N4 Electrotechnics

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Contents

Module 5

AC machines

What is covered?

This module covers the basic construction of induction motors by discussing each of its parts. The module also addresses the basic operation of an induction motor and its applications. Finally, the module shows how to draw circuit diagrams for single-phase induction motors.

Learning outcomes

After studying this module, you should be able to:

Unit 1

- Describe the three main parts of an induction motor
- Describe the two types of rotors of a three-phase induction motor.

Unit 2

- Explain the basic operation of an induction motor
- Define slip, explain the function of slip and calculate slip, frequency, poles, synchronous speed and rotor speed of induction motor
- List the applications of an induction motor.

Unit 3

- Draw labelled circuit diagrams for single induction motors that makes use of resistance starting, capacitor starting, and capacitor-start capacitor run
- Explain how to reverse the rotation of an induction motor.

Unit 1: Basic construction of an induction motor

LEARNING OUTCOMES

- Describe the three main parts of an induction motor.
- Describe the two types of rotors of a three-phase induction motor.

Introduction

An electric motor converts electrical energy into rotational mechanical energy. An alternating current (AC) motor is a motor that uses alternating current as its source of power (the power that drives it). An induction motor is a type of AC motor,

A three-phase induction motor is an electric motor in which energy is transferred from the stator to rotor magnetically. This unit explores the construction of three-phase induction motors. The unit also describes two types of rotors used in three-phase induction motors, namely, squirrel-cage rotors and wound rotors.

1. Parts of an induction motor

Figure 5.1 shows the construction of a three-phase induction motor. The main parts of the motor are the stator, rotor and end plates.

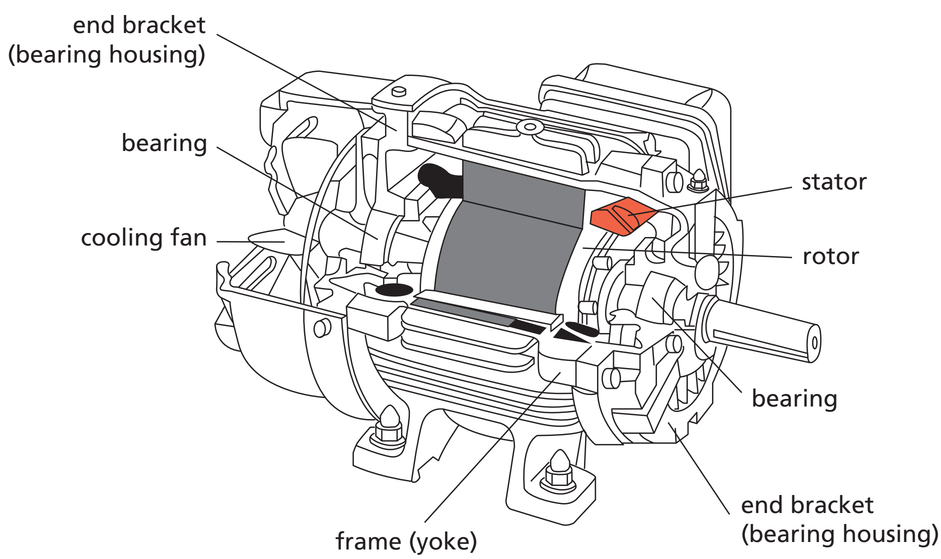

Figure 5.1 Construction of a three-phase induction motor

We now discuss each of these parts in turn.

1.1 Stator

The **stator** is the non-moving part of an induction motor. It consists of three parts:

- stator frame
- stator core
- stator windings.

Keywords

stator the non-moving part of an induction motor

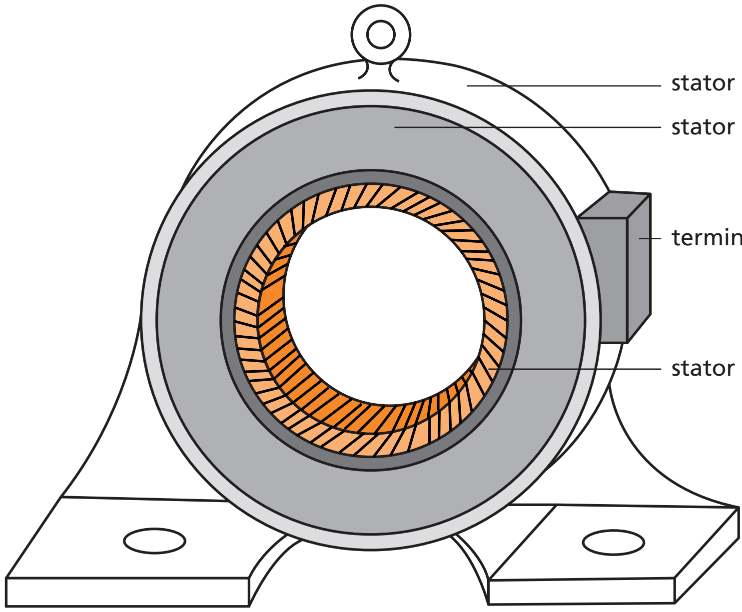

Figure 5.2 The stator

1.1.1 Stator frame

The stator frame is the outermost casing of the induction motor. It provides mechanical strength and protects all inner parts of the induction motor.

1.1.2 Stator core

The function of the stator core is to carry an alternating magnetic field. It consists of thin laminated steel plates that reduce eddy current losses and **hysteresis losses**.

1.1.3 Stator windings

Stator windings consist of three windings used to produce the main rotating magnetic field.

Keywords

hysteresis loss loss in the form of heat caused by the magnetisation and demagnetisation of the core as current flows in the forward and reverse directions

rotor the rotating part of an induction motor

1.2 Rotor

As the name implies, a **rotor** is the rotating part of an induction motor. The rotors of three-phase induction motors are classified as squirrel-cage rotors or wound (slipring) rotors.

1.2.1 Squirrel-cage rotor

As shown in Figure 5.3, a squirrel-cage rotor consists of copper or aluminium rotor bars which are permanently shorted with the help of end rings. The copper and aluminium rotor bars are skewed to reduce magnetic noise and to ensure that the motor has a smooth and silent operation.

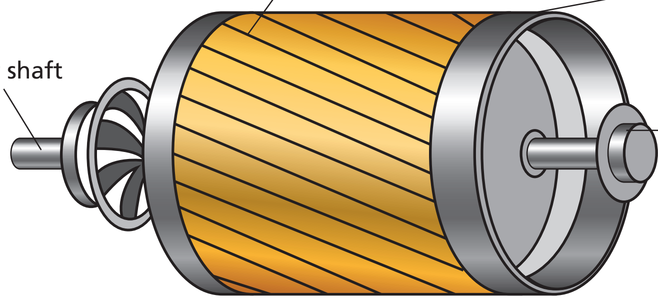

Figure 5.3 Squirrel-cage rotor

The advantages of a squirrel-cage rotor are as follows:

- The construction of the motor is very simple.
- The motor is cheap to produce.
- The motor requires minimum maintenance.
- The motor is sturdy. It has a strong construction.
- The motor is highly efficient since rotor copper losses are minimum.

The disadvantages of a squirrel-cage rotor are as follows:

- The motor has a low starting torque.
- Speed control not possible by rotor resistance.
- It is not possible to add external resistance so as to limit starting currents.

1.2.2 Wound rotor

A wound (or slipring) rotor is a three-phase winding, star-connected with one end brought out to three sliprings mounted out to the motor shaft. Current induced in the rotor winding can be controlled by connecting external resistors to the rotor current. High starting torque is obtained, and high starting currents are limited by these external resistors. When the motor speed increases, the external resistors are removed from the circuits.

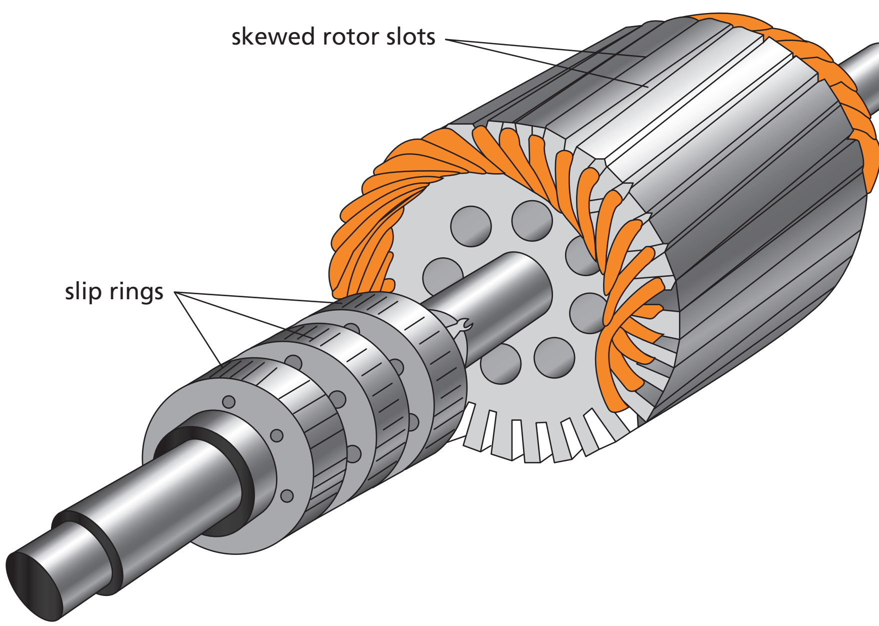

Figure 5.4 A wound rotor

The advantages of a wound rotor are as follows:

- High starting torque is possible.
- High starting currents can be limited.
- Speed control is possible because of external resistance.

The disadvantages of a wound rotor are as follows:

- Construction is complicated.
- The rotor requires regular maintenance because of the brushes in the circuit.
- The motor is costly because of the sliprings.

1.3 End plates

End plates are used to hold the bearing and electrical terminations of the motor. End plates are also called end shield or cover plates.

ACTIVITY 5.1 Construction of a three-phase induction motor

1. Name THREE main parts of a three-phase induction motor.
2. Name TWO types of rotors used in three-phase induction motors.
3. Explain why the rotor bars of a squirrel-cage induction motor are skewed.
4. Give ONE function of a stator frame of an induction motor.
5. Give ONE function of a stator core of a three-phase induction motor.
6. Give ONE function of stator windings of a three-phase induction motor.
7. What is the function of end plates in a three-phase induction motor?
8. What is the other name given to a wound rotor of a three-phase induction motor?
9. Give TWO types of rotors found in three-phase induction motors.
10. List TWO advantages of a squirrel-cage rotor.
11. List TWO advantages of a wound rotor.
12. List TWO disadvantages of a squirrel-cage rotor.
13. List TWO disadvantages of a wound rotor.

Unit 2: Basic operation and application of an induction motor

LEARNING OUTCOMES

- Explain the basic operation of an induction motor.
- Define slip, explain the function of slip and calculate slip, frequency, poles, synchronous speed and rotor speed of induction motor.
- List the applications of an induction motor.

Introduction

This unit explains the basic operation of a three-phase induction motor. The unit then defines and shows how to calculate the concepts of slip, frequency, poles, synchronous speed, rotor speed and relative speed. Finally, the unit lists some applications of two types of three-phase induction motor, namely squirrel-cage rotors and wound rotors.

1. Basic operation of an induction motor

In a three-phase induction motor, current from the supply is applied to the stator windings. A magnetic field builds up in each of the stator windings and combines to form the main rotating magnetic field. This main rotating magnetic field rotates inside the stator at synchronous speed. As the main magnetic field rotates inside the stator, it cuts across the rotor bars and induces an electromotive force in the rotor bars, which produces a secondary magnetic field. The main rotating magnetic field interacts with the secondary magnetic field and creates a force. This force is exerted on the rotor and the rotor will rotate at normal or actual speed.

Keywords

slip the difference between the speed of the main rotating magnetic field and the actual rotor speed. Slip is also defined as the difference between synchronous speed and rotor speed.

Synchronous speed speed of the main rotating magnetic field.

2. Slip

Slip is the difference between the speed of the main rotating magnetic field and the actual rotor speed. The speed of the main rotating magnetic field is known as **synchronous speed**. Slip can be expressed as a percentage or per unit. The other name for slip is relative speed. There are no units for slip.

$$\text{Percentage slip} = \frac{N_s - N_r}{N_s} \times 100\%$$

$$\text{Per-unit slip} = \frac{N_s - N_r}{N_s} \times 100\%$$

2.1 The function of slip

Slip enables the rotor to rotate by inducing an EMF in the rotor bars that exerts a force on the rotor. Without slip, there will be no rotor current and no secondary magnetic field. Consequently, there will be no force exerted on the rotor to enable the rotor to rotate.

2.2 Methods used to find slip

You can work out the slip of an induction motor by:

- actual measurement of the rotor speed
- measurement of rotor frequency
- using the stroboscopic method
- By calculation (also another method of calculating slip).

Worked example 5.1 — Slip and synchronous speed

A three-phase, eight-pole induction motor rotates at 600 r/min while being supplied from 415 V, 50 Hz source. Calculate:

1. The percentage slip at which the rotor of the induction motor is operating.
2. The per-unit slip at which the rotor is operating.

Solution

Given: $f = 50$ Hz and $p = \frac{8}{2} = 4$

Percentage slip $= \frac{N_S - N_r}{N_S} \times 100\%$

1. $N_S = \frac{60f}{p}$

$= \frac{60 \times 50}{4}$

$= 750$ r/min

Percentage slip $= \frac{N_S - N_r}{N_S} \times 100\%$

$= \frac{750 - 600}{750}$

$= 0{,}2 \times 100\%$

$= 20\%$

2. Per-unit slip $= \frac{N_S - N_r}{N_S}$

$= \frac{750 - 600}{750}$

$= 0{,}2$ pu

Note

There are no units for slip.

2.3 Synchronous speed

Synchronous speed is the speed of the main rotating magnetic field. To calculate the synchronous speed in revolutions per minute (r/min), you multiply the frequency by 60 and then divide the answer by pairs of poles. However, if the slip is expressed in revolutions per second (r/sec), you divide frequency and pairs of poles and the answer will be in revolutions per second.

We use the symbol N_S to represent synchronous speed.

Keywords

synchronous speed the speed of the main rotating magnetic field

Worked example 5.2 — Synchronous speed

A three-phase, six-pole induction motor rotates at 900 r/min while being supplied from 400 V, 50 Hz supply. Calculate the following:

1. The synchronous speed of the main magnetic field in revolutions per minute.
2. The synchronous speed of the main magnetic field in revolutions per second.

Solution

Given: $f = 50$ Hz and $p = \frac{6}{2} = 3$

1. $N_S = \frac{60f}{p}$

$= \frac{60 \times 50}{3}$

$= 1\,000$ r/min

2. $N_S = \frac{f}{p}$

$= \frac{50}{3}$

$= 16{,}67$ r/s

> **Keywords**
>
> **Rotor speed** the speed at which the rotor of the induction motor rotates

2.4 Rotor speed

Rotor speed is the speed at which the rotor of the induction motor rotates. Rotor speed is also called actual speed. We use the symbols N or N_r to represent rotor speed.

From the formula for calculating slip (S), N_S is expressed as the subject formula as shown below:

$$S = \frac{N_S - N_r}{N_r}$$

$$S{\cdot}N_S = N_S - N_r$$

$$S{\cdot}N_S + N_r = N_S - N_r + N_r$$

$$N_r = N_S - S{\cdot}N_S$$

$$= N_S(1 - S)$$

Worked example 5.3 — Calculate rotor speed and number of poles

A 525 V, 50 Hz three-phase induction motor has a synchronous speed of 1 500 r/min. Calculate:

1. The rotor speed if the induction motor is operating at a slip of 20%.
2, The number of poles of the induction motor.

Solution

1. Given: $f = 50$ Hz, $N_r = 1\,500$ r/min and percentage slip = 20%.

$N_r = N_S(1 - S)$

$= 1\,500(1 - 0{,}2)$

$= 1\,500(0{,}8)$

$= 1\,200$ r/min

2. $N_S = \frac{60f}{p}$

$p{\cdot}N_S = 60f$

$p = \frac{60f}{N_S}$

$= \frac{60 \times 50}{1\,500}$

$= 2$

Number of poles = 2 × 2 = 4

Worked example 5.4 Calculate frequency and number of poles

A 380 V, six-pole, three-phase induction motor rotates at 1 000 r/min. If the synchronous speed of the motor is 1 200 r/min, calculate the supply frequency.

Solution

Given: N_S = 1 200 r/min and $n = \frac{6}{2} = 3$

$$N_S = \frac{60f}{p}$$

$$p \cdot N_S = 60f$$

$$f = \frac{p \cdot N_S}{60}$$

$$= \frac{3 \times 1\,200}{60}$$

$$= 60 \text{ Hz}$$

3. Application of a three-phase induction motor

There are two types of three-phase induction motors: squirrel-cage rotor and wound rotor. The application of a three-phase induction motor depends on the type of rotor being used.

3.1 Application of a squirrel-cage induction motor

A squirrel-cage induction motor could be used for:

- cooling fans
- lathe machines
- blowers.

3.2 Application of a wound rotor induction motor

We could use a wound rotor induction motor for:

- driving hoists
- driving cranes
- driving elevators.

ACTIVITY 5.2 Operation of a three-phase induction motor

Explain briefly the operation of a three-phase induction motor by answering the following questions.

1. Define slip.
2. Explain the function of slip.
3. Explain what is meant by synchronous speed of a three-phase induction motor.
4. Define relative speed.
5. What is the other term used to refer to relative speed?
6. Define synchronous speed of a three-phase induction motor.
7. Explain briefly what is meant by rotor speed of a three-phase induction motor.
8. Explain what will happen to a three-phase induction motor if the rotor speed is equal to synchronous speed.
9. List three uses of a squirrel-cage induction motor.

10. List three uses of a wound rotor induction.
11. A three-phase, eight-pole induction motor rotates at 800 r/min while being supplied from 380 V, 50 Hz supply. Calculate:
    a) The speed (synchronous speed) of the main magnetic field in revolutions per minute.
    b) The speed (synchronous speed) of the main magnetic field in revolutions per second.
12. A three-phase, six-pole induction motor rotates at 900 r/min whilst being supplied from a 415 V, 50 Hz supply. Calculate:
    a) The percentage slip at which the induction motor is operating.
    b) The per-unit slip at which the induction motor is operating.
13. A 380 V, six-pole, three-phase induction motor rotates at 900 r/min. If the synchronous speed of the main magnetic field is 1 000 r/min, calculate the supply frequency.
14. A 525 V, 50 Hz, three-phase induction motor has a synchronous speed of 1 200 r/min. Calculate:
    a) The rotor speed if the induction motor is operating at a slip of 10%.
    b) The number of poles of the induction motor.

Unit 3: Motor starting

LEARNING OUTCOMES

- Draw labelled circuit diagrams for single induction motors that make use of resistance starting, capacitor starting, and capacitor start and capacitor run.
- Explain how to reverse the rotation of an induction motor.

Introduction

Unit 2 considered three-phase induction motors and showed that they are self-starting. This unit focuses on single-phase induction motors, which are not self-starting. The unit shows how to draw circuit diagrams for single-phase induction motors that make use of resistance starting and capacitor starting for induction motors, and capacitor starting for capacitor-run motors. Finally, the unit explains how to reverse the rotation of an induction motor.

1. Methods of motor starting

This section explores resistance starting and capacitor starting for single induction motors, and capacitor starting for capacitor-run motors.

1.1 Resistance-starting for induction-run motors

A resistance-start induction-run motor consists of a start winding connected in series with a centrifugal switch and parallel with the run winding. The main difference between a run winding and start winding is that the run winding consists of a thick cross-sectional area and has many turns enabling it to have low resistance and high inductance.

By connecting the run winding and start winding in parallel, a displacement of 90° electrical is obtained between the two windings so that a rotating magnetic field will be produced. Resistance-start induction-run motors are used in electric fans, washing machines and tumble dryers.

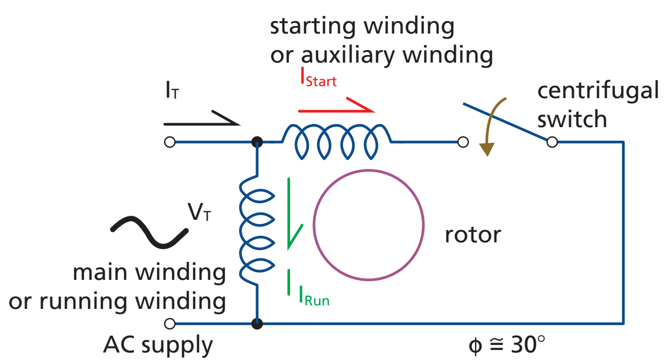

Figure 5.5 Resistance-starting – induction-run motor

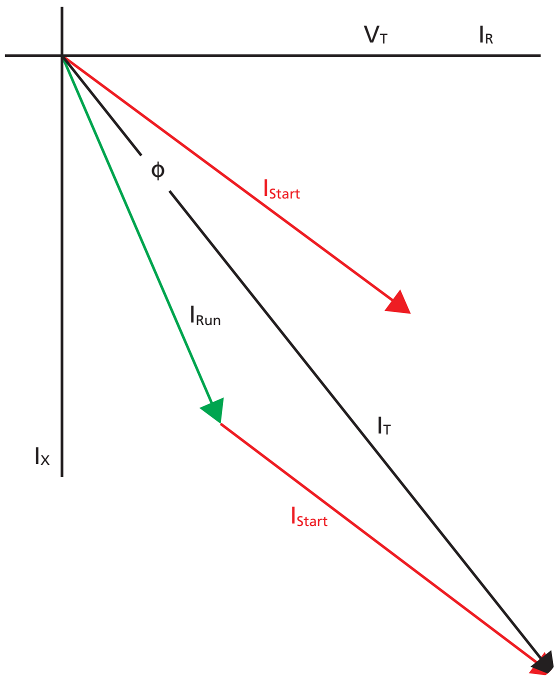

Figure 5.6 Vector diagram for resistance-starting – induction-run motor

1.2 Capacitor-starting for induction-run motors

Single-phase induction motors are not self-starting. To start a single-phase motor an electrolytic capacitor is connected in series with a starting winding and parallel with the running winding. A run winding is also referred to as a main winding, and a start winding is also known as an auxiliary winding. By connecting the electrolytic capacitor in this way, a greater phase difference is created between the starting winding and running winding enabling the motor to produce a rotating magnetic field.

The contacts of a centrifugal switch are always closed when the motor is not running, which allows current to flow through the starting winding. When the speed of the motor reaches about 75% of its rated speed, the centrifugal switch opens its contacts and the start winding and start capacitor are removed from the circuit. The motor then continues to operate on the run winding. These motors are used, for example, in driving conveyors, pool pumps and lawnmowers.

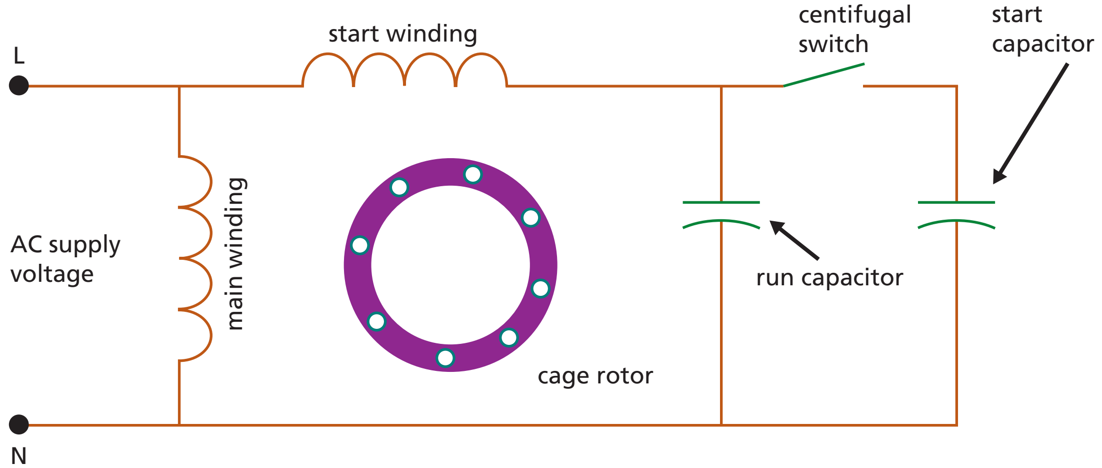

Figure 5.7 Capacitor-starting – induction-run motor

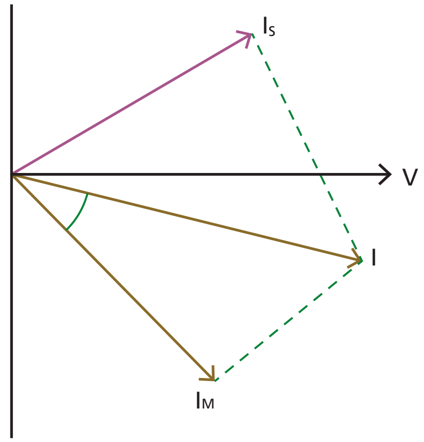

Figure 5.8 Vector diagram for capacitor-starting – induction-run motor

1.3 Capacitor starting for capacitor-run motors

The capacitor–start capacitor–run induction motor shown in Figure 5.9 looks almost similar to the capacitor–start induction–run motor shown earlier. The main difference is that this motor has a run capacitor connected in series with the start winding but in parallel with the run winding.

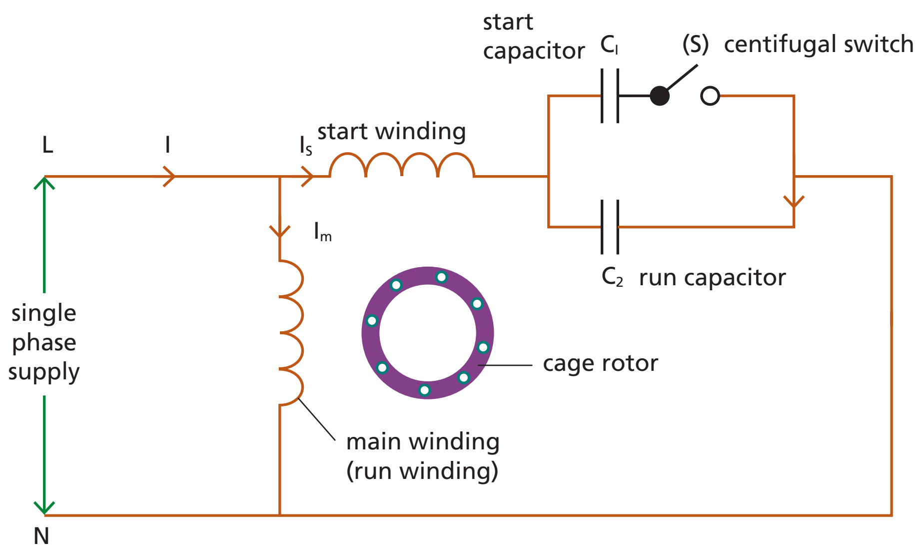

Figure 5.9 Capacitor–starting – capacitor–run motor

A difference between the start capacitor and the run capacitor is that the start capacitor is bigger than the run capacitor. Operation of a capacitor-start capacitor-run motor is almost similar to that of a capacitor–start induction–run motor except that the former has better efficiency and a higher starting and operating torque because of the extra run capacitor and the starting winding that remains in the circuit when the start capacitor has been removed in the circuit by the centrifugal switch. The run capacitor and the run winding also remain in the circuit even if the contacts of the centrifugal switch opens because they are connected in parallel with the centrifugal switch. These motors are typically used in compressors, air conditioners and refrigerators.

2. Reversing the direction of an induction motor

The direction of rotation of a single-phase induction motor can be reversed by changing either the connection of the running winding or starting winding, but not both at the same time. Changing the connection of the starting winding will cause the magnetic field to change direction, which results in the motor reversing its direction of rotation.

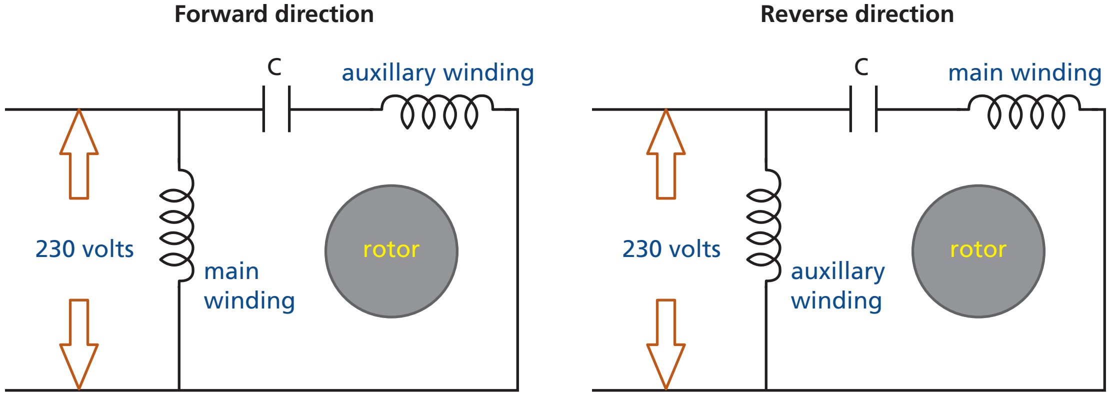

Figure 5.10 Reversing the direction of rotation of a single-phase induction motor

ACTIVITY 5.3 — Motor starters

1. Name THREE types of single-phase induction motors.
2. Draw a fully labelled diagram of a resistance-start induction-run motor.
3. Draw a fully labelled circuit diagram of a capacitor-start induction-run motor.
4. Draw a fully labelled circuit diagram of a capacitor-start capacitor-run induction motor.
5. What is the function of a centrifugal switch in a capacitor start induction-run motor?
6. What is the difference between the start capacitor and run capacitor in a capacitor-start capacitor-run motor?
7. What is the other name given to the start winding of a single-phase induction motor?
8. What is the other name given to the run winding of a single-phase induction motor?
9. With the aid of a circuit diagram briefly explain how to reverse the direction of rotation of a single-phase induction motor.

Module summary

- Main parts of an induction motor are the rotor, stator and end plates.
- The two types of rotors of a three-phase induction are squirrel-cage rotors and wound rotors.
- A wound rotor is also called a phase wound or slipring rotor.
- When a three-phase voltage is applied across the stator windings of a three-phase induction motor, a rotating magnetic field is produced and will rotate at synchronous speed.
- The main magnetic field cuts across the rotor bars and induces an EMF in the rotor bars to produce a secondary magnetic field.
- The main magnetic field interacts with the secondary magnetic and produces a force that is exerted on the rotor.
- Energy transfer between rotor and stator is entirely magnetically.
- Rotor speed is the speed at which the rotor of the induction motor rotates.
- Synchronous speed is the speed of the main magnetic field.
- The rotor of an induction motor cannot rotate at synchronous speed – the rotor will rotate at actual speed.
- Slip is the difference between synchronous speed and rotor speed.
- Slip enables the rotor to rotate.
- Without slip, there will be no rotor current and no secondary magnetic field to produce a force that causes the rotor to rotate.
- Slip can be found by actual measurement of the rotor speed, measurement of the rotor frequency and by using a stroboscopic method.
- Induction motors are used to drive hoists, cranes and elevators.
- The three types of single-phase induction motors are resistance start-induction-run, capacitor-start induction-run and capacitor-start capacitor-run motors.
- Three-phase motors are self-starting whereas single-phase motors are not self-starting.
- The direction of rotation of a single-phase induction motor can be achieved by changing the polarity or the connection of the run winding or start winding but not both at the same time.

Exam practice questions

1. Why are rotor bars of an induction motor skewed? (2)
2. What is the main difference between a single-phase induction and a three-phase induction motor in terms of starting methods? (4)
3. Name THREE main parts of an induction motor. (3)
4. What is the purpose of a capacitor in a single-phase capacitor motor? (2)
5. What is the purpose of a centrifugal switch in a single-phase capacitor motor? (3)
6. Give ONE function of a stator frame of a three-phase induction motor. (1)
7. Name TWO types of rotors of a three-phase induction motor. (2)
8. Define the term slip. (2)
9. Define synchronous speed of three-phase induction motor. (2)
10. List THREE uses of a three-phase squirre-cage induction motor. (3)
11. List THREE uses of a three-phase wound rotor induction motor. (3)

12. **12.** Draw a fully labelled circuit diagram of a single-phase capacitor-start capacitor-run motor. (5)
13. **13.** Draw a fully labelled diagram of a single-phase capacitor-start induction-run motor. (5)
14. **14.** Draw a fully labelled circuit diagram of a single-phase resistance-start induction-run motor. (5)
15. **15.** A three-phase, eight-pole induction motor rotates at 800 r/min whilst being supplied from 380 V, 50 Hz supply source. Calculate:
    - **a)** The synchronous speed of the main magnetic field in revolutions per minute. (3)
    - **b)** The synchronous speed of the main magnetic field in revolution per second. (3)
16. **16.** A 525 V, 50 Hz three-phase induction motor has a synchronous speed of 750 r/min. Calculate:
    - **a)** The rotor speed of the induction motor operating at a slop of 10%. (3)
    - **b)** The number of poles of the induction motor. (3)
17. **17.** A 380 V, six-pole, three-phase induction motor rotates at 750r/min. If the synchronous speed of the main magnetic field is 1 000 r/min, calculate:
    - **a)** The supply frequency. (3)
    - **b)** The percentage slip. (3)
    - **c)** The per unit slip. (3)
18. **18.** Briefly explain with the aid of a circuit diagram how to reverse the rotation of a single-phase induction motor. (6)
19. **19.** Explain why the rotor of a three-phase induction cannot rotate at synchronous speed? (4)
20. **20.** Name TWO methods used to connect three-phase motors. (2)

Total: 75 marks