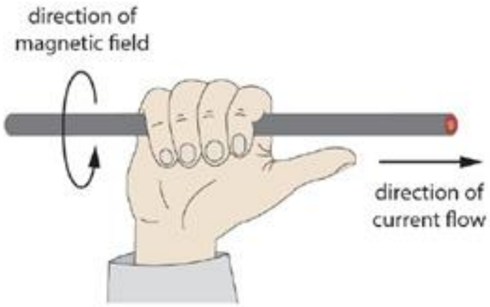
6. Single Phase AC Motors

Three phase induction motors are used widely in industry to provide a range of services and facilitate various industrial processes, and so it is important for electrical workers to understand their operating principles. In this topic, you will re-visit the principles of electromagnetism and learn about how these principles apply to the operation of three phase induction motors.

Fleming's Right Hand Grip Rule

Fleming's right hand grip rule indicates the relationship between current flow and the resulting magnetic field surrounding a conductor or solenoid (coil).

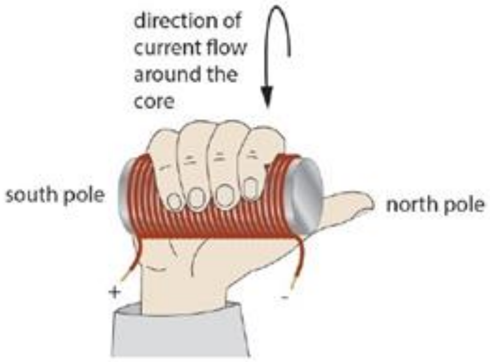
Fleming's right hand (grip) rule for conductors is shown below:



In the right hand grip rule for conductors:

- The fingers indicate the direction of the magnetic field.
- The thumb indicates the direction of current flow.

Fleming's right hand (grip) rule for solenoids is shown below:

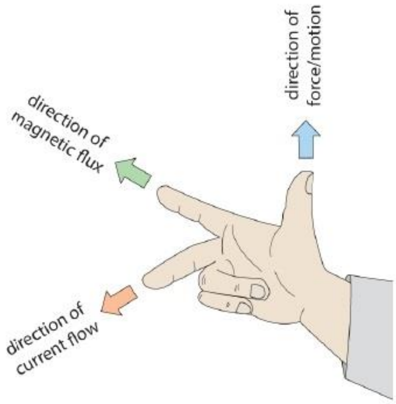


In the right hand grip rule for solenoids:

- The fingers indicate the direction of current flow.
- The thumb indicates magnetic north.

Fleming's Right Hand Generator Rule

A further development of the right hand rule can be used to represent the relationships between flux, current and force in a generator. Fleming's right hand generator rule is illustrated below:

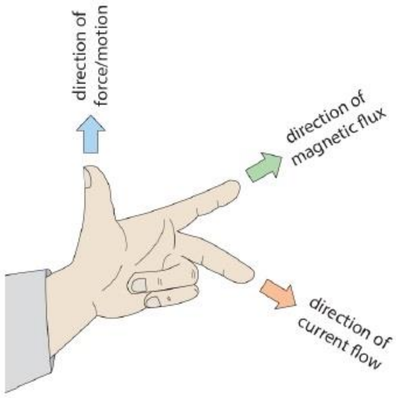


In the right hand rule for generators:

- The thumb indicates the direction of motion/force.
- The first finger indicates the direction of flux.
- The middle finger indicates the direction of current flow.

Fleming's Left Hand Motor Rule

Using the left hand instead of the right hand will indicate the relationships between flux, current and force in a motor. Fleming's left hand motor rule is illustrated below:

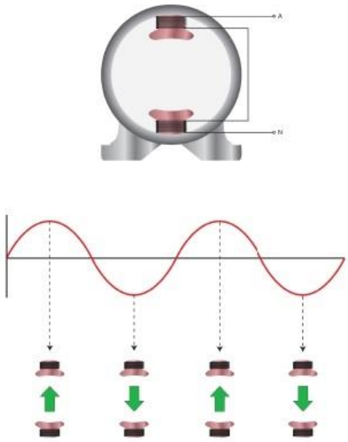


In the left hand rule for motors:

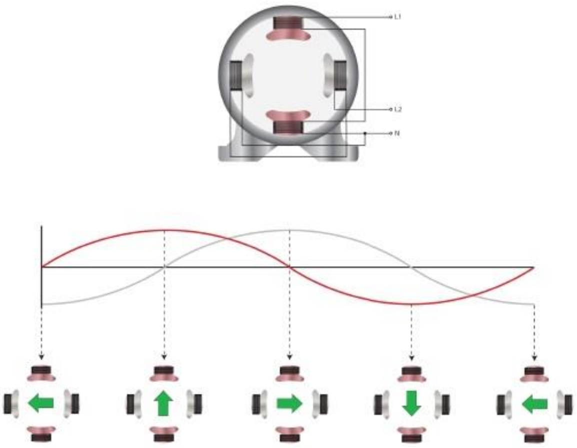
- The thumb indicates the direction of motion/force.
- The first finger indicates the direction of flux.
- The middle finger indicates the direction of current flow.

Rotating Magnetic Fields

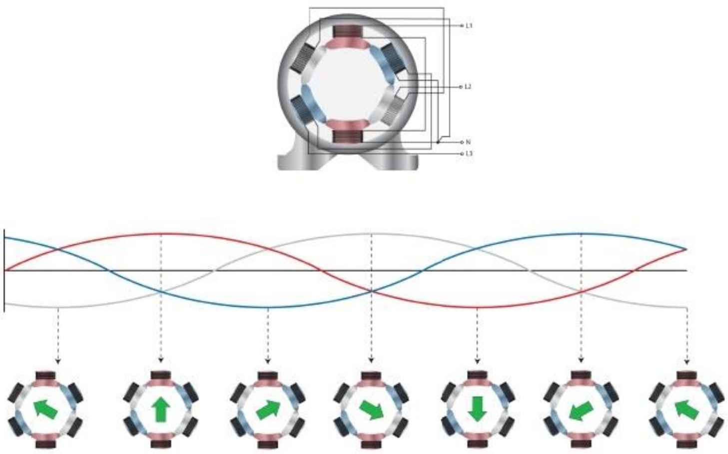
If a single phase a.c. supply is applied to a single winding, a pulsating magnetic field is produced. The field switches polarity back and forth between the poles as the current changes direction. A single phase winding arrangement and the resulting magnetic field are illustrated below:



When a two phase a.c. supply is applied to a pair of windings that are displaced by 90⁰, a rudimentary rotating magnetic field is produced. The field produced by each individual winding pulsates, but due to the 90⁰ displacement, the resultant field rotates. A two phase winding arrangement and the resulting magnetic field are illustrated below:



When a three phase a.c. supply is applied to a set of three windings, each displaced by 120⁰, a smooth rotating magnetic field is produced. Three phase winding arrangements and the resulting magnetic field are illustrated below:



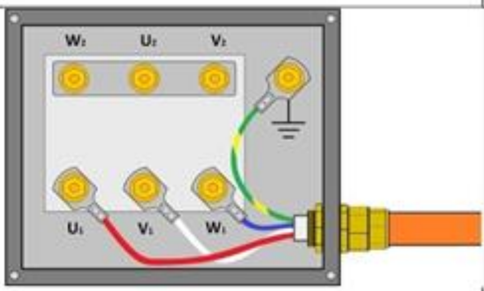
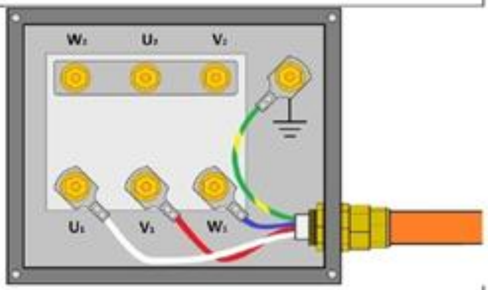
Direction of Rotation

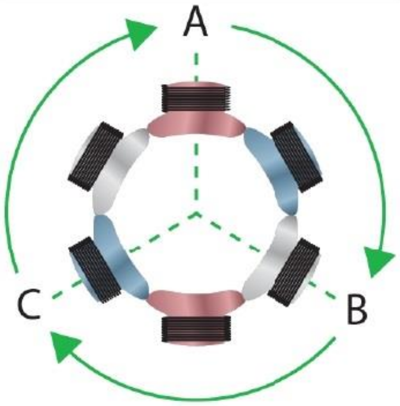
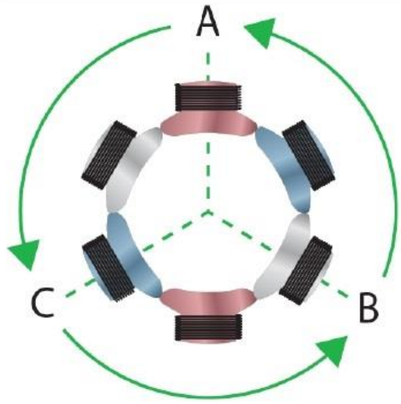
The direction that a three phase induction motor will rotate depends on the order in which the three phases reach their maximum values, referred to as the *phase sequence*. If the phase sequence is reversed, then the direction of rotation will also reverse.

It can be very important to verify the phase sequence of the supply prior to connecting a three phase induction motor – in some cases, reverse rotation of the motor could cause serious damage to the coupled equipment.

Sometimes it may be desirable to reverse the rotation of a three phase induction motor. This can be achieved by interchanging any two of the supply phase conductors at the motor terminals.

The following diagrams show the connections for forward and reverse operation of a star-connected motor. Note that Terminals U_1, V_1 and W_1 are connected to the start of each winding, and the ends of each winding are bridged together (star-connection) at terminals U_2, V_2 and W_2.

Three Phase Induction Motor – Reversal	
Forward Rotation	**Reverse Rotation**
	

In this scenario, the motor is connected so that: • A phase (red) supplies winding U. • B phase (white) supplies winding V. • C phase (blue) supplies winding W. This means that the rotation will follow the phase sequence A-B-C, as shown below.	In this scenario, A phase and B phase have been swapped so that: • B phase (white) supplies winding U. • A phase (red) supplies winding V. • C phase (blue) supplies winding W. This means that the rotation will follow the phase sequence A-C-B, as shown below.
 	

Speed of Rotation

The speed of a rotating magnetic field is known as the 'synchronous speed' (n_{sync}). The synchronous speed of an induction motor depends on:

- The number of poles.
- The frequency of the supply.

Synchronous speed can be determined by applying the following equation:

$$n_{sync} = \frac{120\,f}{P}$$

Where:

N_{sync} = synchronous speed in rotations per minute (r.p.m.)

f = frequency of the supply in hertz (Hz)

P = number of poles

Worked Example – Synchronous Speed

Calculate the synchronous speed of a 400 V, 50 Hz, four pole induction motor.

$$n_{sync} = \frac{120 \times 50}{4}$$

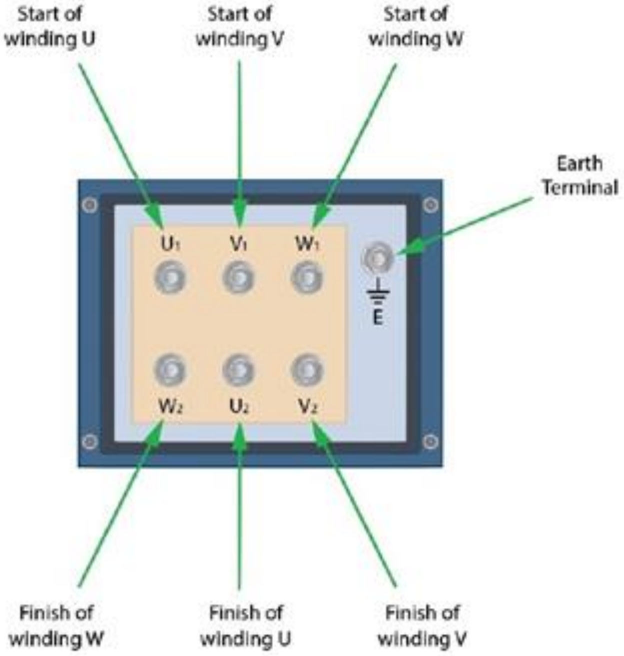
$$n_{sync} = \frac{6{,}000}{4}$$

$$n_{sync} = 1{,}500\ r.p.m.$$

Induction Motor Connections

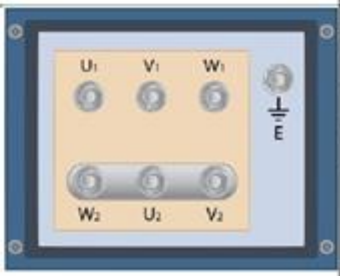
Each end of the three phase stator windings are connected to a terminal in the motor terminal block, meaning there are six terminals altogether (plus an earth terminal).

The three windings are identified using the letters U, V, and W, with a subscript number identifying the start and finish of each winding. The following diagram shows a typical three phase induction motor terminal block.



Connection Configurations

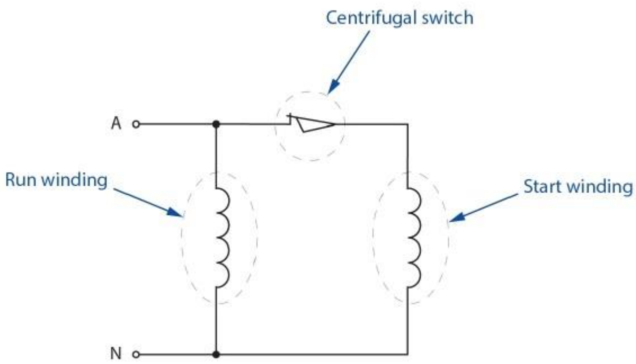
Terminal links (or 'bridges') are used to connect the windings in either star or delta, as shown in the following table.

Three Phase Induction Motor – Connection Configurations		
Configuration	**Illustration**	**Characteristics**
Star Connection		A terminal link is used to join the finishes of each winding together. The three supply conductors are connected to the unbridged terminals (U_1, V_1 and W_1). When a star connection is used: • A lower voltage is applied across each winding (approx. 58% of the line voltage). • A lower line current is drawn from the supply. • Power output from the motor is 33.3% of the delta power.

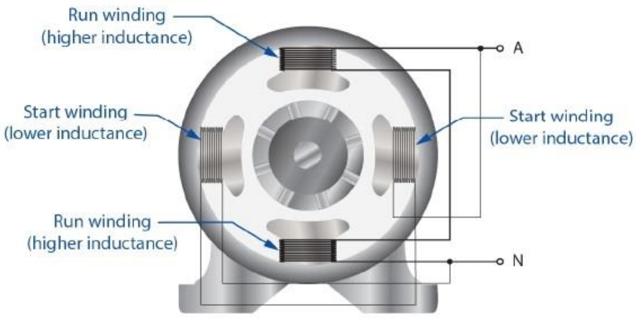
Rotor	Squirrel Cage Rotor	• Standard squirrel cage construction consisting of several skewed bars, joined at each end, and combined with a laminated steel core.

	Switching Mechanism	• The switch is generally positioned on or in proximity to the rotor shaft.
		• Its purpose is to disconnect the start winding once the motor has reached a pre-determined speed, usually around 75 % of the rated speed.
		• There are several types of switches that can be used for this purpose, including the following:
		  ○ Centrifugal
		  ○ Current sensing
		  ○ Voltage sensing
		  ○ Thermal
		  ○ Solid state (electronic).

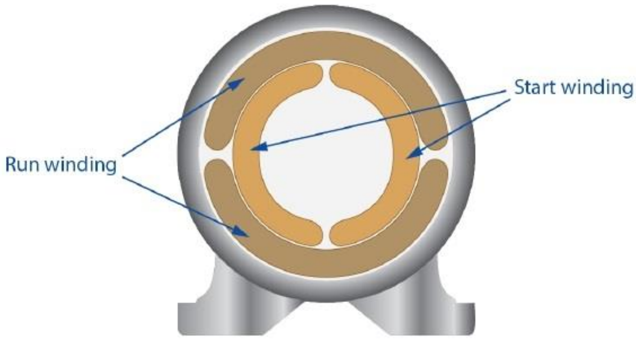
The following diagram shows the circuit diagram of a split phase motor.



The following diagram shows the electrical arrangement of windings in a split phase motor.



The following diagram shows the physical displacement of windings in a split phase motor.



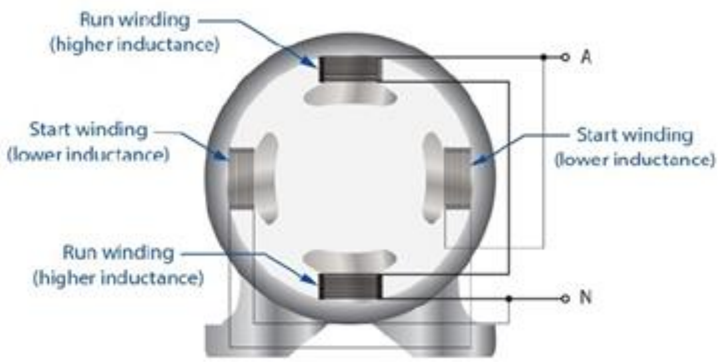
Operating Principles

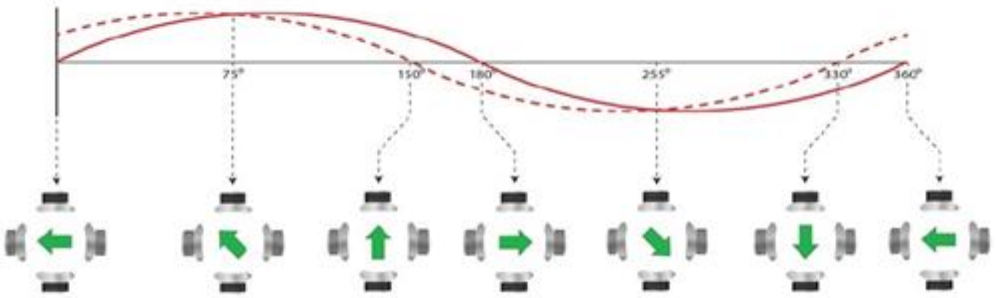
A split phase motor operates according to the same principles as a three phase induction motor:

- An e.m.f. applied to the stator windings produces a magnetic field.
- The stator field induces an e.m.f. into the rotor.
- The induced e.m.f. causes current flow in the rotor.
- Current flow in the rotor produces a magnetic field.
- The interaction between the stator field and the rotor field causes the rotor to rotate.

A single phase winding alone however does not produce a rotating magnetic field, and so cannot develop starting torque. To solve this problem, a split phase motor uses a start winding to produce a rotating magnetic field during starting. The start winding is of a lower inductance when compared with the run winding, resulting in a phase difference of around 30° between the winding currents, and therefore the resulting flux. This small shift in flux and the 90° physical displacement of the windings allows the motor to start.

The following diagram shows the resultant magnetic field from the flux produced in a split phase stator. The unbroken sine wave represents the current flowing in the run winding and the dashed sine wave represents the current flowing in the start winding (30° phase shift).



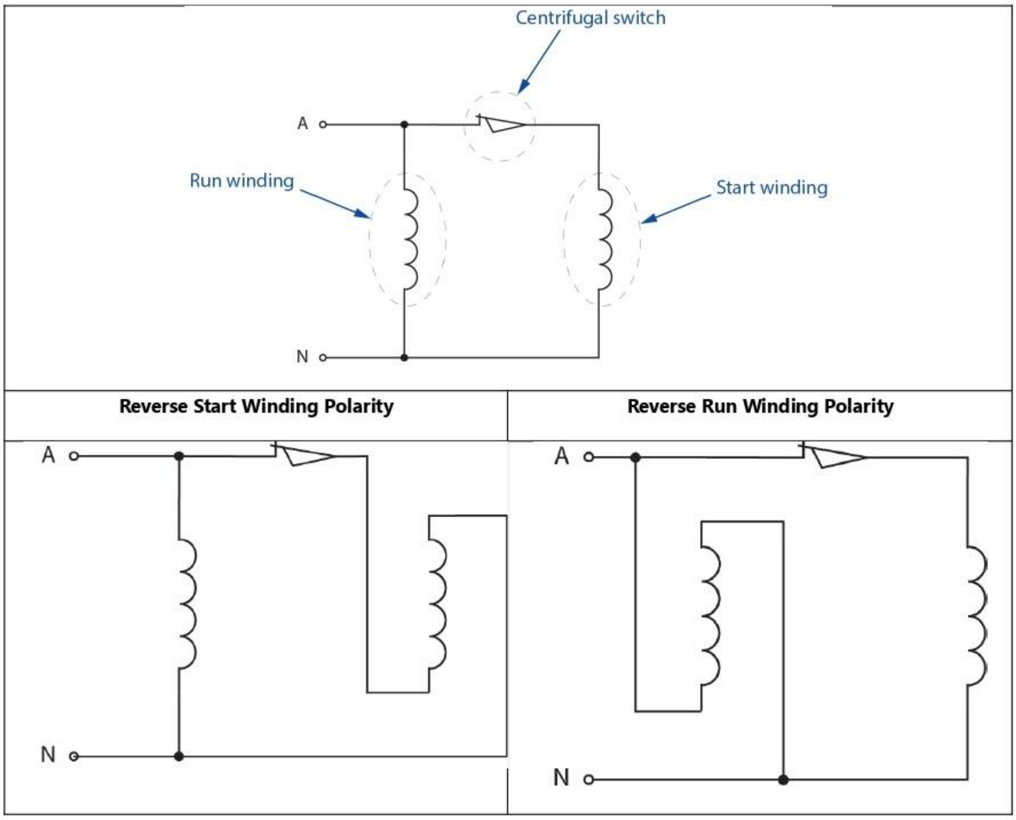


Once the motor is up to speed, the centrifugal switch disconnects the start winding and the rotor rotates purely due to the pulsating magnetic field produced by the run winding.

Reversing a Split Phase Motor

A split phase motor can be reversed by reversing the supply polarity to either the start winding, or the run winding (but not both).

Split Phase Motor Reversal

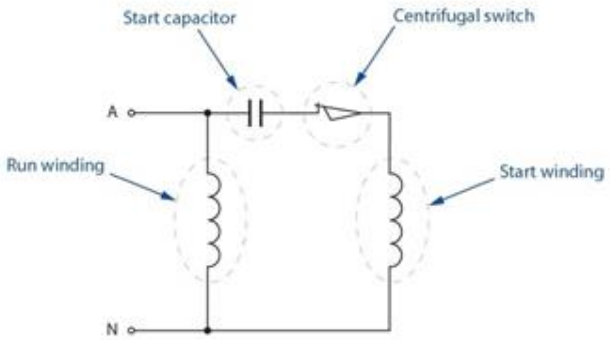

Centrifugal switch
A
Run winding
Start winding
N
Reverse Start Winding Polarity
Reverse Run Winding Polarity
A
N
A
N

Introduction

A number of variations on the basic split phase motor have been developed to produce improved starting and running characteristics. Each variation has different characteristics making each variation suitable for a different range of applications. In this topic, you will learn about the different types of single phase motors. A good understanding of the construction, operating principles, characteristics and applications of single phase motors is essential for effective troubleshooting and to ensure safety.

Capacitor Start Motors

A single phase capacitor start motor has the same construction as a split phase motor, with the addition of a capacitor mounted on the exterior of the frame. The capacitor is connected in series with the centrifugal switch and the start winding. The following diagram shows the arrangement of a single phase capacitor start motor.



The purpose of the capacitor is to increase the phase shift between the start winding and the run winding. By selecting the correct value of capacitance, a phase shift of up to 90° can be achieved however care must be taken to ensure series resonance is avoided.

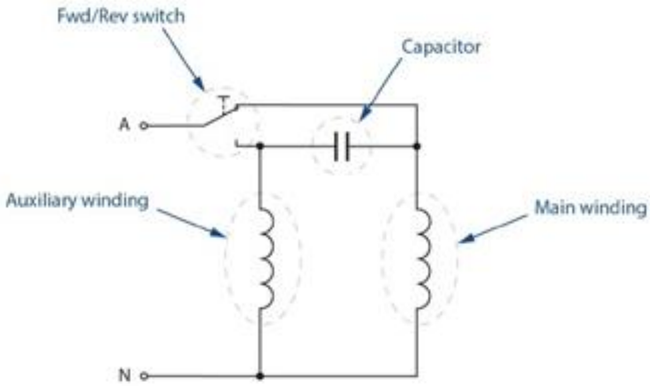
Characteristics

The increased phase shift between the alternating flux of the start and run windings produces a much higher starting torque of up to 400 % of the rated full load torque. Once the motor has reached a pre-determined speed, the centrifugal switch disconnects the capacitor and start winding from the circuit.

The following graph shows typical torque/speed characteristics of a capacitor start motor.

Permanently Split Capacitor (PSC) Motors

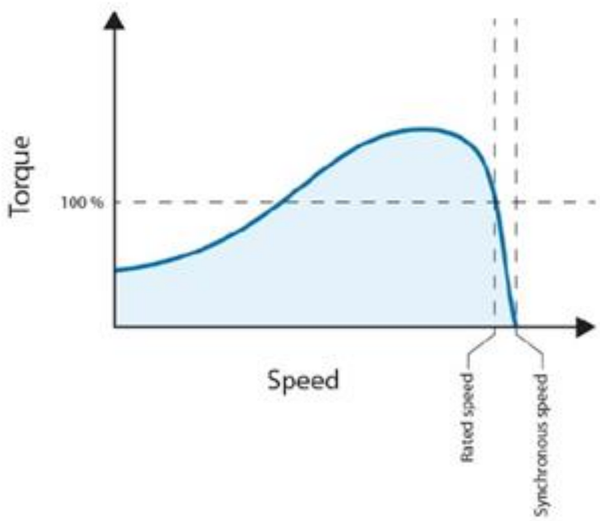
A permanently split capacitor (PSC) motor has the same construction as that of a capacitor start motor, except that it has no centrifugal switch. The two windings of a PSC motor are referred to as the 'main winding' and 'auxiliary winding', as both windings are used during start and run operations. The phase shift between the two windings is achieved by having a capacitor permanently connected in series with one winding. The PSC motor shown below is set to rotate forwards, as the capacitor is connected in series with the auxiliary winding.



The capacitor must be designed for continuous use, and provides a moderate phase shift resulting in low starting torque and relatively low starting current.

Characteristics

PSC motors are most suited to applications requiring low power, low starting torque, frequent starting and stopping, and/or frequent reversal or speed control. The following graph shows the torque/speed characteristics of a PSC motor.



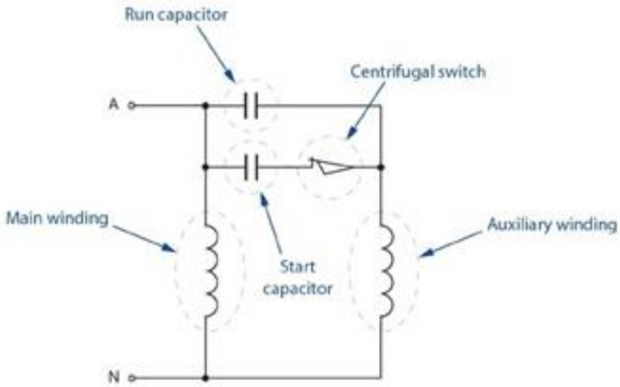
The advantages of PSC motors include:

- Simple construction.
- Ease of reversal.
- Ease of speed control.
- Low noise and vibration.

Capacitor Start, Capacitor Run Motors

A single phase capacitor start, capacitor run motor has the same basic construction of a capacitor start motor, except that it has an additional 'run capacitor'. The two windings of a capacitor start, capacitor run motor are referred to as the 'main winding' and 'auxiliary winding' as both windings are used during start and run operations.

The auxiliary winding is connected to both a start capacitor in series with a centrifugal switch, and a run capacitor.



The start capacitor is typically an electrolytic capacitor with a higher capacitance and a short term rating.

The run capacitor is typically an oil-filled capacitor with a lower capacitance and a continuous rating.

Characteristics

Due to both windings being continuously operational, a capacitor start, capacitor run motor has:

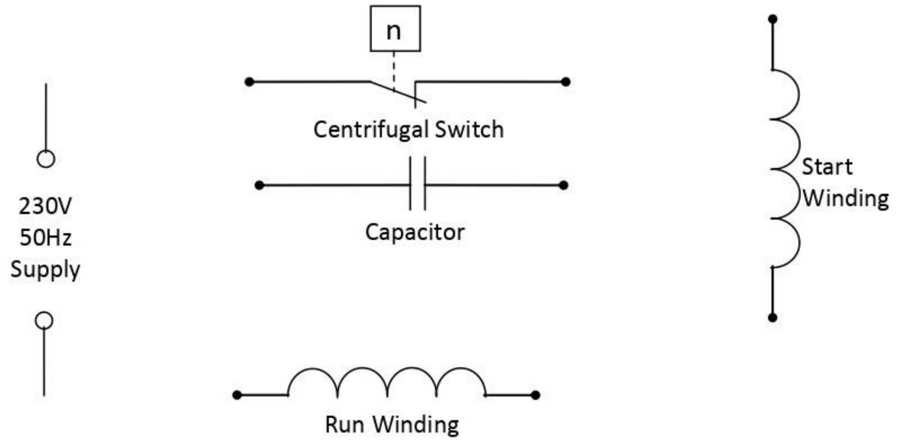
- Increased starting and running torque.
- Improved efficiency and power factor.
- Reduced noise and vibration.

The following graph shows the torque/speed characteristics of a capacitor start, capacitor run motor.

Single phase ac motor circuit connection

Using the electrical machine schematic drawing symbols below,

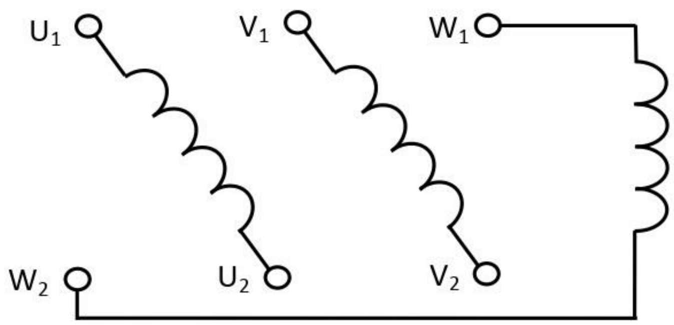
a. **draw the connections** for the machine to operate as a **single phase capacitor start motor**:



Correct connections ☐

Three phase ac motor circuit connections

The drawing below shows the **internal winding connections** for a standard 3 phase induction motor terminal block.



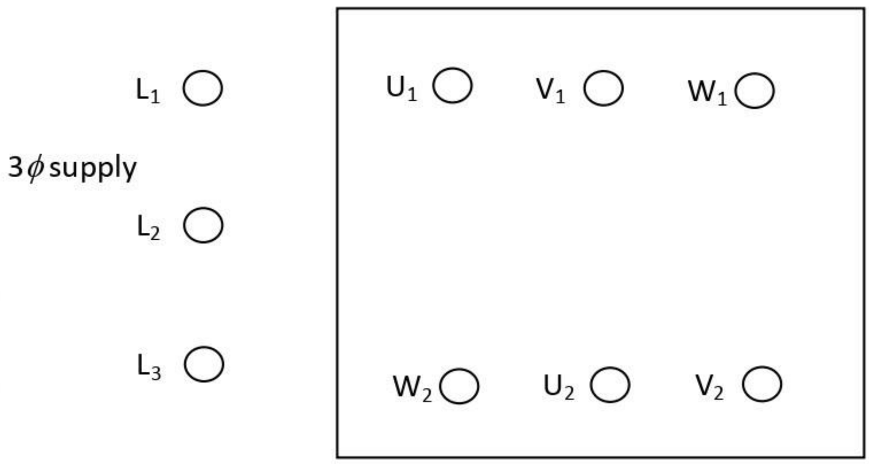
For the **standard three phase induction motor terminal block** shown here:

a. Draw the **external connecting links on the terminal block** to operate the three phase motor in **delta Δ**

Correct terminal block connections ☐

b. Also draw the **supply line connections** between the motor terminal block and the 3ϕ supply

Correct supply line connection ☐



Standard 3ϕ induction motor terminal block