CONTENTS

Resources and references

The following books are recommended for this module:

Jenneson, J.R.
Electrical Principles for Electrical Trades.
ISBN 0 07 470222 X
McGraw-Hill Book Company, Roseville, NSW.

Australian Standard AS 3000 - 1991 (or latest version)
Electrical Installations-Buildings, structures and premises known as the
SAA Wiring Rules
ISBN 0 07262 7107 1
Standards Association of Australia, North Sydney, NSW.

You will need the following items to complete this topic:

- pens, pencils, etc.
- calculator
- writing paper.

Information for teachers

This resource manual contains learning exercises, review questions and sample assessment instruments. It is intended to assist in delivery of the module and is an example of the depth and breadth of learning expected.

The topics are arranged in the following learning sequence.

1. Operating principles of three-phase induction motors
2. Three-phase induction motor construction
3. Three-phase induction motor characteristics
4. AS 3000 and service rule requirements. D.O.L. motor starters
5. Reduced voltage three-phase induction motor starters
6. Electronic ("soft start") starters and secondary resistance starters
7. Braking and rotation reversal of three-phse induction motors
8. Three-phase induction motor operation - load conditions
9. Protection of three-phase induction motors.

It is recognised that this is not the only sequence in which the material could be learnt. Assessment arrangements and sample assessment instruments are based on the sequence of topics listed above. If for a particular student or goup of students a teacher decides that it is more effective to present the topis in a difference sequence then the students must be informed in writing before starting the module, of the resulting changes in the assessment arrangements.

MODULE SECTIONS

Section 1: Operating principles of three-phase induction motors

SUGGESTED DURATION	PREAMBLE
8 hours	This section introduces the fundamental principles of operation of three-phase AC motors.

This section covers part of the learning outcome 1 of the National Module Descriptor.

Objectives

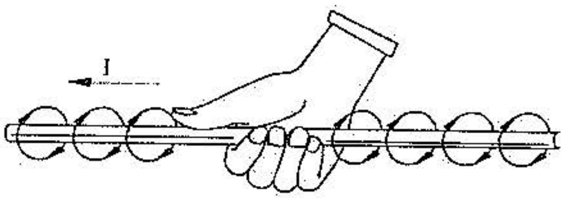
At the end of this section the successful students will be able to:

- ☐ apply the right hand (grip) rule for conductors and solenoids and Fleming's left and right hand rules to determine circuit operating characteristics
- ☐ list the characteristics of the magnetic field produced by a three-phase winding
- ☐ calculate the speed of rotation of a rotating magnetic field
- ☐ describe the basic principle of operation of an induction motor
- ☐ reverse the direction of rotation of a three-phase induction motor.

Revision of the principles of electromagnetism

The right hand conductor rule

The thumb points in the direction of current and the fingers indicate the direction of the magnetic field.



The right hand conductor rule

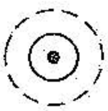
Conventional symbols for the direction of current flow in a conductor

⊗ this symbol is used to indicate current flow is away from the observer.

⊙ this symbol is used to indicate current flow is towards the observer.

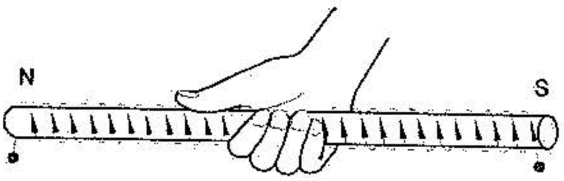
Student exercise 1

Using the right-hand conductor rule, and the conventional symbols for current flow, show the direction of current flow and field direction.



The right hand solenoid rule

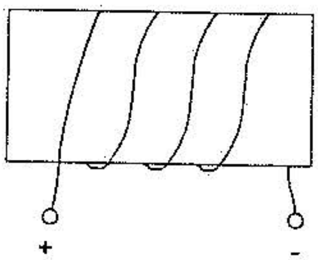
The thumb points in the direction of the north pole when the fingers indicate the direction of current, as shown.

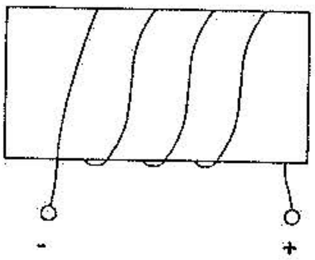


The right hand solenoid rule

Student exercise 2

Using the right-hand solenoid rule, indicate on the diagram the field polarity of the coils drawn below.



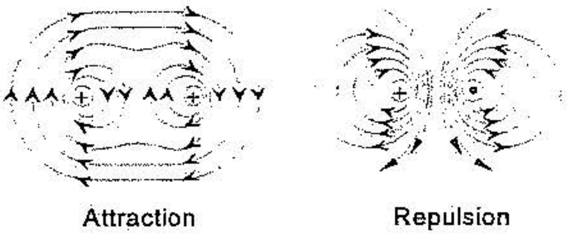


Field strength is controlled by:

- current
- number of turns
- core materials (air, iron)

Force developed by parallel current carrying conductors:

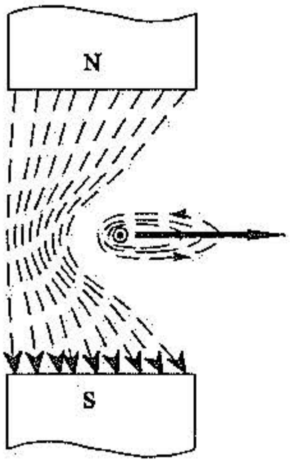
A force is developed between parallel current carrying conductors. The magnitude of the force is governed by the current value. The direction of the force is governed by the direction of the current flow.



Force due to current carrying conductors

Motor action

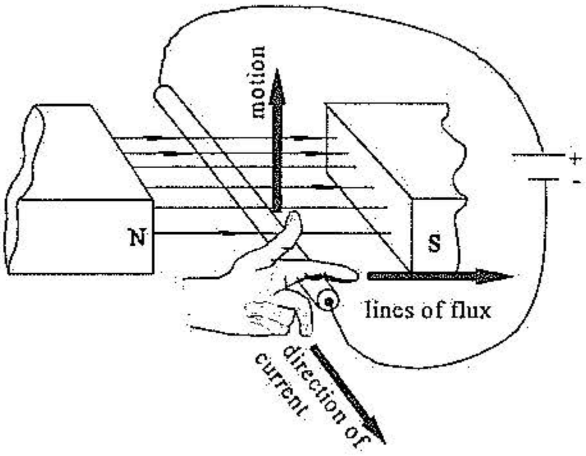
The principle behind the operation of any electric motor is due to the interaction of two magnetic fields.



Principle of motor action

Fleming's left hand *motor* rule

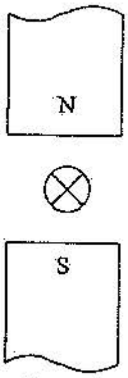
Fleming's left hand rule is used to determine conductor motion from the field polarity and current direction.



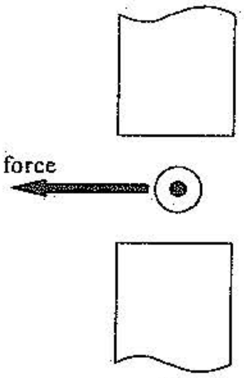
Fleming's left-hand rule

Student exercise 3

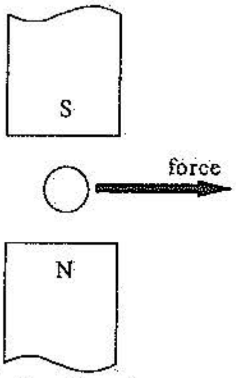
Use Fleming's left-hand rule to determine direction of force, field polarity or direction of current flow in the diagrams below:



direction of force ?



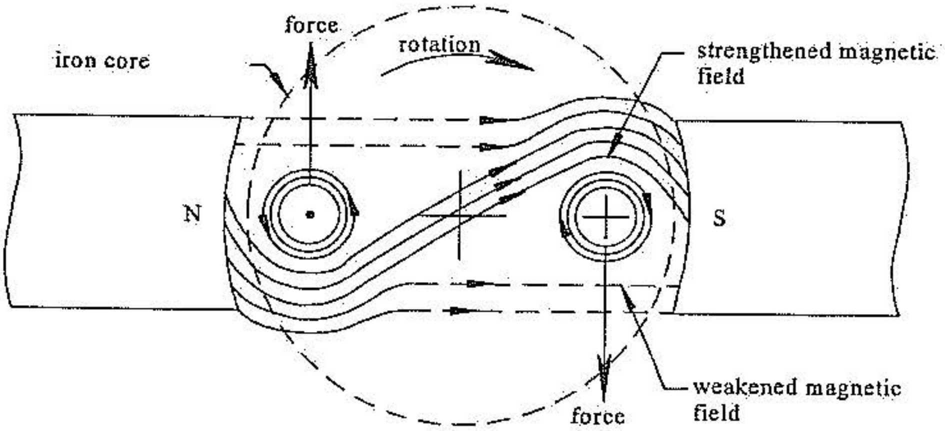
field polarity ?



direction of current flow ?

Torque or *Turning effort*

If a current carrying conductor is wound into a coil, a force will be developed on each of the coil sides, causing the coil to rotate through the field. This rotation or turning effort is known as *torque.*

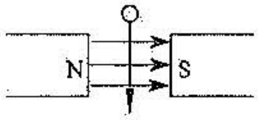


Motor effect

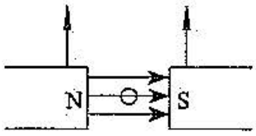
Generator action

An electromotive force (emf) will be induced in a conductor whenever there is *relative motion* between the conductor and a magnetic field.

Relative motion refers to the conductor's movement in relation to the magnetic field. Often the conductor is stationary and the magnetic field is in motion. Both conductors shown have the same relative motion ie. *DOWN.*



moving conductor

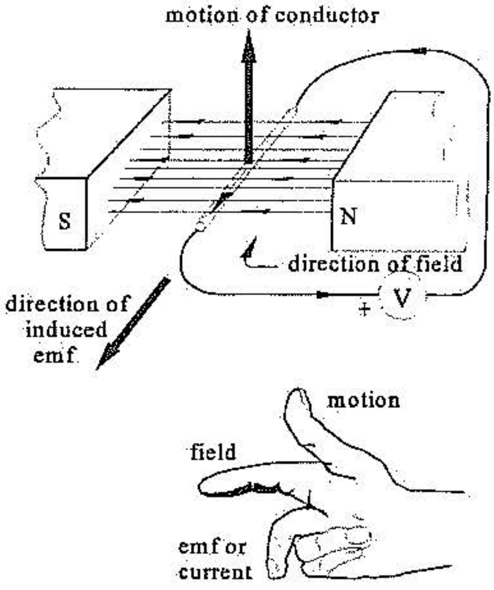


moving field

Relative motion

Fleming's right hand *generator* rule

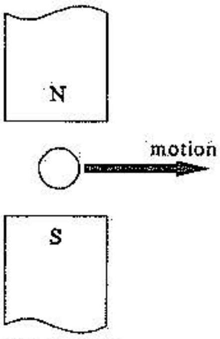
Fleming's right hand rule is used to determine the direction in which an induced emf acts, given field polarity and conductor motion.



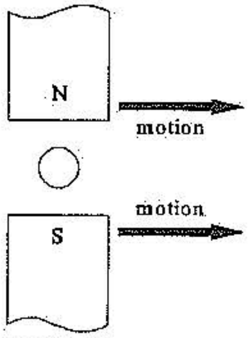
Fleming's right hand rule

Student exercise 4

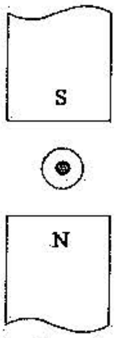
Use Fleming's right hand rule to determine direction of induced emf, or direction of conductor movement in the diagrams below:



direction of induced emf ?



direction of induced emf ?



direction of conductor movement ?

Mutual induction

An emf will be induced in a stationary conductor if it is under the influence of a varying magnetic field such as that produced by a sinusoidal voltage.

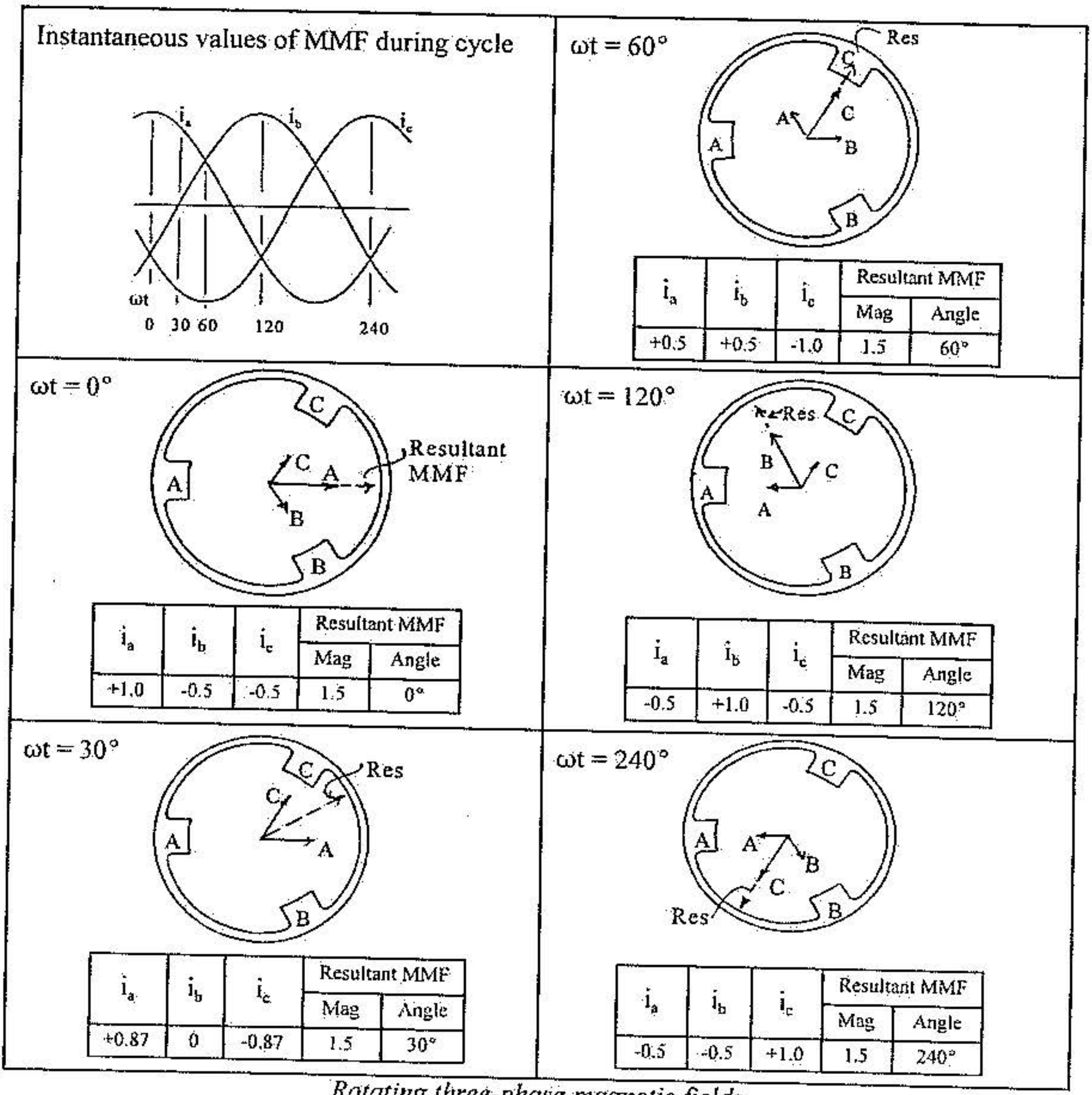
The production of a rotating magnetic field

The production of a rotating magnetic field (RMF) is essential for the operation of a.c. induction motors.

Three-phase a.c. fields:

The resultant field of a three-phase winding, with each winding displaced by 120°E, will:

- rotate in space
- maintain a uniform strength equal to 1.5 times the maximum value produced by a single phase winding as shown on the diagram. Note that a positive current is deemed to produce a flux which leaves the salient pole and whose magnitude is directly proportional to the magnitude of the current. Similarly for negative currents.



ωt = 0°

i_a	i_b	i_c	Resultant MMF	
			Mag	Angle
+1.0	-0.5	-0.5	1.5	0°

ωt = 30°

i_a	i_b	i_c	Resultant MMF	
			Mag	Angle
+0.87	0	-0.87	1.5	30°

ωt = 60°

i_a	i_b	i_c	Resultant MMF	
			Mag	Angle
+0.5	+0.5	-1.0	1.5	60°

ωt = 120°

i_a	i_b	i_c	Resultant MMF	
			Mag	Angle
-0.5	+1.0	-0.5	1.5	120°

ωt = 240°

i_a	i_b	i_c	Resultant MMF	
			Mag	Angle
-0.5	-0.5	+1.0	1.5	240°

Rotating three-phase magnetic fields

Synchronous speed (RMF speed)

The speed of rotation of a RMF is known as the *synchronous speed* and will be governed by the value of the supply frequency and the number of poles wound per phase winding.

The symbol for synchronous speed is N_{sync} and is calculated from the equation:

$$N_{sync} = \frac{120f}{P} \ (rpm)$$

where f = the supply frequency in hertz
P= the number of poles per phase winding

Student exercise 5

Determine the synchronous speed of the RMF of an eight pole three-phase winding if the supply frequency is 50Hz

Working:

Answer: ____________________

Student exercise 6

Determine the number of poles per phase if the RMF rotates at 1500 rpm when the supply frequency is 25Hz

Working:

Answer: ____________________

Student exercise 7

Determine the supply frequency required to cause the RMF of a four pole winding to rotate at 1200 rpm

Working:

Answer: ____________________

Phase sequence

Phase sequence is the order in which the phases of a three-phase supply are connected to a load e.g. A-B-C. The phase sequence determines the direction of the RMF of a three phase motor. The correct phase sequence can be found by using a phase sequence indicator.

Three-phase induction motor action:

The operation of a 3-phase induction motor relies on:

- electromagnetic induction
- force on a current carrying conductor when under the influence of a magnetic field.

To understand how an induction motor operates you have to be familiar with its two main parts:

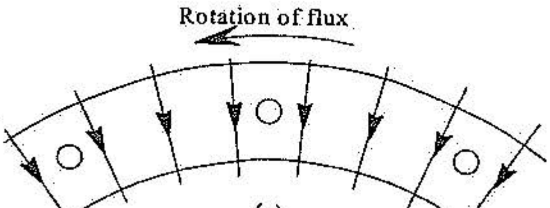
- the *stator*, which houses the winding which produces the RMF.
- the *rotor*, which houses the conductors which are acted upon by the RMF.

The field produced by a three-phase winding will rotate around the stator at synchronous speed.

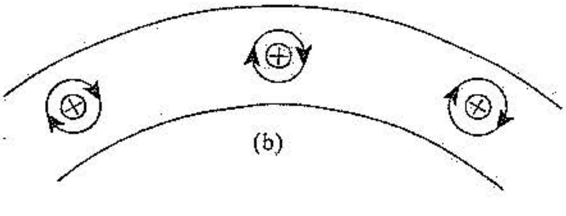
The RMF will cut rotor conductors, therefore inducing an emf in these conductors. The rotor current that flows due to the emf, establishes a rotor field. You can apply Fleming's right hand solenoid rule to determine the direction of the field.

Two magnetic fields now exist within the machine:

- RMF of the stator
- an induced rotor field.

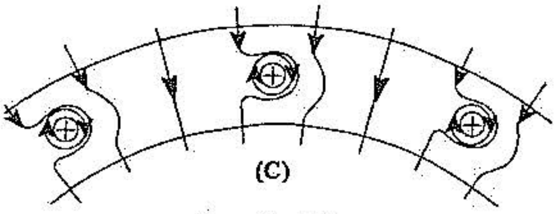


(a)
Stator flux only



Rotor flux only

The interaction of these two fields will produce a torque, causing the rotor to turn in the *same* direction as the RMF of the stator. You can apply Fleming's left hand rule to determine direction of rotation.



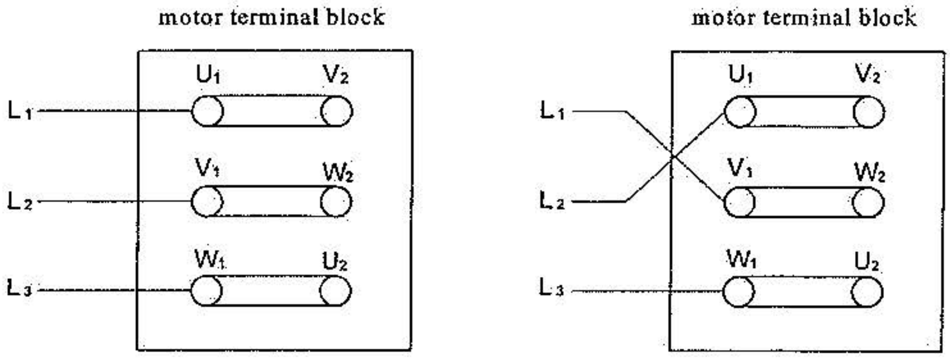
Resultant flux

To maintain an induced rotor field the rotor must always run at a speed lower than that of the RMF. This speed difference is known as *slip*.

Three-phase induction motor reversal:

Since the rotor follows the RMF, to reverse the direction of rotation of an induction motor you must reverse the direction of the RMF.

To change the direction of the RMF you must change the supply phase sequence by interchanging any two supply lead connections.



Three-phase induction motor reversal

Skill practice SP1
Three-phase motor reversal

Task

To verify that:

- an induction motor requires a RMF to develop a torque.
- the supply phase sequence determines the direction of rotation of a three-phase induction motor.
- reversal of rotation of a three-phase induction motor is brought about by interchanging any two supply leads.

Equipment

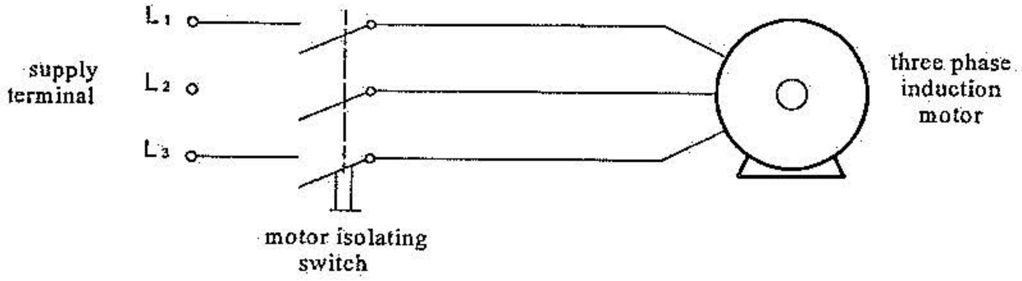
1 x three-phase induction motor
1 x 10A triple pole isolating switch
1 x phase sequence indicator

Remember: Work safely at all times!

- isolate supply before connecting or altering circuits
- always select the correct test equipment
- be careful when working near rotating machines

Procedure

1. Connect the equipment as shown below leaving line two disconnected.

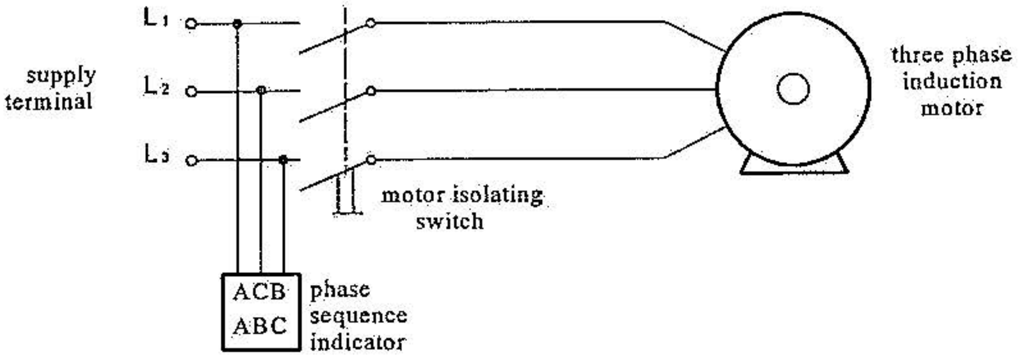


2. Energise the supply and close the motor isolating switch. Record the effect on the operation of the motor.

Motor rotation = ________________________

3. Open the motor isolating switch and isolate the supply. Connect line two to the motor isolating switch.

4. Energise the supply and monitor the phase sequence of the supply with the phase sequence indicator, as shown in the diagram below:

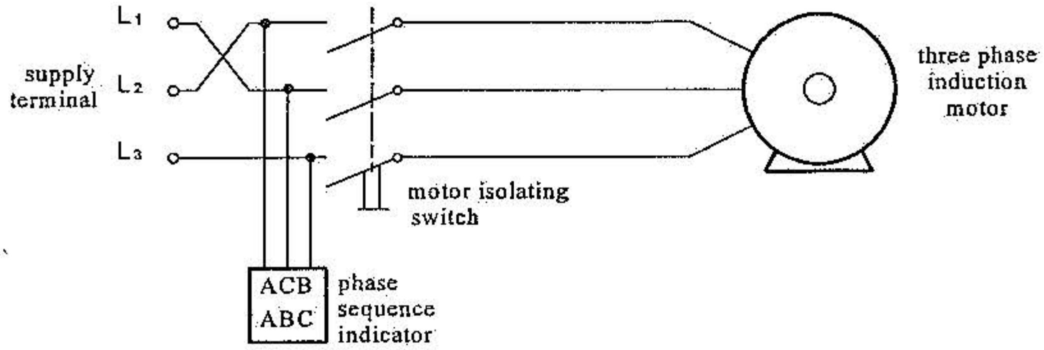


Record supply phase sequence = ______________________

5. Close the motor isolating switch and record the effect on the operation of the motor.

Motor rotation = ______________________

6. Open the motor isolating switch and isolate the supply. Interchange the supply connections between lines one and two as shown in the diagram below:



7. Energise the supply and monitor the phase sequence of the supply with the phase sequence indicator, as shown in the diagram in step 6.

Supply phase sequence = ______________________

8. Close the motor isolating switch and note the effect on the operation of the motor.

Motor rotation = ______________________

9. Isolate the supply and return all equipment to its appropriate location.

Review questions

These questions will help you revise what you learnt in Section 1.

1. What is the minimum number of phase windings required to produce a rotating magnetic field?

   ____

2. What type of magnetic field will be produced by a single phase supply?

   ____

3. At what speed does the RMF produced by the stator winding rotate?

   ____

4. What determines the direction in which a three-phase magnetic field will rotate around the stator?

   ____

5. What is the relationship between the direction of rotation of the RMF and the rotor?

   ____

6. What is the difference in magnitude between the resultant RMF of a three-phase motor stator compared to the flux produced by one phase alone?

   ____

7. What is developed in the rotor of an induction motor by the interaction of the rotor and stator fields?

   ____

8. How is the rotor field of an induction motor produced?

   ____

   ____

9. What determines the speed of rotation of the RMF produced by a three-phase induction motor?

____

10. Briefly explain why the rotor speed of an induction motor is always less than the speed of the stator RMF.

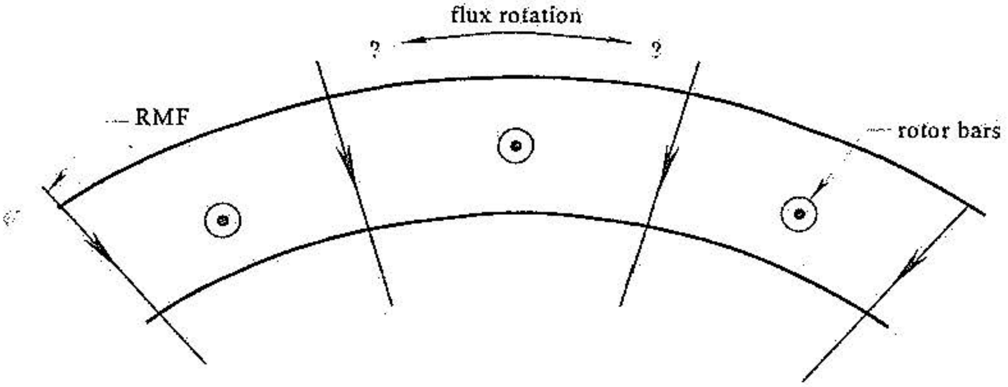
____

____

____

____

11. The diagram below shows the RMF and the induced rotor conductor current. On the diagram show in which direction the RMF must rotate to induce the current shown and draw in the resultant flux.



12. Calculate the synchronous speed of an eight pole, 50Hz induction motor.

Answer ______________________

13. If the synchronous speed of a 50Hz induction motor is 3000 rpm, calculate the number of stator poles.

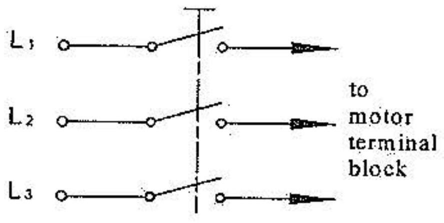
Answer ______________________

14. Explain the effect of operating a motor designed to operate on 60Hz if it is connected to a 50Hz supply.

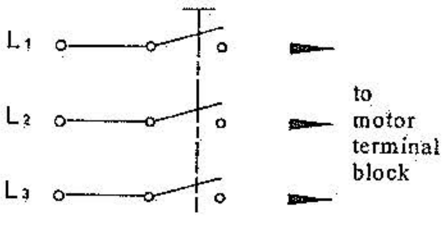
15. Explain how a rotor field is established, even though there is no electrical connection between the rotor and the AC supply.

©: 12/2/10

16. Figure A represents the isolating switch of a three-phase induction motor. When energised the motor is found to rotate in the wrong direction. Show the changes needed to reverse the direction of rotation on figure B.



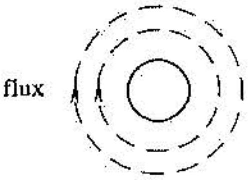
A

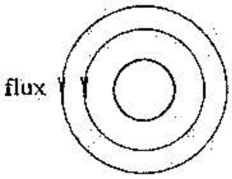


B

Review questions

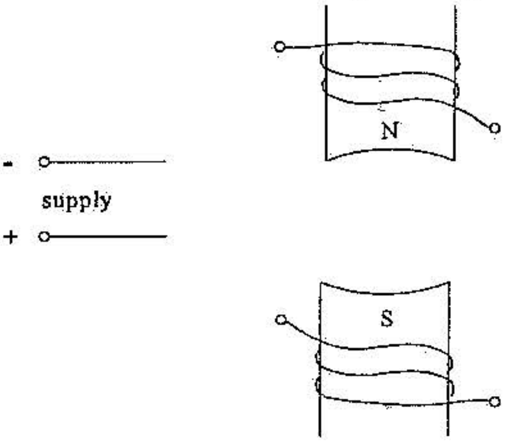
17. On the diagrams below draw the symbol to represent the conventional direction of current flow to establish the magnetic fields shown.



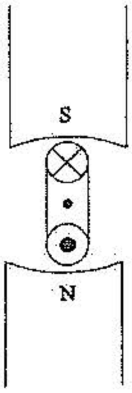


18. On the diagrams below show the direction in which the resulting force will act.

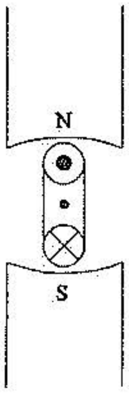
19. On the diagram below show the connections required to produce the required field polarity.



20. Apply Fleming's rule to each of the figures below to determine the rotation direction of each machine.



motor rotation



generator rotation

Notes

Section 2: Three-phase induction motor construction

SUGGESTED DURATION	PREAMBLE
4 hours	This section introduces the basic construction of three-phase induction motors.

This section covers part of the learning outcomes 1 and 6 of the National Module Descriptor.

Objectives

At the end of this section you should be able to:

☐ identify the basic component parts of a three-phase induction motor

☐ list the types of rotors used in three-phase induction motors

☐ connect a three-phase induction motor in both star and delta

☐ list the steps for dismantling a three-phase induction motor

☐ check the insulation resistance of a three-phase induction motor prior to connection to the supply

☐ check the winding resistance (ohmic value and continuity) of a three-phase induction motor prior to connection to the supply.

Induction motor construction

The induction motor consists of two main parts:

- a stationary part, called the *stator*.
- a moving part, called the *rotor*.

Three-phase induction motors are of two kinds:

- the *squirrel cage* motor, which has a short circuited rotor;
- the *slip ring* motor, which has a wound rotor

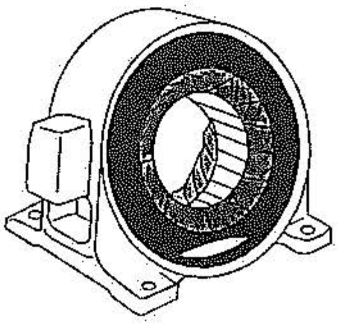
There is no constructional or electrical difference between the stators of these two types of motors.

For each of the motor types there is no electrical connection between the stator and rotor.

Stator construction

The stator consists of three main parts:

- the frame
- the core laminations
- the winding



Stator construction

Frame

- The frame is of cast or fabricated steel, or cast aluminium.
- The stator core is pressed directly into the frame.
- Motor frames are manufactured in various forms. The type of frame used will be governed by the environmental conditions the motor is to operate under.
  - open type which allows free ventilation to take place
  - drip proof which has a closed upper half, while allowing ventilation through the lower half.
  - totally enclosed which prevents the exchange of air between the inside and outside of the frame.
- Two end shields that house bearings to support the rotor are bolted to the frame.

Core laminations

- The stator core has laminations that are of a special low loss sheet steel (silicon steel).
- The laminations are lightly insulated from one another to reduce eddy current losses.
- The stator core is slotted on the inside circumference to carry the stator winding.

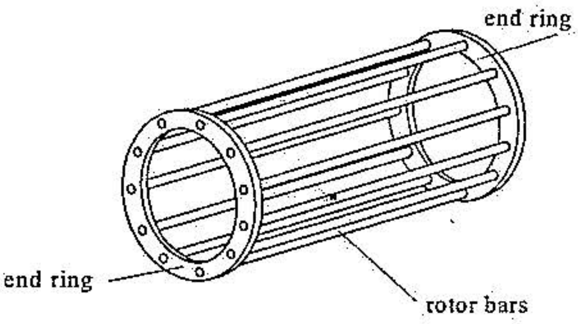
Winding

- The stator winding consists of three identical phase windings which are displaced by 120°E around the stator.
- Each of the windings consists of a number of series connected coils which produces the required number of poles per phase.

- The windings are generally connected in delta, but may be sometimes connected in star. In either case the conductors must be of sufficient cross sectional area to carry the line current when connected in star and $\frac{1}{\sqrt{3}}$ of the line current when connected in delta.

Squirrel cage rotors

The squirrel cage rotor induction motor is the most commonly used AC motor. The squirrel cage winding consists of solid copper alloy or aluminium bars embedded in the rotor slots. Each bar is short circuited by end rings.



Squirrel cage

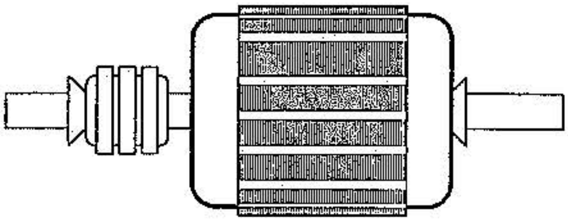
In smaller motors the complete rotor winding, including bars, end rings, and fan, is a one-piece cast. In larger motors the conductors are formed bars, generally copper, inserted in slots in the rotor laminations, which are then welded to the short circuiting end rings.

Rotor slots are generally *skewed* to reduce any magnetic locking between the stator and the rotor and to reduce magnetic noise when the motor is running. Skewing of the rotor conductors also provides smoother acceleration.

The rotor is supported on bearings so that it can rotate freely. The air gap clearance between the rotor and the stator is typically about 0.5mm.

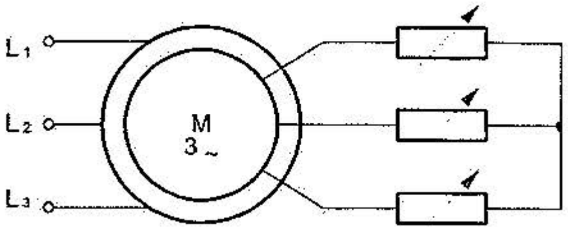
Wound rotors

This type of rotor has a three-phase winding similar to its stator winding, ie. it is wound with the same number of poles as the stator. The wound rotor winding is star connected with the open ends of the connection brought out to slip rings mounted on the rotor shaft. Brushes ride on the slip rings and during the starting period they are connected to external resistor banks.



Wound rotor

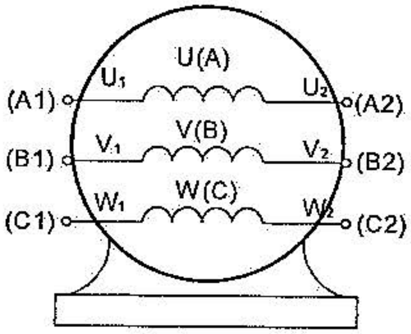
This type of motor can have its operational characteristics controlled by varying the resistance of the rotor circuit.



Wound rotor induction motor circuit

Terminal block markings

The three-phase supply is connected to the stator windings at the motor terminal block. The windings may be connected internally in delta or star. The connection method will appear on the nameplate. Often the six leads (a start and a finish for each winding) are brought out to the motor terminal block.



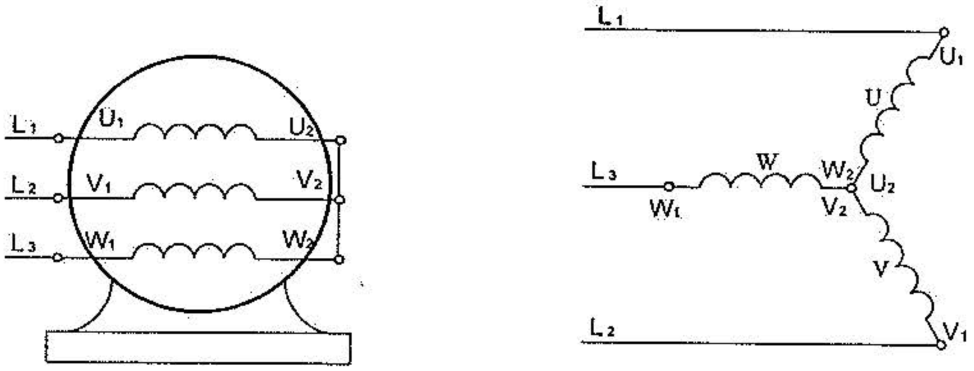
Lead identification

The international standard for naming each winding is U, V and W with the leads for each winding marked U_1, U_2, V_1, V_2 and W_1, W_2. These markings represent the start and finish of each of the phase windings. The markings of the winding leads are to assist in the correct connection of the windings.

Other winding lead terminal markings that you may encounter are A_1, A_2 ; B_1, B_2 and C_1, C_2. Motors manufactured in North America may be marked T_1, T_4, T_2, T_5 and T_3, T_6.

The star connection

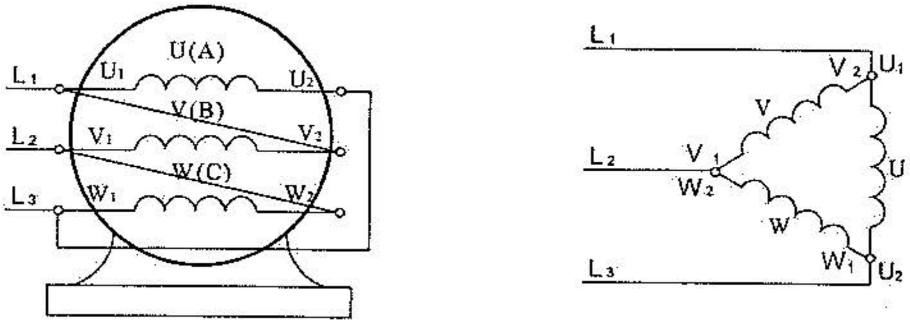
Three common ends of each winding (ie. starts or finishes) are connected together and the supply (L_1, L_2, L_3,) is connected to the other end of each winding.



Star connection

The delta connection

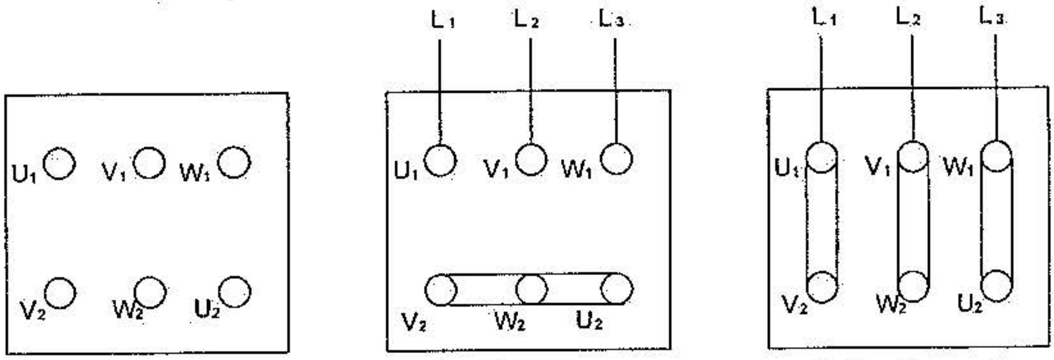
Dissimilar ends of each winding (ie. start to finish) are connected together, with a supply line connected to each start and finish junction.



Delta connection

Motor terminal arrangements and reversal

Motor terminals are arranged for easy connection in either star or delta by the connection of terminal block links. You should be able to identify the connection method used by the placement of the links.



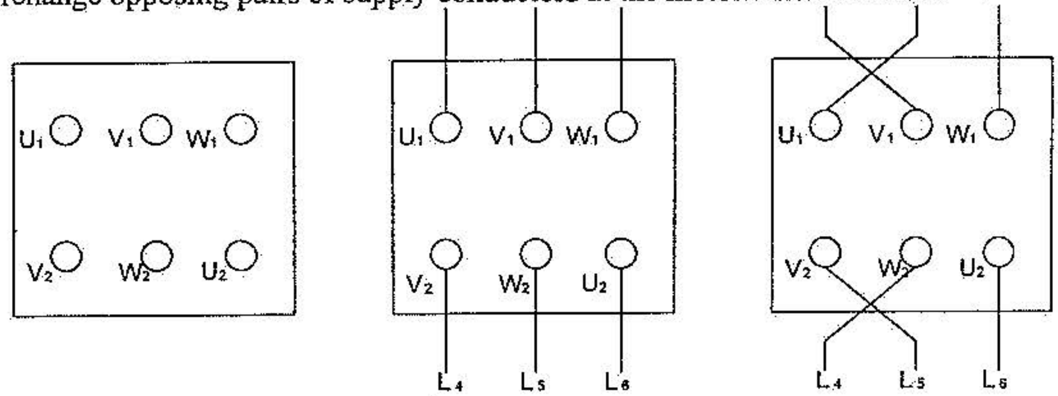
Star Connection

Standard terminals

Delta Connection

The direction of rotation of a three-phase motor bridged for star or delta operation can be reversed by interchanging any two supply line connections.

You may find that some motor terminal blocks do not contain any links. This type of motor is suited for connection to a starting method where both star and delta connections are used. To reverse a motor started by star delta connections you must interchange opposing pairs of supply conductors at the motor terminal block.



Star/delta reversal

Motor maintenance and electrical testing

To maintain a high reliability, induction motors need to be regularly tested and serviced, however due to their simple and rugged construction maintenance is easily carried out. Periodically dismantle the motor so that bearings can be replaced, any build up of foreign material can be removed from cooling paths (vents), and removal of any corrosion and repairs can be done.

Electrical isolation

- As with any piece of electrical equipment, the supply must be safely isolated and tested prior to carrying out any repairs.
- Danger tags must be fitted to isolators.
- A sketch of terminal block connections and the marking of supply leads will ensure that the motor will have the same direction of rotation when reconnected.

Removal and dismantling

- Care must be taken when lifting any heavy objects. Lift by bending knees, keeping a straight back.
- Larger motors usually have lifting eyes incorporated in the frame so that slings can be attached.
- The correct size sockets and spanners should always be used when dismantling the motor.
- Witness mark end shields to the frame and note from which endshield the rotor shaft is to protrude.
- After reassembly the rotor shaft should freely turn by hand.

Electrical testing

- The stator windings represent a balanced load, ie. each phase winding should have a similar resistance.
- Use an ohmmeter to measure the resistance of each phase winding.
- Windings in good condition will all have a similar resistance of several ohms or more.
- Damaged windings will have short circuits resulting in a much lower resistance, or open circuits resulting in the ohmmeter reading infinite resistance.
- Insulation resistance must be checked using an insulation resistance tester (megger).
- The insulation resistance of each phase winding to the motor frame must be in excess of 1MΩ as should be the insulation resistance between the phase windings.
- When connected to the supply the frame of the motor has to be solidly earthed.
- Cable protection such as flexible conduit must be secured to the motor.
- Check the operation of the motor once connected by using a clip on an ammeter to measure the motor line currents.
- These should be three similar currents that do not exceed the nameplate rated current.

Skill practice SP2
Three-phase induction motor construction

Tasks

- to measure the resistance of the phase windings of a three-phase induction motor.
- to measure the insulation resistance of the phase windings of a three-phase induction motor.
- to correctly connect the motor so that it will run in star and delta.
- to measure the shaft speed and line currents for both the star and delta connections.

Equipment

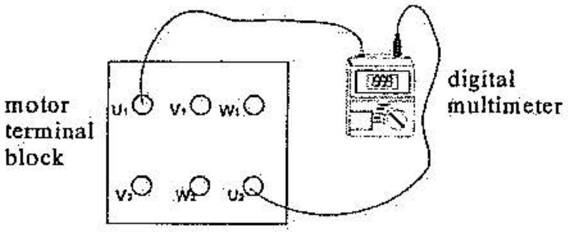
1 x six terminal three-phase induction motor
1 x digital multimeter
1 x insulation resistance tester (megger)
1 x clip on ammeter
1 x hand held tachometer

> Remember: Work safely at all times!
>
> - isolate supply before connecting or altering circuits
> - always select the correct test equipment
> - be careful when working near rotating machines

Procedure

1. Remove all links from the terminal block of the three phase motor.

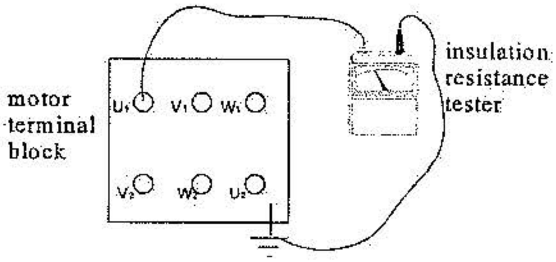
2. Using the digital multimeter measure the resistance of each of the phase windings and record below.



Phase resistance measurement

Terminals	*Resistance*
U_1 to U_2	
V_1 to V_2	
W_1 to W_2	

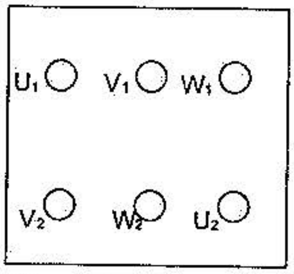
3. Using the insulation resistance tester, measure the insulation resistance between each phase winding and each winding to the motor frame. Record your results below.



Insulation resistance testing

Winding connection	*Insulation resistance*
U_1 to frame	
V_1 to frame	
W_1 to frame	
U_1 to V_1	
V_1 to W_1	
W_1 to U_1	

4. Draw in the link connections on the diagram opposite for the star connection of the motor.



Star link connections

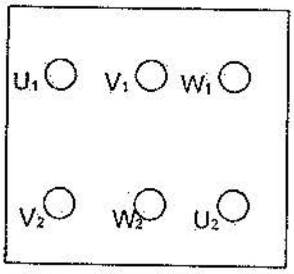
5. Connect the links as you have drawn and connect the motor to the supply.

6. Operate the motor and measure the line currents with the clip on ammeter and the shaft speed with the hand held tachometer. Record your results below.

Line current	*Shaft speed*
Line 1 = ______________ A	______________ rpm
Line 2 = ______________ A	
Line 3 = ______________ A	

7. Isolate the motor from the supply and remove the links from the terminal block.

8. Draw in the link connections on the diagram opposite for the delta connection of the motor.



Delta link connections

9. Connect the links as you have drawn them and connect the motor to the supply.

10. Operate the motor and measure the line currents with the clip on ammeter and the shaft speed with the handheld tachometer. Record your results below.

Line current *Shaft speed*

Line 1 = ________________ A ________________ rpm

Line 2 = ________________ A

Line 3 = ________________ A

11. Isolate the motor and return all equipment.

Review questions

These questions will help you revise what you have learnt in Section 2.

1. To reverse the direction of rotation of a squirrel cage motor you would: *(tick the correct box)*

   ☐ disconnect and reverse the slip ring connections
   ☐ replace the squirrel cage rotor with a wound rotor
   ☐ interchange any two supply lead connections
   ☐ change the delta connected stator winding to a star connection.

2. The rotor winding of a wound rotor induction motor is usually connected in: *(tick the correct box)*

   ☐ delta
   ☐ star
   ☐ series
   ☐ parallel.

3. The stator core is laminated to: *(tick the correct box)*

   ☐ improve starting torque
   ☐ provide silent running
   ☐ reduce hysteresis loss
   ☐ reduce eddy current loss.

4. Rotor bars are usually made from: *(tick the correct box)*

   ☐ steel or copper
   ☐ steel or aluminium
   ☐ carbon or copper
   ☐ copper or aluminium.

5. To improve starting torque and to reduce operation noise rotor bars are: *(tick thecorrect box)*

   ☐ skewed with respect to the stator slots
   ☐ cast aluminium
   ☐ star connected
   ☐ the same number as the stator slots.

6. How many slip rings would you expect to find on the shaft of a squirrel cage rotor? *(tick the correct box)*

   ☐ four
   ☐ three
   ☐ two
   ☐ none.

7. Interchanging any two slip ring connections of a wound rotor would: *(tick the correct box)*

   ☐ reverse the rotation of the motor
   ☐ prevent the motor from operating
   ☐ cause the motor to overload
   ☐ have no effect on the motor operation.

8. After carrying out an insulation test between each of the stator windings and earth, the motor would pass if all test results were: *(tick the correct box)*

   ☐ less than 2 ohms
   ☐ between 2 ohms and 10 kilohms
   ☐ between 10 kilohms and 1 megohm
   ☐ greater than 1 megohm.

9. The typical phase resistance of a stator winding for an induction motor would be: *(tick the correct box)*

   ☐ almost zero ohms
   ☐ 10 to 100 ohms
   ☐ 100 to 1000 ohms
   ☐ greater than 1 megohm.

10. The air gap between the rotor and the stator core is typically *(tick the correct box)*

   ☐ 0.05mm
   ☐ 0.5mm
   ☐ 5.0mm
   ☐ 50mm.

11. What type of three-phase induction motor would allow resistance to be added to the rotor?

____

12. Explain how aluminium rotor bars are fitted into the slots of a squirrel cage rotor.

____

13. What type of enclosure must be used for flame proof motors?

____

14. What effect will changing a star connected stator into a delta connected stator have on the direction of rotation of the motor?

____

15. Where would you use witness marks?

____

16. You are required to isolate, remove, and dismantle a three-phase induction motor for routine maintenance. List in point form the steps that you will follow to prepare the motor for dismantling.

- ____
- ____
- ____
- ____
- ____

Section 3: Three-phase induction motor characteristics

SUGGESTED DURATION	PREAMBLE
6 hours	This section introduces the behaviour and characteristics of squirrel cage, dual (double) squirrel cage and wound rotor (slip ring) three-phase induction motors.

This section covers part of the learning outcomes 1 and 3 of the National Module Descriptor.

Objectives

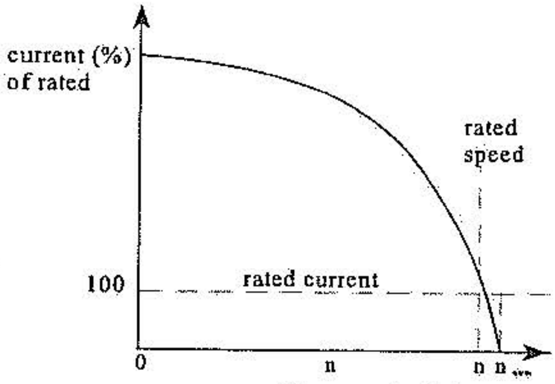
At the end of this section you should be able to:

- ☐ interpret information from speed/torque curves of AC induction motors
- ☐ list the operating characteristics of squirrel cage motors
- ☐ list the operating characteristics of slip ring motors
- ☐ calculate rotor speed from synchronous and slip speeds
- ☐ calculate slip % from rotor frequency
- ☐ identify details from motor nameplate
- ☐ calculate the efficiency of induction motors
- ☐ identify typical motor faults from motor performance.

Induction motor action

When the stator winding is energised
the following events occur
- an RMF is set up at synchronous speed
- stator flux induces an emf in the rotor bars
- rotor current flows in the rotor bars
- rotor flux reacts with the stator flux to cause motor action

Motor action only occurs when the rotor speed is less than synchronous speed. Between zero rotor speed and operating speed the electrical characteristics change. The diagram opposite shows typical changes.



Current speed curve

Acceleration of the rotor ceases when the induced rotor current is of sufficient value to develop the necessary load torque. If the load torque increases, the machine has to slow down to induce a larger rotor current to accommodate the extra load.

Slip

Slip is the term used to describe the speed differential between the RMF and the actual rotor speed. Around the normal operating range, the larger the slip the larger the amount of torque developed.

Slip speed is determined from: $N_{slip} = N_{sync} - N_{rotor}$ (rpm)

Student exercise 1

A 4 pole 50Hz induction motor operates with a rotor speed of 1440rpm. Determine the slip speed.

N_{sync} = ______________________

N_{slip} = ______________________

Slip speed is usually expressed as a percentage of the synchronous speed.

Slip % is determined from: $Slip\ \% = \frac{N_{slip}}{N_{sync}} \times \frac{100}{1}$

Student exercise 2

Determine the slip % for the motor described in student exercise 1.

Slip % = __________________________

Actual rotor speed is expressed as the difference between the synchronous speed and the slip speed: $N_{rotor} = N_{sync} - N_{slip}$

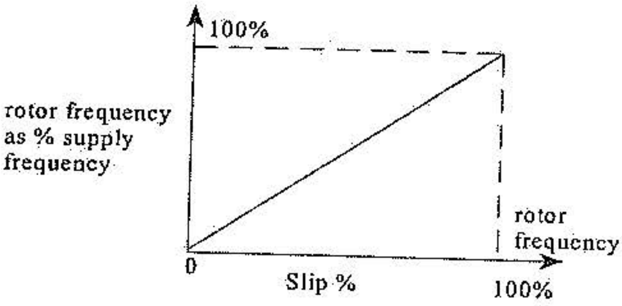
Student exercise 3

An induction motor operates with a 2% slip. If the synchronous speed of this motor is 1500rpm, determine the actual rotor speed.

Rotor speed = __________________________

Rotor frequency

At standstill the frequency of the induced rotor voltage is equal to the supply frequency. As the rotor accelerates, the rate by which the rotor conductors are being cut by the RMF decreases, thereby decreasing the frequency of the induced rotor voltage. If the rotor could run at synchronous speed there would be no induced voltage in the rotor, producing zero rotor frequency.



Rotor frequency and slip %

Rotor frequency is inversely proportional to rotor speed **or** directly proportional to slip %. Provided you know the supply frequency and the slip % you can determine the frequency of the rotor from:

$$f_{rotor} = \frac{slip\ \%}{100} \times f_{supply}$$

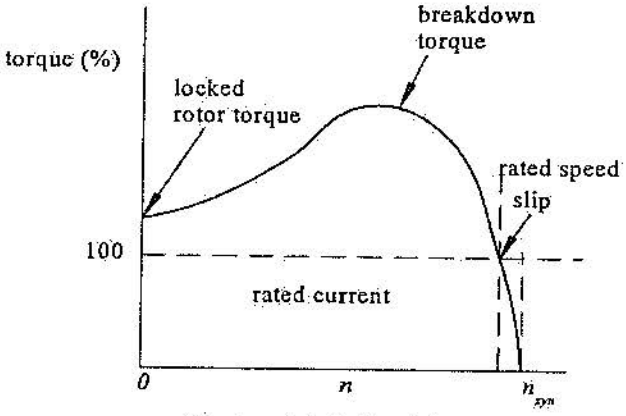
Example of calculation 4

Determine the rotor frequency of the motor in student exercise 3, if the supply frequency is 50Hz.

Rotor frequency ________________________

Torque developed by an induction motor is dependent on the ratio of the rotor resistance to the rotor reactance. The rotor reactance varies with rotor frequency which is speed dependant.

Torque speed curves (see below) show the variation in motor torque with changes in motor speed or slip.



Torque / speed curves

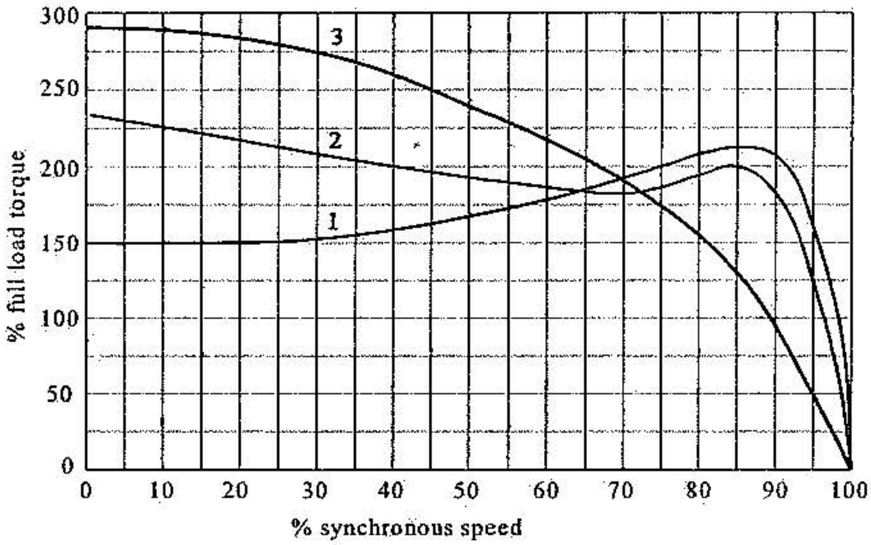
The torque/speed curve shown above indicates that:

- Locked rotor torque or *starting* torque is the torque developed at the instant of starting. ($X_R > R_R$)
- For the machine to accelerate, the torque developed at starting must be greater than the standstill torque of the load.
- As the machine accelerates, rotor reactance decreases in value and approaches the value of the rotor resistance.
- Maximum torque will occur when rotor resistance is equal to rotor reactance.
- ($X_R = R_R$) The point on the curve where this occurs is known as the *breakdown* torque or the *stalling* torque. If the load torque exceeds this value the motor will stall.
- Further acceleration decreases rotor reactance, causing torque to decrease.
- ($X_R < R_R$)
- The motor will accelerate to a speed that allows the machine to develop sufficient torque to meet the needs of the load.

Squirrel cage motor characteristics

The performance characteristics of the squirrel cage machine are governed by rotor design and winding connection method.

Standard squirrel cage motors are manufactured in three general types with characteristics as shown in the table below:



Squirrel cage characteristics

1. Normal starting torque: 1.5 times full load torque
   Low starting current: 6 to 7 times full load current
   Normal slip: less than 5%

   Applications: General purpose motors where load power requirements are not severe. Examples: driving fans, blowers and machine tools.

2. High starting torque: 2 times full load torque
   Low starting current: 5 to 6 times full load current
   Increased slip: around 5%

   Applications: Used where the motor is required to start at full load. Examples: driving conveyors, reciprocating pumps and compressors.

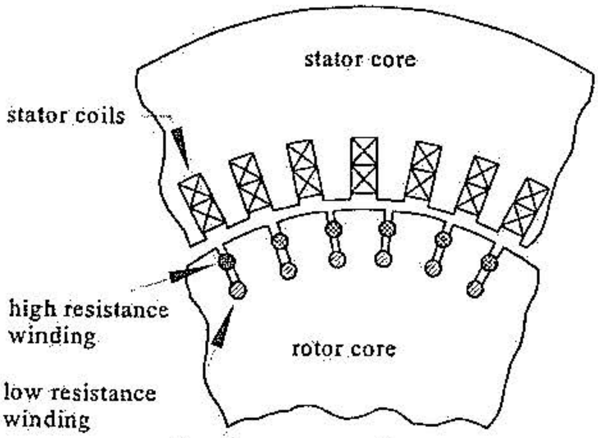
3. High starting torque: 3 times full load torque
   Low starting current: 5 times full load current
   High slip: up to 10%

   Applications: Flywheel mounted machines such as presses and punches.

Note: Star connection of the stator windings produces characteristics ⅓ times delta values.

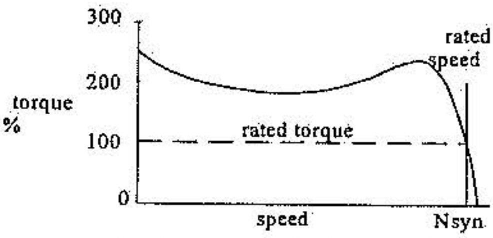
Dual cage rotors

Dual cage rotors are manufactured to obtain a high starting torque. This is achieved by manufacturing a rotor which has two rotor cages. The outer cage is of a resistive material of a smaller cross sectional area. (high R, low X). The inner cage is copper and is deeper in the core of the rotor. (low R, high X)



Dual cage rotor characteristics

Application: Air compressors, crushers, refrigerator compressor motors or reciprocating force pumps.

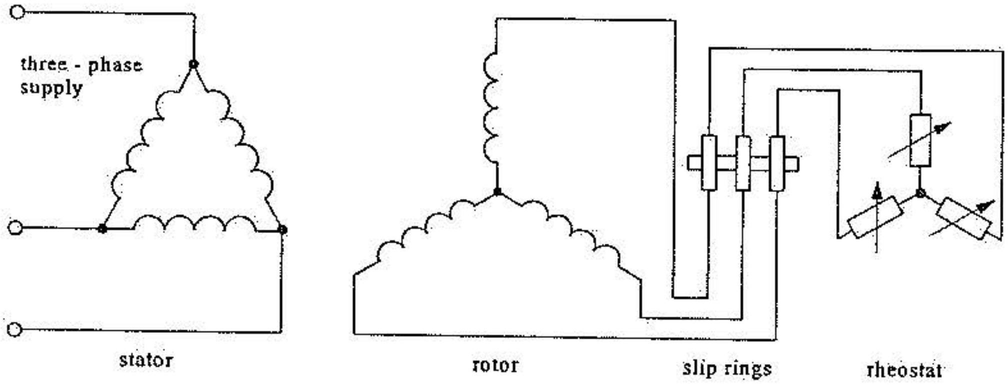


Dual cage rotor characteristics

Wound rotor induction motors

The squirrel cage motor is limited by having a constant rotor resistance. Under normal running conditions a high efficiency is desired which calls for a low rotor resistance. This in turn creates a low starting torque with a high starting current. Squirrel cage rotors are designed with these characteristics.

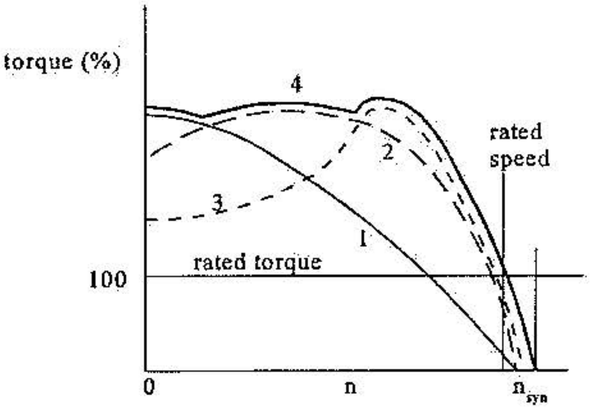
Wound rotor machines have the advantage in that maximum torque can be made to occur at any speed by adding resistance to the rotor circuit to match the rotor reactance.



Rotor resistance starting

Rotor circuit rheostat (variable resistance) is changed to achieve a speed torque characteristic which suits the nature of the load. The following curves show variations in rotor circuit resistance.

Curve 1	Rotor resistance equals rotor standstill reactance.
Curve 2	Rotor resistance is lower than standstill reactance.
Curve 3	No added rotor resistance
Curve 4	The starting characteristic that is achieved by varying the external resistance as the machine accelerates.



Wound rotor characteristics

Applications:
Since the maximum torque can be maintained throughout the accelerating period, the wound rotor motor is used for the starting of high inertia loads, for example machinery with large flywheels, such as presses, guillotines, rock crushers and plunger pumps.

Comparison of squirrel cage and wound rotor induction motors

Advantages of squirrel cage induction motors

- simplicity and ruggedness of mechanical construction
- no sliding electrical contacts, therefore no sparking in the machine so they can be used in explosive atmospheres (provided they have an appropriate enclosure)
- wide range of speed control when used with variable frequency controllers (electronic)

Disadvantages of squirrel cage induction motors

- relatively poor starting torque
- large starting current
- characteristics fixed

Advantages of wound rotor induction motors

- high starting torque
- relatively small starting current
- smooth speed control over a wide range

Disadvantages of wound rotor induction motors

- high production cost compared to the squirrel cage motor
- brushes and brush gear must be used causing the possibility of sparking and increased maintenance
- inefficient speed control

Nameplate details

Motor nameplates provide information from which you can:

- Determine electrical wiring requirements for conduit and wiring or suitable protection rating etc.
- Obtain design and performance data for maintenance.
- Obtain a proper replacement motor if required.
- Typical information found on the motor nameplate may be:
    - the manufacturer
    - the type of motor
    - serial number and model number for identification
    - frame size to identify motor physical measurements
    - output rating in mechanical power
    - ampere rating when operating at full load
    - voltage rating
    - frequency rating
    - number of phases
    - RPM when all other nameplate conditions are met
    - winding connection method
    - duty, or the cycle of operation in which it can operate safely ie. *continuous*
    - ambient temperature - maximum temperature of the surrounding air in which the motor can operate when delivering rated output

Motor rating

Motors convert electrical energy into mechanical energy. They are rated in terms of their output power.

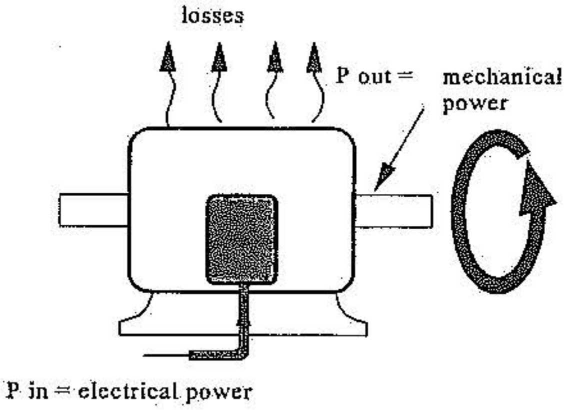
Motor *output* power is determined by:

$$P_{out} = \frac{2\pi NT}{60} = watts$$

Where N = actual rotor speed in rpm
T = torque in Newton metres

Motor *input* power is determined by:

$$P_{in} = \sqrt{3}\ V_L\ I_L \cos\phi = watts$$



Energy flow in an induction motor

Motor efficiency

Motor efficiency varies with changes in load conditions. At maximum efficiency the input power is less than for other conditions for the same given load.

Efficiency is determined by:

$$\text{Efficiency \%} = \frac{output\ power}{input\ power} \times \frac{100}{1}$$

Output power is always less than the input power due to the losses that occur in the energy converter process.

Power loss is determined by:

Power loss = input power - output power

Example

Calculate the full load efficiency of a three-phase induction motor given:

Rating = 10kW
Voltage = 415V
p.f. = 0.8
I f/L = 20A

$$\text{Efficiency \%} = \frac{Output}{Input} \times 100$$

$$\text{Input} = \sqrt{3}\ V.\ \text{I}.\ \cos\ \Phi$$

$$= \sqrt{3} \times 415 \times 20 \times 0.8$$

$$= 11.5\text{kW}$$

$$\text{Efficiency \%} = \frac{10}{11.5} \times 100$$

$$= 86.96\%$$

Student exercise 4

Calculate the power output and full load line current of a three-phase induction motor, given the following specifications.

Efficiency:	85%
Supply voltage:	415V
Speed:	1440rpm
Power factor:	0.85
Torque:	65Nm

- Power output = ____________________

- Full load line current = ____________________

Motor faults

Low terminal voltage

Torque varies in proportion to the square of the voltage. For example if the motor terminal voltage is reduced to 80% of its rated value the torque developed will be $(80\%)^2$ of its rated value ie. 64%. The drop in torque associated with low voltage may cause the motor to stall or have a prolonged acceleration period during start up, simulating an overload condition which will cause the protection devices to operate.

Single phasing

Single phasing is the condition that occurs when one line of the three-phase supply is open-circuited or one of the motor windings is open-circuited. The effects on motor performance may be:

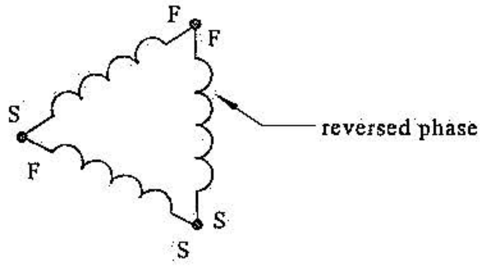
- RMF is either destroyed or unbalanced
- decrease in speed
- difficulty in starting
- higher than normal current
- low pitched *growling* noise at start
- high pitched *whine* if single phasing occurs during operation

Phase reversal

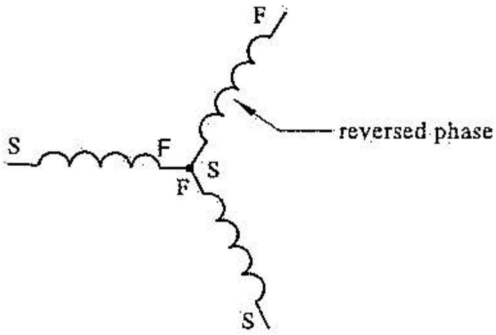
Effects on motor performance due to an incorrect connection may be:

- difficulty in starting
- loss of torque
- low speed
- unequal phase winding current
- high line currents
- low pitched *growling* noise
- increased machine vibration

Incorrect connections are shown in the diagrams below:



Delta phase reversal



Star phase reversal

Skill practice SP3
Three-phase induction motor characteristics

Task

To monitor the operations of:

- correctly connected star and delta squirrel cage motors
- a star connected motor which is single phasing
- a delta connected motor which is single phasing
- a star connected motor which has a phase reversal
- a delta connected motor which has a phase reversal

Equipment

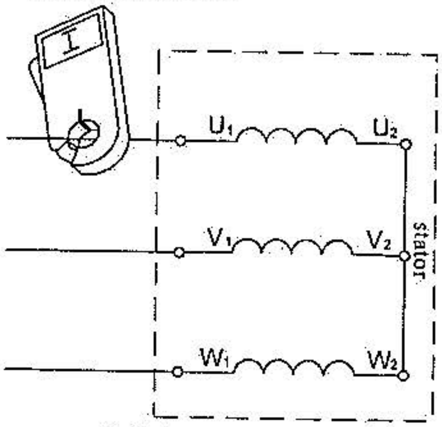
1 x 6 terminal three-phase motor
1 x clip on ammeter
1 x hand held tachometer
1 x digital multimeter

Remember: Work safely at all times!

- isolate supply before connecting or altering circuits
- always select the correct test equipment
- be careful when working near rotating machines

Procedure

1. Connect the motor in star as shown below:



Star connection

2. Start the motor and measure each line current and shaft speed.

I_{L1} = ________________ A

I_{L2} = ________________ A

I_{L3} = ________________ A

N = ________________ rpm

Stop the motor.

3. Open circuit one line and start the motor. Measure each line current and shaft speed.

I_{L1} = ________________ A

I_{L2} = ________________ A

I_{L3} = ________________ A

N = ________________ rpm

Stop the motor and reconnect the line.

4. Open circuit one phase winding and start the motor. Measure each line current and shaft speed.

I_{L1} = ________________ A

I_{L2} = ________________ A

I_{L3} = ________________ A

N = ________________ rpm

Stop the motor and reconnect the winding.

5. Reverse one phase winding and start the motor. Measure each line current and shaft speed.

I_{L1} = ________________ A

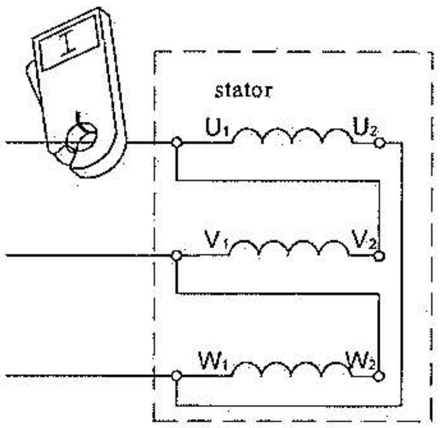
I_{L2} = ________________ A

I_{L3} = ________________ A

N = ________________ rpm

Stop the motor and disconnect.

6. Connect the motor in delta as shown below:



Delta connection

7. Start the motor and measure each line current and shaft speed.

I_{L1} = ______________ A

I_{L2} = ______________ A

I_{L3} = ______________ A

N = ______________ rpm

Stop the motor.

8. Open circuit one line and start the motor. Measure each line current and shaft speed.

I_{L1} = ______________ A

I_{L2} = ______________ A

I_{L3} = ______________ A

N = ______________ rpm

Stop the motor and reconnect the line to the motor.

9. Open circuit one phase winding and start the motor. Measure each line current and shaft speed.

I_{L1} = ______________ A

I_{L2} = ______________ A

I_{L3} = ______________ A

N = ______________ rpm

Stop the motor and reconnect phase winding.

10. Reverse one phase winding and start the motor. Measure each line current and shaft speed.

I_{L1} = ______________ A

I_{L2} = ______________ A

I_{L3} = ______________ A

N = ______________ rpm

Stop the motor and disconnect.

Report

1. For the star connected motor:
   - (a) Tabulate the currents and motor speed for normal and abnormal operating conditions
   - (b) Explain the difference between normal and abnormal values.
   - (c) Comment on the operation of the motor under normal and various abnormal conditions.

2. Report for the delta-connected motor.
   - (a) Tabulate the currents and motor speed for normal and abnormal ooperating conditions
   - (b) Explain the difference between normal and abnormal values
   - (c) Comment on the operation of the motor under normal and various abnormal conditions.

Review questions

These questions will help you revise what you have learnt in Section 3.

1. A standard eight pole squirrel cage motor on 50Hz supply could have a rated rotor speed of: *(tick the correct box)*

☐ 735rpm
☐ 980rpm
☐ 1450rpm
☐ 2880rpm.

2. Slip speed is the difference between: *(tick the correct box)*

☐ standstill and rotor speed
☐ rotor speed and stalling speed
☐ synchronous speed and rotor speed
☐ synchronous speed and standstill speed.

3. Torque developed by a squirrel cage motor is at a maximum:*(tick the correct box)*

☐ when the rotor is at standstill
☐ at rated speed
☐ at synchronous speed
☐ when rotor resistance equals rotor reactance.

4. Rotor torque varies proportionally to the : *(tick the correct box)*

☐ supply voltage squared
☐ rotor speed
☐ supply current
☐ supply frequency.

5. Dual cage rotor machines when compared to conventional single cage machines have: *(tick the correct box)*

☐ higher starting torque and lower full-load slip
☐ higher starting torque and higher full-load slip
☐ lower starting torque and lower full-load slip
☐ lower starting torque and higher full-load slip.

6. A wound rotor motor induction motor would be used to drive a:
(tick the correct box)

☐ lathe
☐ rock crusher
☐ blower
☐ pedestal drill.

7. Induction motor power factor: *(tick the correct box)*

☐ is constant
☐ increases with load increases
☐ decreases with load increases
☐ increases with load decreases.

8. The frequency of the rotor currents: *(tick the correct box)*

☐ increases with speed increases
☐ increases with slip increases
☐ decreases with slip increases
☐ decreases with load increases.

9. Torque of an induction motor is directly proportional to slip:
(tick the correct box)

☐ for all values of slip
☐ for high values of slip
☐ for low values of slip
☐ for medium values of slip.

10. The results obtained from a locked rotor test would be: *(tick the correct box)*

☐ maximum torque and current
☐ full load torque and current
☐ starting torque and current
☐ no-load torque and current.

11. As the slip of a motor decreases, what happens to the rotor speed?

____

12. What would be the torque developed if the rotor speed was equal to synchronous speed?

____

13. When does maximum torque occur for three-phase induction motors?

____

____

14. What would happen if the load torque became greater than the rotor torque developed by the motor?

____

____

15. What effect does adding resistance to the rotor circuit of a wound rotor motor have on the motor's starting torque?

____

____

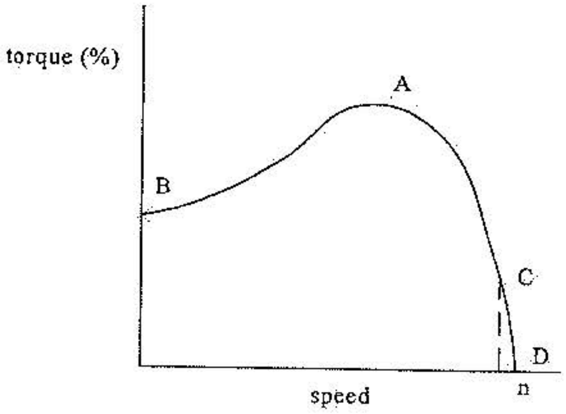
16. Name the points marked on the diagram opposite:

A ____________________

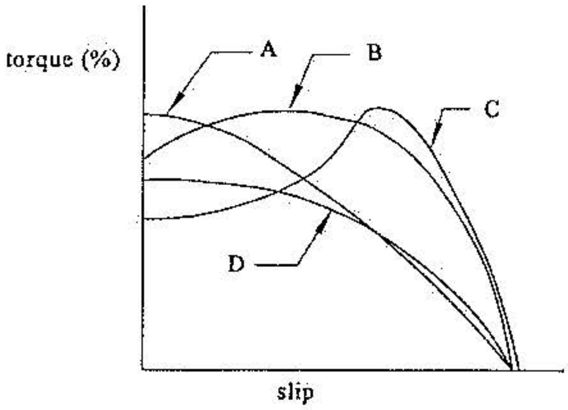
B ____________________

C ____________________

D ____________________



17. Which of the torque slip curves drawn would represent that of a wound rotor machine with its brushes short-circuited? (Circle the correct letter)



18. A six pole 50Hz induction motor operates with a 4% slip. Determine the rotor speed.

Answer: ____________________

19. A 50Hz induction motor has rotor currents with a frequency of 2Hz. Determine the slip % that this motor operates with.

Answer: ____________________

20. A three-phase induction motor on full voltage develops a starting torque of 120Nm. Determine the torque developed if the supply voltage is 75% of the rated value.

Answer: ____________________

Section 4: AS 3000 and service rule requirements and DOL motor starters

SUGGESTED DURATION	PREAMBLE
8 hours	To introduce the requirements for starting large motors, and the operating principles, connection and fault finding for the direct on line motor starter. AS 3000 and service rules.

This section covers part of the learning outcomes 3 and 6 of the National Module Descriptor.

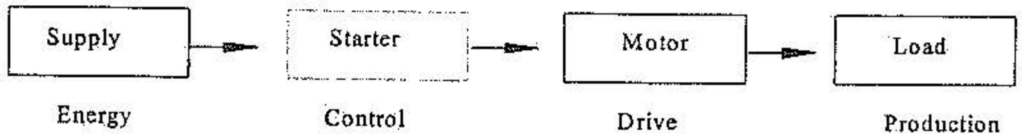
Objectives

At the end of this section you should be able to:

- ☐ state the reasons for limiting the starting current of large motors
- ☐ list the requirements of the SAA wiring rules and the local supply authority with regard to starting, control and protection of induction motors
- ☐ list the types of AC motor starters commonly used by industry
- ☐ describe the operating principle of a DOL motor starter
- ☐ list the main advantages and disadvantages of a DOL motor starter
- ☐ connect a DOL motor starter and carry out fault finding on power and control circuits.

AC motor starters

Motor starters are devices which are connected between the supply lines and the motor in a functional system.



Functional system

The characteristics of motors are that the current and torque conditions are considerably different during the starting sequence and under normal running conditions.

As one example, a squirrel cage motor has a starting current up to eight times the rated full load current and a starting torque three times the full load torque. Large increases in current and torque can be harmful to the:

- motor
- load being driven or
- supply providing the electrical energy.

Student exercise

Using the Australian Standard AS3000 state the clause number and summarise the main points relating to the control and starting of motors.

Limitation of starting and transient current - Clause No: ____________________

____

____

Automatic restarting - Clause No: ____________________

____

____

Control switches - Clause No: ____________________

____

____

Isolating switches - Clause No:

Types of 3 phase induction motor starters

The types of AC motors starters which are commonly used throughout industry are:

- DOL starter
- star-delta starter
- primary resistance starter
- auto-transformer starter
- electronic (soft-start)starter
- secondary resistance starter.

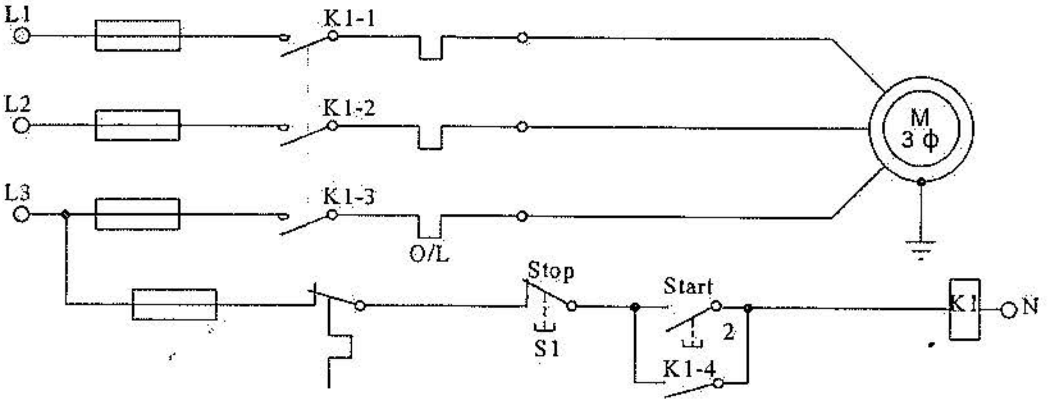
Control features

Motor starters can provide several control features, some of which are listed below:

- local and remote starting and stopping
- over-current and under-voltage motor protection
- torque control (not all types)
- speed control (not all types)
- automatic or manual operation.

Direct on line motor starter (DOL)

The basic form of starter is the *manually* operated direct-on-line (DOL) starter. This is simply a load rated manual switch known as a contactor with a thermal overload device that will trip the switch in the event of an over-current condition. The most common form of starter is the *automatic* DOL starter which has the added features of being able to be operated from remote or local buttons or automatically by special control devices.



DOL motor starter circuit

Contactors

Contactors used in three-phase motor starters have three normally open main contacts capable of switching high currents. Also incorporated in the contactor is at least one normally open auxiliary (or control) contact. This contact is known as the holding contact. Additional control contacts, either normally open or normally closed, may also be included depending on the requirements of the control circuit. The contacts are operated by an electromagnet.

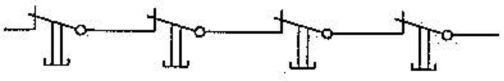
Control devices

The basic devices in a motor starter control circuit are the stop button, the start button, the holding contact and the overload control contact.

Stop and start buttons can be remote from the starter and there can be as many as required. Other devices that can be used to stop or start a motor are limit switches, pressure switches, proximity switches, level switches, temperature operated switches, rotation speed switches and other switching device.

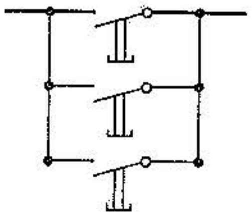
The general principles for the circuit arrangement of these devices is:

- All stop devices are `normally closed' and are connected in series with each other.



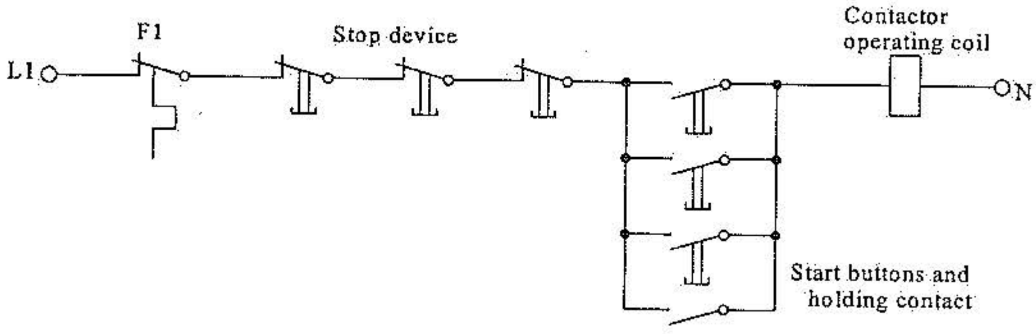
Stop devices

- Start devices and `holding' contacts are `normally open' and are connected in parallel with each other.



Start devices

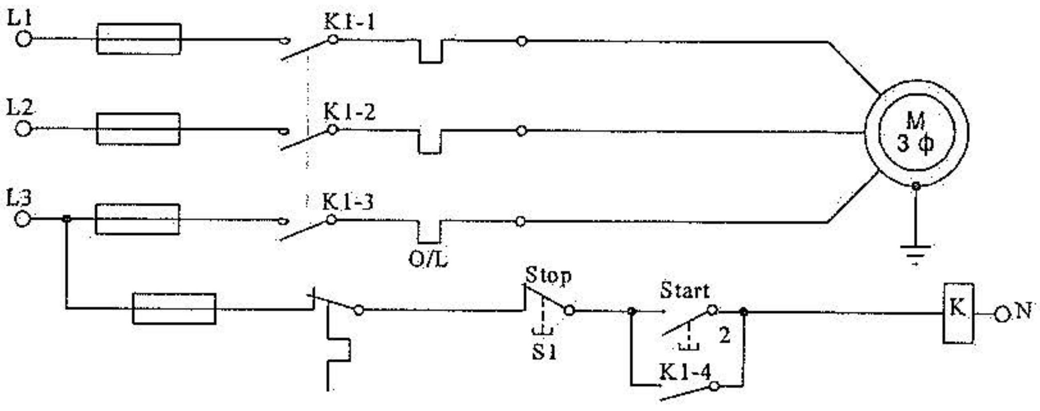
- The stop and start devices are connected as shown below:



Control circuit

Student exercise

List the sequence of operation of the DOL motor starter circuit shown below after the start push button S2 is pressed:



DOL motor starter circuit

What happens if K1-4 contact opens during motor operation?

Advantages of DOL motor starters

- Fail safe operation of the control circuit
- Simple operation
- Low initial cost
- Remote stop-start features of control

Disadvantage of DOL motor starters

- No current limiting ability, therefore maximum current occurs at start.

Skill practice 4
Induction motor full load and starting characteristics

Task

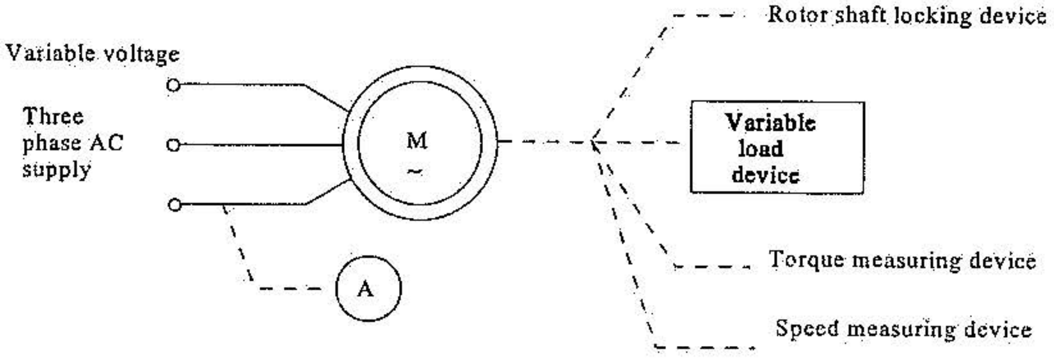
To conduct a test on a squirrel cage induction motor and to determine current and torque characteristics at full load and starting.

Equipment

- three-phase power supply - variable voltage
- three-phase squirrel cage induction motor
- variable load device (may double for rotor locking device)
- torque measuring device
- ammeter
- rotor shaft locking device (if required).

Procedure

1. Connect the equipment as shown in the diagram below.



2. From the motor nameplate record the details in the spaces provided below.

Number of phases ________________

Voltage ________________

Output power ________________

Rated speed ________________

Frequency ________________

Connection ________________

Rated full-load current ________________

Insulation class ________________

3. Using the details recorded above calculate the full load torque.

$$P_{output} = \frac{2\Pi n T_{F/L}}{60}\ Watts$$

$$T_{F/L} =$$

Answer: ____________________

4. Turn on the three-phase supply at rated voltage and adjust the variable load device until the motor reaches the calculated full load torque value.

5. Measure the line current and rotor speed and record the results in the table below.

Line current *A*	*Rotor speed* *rpm*

6. Reduce the load and turn off the supply.

7. Install the device that locks the rotor shaft (your variable load device may be capable of stalling the motor).

8. *Safety check*: Before proceeding, ask the teacher to check that the equipment is properly connected.

9. Reduce the supply voltage to the value given ____________ V_{test}
(This may not be necessary with some equipment)

10. Turn on the three-phase supply and measure the line current and starting torque and record the results in the table below.

Line current I_{test}	*Starting torque* T_{test}

11. Use the voltages given in Steps 2 and 9 and the measurements taken in Step 10, to calculate the starting current and starting torque for rated voltage conditions. Use the following ratios.

For starting current

$$\frac{I_{test}}{I_{start}} = \frac{V_{test}}{V_{start}}$$

For starting torque

$$\frac{T_{test}}{T_{start}} = \frac{V^2_{test}}{V^2_{start}}$$

Answer: ______________________

Answer: ______________________

12. Finalise this skill practice by completing the following.

(a) Calculate the ratio of the starting current (step 11) to the full load current (step 2) as a percentage.

Answer: ____________________

(b) Compare the value obtained in step (a) above with the known theoretical value.

____

____

____

(c) Calculate the ratio of the starting torque (step 11) to the full load torque (step 3) as a percentage.

Answer: ____________________

(d) Compare the value obtained in (c) above with the known theoretical value.

____

____

Skill practice 5
DOL starter and fault finding

Task

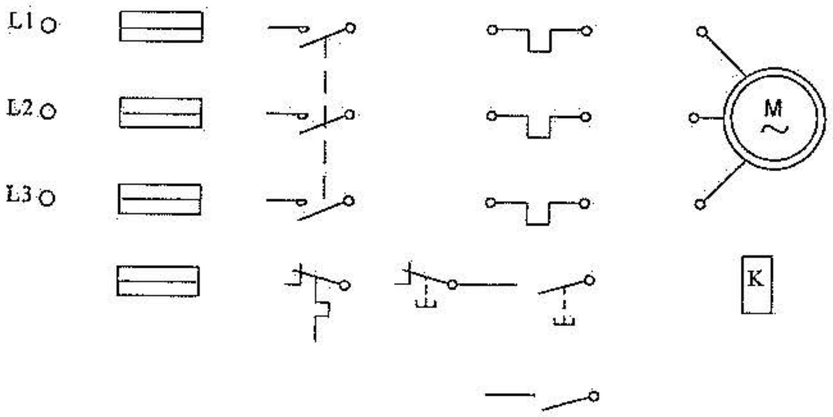
To draw the circuit diagram of a DOL starter, connect and run the starter and find the cause of introduced faults in the starter.

Equipment

- three-phase AC supply
- four fuses
- 1 three-phase contactor
- 1 start stop station
- overload
- 1 motor terminal block (or motor)
- 1 DOL starter control circuit with faults
- voltmeter
- continuity tester
- ammeter
- insulation resistance tester.

Procedure

1. Complete the following diagram by providing the power and control circuit connections between the equipment identified. Label all components using standard symbols.



2. Using the equipment provided and your connection diagram connect the equipment.

3. Turn on the supply and test the operation of the start and stop buttons.

4. With the motor running, remove the fuse in the control circuit to determine if this causes the motor to stop. Replace the fuse.

5. Manually operate the overload device then press the start button to determine that the motor will not start.

6. Turn off the supply.

7. With the equipment supplied conduct the tests necessary to determine the cause of each of four separate faults. Record the results for each in the table below.

   Note: These faults will be introduced by your teacher.

Fault number	*Test equipment used to find fault*	*Test equipment indication or reading*	*Description of fault*
1			
2			
3			
4			

7. Finalise this skill practice by completing the following observations.

   For each of the fault conditions give a brief explanation of the repairs needed to make the DOL starter operate satisfactorily.

   Fault 1 ____________________

   ____

   ____

   Fault 2 ____________________

   ____

   ____

   Fault 3 ____________________

   ____

   ____

   Fault 4 ____________________

   ____

   ____

Review questions

These questions will help you revise what you have learnt in Section 4.

1. Using AS3000 summarise the definition of a fuse.

____

____

2. Using AS3000, give the clause number related to protection of motors against over temperature and summarise the clause below.

____

____

3. Using AS3000 give the clause number related to the selection of fuses and circuit breakers which protect motors subject to short time overcurrent and summarise the clause below.

____

____

____

____

4. Using AS3000, give the clause numbers related to isolation and control of motor circuits in a normal environment and summarise the clause below.

____

____

____

____

5. Summarise the main requirements for the protection of motors and associated control equipment when located in high humidity environments.

____

____

6. List **three** reasons for limiting the starting current to AC motors.

- ________________________________
- ________________________________
- ________________________________

7. List **three** types of AC motor starters used with 3 phase induction motors.

- ________________________________
- ________________________________
- ________________________________

8. What is the major advantage of a DOL motor starter over an isolator/control switch?

____

____

9. The test performed to determine the DOL values of current and torque of a motor is known as a/an: *(tick the correct box)*

☐ starting current test
☐ torque meter test
☐ reduced voltage test
☐ locked rotor test.

10. A 415 V 3 phase motor is rated at 50 kW and draws 82 A on full load. The approximate starting current when started DOL would be: *(tick the correct box)*

☐ 82 A
☐ 200 A
☐ 500 A
☐ 5000 A.

11. The motor which has a full load current of 82 Amps is subject to a limitation on starting current by the local supply authority. If the limitation is $(2 \times I_{F/L}) + 33$ A, the maximum allowable starting would be: *(tick the correct box)*

☐ 82 A
☐ 197 A
☐ 278 A
☐ 345 A

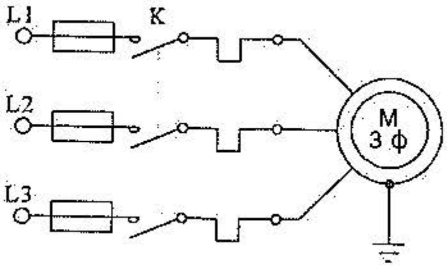
12. The effect of reducing the voltage applied to a motor is to: *(tick the correct box)*

☐ reduce starting current, increase starting torque
☐ reduce starting current and starting torque
☐ increase starting current, reduce starting torque
☐ increase starting current and starting torque.

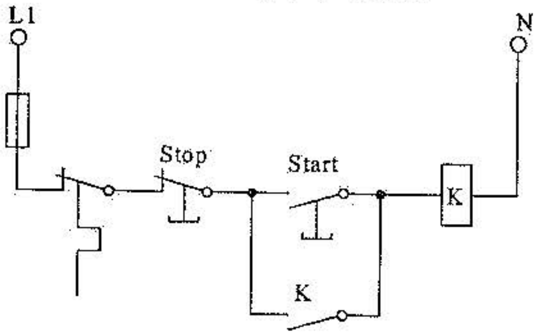
13. DOL starters are used as they provide: *(tick the correct box)*

☐ non-automatic restart function and fail-safe operation
☐ the use of a three-phase switch only for on/off control
☐ control over starting current and/or starting torque
☐ reduced voltage and torque at start.

The following questions 14 to 16 refer to the DOL starter circuits below:



DOL starter power circuit



DOL starter control circuit

14. How many contacts does the coil K control? *(tick the correct box)*

- ☐ 1
- ☐ 3
- ☐ 5
- ☐ 4.

15. The contact in parallel with the start switch is termed a/an: *(tick the correct box)*

- ☐ interlock contact
- ☐ isolating contact
- ☐ latching contact
- ☐ lockable contact.

16. When the start button was pressed the motor did not run and the main contactor did not operate. The most likely fault would be: *(tick the correct box)*

- ☐ low insulation resistance values
- ☐ high earth continuity values
- ☐ open circuited contactor coil
- ☐ open circuit in L2.

Notes

Section 5: Reduced voltage three-phase induction motor starters

SUGGESTED DURATION	PREAMBLE
4 hours	To connect, operate and find faults on three common types of reduced voltage starters.
This section covers part of the learning outcome 3 of the National Module Descriptor.	

Objectives

At the end of this section you should be able to:

- ☐ describe the operating principles of the star-delta, auto transformer and primary resistance starters
- ☐ list the effects on line current, motor current and motor torque when using these starters
- ☐ list the advantages and disadvantages of these starters
- ☐ state common applications for each starter
- ☐ connect each starter power and control circuit for correct operation
- ☐ carry out fault finding as applied to the starter power and control circuits.

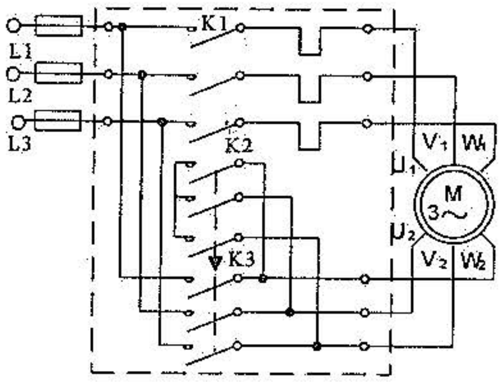
Reduced voltage starters

Motors controlled by these types of starters will reduce the starting current to practical levels and produce a torque less than DOL starting. As a result reduced voltage starters are selected to match load starting requirements.

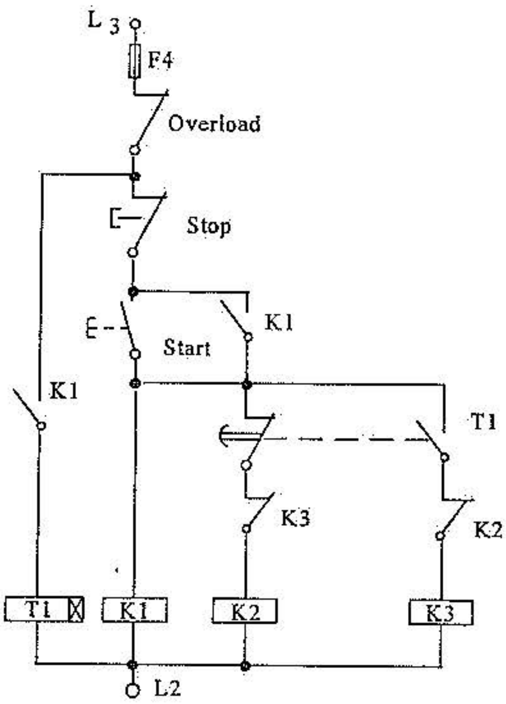
The star-delta starter

This starter switches the motor from star connection at starting to delta connection for running. These starters require six wires (one for each terminal) from the motor terminal block to the starter.

The power circuit and control circuit for a star delta starter are shown below. Other circuit arrangements are possible.



Power circuit



Control circuit

Features of the star delta starter

Star delta starters have the following features:

- during the starting sequence the voltage across each phase winding is 57.7% of the line voltage

- the reduction in voltage causes a reduction to 33% of the starting current and 33% of the starting torque. ie.

$I_{start} = \frac{1}{3} I_{DOL}$

and

$T_{start} = \frac{1}{3} T_{DOL}$

- the control circuit provides electrical interlocking of the star and delta contactors. This interlocking minimises the possibility of a short circuited supply by the simultaneous operation of both contactors. The star and delta contactors should also be mechanicaly interlocked.

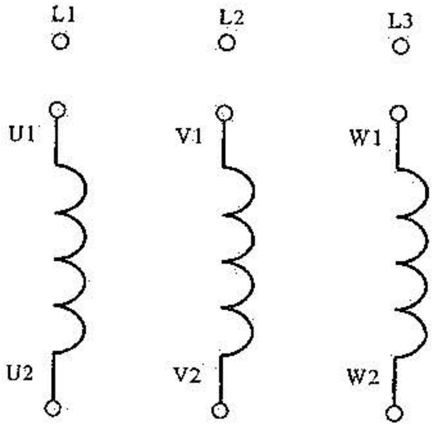
- the time period for transition between star and delta connection can be varied when timing devices are used. The time period is normally adjusted so the transition occurs when the motor reaches approximately 60%-80% of the rated motor speed

- the six coil ends of the three windings need to be available at the motor terminals to effect star and delta connections

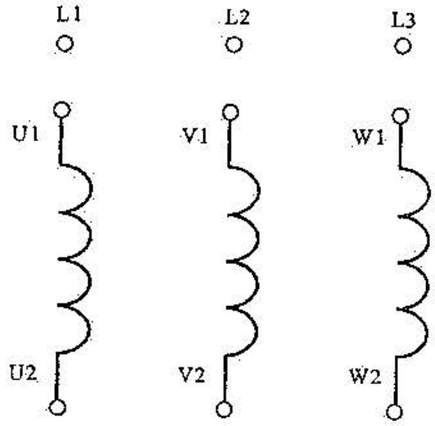
- for the circuit shown above the overload is set to trip at 58% of the motor rated full load current.

Student exercise 1

Connect the motor windings in the diagrams below for starting and running conditions.



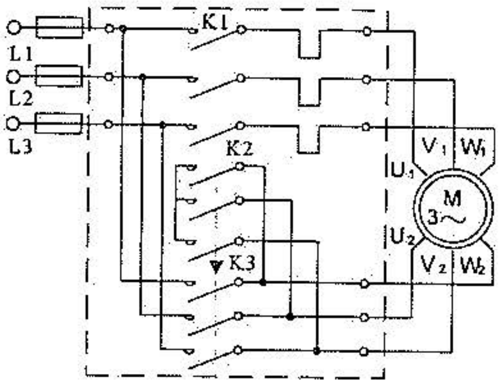
Starting - star connected stator



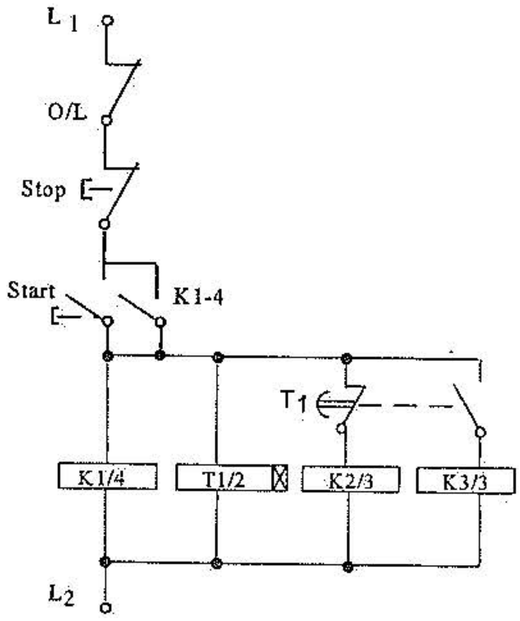
Running - delta connected stator

Student exercise 2

Using the following diagram, briefly describe the sequence of operation of the starter to bring the motor up to operating speed.



Power circuit



Control circuit

Student exercise 3

A 415 V, 3 phase induction motor is started by means of a star-delta starter. When started in delta the starting current is 75 amps and the starting torque is 50 newton-metres. Determine:

(a) voltage across each phase winding of the motor at starting
(b) starting current.
(c) starting torque.

Answer (a) ____________________

Answer (b) ____________________

Answer (c) ____________________

Advantages and disadvantages of the star-delta starter

Advantages

- it is a relatively cheap method of starting
- it provides good torque/current performance
- it is physically compact in most cases
- it is available in a range of kW sizes
- in most applications it is easily installed.

Disadvantages

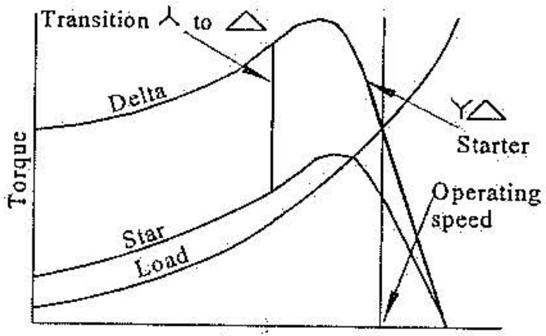
- it is generally restricted to loads that have a low starting torque
- a 6 terminal motor is required, hence 6 wires to the motor are needed
- during the changeover from star to delta, transient currents result (the motor goes off line during the transition)
- problems can easily arise from incorrect connections

Applications

The type of load normally is a low inertia type or the motor is started on no-load. Examples are fans and small centrifugal pumps.

Motor and load torque and their speed relationship

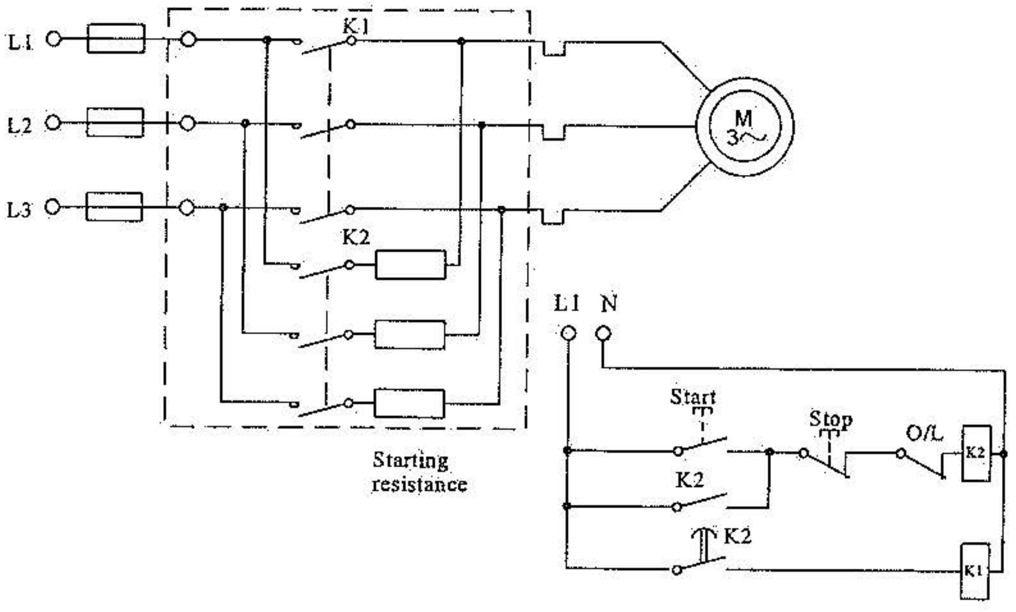
For a motor to accelerate up to its operating speed the torque of the motor must be greater than the torque of the load. The following diagram shows a typical motor and load torque speed relationship.



Star delta starter and load characteristic

Student exercise 5

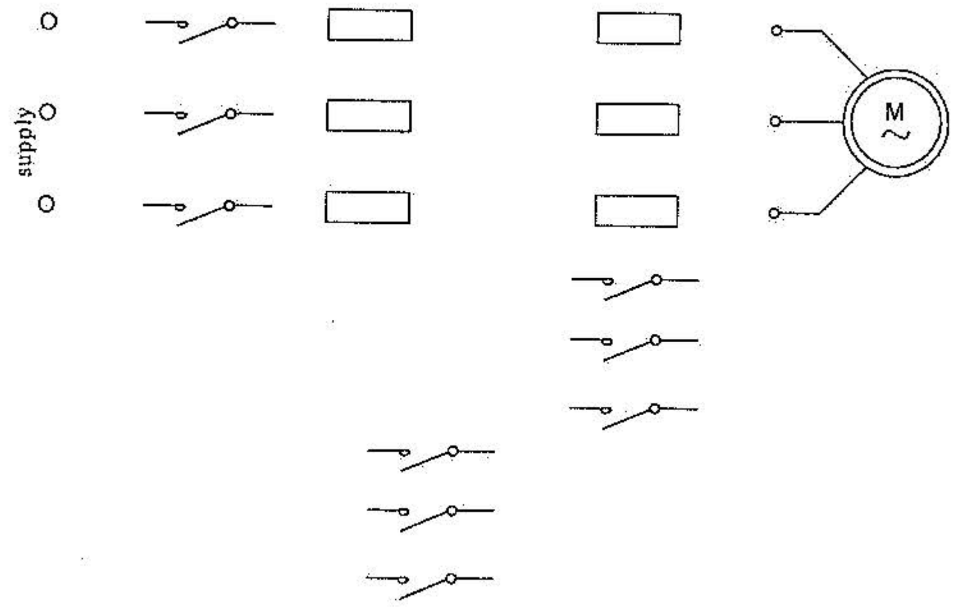
Using the following diagram briefly describe the sequence of operation of the starter to bring the motor up to speed.



Power circuit *Control circuit*

Student exercise 6

Complete the following diagram by drawing the connections needed for the power circuit of a three step primary resistance starter.



Identify the components using standard lettering then in the space below identify the sequence in which the three contactors close. 1st ____________________

2nd ____________________ 3rd ____________________

Advantages and disadvantages of the primary resistance starter

Advantages

- For one step resistance starters, the control circuit is less complex than star-delta starters
- is more cost effective than the auto-transformer starter
- allows the motor to run up to speed without a break in the supply
- affords better current and torque characteristics if the resistance is reduced in steps during starting
- three wire connections to the motor.

Disadvantages

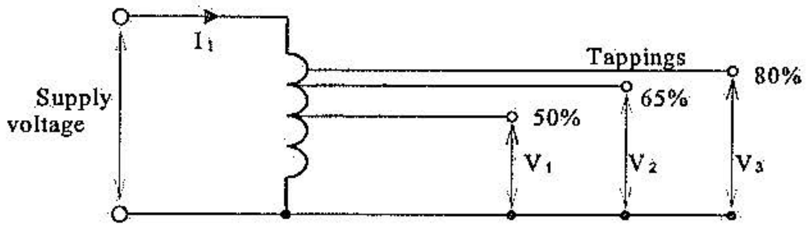
- wasteful of power
- the resistors are physically large
- current/torque relationship is poor, in that the line current is still quite high, whilst the torque is low.

Applications

The starters are used on lower starting torque loads such as, fans, water pumps.

The auto-transformer starter

This starter incorporates the use of an auto transformer which reduces voltage to the motor at start. After the starting period, the motor is switched to full line voltage. Auto transformers used for motor starting usually are equipped with three tappings - 50%, 65% and 80% as shown in the diagram.

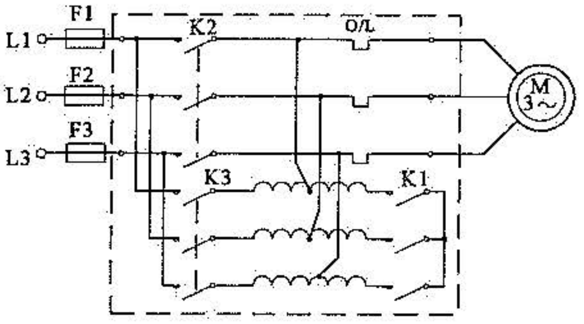


Auto-transformer

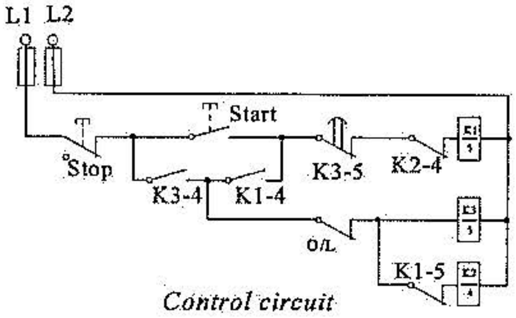
Multi tapped auto transformers are connected in each line of the supply to the motor. By selecting an appropriate tapping the voltage to the motor terminal is restricted.

There are two basic types of auto-transformer starters:

- two step - open transition
- three step - closed transition that is also called the Korndorfer connection (shown below)



Power circuit



Control circuit

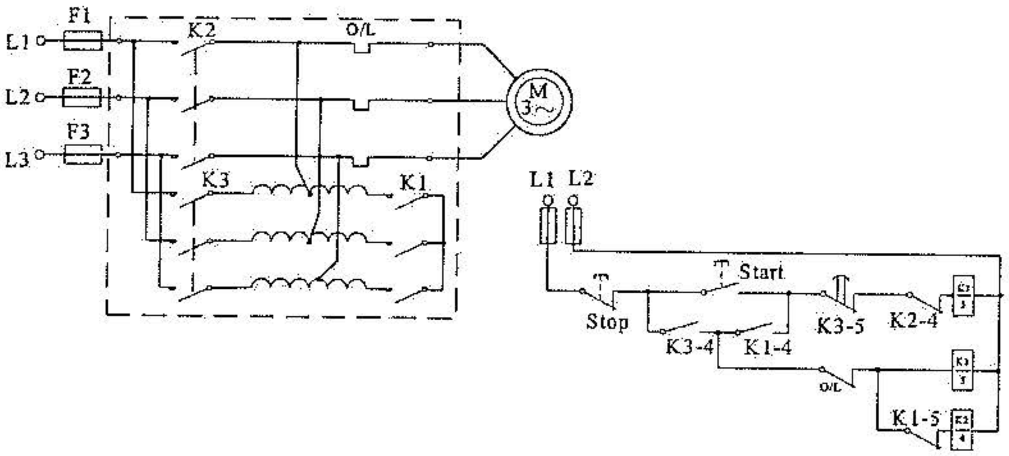
Features of auto transformer starters

The auto transformer starter has the following features.

- considerable reduction in line current is gained while maintaining relatively high values of starting torque
- two coil (open delta) auto transformers can be used on three-phase motors
- the tappings can be changed to obtain maximum torque or to suit a change in load conditions
- the transformer is rated for intermittent use
- the motors are permanently connected in star or delta
- the motor current reduction is in proportion to the percentage tap connected. Thus if the voltage tap is on 50%, the motor current will be 50% of the DOL current.
  $I\ \text{motor} = \%\ \text{tap} \times I_{DOL}$
- the supply line current is reduced in proportion to the percent tap squared expressed as a decimal. ie., if the voltage tap is 50% the line current is 25% of the DOL current
  $I\ \text{line} = (\text{tap})^2 \times I_{DOL}$
- motor torque is reduced in proportion to the percent tap squared. ie. if the voltage tap is 50% the motor torque is 25% of the DOL torque.
  $T\ \text{motor} = (\text{tap})^2 \times T_{DOL}$

Student exercise 7

Using the following diagram briefly describe the sequence of operation of the starter to bring the motor up to speed.



Student exercise 8

A 415 V, 3 phase squirrel cage induction motor takes a starting current of 160 A and has a starting torque of 54 newton-meters, when connected DOL. If an auto-transformer starter, with the motor connected to the 80 per cent tapping, is used to start the motor, determine:

(a) voltage applied to the motor at starting
(b) starting current taken from the supply
(c) starting current taken by the motor
(d) starting torque

(a)

(b)

(c)

(d)

Advantages and disadvantage of the auto-transformer starter

Advantages

- gives uninterrupted supply to the motor during starting if the Korndorfer method is used
- is less wasteful of power during starting than primary resistance starting
- line current to starting torque characteristic is an optimal value
- the tappings can be adjusted to suit almost any load condition within the load range of the starter.

Disadvantages

- requires expensive auto-transformers
- physically large and heavy in comparison to other starter types
- auto-transformer must be matched to the motor

Applications of the auto-transformer

These starters are used where the load has a relatively high starting and running torque and energy efficiency is required in the starting sequence.

Reduced voltage motor starter fault finding

The faults found in a DOL starter can also occur in reduced voltage starters. Additionally, problems associated with reduced voltage starting often occur with the change over from start to run. These problems normally are:

Problem: Motor has a delayed start (after the start button is pressed)

Possible cause	*Action*
Starting load too great	• Check the load for correctly operating unloading devices at start. eg. compressor unload solenoid valve. *Note*: Reduced voltage starting does not allow a motor to produce maximum starting torque and therefore can only start on light loads.

Problem: Motor starting on reduced voltage does not develop full speed and runs noisily.

Starting load too great	• Isolate the supply and remove the starter cover. Identify the start and run contactors. • Use an assistant to keep the test area clear of other personnel before restoring the power. • Restore the supply and start the motor. • Observe the starter operating and note the sequence of each control device.

Skill practice SP6 Star-delta starter

Task

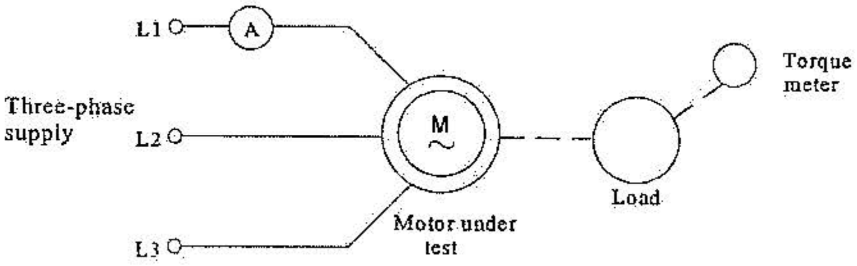
To measure the starting current and starting torque of a three-phase squirrel cage motor when connected in star and delta, then to connect, operate and fault find the starter.

Equipment

- three-phase 50 Hz power supply
- three-phase squirrel cage induction motor
- suitable load with attached torque meter
- ammeter - clip on type
- timer
- thermal overload
- stop/start push button station
- connection leads.

Procedure - starting conditions

1. Connect up the circuit as shown in the diagram below.



Note: The motor under test is to be connected in star.

2. Set the motor and load up for the locked rotor condition.

   Note: The teacher will tell you how this condition can be set up on your equipment.

   Perform the following measurements as quickly as possible.

3. Turn on the three-phase supply, record voltage then start the motor and measure and record the starting line current and starting torque as quickly as possible.

   Test voltage = ________ V

   Starting line current = ________ A

   Starting torque = ________ Nm.

4. Turn off the three-phase supply.

5. Do not proceed until the teacher has checked your work.

6. Reconnect the motor under test to delta.

7. Turn on the three-phase supply record voltage and measure and note the starting line current and starting torque as quickly as possible.

Test voltage = ____________ V

Starting line current = ____________ A

Starting torque = ____________ Nm.

8. Turn off the three-phase supply.

9. Do not proceed until the teacher has checked your work.

10. Adjust the locked rotor measurements to rated values by calculation.

$I \propto V \qquad T \propto V^2$

Star connection
Starting current = ____________ x ____________ = ____________ A

Starting torque = ____________ x ____________ = ____________ Nm

Delta connection
Starting current = ____________ x ____________ = ____________ A

Starting torque = ____________ x ____________ = ____________ Nm

11. Determine the ratio of DOL starting current (delta connection) to starting current when star connected.

$\frac{I\ \Delta}{I\ Star}$ = ____________ =

12. Determine the ratio of DOL starting torque (delta connection) to starting torque when star connected.

$\frac{T\ \Delta}{T\ Star}$ = ____________ =

13. Finalise this part of the skill practice by answering the following questions.

(a) The theoretical ratio of the current in delta to the current in star is 3 to 1. Compare the values you obtained to this theoretical value.

____

____

(b) The theoretical ratio of torque in delta to torque in star is 3:1. Compare the values you obtained to this theoretical value.

(c) A local supply authority has placed a limit on starting current to (3.5 x $I_{F/L}$) + 15A. A motor has a full load current of 50 A, and a DOL starting current of 345 A. Would a star-delta starter be able to limit the current of the requirements of the supply authority? Support you answer with simple calculations.

Procedure - connection and operation

1. Sketch a star-delta motor starter power and control circuit. The circuit must contain 3 contactors, one timer, one stop/start push button station and thermal overloads.

Sketched circuit diagram

2. Connect up the circuit using the start/stop push button station, contactor, thermal overload and motor. Do not proceed until the teacher has checked your work.

3. Test run your circuit ensuring the stop/start station pushbuttons and thermal overload operates correctly.

4. Do not proceed until the teacher has checked your work.

Procedure - fault finding

In the following exercises you are to test motor circuits for various faults. The motor circuits will have only one fault at any one time. The teacher will provide the faults as you require them.

1. Carry out each test and record the results in the table below.

MOTOR STARTER FAULTS

Test	*Test equipment used to find fault*	*Test equipment indication or reading*	*Fault*
1			
2			
3			
4			

2. Ask the teacher to check your work.

3. Finalise this section of the skill practice by completing the following observations.

For each of the fault conditions give a brief explanation of the repairs needed to make the star-delta starter operate satisfactorily.

Fault 1 ______________________________

____

____

Fault 2 ______________________________

____

____

Fault 3 ______________________________

____

____

Fault 4 ______________________________

____

____

Review questions

These questions will help you revise what you have learnt in Section 5.

1. State the effect on starting current (line) if a three-phase squirrel cage induction motor is started by:

   (a) Star-delta starter

   (b) Primary resistance starter

   (c) Auto-transformer starter (65% tapping)

2. State the effect on starting torque if a three-phase squirrel cage induction motor is started by:

   (a) Star-delta starter

   (b) Primary resistance starter

   (c) Auto-transformer starter (65% tapping)

3. List **three** advantages and disadvantages of a star-delta starter.

Advantages	Disadvantages
____________________	____________________
____________________	____________________
____________________	____________________

4. List **three** advantages and disadvantages of a primary resistance starter:

Advantages	Disadvantages
____________________	____________________
____________________	____________________
____________________	____________________

5. List **three** advantages and disadvantages of an auto-transformer starter.

Advantages	Disadvantages
____________________	____________________
____________________	____________________
____________________	

6. Describe **two** applications of a three-phase induction motor, if it is started by a:

(a) Star-delta starter

- ____
- ____

(b) Primary resistance starter

- ____
- ____

(c) Auto-transformer starter

- ▪ ____
- ▪ ____

7. An advantage of using the `closed transition' method of connection of an auto transformer starter is: *(tick the correct box)*

☐ the motor may be started with load
☐ less sparking occurs at the contacts
☐ it has good torque/current performance
☐ it allows the motor to run up to speed without a break in the supply.

8. Liquid resistance used in a primary resistance starter exhibit a: *(tick the correct box)*

☐ NTC characteristic
☐ PTC characteristic
☐ ZTC characteristic
☐ a constant tone characteristic.

9. For star-delta starting, the number of terminals required at the induction motor terminal block is: *(tick the correct box)*

☐ 2
☐ 3
☐ 4
☐ 6.

10. During the starting sequence of a star-delta starter, the voltage applied to each phase of the stator of the motor is: *(tick the correct box)*

☐ 3 times the line voltage
☐ equal to the line voltage
☐ 1/3 times the line voltage
☐ $\frac{1}{\sqrt{3}}$ times the line voltage.

Review questions

11. In a primary resistance starter, the starting resistors are connected: *(tick the correct box)*

☐ in series with the stator windings
☐ in series with the rotor windings
☐ in parallel with the stator windings
☐ in parallel with the rotor windings.

12. During the starting sequence of an induction motor, using a primary resistance starter, the: *(tick the correct box)*

☐ starter resistance is gradually increased
☐ starter resistance is gradually decreased
☐ rotor resistance is gradually increased
☐ rotor resistance is gradually decreased.

13. When starting a three-phase motor using a star-delta starter, the starting torque, when compared to the DOL value, is approximately: *(tick the correct box)*

☐ 33%
☐ 57%
☐ equal
☐ 3 times.

14. When starting a three-phase motor using a star-delta starter, the starting current, when compared to the DOL value in delta, is approximately: *(tick the correct box)*

☐ 60%
☐ 36%
☐ 33%
☐ 30%.

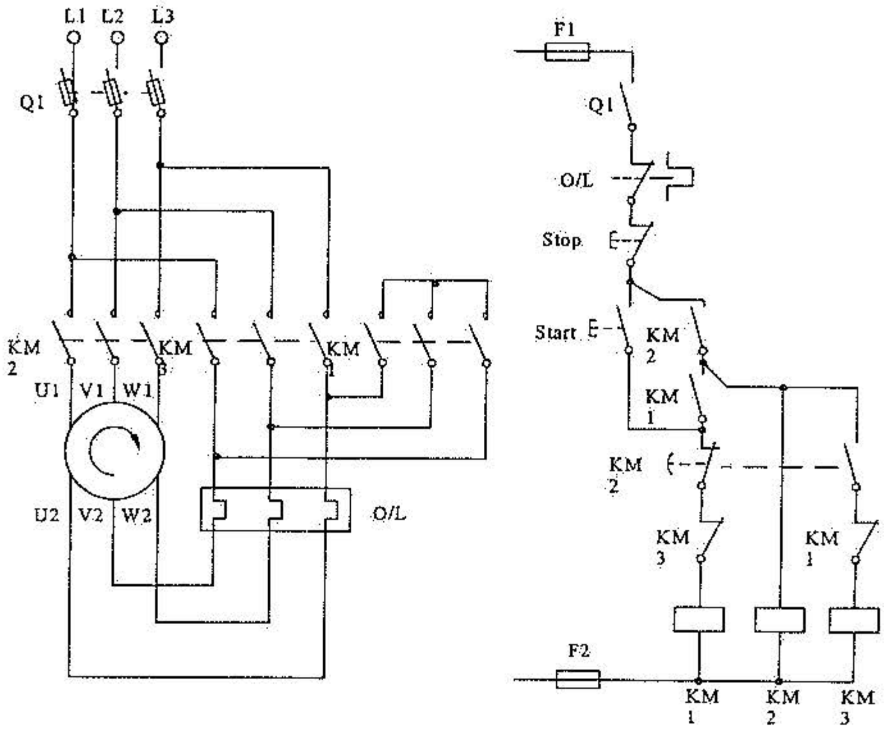
15. A disadvantage of primary resistance starting is: *(tick the correct box)*

☐ it is small and compact
☐ it is the most expensive type of starter
☐ it can only be started on low loads
☐ it is wasteful of power.

16. An advantage of using an auto-transformer starter is that it: *(tick the correct box)*

- ☐ may be used on high inertia loads
- ☐ is small and compact
- ☐ is simple in construction
- ☐ is very economical in capital cost.

With reference to the following circuit of a star-delta starter, complete questions 17, 18 and 19.



17. How many contacts do the KM1 and KM3 coils control? *(tick the correct box)*

- ☐ 4 and 4 respectively
- ☐ 5 and 5 respectively
- ☐ 4 and 5 respectively
- ☐ 5 and 4 respectively.

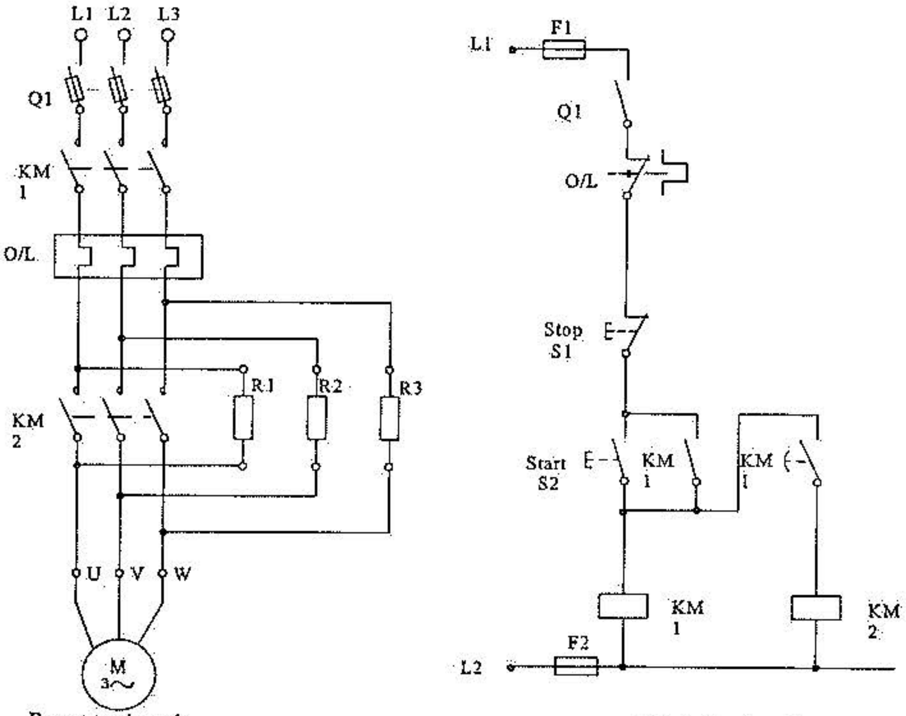
18. If the time delay contact KM2 does not operate the motor will: *(tick the correct box)*

- ☐ stop
- ☐ stay in star configuration
- ☐ change to delta and stop
- ☐ stop start continuously.

19. The purpose of the KM3 contact in series with the KM1 coil is termed a/an: *(tick the correct box)*

- ☐ interlock contact
- ☐ isolating contact
- ☐ latching contact
- ☐ lockable contact.

Questions 20, 21 and 22 refer to the primary resistance starter, shown below.



Power circuit

Control circuit

20. When switch S2 is closed: *(tick the correct box)*

- ☐ coils KM1 and KM2 energise simultaneously
- ☐ coil KM2 energises first
- ☐ coil KM1 energises first
- ☐ has no effect.

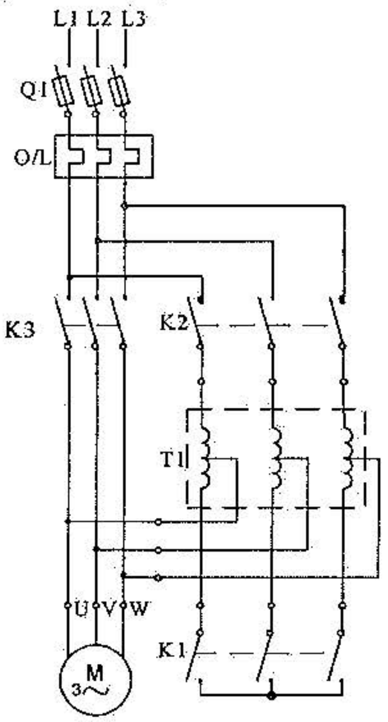
21. Using a sequence of events technique, the next step after the time delay contact KM1 closes is: *(tick the correct box)*

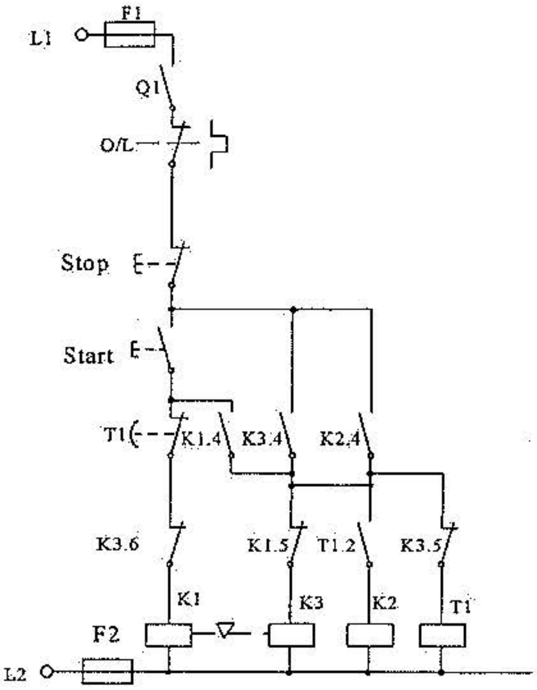
- ☐ coil KM2 energises
- ☐ coil KM2 de-energises
- ☐ coil KM1 de-energises
- ☐ contacts KM1 open.

22. The purpose the KM2 contacts in the power circuit is to: *(tick the correct box)*

- ☐ start the motor
- ☐ stop the motor
- ☐ short circuit the resistors
- ☐ protect the motor from overload.

Questions 23, 24 and 25 refer to circuit of an auto-transformer starter shown below.





23. The triangle symbol between coils K1 and K3 represents: *(tick the correct box)*

- ☐ a temperature sensor
- ☐ a pressure switch
- ☐ a pneumatic timer
- ☐ a mechanical interlock.

24. Using a sequence of events technique, the second coil which energises is: *(tick the correct box)*

- ☐ K1
- ☐ K2
- ☐ K3
- ☐ T1.

25. Refer to the diagram. What will happen if the K1.5 contact connected in series with the coil K3 fails to operate? The motor will: *(tick the correct box)*

- ☐ stop
- ☐ run with reduced torque
- ☐ run with increased torque
- ☐ cycle on/off.

Section 6: Electronic ("soft start") starters and secondary resistance starters

SUGGESTED DURATION	PREAMBLE
4 hours	To introduce the principle of operation of the electronic soft start motor starter and the operating principle, connection method and fault finding techniques for the secondary resistance motor starter.

This section covers part of the learning outcome 3 of the National Module Descriptor.

Objectives

At the end of this section you should be able to:

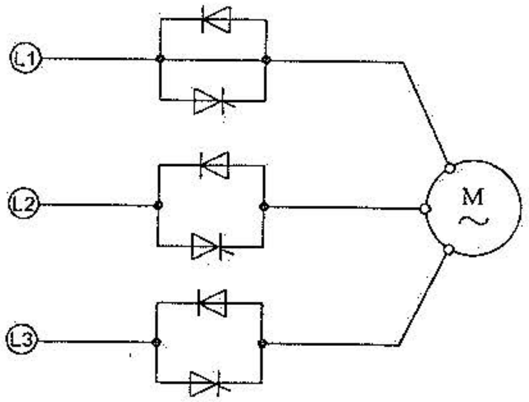
- ☐ describe the operating principles of the electronic (soft) starter and the secondary resistance starter
- ☐ list the effects of these starters on line current, motor current and motor torque
- ☐ list the advantages and disadvantages of these starters
- ☐ state common applications for each starter
- ☐ connect the secondary resistance starter power and control circuit for correct operation
- ☐ carry out fault finding on a secondary resistance starter power and control circuits.

Reduced voltage AC motor starters

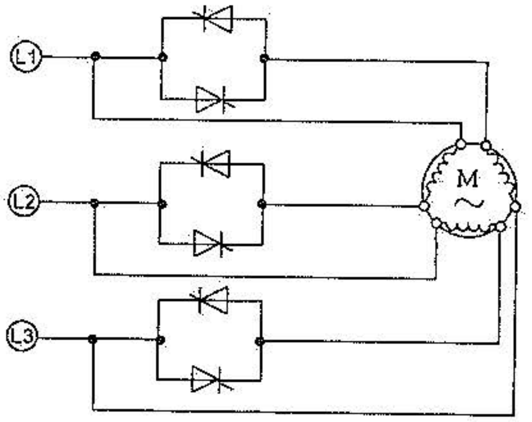
Electronic (soft) starters

This type of starter uses an electronic switching technique that changes the waveshape that is connected to the motor terminals during the start period. The waveshape change varies the rms voltage which affects the starting current and torque.

The power circuit, in simple form, for two types of electronic soft starters are shown below.



Three-phase half wave controller



Three-phase full wave controller

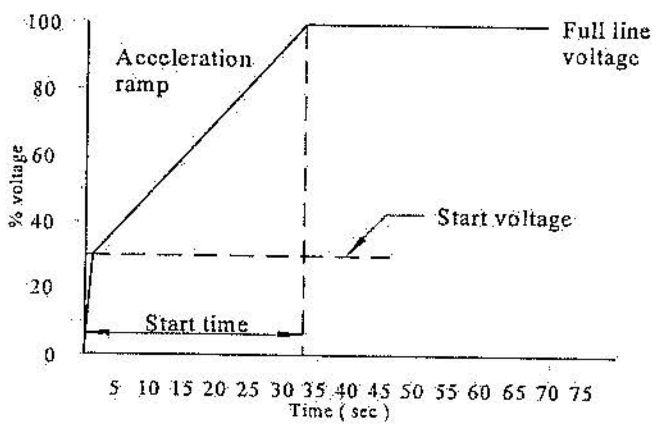
Features of the electronic soft starter:

Electronic soft starters have the following features.

- The use of solid state components eliminates contact wear.
- Motor protection is normally included for overcurrent, overvoltage, undervoltage, phase failure and phase reversal.
- The half wave controller can be used with motors having typical ratings between 7.5 and 285 kW.
- The full wave controller can also be used with motors above 285 kW.
- They provide for a variety of start sequences to effect smooth (stepless) acceleration with optimal current and torque features.
- Acceleration (ramp) time and deceleration can be set at the time of installation.
- Adjustable current (current limit)

Examples of ramp times

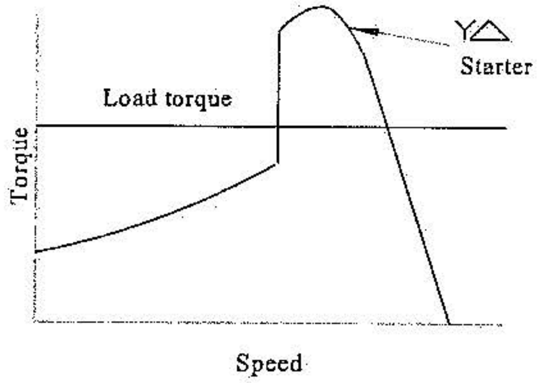
Low inertia load - short ramp time



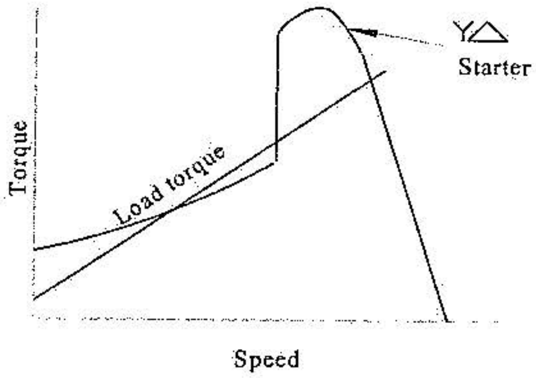
Student exercise 4

For each of the load and motor characteristics conditions given in the following diagrams briefly explain what would occur to the motor during the starting period.

(a)



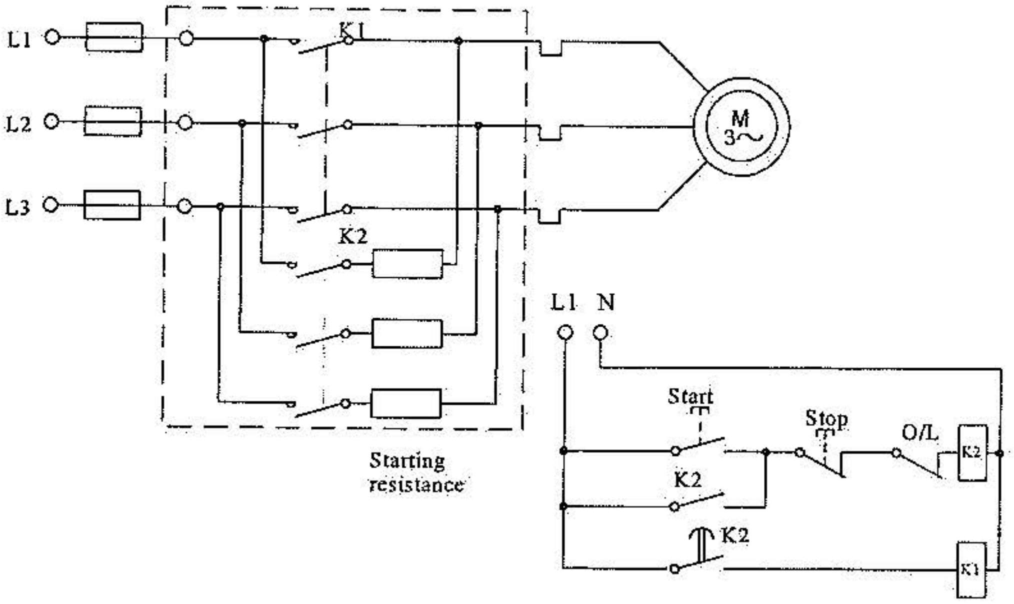
(b)



The primary resistance starter

This starter has resistance added to the motor circuit at start which reduces the motor terminal voltage. During the starting period the resistance is automatically reduced in one or more steps until rated voltage is connected to the motor.

The power and control circuits for a primary resistance starter are shown below. Other circuit arrangements are possible.



Power circuit

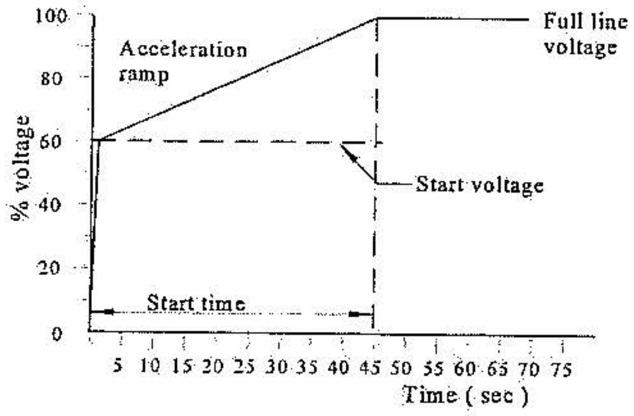
Control circuit

Features of the primary resistance starter are:

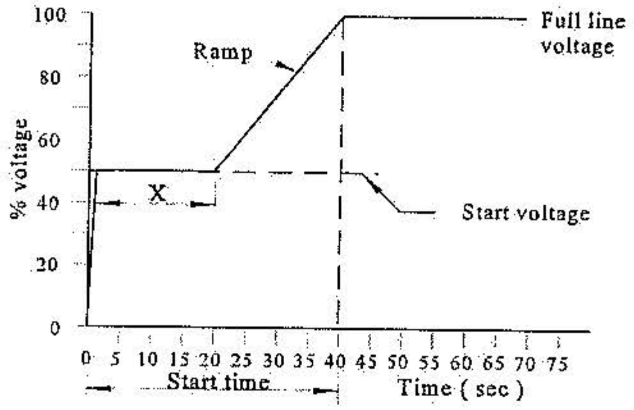
Primary resistance starters have the following features.

- the motor is permanently connected in either star or delta
- the resistance added to the motor circuit is disconnected in stages that best match the motor electrical conditions to the load performance requirements
- the resistors are generally wire wound for small rated motors and cast iron grids for large motors
- the resistance can be a liquid which provides for a more even acceleration during starting because of the negative temperature coefficient of resistance of the electrolyte.
- the starting current and torque are dependent on the motor terminal voltage which depends on the difference between the supply voltage and the voltage drop across the starting resistance.

High inertia load - long ramp time

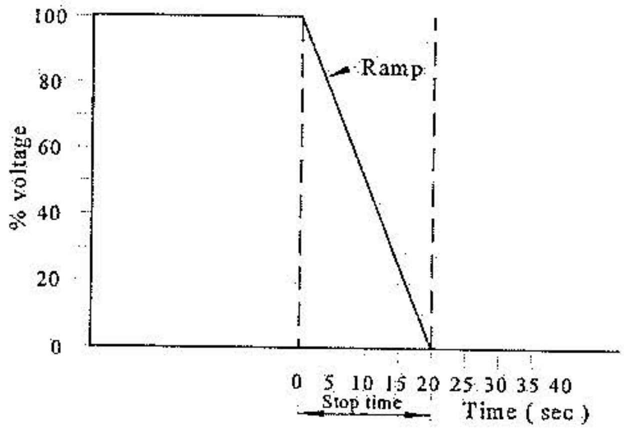


High inertia load - tri slope ramp



This arrangement provides for a fixed period (X) of starting voltage which gives reasonable starting torque while maintaining relatively low starting current during the initial period of acceleration.

Adjustable deceleration - soft stop



This arrangement allows the motor to decelerate over a period of time. The feature is used in applications such as fluid pumping where fluid hammer needs to be minimised.

Student exercise 1

On the axis below draw a graph that represents the starting sequence of a soft starter having the following specification.

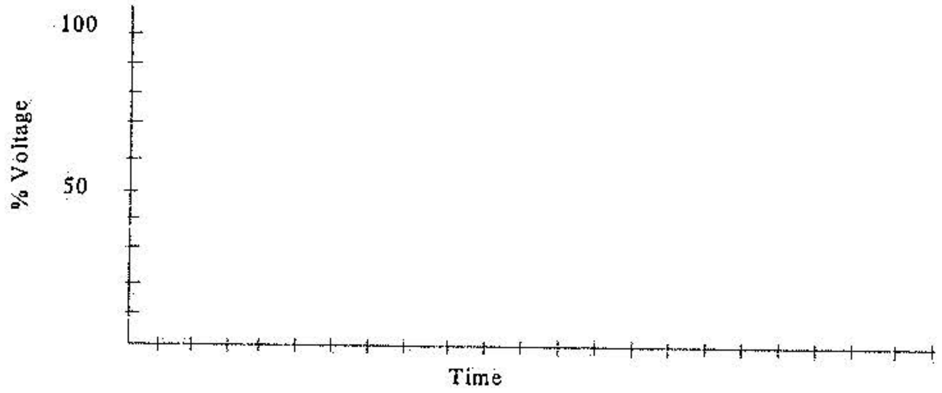
Start voltage = 45% of full line voltage

Acceleration time to full speed = 25 seconds

Run time = 10 minutes

Stop time = 15 seconds

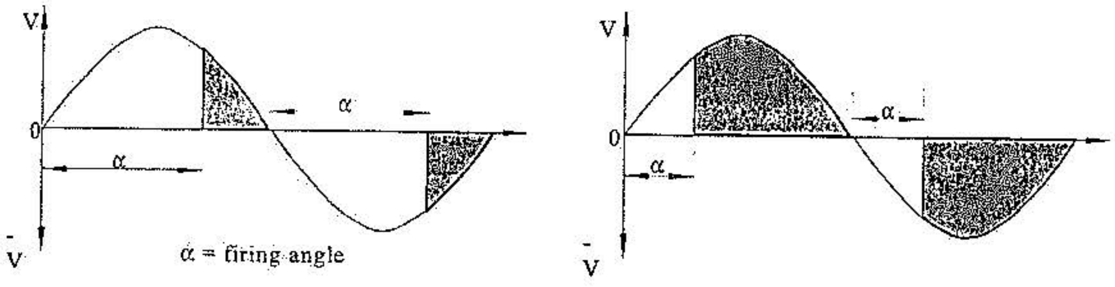
On the graph, highlight each period showing the time taken and the sequence occurring during that interval.



Switching

The voltage connected to the motor changes due to the switching sequence of the supply to the motor during each cycle of the supply. This is achieved using silicon controlled rectifiers and is known as phase angle switching. This technique changes the supply waveshape from sinusoidal to non sinusoidal which causes voltage variation.

The drawing below shows different phase angles for switching. The shaded areas indicate the period in each cycle when energy is being delivered to the load.



Phase control

Advantages and disadvantages of electronic (soft) starters

Advantages

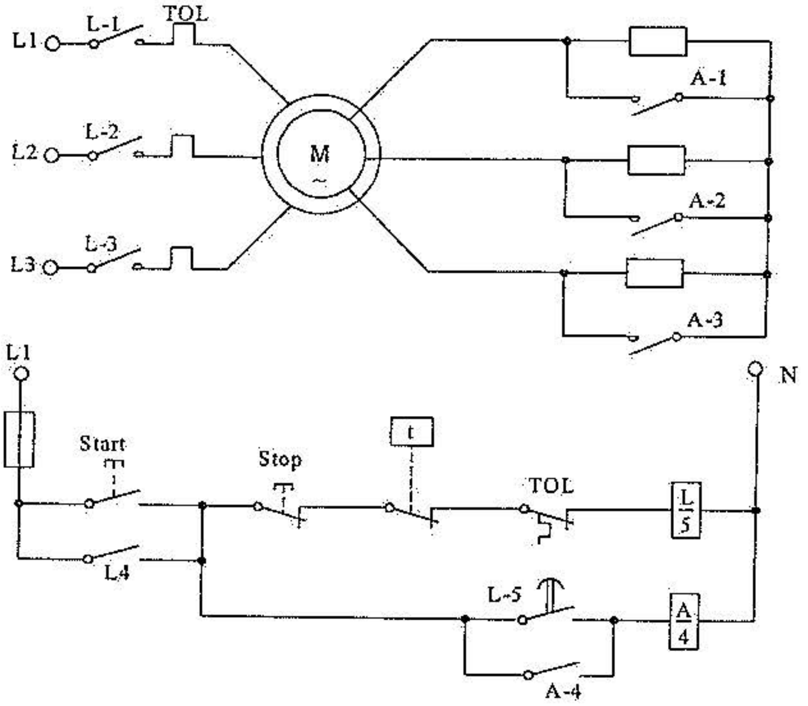
- maximum torque is maintained during starting
- speed control is available
- low starting current during starting

Disadvantages

- increased cost of installation
- suitable only for squirrel cage motors.

Secondary resistance starters

These type of starters are only used with slip ring (wound rotor) induction motors where external resistance is connected to the rotor circuit via a set of slip rings, during the starting period. The power and control circuit are shown below. Other circuit arrangements are possible.



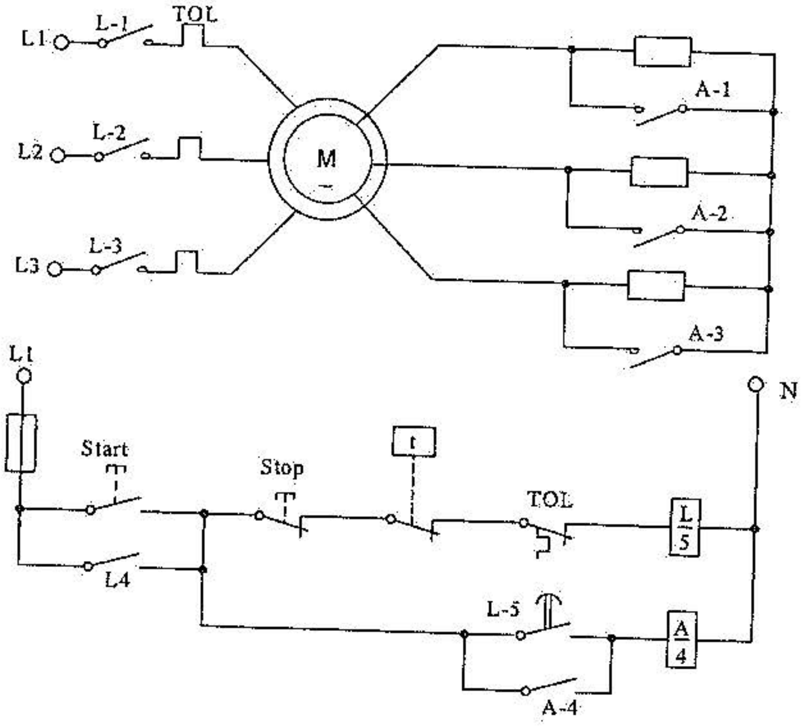
Features of secondary resistance starters

Secondary resistance starters have the following features.

- The motor must have a wound rotor.
- The wound rotor is star connected.
- The rotor winding is connected via brushes and slip rings to terminals which provide for connection to the external circuit.
- Starting resistance can be metallic (wire wound, cast iron grids or stainless steel grid) or liquid (electrolyte).
- The number of starting steps depends on the load characteristic.

Student exercise 2

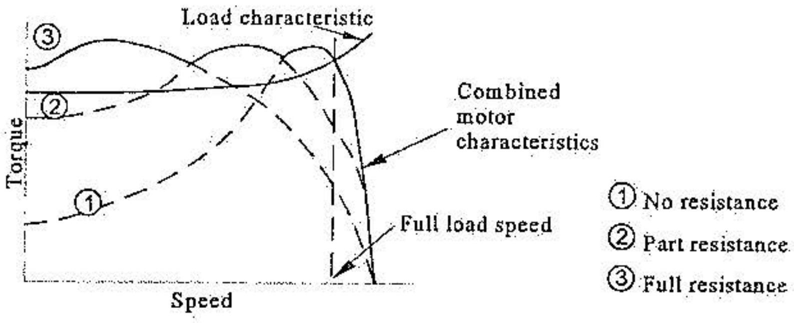
Using the following diagrams briefly explain the sequence of operation of the starter to bring the motor up to speed.



Motor and load torque and speed relationship

Secondary resistance starters are generally used when maximum motor torque is required during the start up period.

Maximum motor torque occurs when the rotor reactance equals the rotor resistance. Rotor reactance decreases with speed hence the total pre determined value of resistance is connected to the rotor at start and is reduced in steps to maintain approximately equal reactance to resistance proportionality. The diagram below shows a three step starter torque speed characteristic.



Wound rotor motor and load characteristics

Advantages and disadvantages of secondary resistance starters

Advantages

- maximum torque is maintained during the entire starting process
- line current can be maintained at approximately twice full load
- speed control is available
- optimum current/torque relationship, ie. low starting current, high starting torque
- liquid resistance starters provide for relative smooth acceleration due to the negative temperature effect on the electrolyte resistance.

Disadvantages

- increased cost of installation
- only suitable to one type of motor (wound rotor)

Applications of secondary resistance starters

As maximum torque is developed at start, high inertia loads are suited to this type of motor. Examples are material handling plant (conveyors), large flywheel type loads, large air conditioning fan motors, ball and crusher mills, feed pumps.

Skill practice SP7 Secondary resistance starter

Task

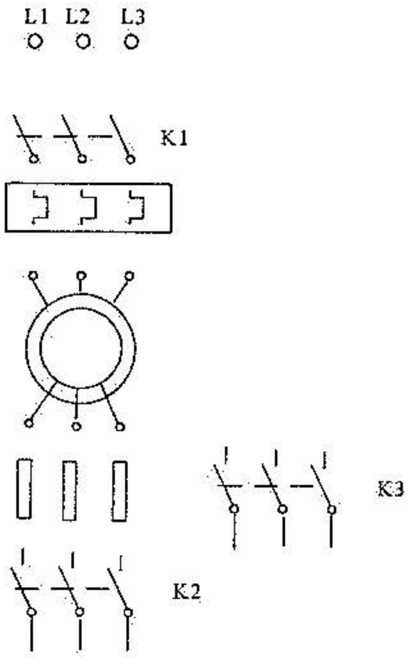
To draw the circuit diagram of a secondary resistance starter, connect and run the starter and find the cause of introduced faults in the starter.

Equipment

- three-phase supply
- fuses
- three-phase contactors
- start stop station
- overload
- motor terminal block (or motor)
- control circuit with faults
- meters
- starting resistors.

Procedure - connection and operation

1. Complete the following diagram by drawing the power circuit connections between the equipment items identified. Then design and draw your own control circuit diagram in the grid provided.



2. Connect the circuit using the equipment provided.

3. Test run your circuit, ensuring the start/stop station pushbuttons and the thermal overload operates correctly and the starting sequence is correct.

4. Do not proceed until the teacher has checked your work.

Skill practice SP8
fault finding

In the following exercises you are to test motor circuits for various faults. The motor circuits will have only one fault at any one time. The teacher will provide the faults as you require them.

1. Carry out each test and record the results in the table below.

MOTOR STARTER FAULTS

Test	*Test equipment used to find fault*	*Test equipment indication or reading*	*Fault*
1			
2			
3			

2. Ask the teacher to check your work.

3. Finalise this section of the skill practice by completing the following observations.

   For each of the fault conditions give a brief explanation of the repairs needed to make the secondary resistance starter operate satisfactorily.

   (a) Test 1 ______________________________

   ____

   ____

   (b) Test 2 ______________________________

   ____

   ____

   (c) Test 3 ______________________________

   ____

   ____

Review questions

These questions will help you revise what you have learnt in Section 6.

1. Name **two** common types of electronic starters.

   - ____________________
   - ____________________

2. List **three** advantages and **two** disadvantages of electronic starters.

   - ____________________
   - ____________________
   - ____________________
   - ____________________
   - ____________________

3. What type of AC induction motor is used with secondary resistance starters?

   ____

4. What is the effect on line current and motor torque if secondary resistance starting is used?

   ____

   ____

5. List **two** advantage and **two** disadvantages of the secondary resistance starter.

   - ____________________
   - ____________________
   - ____________________
   - ____________________

6. List an application for the use of both electronic starters and secondary resistance starters.

7. Most soft starters provide: *(tick the correct box)*

☐ adjustable starting voltage and fixed starting time
☐ fixed starting voltage and fixed starting time
☐ adjustable starting voltage and adjustable starting time
☐ fixed starting voltage and adjustable starting time.

8. The most practical soft starter circuit used to start a squirrel cage induction motor over 300 kW would be a: *(tick the correct box)*

☐ fully controlled AC controller
☐ half control AC controller
☐ fully controlled rectifier
☐ half controlled rectifier.

9. Describe how soft starters limit starting current.

10. Soft starters can provide deceleration of the motor. This would most commonly be used in: *(tick the correct box)*

☐ pumping applications
☐ cooling fan applications
☐ machine tools applications
☐ traction drives.

Review questions

11. A disadvantage of electronic starters is they: *(tick the correct box)*

- ☐ are large and bulky
- ☐ only work with particular motors
- ☐ must be started on reduced load
- ☐ produce radio frequency interference.

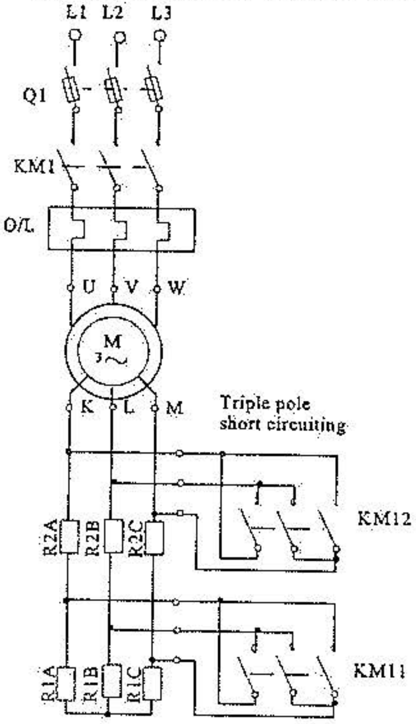
12. The main features of the secondary resistance starter are: *(tick the correct box)*

- ☐ low line current and high torque at start
- ☐ high line current and high torque at start
- ☐ low line current and low torque at start
- ☐ high line current and low torque at start.

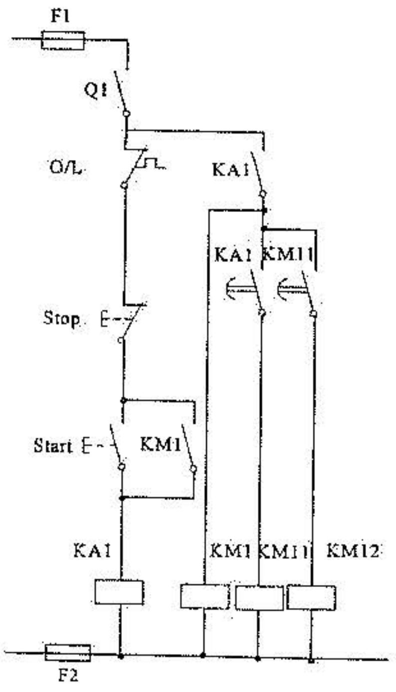
13. The typical application area for a secondary resistance starter is: *(tick the correct box)*

- ☐ low inertia loads
- ☐ no load at start
- ☐ high inertia loads
- ☐ none of the above.

For Questions 14, 15 and 16 refer to the circuit of the secondary resistance starter shown below.



Power circuit



Control circuit

14. How many steps are there in the power circuit starting sequence in this starter? *(tick the correct box)*

    - ☐ 2
    - ☐ 3
    - ☐ 4
    - ☐ 5.

15. Using a sequence of events approach, the second coil which energises is: *(tick the correct box)*

    - ☐ KM1
    - ☐ KM11
    - ☐ KM12
    - ☐ KA1.

16. Using a sequence of events approach, what will happen in the control circuit if the KM1 contact in parallel with the start button fails to close? *(tick the correct box)*

    - ☐ no effect on control circuit
    - ☐ coils KM11 and KM12 cannot operate
    - ☐ coil KA1 will drop out when the start button is released
    - ☐ coil KA1 de-energises, coils KM1, KM11 and KM12 remain energised.

Notes

Section 7: Braking and rotation reversal of three-phase induction motors

SUGGESTED DURATION	PREAMBLE
4 hours	Identify the features of the various motor braking methods and connect motor braking circuits.

This section covers part of the learning outcome 4 of the National Module Descriptor.

Objectives

At the end of this section successful students will be able to:

- ☐ list the types of braking used for three-phase AC induction motors
- ☐ describe the operating principle of the braking methods used for three-phase AC induction motors
- ☐ list the advantages and disadvantages of the braking methods used
- ☐ describe the principles of reversal of rotation of three-phase induction motors
- ☐ connect a circuit with a braking feature to operate a three-phase motor.

Braking and reversal of rotation of induction motors

Braking

To stop, retard or brake the rotation of the rotor of an induction motor requires an alteration in the relationship between the rotor direction of rotation and the rotating magnetic field that causes motor action, and the removal of the stored kinetic energy that exists in the mass of the rotor and load.

This can be achieved by turning off the supply which removes the rotating magnetic field, allowing the motor to gradually slow until it stops, or by applying one of the following braking methods.

Plug braking

Plugging is achieved by reversing the direction of the stator rotating magnetic field (RMF) by disconnecting the supply and swapping any two phases of the supply, then reconnecting the supply to the motor.

A speed sensitive switch is used to detect zero speed which disconnects the supply when the rotor comes to rest. This eliminates rotor direction reversal.

Line current may become excessive during plugging and can be reduced by incorporating resistors in the plug control circuit.

Advantages and disadvantages of plug braking

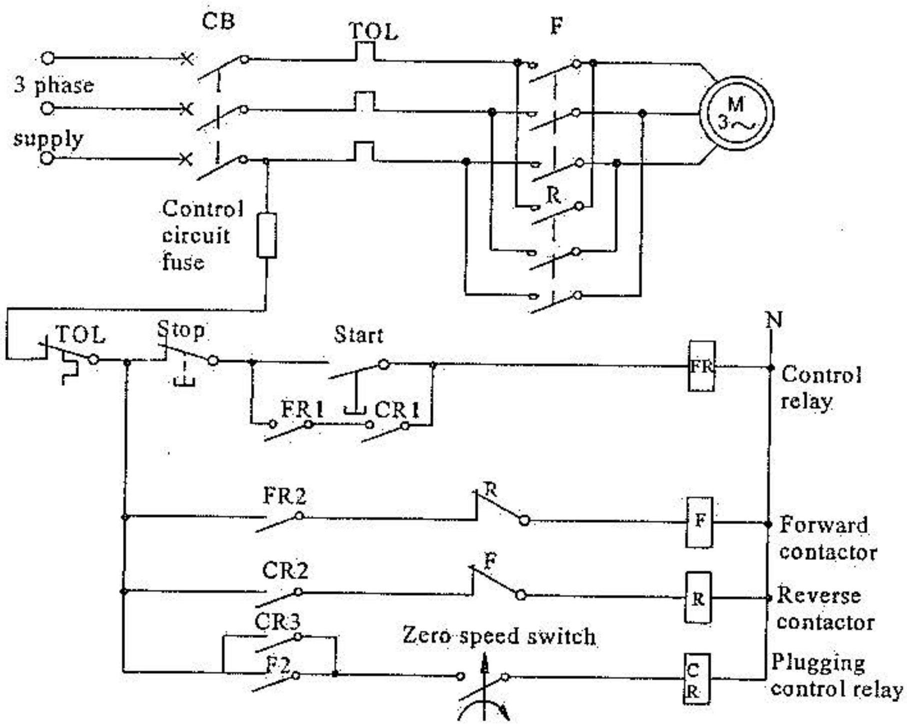
Plug braking has the following advantages:

- high braking force maintained down to zero speed
- low cost
- simple circuit to implement
- reliable
- fast in operation
- no mechanical wear.

Plug braking has the following disadvantages:

- zero speed switching is difficult to achieve, so other forms of braking are often required to completely stop the motor
- the motor and the motor/load coupling need to be of a robust nature
- external mechanical brakes are required to prevent creeping
- excessive current unless braking resistance is used.

The typical circuit for plug braking is shown in the diagram.



Student exercise 1

Using the above diagram explain the operation of the following circuit components.

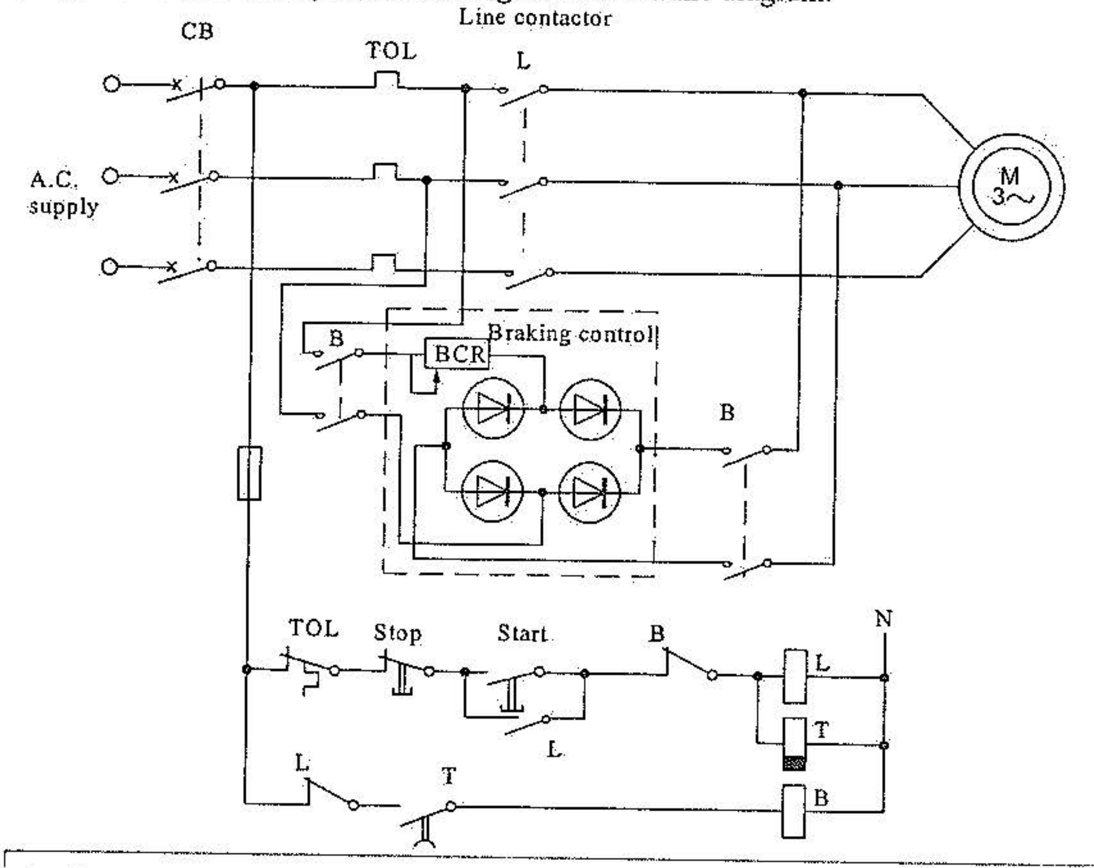
- plugging control relay

- zero speed switch

Dynamic braking

Dynamic braking is achieved by disconnecting the AC supply to the motor stator and connecting a DC supply.

A typical circuit with dynamic braking is shown in the diagram.



Student exercise 2

Using the above diagram explain the operation of the following circuit components:

Timer: ______________________________

____

Braking contactor: ______________________________

____

Advantages and disadvantages of dynamic braking

Dynamic braking has the following advantages:

- braking effort is controlled by the magnitude of the DC current injected into the stator
- braking of the motor is fully achieved by DC injection
- circuit is simple in design
- cost is low
- motor does not reverse after stopping.

Dynamic braking has the following disadvantages:

- two types of voltage sources are required for the same circuit
- external mechanical brakes are required to fully stop the motor and prevent creeping
- the DC supply should be disconnected to reduce excessive stator heating, when the motor is fully stopped.

Regenerative braking

Regenerative braking is a means of reducing the speed of a motor by returning energy to the supply and thus loading the motor.

Advantages and disadvantages of regenerative braking

Regenerative braking has the following advantages

- no extra control circuit is required
- energy is returned to the source ie. energy recovery system.
- can be used to control over speed.

Regenerative braking has the following disadvantage

- it cannot be used to stop a motor.

Eddy current braking

Eddy current brakes have electromagnets, supplied by direct current that are mounted on the motor shaft, with a stationary metal drum mounted around the electromagnets.

When DC is supplied to the electromagnets, eddy currents are induced into the stationary drum which will produce a retarding torque on the rotating electromagnet, causing braking to occur.

Brake control is through the DC supply and can be increased or decreased with the use of a potentiometer. If the DC is increased, the braking effort is increased.

Advantages and disadvantages of eddy current braking

Eddy current braking has the following advantages:

- no mechanical wear
- good control over braking effort

Eddy current braking has the following disadvantage

- high initial cost of braking unit
- external mechanical brakes are required to prevent creeping.

Mechanical braking

To decrease and control the time required to bring the rotor to a stationary condition a mechanical brake may be used to quickly dissipate the kinetic energy as heat through friction in the brake pads or linings.

Advantages and disadvantages of mechanical braking

Mechanical braking has the following advantages

- it can provide fail-safe operation ie. the brake is released when the motor is switched on and is automatically applied when the motor is switched off or loses power
- low cost
- controls not complex
- can slow down motors
- can stop motors and prevent creeping.

Mechanical braking has the following disadvantages
- high level of maintenance required
- on-going expense of brake linings.

Reversal of direction of three-phase motors

To reverse the direction of rotation of a three-phase motor the direction of rotation of the rotating magnetic field is reversed. This is achieved by changing the phase sequence to the stator windings by interchanging any two of the three supply lines. Contactors are normally used to provide automatic reversal.

Skill practice SP9: AC motor braking

Task

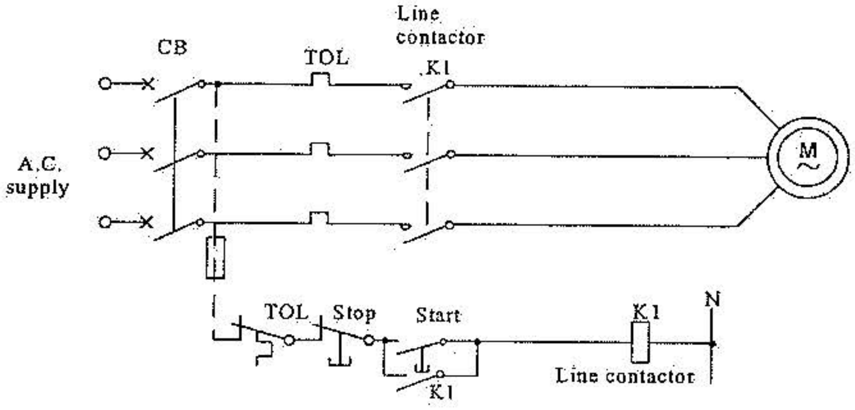
To measure the braking time of plug braking and dynamic braking circuits.

Equipment

- three-phase 50 Hz power supply
- three-phase squirrel cage induction motor
- inertia load
- contactors - 2 off
- relays - 2 off
- stop/start push button station
- thermal overload
- zero speed switch
- dynamic braking unit (DC supply)
- braking resistors - 3 off
- timer
- stop watch
- ammeter - analogue type
- connection leads.

Procedure

1. Connect the circuit as shown in the diagram below.



Note: The motor should be connected to the load at this stage.

2. Do not proceed until your teacher has checked your work.

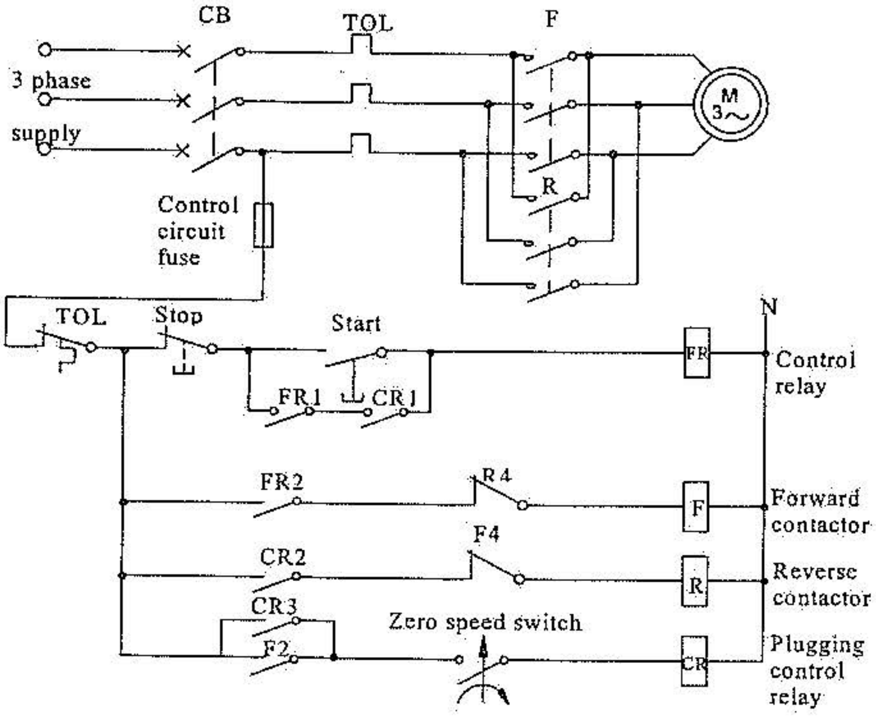
3. Start the motor and allow it to reach its normal operating speed.

4. Stop the motor, measure the time from when you push the stop button until when the motor comes to a standstill. Record values in the table of results.

TABLE OF RESULTS: BRAKING TIME

Braking method used	*Starting Current*	*Breaking time*	*Breaking current*
No braking			
Plug braking			
Plug braking with resistors			
Dynamic braking minium current			
Dynamic braking maximum current			

5. Connect the plug braking circuit (without resistors) as shown in the diagram below.



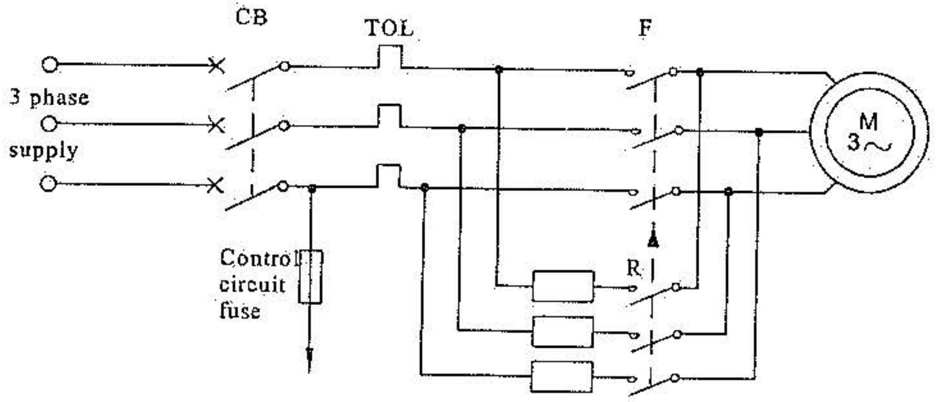
6. Do not proceed until your teacher has checked your work.

7. Start the motor, measure and record the starting current. Allow the motor to reach its normal operating speed.

8. Stop the motor, measure and record the breaking current and the time from when you pushed the stop button until when the motor comes to a standstill. Record values in the table of results.

9. Do not proceed until your teacher has checked your work.

10. Modify your plug braking power circuit by inserting the braking resistors as shown in the diagram below.



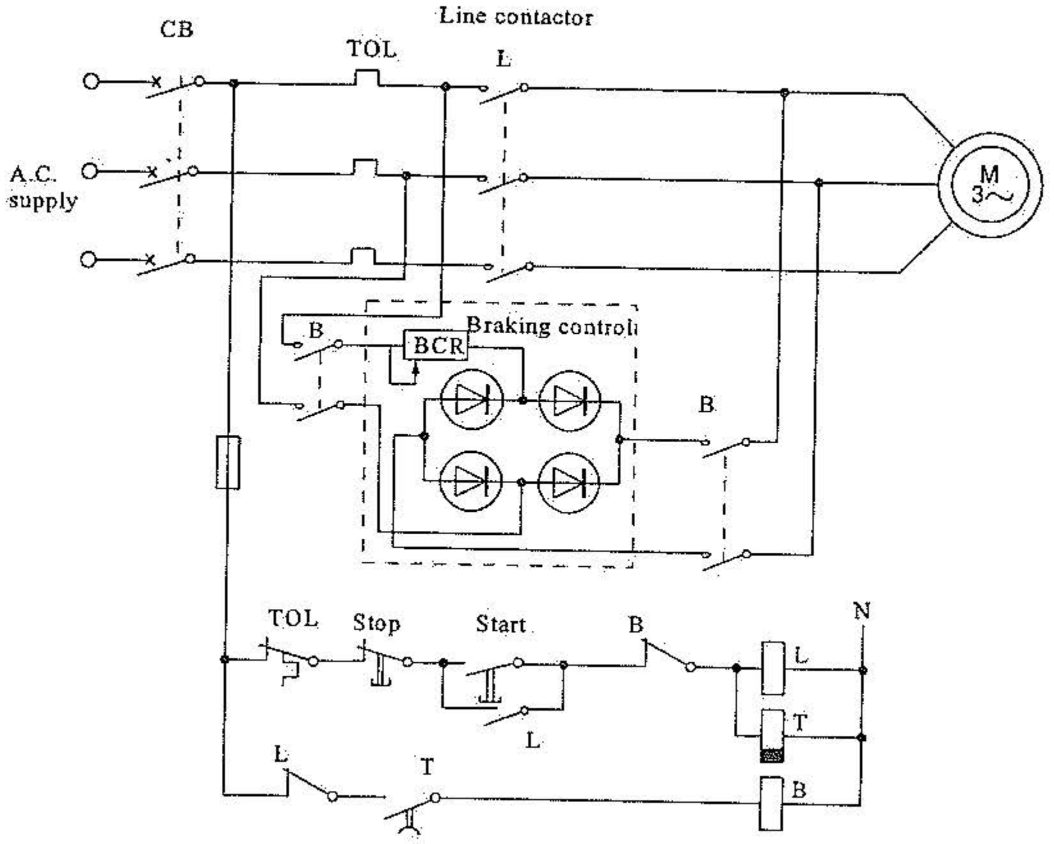
Note: The teacher will advise you on the actual size of the resistors to use.

11. Do not proceed until your teacher has checked your work.

12. Start the motor, measure and record the starting current and allow it to reach full speed.

13. Stop the motor and note and record the peak braking current and the stopping time in the table of results.

14. Connect the dynamic braking circuit as shown in the diagram below.



15. Do not proceed until your teacher has checked your work.

16. Set the dynamic braking unit to the *minimum* current setting.

17. Start the motor, measure and record the starting current and allow the motor to reach full speed.

18. Stop the motor, measure and record the peak braking current and braking time and record the values in the table of results.

19. Adjust the dynamic braking unit to the *maximum* current setting.

20. Start the motor again, measure and record the starting current and allow it to reach full speed.

21. Stop the motor, measure and record the peak braking current and braking time and record the values in the table of results.

22. Do not proceed until your teacher has checked your results.

23. Complete the skill practice by completing the following observations and calculations.

    (a) From the table of results calculate the percentage decrease in braking time for each braking method: Record your answer in the table below.

    $$\% \text{ reduction} = \frac{t_0 - t_b}{t_0} \times \frac{100}{1}$$

    Where t_0 = time to stop with no braking

    Where t_b = braking time in seconds.

Braking method	*% reduction*
Plug braking	
Plug braking with resistors	
Dynamic braking minium current	
Dynamic braking maximum current	

    From the results in the above table, which braking method brings the motor to zero speed in the shortest time?

    (b) When plug braking, what is the purpose of using the resistors?

(c) When plug braking, the initial braking current measured is higher than the full load current. Calculate the % of braking current to full load current.

without plug braking resistors, $\frac{I\ braking}{I_{F/L}} \times \frac{100}{1} =$ ____________________

with plug braking resistors, $\frac{I\ braking}{I_{F/L}} \times \frac{100}{1} =$ ____________________

(c) Briefly explain why the plug braking current is greater than the starting current.

____

____

(d) When dynamic braking, what is the effect on the stopping time of increasing the DC current.

____

Review questions

These questions will help you revise what you have learnt in Section 7.

1. List the methods used in braking a three-phase induction motor.

2. Why are resistors often incorporated into the power circuit when plug braking is employed?

3. When a three-phase induction motor is being braked using dynamic braking, what type of voltage is applied to the stator windings?

4. List **two** advantages and **two** disadvantages of the following types of braking.

(a) Plug braking

Advantages: (1) ____________________ (2) ____________________

Disadvantages: (1) ____________________ (2) ____________________

(b) Dynamic braking

Advantages: (1) ____________________ (2) ____________________

Disadvantages: (1) ____________________ (2) ____________________

(c) Regenerative braking

Advantages: (1) ____________________ (2) ____________________

Disadvantages: (1) ____________________ (2) ____________________

(d) Mechanical braking

Advantages: (1) ____________________ (2) ____________________

Disadvantages: (1) ____________________ (2) ____________________

5. What is fail-safe braking?

____

____

6. How is creeping prevented or limited?

____

____

7. Describe how the direction of rotation of a three-phase induction motor is reversed.

____

____

____

8. A speed sensitive switch is used in plug braking circuits to: *(tick the correct box)*

☐ relay information to the operator
☐ indicate the speed of the rotor
☐ operate controls to disconnect the motor supply
☐ detect when the motor is at zero speed.

9. The initial braking current in plug braking is approximately equal to: *(tick the correct box)*

☐ DOL starting current
☐ full load current
☐ twice full load current
☐ more than DOL starting current.

10. The method of braking that returns power to the mains supply is known as: *(tick the correct box)*

☐ dynamic braking
☐ regenerative braking
☐ plug braking
☐ electro-mechanical braking.

11. Fail-safe braking is where: *(tick the correct box)*

☐ an operator is present at all times while the machine is used
☐ an automatic mechanical braking function occurs to protect against loss of supply
☐ two switches must be closed in unison to prevent inadvertent braking
☐ the brake is energised when the power is on.

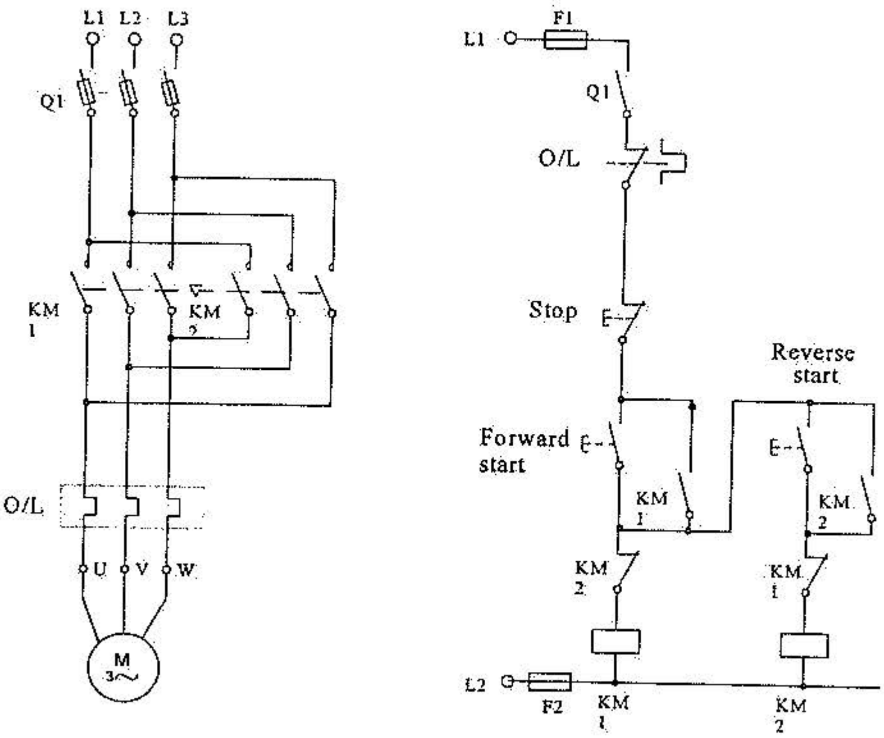
12. To reverse the rotation of a three-phase induction motor: *(tick the correct box)*

☐ swap all the supply lines to the motor
☐ reverse one winding in the stator
☐ reverse two windings in the stator
☐ swap two of the supply lines to the motor.

13. A disadvantage of dynamic braking is: *(tick the correct box)*

☐ it may only be used with an overhauling load
☐ braking of the motor is uncontrollable
☐ two types of voltage supply are required
☐ it is expensive to install on large motors.

To answer Questions 14, 15 and 16 refer to the following circuit of a reversing motor power and control circuit.



14. What phases/lines are being swapped in the motor supply: *(tick the correct box)*

☐ L1 and L2
☐ L1 and L3
☐ L2 and L3
☐ L1, L2 and L3.

15. The triangle symbol between contacts KM1 and KM2 in the power circuit represents: *(tick the correct box)*

☐ a mechanical interlock
☐ an electric interlock
☐ a pneumatic interlock
☐ a flexible coupling.

16. Using a sequence of events approach, if coil KM1 is energised, what happens in the control circuit if the reverse start push button is operated: *(tick the correct box)*

☐ coil KM2 energises
☐ coil KM1 de-energises
☐ no effect on control circuit
☐ coil KM1 de-energises and coil KM2 energises.

Notes

Section 8: Three-phase induction motor operation - load conditions

SUGGESTED DURATION	PREAMBLE
4 hours	To understand the behaviour of three-phase induction motors under load and to identify speed control methods for three-phase AC motors from their circuit arrangements and connect a controller to a motor and confirm that it operates as intended.

This section covers part of the learning outcomes 3 and 4 of the National Module Descriptor.

Objectives

At the end of this section successful students will be able to:

- ☐ describe the behaviour of a three-phase induction motor under load, based on the speed-torque characteristics of the motor and the load
- ☐ list the common types of speed control methods used on three-phase induction motors
- ☐ describe the operating principles of pole changing, variable voltage/variable frequency drives and secondary resistance speed control
- ☐ list common applications for each speed control method
- ☐ connect and run a speed controller with a motor.

Speed control of three-phase induction motors

The actual speed of an induction motor is the difference between the synchronous speed and the slip speed.

Speed control can be effected by:
- varying the synchronous speed
- varying the supply frequency
- varying the slip speed.

Actual speed = synchronous speed - slip speed

Hence

$$\text{Actual speed} = \frac{120f}{p} - slip\ speed\ rpm$$

From the equation it can be determined that:
- actual speed is approximately proportional to supply frequency
- actual speed is approximately inversely proportional to the number of magnetic poles
- actual speed decreases as slip speed increases.

Pole changing

This technique adopts the approach of varying the synchronous speed to change the actual speed. Two methods are generally used, these are:
- two separate stator windings providing the mechanism for producing a different number of poles
- one winding that can be connected to produce a consequent pole effect. Consequent poles are produced by changing current direction in half of the pole coils. This changes all of the main poles to the same polarity and artificial poles are formed between the main poles. Therefore the rotor speed will be approximately halved.

In addition to the general connections arrangement for both methods the windings can be tapped. With appropriate control mechanisms three characteristics for the various speeds can be achieved, these are:
- constant torque
- constant power
- variable torque.

Variable frequency

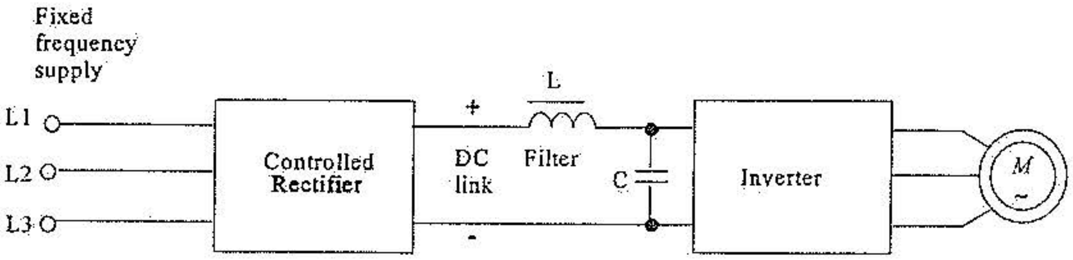
This technique adopts the approach of varying the frequency applied to the motor to vary the actual speed. To maintain the electrical condition a change in supply voltage also is required to compensate for the change in the stator winding impedance which results from frequency change.

Motors operated at low rotor speed often require separate force draught cooling due to loss of normal cooling.

VF drive circuit configurations

Three common configurations are used for obtaining the variable voltage, variable frequency supply to the motor.

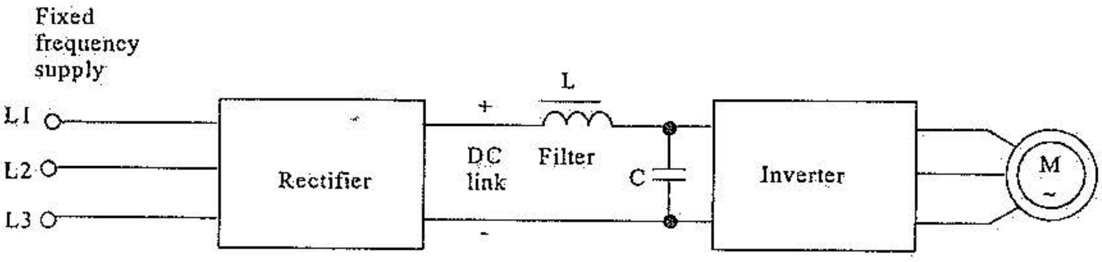
- Controlled rectifier/inverter



PAM control

  - controlled rectifier provides voltage control (variable voltage)
  - inverter provides frequency control (variable frequency)

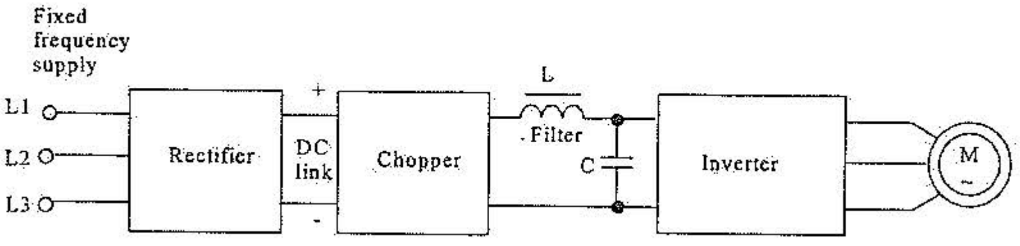
- Rectifier/inverter



PWM control

  - rectifier provides DC
  - inverter provides voltage and frequency control

- Rectifier/chopper/inverter



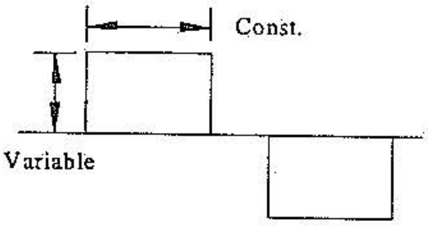
PAM control

  - rectifier provides DC supply to chopper
  - chopper (DC to DC converter) provides voltage control
  - inverter provides frequency control

Waveforms

The output voltage waveform from the inverter can be either pulse amplitude modulation (PAM) or pulse width modulation (PWM) control.

PAM control



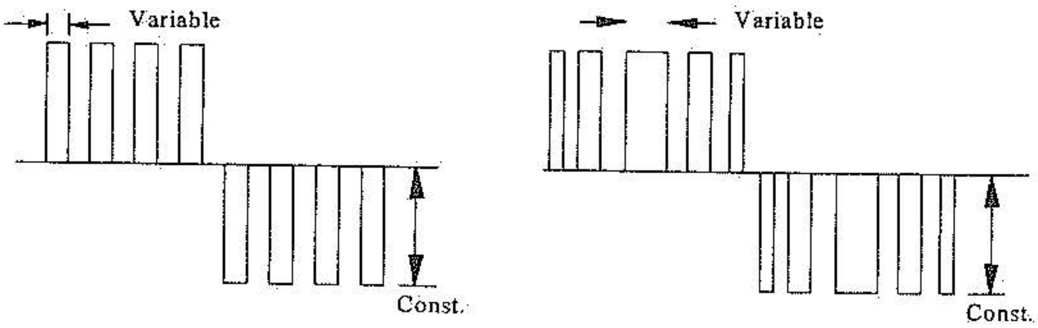
Advantages

- Good speed holding with varying loads ≤ 0.5% without feedback
- good starting and running torque
- low harmonics
- switching on the output available eg. for parallel motors
- quiet motor running
- able to control the current limit

Disadvantages

- more expensive unit - complex power circuit
- less than mains voltage at 50 Hz.

PWM control



PWM symmetrical wave *PWM sine-coded wave*

Advantages

- simple power circuitry
- cheaper to manufacture

Disadvantages

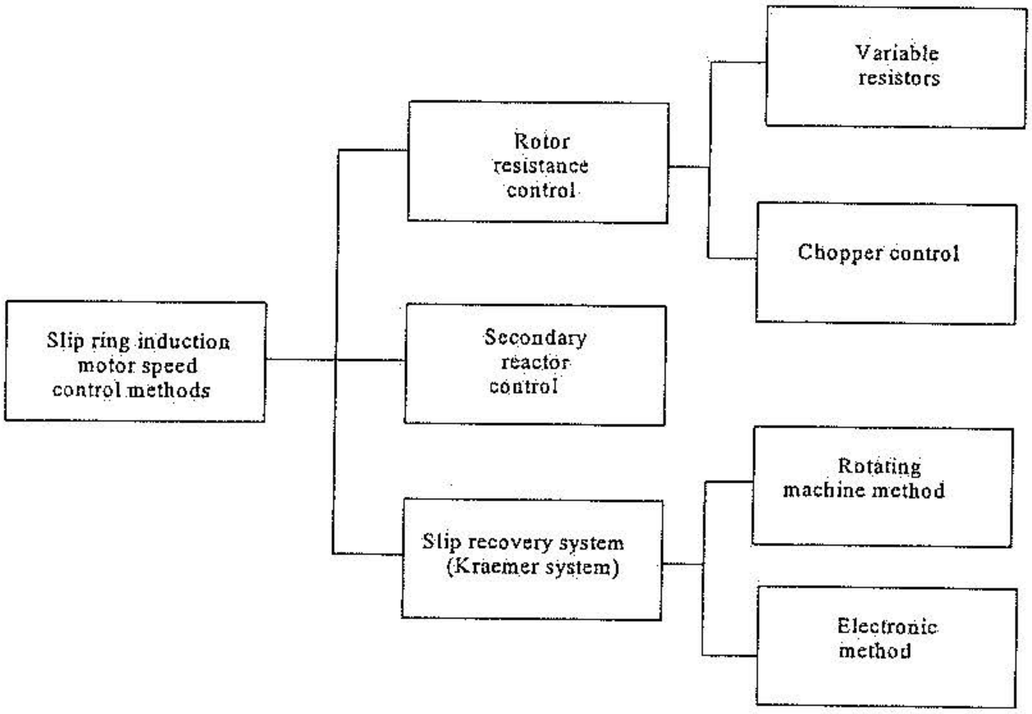
- Less than mains voltage on output at 50 Hz unless 3rd harmonic is introduced.
- High motor magnetising noise
- Unable to switch on the output
- Motor must be derated because of output wave shape
- Poor starting torque
- Must have controlled acceleration.

Applications of VF drives

- Textile industry - winder spinning machines and knitting machines
- Machine tools - milling machines, grinders, drilling machines and lathes
- Food industry - packaging machines, packing machines, conveyors and mixers
- Glass industry - drawing, blowers and grinders
- Woodworking machines - routers and sawing machines
- Metal working industry - table rollers, slitters and winding machines
- Chemical industry - pumps, fans and film winders
- Transport - conveyor, trucks and travelling hoists.

Motor slip control - varying rotor impedance

This technique adopts the approach of varying the slip speed. This can only be achieved with slip ring induction motors where the rotor connections are accessible. The different types are shown below.



Note: Only the variable resistor type will be covered in this module.

Variable resistor control

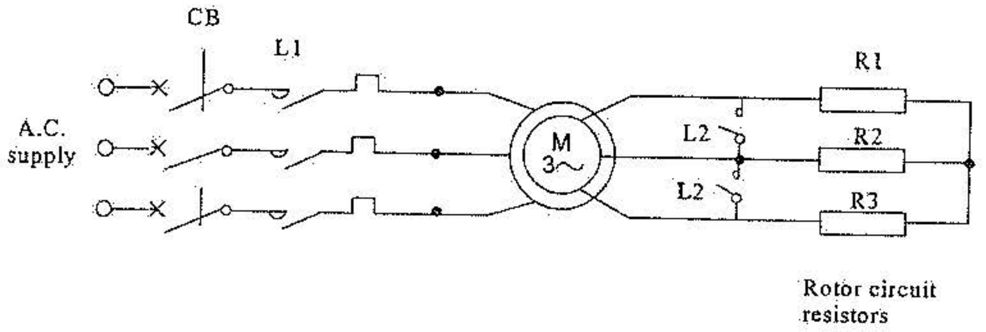
The resistors used to control the speed of a slip ring induction motor are normally the same resistors used to limit starting current and torque; provided the resistors are rated for constant use.

By adding resistance into the rotor circuit the speed will decrease and by removing resistance the speed will increase.

This method of speed control is inefficient and provides poor speed regulation but is effective.

Student exercise

The power circuit for a slip ring motor with rotor resistance added is shown. In the grid provided sketch the control circuit diagram which will provide for motor starting and speed control using the same rotor resistance.



Skill practice SP10: Squirrel cage induction motor speed control

Task

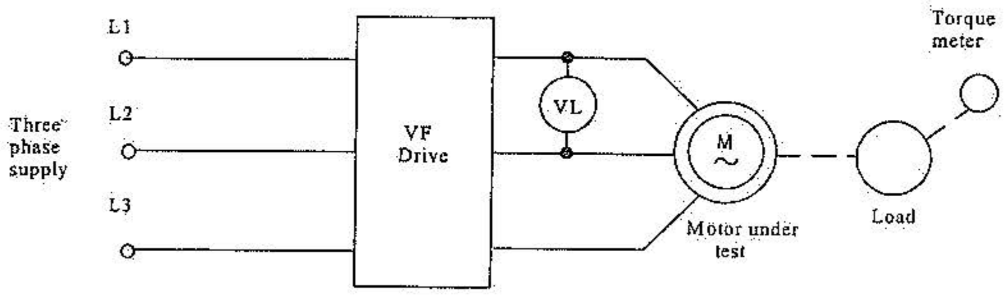
To examine the relationship of speed and frequency and line voltage and frequency when using variable frequency drives on no load and load conditions.

Equipment

- three-phase 50 Hz power supply
- three-phase squirrel cage induction motor
- suitable load with attached torque meter
- variable frequency drive to suit motor and supply
- voltmeter
- stop watch
- tachometer
- ammeter, clip-on type
- connection leads.

Procedure

1. Connect the circuit as shown the diagram below.



2. Do not proceed until your teacher has checked your work.

3. Operate the variable frequency drive to obtain the following.

   - Minimum speed: ____________ rpm.
   - Maximum speed: ____________ rpm.
   - Acceleration: ____________ seconds.
   - Deceleration: ____________ seconds.
   - Voltage boost: ____________ volts.

4. Without the load connected run the motor at a frequency of 5 Hz. Measure and record the motor speed and motor line voltage in the table below.

5. Repeat Step 4 using increasing values of frequency as shown in the table below.

6. For each step calculate the ratio of motor line voltage to frequency and record the values in the table below.

TABLE OF RESULTS

Frequency Hz	*Speed of motor rpm*	*Motor line voltage Volts*	*Voltage to frequency ratio*
5			
10			
15			
20			
25			
30			
35			
40			
45			
50			
55			
60			

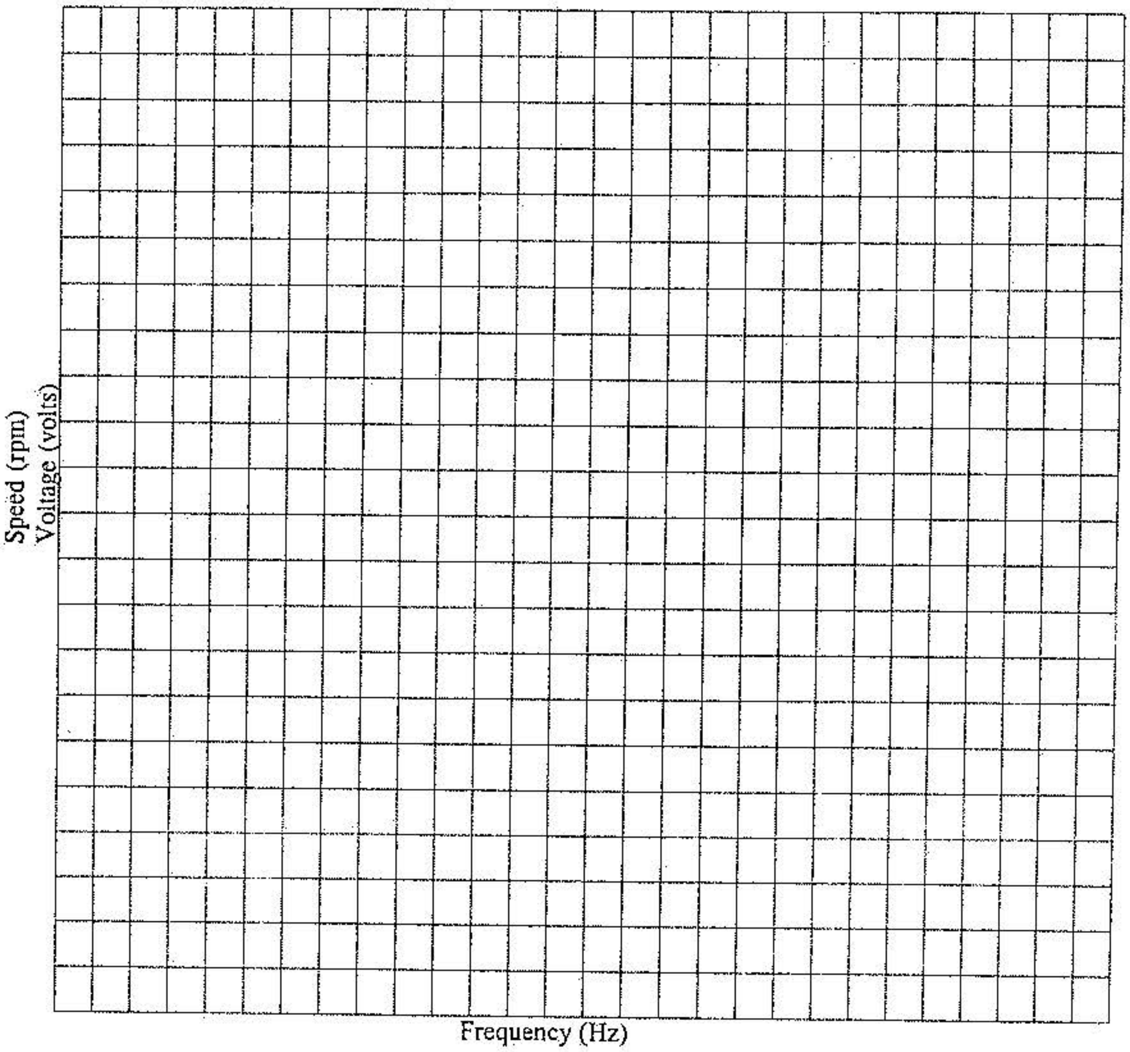
7. Connect the load.

8. Turn on the motor and adjust the frequency and load until the motor is operating at its rated speed (rpm) and a given value of load torque (Nm).

9. For each value of frequency shown in the table above measure and record the motor speed and line volts.

10. For each step calculate the ratio of motor line voltage to frequency and record in the table above.

11. On the grid plot the separate curves of speed and voltage against frequency for no load and load conditions.



12. Finalise the skill practice by making the following observations.

(a) From the graph determine the difference in motor speed for the no load and load conditions for the following frequencies.

Frequency Hz	*Speed difference rpm*
10	
20	
30	
40	
50	
60	

Explain the reason for any differences.

(b) Explain why there is a change in voltage for each corresponding change in frequency.

(c) Explain why the voltage to frequency ratio is higher above 50 Hz than it is below 50 Hz.

Review questions

These questions will help you revise what you have learnt in Section 8.

1. List **two** ways to change the speed of a squirrel cage induction motor.

   - ______________________________
   - ______________________________

2. What are consequent poles, and how are they created?

   ____

   ____

3. Name **two** types of electronic speed control methods which are available to control three-phase induction motors by changing the frequency.

   - ______________________________
   - ______________________________

4. How may the speed of a slip-ring induction motor be controlled?

   ____

   ____

5. List **two** applications where speed control is required.

   - ______________________________
   - ______________________________

6. List **two** advantages and **two** disadvantages of VF drive.

Advantages	*Disadvantage*
■ ____________________	■ ____________________
■ ____________________	■ ____________________

7. List **two** types of mechanical speed controllers used to control three-phase induction motors.

- ______________________________
- ______________________________

8. Using the consequent pole method of speed control, the speed may be varied to give: *(tick the correct box)*

☐ two speeds for a single wound motor
☐ four speeds for a single wound motor
☐ infinitely variable speeds
☐ gives a constant torque for any speed of the motor.

9. Speed control of induction motors by pole changing can be applied to: *(tick the correct box)*

☐ three-phase slip ring motors only
☐ single phase squirrel cage motors only
☐ three-phase squirrel cage motors only
☐ both three and single phase motors.

10. When using variable frequency electronic speed control, the voltage is: *(tick the correct box)*

☐ increased with frequency increase for all speeds
☐ increased with the frequency increase for speeds up to rated speed
☐ inversely varied as the frequency for all speeds
☐ inversely varied as the frequency for speeds up to rated speed.

11. If three-phase induction motor uses a variable frequency drive and usually runs at slow speeds, an additional precaution needed would be: *(tick the correct box)*

☐ separate force draught cooling
☐ undervoltage protection reduced to half
☐ by-passing the phase failure protection
☐ a second set of thermal overloads connected in series.

12. If additional resistance is placed in series with the rotor resistance of a wound rotor induction motor, the motor will: *(tick the correct box)*

☐ speed up to a higher speed
☐ slow down
☐ draw more line current
☐ have higher torque at a speed.

13. The control of voltage in a variable frequency drive can be achieved by a: *(tick the correct box)*

☐ rectifier circuit
☐ auto-transformer
☐ series inductor
☐ chopper.

14. If the supply voltage from the variable frequency drive supplying a three-phase induction motor is not reduced at lower frequencies the result would be: *(tick the correct box)*

☐ a decrease in speed
☐ air gap flux will be reduced
☐ motor overheating
☐ a increase in speed.

Notes

Section 9: Protection of three-phase induction motors

SUGGESTED DURATION	PREAMBLE
6 hours	To introduce the need for three-phase motor protection. To describe protective devices and the types of fault conditions that can develop in motor control circuits.

This section covers part of the learning outcome 2 of the National Module Descriptor.

Objectives

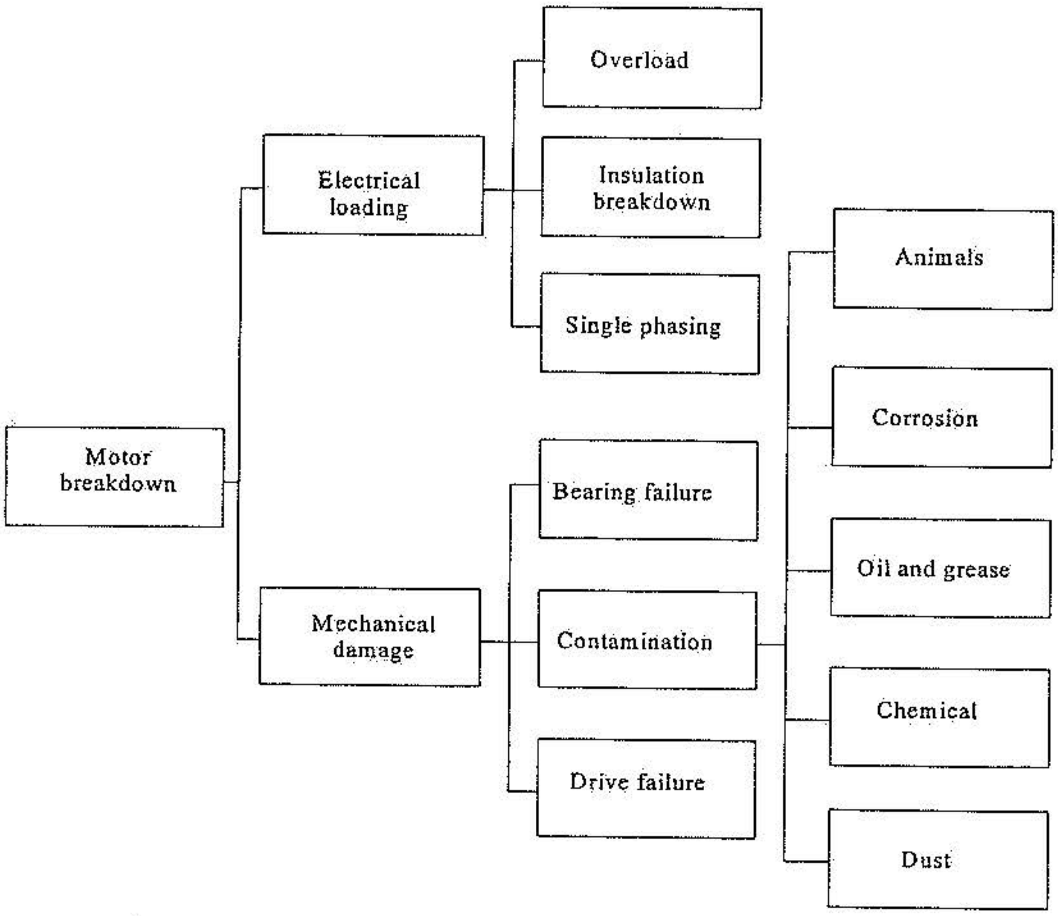
At the end of this section successful students will be able to:

- ☐ state the reasons why motor protection is required
- ☐ describe the types of motor overload protection
- ☐ describe the operating principle of thermal and magnetic motor protection devices
- ☐ describe the electrical features of motor protection fuses
- ☐ describe the effects of under voltage and over voltage on motor circuits
- ☐ state the effects of repetitive starting and /or reversing on motors
- ☐ state the special requirements for motor protection, in high humidity or moist environments, high temperature areas and corrosive atmospheres
- ☐ select a suitable protective device for a given motor and starter combination.

Protection

Motor protection is required to prevent motor windings becoming permanently stressed or damaged (burnt out). Damage is caused by adverse electrical or mechanical conditions and breakdown occurs.

Motor breakdown is typically due to electrical loading or mechanical damage as shown below.



Block diagram showing typical causes for electric motor breakdown

Irrespective of the cause of motor breakdown the effect is often a rise in the motor temperature due to an increase in motor current.

Excessive rise in motor phase current is due to one or more of the following:

- mechanical load is greater than its designed capacity
- rotor shaft becomes locked
- part loss of supply phase voltage (single phasing)
- reduction in supply phase voltages
- unbalanced supply phase voltages
- winding insulation breakdown

Protection devices

Protection devices installed in the electrical circuit must be capable of discriminating between normal operating conditions and conditions which may cause damage.

Protection devices are designed to either monitor short duration high current overload conditions or short circuits or long duration medium to low current overload conditions. Thermal and magnetic overloads, fuses and circuit breakes are used alone or in combinations to provide effective protection.

Thermal overload

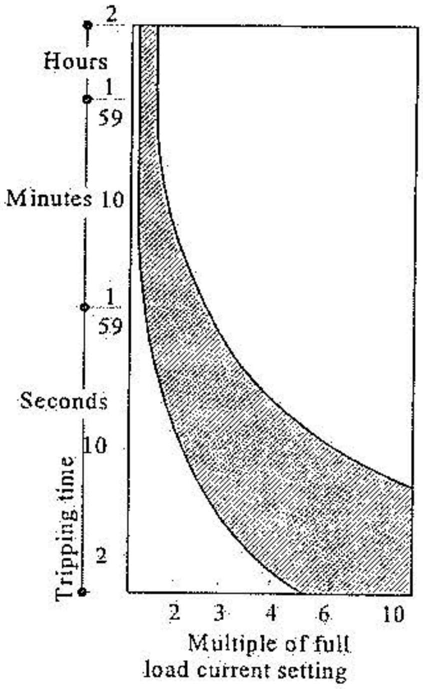
There are two common types of over temperature devices which both detect temperature change.

- devices that detect excessive line current directly control contacts and use bi-metal strips connected in the motor control circuit
- devices that directly detect winding temperature using PTC thermistors that are physically located in the motor winding.

Inverse time characteristics of overloads

Overload devices have a design feature that reduces the operating time when there is an increase in overload conditions.

The graph below illustrates a typical inverse time characteristic for a thermal overload device. Protection is provided against sustained overloads but the inherent characteristic prevents tripping on normal starting currents or harmless momentary overloads.



Applications for each type of overload

- bi-metal type for standard overload and stalled rotor conditions
- thermistor type for varying overloading conditions whilst operating, including varying ambient temperature, defective motor cooling and standard overload.

Setting and re-setting of overloads

- Only in-line overloads may be set.
- Correct settings must be made to specifications, otherwise:
  - motor may nuisance trip due to low setting

    or
  - motor may burn out due to high setting. This reason is very important for modern motors because as their design efficiency has increased, so has their operating temperature.

Student exercise 1

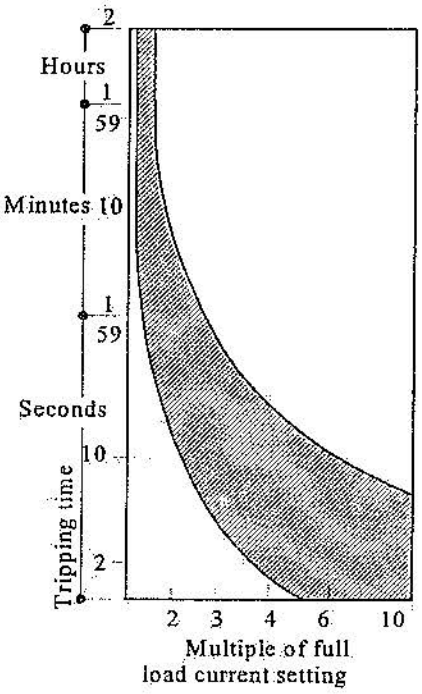
From the inverse time characteristic determine:

(a) the minimum and maximum times taken for the overload device to trip if the motor current increased to a constant value of twice its rated full load value.

Answer: ______________________

(b) the percentage overload that would cause the overload to operate in 10 seconds.

Answer: ______________________



Magnetic overloads

Magnetic overloads detect an increase in the magnetic field surrounding the motor supply conductors. These devices provide a quicker response time to high magnitudes of overload in current than thermal devices. They feature instantaneous trip characteristics. Well designed overloads normally have thermal and magnetic features.

Fuses and circuit breakers

In addition to providing protection for motors against excessive current overloads, fuses and circuit breakers also protect the motor and the control circuit equipment and wiring from damage due to short circuits.

In most cases fuses are of the high rupturing capacity (HRC) type and circuit breakers are the combination type.

HRC fuses on motors have the special characteristic that provides for normal operation during starting.

Other control and protection features

Isolation

The circuit between the motor supply and its associated control circuit must be capable of being isolated against electrical and machine operating hazards.

Isolation can be through a switch or a control device. In each case it must comply with AS 3000 requirements.

Undervoltage and overvoltage

Effects of undervoltage on control and motor circuits are:

- relays and contactors do not operate correctly
- sensing devices do not respond as required
- increased heating of motor because of increased current

Control features can be introduced to protect against these adverse effects.

Effects of overvoltage on control and motor circuits are:

- increased power consumption in control circuit
- sensing and controlling devices operating incorrectly
- increased motor heating due to increased iron losses.

Control features can be introduced to protect against these adverse effects.

Problems associated with repetitive starting and repetitive reversing

- increased heating of protective devices
- increase heating of the motor
- motor placed under extra stress
- control contacts, both power and auxiliary, have increased operations, thus lowering the life span
- coupling between motor and load is subjected to increased stress

Control features can be introduced to protect against these adverse effects.

Motor protection for equipment located in high humidity environments

Rules apply for the location of motor protection equipment located in high humidity environments. A knowledge of the rules is important for installation and design work.

Motor protection for motors located in corrosive atmospheres

There are two corrosive atmosphere areas, non-hazardous and hazardous.
If classed as a non-hazardous area, refer to the previous section on damp situation.
If classed as a hazardous area, refer to AS 3000.

Fault finding in three-phase motor installations

An electric motor may not operate due to a fault within the motor or a fault in the circuit supplying the motor. A fault in the load the motor is intended to drive, can also affect motor performance. Remember, a motor is a device that converts electrical energy to mechanical energy and therefore a mechanical fault will be reflected in the electrical circuit.

The general areas where faults in motors (and motor circuits) occur are:

- the supply (and controls) to the motor
- within the motor itself *and*
- in the load being driven by the motor.

Fault finding is a problem solving exercise and like all problems it must be clear what the problem is, if it is to be solved efficiently. The possible causes need to be investigated and appropriate action taken to eliminate the problem.

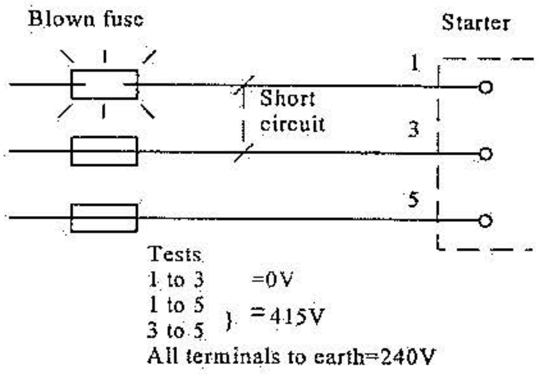
Following are typical problems encountered with three-phase motors, the possible causes of the problem and the action that should be taken in each case.

Motor circuit faults

Problem: Motor will not run, no noise from the motor.

Possible causes

(a) No supply to the motor due to circuit protection device operation (ie. fuse blown or circuit breaker tripped).



(b) No supply to motor due to overload tripped.

Action

- Place all motor control devices in the off position before resetting the circuit breaker or replacing the fuse. In the case of a fuse, test across adjacent fuse holder terminals to check that the wiring to the motor control device has not short circuited. Remember never replace fuses on a short circuit.
  In the case of a circuit breaker the same problem will be indicated if the breaker trips immediately it is reset. Both these cases indicate a short circuit in the wiring.
- Once the circuit protection device has been restored to normal, switch the motor on. If the circuit protection device operates further investigation is necessary.

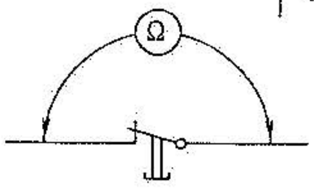
  Testing at the supply side of the starter could also reveal a short circuit in the wiring as shown in the diagram.
- Switch off the control devices for the motor.
- Reset the motor overload or allow the motor to cool.
- Switch on the motor. It may take some time for the motor overload to react to an overload condition so it is important to check the current of the motor although it may appear to run correctly.
- Use a tong (clip-on) ammeter to measure the current in each line and compare this to the current rating shown on the nameplate. The current should be balanced in each line.
- If the current is too high or the overload trips out, further investigation is necessary.

(c) Control circuit open.

1. - Check all control circuit stop buttons, overloads and stop devices to ensure they are in the closed (run) position. If overload is tripped refer to (b).
   - If a stop button is off, investigate further to make sure no person has attempted to isolate the motor without properly tagging the point of isolation. The location of some stop devices may not be immediately obvious. In these cases consult the location diagram for the equipment if this is available. Alternatively the person responsible for operating the equipment can often help with this information.

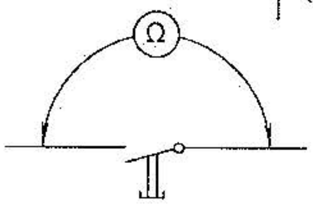
2. - If the stop devices are in the correct position, **isolate the circuit.**
   - Test the continuity across each control device in the normal and actuated position.

Position	Ω
run	0
stop	∞ (actuated)



Stop device, pushbutton or overload

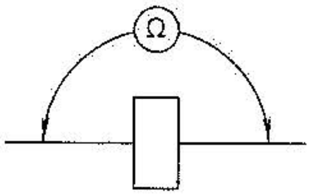
Position	Ω
run	0(actuated)
stop	∞ (actuated)



Start device, pushbutton or hold in contact

Note: It may be necessary to disconnect one side of the pushbotton for these tests.

Position	Ω
240V-415V	1KΩ to 5KΩ
24V	100Ω to 1KΩ



Contactor operating coil

If the test results are not those shown on the diagrams then the control device will need replacing.

- After replacement restore the supplies and test circuit operation.

Skill practice SP11: Thermal overload protection of induction motors

Task

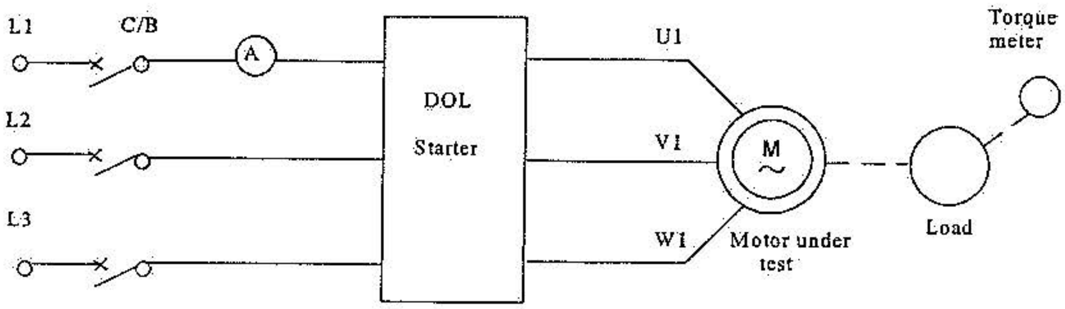
To correctly set a thermal overload to trip if the motor current is exceeded by a given percentage.

Equipment

- three-phase 50 Hz power supply
- three-phase squirrel cage induction motor
- suitable load with attached torque measuring device
- DOL starter complete with a suitable thermal overload to match motor
- ammeter - clip on type
- connection leads
- timing device.

Procedure

1. Connect the circuit as shown below.



2. Set the thermal overload
   - From the motor nameplate determine and record the full load current and full load torque. (calculations may be required)

     $I_{F/L}$ = ______________ A

     $T_{F/L}$ = ______________ Nm

   - Set the DOL motor starter thermal overload to the value of full load current determined above.

3. Do not proceed until your teacher has checked your work.

4. Calculate motor overload settings.
   - Using the value of the full load torque in step 2, calculate the torque produced by the motor for each of the overload conditions.

     150% overload = $T_{F/L}$ x 1.5 ______ x 1.5 = ______Nm
     200% overload = $T_{F/L}$ x 2.0 ______ x 2.0 = ______Nm
     250% overload = $T_{F/L}$ x 2.5 ______ x 2.5 = ______Nm

5. Measure overload tripping time

Note: Adjustments need to be made quickly.

- Start the motor and adjust the load to operate at overload setting as indicated by the torque measuring device. Measure the line current and the time it takes for the overload to trip. Record the results in the table below.
- Repeat the test for 200% and 250% overload settings.

Note: Allow time between each test for the thermal overload to cool down.

TABLE OF RESULTS

Load % of F/L	*Line current (Amperes)*	*Time to trip (Seconds)*
150%		
200%		
250%		

6. Do not proceed until your teacher has checked your work.

7. Complete the skill practice by completing the following observations and calculations.

   (a) The teacher will provide you with the thermal characteristics (inverse time/current graph) of the thermal overload used in your DOL starter. The following questions will refer to the inverse time/current graph provided.

   (b) For the line current recorded at 150% overload, what are the minimum and maximum tripping times allowed as shown by the characteristic?

   Minimum time: ____________________

   Maximum time: ____________________

   Did the tripping time you recorded fall into this range? *Circle:* Yes or No

   (c) For the line current recorded at 200% overload, what are the minimum and maximum tripping times allowed as shown by the characteristic?

   Minimum time: ____________________

   Maximum time: ____________________

   Did the tripping time you recorded fall into this range? *Circle:* Yes or No

(d) For the line current recorded at 250% overload, what are the minimum and maximum tripping times allowed as shown by the characteristic?

Minimum time: ____________________

Maximum time: ____________________

Did the tripping time you recorded fall into this range? *Circle*: Yes or No

(e) From the comparisons made above, did the thermal overload under test perform as shown in the characteristic provided. *Circle*: Yes or No

(f) If your answer was 'No' in the last question, describe what corrective action should be taken.

____

____

____

____

(g) Explain what is meant by the term 'inverse time characteristic'.

____

____

(h) Describe what would happen if the thermal overload setting was adjusted to low.

____

____

(i) Describe what would happen if the thermal overload setting was adjusted to high.

____

____

Review questions

These questions will help you revise what you have learnt in Section 9.

1. Name the **three** types of overload conditions that may occur within a motor circuit.

   - ______________________________
   - ______________________________
   - ______________________________

2. What operational circumstances create a short duration overload?

   ____

   ____

   ____

3. Name the **two** types of locked rotor overloads which may occur during operation of a three-phase induction motor.

   - ______________________________
   - ______________________________

4. List common types of thermal overload relays.

   ____

   ____

5. Where are in-line thermal overloads connected in the motor circuit?

   ____

   ____

6. What are **three** advantages of HRC fuses?

   - ______________________________
   - ______________________________
   - ______________________________

7. Using AS 3000 summarise the definition of a fuse.

8. Name the **three** types of magnetic overload relays.

-
-
-

9. Name applications where each type listed in question 8 may be used.

10. Describe the effect on the control circuit and the motor if the supply voltage is low.

11. Describe the function of a No-volt coil.

12. Describe the effects on the control circuit and the motor if the supply voltage is high.

13. List **three** problems associated with repetitive starting.

-
-
-

14. What protection is required for the motor and its associated controls if they are located in high humidity areas?

15. Thermistor protection is used to: *(tick the correct box)*

☐ detect and indicate abnormal motor temperature
☐ detect and indicate abnormal circuit temperature
☐ detect abnormal motor temperature and disconnect the motor
☐ detect excess motor current and operate the control circuit.

16. In regard to thermal overloads: *(tick the correct box)*

☐ all thermal overloads may have their current setting altered
☐ only motor circuit located overloads may have their current setting altered
☐ only in-line overloads can have their current setting altered
☐ overloads cannot have their current setting altered.

17. The inverse time characteristic of thermal overloads means that the overload will react: *(tick the correct box)*

    ☐ faster to a larger overload current than to a small overload current
    ☐ to any overload current regardless of the currents value
    ☐ slower to a larger overload current than to a small overload current
    ☐ faster to a smaller overload current than to a larger overload current.

18. Electronic type thermal protection units operate in conjunction with a: *(tick the correct box)*

    ☐ NTC thermistor
    ☐ ZTC thermistor
    ☐ PTC thermistor
    ☐ a bi-metal strip.

19. Indicate the correct statement: *(tick the correct box)*

    ☐ all overloads are accidental
    ☐ thermal overloads control short circuits
    ☐ some overloads are intentional
    ☐ locked rotor current is short circuit current.

20. In-line thermal overload heaters are connected: *(tick the correct box)*

    ☐ in two of the motor supply lines
    ☐ in series with the motor windings
    ☐ in series with the motor control circuit
    ☐ in the control circuit.

21. The relationship between operating time and current of a thermal protection device is known as the: *(tick the correct box)*

    ☐ time to current ratio
    ☐ inverse time characteristic
    ☐ proportional time characteristic
    ☐ tripping time.

22. The setting on a thermal overload is adjusted to: *(tick the correct box)*

- ☐ the full load current of the motor
- ☐ 150% of the motor full load current
- ☐ 200% of the motor full load current
- ☐ anywhere within the adjustment range.

23. If the setting on a thermal overload is set to the maximum possible adjustment, the overload will: *(tick the correct box)*

- ☐ operate correctly
- ☐ not provide effective protection
- ☐ only protect on low currents
- ☐ protect for short circuits as well.

24. A three-phase induction motor is started DOL and locks up at start. The expected protection operation would be: *(tick the correct box)*

- ☐ rapid tripping of the motor overload protection
- ☐ instantaneous tripping of the short circuit protection
- ☐ instantaneous tripping of the motor overload protection
- ☐ slow tripping of the motor overload protection.

25. A common cause of a motor overload is: *(tick the correct box)*

- ☐ adjacent conductors touching
- ☐ one conductor touching the motor frame
- ☐ the motor load partially seized
- ☐ operating in high ambient temperatures.

26. The contact associated with a thermal overload is: *(tick the correct box)*

- ☐ normally open and is connected in series with the control circuit
- ☐ normally closed and is connected in series with the control circuit
- ☐ normally open and in parallel with the motor contactor coil
- ☐ normally closed and in parallel with the stop button.

27. If the setting on a thermal overload is set to the minimum possible adjustment, the overload will: *(tick the correct box)*

- ☐ operate correctly
- ☐ not provide effective protection
- ☐ only protect on low currents
- ☐ allow for longer starting periods on heavy load.

28. When properly matched to a motor, a thermal overload will: *(tick the correct box)*

- ☐ close on rated full load current
- ☐ reflect the thermal characteristics of the motor
- ☐ operate on 200% rated full load current
- ☐ allow for longer starting periods on heavy load.

29. A problem associated with repetitive starting is: *(tick the correct box)*

- ☐ increased operator control for all applications
- ☐ motor power factor is altered
- ☐ controls have to be ventilated
- ☐ control accessories have shorter life span.

30. Instantaneous magnetic overload relays must have their rated trip current: *(tick the correct box)*

- ☐ equal to the starting current of the motor
- ☐ slightly exceeding the starting current of the motor
- ☐ slightly exceeding the full load current of the motor
- ☐ equal to the full load current of the motor.

31. A magnetic overload is: *(tick the correct box)*

- ☐ too insensitive to operate under its set current
- ☐ complex to install
- ☐ capital cost intensive to install
- ☐ harmonic distortion sensitive to the supply lines.

32. The motor in the diagram has a full load current of 100 A. What setting of the O/L is required for correct protection? *(tick the correct box)*

    - ☐ 33.3 A
    - ☐ 57.7 A
    - ☐ 85 A
    - ☐ 100 A.