replace the stator.
Mechanical noise.	Fan is rubbing the air shield.	Locate the interference and remove it.
	Fan is striking the insulation.	Locate the interference and remove it.
	Motor has become loose on bedplate.	Tighten the bolts that hold it to the plate.
	Bearing or bearings have failed.	Replace the bearing(s).
	Excessive vibration.	Rebalance the rotor.
	Rotor rubbing.	Replace the bearings.
	Coupling is loose.	Tighten the bolts on the coupling.
Magnetic noise.	Air gap not uniform.	Adjust the fit of the bracket and bearings.
	Bearings are loose.	Replace the bearings.
	Rotor not balanced.	Rebalance the rotor.


Now do Self-Test 4 and check your answers.

Self-Test 4

1. Many motors fail early because a simple maintenance program is not implemented.

   a. True

   b. False _____

2. Why is it important to ensure unrestricted air flow around the motor?

3. Is too much grease better than too little grease on the bearings of motors? (Give the reason for your answer.)

4. As a general rule, what minimum resistance is acceptable for a low-voltage motor?

5. Is excessive vibration likely caused by a misaligned motor and load?

6. When taking an insulation-resistance test with a megger, the pointer first dips down to low resistance and then slowly rises. Is this cause for concern? (Give the reason for your answer.)

7. To clean dust out of some motors it is better to use a vacuum cleaner than compressed air.
   a. True
   b. False _____

8. List four senses that should be used when inspecting motors.

_____

_____

_____

_____

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 5:

Describe the constructional features of the wound-rotor induction motor

The principal components of the three-phase wound-rotor induction motor are the:

- Stator
- Rotor
- Slip rings and brushes
- End bells and bearings
- Nameplate

Stator

The stator of a three-phase wound-rotor induction motor is the same as that of the three-phase squirrel-cage induction motor. The rotating magnetic field is produced in exactly the same way. The windings may be connected in either wye or delta and are also available in single or dual voltage. Stator terminal identification is also the same as for the squirrel-cage induction motor.

Rotor

The rotor in the wound-rotor induction motor is where the difference lies, since it does not have a squirrel-cage design. The rotor consists of a laminated cylindrical iron core containing an insulated, three-phase winding. This winding is wound to have the same number of poles as the stator. They are laid out like the stator windings except that the rotor windings must be able to withstand the rotational forces. The rotor windings may be connected in either wye or delta, with three leads brought out and connected to three slip rings mounted on the rotor shaft.

Since the rotor, like a transformer, receives its power through electromagnetic induction, the rotor circuit is often referred to as the *secondary circuit* of the motor.

Slip rings and brushes

Brush holders, mounted on the stationary part of the motor, support the brushes, which ride on the slip rings. The three brushes are connected to terminals designated M_1, M_2 and M_3. The brushes and slip rings allow the rotor windings to be connected to an external resistance grid, as shown in Figure 1.

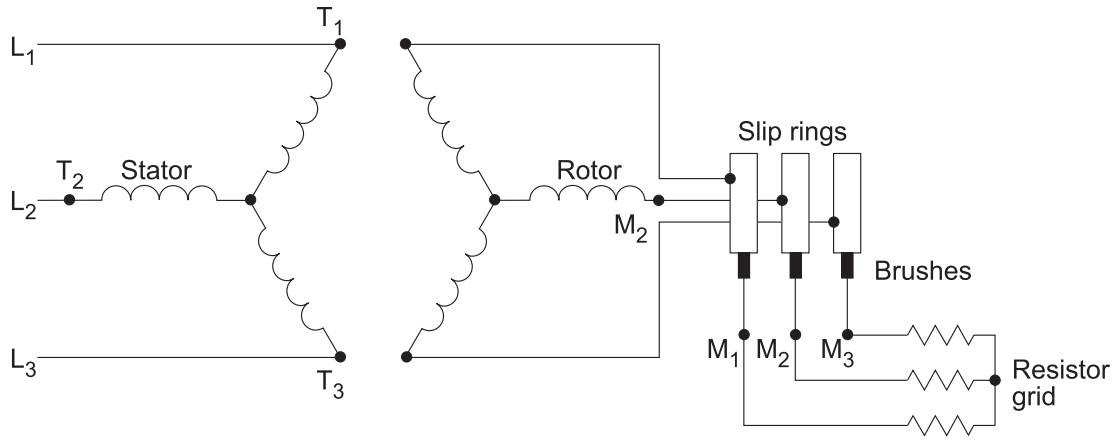


Figure 1—Rotor connection to an external resistance grid

The three slip rings are usually made of brass or copper and are insulated from the rotor shaft.

The brushes are commonly graphite carbon, although other materials may be used as well. The brushes carry induced rotor current from the slip rings to the external resistor circuit. They must make good electrical contact and have long life without causing excessive wear on the slip rings.

The brushes are attached by means of brush arms and brush holders, to the stationary part of the motor so they will be held still as the rotor turns (Figure 2). The brushes are free to slide in their holders and a spring is used to force the brush against its slip ring. This allows for continuous contact between the brushes and the slip rings.

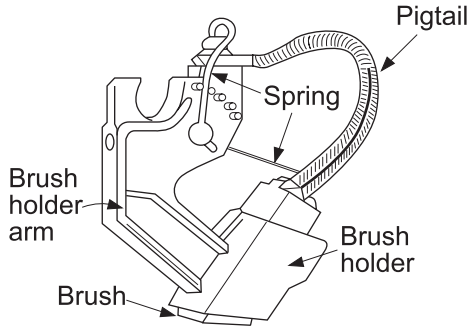


Figure 2—Brush holders mounted on the motor support

Attached to each brush is a piece of flexible conductor (called a *pigtail* or *shunt*) that is used to connect the brushes to the external rotor (secondary) terminals.

End bells and bearings

The end bells and bearings serve the same function as in the squirrel-cage motor. As well, the end bells often provide the support for the brush holder mechanisms.

Nameplate

The nameplate of a wound-rotor induction motor contains the same information as that on a squirrel-cage induction motor. The wound-rotor induction motor nameplate also lists the maximum rotor voltage and current ratings. These two ratings are important for selecting the proper insulation ratings and current ratings for equipment attached to the secondary circuit of the motor.

 Now do Self-Test 5 and check your answers.

Self-Test 5

1. How does the rotor of a wound-rotor induction motor differ from that of a squirrel-cage induction motor?

2. What is the purpose of the three slip rings and their corresponding brushes on the wound-rotor motor?

3. How are the three rotor terminals designated?

4. What is the purpose of the spring on the brush holders?

5. What is the purpose of the pigtail or shunt attached to each brush?

6. What two additional pieces of information are normally supplied on the nameplate of a wound-rotor induction motor that you would not find on a squirrel-cage induction motor?

7. For what would an electrician use the two pieces of information in Question 6?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 6:

Describe the operating characteristics of the wound-rotor induction motor

Many of the operating characteristics of the wound-rotor induction motor are the same as those of the squirrel-cage induction motor. This Learning Task describes some of the particular characteristics of the wound-rotor induction motor.

The rotating magnetic field

The rotating magnetic field and its synchronous speed are produced in exactly the same way as in the squirrel-cage induction motor. The synchronous speed may be calculated by the following equation:

$$n = \frac{f \times 60}{p}$$

where:

- n = the synchronous speed of the motor in rpm
- f = the frequency of the supply voltage in Hz
- p = the number of pairs of poles per phase in the motor
- 60 = used to convert from cycles per second to cycles per minute

Induced rotor currents

As the magnetic field cuts across the rotor windings, it induces an alternating voltage in the windings, just as it did in the squirrel-cage induction motor. If an external connection is made between the secondary terminals M_1, M_2 and M_3, the secondary circuit is completed. Current will then flow in the secondary windings. This current will produce a torque—just as it did in the squirrel-cage induction motor—that will tend to cause the rotor to turn in the same direction as the rotating stator field.

Torque versus speed characteristics

You have learned that the resistance value of the rotor affects the torque characteristics of the motor. In a squirrel-cage motor, this can only be done at the motor's design stage, since the resistance of the rotor depends upon the length and area of the rotor bars.

In a wound-rotor motor, changing the resistance of the rotor circuit may be done at any time because the rotor circuit is completed outside of the motor at the terminals M_1, M_2 and M_3. Figure 1 shows how the resistance connected between the three terminals may be varied.

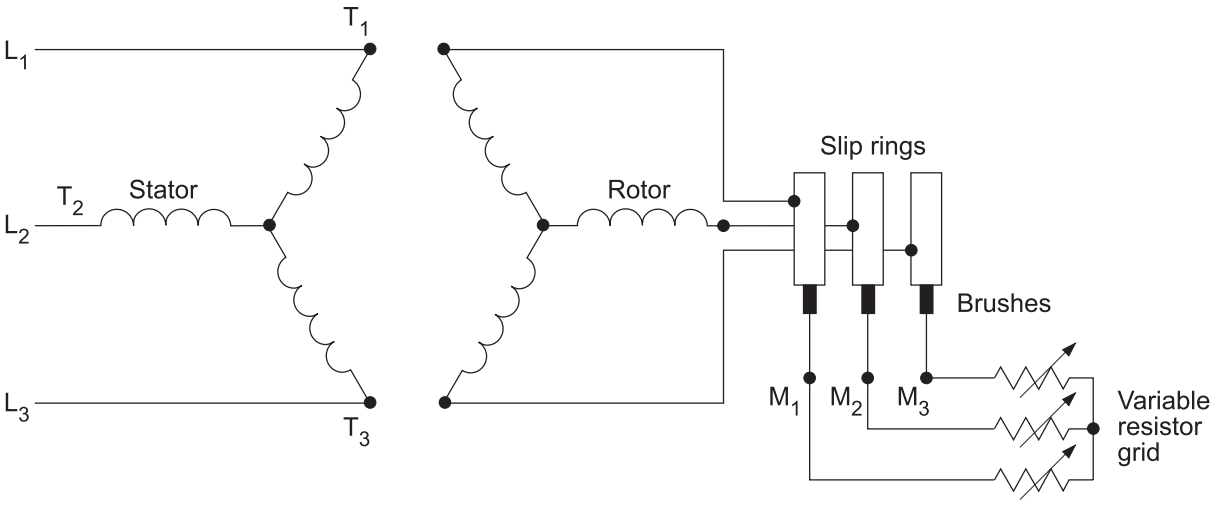


Figure 1—Variable resistance in the rotor circuit

The maximum torque is produced in the induction motor at the speed where the resistance of the rotor circuit is approximately equal to the rotor reactance. Changing the resistance of the rotor circuit does not affect the magnitude of the maximum torque produced by the motor. This is only true up to the point where the resistance of the rotor circuit is equal to the locked rotor reactance of the circuit. Increasing the resistance any further than this decreases both the starting torque and the breakdown torque.

By changing the resistance of the rotor circuit you can easily change the speed at which breakdown torque occurs.

The windings of the wound-rotor induction motor have many turns, giving the rotor a much higher inductance than that of a squirrel-cage induction motor. When the motor is started, slip is 100% and the frequency of the voltage induced in the rotor is equal to that of the supply. With the secondary terminals of the wound-rotor motor short-circuited and the rotor not turning, the power factor of the rotor is very low and at its worst at this point. The current in the rotor lags the stator flux by a large angle, producing a very poor torque and an inability of the motor to start. Figure 2 shows a torque versus slip curve for a wound-rotor induction motor with its secondary terminals short-circuited (no external resistance connected).

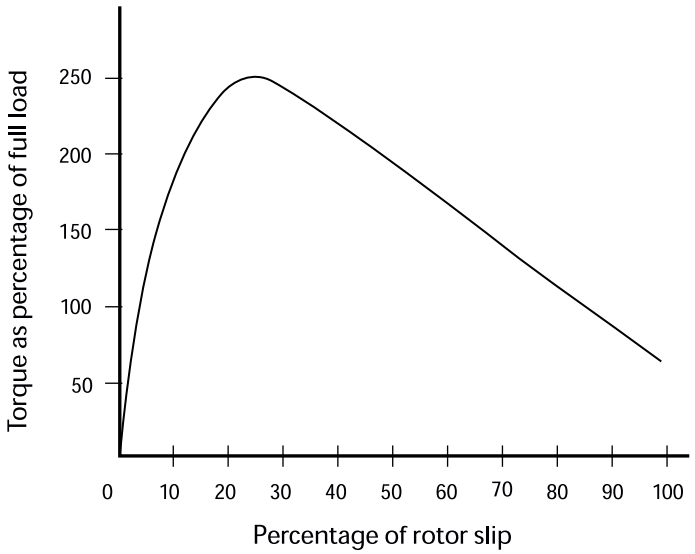


Figure 2—Torque versus slip with secondary terminals short-circuited

The starting torque of a wound-rotor motor is improved by inserting resistance across the secondary terminals M_1, M_2 and M_3. This lowers the rotor current but at the same time improves the rotor power factor. The effect of the improved power factor is greater than that of the decreased current. Since both are directly proportional to the torque produced by the motor, the starting torque increases. Maximum starting torque is produced when the resistance of the secondary circuit is equal to its locked rotor reactance. In this case, starting torque is equal to breakdown torque. Figure 3 shows a graph of torque versus slip for the motor when the optimal starting resistance is placed in the secondary circuit.

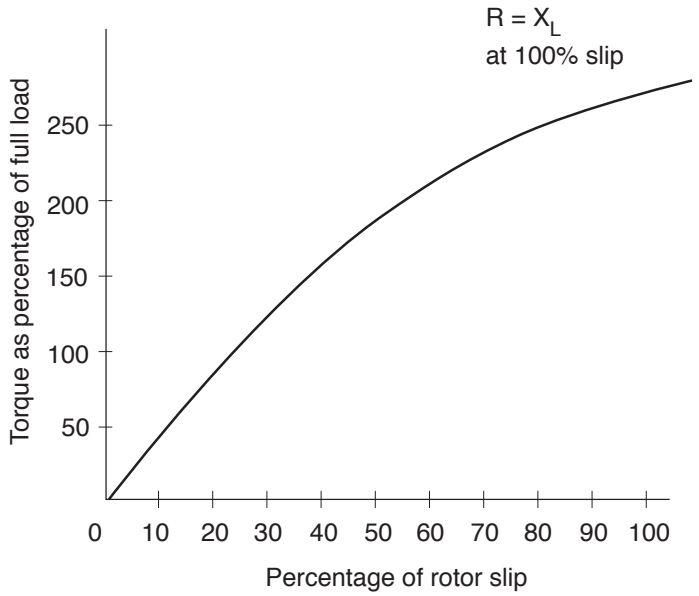


Figure 3—Torque versus slip when the optimal starting resistance is placed in the secondary circuit

If the starting resistance is left in as the motor accelerates, the torque produced by the motor immediately starts to decrease. Notice in Figure 3 that full-load torque occurs at approximately 22% slip. This would be unacceptable speed regulation. To improve the torque output of the motor and the speed regulation, the resistance in the rotor circuit is decreased as the speed of the motor increases. This changes the speed at which breakdown torque occurs. Figure 4 shows the torque versus slip for the motor when half of the starting resistance is removed from the rotor circuit.

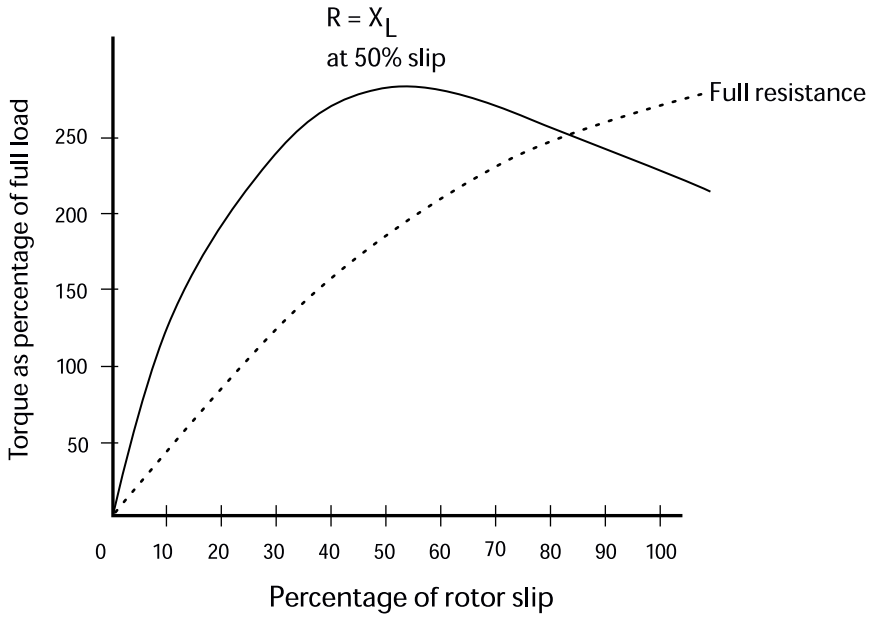


Figure 4—Torque versus slip when half of the optimal starting resistance is removed from the secondary circuit

Notice that the breakdown torque has been shifted over so that it now occurs at 50% slip rather than 100% slip. With this resistance left in the circuit, the motor will accelerate and reach full-load torque at about 10% slip. A slip of 10% is still relatively high speed regulation, and a great deal of heat energy is being wasted by the resistors in the secondary circuit.

If all of the rotor circuit resistance were moved, the torque curve would again shift so that the breakdown torque occurs at about 25% slip and full-load torque occurs at less than 5% slip. This is shown in Figure 5.

This speed regulation is quite acceptable and there is much less energy being wasted as heat at the secondary resistors.

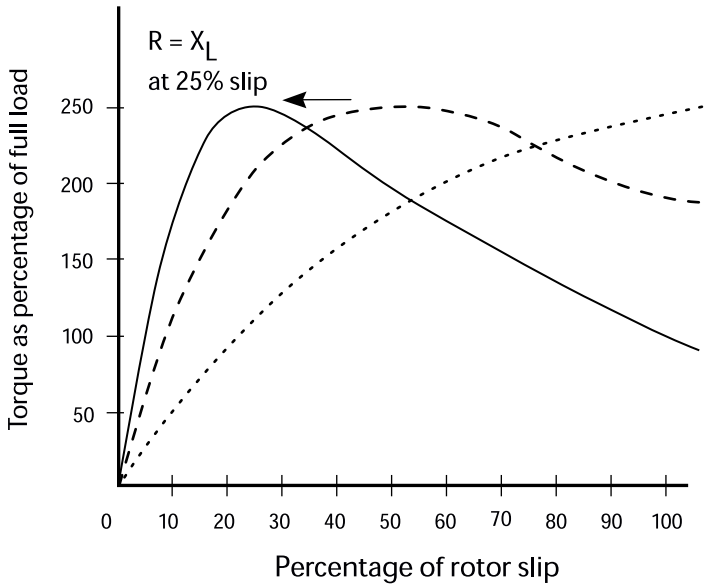


Figure 5—Torque versus slip when all of the secondary resistance is removed and the secondary leads are short-circuited

Efficiency

The efficiency of a wound-rotor induction motor is very low when the resistance is left connected in the secondary circuit. A great deal of energy is being converted into heat at the secondary resistors. However, once the resistance is removed from the secondary circuit, the efficiency is comparable to that of the squirrel-cage induction motor.

Speed control

The wound-rotor motor is intended to be a variable-torque motor, but it may also be used (to a limited extent) as a variable-speed motor.

The motor speed may be controlled somewhat by controlling the slip of the rotor. As more resistance is added to the rotor circuit, the slip increases. You can vary the speed of the wound-rotor motor up to about 50% slip by simply adding resistance to the secondary circuit of the motor. At speeds of more than 50% slip, the speed stability of the motor becomes unsatisfactory, and the efficiency of the motor decreases considerably.

Figure 6 shows graphs of torque versus slip for four different values of rotor resistance, with:

- Graph A having *no* external resistance in the rotor circuit
- Graph D having the *maximum* resistance in the rotor circuit

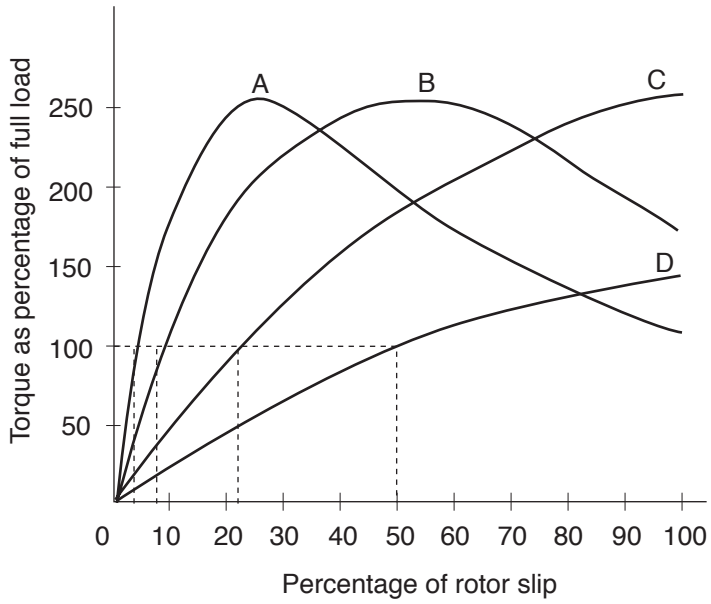


Figure 6—Slip at full-load torque versus rotor resistance

A vertical line dropped to the horizontal axis at the point where each graph passes through 100% of full-load torque shows the slip at full-load torque. Notice that even a small change in torque required by the load on graph D represents a large change in rotor speed. This shows the speed instability.

Regenerative electronic speed controllers may be used in place of secondary resistors. The resistors change electrical energy into heat that is wasted. However, electronic controllers convert this energy into three-phase energy and feed it back into the supply side of the wound-rotor motor, which is a form of regeneration.

Duty cycle of secondary resistors

The resistors used for starting and speed control must dissipate a large amount of energy in the form of heat. To avoid damaging the resistors by this heating, their wattage rating must be determined. Resistors used only for starting generally have long periods of cooling between starts. Those used for speed control must be able to dissipate this energy on a continuous basis. For this reason, the resistors used for starting may be made smaller and given a duty cycle.

Reversing the rotation

Reversing the direction of rotation on a wound-rotor motor is done exactly as on a squirrel-cage induction motor. The rotor follows the direction of the rotating magnetic field created in the stator. To reverse the direction of the motor, the direction of the rotating field must be reversed. This is accomplished by interchanging any two of the line leads to the stator.

Advantages of wound-rotor motors

The main advantage of the wound-rotor induction motor over the squirrel-cage induction motor is its adjustable torque. This leads to the following advantages:

- High starting torque with low current
- Smooth acceleration under heavy load
- No abnormal heating during starting
- Good running characteristics after the starting resistance is removed
- Adjustable speed

High starting torque with low current

When resistance is added to the rotor circuit at starting, the power factor of the rotor circuit is improved and the current in the rotor circuit becomes more in phase with the stator flux. This means more of the rotor conductors produce a torque in the desired direction, increasing the resultant torque. The resistance also lowers the rotor current, which tends to reduce the rotor torque. However, the reduced current has much less effect than that of the improved power factor at starting.

Smooth acceleration under heavy load

A motor will continue to accelerate as long as the torque produced by the motor exceeds that required by the load. The greater the difference between the torque produced by the motor and the torque required by the load, the faster the acceleration.

Normally, as a wound-rotor motor is started and accelerated, the resistance in the rotor circuit is reduced in steps. By timing the reduction of resistance, the accelerating torque can be held relatively constant. Figure 7 shows a resistance grid connected to a wound-rotor motor. This motor is started in four steps (described following Figures 7 and 8).

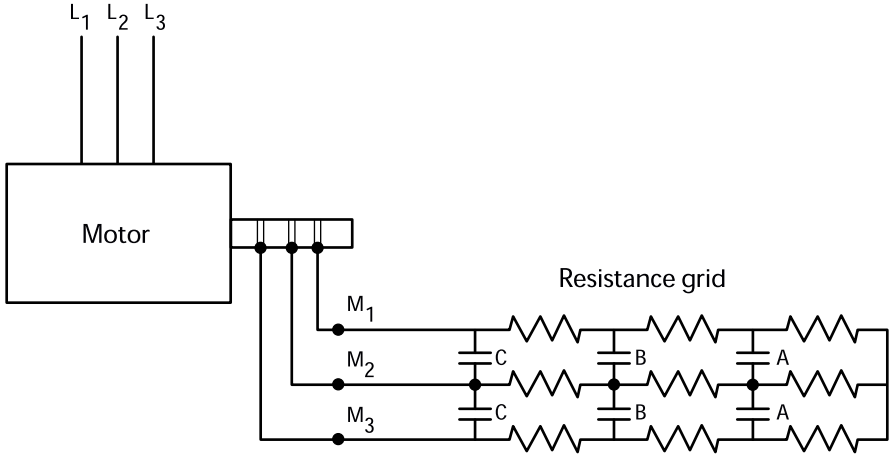


Figure 7—Four-step starting of a wound-rotor motor

The torque curves for each of the steps are shown in Figure 8.

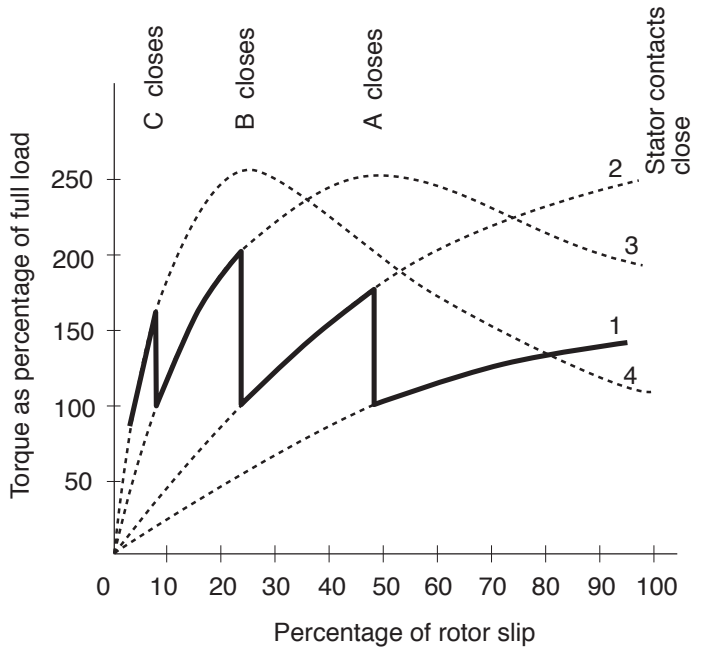


Figure 8—Torque curves for the four-step starter

Step 1: The primary line contacts are closed and contacts A, B and C are open. This places the whole secondary resistance in the rotor circuit. Notice that when a set of contacts closes, it simply moves the wye point closer to the motor. Any of the resistors to the right of the wye point are then short-circuited and may be considered ineffective. The torque curve for this secondary resistance with all contacts open is shown as curve number 1. The motor produces a starting torque of approximately 150% of full-load torque.

As the motor accelerates, the torque begins to drop off.

Step 2: At about 50% slip, the torque has fallen to 100% of full-load torque. If no resistance is removed from the rotor circuit, the motor will stop accelerating and maintain this speed. However, at this point, the A contacts close, removing some resistance from the rotor circuit. The torque rises to about 175% of full-load torque and the motor starts to follow torque curve number 2.

Again, as the motor continues to accelerate, the torque begins to drop off.

Step 3: At about 25% slip, the torque has fallen to 100% of full-load torque. Contacts B close. The torque rises to about 200% of full-load torque and the motor starts to follow torque curve number 3.

Once again the torque begins to drop off as the motor accelerates.

Step 4: At about 8% slip, the torque has fallen to 100% of full-load torque. Contacts C close. The torque rises to about 160% of full-load torque and the motor starts to follow torque curve number 4.

The motor now accelerates up to full-load speed and stabilizes at about 3% slip.

Notice that from 100% slip up to about 3% slip, the accelerating torque is fairly steady between about 100% and 200% of full-load torque. This leads to a relatively smooth acceleration under heavy loads. The more steps incorporated in the starter, the smoother the acceleration can be.

No abnormal heating during starting

In a squirrel-cage induction motor, the current in the rotor is inversely proportional to the speed. If a high inertial load is driven by this motor, it may take a long time to accelerate up to speed. During the time this motor is accelerating, the current in the rotor circuit is higher than normal, causing the rotor to become hot. If the acceleration lasts too long, or if the motor is started and stopped often, the rotor may overheat (as well as the stator).

In a wound-rotor motor, the current in the rotor is kept low during acceleration by the external resistance added to the rotor circuit. Because the rotor current is kept low, the rotor is not subject to the same overheating problem. The wound-rotor motor is, therefore, better suited to prolonged high-inertia starts.

Good running characteristics after the starting resistance is removed

A squirrel-cage motor that is designed to produce a high starting torque typically has a high speed regulation associated with it. The wound-rotor motor can have both high starting torque and low speed regulation. By inserting resistance in the rotor circuit during starting, it has the high starting torque. If the rotor resistance is removed as the rotor comes up to speed, it will behave like a low resistance rotor at rated load. In other words, it will have a low percentage of slip. Typically, the percentage of slip is not as good as that of a standard squirrel-cage motor but usually less than 5%.

Adjustable speed

The speed of the wound-rotor motor may be varied by changing resistance to the secondary circuit to alter the torque versus speed characteristics. This affects the percent slip of the motor.

Disadvantages of the wound-rotor motor

If the wound-rotor motor only had advantages over the squirrel-cage induction motor, no one would use squirrel-cage induction motors. However, there are more squirrel-cage induction motors in use than wound-rotor motors. Some of the disadvantages of wound-rotor motors are:

- Physical size
- Higher initial and maintenance costs
- More complicated control
- Poor speed regulation when the secondary resistance is left in the circuit

Physical size
The wound-rotor motor is much larger and heavier than the squirrel-cage induction motor. The brushes and slip rings required in the wound-rotor motor occupy space and increase the motor's size. In some situations, wound-rotor motors cannot be used because the motor is impossible to fit in a limited space, or the overall weight of the machine is too great.

Higher initial and maintenance costs
Because much more labour is needed in its production, the wound-rotor motor is more expensive to manufacture than a simple squirrel-cage rotor. Maintenance costs are also higher than with squirrel-cage induction motors because the slip rings and brushes require periodic maintenance.

More complicated control
The control of a wound-rotor motor is more complicated. It involves components in both the primary and secondary circuits of the motor. These extra components may also add to the maintenance costs of the motor.

Poor speed regulation when the secondary resistance is left in the circuit
When resistance is left in the secondary circuit for speed control, the speed regulation of the motor is much poorer. This is not a problem if the secondary resistance is only used to control the starting torque and is removed once the motor has accelerated up to speed. The speed regulation of a wound-rotor motor with no secondary resistance left in the circuit is only slightly worse than that of a standard squirrel-cage motor.

As well as poor speed regulation, the efficiency of the wound-rotor motor is reduced when the resistance is left in the secondary circuit because of the heat dissipated by the resistors.

Applications for wound-rotor motors
The wound-rotor motor is basically a variable-torque motor, although it may also be used for limited applications where speed control is required. Most applications for wound-rotor motors are those requiring high starting torque and/or smooth acceleration.

Wound-rotor motors have been used for:

- Driving overhead cranes
- Starting ball mills
- Driving loaded conveyors

Overhead cranes
Bridge cranes (overhead cranes) are used in many construction and maintenance shops. These cranes are installed above the shop floor on two beams mounted on opposite walls. The crane travels on the beams, which stretch from one end of the shop to the other. They have both side-to-side and end-to-end motion as well as the ability to raise and lower the load. In this way, a load may be picked up and put down anywhere in the shop.

To enable such cranes to travel, wound-rotor motors are often used. This is where a large torque is needed to move the load and the whole crane along the beams. The acceleration must also be very controlled and smooth so that the load does not swing too much.

The hoist on the bridge crane may also incorporate a wound-rotor motor connected through a gearbox to reduce the speed of the load and the amount of torque required from the crane motor.

Ball mills

A *ball mill* is a large drum used for crushing ore. The ore and the iron balls are placed in the drum and tumbled to break up the ore into smaller pieces. A wound-rotor motor provides the required torque to start this extremely heavy drum and bring it up to speed.

Loaded conveyor

A conveyor fully loaded with something like gravel requires a great deal of torque to get moving again once it stops. If the conveyor takes a long time to get up to speed and is stopped and started often, the rotor of a squirrel-cage motor might overheat. The wound-rotor motor limits the starting current at the same time as it produces the high torque requirements. A torque curve for a three-step starter that might be used to provide the maximum rate of acceleration is shown in Figure 9.

Notice that the starting torque is kept high by closing contacts to remove resistance just at the point where the torque curves cross each other. In this way the pull-up torque is kept above 200% of full-load torque up until about 10% slip. This would, however, put tremendous stress on the whole conveyor system.

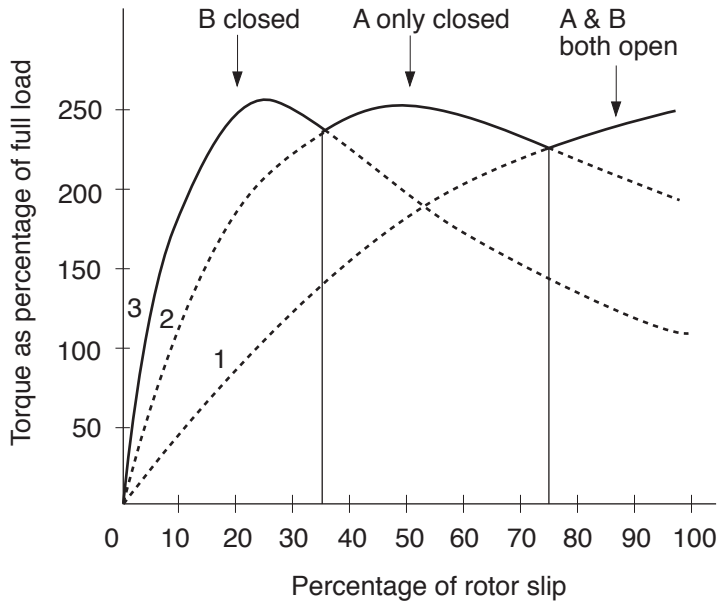


Figure 9—Torque curve of a three-step starter used to achieve maximum rate of acceleration

Other examples

Other examples of where a wound-rotor motor might be used are: train car pullers, loaded compressors, drum driers, extruders, semisolid mixers, loaded pumps and starting motors for inertia drives.

 Now do Self-Test 6 and check your answers.

Self-Test 6

1. Calculate the rotor speed of an eight-pole, 60-hertz wound-rotor motor operating at 30% slip.

2. A wound-rotor motor is designed mainly to be a variable-_____ motor.

3. With respect to locked rotor reactance, what value of rotor resistance will give maximum starting torque?

4. Torque is directly proportional to rotor current. Why is it, then, that increasing the resistance of the rotor circuit increases the torque output of the motor?

5. With the secondary terminals M_1, M_2 and M_3 short-circuited, will the starting torque of the wound-rotor motor be high or low?

6. Why is the efficiency of the wound-rotor motor poor when resistance is left in the rotor circuit?

7. To decrease the speed of a wound-rotor motor, the resistance is:

   a. added to the rotor circuit, or

   b. taken out of the rotor circuit _____

8. Why is it not practical to control the speed of a wound-rotor motor below 50% slip?

9. What does the term *duty cycle* mean when applied to the secondary resistors?

10. How is the direction of rotation reversed on a wound-rotor motor?

11. State three advantages a wound-rotor motor has over a squirrel-cage induction motor.

12. State three disadvantages a wound-rotor motor has over a squirrel-cage induction motor.

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 7:

Describe basic maintenance and troubleshooting for wound-rotor induction motors

The troubleshooting procedures for the wound-rotor motor include those listed for squirrel-cage motors in Unit 1. The differences in maintaining and troubleshooting a wound-rotor motor are associated with the differences in the rotor design. The squirrel-cage motor does not have brushes and slip rings, nor the external secondary circuit.

Brush and slip ring maintenance

The rotor circuit is completed externally on a wound-rotor motor. Completion of this circuit depends on the brushes and slip rings doing their job properly. As the motor turns, the brushes ride on the slip rings. An electrical connection is made between the moving slip rings and the stationary brushes.

Friction occurs between the slip rings and the brushes. So brushes are designed to be softer and wear out faster than the slip rings. Periodically you must inspect the brushes for wear and replace them when they are worn to about ¼ of their useful length.

If you notice rapid brush wear or arcing at the brushes, check the brush holder and spring tension. You should also inspect the brush holder for its mechanical condition, and to ensure that the brush is free to move inside the holder.

The spring tension should be neither too weak nor too strong. Use the manufacturer's specifications to adjust spring tension. Where specs are not available, use a pressure of 2 psi (1.38 kPa) as a relatively safe rule.

- Too much spring pressure causes excessive wear but is better than too little spring pressure.
- Too little spring pressure causes poor electrical contact and can cause heat and arcing, which will do far more damage than too much pressure.

New brushes should be properly seated on the slip rings to avoid a poor surface contact.

Open circuit in the secondary circuit

Current must flow in the rotor windings to produce torque. If an open circuit occurs in the secondary circuit, it will prevent current from flowing in the secondary rotor windings. The open may occur in a number of places:

- In the rotor windings themselves
- At the brushes
- In the resistance bank or controller
- In the interconnecting wiring

Opens in the secondary circuit can cause a failure of the motor to start or a slow running motor.

To determine if the open is in the rotor itself or in the external circuit, the slip rings may be short-circuited. This eliminates the external secondary circuit altogether. If the motor behaves properly, the open is likely in the external circuit. It is important when performing this task that the motor be unloaded or very lightly loaded. This is because the motor will produce a low torque with shorted slip rings.

 Now do Self-Test 7 and check your answers.

Self-Test 7

1. What sort of symptoms might you expect if an open occurs in the secondary circuit of a wound-rotor motor?

2. Where might the open mentioned in Question 1 occur?

3. If the manufacturer's specifications for brush pressure are not available, what is a safe rule to use?

4. Is it better to have the brush pressure too high or too low?

5. When should a brush be replaced?

6. If a wound-rotor motor is connected up and runs with the wrong rotation, how do you remedy this situation?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 8:

Describe the constructional features of three-phase synchronous motors

Stator

The stator of a three-phase synchronous motor is similar to that of the squirrel-cage induction motor described earlier. The rotating magnetic field is produced in exactly the same way. The windings may be connected in either wye or delta and are also available in single or dual voltage. Stator terminal identification is the same as for the squirrel-cage induction motor.

Rotor

The rotor of a synchronous motor is essentially a DC electromagnet with the same number of field poles as in the stator. The poles in most rotors are of the salient type: they project out from the rotor as shown in Figure 1.

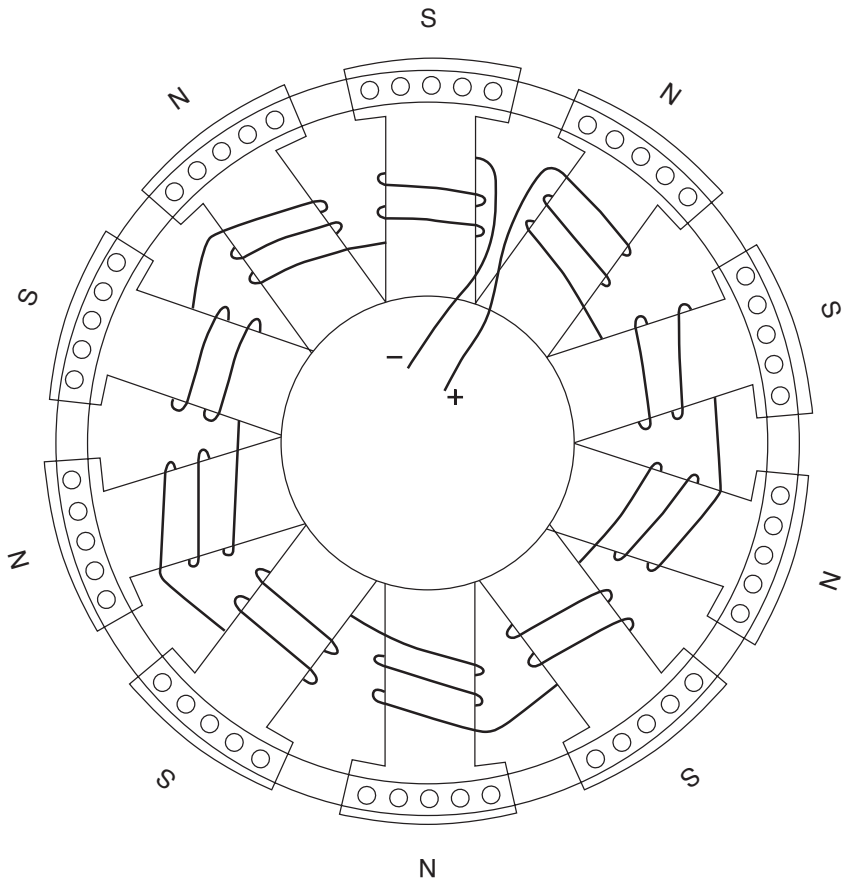


Figure 1—Rotor for a 10-pole synchronous motor

The field poles are fed from a direct-current source, so the poles remain constant and do not change polarity.

Synchronous motors also incorporate a squirrel cage in their rotor construction. Conductive bars are placed near the surface of the rotor and short-circuited at both ends to form the squirrel cage. This cage design is sometimes referred to as a *damper winding* or *amortisseur winding*. It is used to dampen any momentary speed fluctuations that may occur when the load on the motor is suddenly changed. On some machines, the amortisseur winding is also used for starting the motor.

Slip rings and brushes

The direct-current field pole windings are connected to two slip rings mounted on the rotor shaft. Brush holders mounted on the end bells support the brushes that complete the electrical connection between the slip rings and the rotor circuit. The two brushes are connected to two terminals marked F_1 and F_2. The DC source is connected to these two terminals to supply the field winding excitation.

There are three common methods of supplying the synchronous motor with DC field current:

- External converters
- Built-in exciters
- Brushless exciters

External converters

Usually an external converter is simply a rectifier. This method of DC field current is used normally when the supply is already available in the plant to supply other machines. Figure 2 shows a synchronous motor with its stator connected to a three-phase AC supply and its rotor connected to a DC supply.

Note that this is a simplified diagram and does not contain many of the control devices. The rheostat shown controls the level of DC excitation. Control circuit details for synchronous motors will be discussed later.

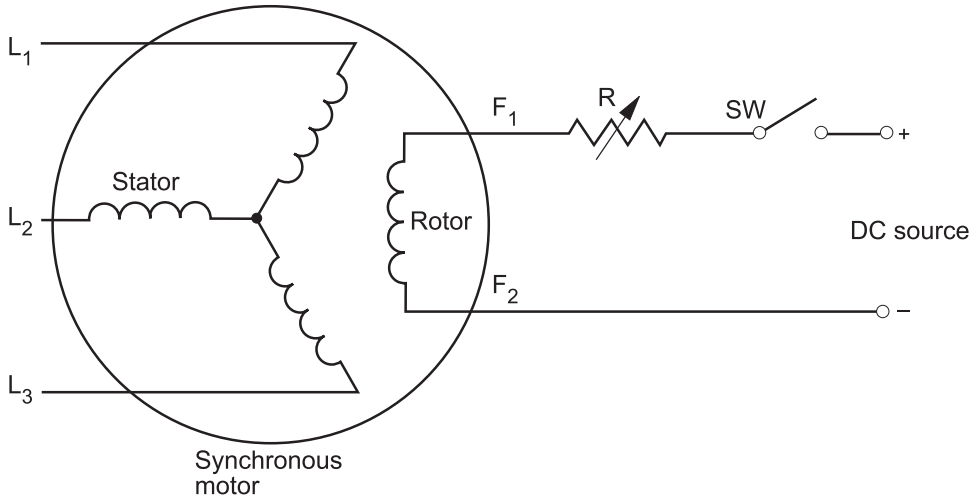


Figure 2—Synchronous motor with external converter

Built-in exciters

The built-in exciter is a small DC generator that is mounted on the same shaft as the synchronous motor.

Figure 3 shows a simplified circuit for an exciter mounted on the same shaft as the motor.

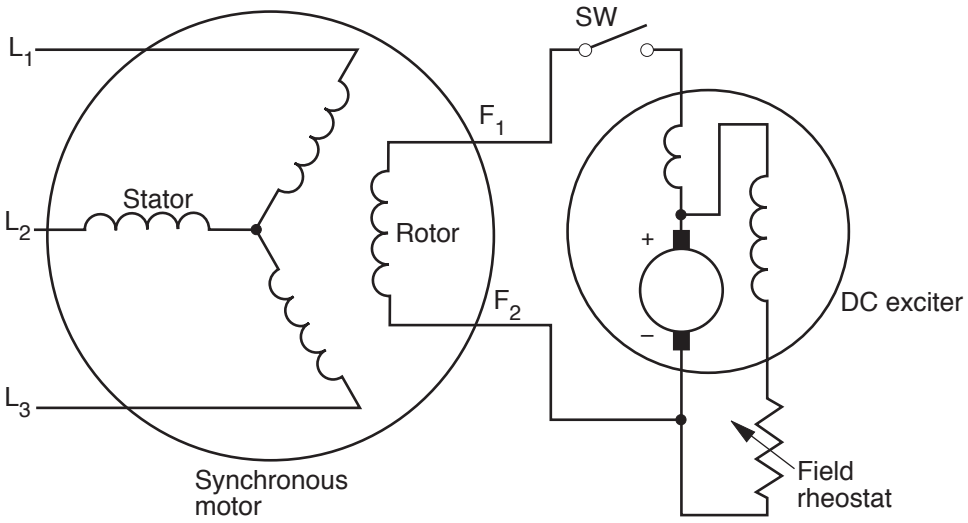


Figure 3—Built-in exciter

The exciter is a DC generator with the armature turning inside a stationary magnetic field. The field excitation of the synchronous motor is controlled by varying the voltage output of the DC exciter. This is done by placing a rheostat in series with the shunt field of the exciter, as shown in Figure 3.

Brushless exciters

The brushless exciter is normally a three-phase alternator and rectifier assembly mounted on the rotor of the machine (Figure 4). The field coils of this alternator are mounted on the stator while the armature coils are mounted on the rotor. Since the alternator, rectifier and field of the synchronous motor all rotate together, there is no need for commutators, slip rings or brushes.

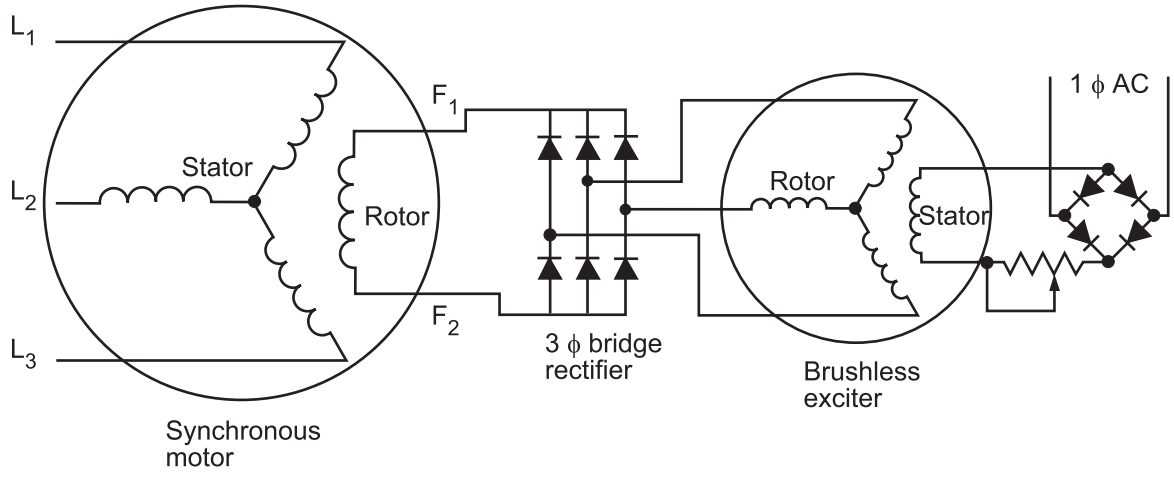


Figure 4—Brushless exciter

The AC output of the alternator is converted to a DC output by the rectifier. It is then fed to the DC field of the synchronous motor. The excitation of the synchronous motor field is controlled by varying the voltage output of the brushless exciter.

End bells and bearings

The end bells and bearings provide the same functions as they do in other motors. The end bells support the bearings and the bearings support the rotor shaft. Together they keep the rotor in proper alignment with the stator.

 Now do Self-Test 8 and check your answers.

Self-Test 8

1. What is the name of the squirrel-cage winding placed near the surface of the field poles in a synchronous motor?

2. What are the two functions of this squirrel-cage winding?

3. Is the rotor field winding fed with alternating current or direct current?

4. How is the field excitation supplied to the rotor?

5. How are the field terminals of the synchronous motors identified?

6. What is the purpose of the end bells and bearings?

7. When are external converters normally used to supply the field excitation to a synchronous motor?

8. How is the level of DC excitation controlled in an external converter?

9. Where is a DC exciter for a synchronous motor normally mounted?

10. How is the level of DC excitation controlled in a built-in exciter?

11. What provides the DC excitation in a synchronous motor with a brushless exciter?

12. How is the level of DC excitation controlled on a synchronous motor equipped with a brushless exciter?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 9:

Describe the operating principles of three-phase synchronous motors

Synchronous motors are not self-starting. With the motor at rest, consider what happens when both the rotor and stator are energized:

1. Instantly the stator field rotates at synchronous speed. As stator poles approach similar poles on the rotor, torque is produced that tries to turn the rotor in the same direction as the rotating stator field.
2. At the point where the stator poles pass over the centre of the similar rotor poles and start to move away, the torque changes direction and tries to move the rotor in the direction opposite to the rotating stator field.
3. As the stator poles continue moving and approach the next rotor poles (which are opposite in polarity), the torque produced continues to try to move the rotor in a direction opposite to that of the rotating field.
4. At the point where the stator poles pass over the centre of the opposite-polarity rotor poles and start to move away, the torque changes direction and tries to move the rotor in the same direction as the rotating stator field.

You can see from this explanation that for one-half of the time, the motor produces torque in one direction. For the other half of the time it produces torque in the opposite direction. This results in a net torque of zero and the rotor does not move. So, another method must be used to accelerate the rotor close to synchronous speed before the rotor field is energized.

Amortisseur winding

In most synchronous motors the *amortisseur winding* is used to accelerate the synchronous motor close to synchronous speed. The amortisseur winding is simply a squirrel-cage winding placed near the surface of the pole faces. Its main purpose is to dampen any speed fluctuations that may occur as a result of sudden load changes. It is also used to accelerate the motor during starting. As the rotating field moves past the winding, it induces currents in the winding that produce torque and accelerate the motor. It works exactly the same way as a squirrel-cage motor.

Once the motor is up to 95–97% of full-load speed, direct current is applied to the rotor field and the rotor pulls into synchronism with the stator field. The actual slip speed at which the DC voltage is applied to the field will depend upon the inertia and torque requirements of the load and machine.

Note that the amortisseur winding is not designed to handle the motor load over an extended period of time. If the acceleration takes too long, or if the motor is accelerated too often in a short period of time, the amortisseur winding can overheat.

Starters for synchronous motors are designed to time the application of the DC so that it happens when the rotor poles are adjacent to opposite-polarity stator poles, or the rotor

may stall. Once the rotor is turning at synchronous speed, voltage is no longer induced in the amortisseur winding because it is no longer moving relative to the stator field.

Pony motor

Synchronous motors that have very large starting torque requirements are sometimes started using a wound-rotor motor mounted on or coupled to the same shaft. This motor is often referred to as a *pony motor*. You learned that wound-rotor motors are well suited for smooth acceleration of loads requiring large torque.

Field discharge hazards

When the rotor is moving slower than the stator field, the conductors in the DC field windings are cut by the stator flux. This induces a voltage in the field windings. Because these windings have a large number of turns in series with each other, a large voltage may be induced in the rotor windings. To reduce the magnitude of the induced voltage in the field windings, they are normally short-circuited or connected to a field discharge resistor during acceleration.

Reversing the synchronous motor

Reversing the direction of rotation of a synchronous motor is done exactly the same way as on a squirrel-cage induction motor. The rotor follows the direction of the rotating magnetic field created in the stator. The direction of the rotating field must be reversed in order to reverse the direction of the motor, by interchanging any two of the line leads to the stator.

Pull-in torque

The torque required to pull the rotor into synchronism is called the *pull-in torque*. Pull-in torque is the maximum constant torque under which the motor will pull its connected inertia load into synchronism when its field excitation is applied. The pull-in torque of a synchronous motor can be quite high, but for it to be effective, it must be properly timed.

Once the synchronous motor has accelerated and pulled into synchronism, each rotor pole lines up with an opposite-polarity stator pole. The rotor is pulled along by the rotating field of the stator. You can think of the flux linkage between the stator and rotor poles as acting like invisible elastic bands (Figures 1a and 1b).

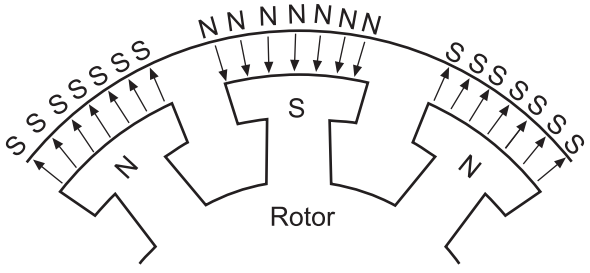


Figure 1a—Torque angle at no load

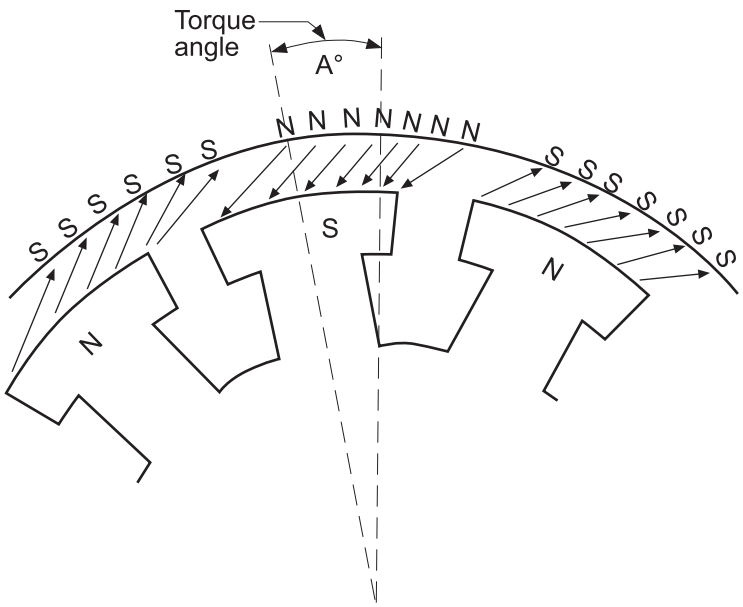


Figure 1b—Torque angle at rated load

As load is added to the motor, the elastic bands are stretched and the rotor poles lag behind the stator poles by a small angle (Figure 1b). This angle between the centre of the rotor pole and the centre of the stator pole is measured in electrical degrees. It is referred to as the *torque angle*. As load is removed from the motor, the elastic bands contract and the torque angle decreases.

Pull-out torque

If too much load is added to the motor, the torque angle will increase to the point where the flux can no longer pull the rotor along at synchronous speed. At this point, the elastic bands snap and the rotor pulls out of synchronism with the stator. The motor then slows down and stalls. This maximum sustained torque that the motor can develop at synchronous speed is referred to as the *pull-out torque*. If it is exceeded, the motor will pull out of synchronism. Typical angles at which pull-out torque occurs may be as high as 60–70º.

Effects of mechanical load

Since the resistance of the stator windings is relatively low, the current flowing in the stator windings is controlled mainly by the amount of counter emf (cemf) that must be created in these windings. This cemf is generated by the changing current in the stator, which causes a changing flux. The stator will allow just enough current to flow to cause just enough changing flux to produce the proper amount of cemf.

The amount of cemf produced in the stator is the phasor sum of the voltage applied to the stator and the emf induced into the stator by the rotating field.

Since the rotor flux uses the stator iron to complete its magnetic circuit, it has an effect on the resultant stator flux which, in turn, affects the counter emf produced in the stator windings. Any change in the rotor flux will also affect the resultant stator flux. The rotor flux is normally

maintained at a fairly constant level, but the angle between it and the stator flux changes as the load on the motor changes.

As load is added, the input power to the motor must increase to supply that additional load. Since the supply voltage is fixed and relatively constant, the increased input power must be supplied by an increase in stator current. As load is added, the motor's torque angle changes, which also changes how the rotor flux interacts with the stator flux and causes an increase in stator current.

The voltage applied to the stator may be considered as fixed in both magnitude and phase angle. For this reason, it is used as the reference phasor (labelled E_S in the diagrams that follow).

As the rotor turns:

1. It induces in the stator windings an emf that has a constant magnitude.
2. For a zero degree torque angle, the rotor emf would be 180° out of phase with the source emf.
3. However, when the torque angle changes, the angle of the rotor emf will also change.
4. As load is added, the torque angle increases, which means the induced voltage will happen later in time. This phasor is labelled E_C.

The two voltage vectors, E_S and E_C, add together to yield the resultant voltage, E_R. This voltage divided by the impedance of the stator windings (Z_S) determines the stator current, I_S.

- Any time E_R increases, I_S also increases.
- The stator current has to produce the counter emf to oppose E_R, so anytime E_R increases, the stator current increases. This stator current will always lag the resultant voltage E_R by approximately 90° because of the inductive reactance of the motor.

$$I_S = \frac{E_S + E_C}{Z_S}$$

$$I_S = \frac{E_R}{Z_S}$$

Figures 2 to 4 show how the armature current in a synchronous motor changes with load.

Figure 2 shows the phasor diagram at no load. Notice that even at no load, the torque angle (A_1°) is greater than zero since the motor still has to overcome such things as windage and friction. This means the emf created by the rotor will never actually be 180° out of phase with the supply voltage.

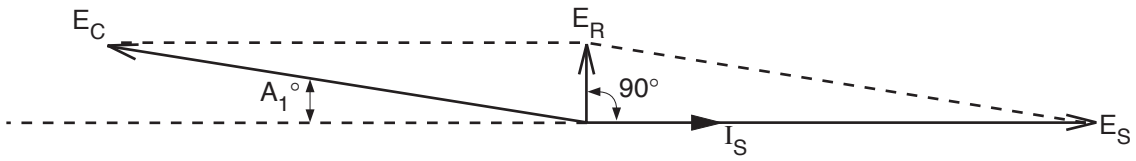


Figure 2—Phasor diagram at no load

Figure 3 shows the phasor diagram with increased load on the motor. The increased load is indicated by the increase in the torque angle ($A_2°$). Notice the lengths of phasors E_S and E_C have not changed, but the angle between them has. The resultant E_R has thus become longer, resulting in a larger stator current, (I_S).

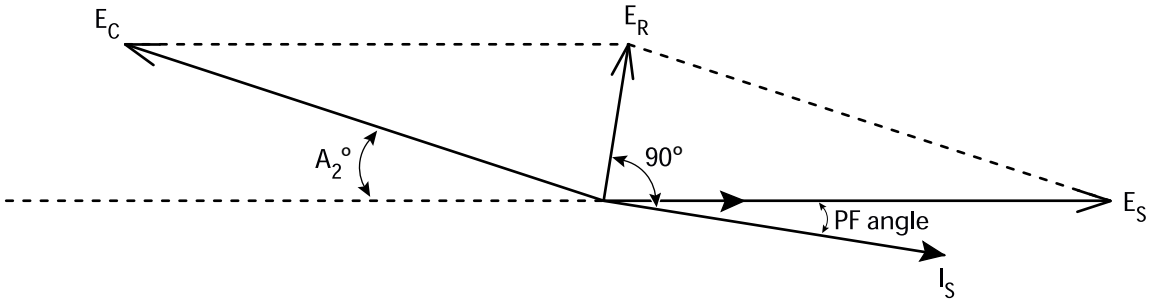


Figure 3—Armature current at increased mechanical load

Figure 4 shows what happens when the load is increased still further. The torque angle is again increased. The lengths of phasors E_S and E_C have not changed, as the magnitude of these two voltages does not change with load. However, since the torque angle has increased, this results in an increase in both E_R and I_S.

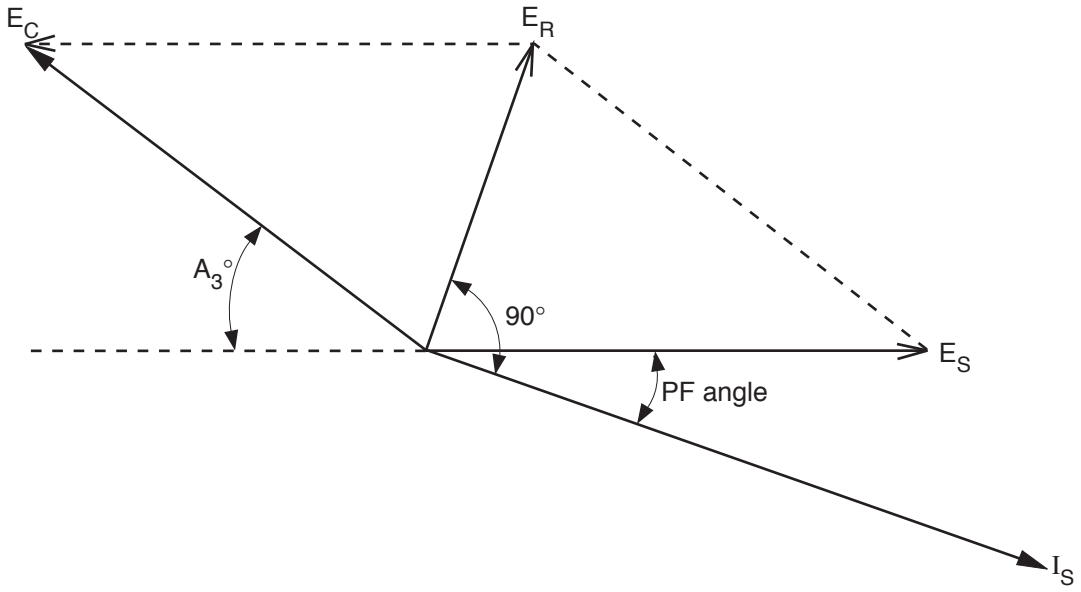


Figure 4—Armature current at further increased mechanical load

Notice that each time the load is increased, the power factor of the motor becomes more lagging.

In induction motors, the rotor slows down as the load is increased. This results in an increase in the emf induced in the rotor. The increased emf causes an increase in rotor current and torque output to supply the increased load.

In a synchronous motor, the rotor cannot slow down. The increase in motor torque is produced by an increase in the torque angle between the stator field and the rotor field. The increased torque angle causes an increase in stator current which, in turn, increases the torque.

Effects of rotor field excitation

Figure 5 shows a field rheostat connected in series with the DC supply and the rotor field. This connection controls the flow of current through the rotor field:

- Increasing the rheostat's resistance decreases the rotor current and the rotor field flux density.
- Decreasing the rheostat's resistance increases the rotor current and the rotor field flux density.

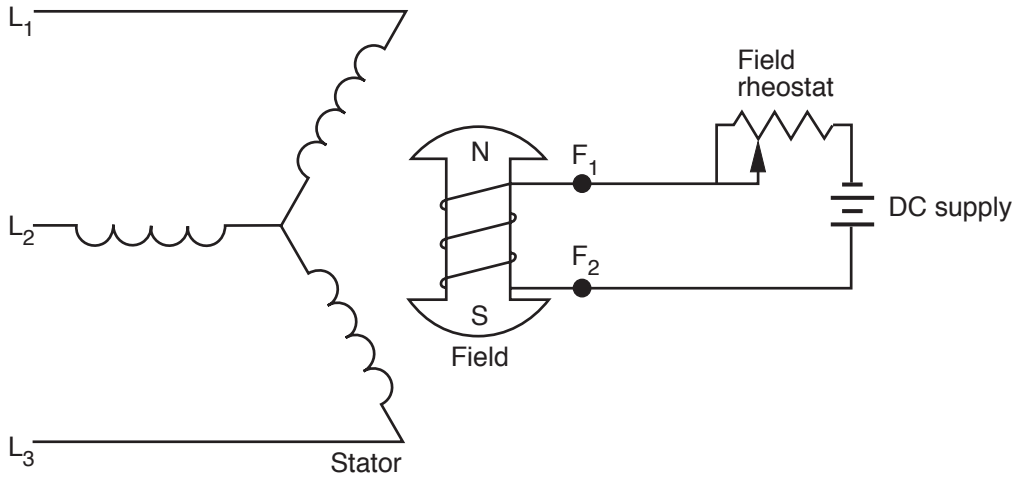


Figure 5—Field rheostat used to adjust field excitation

As the current through the field windings increases, the density of the rotor field increases. Increasing the flux density of the rotor field increases the magnitude of the emf it induces in the stator. Each time the field current is varied, the length of phasor E_C will change. Each time the length of E_C changes, it will vary the resultant E_R.

Figure 6 is a phasor diagram of a synchronous motor operating at unity power factor.

The excitation current in the field winding is adjusted to produce a unity power factor. The resultant voltage E_R is at approximately 90° to the applied stator voltage. The stator current is determined by this resultant voltage and lags it by approximately 90° so that it is in phase with the voltage applied to the stator.

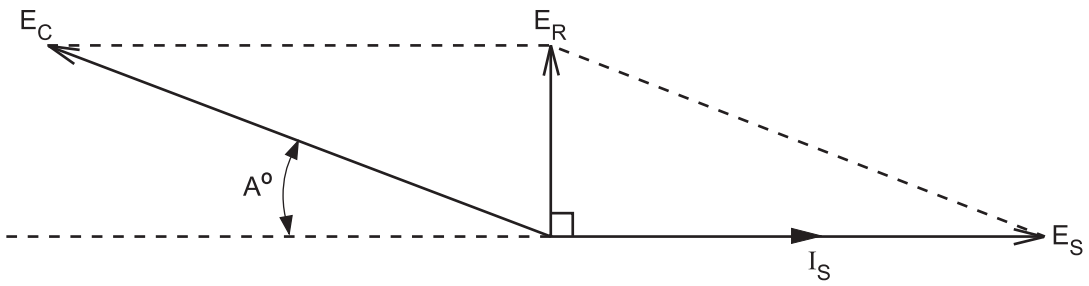


Figure 6—Motor operating at unity power factor

Under-excited rotor field

Figure 7 is a phasor diagram of the same synchronous motor operating with a *lagging* power factor.

The load has not changed, so the torque angle is as it was in Figure 6. However, the field excitation has been reduced. This can be seen by the fact that phasor E_C is now shorter, indicating that the emf generated in the stator by the rotor has been reduced. This establishes a new angle and magnitude for the resultant voltage (E_R) and the stator current it causes to flow (I_S).

Notice that the stator current now lags the stator voltage and has increased in magnitude. The in-phase component (the part that does useful work) has remained the same, but the stator current has increased to supply lagging VARs of reactive power.

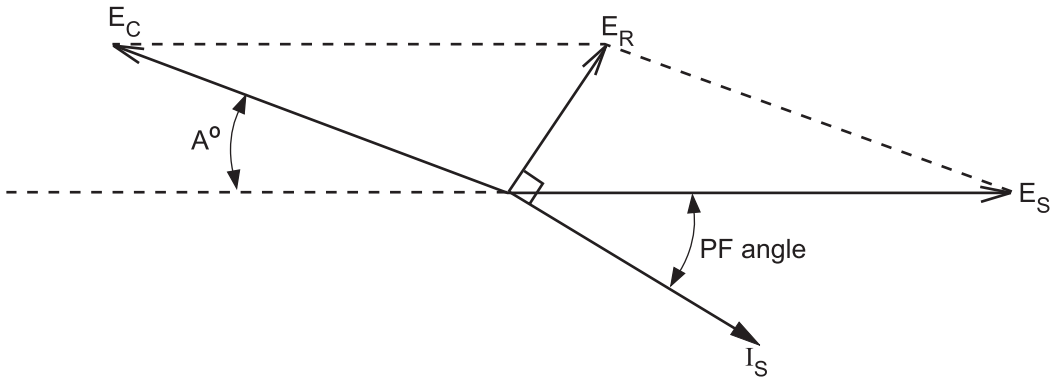


Figure 7—Under-excited field operation

You can see from the phasor diagram in Figure 7 that decreasing the field current will cause the power factor to become more lagging (or less leading). When a synchronous motor is running with a lagging power factor, it is said to be *under-excited*. When the machine is under-excited, the stator must supply the magnetizing current that the rotor is not supplying.

Over-excited rotor field

Figure 8 is a phasor diagram of the same synchronous motor operating with a *leading* power factor.

Once again, the load has not changed, so the torque angle is the same as it was in Figures 6 and 7. The field excitation has been increased above that in Figure 6. This can be seen by the fact that phasor E_C is longer than it was in Figure 6, indicating that the emf generated in the stator

by the rotor has been increased. This establishes a new angle and magnitude for the resultant voltage (E_R) and the stator current it causes to flow (I_S).

Notice that the stator current now leads the stator voltage and has also increased in magnitude. The in-phase component (the part that does useful work) has remained the same, but the stator current has increased to supply leading VARs of reactive power.

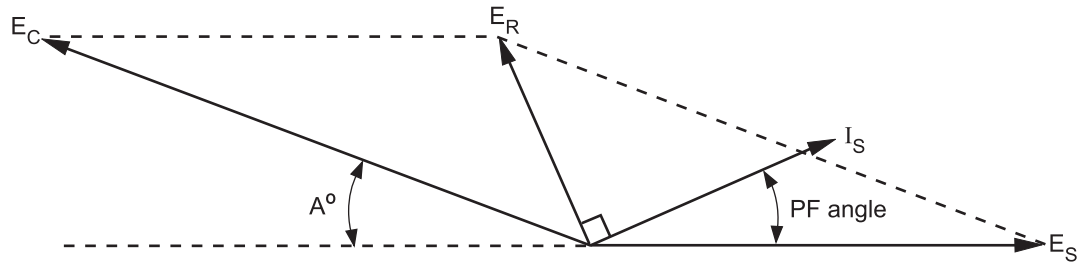


Figure 8—Over-excited field operation

You can see from the phasor diagram in Figure 8 that increasing the field current will cause the power factor to become more leading (or less lagging). When a synchronous motor is running with a leading power factor, it is said to be *over-excited*. When the motor is over-excited, the stator must supply a demagnetizing current to compensate for the over-magnetization caused by the rotor.

A synchronous motor running at unity power factor draws less current from the AC source, but sometimes synchronous motors are deliberately run over-excited. These motors are used for power factor correction of induction motors with lagging power factors. You can do this as long as the stator winding current rating is not exceeded.

Synchronous capacitors

Synchronous motors, when over-excited, may be used for power factor correction. For this reason, some synchronous motors are constructed without an output shaft. These motors, called *synchronous capacitors*, are used solely for power factor correction.

Following are two examples of synchronous motors used in a plant for power factor correction.

Example 1: An industrial plant has a 600 V, three-phase load of 1500 kVA at an average lagging power factor of 60%. Neglecting all losses, calculate:

a. total kilowatt load

b. line current with no power factor correction

c. kVA capacity of a synchronous capacitor required to correct the plant to unity power factor

d. line current after correction of the power factor to unity

e. kVA capacity of a synchronous capacitor required to correct the plant to 90% lagging power factor

f. line current after correction of the power factor to 90% lagging

Remember that as the power factor is corrected, the only thing that does not change is the true power.

Solution:
Construct a power triangle for the existing plant load.

$$kW = kVA \times PF$$
$$= 1500 \times 0.60$$
$$= 900 \text{ kW}$$

$$kVARs = \sqrt{kVA^2 - kW^2}$$
$$= \sqrt{1500^2 - 900^2}$$
$$= 1200 \text{ kVARs lagging}$$

a. Total kilowatt load

b. True power equals 900 kW.

c. Line current with no PF correction

$$VA = \sqrt{3} \times E_L \times I_L$$
$$I_l = \frac{VA}{\sqrt{3} \times E_L}$$
$$= \frac{1\,500\,000 \text{ VA}}{\sqrt{3} \times 600 \text{ V}}$$
$$= 1443 \text{ A}$$

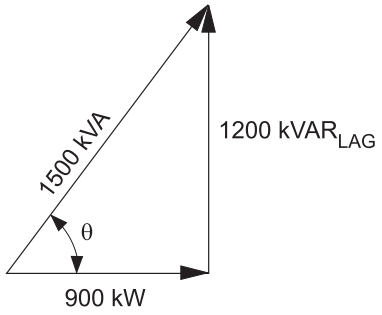


Figure 9—Uncorrected power triangle

d. kVAR capacity required to correct to unity PF

The synchronous capacitor would have to supply an equal number of leading VARs to lagging VARs in the plant.

From Figure 9, the plant's reactive power was 1200 kVAR. Therefore, the synchronous capacitor would have to supply 1200 leading kVAR.

e. Line current after correction of PF to unity

After correction of the power factor to unity, the voltamps would equal the watts.

$$VA = \sqrt{3} \times E_L \times I_L$$
$$I_L = \frac{VA}{\sqrt{3} \times E_L}$$
$$= \frac{900\,000 \text{ VA}}{\sqrt{3} \times 600 \text{ V}}$$
$$= 866 \text{ A}$$

f. kVAR required to correct to 90% lagging PF

Construct a power triangle for a 900 kW load at a 90% lagging power factor.

I. Calculate the phase angle at 90% lagging power factor.

$\theta = \cos^{-1} 0.9$

$= 25.84°$

II. Calculate the kVAR at 90% power factor (given the watts).

$kVAR = kW \times \tan$

$= 900\ kW \times \tan\ 25.84°$

$= 436\ kVAR\ lagging$

III. Subtract the 436 kVAR lagging from the total lagging kVAR to determine how many leading kVAR are required.

$1200\ kVAR - 436\ kVAR = 764\ kVAR\ leading$

The synchronous capacitor would have to supply 764 kVAR leading of reactive power to correct the power factor to 90% lagging (Figure 10).

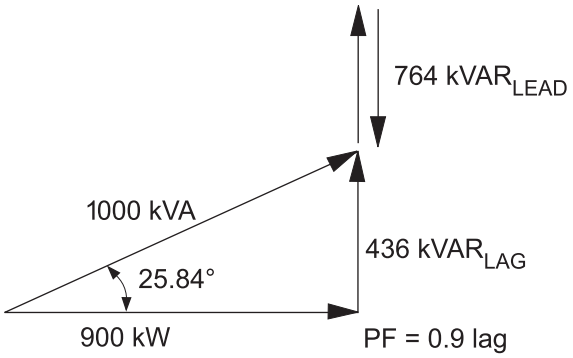


Figure 10—Corrected power triangle

g. Line current after correction of PF to 90% lagging

I. Calculate the total kVA at 90% power factor.

$kVA = kW \div 0.9$

$= 900\ kW \div 0.9$

$= 1000\ kVA$

II. Calculate the current.

$$VA = \sqrt{3} \times E_L \times I_L$$

$$= \frac{VA}{\sqrt{3} \times E_L}$$

$$= \frac{1\,000\,000 \text{ VA}}{\sqrt{3} \times 600 \text{ V}}$$

$$= 962 \text{ A}$$

Example 2: A plant has a load of 1200 kW at a lagging power factor of 75%. A synchronous motor is to be installed to supply a 300 kW load and provide power factor correction to the plant. If the power factor is to be corrected to 92% lagging, what is the minimum kVA rating required for the new synchronous motor?

Solution:
Construct a power triangle for the existing plant load before the installation of the synchronous motor. Refer to Figure 11.

$$kW = kVA \div PF$$

$$= 1200 \text{ kW} \div 0.75$$

$$= 1600 \text{ kVA}$$

$$kVAR = \sqrt{kVA^2 - kW^2}$$

$$= \sqrt{1600^2 - 1200^2}$$

$$= 1058 \text{ kVAR lagging}$$

Add the existing kW load to the kW load to be supplied by the synchronous motor.

$$kW_T = 1200 \text{ kW} + 300 \text{ kW}$$

$$= 1500 \text{ kW}$$

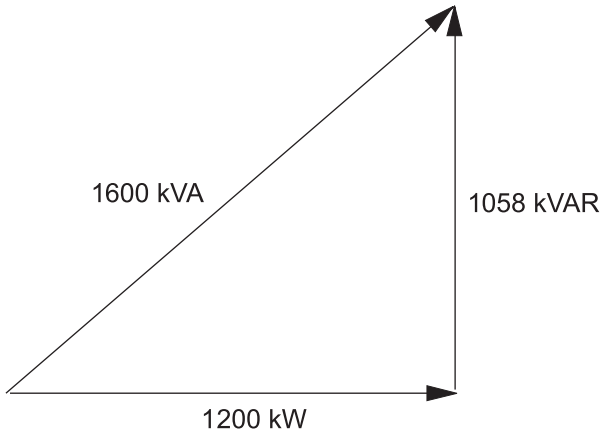


Figure 11—Uncorrected power triangle

Now construct a new power triangle with this new total kilowatt load at the 92% power factor. Refer to Figure 12.

$$kVA = kW \div PF$$

$$= 1500\ kW \div 0.92$$

$$= 1630\ kVA$$

$$kVAR = \sqrt{kVA^2 - kW^2}$$

$$= \sqrt{1630^2 - 1500^2}$$

$$= 638\ kVAR\ lagging$$

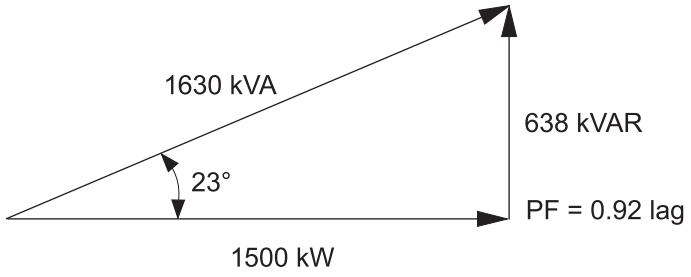


Figure 12—Corrected power triangle

The synchronous motor will have to supply the difference between the original kVAR and the desired kVAR.

$$kVAR = 1058\ kVAR - 638\ kVAR$$

$$= 420\ kVAR\ leading$$

Construct a power triangle for the synchronous motor with 300 kW and 420 kVAR to determine the minimum kVA capacity required for the synchronous motor. Refer to Figure 13.

$$kVA = \sqrt{kW^2 + kVAR^2}$$

$$= \sqrt{300^2 + 420^2}$$

$$= 516 \text{ kVA}$$

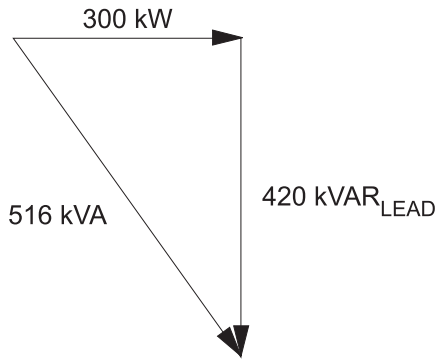


Figure 13—Power triangle for the synchronous motor

Now do Self-Test 9 and check your answers.

Self Test 9

1. Why is the synchronous motor not self-starting?

2. At what point in the starting process is the DC excitation applied to the field?

3. During acceleration and deceleration of the rotor, why is the field short-circuited or connected across a discharge resistor?

4. Can the direction of rotation of a synchronous motor be reversed by reversing the polarity of the DC field supply?

5. What type of induction motor is sometimes used to start synchronous motors that have large starting torque requirements?

6. Why is no current induced in the amortisseur winding when the rotor is rotating at synchronous speed?

7. Why is it a problem for the synchronous motor to turn at lower-than-synchronous speed for extended periods of time?

8. Define the term *pull-in torque*.

9. What is the term used to describe the angle between the centre of the stator poles and the centre of the rotor poles?

10. Does this angle increase or decrease as load is added to the motor?

11. Define the term *pull-out torque*.

12. What happens if the pull-out torque is exceeded?

13. As load is added to a synchronous motor, what happens to the power factor of the motor?

14. What controls the magnitude of the current flowing in the stator windings?

15. How does the torque angle of the rotor affect the stator currents?

16. With the load fixed, which of the following cases will cause the lowest stator current?
    a. unity power factor operation
    b. under-excited field operation
    c. over-excited field operation

17. What happens to the power factor of a synchronous motor when the field current is increased under a fixed load?

18. When a synchronous motor is operated over- or under-excited, does this change the in-phase component of the stator current?

19. An industrial plant has a 480 V, three-phase load of 1200 kVA at an average plant power factor of 65%. Neglecting all losses, calculate:
    a. total kilowatt load

    b. line current with no PF correction

    c. kVA capacity of a synchronous capacitor required to correct the plant to unity PF

    d. line current after correction of the PF to unity

    e. kVA capacity of a synchronous capacitor required to correct the plant to 90% lagging PF

    f. line current after correction of the PF to 90% lagging

20. A plant has a load of 1800 kW at a lagging PF of 65%. A synchronous motor is to be installed to supply a 500 kW load and provide PF correction to the plant. If the PF is to be corrected to 92% lagging, what is the minimum kVA rating required for the new synchronous motor?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 10:

Identify common connections for three-phase synchronous motors

The stator construction of three-phase synchronous motors is essentially the same as for three-phase induction motors. The three-phase windings can be connected either in wye or in delta, and the coil ends are identified as T_1, T_2 and T_3. Since the rotor field is excited from a DC supply, its leads are identified as F_1 and F_2. See Figure 1.

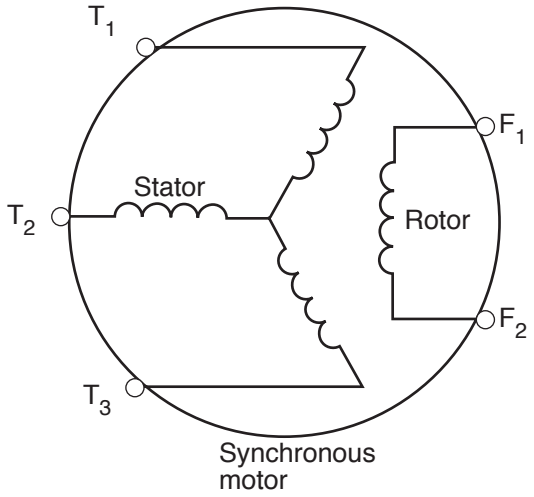


Figure 1—Synchronous motor terminal markings

In order to increase the versatility of the motor, the stator may be designed to give access to each of the phase coils, as shown in Figure 2. In this case, the six leads are brought out and identified as T_1 to T_6. This permits the stator to be connected in either wye or delta, giving it dual-voltage capability.

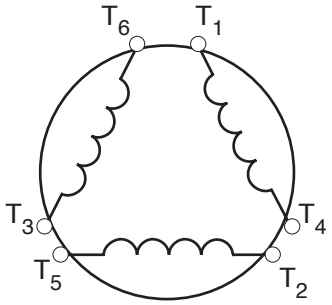
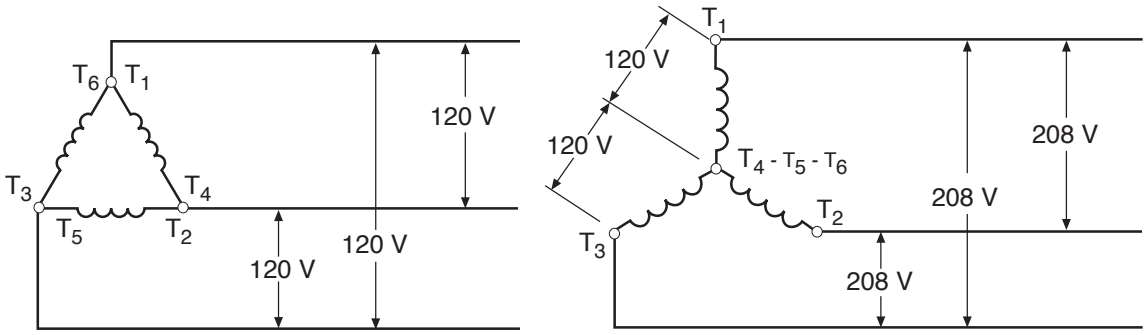


Figure 2—Six-lead stator markings

Figure 3 shows how the stator coils could be connected for either wye or delta operation. Notice that the delta connection is used for low-voltage operation (in this case, 120 V), and the wye connection is used for high-voltage operation (in this case, 208 V).



a. Delta-connected for operation 120 V b. Wye-connected for20 BU operation

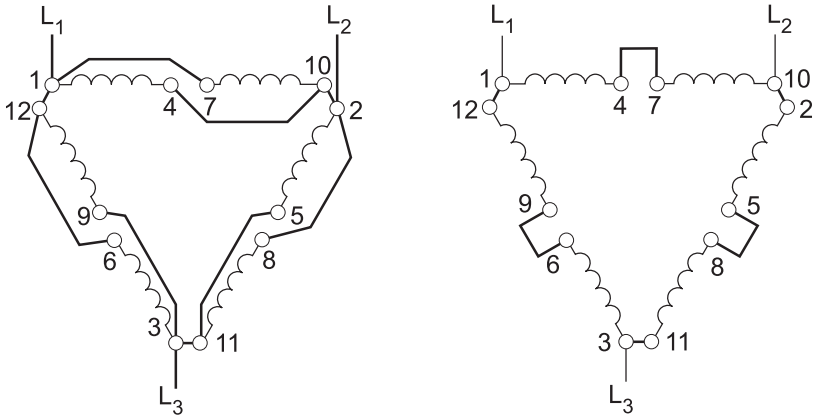
Figure 3—Dual-voltage connections

To further increase the versatility of the motor, the wye-delta stator shown above could be designed with two coils per phase to provide a 12-lead motor. This allows for the following connection combinations:

- Series delta
- Parallel delta
- Series wye
- Parallel wye

Figure 4 illustrates the series delta and parallel delta connections. If each individual stator coil was rated for 120 V, then:

- For Figure 4a the input for the stator would be 120 V, three-phase.
- For Figure 4b the input for the stator would be 240 V, three-phase.



a. Parallel delta b. Series delta

Figure 4—12-lead delta connections

Figure 5 illustrates the series wye and parallel wye connections. Again, if each stator coil is rated for 120 V, then:

- For Figure 5a the input for the stator would be 208 V, three-phase.
- For Figure 5b the input for the stator would be 416 V, three-phase.

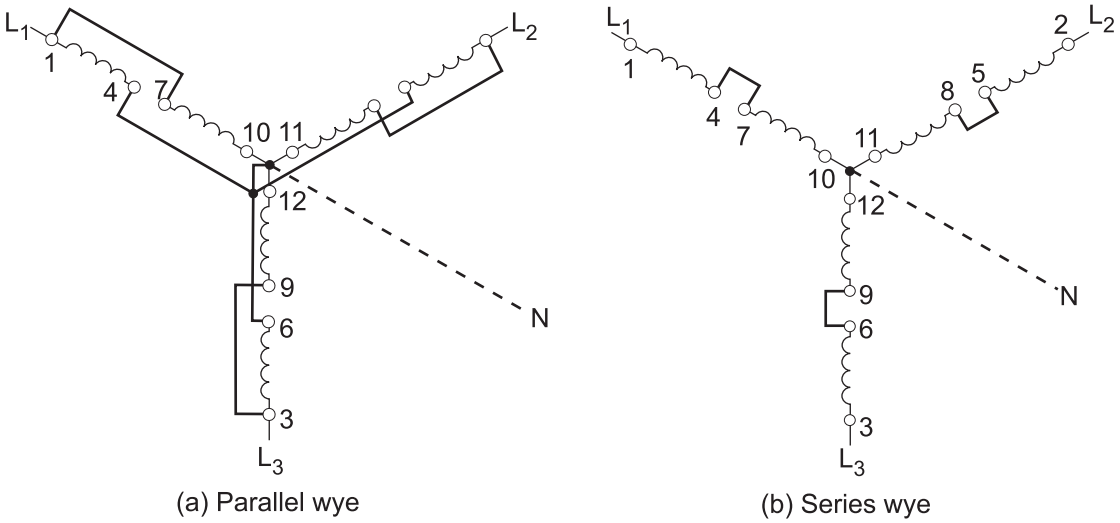


Figure 5—12-lead wye connections

Now do Self-Test 10 and check your answers.

Self-Test 10

1. A nameplate on a small, wye-delta, synchronous motor lists the three-phase AC values as 26 A/15 A and 120 V/208 V. What are the voltage and current ratings when the motor is connected:

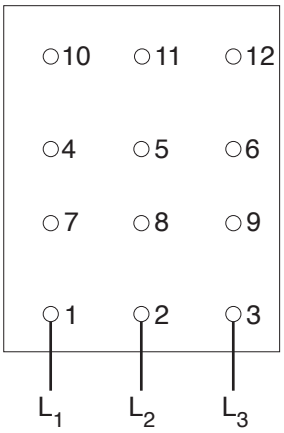
   a. in wye

   _____

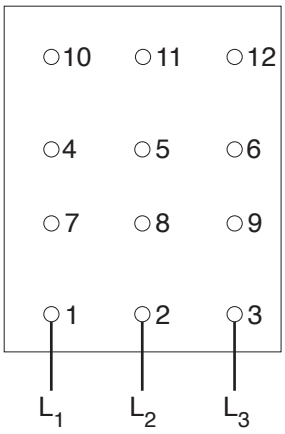
   b. in delta

   _____

2. Complete the terminal box connections for a 12-lead, synchronous machine connected in parallel delta.



3. Complete the terminal box connections for a 12-lead, synchronous machine connected in series wye.



4. If each of the individual coils for the connections in Questions 2 and 3 were rated at 120 V, 60 Hz, what would be the rated voltage for the:

   a. series wye connection

   _____

   b. parallel delta connection

   _____

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 11:

Describe basic maintenance and troubleshooting for three-phase synchronous motors

Troubleshooting procedures for the synchronous motor include those listed previously for three-phase induction motors. The differences in maintaining a synchronous motor as opposed to a squirrel-cage induction motor are associated with the differences in the rotor. The squirrel-cage motor does not have brushes and slip rings and does not have the DC field circuit.

For maintenance information on brush and slip rings, refer to the Learning Task 7 on wound-rotor
induction motors.

Troubleshooting the DC field circuit

Problems with the field circuit that may cause the motor to fail to synchronize or to pull out of synchronism are:

- Open in the field coils
- No exciter voltage
- Open in the field rheostat
- Rheostat resistance set too high (field current too low)

Setting the field current too high or too low may cause the motor to overheat. These settings will cause the motor to draw reactive power, which will increase the current in the stator windings. If the current in the stator windings is higher than rated current, the motor will overheat, even though the mechanical load is less than the rated horsepower of the motor.

Loose connections on the squirrel-cage winding

To complete the short-circuiting connections on the ends of the squirrel-cage amortisseur winding, segments of copper bar are bolted between the adjacent field pole cage sections (Figure 1). The bolts on these segments should be checked periodically for tightness.

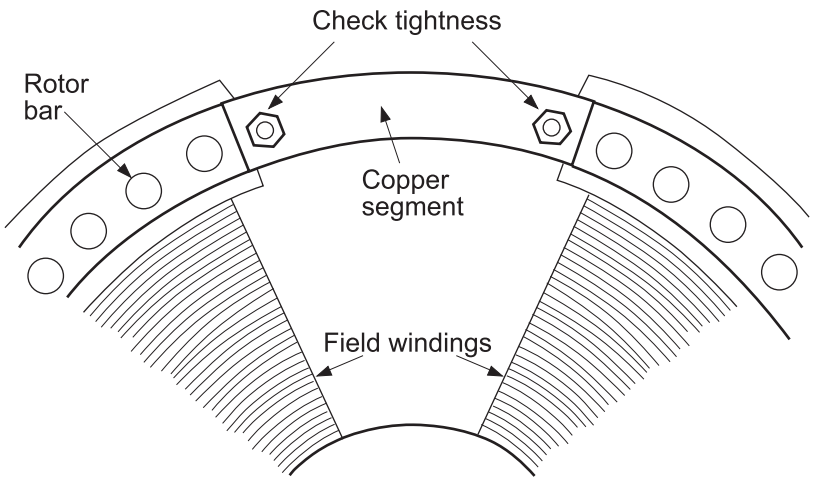


Figure 1—Copper bar bolted between cage sections

Now do Self-Test 11 and check your answers.

Self-Test 11

1. List four problems with the field circuit that could cause the motor to fail to synchronize.

2. How can too high or too low of a rotor excitation current cause a synchronous motor to overheat?

3. If the manufacturer's specifications for brush pressure are not available, what is a safe rule to use?

4. Is it safer to have the brush pressure too high or too low?

5. At what point should a brush be replaced?

6. A synchronous motor is connected up and runs with the wrong rotation. What can be done to remedy this situation?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 12:

Describe the constructional features of split-phase induction motors

The principal components of the split-phase induction motor are the:

- Stator (main and auxiliary) windings
- Rotor
- Centrifugal (starting) switch
- End bells and bearings

Stator windings

Although the stator core of the split-phase motor is similar to that of the three-phase motor, the windings are designed differently. In all induction motors the rotor follows the rotating magnetic field of the stator. This is easy to create in a three-phase motor, but it requires a different design in a single-phase motor. At least two independent fields of flux that are out of phase with each other must be created.

This is done by using two separate windings:

- The *main* or *run* winding
- The *auxiliary* or *start* winding

The main winding is constructed of larger wire and is placed deep in the slots of the stator core. This gives it a low resistance and high inductance property. The auxiliary winding is constructed of smaller wire and is placed near the top of the slots in the stator core. This gives it a higher resistance and a lower inductance than the main winding.

When these two windings are connected in parallel across the same source, the current through the main winding will lag behind the current in the start winding. Since the flux in each winding is in phase with the current flowing through that winding, the two magnetic fields will be out of phase with each other. Also, these two windings are placed in the stator core to be 90 electrical degrees apart from each other.

Rotor

The rotor of the split-phase induction motor is the same squirrel-cage construction as the rotor of a three-phase induction motor. It contains conductive bars located in the punchings of a laminated cylindrical core. These conductive bars are short-circuited on both ends by conductive rings. The bars are skewed slightly to the slots in the stator core so that the motor will run smoother and quieter.

Centrifugal (starting) switch

The split-phase motor contains a centrifugal switch that has flyweights mounted on the rotor shaft. As the motor accelerates, centrifugal force moves the flyweights outward against the force of a spring (Figure 1).

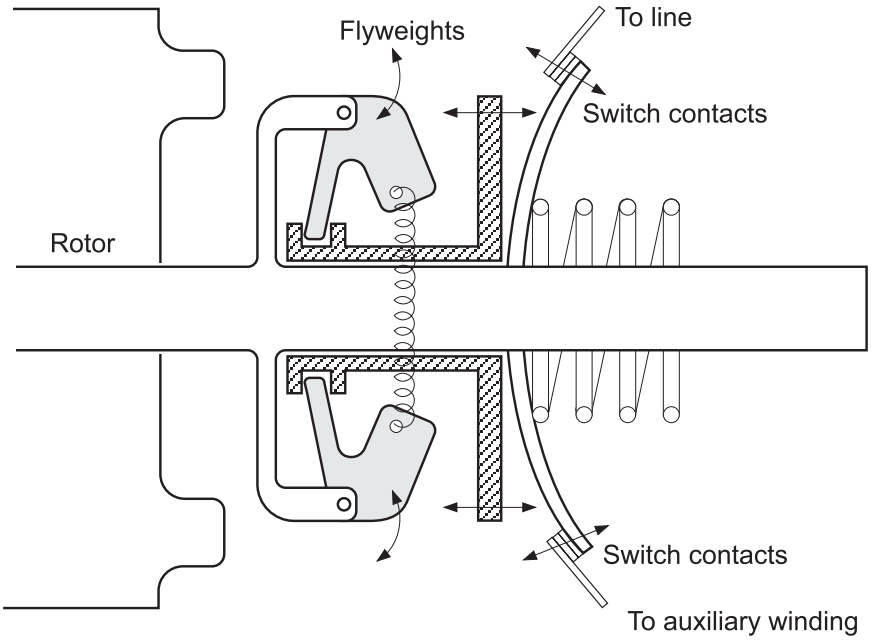


Figure 1—Centrifugal switch

As the flyweights move out they force a collar to move along the rotor shaft and push the switch contacts open. This occurs when the motor reaches about 75% of its rated speed.

As the motor slows down, the centrifugal force on the flyweights decreases and the spring forces them back to their former position. This permits the switch contacts to close again.

End bells and bearings

The end bells mount to the frame of the motor on either end. Their purpose is to house the bearings that support the rotor shaft and keep it in alignment with the stator so that it can turn freely within the stator. The end bells complete the motor enclosure and protect the inner parts of the motor.

Nameplate data

The type of information on the nameplate for single-phase motors is essentially no different from what was discussed previously for three-phase motors. Figure 2 shows a nameplate taken from a single-phase motor. Some nameplate data that is vital to the electrician during the installation of a motor typically includes:

- Current rating (to determine wire size and overcurrent protection)
- Voltage rating (for wire, overcurrent and control equipment)

- Horsepower rating (for disconnect and control equipment)
- Insulation class or temperature rise (for conductor ratings)

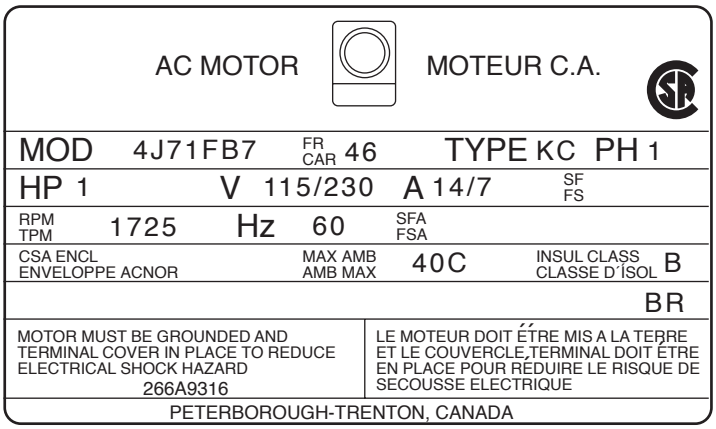


Figure 2—Single-phase motor nameplate

Now do Self-Test 12 and check your answers.

Self-Test 12

1. Explain the reason for skewing the rotor bars relative to the slots in the stator core.

2. At approximately what percentage of full-load speed do the centrifugal switch contacts open?

3. State the purpose of the end bells and bearings.

4. Describe the constructional difference between the main and auxiliary windings.

5. For the nameplate shown in Figure 2 in Learning Task 12, what is the current rating for the 115 V connection?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 13:

Describe the operating principles of split-phase induction motors

The split-phase motor (sometimes called the *resistive-start, induction-run motor*) contains two separate windings:

- the run winding, which has a high-inductance and low-resistance component
- the start winding, which has a high-resistance and a low-inductance component

The two windings are connected in parallel across the AC source as shown in Figure 1. (The switch shown in Figure 1 is the centrifugal switch discussed in Learning Task 12.)

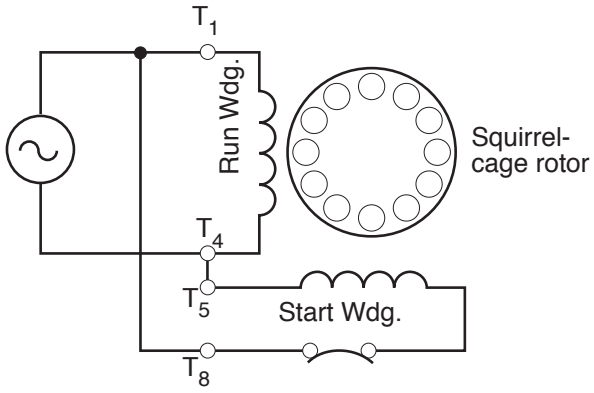


Figure 1—Electrical connections in a split-phase induction motor

The current in the run winding (I_R) will lag behind the applied voltage by a large angle (close to 90°). The current through the start winding (I_S) will lag behind the applied voltage by a small angle (closer to 0°).

Although the ideal phase displacement is 90°, typically, the angle between the two currents falls in the range of 30–50 electrical degrees. This is shown in the phasor diagram (a) and sine wave graph (b) of Figure 2.

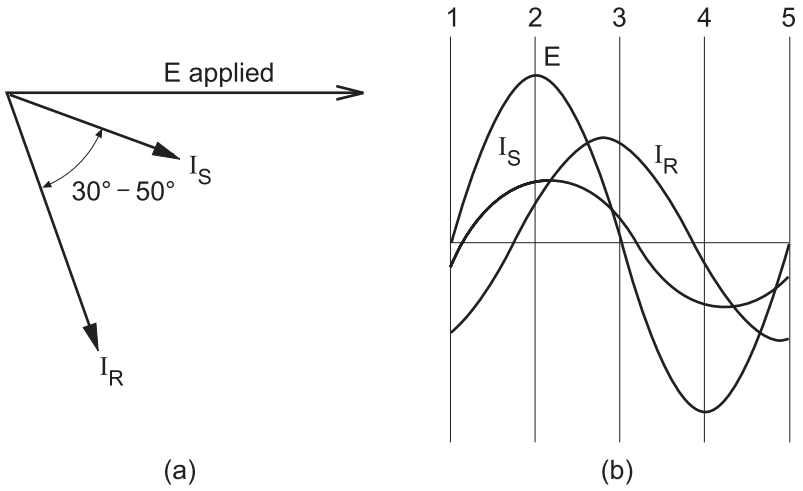


Figure 2—Current relationships in a split-phase induction motor

The flux produced by the current flowing through the windings is in phase with the current. Since the currents through the start and run windings are out of phase with each other, the two fields created by each winding will also be out of phase with each other.

Physically, these two windings are positioned 90 electrical degrees apart from each other in the stator core.

Stator field development

The relationship between the two currents at any time during their cycle can be seen by drawing a vertical line through the sine wave graph as in Figure 2. To examine how the field moves as the cycle progresses, five vertical lines have been drawn through the graph.

Flux in the stator at position 1

At position 1 on the sine wave graph in Figure 2b, the current in the start winding is almost zero while the current through the run winding is almost at its maximum in the negative direction. Figure 3 shows the stator field at this point.

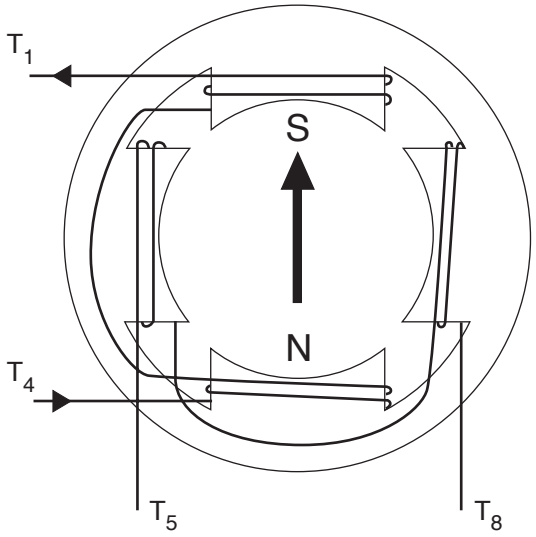


Figure 3—Flux in the stator at position 1

The current will be flowing into the terminal T_4 of the run winding and out T_1 of the same winding. When the left-hand coil rule is applied, you can see that the flux set-up will be as shown in Figure 3.

Flux in the stator at position 2

At position 2 on the sine wave graph in Figure 2b, the current in the start winding is almost at its peak in the positive direction while the current in the run winding is at a very low value.

The current will be flowing into the T_8 terminal of the start winding and out the T_5 terminal of the same winding. When the left-hand coil rule is applied, you can see that the flux set-up will be as shown in Figure 4.

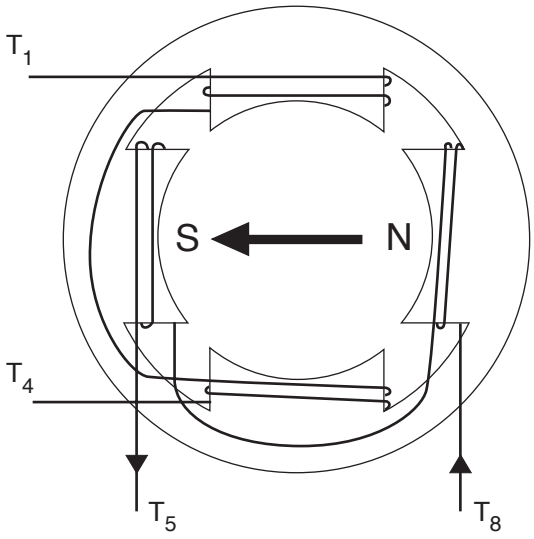


Figure 4—Flux in the stator at position 2

Flux in stator at position 3

At position 3 on the sine wave graph in Figure 2b, the current in the start winding is almost at zero again while the current through the run winding is almost at its maximum in the positive direction.

The current will now be flowing into terminal T_1 of the run winding and out T_4 of the same winding. When the left-hand coil rule is applied you can see that the flux set-up will be as shown in Figure 5.

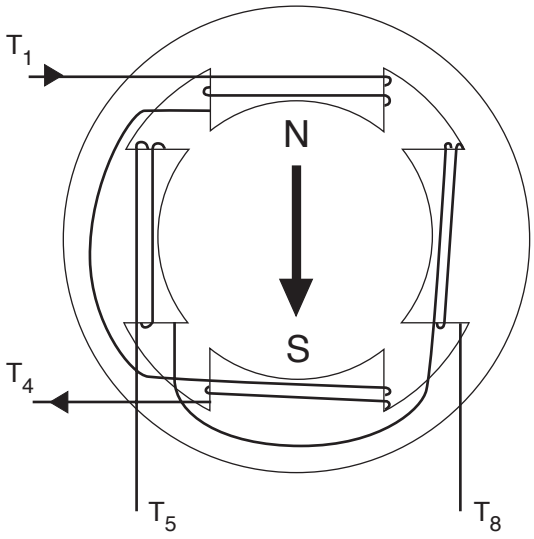


Figure 5—Flux in the stator at position 3

Flux in the stator at position 4

At position 4 on the sine wave graph in Figure 2b, the current in the start winding is almost at its peak in the negative direction while the current in the run winding is at a very low value.

The current will be flowing into the T_5 terminal of the start winding and out the T_8 terminal of the same winding. When the left-hand coil rule is applied, it can be seen that the flux set-up will be as shown in Figure 6.

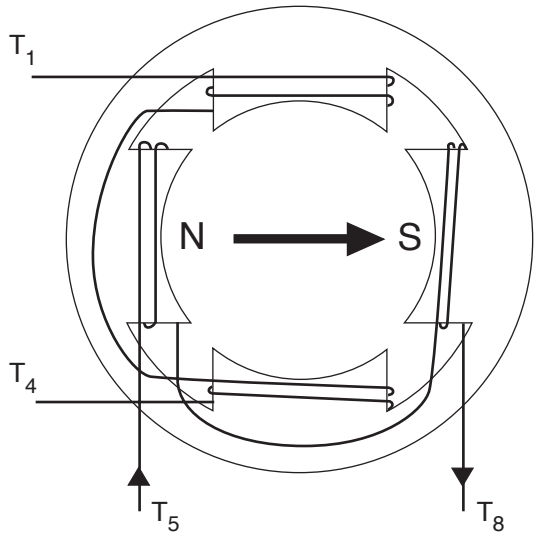


Figure 6—Flux in the stator at position 4

Flux in the stator at position 5

The stator shown in Figures 3–6 is a two-pole motor. (It has two start poles and two run poles.) The magnetic field completes one revolution each cycle. At position 5, one cycle has been completed, so position 5 is really position 1 of the next cycle.

Torque development

As the magnetic field rotates, the flux lines cut across the bars of the squirrel-cage rotor and induce currents in these bars. These rotor currents react with the magnetic stator flux to create a torque on the rotor that turns the rotor in the same direction in which the magnetic field rotates.

The flux created by the rotor cuts across the conductors in the stator windings and affects the inductance of these windings. This affects the phase angle between the currents in the two windings and therefore the torque created by the motor.

At about 75% of rated speed the flux from the run winding alone creates as much torque as the combined flux from the start and run windings together. At rated speed the torque produced from the combined flux of the two fields is lower than that created by the run winding itself. For this reason, the start winding is disconnected from the source at about 75% of rated speed by the opening of the centrifugal switch connected in series with it.

Resistive-start, split-phase motors have relatively low starting torques because of the low phase angle between the two winding currents. They are suitable for such small loads as furnace blowers, which do not require a high starting torque. The standard split-phase motor is only practical to produce in smaller (fractional hp) sizes of ¾ of a horsepower or less.

Reversing the direction of rotation

The motor rotates in the same direction as the stator field rotation. The motor may be reversed by interchanging the connections to either the run winding or the start winding. Since in some cases it is much simpler to interchange the leads on the start winding, this method is more often used. Because interchanging the leads of either winding reverses the current through that pole winding, the direction of the magnetic field is also reversed in that pole.

Capacitor-start, split-phase motor

Figure 2 showed that currents in the two stator windings are displaced from each other by between 30 and 50 electrical degrees in a typical split-phase motor. However, the two windings are physically displaced from each other by 90 electrical degrees. If a capacitor of the correct rating is placed in series with the start winding (Figure 7), it is possible to have a 90° phase displacement between the currents flowing in the two windings.

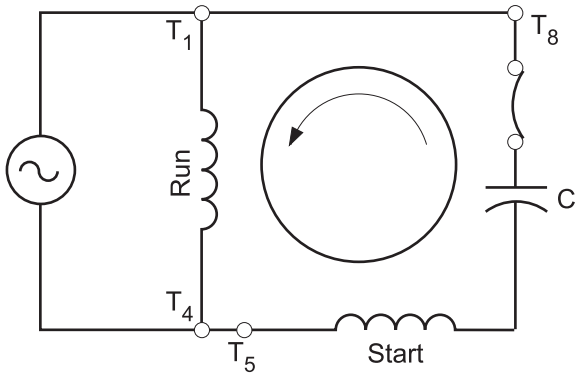


Figure 7—Capacitor-start, split-phase motor

The capacitor causes the current in the start winding to lead the applied voltage by the correct number of degrees (Figure 8).

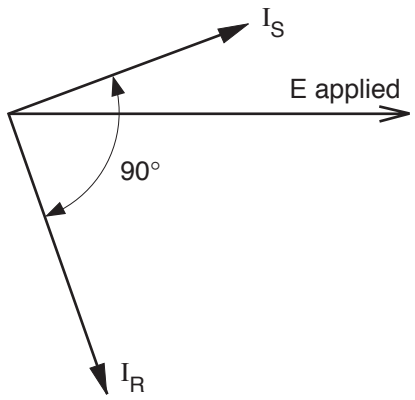


Figure 8—Phase angles in a capacitor-start, split-phase motor

Adding the capacitor results in:

- A phase displacement in the two field fluxes that matches the physical displacement of the two windings
- A much higher starting torque than can be achieved in a standard split-phase motor

This type of motor is referred to as a *capacitor-start, split-phase motor*. It is used where a higher starting torque is required than can be supplied by a standard split-phase motor. Again, at about 75% of rated speed, the centrifugal switch opens the start winding and capacitor from the circuit and the motor operates on the run winding alone.

Capacitor-start motors are capable of producing starting torques as high as 450% of full-load torque. As well, they have improved power factor during starting, and the motor inrush current is reduced.

Dual-capacitor (capacitor-start, capacitor-run), split-phase motor

As you learned earlier, the field induced in the rotor cuts across the conductors in the stator windings, affecting their inductances. For this reason, the capacitor used for starting the motor, if left in, would create too large a phase angle between the run and start windings at rated speed. It is therefore disconnected at about 75% of rated speed.

In one type of split-phase motor, the capacitor-start winding is left in the circuit after the motor has reached full-load speed, but the value of its capacitor is changed. The start winding in this type of motor is referred to as an *auxiliary winding* since it is not removed after the motor is started. The capacitance value of the starting capacitor is about 10–15 times that of the running capacitor.

Figure 9 is a typical schematic diagram of a capacitor-start, capacitor-run, split-phase motor.

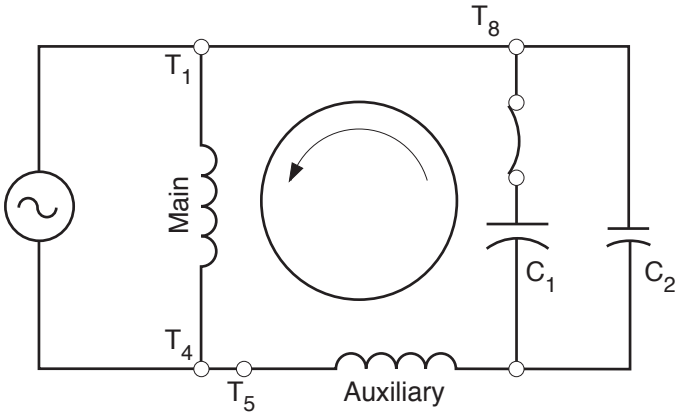


Figure 9—Capacitor start, capacitor-run, split-phase motor

Notice that when the motor is first started, both capacitors are connected in parallel. Once the motor reaches about 75% of rated speed, the centrifugal switch removes one of the capacitors from the circuit. This maintains the optimal phase angle between the two stator field currents.

These motors have high starting torque and better power factors and efficiency when fully loaded. They may develop about 25% greater overload capacity than a standard capacitor-start split-phase motor. This type of motor is well suited for loads such as an air compressor.

Permanent capacitor (capacitor-run), split-phase motor

Another variation on the split-phase motor is the permanent capacitor (or capacitor-run), split-phase motor. This motor has no starting capacitor, but has a capacitor permanently connected in series with the auxiliary winding. Figure 10 is a schematic of a permanent capacitor, split-phase motor.

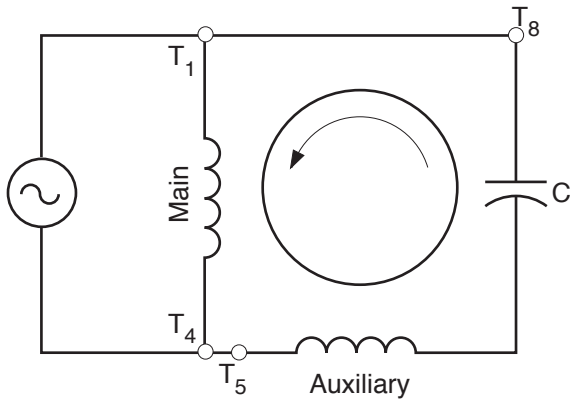


Figure 10—Capacitor-run, split-phase motor

These motors are used where the starting torque requirements are low (typically between 50 and 100% of full-load torque). They are often used on air-moving equipment such as fans and blowers.

Reluctance motor

The reluctance motor is a special split-phase motor that operates at synchronous speed. The squirrel-cage rotor is modified by cutting out parts of the rotor, creating salient poles (Figure 11). The reluctance of the magnetic circuit between the salient poles is much lower than between two points where the rotor material has been removed. There must be the same number of salient poles on the rotor as there are stator poles.

In the reluctance motor, the magnetic lines seek out the path of least reluctance and draw it nearer, just as a coil will seek out a piece of iron and draw it nearer.

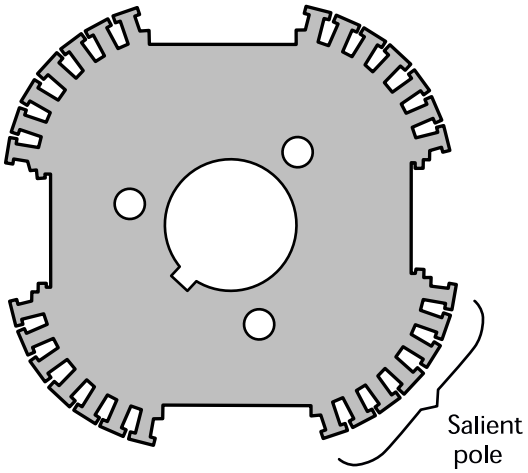


Figure 11—Rotor lamination of a four-pole reluctance motor

For this reason, when the rotor approaches synchronous speed the salient poles become polarized and lock into step with the rotating stator field. This type of motor is used in timers, recording instruments and signalling equipment.

Now do Self-Test 13 and check your answers.

Self-Test 13

1. Flux produced by a winding is:

   a. in phase with the voltage applied to the coil

   b. in phase with the current flowing through the coil _____

2. What is the physical displacement between the main and auxiliary windings of a two-pole split-phase motor?

   _____

   _____

   _____

3. How does a magnetic pole move?

   a. from a main winding to an auxiliary winding

   b. from an auxiliary winding to a main winding in the stator _____

4. How is the direction of rotation reversed in a split-phase motor?

   _____

   _____

   _____

5. Why does a standard split-phase motor (without a starting capacitor) have a low starting torque compared to a capacitor-start, split-phase motor?

   _____

   _____

   _____

6. Which type of split-phase motor combines good starting torque with good overload capacity?

   _____

7. Which type of split-phase motor operates at synchronous speed?

_____

8. What modification is made to the rotor in the motor mentioned in Question 7?

_____

_____

9. For a split-phase motor, at approximately what percentage of rated speed does the centrifugal switch open?

_____

10. In a dual-capacitor type of split-phase motor, which capacitor is larger:

    a. the starting capacitor

    b. the running capacitor _____

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 14:

Identify common connections for split-phase motors

The stator connections for split-phase motors can be identified as either:

- Single voltage
- Dual voltage

Single-voltage motors

The terminals of the main (run) winding are identified as T_1 and T_4 on single-voltage, split-phase motors. The terminals of the auxiliary (start) winding are identified as T_5 and T_8. According to manufacturing standards, the standard direction of rotation (counterclockwise for motors) is obtained when T_4 and T_5 are connected to one line and T_1 and T_8 are connected to the other.

Figure 1 shows the stator connections for both directions of rotation.

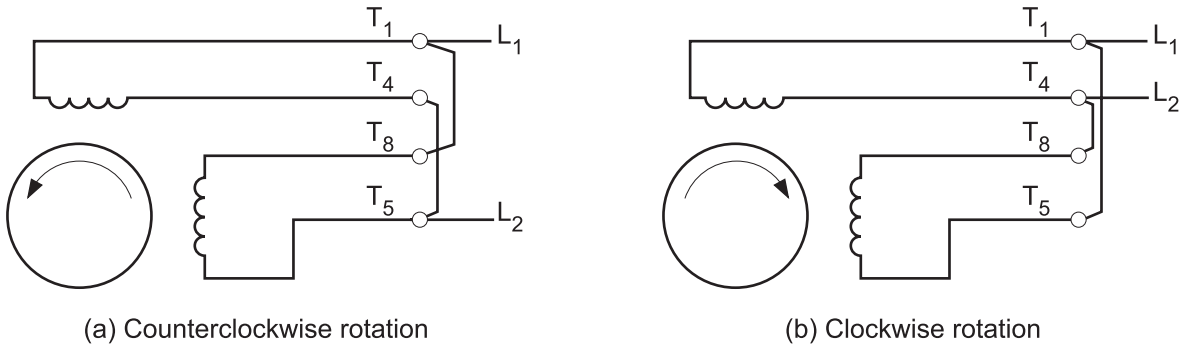


Figure 1—Connections for both directions of rotation

Dual-voltage motors

Dual-voltage motors are intended to be operated on one of two possible supply voltages where one voltage is twice the other. For example, a 115/230 V dual-voltage motor is very common. At the higher voltage, the motor only draws half as much line current at full load as it does when connected to the lower voltage.

The main winding of a dual-voltage motor is assumed to be divided into two equal halves. Each half is rated for the lower of the two voltages shown on the nameplate. The two winding halves are assigned terminal designations T_1 and T_2 for one half and T_3 and T_4 for the other half.

Motor with one auxiliary winding

Most often the motor contains only one auxiliary winding, assigned terminal designations T_5 and T_8. This undivided winding is also rated for the lower of the two voltages on the nameplate.

Motor with auxiliary winding divided

The auxiliary winding may also be divided in two; if so, they are assigned terminal designations T_5 and T_6 for one half and T_7 and T_8 for the other half. Each half is rated for the lower of the two voltages on the nameplate. When connected for the lower voltage rating on the nameplate,

each winding is connected in parallel with the others to the source. When connected for the higher voltage, the two main windings are connected in series and the two auxiliary windings are connected in series. These two groups are then connected in parallel to the source.

Figure 2 shows the connections for both directions of rotation on a motor where the auxiliary winding is divided. Figures 2a and 2b show the lower voltage connection and Figures 2c and 2d show the higher voltage connection.

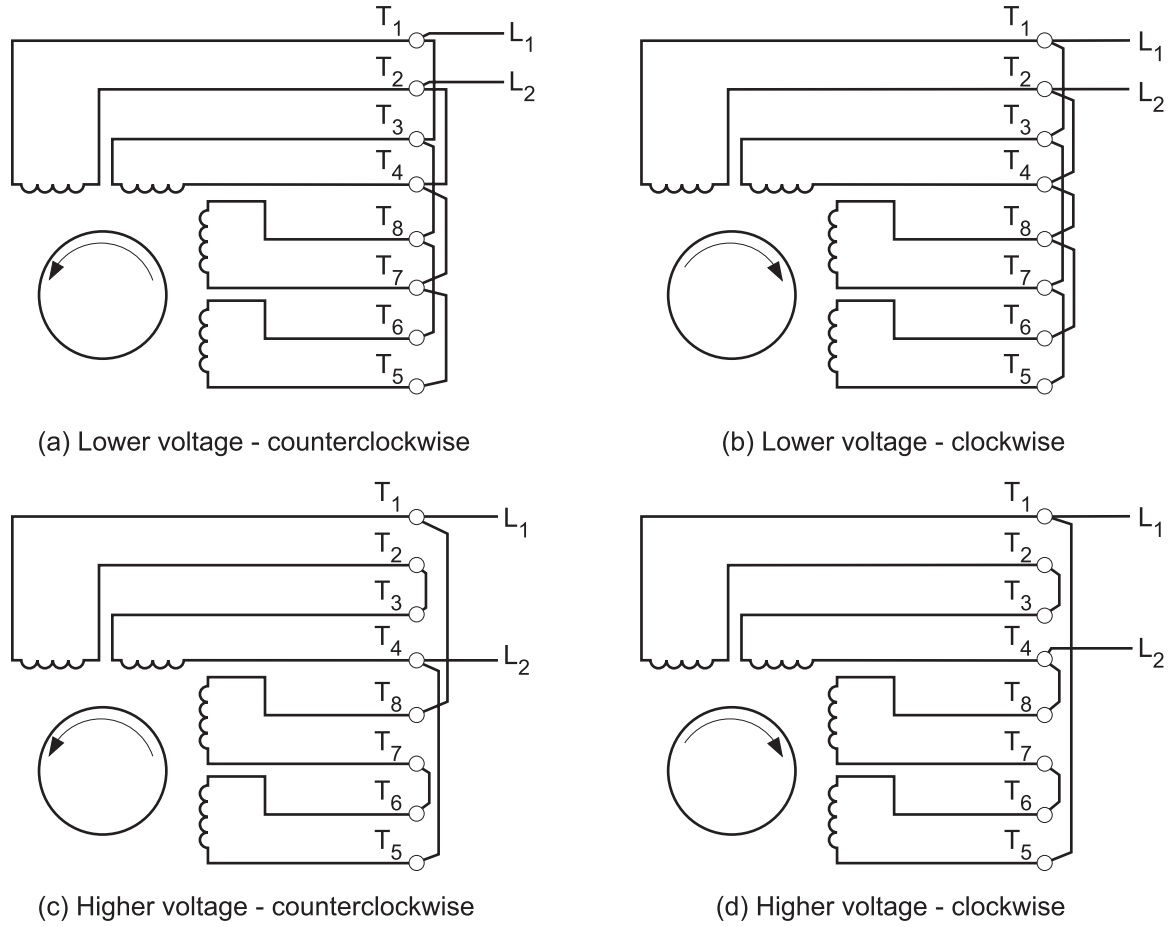


Figure 2—Connections where auxiliary winding is divided

Motor with auxiliary winding not divided

Figure 3 shows the connections for both directions of rotation where the auxiliary winding is not divided. In this case, when the motor is connected for the higher voltage, the auxiliary winding is connected in parallel with only one of the main windings.

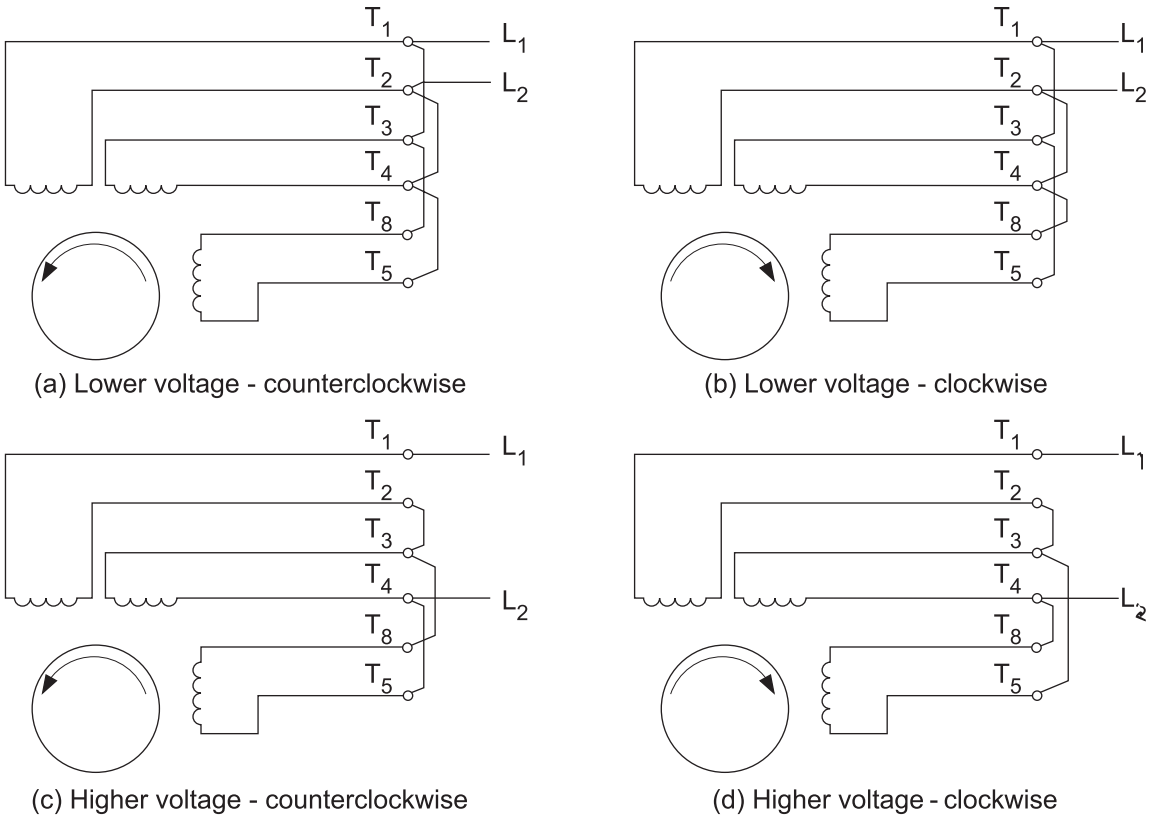


Figure 3—Connections where auxiliary winding is not divided

Notice that in all cases shown in Figures 2 and 3, every winding segment has the lower voltage applied across it. Also, notice that the standard direction of rotation (CCW) is obtained when T_4 and T_5 are connected to one line or where an equivalent circuit connection is made between the main and auxiliary windings. Figure 4 is an example of an equivalent connection where the auxiliary winding is connected across the opposite main winding to that shown in Figure 3.

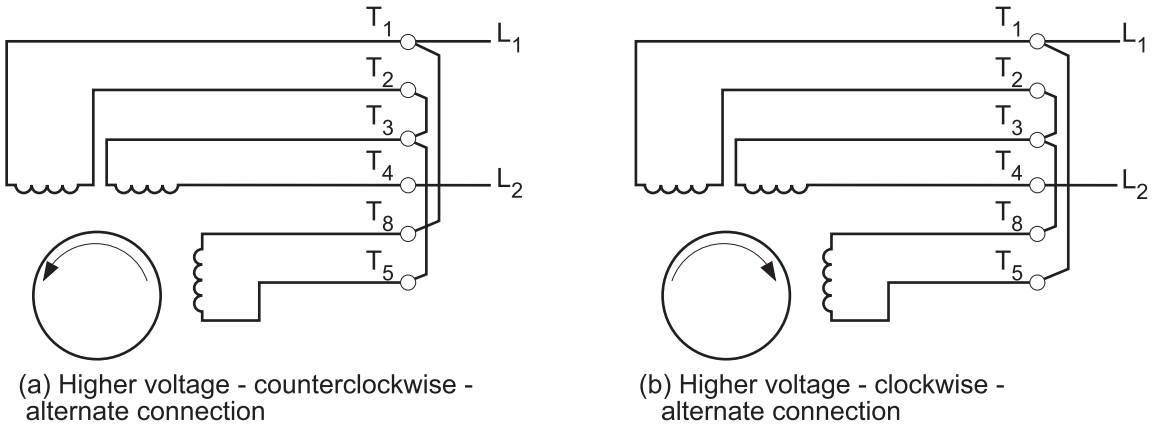


Figure 4—Equivalent connection where auxiliary winding is connected across the opposite main winding to that shown in Figure 3

Now do Self-Test 14 and check your answers.

Self-Test 14

1. On single-voltage, split-phase motors:

   a. The main winding terminals are labelled _____ .

   b. The auxiliary winding terminals are labelled _____ .

2. On a dual-voltage, split-phase motor where only the main winding is divided:

   a. The main winding terminals are labelled _____ .

   b. The auxiliary winding terminals are labelled _____ .

3. On the 120/240 V motor shown in Figure 1, draw the connections so this motor runs counterclockwise on 120 V.

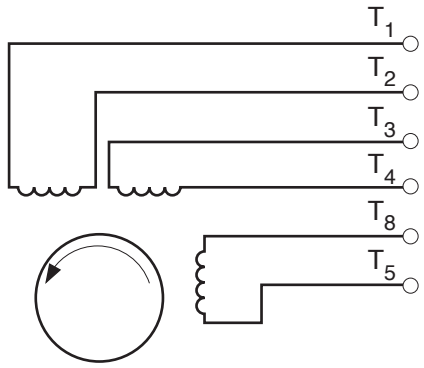


Figure 1

4. How would you reverse the rotation of the motor in Question 3?

_____

_____

_____

5. Figure 2 shows the same motor as in Question 3. Draw the connections so this motor runs clockwise on 240 V.

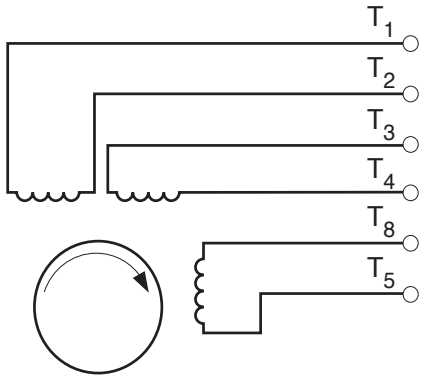


Figure 2

6. How would you reverse the rotation of the motor in Question 5?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 15:

Describe the features of other types of single-phase motors

Although the split-phase motors are probably the type most commonly used in larger power applications, there are several other designs of single-phase motors. In this Learning Task, you will be introduced to the AC series motor and the shaded-pole type of motor.

AC series (universal) motor

The AC series motor is similar in construction to a DC series motor. It is often referred to as a *universal motor* because it will operate on DC as well as AC.

The stator consists of pole cores that are constructed of laminated steel to reduce eddy currents. The pole faces are made larger to reduce the reluctance of the air gap and to distribute the flux more evenly. The field windings in series AC motors usually have fewer turns than DC motors to reduce the inductive reactance. Some series AC motors have compensating windings that are placed in slots on the main field pole faces. They are also connected in series with the armature, so that the current through them is in the opposite direction to that of the adjacent armature conductors.

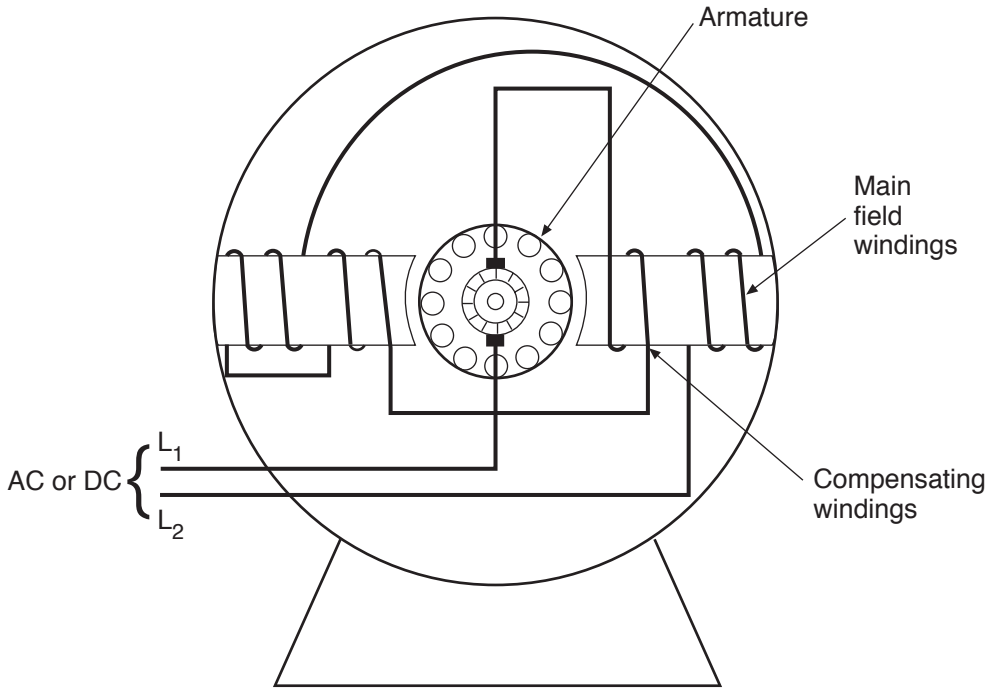


Figure 1—The universal motor

The rotor (or armature) of the universal motor also has a laminated steel core with the winding slots skewed to provide smoother operation. The armature coils terminate at the commutator, where brushes are used to supply current to the rotating armature circuit.

If alternating current is applied to a simple series DC motor it will continue to operate. Since the field pole windings are connected in series with the armature, the field poles will reverse their polarity at the same time as the current reverses its direction in the armature. Figure 2 shows two drawings of a simplified series motor during opposite halves of an AC cycle.

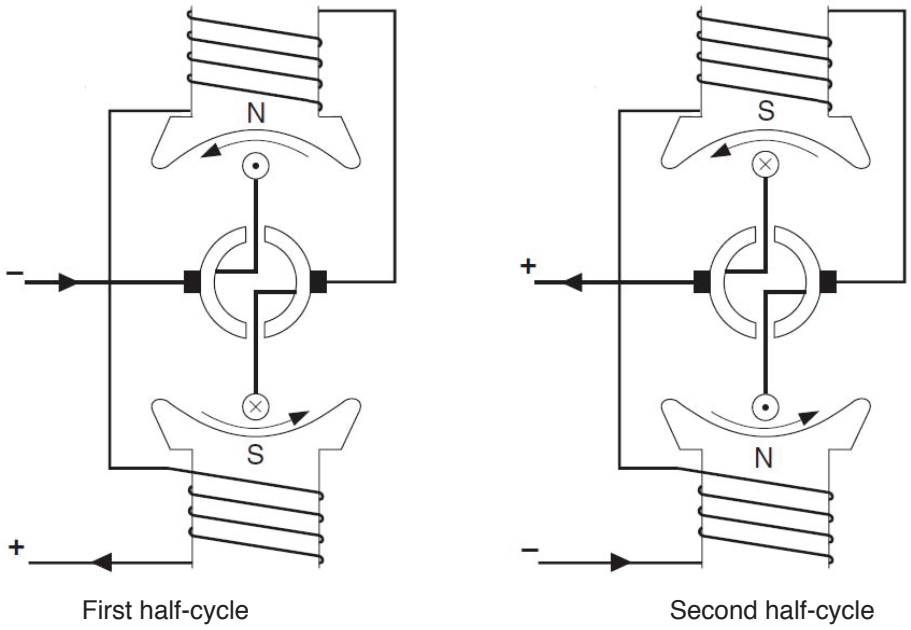


Figure 2—Simple series motor showing each alternation of an AC cycle

Notice that the source polarity has changed in the two drawings. This change in source polarity causes both the magnetic field polarity and the direction of current flow in the armature to change at the same time.

By applying the right-hand motor rule to both drawings, you can see that even though the source polarity has reversed, the direction of motor rotation is the same in either case.

Three problems occur when a DC series motor is operated on an AC supply:

1. The alternating current sets up large eddy currents in the parts of the magnetic circuit that are not laminated, causing excessive heat loss and lower overall efficiency.
2. The reactance of the series field winding causes a large voltage drop across the series field, reduced current through the motor, and poor power factor.
3. The alternating field flux induces high circulating currents in the short-circuited coils that are undergoing commutation. This results in excessive sparking when the brush moves on to the next commutator segment.

The problems become worse as the frequency of the alternating current increases. The AC series motor has several design modifications that help to reduce these effects. Under NEMA standards, AC series motors are to be designed to operate successfully on frequencies of 60 hertz or less and on DC. This is done by incorporating certain design changes:

- The pole cores and that portion of the stator that completes the magnetic circuit are laminated to reduce the eddy-current losses.
- The series winding is designed with fewer turns to reduce its reactance, thus decreasing the voltage drop across it and improving the motor's power factor. The decrease in magnetomotive force that would occur because of this reduction in the number of turns is partially offset by reducing the reluctance of the magnetic circuit. This done by decreasing the air gap and increasing the cross-sectional area of the core.
- To reduce sparking at the commutator, high-resistance leads are used to connect the armature coils to the commutator segments on larger machines. On smaller machines, high-resistance brushes are used instead of the high-resistance leads.

The speed-load characteristics of an AC series motor are similar to those of the DC series motor. It is the counter emf in the armature that limits the current in a series motor.

Figure 3 shows a graph of speed versus load for a typical series motor.

The no-load speed of a series motor is very high. There is a tendency for the motor speed to run away as load is removed from the motor. On smaller machines this is not a problem, as the windage and friction in the motor itself are sufficient to limit the no-load speed. On larger machines, the load is always connected to the motor. This avoids damaging the motor as it tends to run away at no load.

The direction of rotation in a series AC motor is reversed by changing the direction of current through either the armature windings or the series field windings.

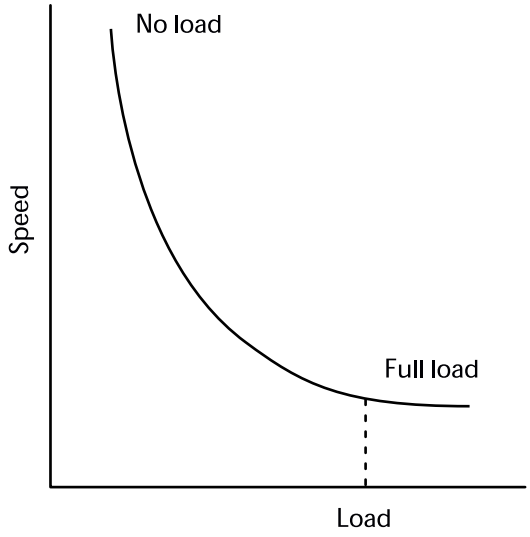


Figure 3—Speed versus load in a series motor

Fractional horsepower series motors are used in applications that take advantage of their high speed, small size, and high starting torque. They are typically used in small, hand-held power tools, as well as in high-speed vacuum cleaners.

With the advent of variable-frequency drives and modifications made to squirrel-cage induction motors, the use of larger series motors is not as common as it once was.

Shaded-pole motor

The shaded-pole motor is one of the cheapest and simplest induction motors to construct. The stator of a shaded-pole motor does not create a rotating magnetic field for the rotor to follow. Instead it creates a magnetic field that shifts from one side of the pole face to the other.

Figure 4 is a drawing of a shaded-pole stator core, consisting of laminated steel plate punchings. Each pole face contains a slot about one-third of the way across the face, dividing the face into two parts.

The stator contains two sets of windings. The first set, called the *exciter winding*, is wound completely around each pole and connected to the AC supply to provide the main field excitation (Figure 5).

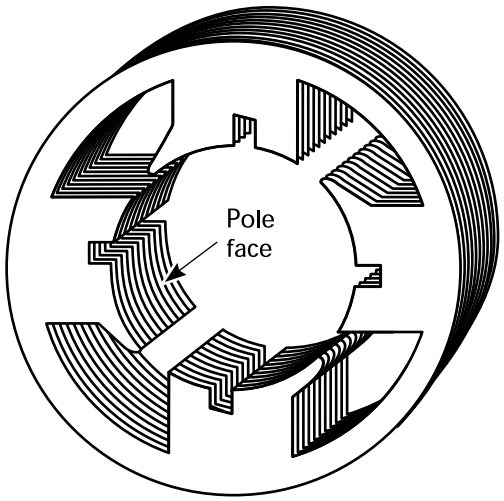


Figure 4—Laminated pole core of stator

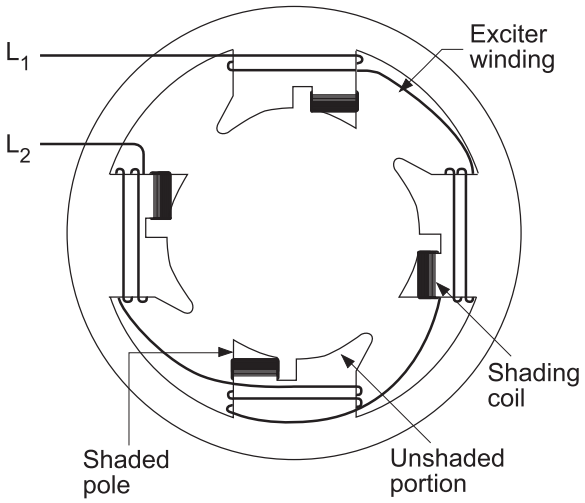


Figure 5—Stator windings

The second stator winding on each pole is called the *shading coil*. It is placed in the slot and surrounds about one-third of the pole face. It is not connected to the source but is simply short-circuited, and receives its energy through electromagnetic induction.

The part of the pole surrounded by the shading coil is called the *shaded* portion of the pole. The part not surrounded by the shading coil is called the *unshaded* portion of the pole. The stator also has a frame or yoke into which the stator core is inserted.

The rotor of the shaded-pole induction motor is a squirrel-cage type identical to other induction motors. It receives its energy through electromagnetic induction.

The exciter winding connected to the AC source produces a changing flux in the pole that cuts across the conductors of the shading coil. You learned earlier that the shading coil is a short-circuited coil with no connection to any electrical source. This changing flux induces a voltage in the shading coil. According to Lenz's law, the direction of the induced emf must be such that any current resulting from it will develop a flux that tends to oppose any change in the original flux.

- The flux during the period shown in Figure 6a on the current sine wave graph would be as shown in the drawing of the pole drawn above it. During this part of the cycle, the current in the exciter winding is increasing at a rapid rate. This means the flux in the pole is also expanding at a rapid rate. This fast rate of flux change causes a large emf to be induced in the shading coil. The large emf produces a large current in the direction shown, which sets up a flux opposite to that of the exciter winding flux. This, in effect, reduces the total flux in the shaded portion of the pole, with the net result that there is a strong north pole produced in the unshaded portion of the pole and a weak north pole produced in the shaded portion of the pole.
- During the part of the current sine wave shown in Figure 6b, the current in the exciter winding is large but is changing very little. This results in a low value of emf being induced in the shading coil. Therefore, very little current is induced in the shading coil, with very little effect on the flux in the shaded portion of the pole. The total flux is spread evenly across the whole pole face, resulting in a strong north pole with its centre in the centre of the whole pole.

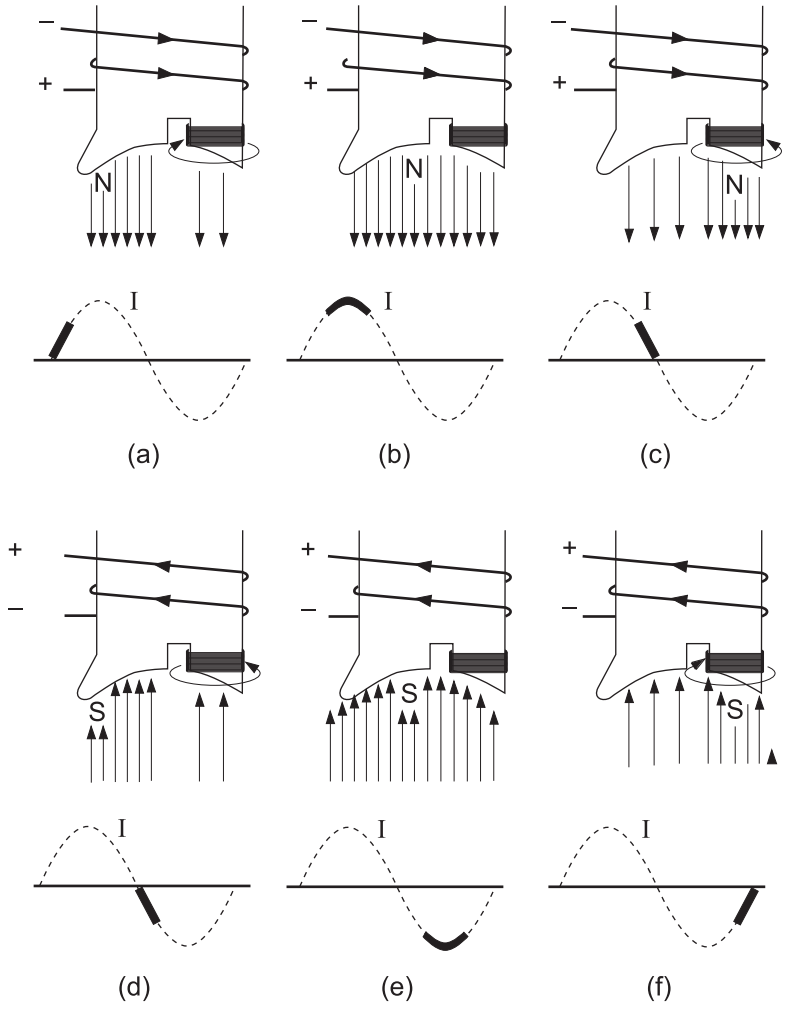


Figure 6—Production of a shifting magnetic field across a single pole

- During the part of the current sine wave shown in Figure 6c, the current in the exciter winding is decreasing rapidly. This results in large emf being induced in the shading coil. This large emf sets up flux in the same direction as the collapsing field to try to maintain the field. For this reason, the field is very strong in the shaded part of the winding, while it is becoming weaker in the unshaded portion of the pole. The north pole centre has now shifted to the centre of the shaded portion of the pole.
- During the part of the current sine wave shown in Figure 6d, the current in the exciter winding is increasing at a rapid rate in the opposite direction to what it was in Figure 6a. This means the flux in the pole is also expanding rapidly, but in the opposite direction. This fast rate of flux change causes a large emf to be induced in the shading coil. The large emf produces a large current in the direction shown, which sets up a flux opposite to that of the exciter winding flux. This, in effect, reduces the total flux in the shaded portion of the pole, with the net result that there is a strong south pole produced in the unshaded portion of the pole and a weak south pole produced in the shaded portion of the pole.
- During the part of the current sine wave shown in Figure 6e, the current in the exciter winding is large but is changing very little. This results in a low value of emf being induced in the shading coil. Therefore, very little current is induced in the shading coil and it has very little effect on the flux in the shaded portion of the pole. The total flux is spread evenly across the whole pole face, resulting in a strong south pole with its centre in the centre of the whole pole.
- During the part of the current sine wave shown in Figure 6f, the current in the exciter winding is decreasing at a rapid rate. This results in large emf being induced in the shading coil. This large emf sets up flux in the same direction as the collapsing field to try to maintain the field. For this reason the field is very strong in the shaded part of the winding while it is becoming weaker in the unshaded portion of the pole. The south pole centre has now shifted to the centre of the shaded portion of the pole.

The shifting field across the pole face cuts across the conductors of the rotor, inducing a current in them as it does in other induction motors. The flux produced by this rotor current creates a flux that interacts with the main stator flux. This produces a torque in the same direction as the motion of the stator field.

Note that the stator flux is always shifting across the pole faces from the unshaded portion to the shaded portion and the rotor will always try to follow the moving field. The simplest way to reverse a shaded-pole motor is to remove both end bells, slide the stator off of the rotor, turn it end-for-end and slide it back over the rotor. After this, the end bells are replaced and the shaded portion of the pole has been moved to the other side of the pole. Figure 7 shows how the shaded pole appears when the stator is turned end-for-end.

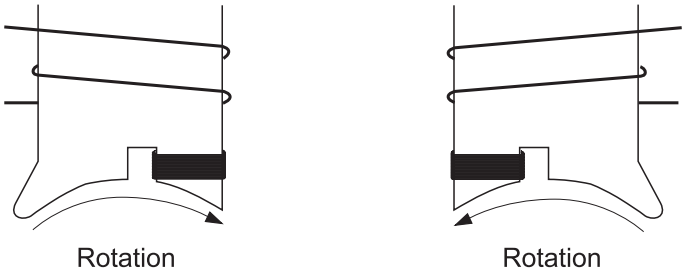


Figure 7—Reversing the direction of rotation

The flux in the stator of the shaded-pole motor tends to pulsate, which produces a torque that also pulsates. The motor has low starting torque, poor overall efficiency and very little overload capacity. However, its low production cost and simple construction make it well suited for some low-horsepower applications. The most common application of this motor is to operate fans and blowers, since they require very little starting torque. They are also used in small devices such as electric can openers, clocks and advertising displays.

Synchronous shaded-pole (hysteresis) motors

A type of shaded-pole motor that rotates at synchronous speed may be constructed by changing only the rotor design (Figure 8). This type of motor is often referred to as a *hysteresis* motor. The rotor is made up of hardened steel, which has a large hysteresis loss.

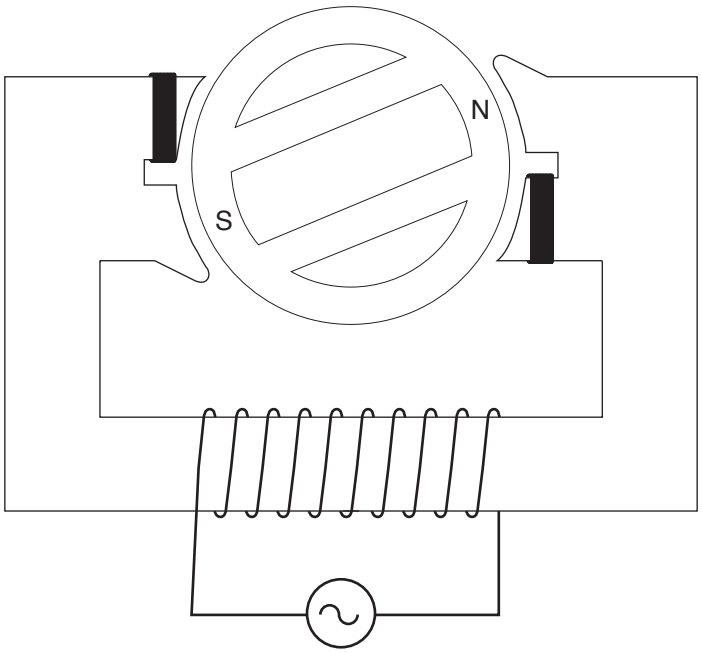


Figure 8—Rotor of hysteresis motor

There are no rotor bars in this motor. It accelerates up to synchronous speed by circulating currents induced in the rotor. Once it approaches synchronous speed the established poles do not reverse easily because of the hardness of the rotor steel. The poles then tend to lock in and follow the stator poles—causing the rotor to turn at synchronous speed. This type of motor has

a very smooth acceleration right up to synchronous speed. The straight bars in the rotor tend to reduce the reluctance of the path between them such that poles are formed on the sides of the rotor shown. The fact that this motor does not have squirrel-cage bars or teeth gives it a very smooth operation. This makes it very suitable for use in sound equipment.

 Now do Self-Test 15 and check your answers.

Self-Test 15

1. State three constructional differences between an AC series motor and a DC series motor.

2. State the relationship between load and speed for a series motor.

3. How does the rotor part of the series motor receive its energy?

4. How is the direction of rotation reversed in a series motor?

5. What may happen if a large series motor is operated with no load connected?

6. What two variables affect the counter emf generated in the armature?

7. What two variables affect the torque developed by the rotor of the series motor?

8. Will an AC series motor operate on DC?

9. Why does the direction of rotation not change each time the alternating current changes direction?

10. Why are the stator and rotor cores of the universal motor laminated?

11. What are the two types of windings in the stator of a shaded-pole motor?

12. How do the two stator windings receive their energy from the source?

13. In what direction does the field move across the pole face in a shaded-pole motor?

14. How is the direction of rotation of a shaded-pole face motor reversed?

15. Is the starting torque of a shaded-pole motor high or low compared to a split-phase motor?

16. At what speed does the rotor of a hysteresis motor rotate?

17. From what type of steel is the rotor of a hysteresis motor rotor made? Why is this the case?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 16:

Describe basic maintenance and troubleshooting for single-phase motors

Cleanliness is probably the most important preventive maintenance measure you can take. This permits the proper flow of cooling air around and through the motor. Periodic checks of the motor for overheating, as well as bearing wear and lubrication, will help to detect early failures.

The troubleshooting procedures for single-phase induction motors include those listed in the extensive troubleshooting table for three-phase motors.

The following are specific problems associated with split-phase motors and series motors.

Split-phase motors

The components of the starting circuit in a split-phase motor are not constructed for continuous operation. The purpose of the centrifugal switch is to open the starting circuit after the motor reaches about 75% of its rated speed. If the switch does not open, or if the load on the motor is so great that it cannot reach 75% of its rated speed, heat damage may occur to the capacitor or the starting winding. Failure of the motor to start can be caused by any of the following problems:

- Blown fuses
- Opens in either the main or auxiliary windings
- Open or short in the starting capacitor
- Overload
- Open in the centrifugal switch

If the motor runs hot or fails to come up to speed, this may indicate that the centrifugal switch is not opening.

Series motors

Most maintenance on series motors involves the commutator, brushes and brush rigging. After several weeks of operation, a good commutator builds up an oxide layer that provides excellent lubrication between the brushes and commutator. This oxide layer normally appears as a light-brown film around the circumference of the commutator. A commutator that has this appearance should be left alone.

- Undesirable films may be either too dull or too shiny but are usually very dark.
- No film at all is shown by a light copper colour and is often an indication that the brushes are too hard.

Sparking

The brushes should make good contact with the commutator and some sparking will normally occur at full load. Excessive sparking, however, is an indication of trouble and should be looked into before it has a chance to do damage. Some of the possible causes of excessive sparking are:

- Overload
- Roughness at the commutator edges (they should be bevelled and smooth)
- High mica between commutator bars
- Brush position not in the neutral plane
- Incorrect brush pressure
- Incorrect brush grade
- Brushes worn excessively (less than one-quarter remaining)
- Vibration of the brushes

The brush holders may become loose or misaligned, and brushes should slide easily in the brush holder. The spring pressure on the brushes should be adjusted to manufacturers' specifications.

 Now do Self-Test 16 and check your answers.

Self-Test 16

1. What is the most important maintenance task that should be performed on any motor?

2. List four possible reasons that a split-phase motor might fail to start.

3. List five possible causes of excessive sparking at the commutator of a universal motor.

4. What should a proper film on the commutator look like?

5. At what percentage of full speed should the centrifugal switch open on a split-phase motor?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 17:

Describe the constructional features of three-phase alternators

There are two types of alternating current generators (alternators) available today:

- Revolving-armature type
- Revolving-field type

Revolving-armature type

For this alternator, the stator is built in the same way as the stator of a DC generator, with field coils wound and held to the frame of the stator by pole pieces. The armature is wound as in a DC machine, except that it has slip rings rather than a commutator (Figure 1).

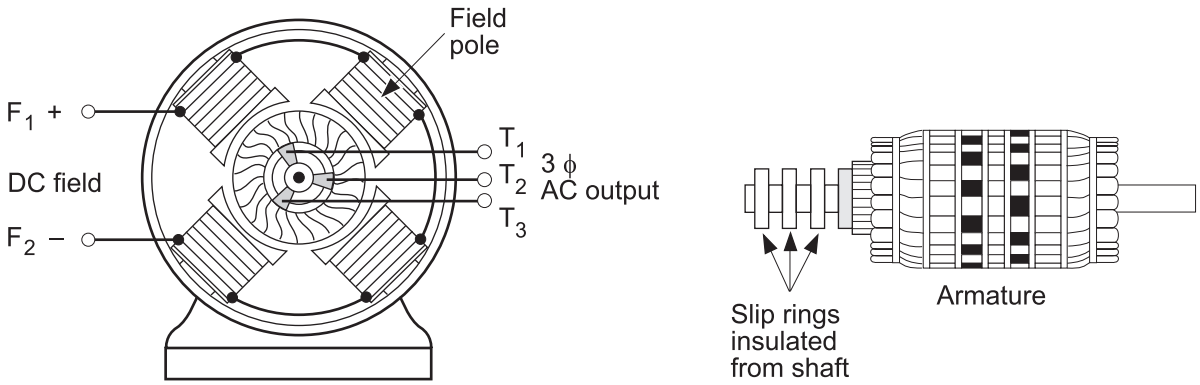


Figure 1—Parts of a revolving-armature alternator

The revolving-armature type of AC generator is seldom used. Its primary limitation is that its output current must be conducted through brushes at the slip rings. This design poses many problems at higher values of voltage and load currents. Consequently, revolving-armature generators are limited to low-current, low-voltage applications.

Revolving-field type

Most alternators are the revolving-field type in which the revolving-field structure or rotor has slip rings and brushes to supply the excitation current from an external DC source. The armature coils are placed into slots in the laminated stator core.

The stator is constructed of thin steel punchings or laminations securely clamped and held in place in the steel frame of the generator. Slip rings and brushes are adequate for the DC field supply because the power level in the field is much lower than in the armature circuit (Figure 2).

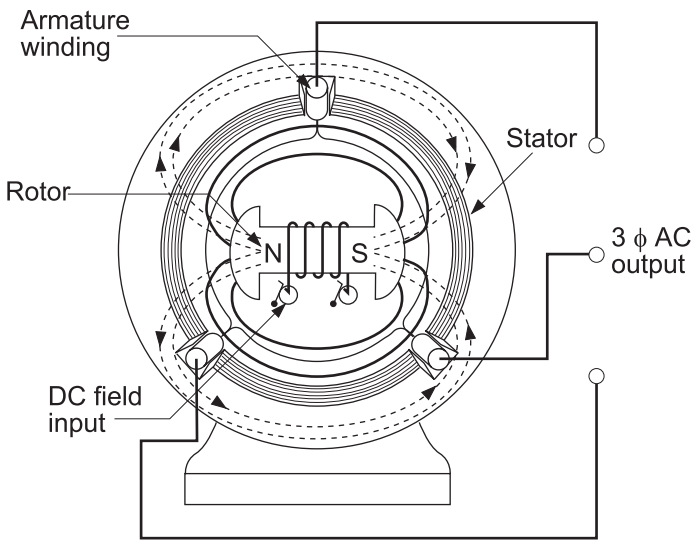


Figure 2—Revolving-field alternator

The revolving-field alternator has several advantages over the rotating-armature type AC generator:

1. Voltages as high as 13 800 V can be generated because the stationary armature windings, are not subject to vibration and centrifugal stresses.
2. The current ratings of alternators can be relatively high. This is because the output of the alternator is taken directly (without the use of slip rings or commutator) from the stator windings, through large, well-insulated cables, to the external circuit.

Alternators may use two different types of construction for the revolving field:

- Salient-pole rotor
- Cylindrical rotor

Salient-pole rotor

The salient-pole alternator has projecting field poles and is used with slow-speed alternators where the speed is below 1800 rpm. Typical prime movers for slow-speed alternators are diesel units and water turbines. The prime mover supplies the mechanical energy input to the generator.

Figure 3 shows a salient-pole stator and rotor used for a slow-speed alternator. Each pole has a laminated steel core to reduce the eddy-current losses. The field coil windings are mounted on the laminated poles and are connected in series to give alternate north and south poles. Two slip rings supply low-voltage DC from an external source to magnetize the field poles.

The salient-pole rotor in Figure 3b shows slots on each of the pole faces in which a damper winding (or amortisseur winding) is placed. The purpose of this winding will be discussed later.

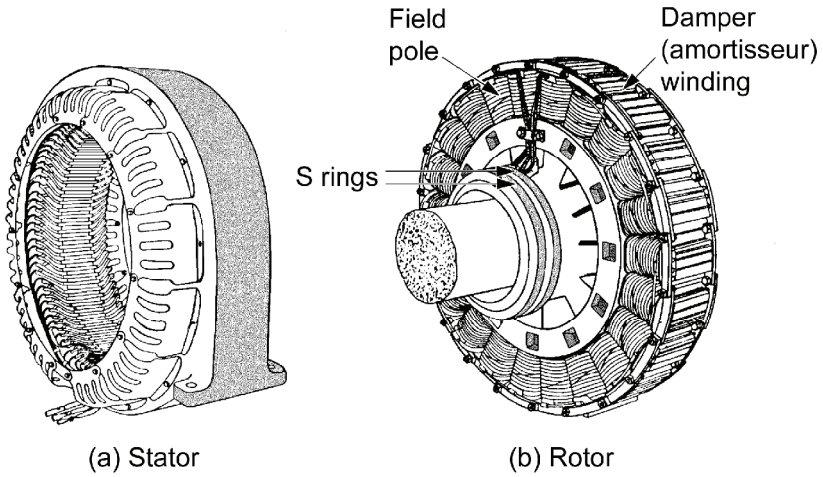


Figure 3—Salient-pole alternator

Cylindrical rotor

A high-speed steam turbine is often used to drive these alternators. For high speed it is difficult to build a rotating field with projecting poles strong enough to withstand the centrifugal force. Projecting poles would also cause excessive windage (air resistance) losses and make the alternator noisy. To overcome these undesirable effects, alternators intended for steam-turbine drives are cylindrical and small in diameter, usually with two or four poles. The stator and rotor for this type of alternator are shown in Figure 4.

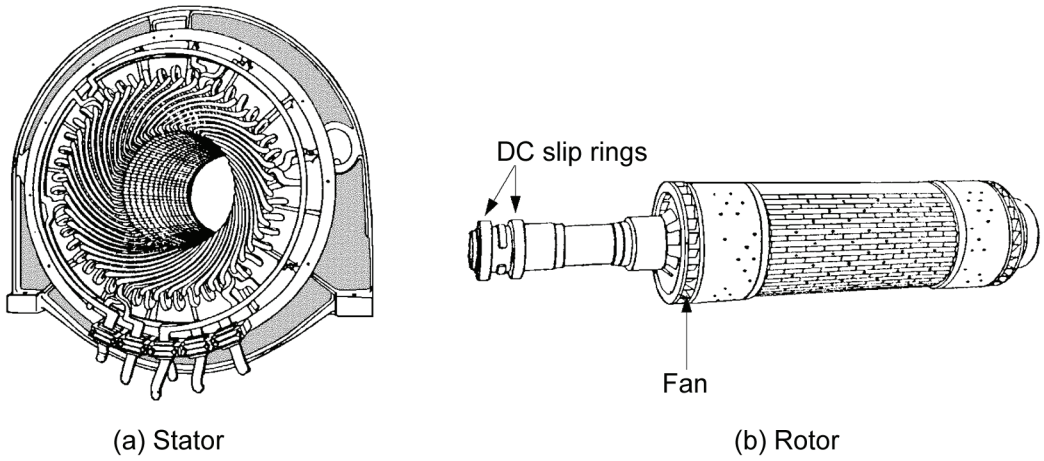


Figure 4—Cylindrical alternator

Field excitation

Since direct current must be used in the field circuit, all alternators must be supplied with a DC source. The direct current is typically supplied by a DC generator operated on the same shaft as the alternator. This DC generator is referred to as the *exciter*. An example of a self-excited alternator and its associated field equipment is illustrated in Figure 5. There are certain installations where several alternators are used. In these cases, the excitation is supplied from a common bus by a separate DC generator and prime mover.

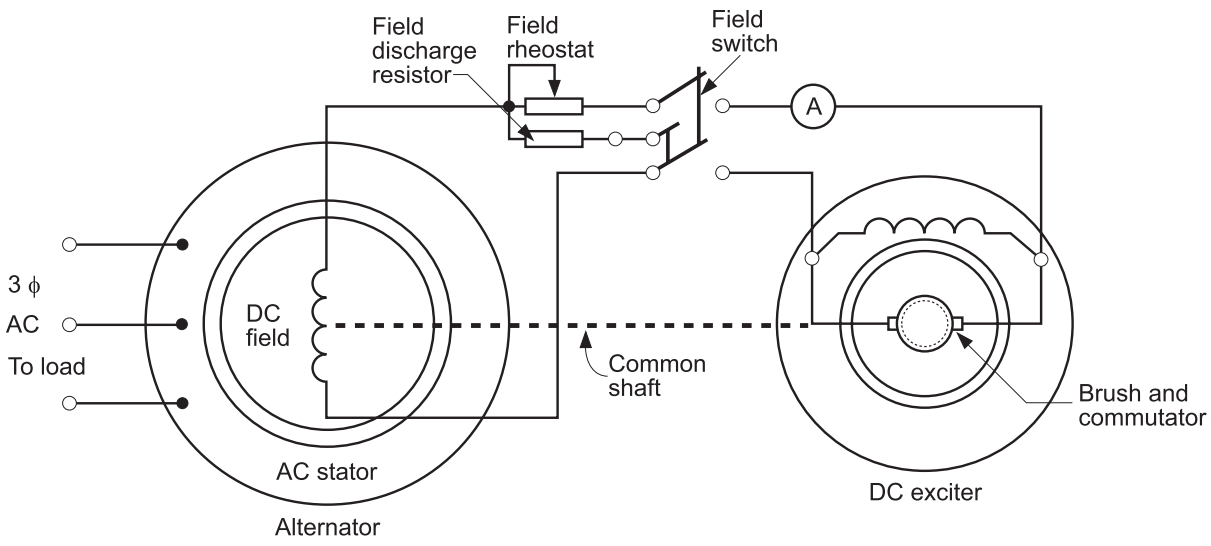


Figure 5—Self-excited alternator and controls

Field discharge circuit

A special field discharge switch is used in the excitation circuit to eliminate danger to personnel and equipment (resulting from the high induced voltage created on opening the field circuit). The field discharge switch has an auxiliary switch blade that is in an open position when the main switch contacts are closed. When the switch is being opened, the auxiliary contact closes before the main switch blades open. All types of alternators use such a field circuit, or one that is very similar (Figure 5). A larger machine may use a field contactor or field circuit breaker for the same purpose.

Brushless exciters

Brushless exciters eliminate all sliding contacts and avoid the destructive effects caused by arcing. Brushless excitation is a common method of providing field excitation:

- Where explosive or extremely wet ambient conditions occur
- Where low maintenance is desirable.

The unique feature of the brushless alternator is its use of a three-phase, full-wave, bridge-connected rectifier (Figure 6). The rectifier is mounted on the shaft of the rotating machine and connects the AC output of a small rotating three-phase alternator (exciter) to the DC rotating field of the larger alternator. The entire excitation circuit (exciter, rectifier and DC field) rotates as a unit and eliminates the need for slip rings and brushes.

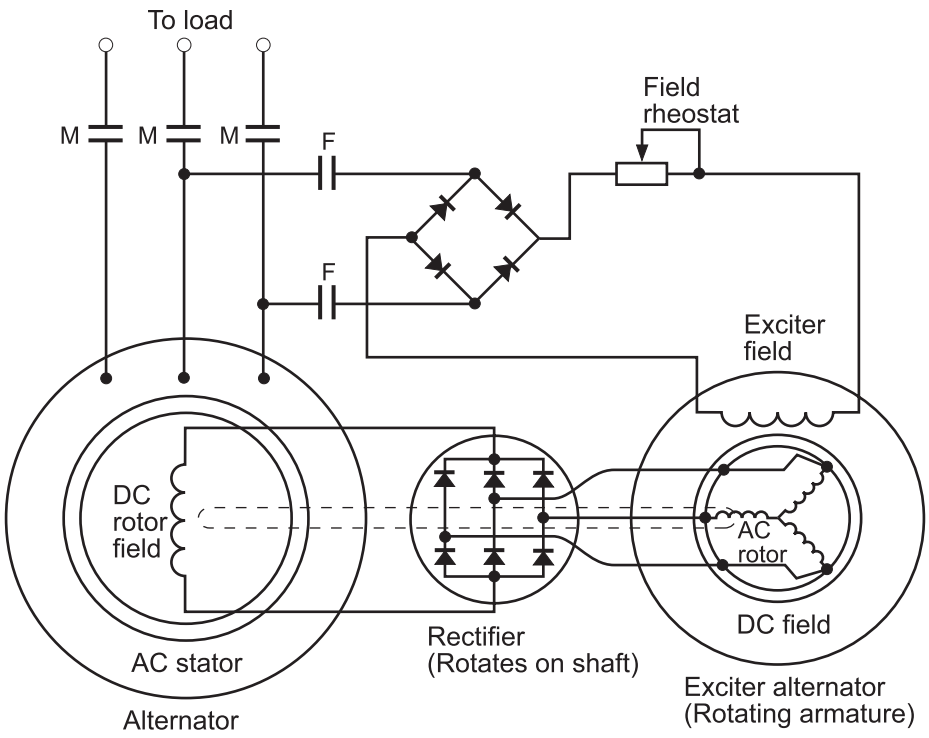


Figure 6—Brushless exciter with bridge-connected rectifier

The primary source of mechanical power for the alternator is generally a reciprocating engine. This engine drives the field-rectifier-exciter assembly. The stationary DC field of the exciter is energized from the output terminals of the alternator, and builds up through the bridge-connected rectifier. A rheostat in the stationary DC field circuit is used to adjust the voltage output of the exciter which, in turn, regulates the DC excitation and the AC output voltage of the alternator.

Nameplate data

The type of information on the nameplate for an alternator is similar to what is found on the nameplate of a motor. Figure 7 shows a typical nameplate. Note that the capacity of an alternator is stated in kVA since the power factor of the connected load will determine the actual kW used. Sometimes a wattage rating is listed to determine the rating of the prime mover. As well, the voltage and current for the DC field excitation are included.

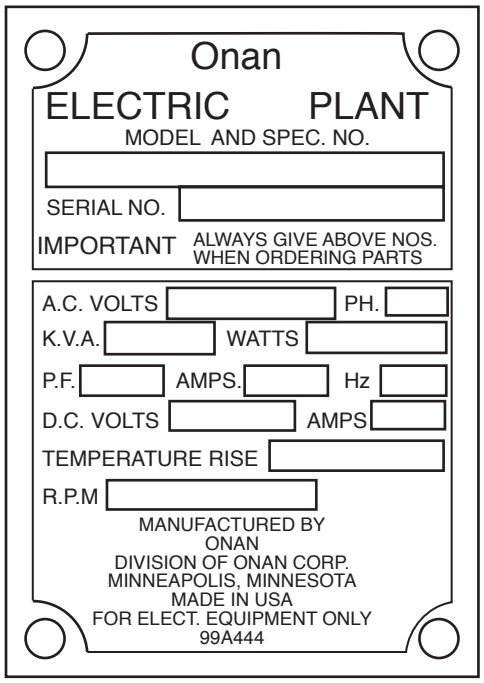


Figure 7—Typical alternator nameplate

Now do Self-Test 17 and check your answers.

Self-Test 17

1. Give the two main reasons for preferring revolving-field alternators to revolving-armature alternators.

2. What is the purpose of an exciter?

3. Explain the construction differences between a salient-pole rotor and a cylindrical rotor.

4. What is the purpose of a field-discharge resistor?

5. Give two reasons why a brushless exciter may be selected over a brush-type exciter for the field of an alternator.

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 18:

Describe operating principles of three-phase alternators

Earlier you learned that whenever a conductor is passed through a magnetic field (or a field cuts a conductor), a voltage will be induced within that conductor. These conditions are expressed in the following formula for a generator:

$$E_g = k\varphi N$$

where:

E_g = generated voltage
k = machine (design) constant
φ = flux (excitation) in Webers
N = rotational speed in rpm

In practical terms, this illustrates that the generated voltage can be controlled either by varying the field strength, or by changing the speed of the prime mover. You should recall that for AC generators, the rotational speed also affects the frequency of the generated voltage, as expressed by the following formula:

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

where:

f = frequency in Hz
P = number of field poles
N = speed in rpm

Therefore, the only practical way to control the generated voltage of an alternator is through field control. Normally this is accomplished by using a rheostat in the DC field circuit.

Voltage regulation characteristics

If there is no load connected to an alternator, its terminal voltage is exactly the same as the generated voltage. When a load is connected, however, load current flows through the stator coils. This brings into play the internal impedance (sometimes called *synchronous impedance*) of the armature.

Two factors determine the internal impedance:

- Resistance of the armature conductors
- Inductive reactance of the armature coils

These same factors affect terminal voltage. How they do this depends on the power factor of the load. Figure 1 shows the effects of load power factor with the same field excitation current on the output voltage of an alternator. From this graph, you can see that both the amount of load and the type of load affect the output voltage.

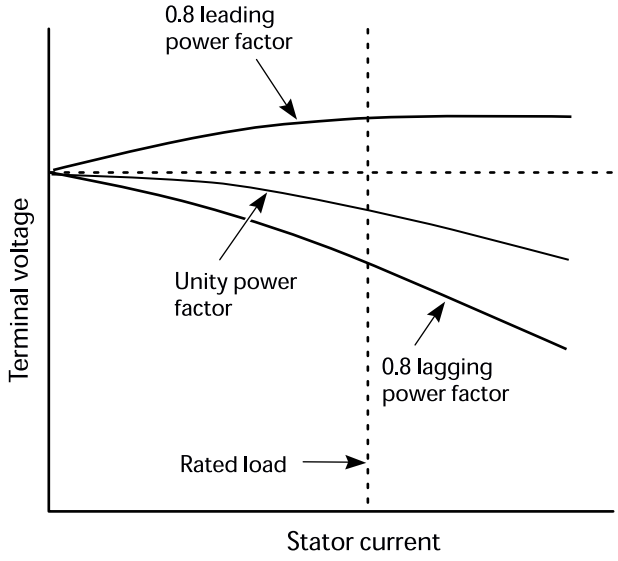


Figure 1—Effects of load and PF on terminal voltage

The change in terminal voltage from full load (FL) to no load (NL) is called *percent voltage regulation*. It is calculated by the following formula:

$$\text{Percent voltage regulation} = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100\%$$

Example: The no-load voltage of a certain generator is 250 V and the full-load voltage is 220 V.

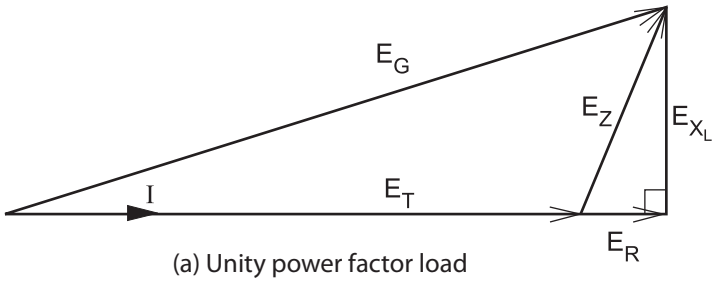
Therefore:

$$\text{Percent voltage regulation} = \frac{250\ \text{V} - 220\ \text{V}}{220\ \text{V}} \times 100\%$$

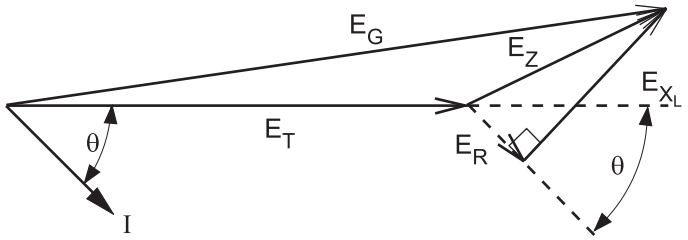
$$= 13.6\%$$

Effects of load PF

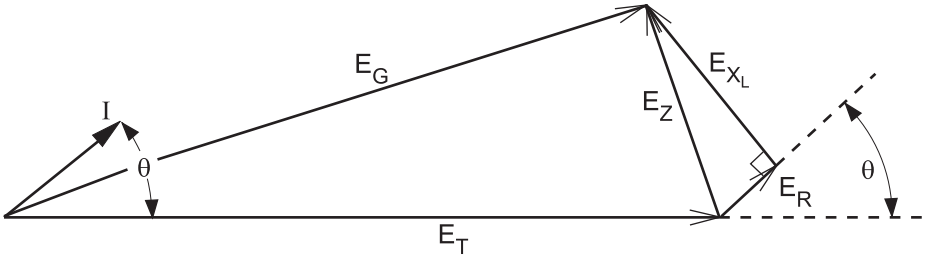
In the stator windings of an alternator there is a voltage drop caused by the effective resistance of the windings (E_R) and another voltage drop caused by the inductive reactance of the windings (E_{X_L}). The combination of these voltage drops is called the *stator impedance voltage drop* (E_Z). To find the induced voltage in the stator windings (E_G), the impedance voltage-drop in the stator windings (E_Z) must be added vectorially to the terminal voltage (E_T), as shown in Figure 2.



(a) Unity power factor load



(b) Lagging power factor load



(c) Leading power factor load

Figure 2—Combined effect of a stator resistance and stator reactance on terminal voltage

Unity power factor loads

Figure 2a shows the vector diagram for a single-phase alternator with a unity power factor load. Note that the stator winding is treated as a series circuit made up of resistance and inductive reactance with the load current (I) used as a reference line.

The load current is in phase with the terminal voltage (E_T) and the voltage drop E_R in the stator windings is caused by resistance. The voltage drop caused by the inductive reactance of the stator windings (E_{X_L}) leads the load current by 90°.

The vector combination of the voltage drops caused by the effective resistance and the inductive reactance is represented as E_Z (the stator impedance voltage drop). The net result is that the terminal voltage (E_T) will usually be 8–20% below its no-load value (E_G).

Lagging power factor loads

Figure 2b is a vector diagram for the same alternator with a lagging PF load. The load current (I) is lagging the terminal voltage (E_T) by angle θ. The stator impedance voltage drop (E_Z) is added vectorially to the induced voltage (E_G) to obtain the terminal voltage (E_T). The vector diagram

shows that when the current lags the terminal voltage, the small impedance triangle shifts in a clockwise direction and results in the terminal voltage being reduced. A lagging power factor load may cause the terminal voltage (E_T) of an alternator to drop as much as 25–50% below the no-load value (E_G).

Leading power factor loads

In Figure 2c we have an example with the load current leading the terminal voltage by angle θ. The phase relationship between the impedance voltage drop in the stator (E_Z) and the induced voltage (E_G) causes the terminal voltage (E_T) to be greater than the induced voltage (E_G). As the angle of lead between the load current and the terminal voltage increases, the stator impedance triangle moves counterclockwise, making the magnitude of the terminal voltage (E_T) larger for the same value of induced voltage (E_G).

Armature reaction

Another item that affects the voltage output of an alternator is armature reaction. At unity power factor, armature reaction consists of minimal distortion of the main field flux.

When an alternator operates with a *lagging power factor*, the current in the stator conductors sets up a magnetomotive force (mmf) that opposes the magnetizing force of the main field and causes a decrease in the main field flux. This, in turn, results in a *decrease in the induced voltage*. The lower the value of the lagging power factor, the greater the stator mmf that opposes and weakens the field (Figure 3).

In those limited applications where an alternator supplies a load with a leading power factor, the stator current sets up an mmf in the stator which aids the main field flux and causes the main field to strengthen. Therefore, the voltage of the alternator will increase with an increase in load current. The lower the value of the leading power factor, the greater will be the aiding effect of the main field to increase the main field flux.

Exactly how much the terminal voltage will drop or rise will depend primarily upon:

- The magnitude of the load current
- The overall power factor of the combined loads

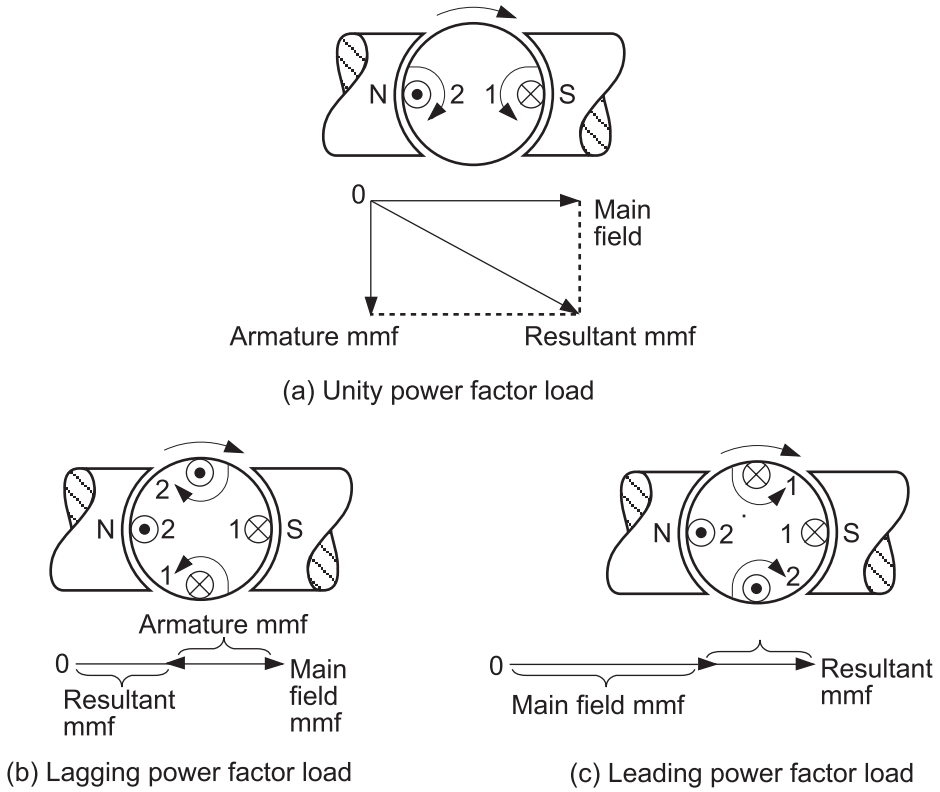


Figure 3—Effects of armature reaction

In review:

- The greater the load, the greater the drop or rise in voltage
- The lower the lagging power factor, the greater the voltage drop
- The lower the leading power factor, the greater the voltage rise

Automatic voltage control

The combined effects of both armature reactance (X_L) and armature reaction can cause considerable change in an alternator's terminal voltage, with changes in load current and load power factor. To maintain a relatively constant terminal voltage under changing load conditions, automatic voltage regulators are often used.

Automatic voltage regulators adjust the alternator field current to compensate for changes in load current. For example, if the terminal voltage decreases, the voltage regulator senses this change and increases the field current. This increase in the field current causes an increase in field flux and induced voltage. In this way, the AC terminal voltage is restored to its original value.

Now do Self-Test 18 and check your answers.

Self-Test 18

1. Name two factors that control the frequency output of an alternator.

   _____

   _____

2. The full-load terminal voltage of an alternator is 240 V. The load is removed and with the same speed and field excitation, the no-load terminal voltage increases to 265 V. What is the percent voltage regulation of the alternator?

   _____

3. The output voltage of an alternator is maintained at a steady level through the use of a(n) _____ .

4. The voltage regulation of an alternator will be poorest with a _____ power factor load.

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 19:

Identify common connections for three-phase alternators

The armatures of three-phase alternators can be connected either in wye or in delta. Probably the most common type of three-phase alternator contains 12 stator leads. This allows the possibility of the following coil group connections:

- Series wye
- Parallel wye
- Series delta
- Parallel delta

Series wye

Series wye has three advantages:

- It provides two different voltages (phase and line).
- It reduces insulation requirements to phase voltages levels.
- It provided a neutral point for system grounding.

Parallel wye

Parallel wye gains a current advantage while maintaining the features of a series wye system.

Series delta

Series delta gains a current advantage. Line current values will be 1.73 times greater than phase values, so smaller coil wire sizes may be used for alternator construction.

Parallel delta

Parallel delta gains a further current advantage, double over the series delta connection.

Most medium-sized machines are supplied with a 12-lead armature. This gives the user a wider choice of voltage and current outputs.



Note that changing lead connections from wye-to-delta or series-to-parallel will not change the machine's kVA rating.

Standard stator connections

Figures 1–4 depict the four possible standard connections for a 12-lead armature. In the examples shown, the DC field excitation is set to produce 120 V per coil and a maximum of 100 A per coil.

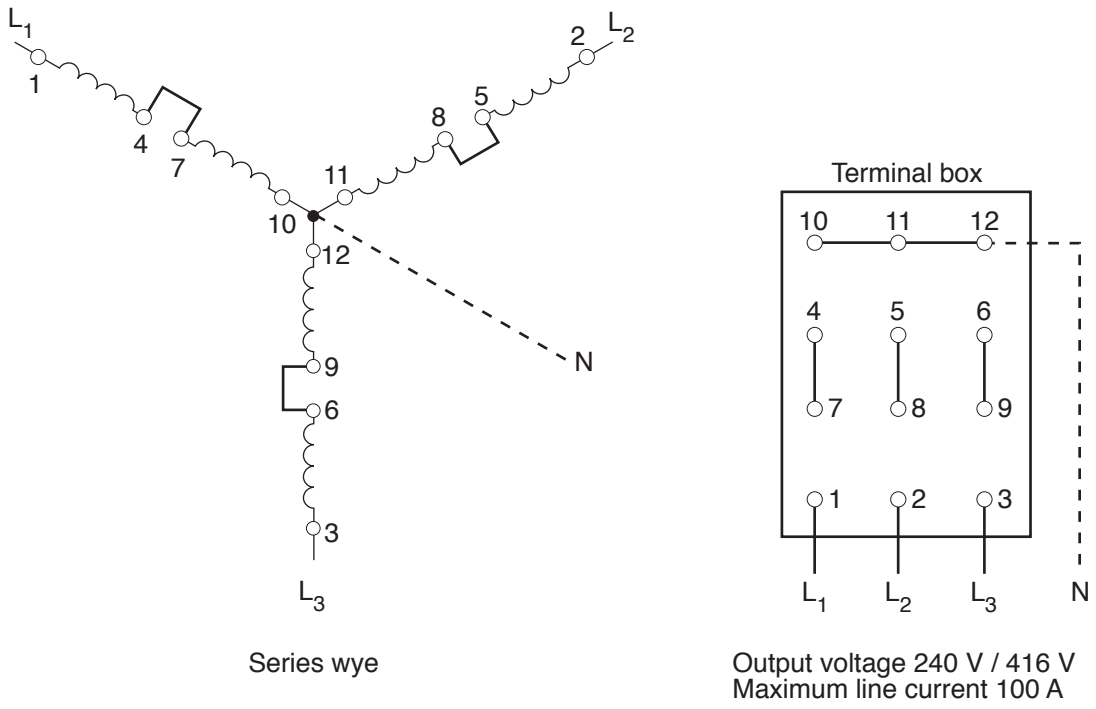


Figure 1—Series wye, high-voltage connection, 240/416 V

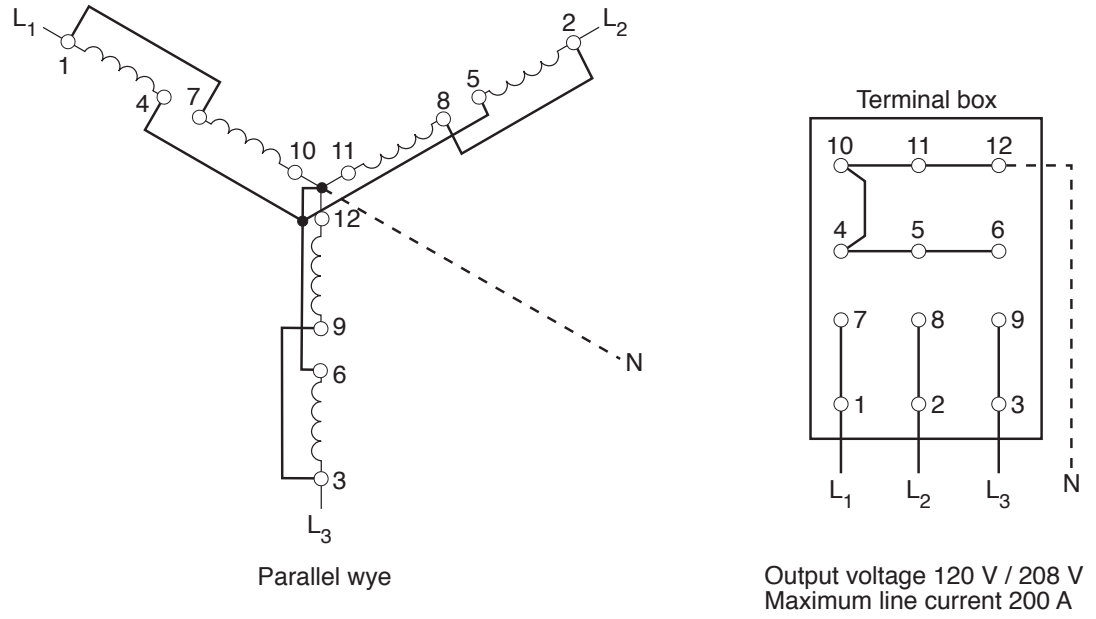


Figure 2—Parallel wye, low-voltage connection, 120/208 V

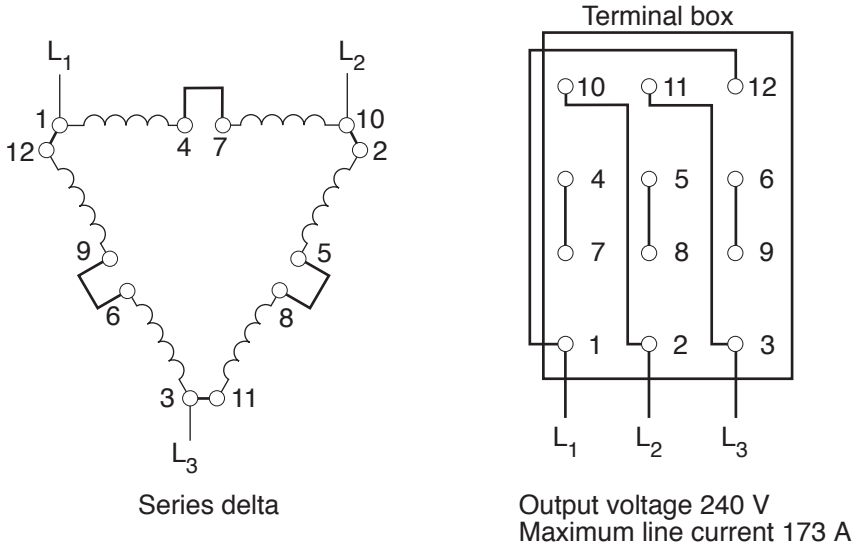


Figure 3—Series delta, high-voltage connection, 240 V

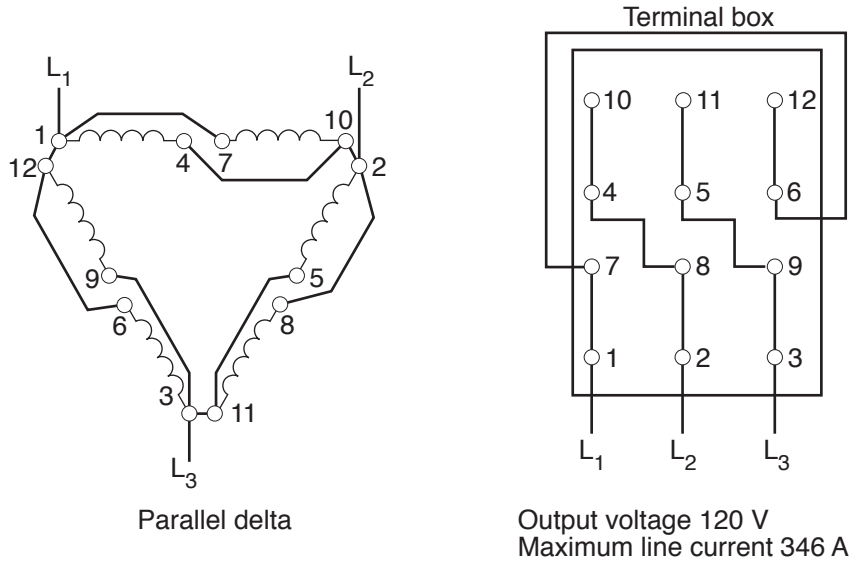


Figure 4—Parallel delta, low-voltage connection, 120 V

There are certain variations in machines and wiring practices. Some of these are as follows:

- Not all three-phase wye machines can be reconnected delta. This is due to small impedance differences in the coils, which may, in turn, set up damaging circulating currents in the stator winding. (Check the nameplate on the alternator or contact the manufacturer of the unit before proceeding.)
- The star point is not necessarily brought out on all machines. This fact does not prevent you from performing the parallel wye connection shown in Figure 2. The two star points, if available, should be connected together for stability.

- Nine-lead armatures are also available to supply three-phase dual voltages. In the wye configuration this is accomplished by making leads 10, 11 and 12 as internal connections. In a delta configuration, leads 1 and 12 are internally connected, as are 2 and 10, and 3 and 11. You are then left with a nine-lead terminal box.



Note that a nine-lead armature cannot be reconnected from one configuration to another, for example, wye-to-delta or delta-to-wye.

- The DC field windings are identified by the prefix "F." For separately excited alternators, there are generally only two field leads brought out: F_1 and F_2.



Now do Self-Test 19 and check your answers.

Self-Test 19

1. What are the three main reasons for connecting a three-phase alternator in wye?

2. What is the prefix for the leads to the:
   a. armature
   b. field

3. Given a six-coil, three-phase alternator, which one of the following connections would yield the highest output current?
   a. parallel wye
   b. parallel delta
   c. series wye
   d. series delta

4. The terminal box in Figure 1 is found on a dual-voltage, 200 kVA, three-phase alternator. Complete the connections for the highest voltage, three-phase, four-wire installation.

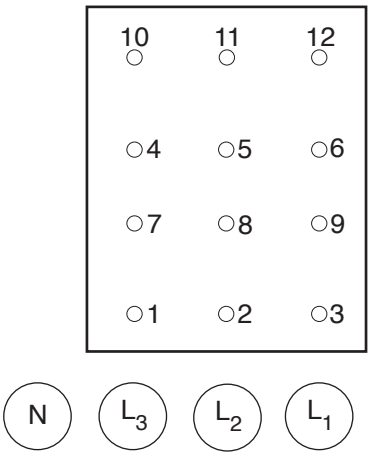


Figure 1

5. If the voltage per coil in Question 4 is 100 V, what would the resultant line voltage be?

6. What would the kVA rating be for the alternator in Question 4 if it were connected parallel delta?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 20:

Describe the conditions for operating alternators in parallel (synchronizing)

There are three main reasons for operating alternators in parallel:

1. The load requirements for any central generating station change continually. During light-load periods the load demands can be met by one or two alternators operating near their full-load ratings, which means they will also be operating at a high efficiency. As the load demands on the central station increase during certain periods of the day, other alternators can be connected in parallel to meet the peak demands. This is preferable to using one huge machine that would be operating at certain periods of each day at only a small fraction of its full-load capacity, with a resultant low efficiency.
2. The electrical power requirements in any area are increasing. To meet these increased demands, power utility companies can increase the physical size of their generating plant and install additional alternators. These machines are operated in parallel with the existing generating equipment. This is a convenient and economical way of increasing the generating capacity of a central station.
3. With several AC generators available, periodic maintenance and repairs can be made to one alternator while the other machines, operating in parallel, supply the load. There is no need to have a power interruption because of generator failure.

Synchronizing alternators

When alternators are large enough and operating at unequal frequencies and terminal voltages, severe damage can result if they are suddenly connected to each other through a common bus. To avoid this, the alternators must be synchronized as closely as possible before connecting them together. The requirements for synchronizing alternators are:

1. The terminal voltage of both machines must be equal. This is accomplished by varying the rotor field excitation.
2. The generated frequencies must be the same. To effect this, you must adjust the speed of the prime mover.
3. The phase sequence of both machines must be the same: either A–B–C or A–C–B. This sequence can be determined by using a phase-sequence indicator or the three-dark lamp method described below.
4. The alternators must be in step or in phase at the moment of paralleling. You do this by raising or lowering the speed of the incoming alternator. In this case, you need either a synchroscope or synchronizing lamps.
5. The prime movers must have relatively similar speed–load characteristics.

Figure 1 shows two methods in which lamps are used for synchronizing three-phase alternators:

- Three-dark method
- Two-bright, one-dark method

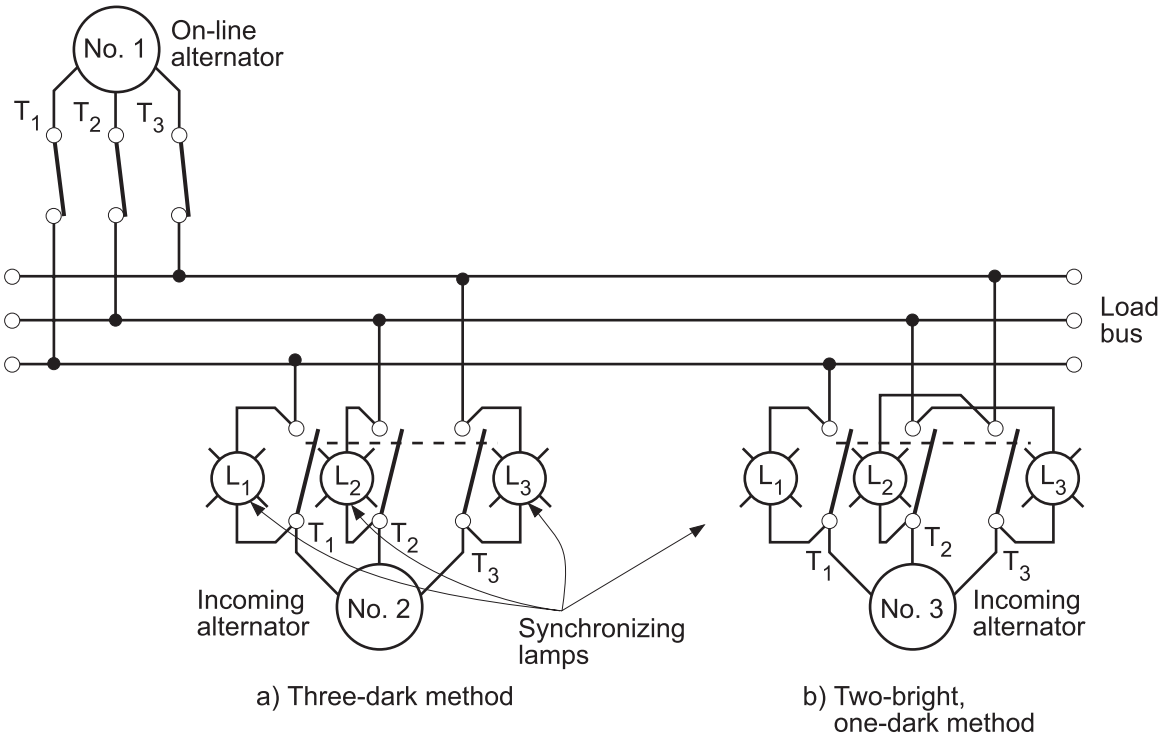


Figure 1—Methods of using lamps for synchronizing three-phase alternators

Three-dark method

In Figure 1, Alternator 1 is supplying energy to the load. Alternator 2 is to be paralleled with Alternator 1. Three lamps, each rated at the terminal voltage of the alternator, are connected across each switch. With both machines operating, one of two possible effects will be observed:

1. The three lamps will go on and off in unison at a rate that depends on the frequency difference between Alternator 2 and Alternator 1.
2. The three lamps go on and off, but not in unison. Their on-and-off rate depends upon the frequency difference between the two generators. However, in this case, the phase rotation or phase sequence of Alternator 2 is not the same as that of Alternator 1.

For effect 2, you must now correct the phase sequence of incoming Alternator 2 so that it will be the same as Alternator 1:

1. Interchange the connections of any two leads of Alternator 2. Now the three synchronizing lamps should go on and off in unison. This indicates the phase sequence is correct.

2. By very slight adjustment in the speed of the prime mover for Alternator 2, you can make the frequency of Alternator 2 the same as the frequency of Alternator 1.
3. The rate at which the lamps go on and off represents the difference in frequency between the two alternators.

A disadvantage of the three-dark method is that the lamps are dark even when there is appreciable voltage across their terminals. So the operator is likely to close the switch while considerable difference in voltage exists. This will not harm a small capacity or low-speed unit, but may cause considerable disturbance in a high-speed turbo unit.

Two-bright, one-dark method

The disadvantage of the three-dark method can be eliminated partially by cross-connecting two of the three indicating lamps as shown in Figure 1b. With this connection, when the alternator is near synchronism, Lamp 1 is dark while Lamps 2 and 3 are bright. One of the bright lamps will be increasing in brilliance and the other will be decreasing. At the instant of synchronism, Lamps 2 and 3 will be equally brilliant, indicating precisely when the switch should be closed.

Use of a synchroscope

After the phase sequence is known to be correct and permanent connections have been made, a single-phase instrument called a *synchroscope* is the best device to accurately synchronize two alternators (Figure 2).

A synchroscope indicates differences in frequency and the phase relationship between two voltages.

1. Voltage from one phase of the three-phase busbar system is connected to one set of coils in the synchroscope.
2. Voltage from the same phase of the incoming alternator is connected to the other set of coils in the instrument.
3. The synchroscope has a rotating pointer and a dial labelled with slow and fast direction arrows to show the speed relation of the incoming machine. In addition, an index point on the dial shows the actual in-phase position.

During synchronization, as the incoming machine's rotational speed approaches near-synchronism, the speed of the synchroscope pointer drops enough to become visible. (The pointer speed is proportional to the difference between the two alternator speeds.)

- When the pointer stops, the frequencies of the two alternators are the same, but the voltages may not necessarily be in phase.
- When the pointer stops in the vertical upward position, both the frequencies are equal and the voltages are in phase. Therefore, the alternators are in synchronism and the paralleling switch can be closed.

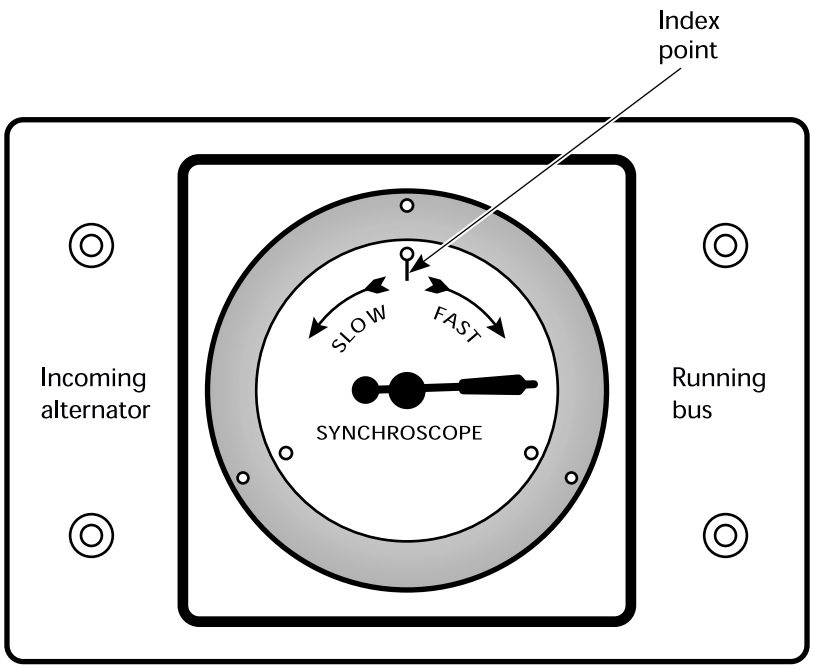


Figure 2—Synchroscope

Procedure for paralleling two machines

Figure 3 shows a simplified circuit for paralleling two three-phase alternators.

Assume that Alternator 2 is on line and operating at the correct voltage and frequency. You must complete the following sequence of operations to parallel the alternators:

1. Energize the prime mover to drive Alternator 1. Adjust the speed of the alternator to the approximate value required to match the frequencies of the alternators (60 Hz).
2. Check that the voltmeter V_1 is indicating the same value as V_2. If not, adjust the field rheostat R_1 until the AC voltages are equal.
3. Check phase rotation. The three lamps will glow bright and then glow dim in unison.
4. Check the frequency and voltage and make any adjustments to Alternator 1 as necessary.
5. The synchroscope should now be turning slowly clockwise. Adjust the speed of Alternator 1's prime mover to suit. The switch S_1 may be closed a few degrees before reaching the index mark. This is done to eliminate any delay in closing S_1 due to such things as operator reaction time or mechanical take-up in S_1.
6. The alternators are now parallel and Alternator 1 is said to be *floating on line*. It is carrying little or no load, as indicated by ammeter A_1. Ammeters A_2 and A_3 should remain nearly identical and unchanged from their previous readings (before paralleling).

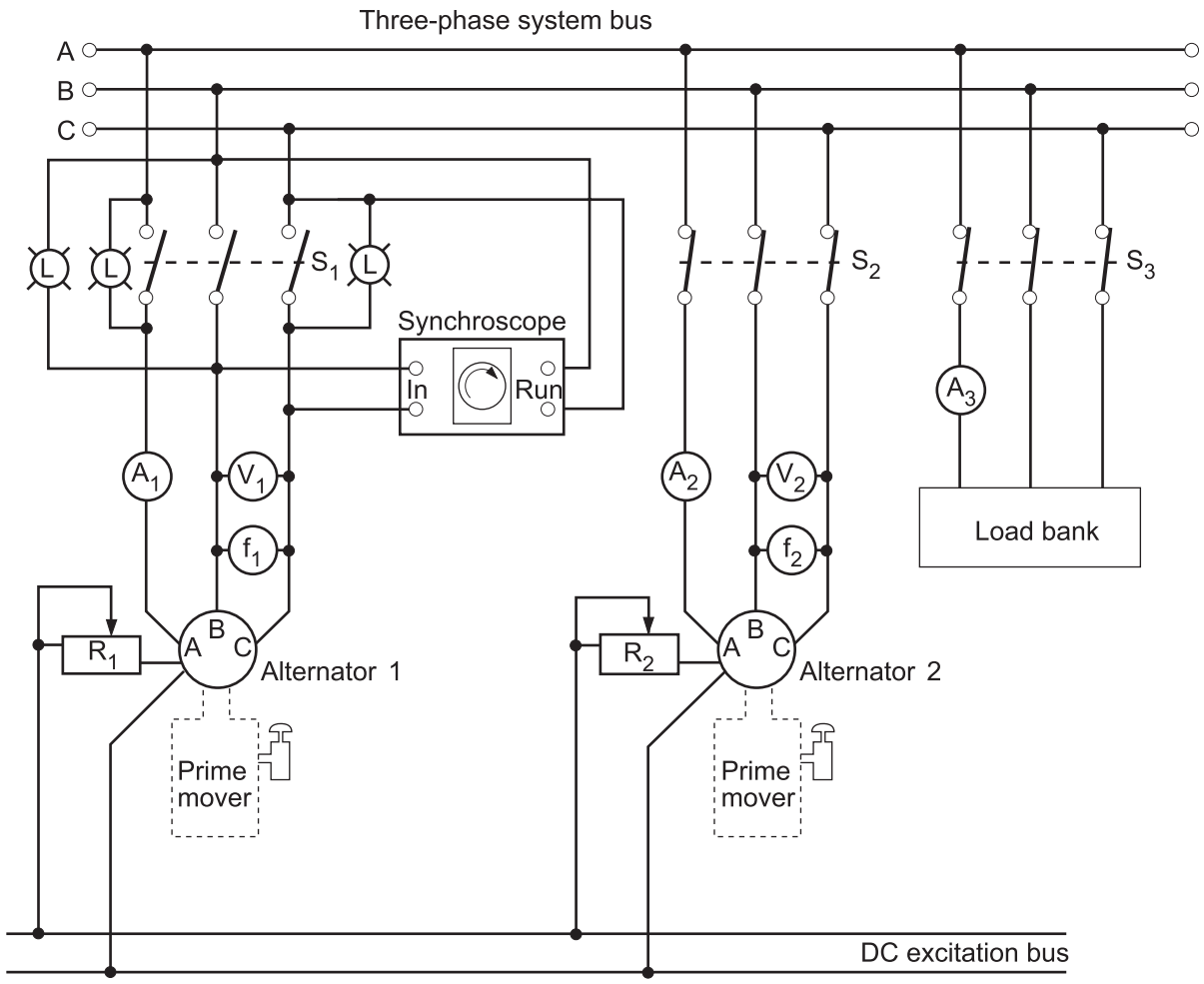


Figure 3—Circuit for paralleling two three-phase alternators

Load sharing between alternators

In order to have Alternator 1 pick up and share the electrical load with Alternator 2, it is necessary to shift the load from Alternator 2 to Alternator 1. This is accomplished by increasing the mechanical power input of the prime mover for Alternator 1, and simultaneously decreasing the mechanical power input of the prime mover for Alternator 2. This process is continued until ammeters A_1 and A_2 indicate equal values.

The governors of both prime movers must be manipulated simultaneously. This helps to keep the system frequency constant.

Effect of varying field excitation

While operating alternators in parallel, be very careful that you make any change in the division of kW load between alternators by changing the input to the prime movers of the machines, and *not* by changing their field excitation.

What effect would changing the field excitation have on alternators in parallel? Suppose that Alternators 1 and 2 (shown in Figure 3) supply equal voltages in phase. These voltages, being in phase relative to the load, are actually 180° out of phase with reference to each other (Figure 4a). Therefore, no current circulates between alternators.

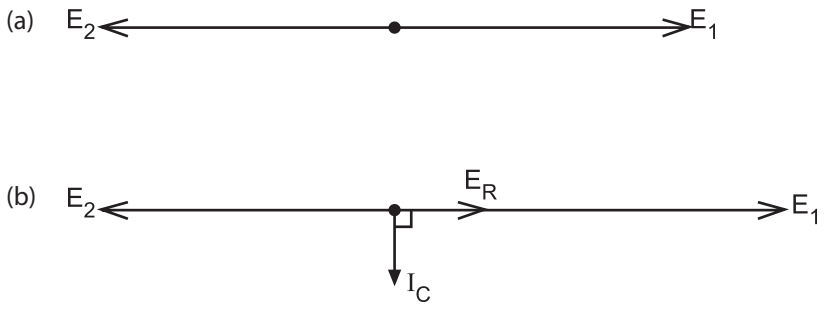


Figure 4—Effect of varying field excited

If the field excitation of Alternator 1 is increased, the voltage E_1 will be greater than E_2 in Figure 1b, with a resultant voltage E_R (equal to $E_1 - E_2$). This voltage will cause a current I_C to circulate between the two alternators. This current is limited by the impedance of the two machines. Because the resistance of the alternators is negligible in comparison to their reactance, the circulating current I_C will lag the resultant voltage E_R by nearly 90°.

This circulating current flows at zero power factor *lagging* through Alternator 1 and at zero power factor *leading* through Alternator 2. The magnetization action of I_C decreases the field flux in Alternator 1 and increases it in Alternator 2. Thus, if an attempt is made to increase the field strength of one alternator, a reactive circulating current will be established that tends to keep the field strengths of the two alternators the same.

You will recall the effects of armature reactance and armature reaction on the terminal voltage of an alternator with different power factor loads as explained earlier. This circulating current may increase the total current in one machine and decrease it in the other. However, the power supplied by each of the alternators is not materially affected because the power factor changes inversely with the current.

Note that an alternator cannot be made to take a load merely by increasing its field current. But increasing the field current can improve the power factor of an alternator and decrease its total current.

Prime mover considerations

The final requirement for the successful paralleling of AC machines is the speed-load characteristic of the prime movers. Each machine in a parallel combination must be driven with similar prime-mover characteristics. However, a problem can arise on a small reciprocating engine-driven machine that is to be paralleled with a similar but not identical machine.

Generally, the gasoline engine, diesel engine, reciprocating steam engine, steam turbine or gas turbine will all have *drooping speed-load* characteristics. This means that, as the torque load increases, the speed decreases or droops.

Also, every type of prime mover will require some sort of governor for speed control. This may result in prime mover–governor combinations with varying characteristics. Some may have 3%, some 10% and so on. Any paralleling combination should have a similar percent speed droop to match a similar percent load. Since the synchronized alternators must run at the same speed or the same ratio of speeds (if they have a different number of poles), their prime movers must droop reasonably close to the same percent speed as the load is increased. This allows the alternators to share the load equally.

Hunting

Hunting is a pulsating or oscillating effect that causes current to surge back and forth between alternators in parallel (which is unsatisfactory). It generally occurs in alternators driven by reciprocating engines because the driving torque of engines is not uniform in a revolution of the flywheel. This results in the alternator rotor periodically moving slightly faster, then slower. In some instances the oscillating effect becomes cumulative and may result in a large increase in the current between the alternators. This, in turn, may cause the overcurrent devices to open the circuit.

Hunting can be corrected by the use of a heavy flywheel, which helps to cut down the oscillating effect. A damper (squirrel-cage) winding is often used in the rotating field structure to minimize this pulsating torque condition.

A damper winding, often called an *amortisseur* winding, which is embedded in slots in each of the pole faces of the rotating field, is shown in Learning Task 1, Figure 3. This amortisseur winding consists of heavy conductors that are brazed or welded to two end rings. At the instant hunting develops, the path of the armature flux changes so that it cuts the short-circuited conductors of the amortisseur winding.

This change in flux path results in induced currents being set up in the damper winding that oppose the force producing them. If the damper winding is properly designed, the effects of hunting are cancelled by the induced currents in the short-circuited conductors.

 Now do Self-Test 20 and check your answers.

Self-Test 20

1. What four basic requirements must be satisfied before AC generators can be operated in parallel?

_____

_____

_____

_____

2. When paralleling alternators, three synchronizing lamps are commonly used, as shown in Figure 1.

   a. State the name given to each method.

   _____

   _____

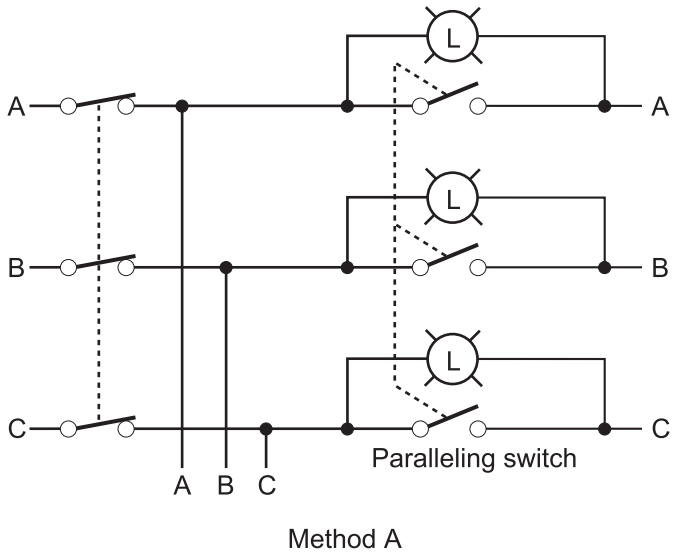
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   b. List an advantage that each method has over the other.

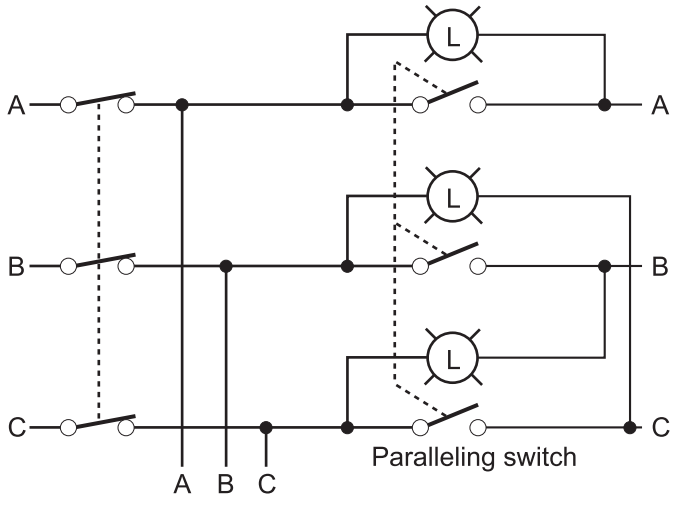
   _____

   _____

   _____



Method A



Method B

Figure 1

3. The three-dark-lamp method of synchronizing alternators has the disadvantage that:

   a. The lamps may burn out.

   b. An undetected voltage may be present at the lamps.

   c. The light is more difficult to see.

   d. All of the above. _____

4. When the pointer of a synchroscope is stationary and points upward during the paralleling operation, the:

   a. Alternators are in synchronism.

   b. Alternators are not in synchronism.

   c. Incoming alternator frequency is too slow.

   d. Incoming alternator frequency is too fast. _____

5. What are three important advantages of using several smaller alternators operating in parallel rather than one large unit?

   _____

   _____

   _____

6. An alternator has just been paralleled with others. Which of the following will cause it to supply a greater load?

   a. increasing its field excitation

   b. decreasing its field excitation

   c. increasing the driving power of the prime mover

   d. decreasing the driving power of the prime mover _____

7. An alternator paralleled with others has its field weakened. Which of the following occurs?

   a. Its voltage decreases.

   b. It supplies less load.

   c. Its power factor becomes more leading.

   d. Its power factor becomes more lagging. _____

8. Define the term *hunting*.

   _____

   _____

9. What are the two methods used to reduce hunting in alternators?

   _____

   _____

10. To maintain a constant output frequency of 60 Hz, a _____ must be employed on the prime mover.

Go to the Answer Key at the end of the Learning Guide to check your answers.

Answer Key

Self-Test 1

1. stator
2. rotor
3. To reduce the eddy-current losses.
4. To make the motor run smoothly and quietly.
5. To house the bearings that support the rotor shaft and to keep it aligned with the stator.
6. • The way they protect the motor from the environment
   • The way they are cooled
7. open machine
8. totally enclosed machine
9. 120
10. • Support the stator windings.
    • Provide a low-reluctance path for the magnetic circuit.
11. the physical dimensions of the motor in NEMA standards
12. output power, at rated speed
13. The service factor, when multiplied by the horsepower rating of the motor, gives the maximum power the motor may be required to supply continuously without damaging the motor.
14. To determine the insulation (temperature) type of the supply conductors.
15. the highest temperature allowed for the cooling medium that contacts the heated parts of the motor
16. revolutions per minute (rpm)
17. It should not vary by more than 5% of the rating on the nameplate.
18. It should not vary by more than 10% of the rating on the nameplate.
19. The relationship between motor torque and motor speed. It must not be confused with the code letter for locked rotor kVA.
20. The full-load current is the current the motor will draw when it operates at rated voltage and supplies rated horsepower.

Self Test 2

1. maximum
2. reverses
3. Increasing the frequency of the supply increases the speed of the rotating magnetic field.
4. Increasing the number of poles in the machine decreases the speed of the rotating magnetic field.
5. The synchronous speed is the speed of the rotating magnetic field.
6. $$n = \frac{f \times 60}{P}$$
$$= \frac{60\ \text{Hz} \times 60}{4}$$
$$= 900\ \text{rpm}$$
7. $$P = \frac{f \times 60}{n}$$
$$= \frac{60\ \text{Hz} \times 60}{720\ \text{rpm}}$$
$$= 5\ \text{pairs of poles} \times 10\ \text{poles}$$
8. through electromagnetic induction
9. Slip speed is the difference between synchronous speed and rotor speed.
10. Percent slip is the slip speed expressed as a percentage of the synchronous speed.
11. Speed regulation is the difference between no-load speed and full-load speed of the rotor.
12. By reversing the direction of the rotating field. This is accomplished by interchanging any two of the stator line connections to the source.
13. The full-load torque of a motor is the torque necessary to produce rated horsepower at rated full-load speed.
14. The breakdown torque of a motor is the maximum torque the motor will produce. It is sometimes referred to as the *stalling torque* because, if the motor load is increased beyond that point, the motor will quickly slow down and stall.
15. The locked rotor torque of a motor is the maximum torque the motor will develop at rest for all angular positions of the rotor with rated voltage and frequency applied to the stator.
16. The starting torque of a motor is the same as the locked rotor torque.
17. when the rotor is at a standstill (100% slip)
18. Loads with starting torques equal to or greater than their breakdown torque. Examples are loads such as large centrifugal blowers, flywheels, crusher drums, loaded compressors, loaded piston pumps and loaded conveyors.

19. Synch speed, $n = \frac{60 \times f}{P}$

$= \frac{60 \times 60}{3}$

$= 1200$ rpm

Slip speed = Synch speed – Rotor speed

$= 1200 - 1158$

$= 42$ rpm

Percentage slip $= \frac{\text{Slip speed}}{\text{Synch speed}} \times 100$

$= \frac{42}{1200} \times 100$

$= 3.5\%$

20. Speed regulation $= \frac{\text{No-load speed} - \text{Full-load speed}}{\text{Full-load speed}} \times 100\%$

$= \frac{1191 - 1171}{1171} \times 100\%$

$= \frac{20}{1171} \times 100$

$= 1.7\%$

21. Power (in hp) $= \frac{\text{Power (in watts)}}{746}$

$= \frac{55.95 \times 10^3 \text{ watts}}{746}$

$= 75$ hp

22. $P_{in} = \sqrt{3}\ V_L\ I_L\ \cos 9$

$= \sqrt{3} \times 600 \times 24 \times 0.87 \div 1000$

$= 21.7\ kW$

$P_{out} = (P \text{ in hp}) \times 746 \div 1000$

$= 25 \times 746 \div 1000$

$= 18.65\ kW$

$$\text{Efficiency} = \frac{\text{Output P}}{\text{Input P}} \times 100$$

$$= \frac{18.65}{21.7} \times 100$$

$= 85.94 \approx 86\%$

23. the stator
24. metres per second
25. The stator travels in the direction opposite that of the moving field.

Self-Test 3

1. T_1, T_4 and T_9
   T_2, T_5 and T_7
   T_3, T_6 and T_8
2. T_1 and T_4
   T_2 and T_5
   T_3 and T_6
   T_7, T_8 and T_9
3. See Figure 9b, Learning Task 3
4. See Figure 10b, Learning Task 3
5. See Figure 9a, Learning Task 3
6. See Figure 10a, Learning Task 3
7. See Figure 11b, Learning Task 3
8. See Figure 12b, Learning Task 3
9. See Figure 11a, Learning Task 3
10. See Figure 12a, Learning Task 3

Self-Test 4

1. a. True
2. The air flow is important to the proper cooling of the motor. If it is restricted, the motor may overheat and damage the insulation.
3. No. Too little grease is better since too much grease can damage the insulation.
4. greater than 1 megohm
5. yes
6. No. The initial dip is likely caused by capacitive charging between the winding being tested and ground.
7. a. True
8. sight, sound, touch and smell

Self-Test 5

1. It contains a three-phase winding rather than a squirrel-cage design. The rotor may be either wye- or delta-connected, with the leads brought out so that external resistance may be placed in the rotor circuit.
2. The slip rings and brushes provide an electrical connection between the moving rotor and the external rotor leads.
3. M_1, M_2 and M_3
4. The spring on each brush holder applies force on the brush to keep it in contact with the slip ring.
5. It makes the electrical connection between the brushes and the external rotor leads.
6. rotor voltage and rotor current
7. To select components for the secondary circuit that have the proper voltage and current ratings.

Self-Test 6

1. $$\text{Slip speed} = \frac{f \times 60}{p} \times 30\%$$

$$\text{Rotor speed} = \frac{f \times 60}{p} \times (1.0 - 0.3)$$

$$= \frac{60 \text{ Hz} \times 60}{4} \times 0.7$$

$$= 630 \text{ r/min}$$

2. torque
3. The resistance should be approximately equal to the locked rotor reactance.

4. Increasing the resistance of the rotor circuit improves its power factor and brings the rotor current more in phase with the stator flux.
5. low
6. The resistors dissipate energy in the form of heat.
7. a. Resistance is added to the rotor circuit to decrease the rotor speed.
8. The speed of the motor becomes too unstable beyond 50% slip.
9. the amount of time the resistors are expected to carry current with respect to the amount of time they are not
10. by interchanging any two of the line leads to the stator
11. Any three of:
    - High starting torque with low current
    - Smooth acceleration under heavy load
    - No abnormal heating during starting
    - Good running characteristics after the starting resistance is removed
    - Adjustable speed
12. Any three of:
    - Large physical size
    - Initial and maintaining costs higher
    - More complicated control
    - Poor speed regulation and efficiency when the secondary resistance is left in the circuit

Self-Test 7

1. failure of the motor to start, or the motor turns slowly
2. in the rotor, at the brushes and slip rings, in the controller, in the resistor bank, or in the connections between these parts
3. two pounds per square inch or 1.38 kPa
4. Too high a brush pressure is better than too low.
5. when the brush is down to about one-quarter of its original length
6. Interchange any two of the line leads to the stator.

Self-Test 8

1. amortisseur winding (or damping winding)
2. The amortisseur winding's main purpose is to dampen any momentary speed fluctuations that may occur when the mechanical load on the motor is suddenly changed. Its secondary purpose on some synchronous motors is to start the motor and accelerate it up to speed.
3. direct current
4. through slip rings and brushes

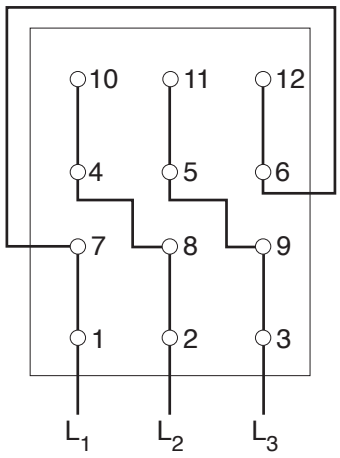
5. F_1 and F_2
6. To support the rotor shaft, permit it to rotate, and keep it in proper alignment with the stator.
7. when the DC supply is required for other loads in the plant
8. by placing a rheostat in series with the DC supply
9. on the same shaft as the synchronous motor
10. by varying the exciter's voltage output, by using a rheostat in series with the shunt field of the exciter
11. a three-phase alternator and rectifier assembly mounted on the rotor of the synchronous motor
12. by varying the field current to the brushless exciter

Self-Test 9

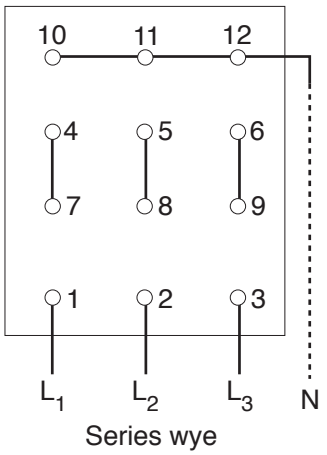
1. The rotating stator field is travelling too fast for the rotor to accelerate and lock in step. The field moving past the rotor produces constant torque reversals. This results in a net starting torque of zero.
2. When the rotor is close to synchronous speed. The percentage of slip varies with the mechanical load on the motor.
3. To prevent a high voltage from being induced in it.
4. No. The direction of rotation is reversed by reversing the direction of rotation of the stator field. This is done by interchanging any two of the supply leads to the stator.
5. wound-rotor induction motor
6. because there is no relative motion between the stator field and the amortisseur winding at synchronous speed
7. The amortisseur winding may overheat.
8. Pull-in torque is the torque required to pull the rotor into synchronism with the rotating stator field once the DC excitation has been applied.
9. torque angle
10. increase
11. Pull-out torque is the maximum sustained torque that the motor can develop at synchronous speed.
12. The motor will pull out of synchronism and slow down.
13. It becomes less leading (or more lagging).
14. the resultant of the applied voltage to the stator and the voltage induced in the stator by the rotor field

15. When the torque angle changes, the angle of the voltage induced in the stator by the rotor also changes. This results in a new resultant emf (ER) in the stator. The new resultant voltage causes a new current to flow in the stator.
16. a. unity power factor operation
17. Increasing the field current with a fixed load will cause the power factor to become more leading (or less lagging).
18. no
19. a. 780 kW
    b. 1443 A
    c. 912 kVAR
    d. 938 A
    e. 534 kVAR
    f. 1042 A
20. 1230 kVA

Self-Test 10

1. a. 15 A, 208 V
   b. 26 A, 120 V
2. 

Parallel delta

3. 

Series wye

4. a. 416 V

   b. 120 V

Self-Test 11

1. • Open in the field coils
   • No exciter voltage
   • Open in the field rheostat
   • Rheostat resistance set too high (field current too low)
2. Too high or too low a field current will cause a large reactive current in the stator windings, which will cause excessive heat in the windings.
3. 2 psi (1.38 kPa)
4. too high
5. Replace when the brush is down to one-quarter of its original useful length.
6. Interchange any two of the line leads to the stator.

Self-Test 12

1. so the motor will run more smoothly and quietly
2. 75%
3. The end bells house the bearings that allow the rotor to turn freely within the stator. Together they keep the rotor in proper alignment with the stator and provide an enclosure for the motor.
4. • The main winding is made of many turns of larger wire and is placed lower in the stator slots to give it a lower resistance and higher inductance.
   • The auxiliary winding is made of fewer turns of smaller wire. It is placed near the surface of the stator slots to give it a higher resistance and lower inductance.
5. 14 amps

Self-Test 13

1. b. in phase with the current flowing through the coil
2. • In a two-pole motor it is 90 mechanical and electrical degrees.
   • In motors with more poles, it will still be 90 electrical degrees but less than 90 mechanical degrees.
3. b. The magnetic pole moves from the auxiliary winding to a similar polarity main winding. The higher inductance of the main winding causes the current and flux in this winding to lag behind the current and flux in the auxiliary winding.
4. by reversing the direction of current through the auxiliary winding
5. The standard split-phase motor has a phase shift between the main and auxiliary winding of 30–50 electrical degrees. The capacitor-start, split-phase motor has a phase shift of 90 electrical degrees, which corresponds better with the physical displacement of the poles in the motor.
6. the capacitor-start, capacitor-run split-phase motor
7. the reluctance motor
8. Parts of the rotor core are cut away to produce salient poles that lock into step with the rotating field.
9. 75%
10. a. The starting capacitor is approximately 10–15 times larger than the running capacitor.

Self-Test 14

1. a. T_1 and T_4
   b. T_5 and T_8
2. a. T_1 and T_2; T_3 and T_4
   b. T_5 and T_8
3. See Figure 3a in Learning Task 14.
4. Interchange leads T_5 and T_8 on the auxiliary winding as shown in Figure 3b in Learning Task 14.
5. See Figure 3d or Figure 4b in Learning Task 14.
6. Interchange leads T_5 and T_8 on the auxiliary winding as shown in Figure 3c and Figure 4a in Learning Task 3.

Self-Test 15

1. Any three of the following:
   - The pole cores and that portion of the stator that completes the magnetic circuit are laminated to reduce the eddy-current losses.
   - The series winding has fewer turns to reduce the inductive reactance.
   - The cross-sectional area of the core is increased and the air gap is decreased to decrease the reluctance of the magnetic circuit.
   - High-resistance brushes are used to reduce commutator sparking.
2. The speed decreases as load is added.
3. through the brushes and commutator
4. by interchanging the two armature leads, or the two series field leads
5. The motor may run away.
6. the speed of the armature and the strength of the series field
7. the current through the armature and the strength of the series field
8. The AC series motor will operate satisfactorily from DC and up to 60 hertz AC.
9. Both the field polarity and the current through the armature change at the same time, resulting in no torque reversal.
10. to reduce eddy-current losses
11. exciter winding, shading coil
12. The exciter winding receives its energy by conduction. The shading coil receives its energy by electromagnetic induction.
13. from the unshaded portion to the shaded portion
14. by removing the stator and turning it end-for-end before replacing it over the rotor
15. low
16. synchronous speed
17. hard steel; because of its large hysteresis loss (retains permanent magnetism)

Self-Test 16

1. keeping the motor clean and the cooling airways unobstructed
2. Any four of the following:
   - Blown fuse(s)
   - Opens in either the main or auxiliary windings
   - An open or short in the starting capacitor
   - Motor overloaded
   - Open in the centrifugal switch

3. Any five of the following:
   - Overload
   - Roughness at the commutator edges (they should be bevelled and smooth.)
   - High mica between commutator bars
   - Brush position not in the neutral plane
   - Incorrect brush pressure
   - Incorrect brush grade
   - Brushes worn excessively; less than ¼ remaining
   - Vibration of the brushes
4. a light-brown film around the circumference of the commutator
5. 75%

Self-Test 17

1. • Higher voltages can be generated.
   • Larger currents can be conducted to the load.
2. to supply DC to the alternator's field circuit
3. A salient-pole rotor is usually larger in diameter than a cylindrical rotor and its pole pieces are protruding, while the cylindrical rotors are smooth faced.
4. A field-discharge resistor is used to eliminate the inductive back-voltage created by opening the field circuit.
5. • When explosive or wet ambient conditions exist
   • When it is necessary to have low maintenance

Self-Test 18

1. • Rotor speed
   • Number of field poles
2. Percent voltage regulation

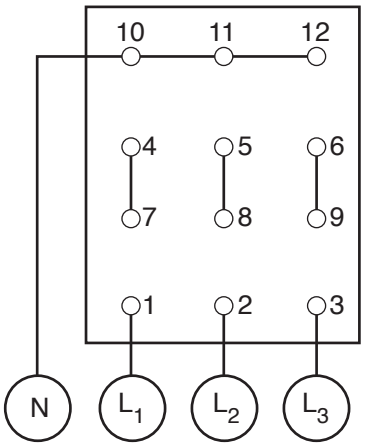
$$= \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100\%$$

$$= \frac{265 - 240}{240} \times 100\%$$

$$= 10.4\%$$

3. automatic voltage regulator
4. low (0%)

Self-Test 19

1. • To obtain two different voltages (phase and line).
   • Insulation requirements are reduced to phase voltages values.
   • Provides a neutral point for system ground.
2. a. "A"
   b. "F"
3. b. parallel delta
4. 

5. 346 V
6. 200 kVA (no change)

Self-Test 20

1. • Equal voltages
   • Identical frequencies
   • Same phase sequence
   • Alternator voltages in phase
2. a. Method A = three-dark method
   Method B = two-bright, one-dark method
   b. Method A readily identifies incorrect phase sequence between the incoming alternator and paralleling bus.
   Method B generators can be more accurately synchronized, causing less line disturbance.
3. b. An undetected voltage may be present at the lamps.
4. a. Alternators are in synchronism.

5. • Improved operating efficiency
   • Added power requirements met more economically
   • Reduced interruption to service
6. c. increasing driving power of prime mover
7. c. Its power factor becomes more leading.
8. Alternator rotor speed is fluctuating.
9. • Amortisseur winding on the rotor
   • Heavy flywheel on the prime mover
10. governor



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