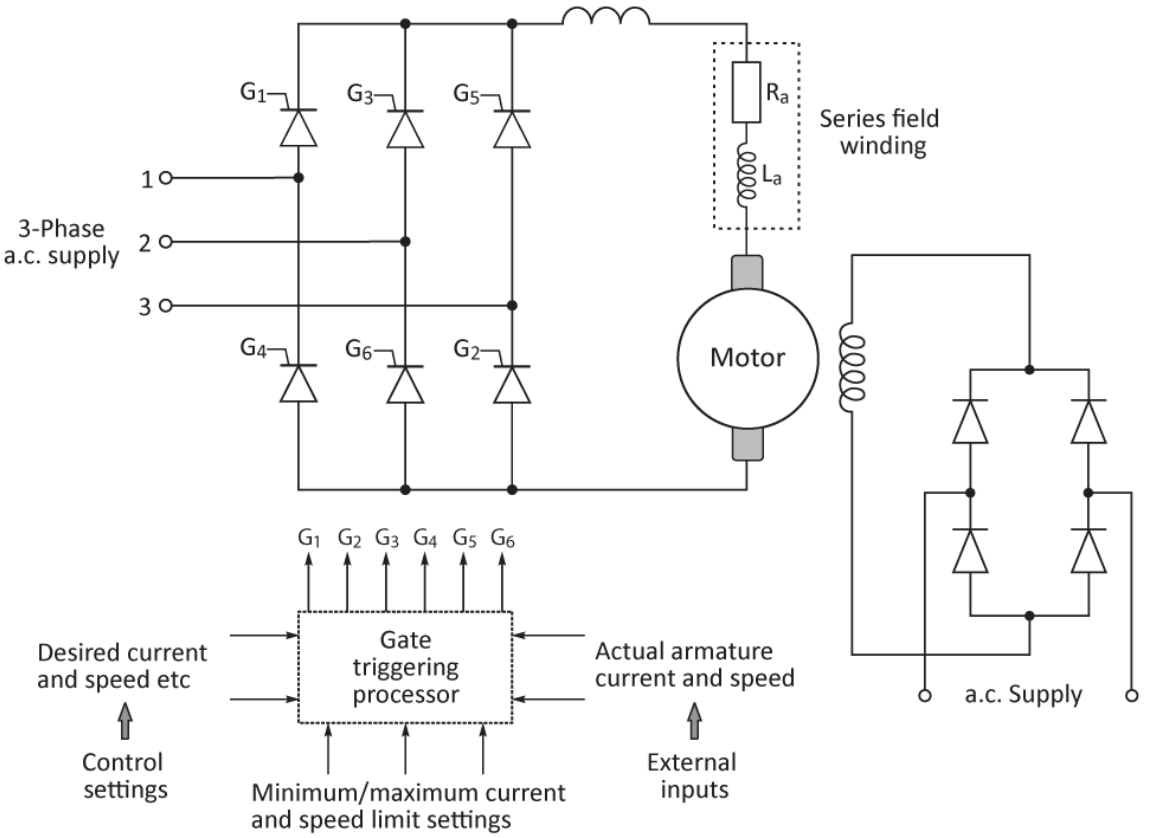
Level 3 Diploma
in
Installing Electrotechnical Systems & Equipment

C&G 2357

Unit 309-8 Understand the operating principles and applications of dc and ac motors



B&B Training Associates Ltd
Learning Materials for the Electrical Industry

Produced by

B&B Training Associates Ltd

For further information contact:

Mrs A Bratley

23 St Pauls Drive,

Tickton, Nr Beverley,

East Yorkshire

HU17 9RN

Tel:-01964 – 543137

Fax:-01964 – 544109

Email:- sales@bbta.co.uk

timbenstead@bbta.co.uk

terry@bbta.co.uk

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Aims and objectives

By the end of this study book you will have be able to:

- State the basic types, applications and describe the operating principles of d.c. machines, including:
  - Series wound.
  - Shunt wound.
  - Compound wound.
- Describe the operating principles of:
  - Single phase a.c. motors
    - Capacitor start.
    - Induction start.
    - Universal.
  - Three phase a.c. motors
    - Squirrel cage.
    - Wound rotor.
  - Inverter motor/variable frequency drive.
  - Synchronous motors.
- State the basic types, applications and limitations of:
  - Single phase a.c. motors
    - Capacitor start.
    - Induction start.
    - Universal.
  - Three phase a.c. motors
    - Squirrel cage.
    - Wound rotor.
  - Inverter motor/variable frequency drive.
  - Synchronous motors.

- Describe the operating principles, limitations and applications of motor control, including:
    - Direct on line starters.
    - Star-delta starters.
    - Rotor resistance starters.
    - Soft start.
    - Variable frequency drives.

1: Machines revision

In this session the student will:

- Describe the basic principle of turning moments and torque.
- Understand the features of speed/torque graphs.
- Understand the effects of a current carrying conductor in a magnetic field.

In the Mechanics module you were introduced to terms such as Force, Mass, Acceleration and Gravity. It was mentioned that Force is generally measured by the effects it produces. If you move an object then you have placed a force on that object.

Therefore, Force can be seen to involve two quantities, its ***mass*** and its ***acceleration***. This brought you to an equation.

$$F = ma$$

$$\text{where:} \quad F = \text{force } (\text{N})$$
$$m = \text{mass } (\text{kg})$$
$$a = \text{acceleration } (\text{ms}^{-2})$$

In most occasions the effects on our object of mass (m), will be due to the effects of gravity.

We can alter our equation to show the gravity term instead of the acceleration one.
Notice that instead of acceleration (***a***), we now have acceleration due to gravity (***g***).

$$F = mg$$

$$\text{where:} \quad F = \text{force } (\text{N})$$
$$m = \text{mass } (\text{kg})$$
$$g = \text{acceleration due to gravity } (\text{ms}^{-2})$$

The acceleration due to gravity is a constant, and is usually accepted as $9.81\,ms^{-2}$. So, in any problem involving the lifting or dropping of an object, the acceleration is assumed to be $9.81ms^{-2}$.

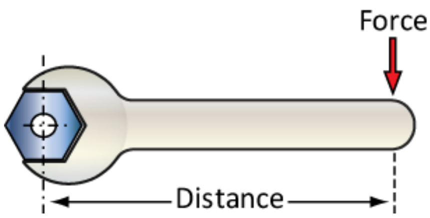
Now that you understand the terms we can use them for the next part which looks at turning moments and torque. These terms are used when we consider motors.

Turning moments

Another word for a turning moment is ***torque***. Torque is the ***turning force*** applied to an object. A steering wheel has a torque applied to it, a car wheel has a torque applied to it, a spanner or wrench has a torque applied to it.

The magnitude of the turning force (from now on called torque) is dependent upon two things:

- force applied
- distance from the turning point



Can you see where the force is applied in relation to the force on the object?

The torque can be determined using the following equation.

$$T = Fd$$

where $T = \text{Torque (Nm)}$

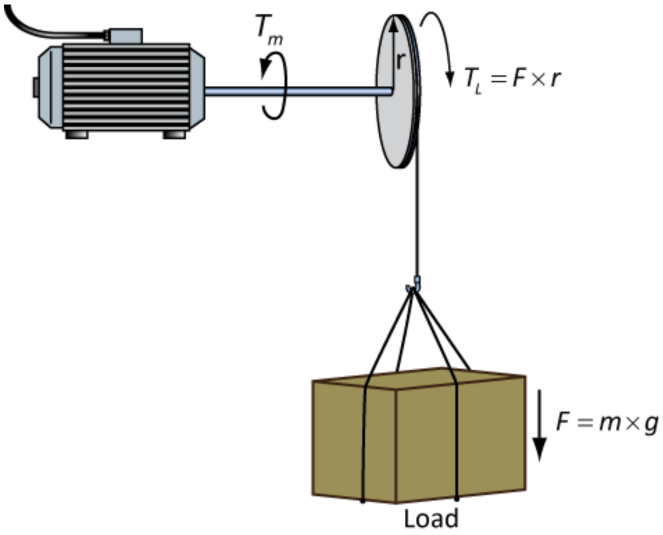
$F = \text{Force (N)}$

$d = \text{Distance (m)}$

The unit used for turning moment is the Newton-metre (***Nm***). The symbol is ***T***. The main point to realise is that the distance is not just how far away the force is applied, but also takes into account the direction in which the force is applied. Most leverage can be obtained if the force was applied at right angles.

With motors we use the term Torque as we are referring to forces that act in a rotational manner. The unit is still the Newton-metre (***Nm***) and the symbol is ***T***.

Consider the diagram below.

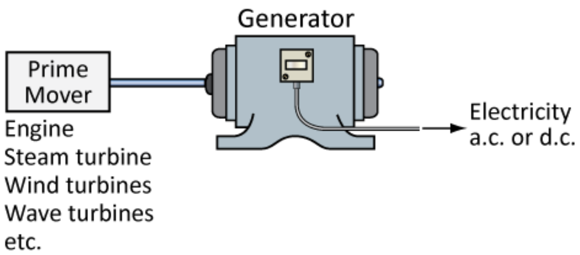


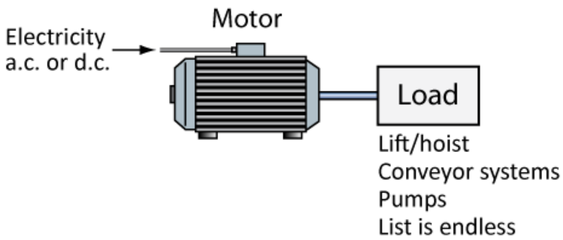
The motor torque has to be greater than the load torque to make the box rise.

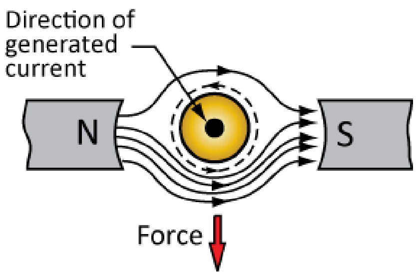
$$T_m \succ T_L$$

Machines

Electrical machines convert either electrical energy into mechanical energy, and are called **motors**, or convert mechanical energy into electrical energy, and are called **generators**.

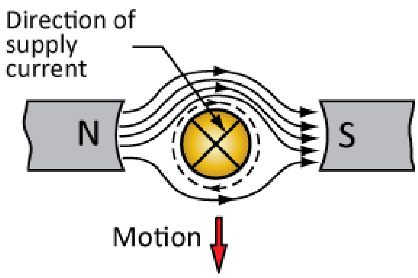






Flemming's Right Hand rule

With a generator, the conductors are moved through a magnetic field under the influence of the prime mover. As the conductors cut the magentic field an emf is generated.



Flemming's Left Hand rule

With a motor, the supply current cause a magnetic field to circulate in the motor conductors, this reacts with the main magentic field and motion is produced.

The basic principle of operation of any electrical machine is remarkably similar, irrespective of whether we are dealing with a.c. or d.c., or even when we look at single-phase or three-phase supplies.

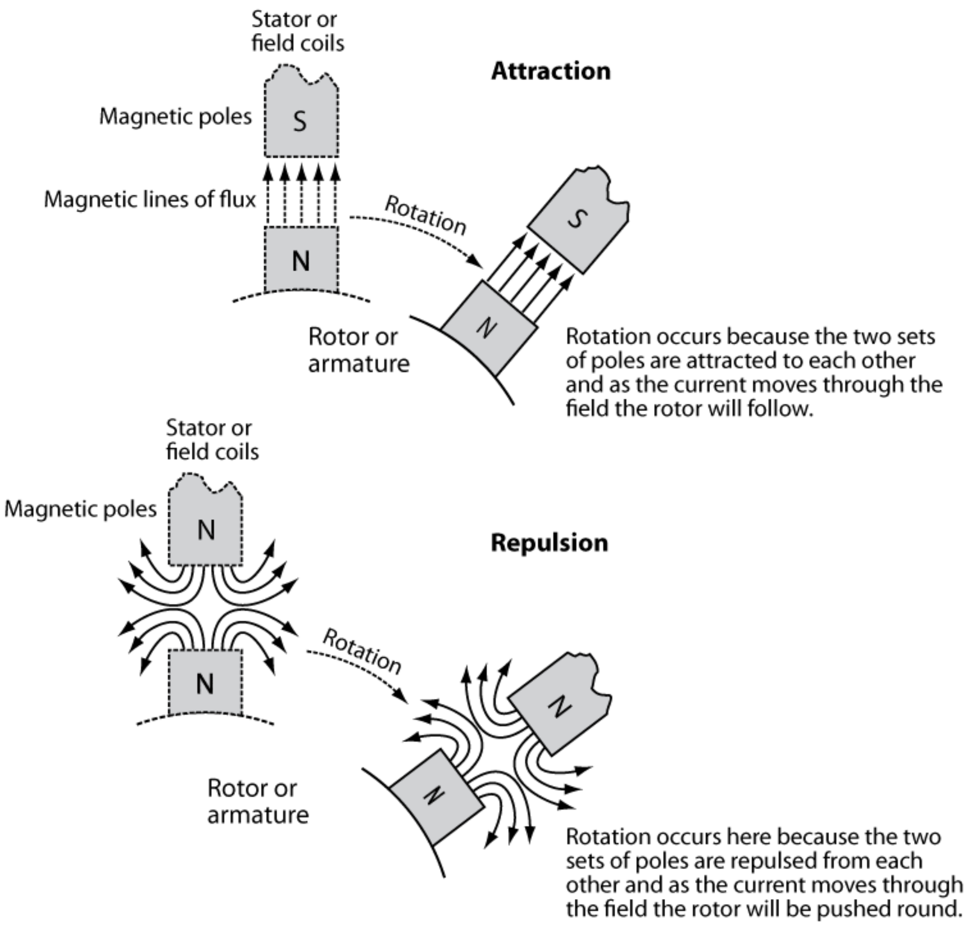
Every electrical machine consists of:

- a static winding called either the stator (a.c.) or field winding (d.c.).
- a rotating winding called either an armature for d.c. machines or a rotor for a.c. machines.

You should be able to see that any electrical machine must have two magnetic fields interacting with one another. Consider the diagram below.

There are two possible options:

- the rotating part 'locks' its magnetic field with the stator (the stationary part)
- the rotating part is repelled by the stator's magnetic field.



Whatever the means of rotation whether it is repulsion or attraction, the underlying condition is that the shaft of a motor rotates because of the torque created by the interaction between the magnetic field of the stationary windings and the magnetic field of the rotor.

When we consider electrical machines, rather than consider whether they attract or repel, we usually split them into their respective supply types. We have therefore two basic types of supply:

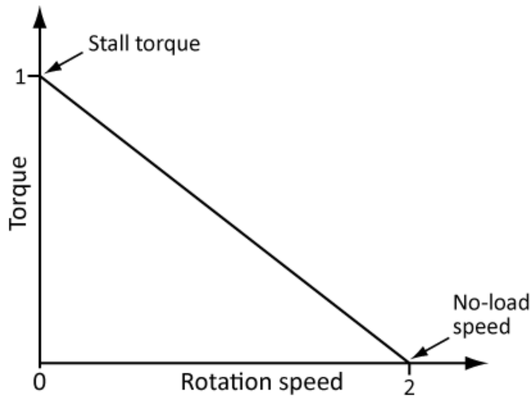
1) D.c
    a. Motors
        i. Series
        ii. Shunt
        iii. Compound
    b. Generators
        i. Series
        ii. Shunt
        iii. Compound

2) A.c
    a. Single-phase motors
        i. Split-phase
        ii. Series/universal
        iii. Capacitor start induction run
        iv. Capacitor start capacitor run
        v. Shaded pole.
    b. Three-phase motors
        i. Synchronous
        ii. Induction
            1. Squirrel cage
            2. Wound rotor.

You can see that although there are two types of supply the range of motors and generators is immense.

Torque/Speed graphs

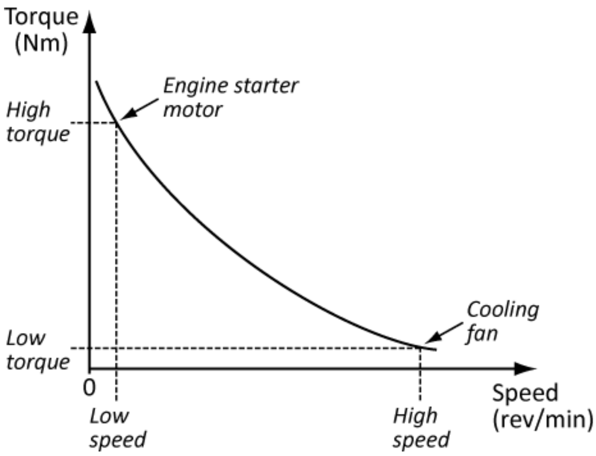
In order to understand the pros and cons of all the motors/generators about to be discussed in the rest of this unit, it would be useful if you had an understanding of the torque/speed curves as this helps to identify a motor for a particular application.



At position 1, this can represent either the instant on switching the motor on or the load torque is too great for the motor. In this case if the motor is not switched off then damage will occur as it will behave like a short-circuited transformer.

The instant of switching on the torque will be high but will reduce as peed is built up.

At position 2, the load torque has been removed and the motor is running at its maximum speed.



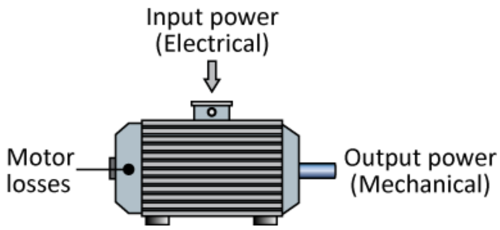
A bit more detail has been put into this characteristic curve.

It can be seen that a motor used to start an engine requires a high starting torque. Imagine turning the ignition key of your car on a cold winter's morning!

A cooling fan has very little load but the intention is for it to spin very fast to create a cooling draught.

Motor Power

Electrical motor efficiency is the ratio between the shaft output power and the electrical input power.



Input power $P_{in} = \sqrt{3} \times U_L \times I_L \times \cos\phi$

Output Power $P_{out} = 2\pi \times T \times \frac{n}{60}$ Where n is in rev/min

Efficiency $\eta = \frac{P_{out}}{P_{in}}$

The efficiency of motors is generally very good and lies between 75% and 98%, depending upon the size of the motor with the larger motor normally having the better efficiency.

Input power

This is the amount of power any motor consumes to produce the output power. This includes the losses which are made up of:

Iron losses –	these losses are the result of the magnetic field not fully linking between the stator and rotor. The supply has to create the magnetic field in the first instance.
Copper losses -	this is the power lost in the windings due to the resistance.
Mechanical losses -	these include friction in the bearings and the fan for air cooling

Output power

This is the amount of power a motor can produce at the shaft and not reduce the life of the motor. It used to be measured in Horsepower (HP), where 1 HP = 746 W, but now watt or kilowatts are solely used.

Regulation 552.1.2 states that every motor having a rating exceeding 0.37 kW ($\frac{1}{2}$ HP), shall be provided with some means of overload protection.

When power of a motor is mentioned, this refers to the output power.

Exercise 1

1. Think about your own home and list all the motors that might be present.

2. An object of mass 500 kg is moved at a rate of 2 ms^{-2}. Calculate the force exerted on it.

3. It takes a force of 72 N to move an object of mass 6 kg. Calculate the acceleration.

4. An object is moved at a rate of 50 ms^{-2} with a force of 20 kN. Calculate its mass.

5. What force is required to hold up an object of mass 20 kg?

6. What would happen if the load torque was greater than the motor torque?

7. If the mass of the load was very small, what speed would you expect the motor to run at?

8. a) A 150 kW electric motor has an efficiency of 92% when it operates at full-load. Calculate the losses in the machine.
   b) Comment upon the size of the losses

9. An electric motor lifts a mass of 500 kg through a height of 30 m in 12 s. Calculate the power developed by the motor.

10. a) An electric motor lifts a load of 1 tonne through a height of 10 m in 20 s. Calculate the input power if the efficiency of the motor is 85%.
    b) If the supply to the motor is three-phase 400 V, and the power factor of the motor is 0.9, determine the supply current.

2: Basic operation of d.c. machines

In this session the student will:

- Gain an understanding of the basic principle of operation of d.c. machines.
- Gain an understanding of the difference between motors and generators.

In the first session we considered the introduction to machines by looking at the mechanical terms.

It was also discussed that every electrical machine consists of:

- a static winding called either the stator (a.c.) or field winding (d.c.).
- a rotating winding called either an armature for d.c. machines or a rotor for a.c. machines.

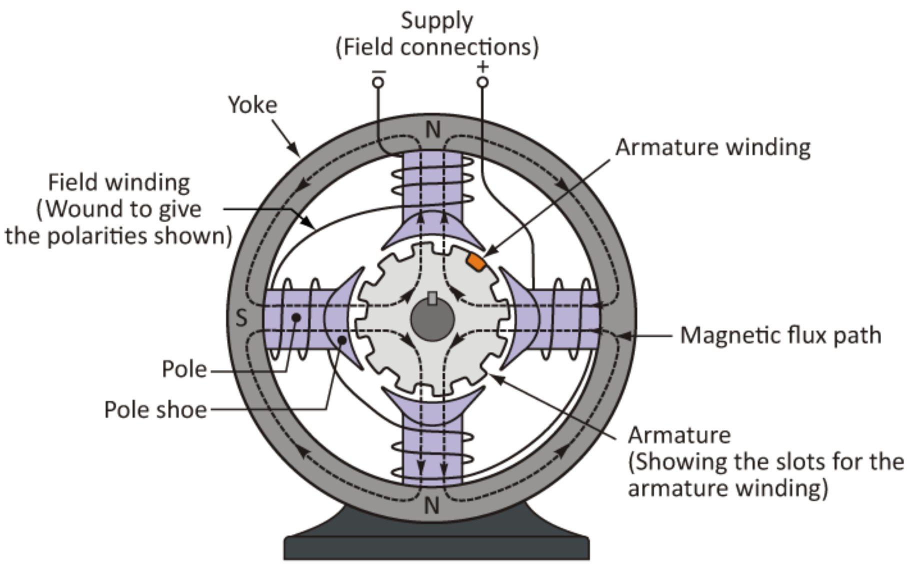
Any electrical machine must have two magnetic fields interacting with one another.

There are two possible options:

- the rotating part 'locks' its magnetic field with the stator (the stationary part)
- the rotating part is repelled by the stator's magnetic field.

We will now consider the basic principle of operation of electrical machine and how they are constructed and arranged.

Below is a diagram showing the basic set-up of all d.c. machines. Remember that we are still only looking at the two basic principles described earlier, and how we can create those two sets of conditions and magnetic field interaction to get a starting torque condition.



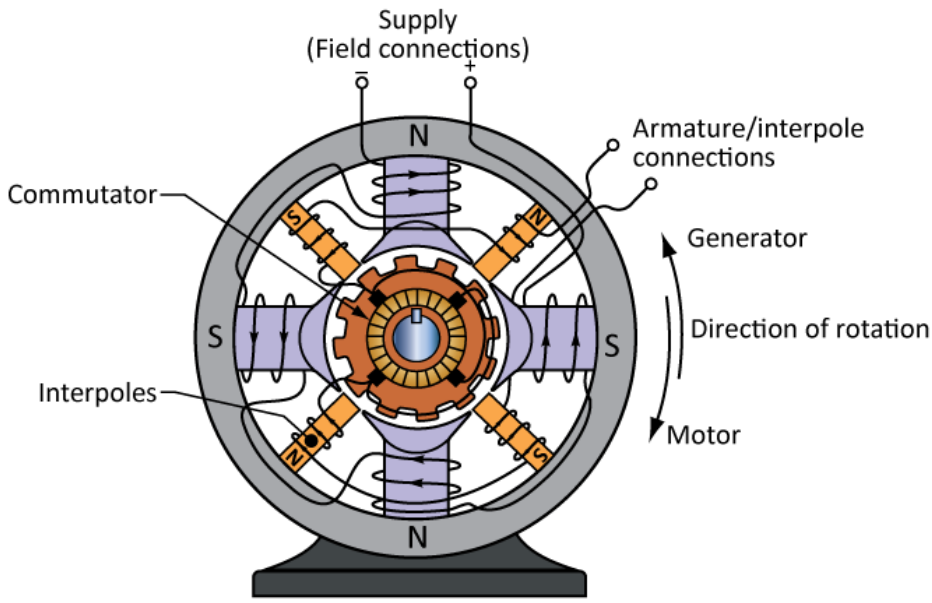
Basic d.c. motor showing the pole arrangement and the magnetic circuit

Beginning from the outside and move towards the centre, the outer casing is usually made from cast iron or some other material that can be easily magnetised and is called the ***yoke***. The yoke becomes part of the magnetic circuit when current is flowing.

In our example, there are four ***pole cores***.

These pole cores are made up of laminated steel and are bolted to the yoke. These pole cores allow for an increase in the area of the magnetic path and provide an even distribution of magnetic flux around the armature. We'll look at the armature shortly.

Certain d.c. machines also have a series of ***compoles*** or ***interpoles*** that are set between the main poles. These help to reduce the sparking that occurs at the brushes.



D.c. motor showing the arrangement of the interpoles and brushes

As you can see, life seems to have become a little bit more complicated. The brushes are the small black squares which are resting on the commutator spaced 90º apart.

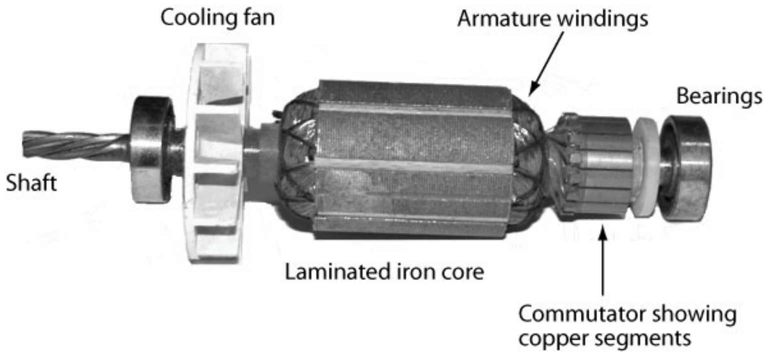
The ***field windings*** are coils wrapped around the pole cores. These windings provide one of the magnetic fields that we were looking at earlier. Current flows in the winding and a magnetic circuit is created within the yoke and the pole cores. This magnetic circuit provides a series of north and south poles.

We have now looked at the parts of the machine that do not rotate or move in any way. We'll now look at the part of the machine that does move.

Armature

On a d.c. machine the part that rotates is called the armature.

The armature has a series of slots running down its length, which contain a series of windings called armature windings. Have a look at the picture below.



The armature windings start and finish at a point on the armature called the ***commutator***. We'll look at the commutator in more detail in a moment.

The final parts of the machine are the **brushes**. The brushes on a d.c. machine are made up of carbon. Carbon has a number of qualities that make it ideal for this purpose:

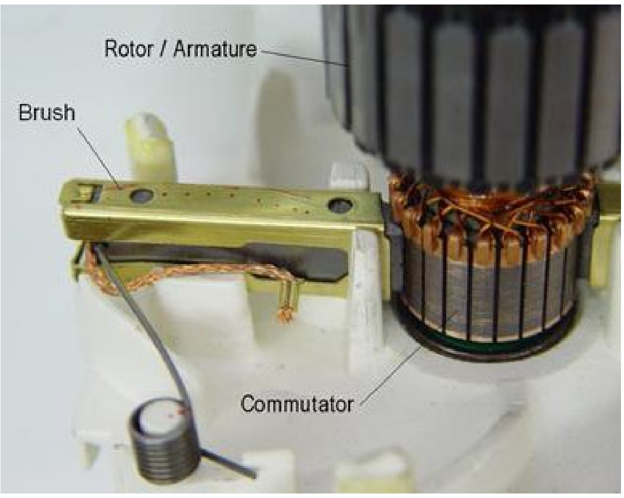
- it is very soft
- it is a conductor
- it self-lubricates.

The brushes provide one of two functions:

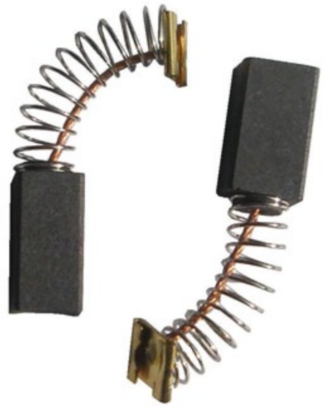
- for a d.c. generator the brushes act to tap the supply off the armature. The brushes act as conductors and lubricators
- for a d.c. motor the brushes act to deliver current to the armature, where again the brushes act as a conductor and lubricator.

The carbon brushes need to act as lubricators so that current can be supplied to the armature or taken from it and to ensure that the brushes don't overheat and weld onto the surface of the commutator.

The pictures over the page show how the necessary pressure is maintained on the carbon brush via a coiled spring.



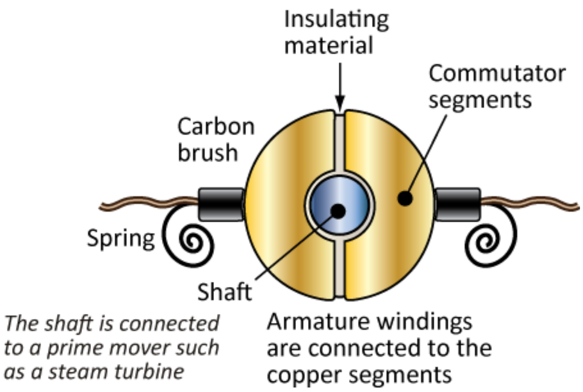
The spring maintains pressure on the brush to sit tightly onto the commutator.



The brushes do wear down and when the brush reaches approximately 6 mm in length, then it should be replaced.

Commutation

A commutator is made up of a series of segments which are conductors separated by thin pieces of an insulator such as mica.

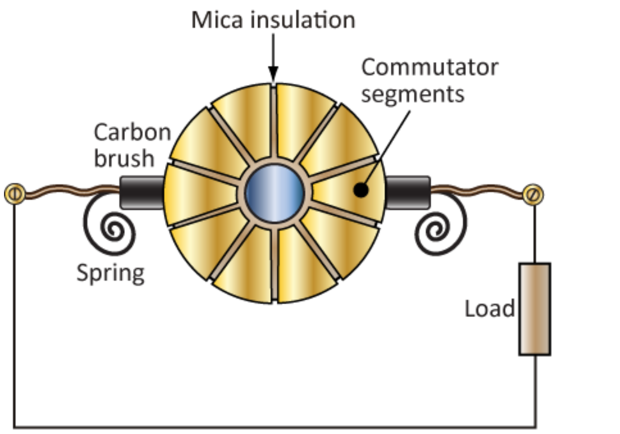


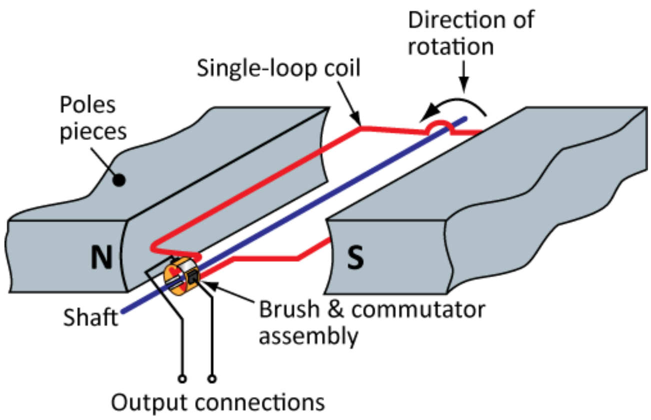
You are looking at the end of the commutator here.

If the machine were a generator, the armature would be driven by an external mechanical source and a d.c. supply would be supplied to the field coil, this supply is called the ***excitation current***. The carbon brushes are set so that one of them acts as the *positive* of the d.c. whilst the other acts as the *negative*. This is also a function of the commutator.

Try to follow the diagrams. We'll assume that we are dealing with a very simple commutator, and that there are only a few segments separated by thin pieces of mica.

Below, we can see the segments and the brushes that are connected to the load, as the armature turns the commutator turns as well. Since the armature windings rotate within the magnetic field produced by the poles, an alternating supply is created.

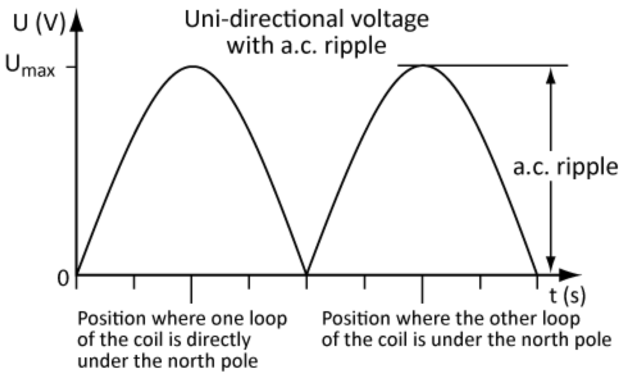


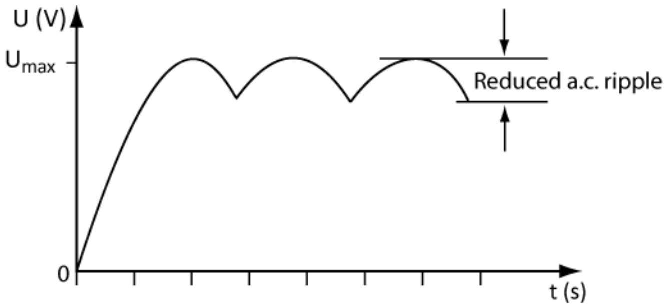


End view of commutator having multiple coils. Single loop coil connected to brushes.

As you learnt in the unit on magnetism, the highest value of voltage is developed when the coil moves under a pole as most flux is being cut. As we have brushes and not slip rings (otherwise, the output would be an a.c. waveform), then the same brush will be collecting the positive flowing current, and the same brush will be collecting the negative current. Hence, the alternating voltage being created is turned into a uni-directional or d.c. supply.

Consider the following waveform diagrams showing the voltage generated from firstly a single-loop generator and then a generator having multiple armature conductors.





As you can see this waveform is still not very even, and so we need to increase the number of commutator segments so that there will be a smoother d.c. output.

The voltage moves in one direction. However, it does vary between 0 and U_{Max}. This variation is called a.c. ripple. Here is the output from a four-segment commutator.

From these two diagrams you can see that by increasing the number of segments on the commutator you get a much-improved d.c. output.

It is probably easier to picture what is happening with a generator, as the armature is driven by an external mechanical source and the electrical output can be seen above.

However, with a motor, current is supplied to the armature via the brushes. The commutator now acts a little bit in reverse. As the d.c. current is interrupted by the insulating segments of the commutator then there is a change in the supply. This change is sufficient to produce a varying magnetic field.

The varying magnetic field is necessary for the motor, not only to start, but also to run, as the magnetic field produced by the armature needs to interact with the magnetic field produced by the field coils.

We now know how a d.c. machine gets two magnetic fields to interact with each other and so turn. Remember that the field coil is provided with a supply or excitation current. This current produces a magnetic field in the yoke, core poles and interpoles.

For a generator, the armature is turned by an external source and the armature winding cuts the lines of magnetic flux produced by the field coil. This induces an emf in itself, which produces a current which is tapped off via the carbon brushes which are in contact with the commutator at the end of the shaft. The commutator turns the alternating emf into d.c.

For the motor, the field coils are supplied with current to produce a magnetic field. The armature is also supplied with current via the brushes and commutator. The supply to the armature produces a varying magnetic field that interacts with the magnetic flux produced by the field coil and so the motor turns.

There are two ways in which the armature windings can be connected to the commutator, ***lap*** and ***wave*** windings. This is beyond where we need to go, suffice to say that there must be field windings and armature windings, how they are arranged is not important at this level of study.

In the next session we will be looking at d.c. motors it more detail. Now attempt exercise 2.

Exercise 2

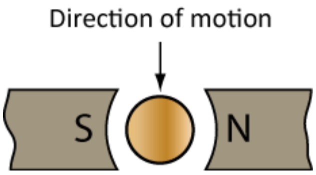
1. What is the purpose of the field coils in a d.c. machine?

2. What is the purpose of the commutator in a d.c. machine?

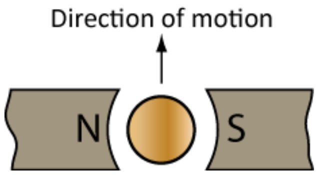
3. Why are pole shoes fitted onto the end of the poles?

4. In considering generators, what do the brushes run on when creating the following supplies?
    a) Alternating current
    b) Direct current load

5. For the following diagrams, state whether the direction of the induced current is flowing into the paper or flowing out of the paper.



a)



b)

6. For the flowing diagrams, state whether the direction of motion is upwards or downwards.

a)

b)

Challenging question

7. Think about the field winding. We already know that the strength of the magnetic field will be dependent on the current flowing in the winding. What will happen to the current flow and the machine should the resistance of the field winding increase?

3: Types of d.c. machines

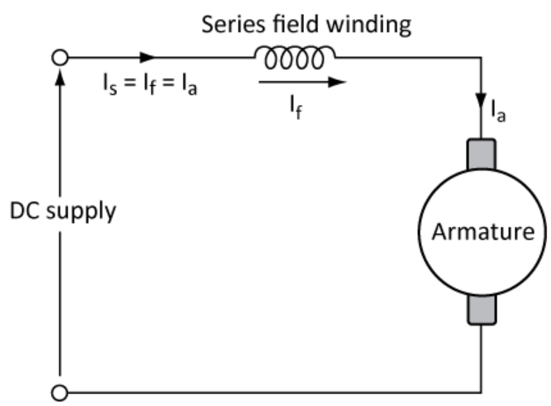
In this session the student will:

- Gain an understanding of the types of d.c. machines.
- Describe the specific types of d.c. machines used.

In the last session we saw the basic setup of a d.c. machine. At its most basic level any d.c. machine has a field winding, which generates a static magnetic field, and an armature winding, which via the commutator creates a changing magnetic field. In this session we are going to consider how these two windings can be connected and think about what the effects are of these connections.

Series motors and generators

This is the first way in which the field winding and the armature can be connected together. Have a look at the diagram below.



When we look at the connection of d.c machines, we are really looking at how the field winding and the armature are arranged.

Direction of rotation can be made by reversing the field (series winding), or the armature connections.

In the series machine, the field coil and the armature are connected in series. This means that the current flowing in this machine is the same in the armature and the field coil. The armature usually has a high current and so the field coil must also be capable of carrying the same current.

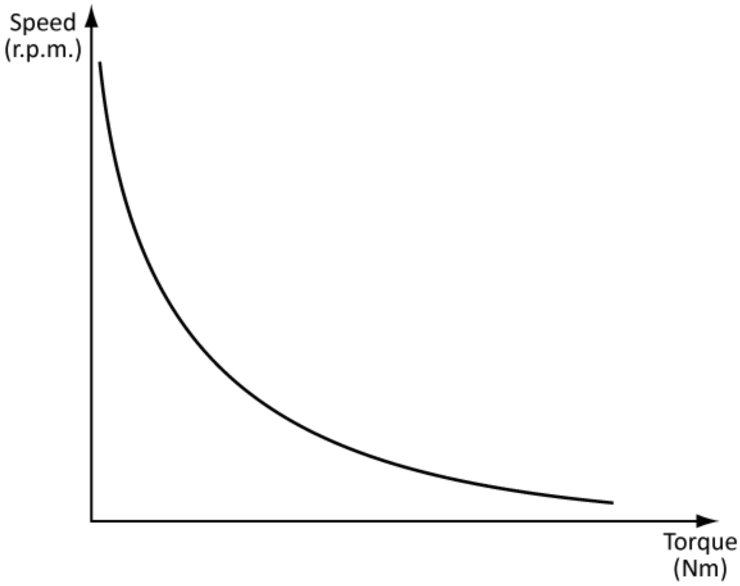
Remember that in a series circuit, it is the current that remains whilst the voltage drops across the various resistors within the circuit.

In our series-wound machine, the resistors are the field coil and the armature winding, along with a little bit of resistance across the brushes. Because of the large current, the field coil usually has a few turns of a large area conductor. The large area of the conductor reduces the resistance.

If more current control is needed, then an additional resistor is connected in parallel with the field winding. This additional resistor is called a ***diverter***.

So why the series-wound machine?

We'll take a look at some basic characteristics of series motors and see how these show us what we get from the machines (Remember that these are characteristics; they are not exact values for a given motor. Change the motor and the values will change, but the general shape of the graphs will not).



In this graph, we can see the speed and torque characteristics of a series motor

If we look at the speed related to the armature current you can see (from the graph above) that the speed falls as the load increases (current increases as the load increases). More importantly however, notice what happens when the current falls. As the load falls and consequently the current, then the speed of the series motor increases rapidly.

If the load were removed altogether then the motor would destroy itself as there would be no limit to the speed.

There is a relationship between torque and current in the series motor.

$$T \propto I^2$$

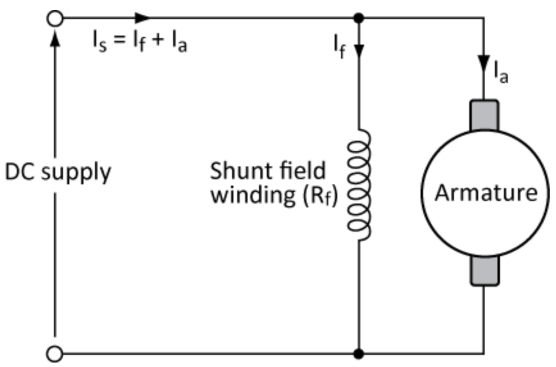
This shows that when the current doubles, then the torque would increase four times!

Looking at the torque related to the armature current you can see that the torque or turning force increases with an increase in the load. This shows that the series motor is ideal for those situations where the motor needs to be able to start up against load such as, cranes, lifts etc.

Shunt wound motors and generators

Shunt wound just means that the field windings are in parallel

Have a look at the diagram below showing a shunt wound motor. Obviously, a generator would have an output, rather than a supply.



With the shunt wound machine, the field coil is connected in parallel with the armature. This means that the field coil and the armature both receive the full supply voltage.

Direction of rotation can be made by reversing the field winding, or the armature connections.

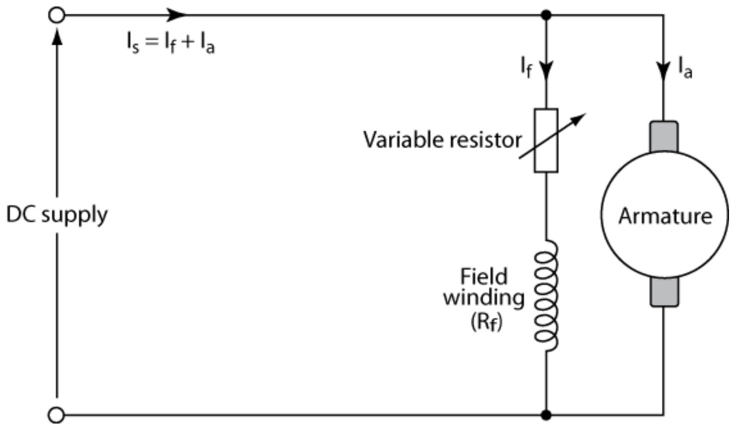
You will remember from your work with series and parallel circuits that the current supplied to or from a parallel network, divides between the various paths depending on the number of routes open to it. For a shunt machine, this means that the field coil usually has quite a small current flowing in it, whilst the armature carries a much greater amount.

When you look at a shunt-wound machine, you may well find that the conductors to the field coil are much thinner than the conductors going to the armature. This is because of the small current flowing through the field coil.

Shunt motor

The shunt motor is considered to be a constant speed motor. Because the supply is connected directly across the field coil the flux created by the current, and hence the induced emf remain constant.

The speed does fall off with an increase in load, although even this can be compensated for by weakening the flux. To get some level of speed control a variable resistor is connected in series with the field coil. This affects the current through the coil and so affects the flux.

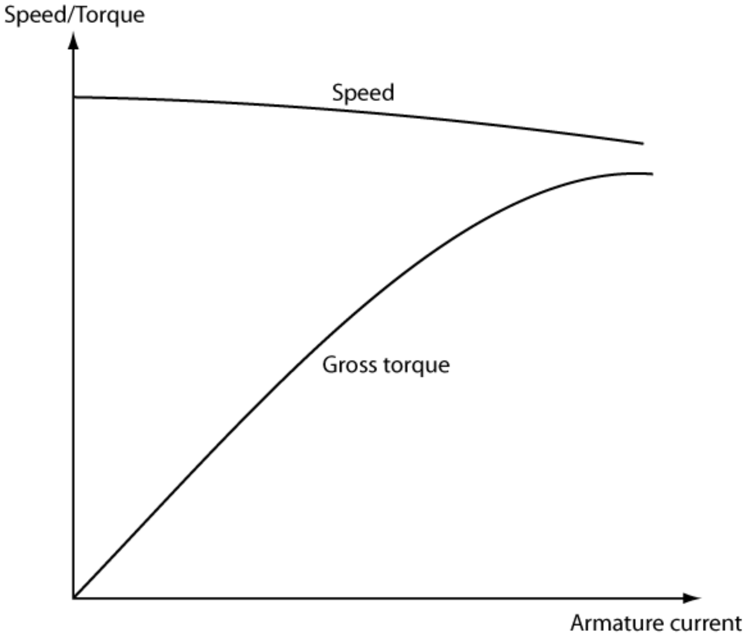


You can see that the current flows from the supply, and then divides at the connection between the field coil and the armature. The field coil current is labelled $\boldsymbol{I_f}$, and the armature current is labelled, $\boldsymbol{I_a}$**.** This can be seen in a simple equation.

$$I_{\text{Supply}} = I_{\text{Armature}} + I_{\text{Field}}$$
$$I_S = I_a + I_f$$

The majority of the current will flow through the armature.

Have a look at the characteristic curves below showing the characteristics of the shunt motor.



Two things should be noted:

- the speed remains reasonably constant over a wide range of loads
- the torque is directly related to the current in the armature. As the current in the armature rises, then so does the torque.

With the series motor, the torque is directly related to the armature current^2.

Shunt $T \propto I_a$

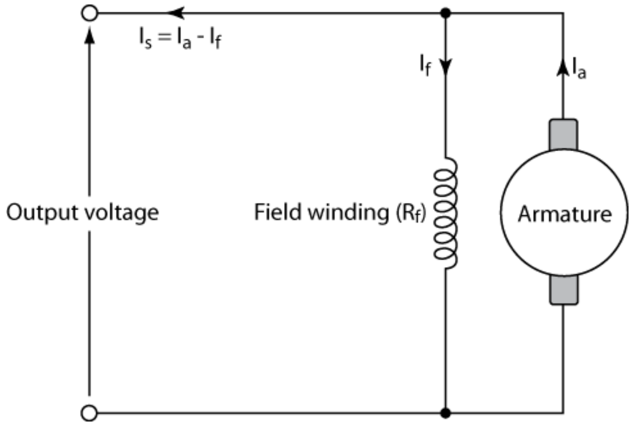
Series $T \propto I_a^2$

The relationship between torque and armature current in the two types of motor can be seen here.

Shunt motors are commonly used on machine tools, fans and conveyors. Their constant speed characteristics give them the advantage over other types of d.c. motor.

Shunt generator

The shunt generator is the same machine as the shunt motor. This time however the machine is driven by an external mechanical source. The induced emf effectively becomes the output of the generator. Have a look at the current distribution in the generator circuit.



This time the current is being supplied from the armature. However, the direction of current can be expressed as an equation.

This time the field current is subtracted from the armature current to give us the supply current.

$$I_{\text{Supply}} = I_{\text{Armature}} - I_{\text{Field}}$$
$$I_S = I_a - I_f$$

The shunt generator has the ability to provide a constant voltage and is less open to speed changes with a variation in load, unlike the series generator.

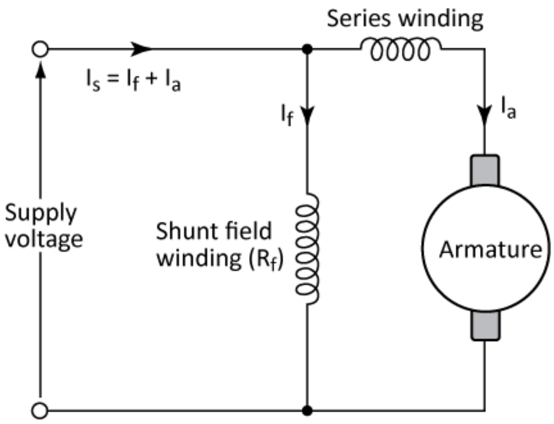
Compound wound motors and generators

As you have seen, there are a number of advantages and disadvantages associated with series and shunt machines:

- series machines are capable of starting up against heavy loads whereas shunt ones can't
- series motors vary their speed when their load varies. Shunt motors have a fairly constant speed as the load varies.

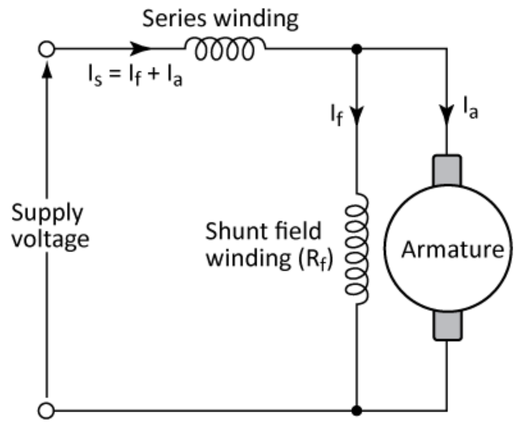
Compound machines combine the two to try to get the advantages of both, that is the ability to start up against the load combined with the constant speed provided by the shunt machine.

There are two ways in which compound wound machines can be connected. These are called ***short shunt*** and ***long shunt***. Have a look at the diagrams below.



Long shunt d.c. compound motor

The field winding is connected in parallel with both the series winding and the armature.



Short shunt d.c. compound motor

Here the field winding is only connected across the armature.

I know that this all sounds a little strange; however the difference between the two is not that large.

These motors are a combination of series and shunt types, they are used where the characteristics of both is required, i.e. where severe starting conditions are needed along with constant speed. Hence, uses would be lifts, conveyor belts, air compressors etc.

Direction of rotation can be made by reversing both the field and series winding, or the armature connections.

Exercise 3.

1. Name three types of d.c. motors and sketch their connections.

2. State how the speed of a d.c. motor can be varied?

3. Which d.c. machine is useful for operating over a wide variety of loads at a constant speed, and which machine is useful for starting up against heavy loads?

3. What would happen to a series motor if the load were reduced to zero?

4. How can the direction of rotation of a d.c. motor be achieved.

4: Basic operation of a.c. induction motors

In this session the student will:

- Describe the nature of a rotating magnetic field.
- Gain an understanding of induction motors.

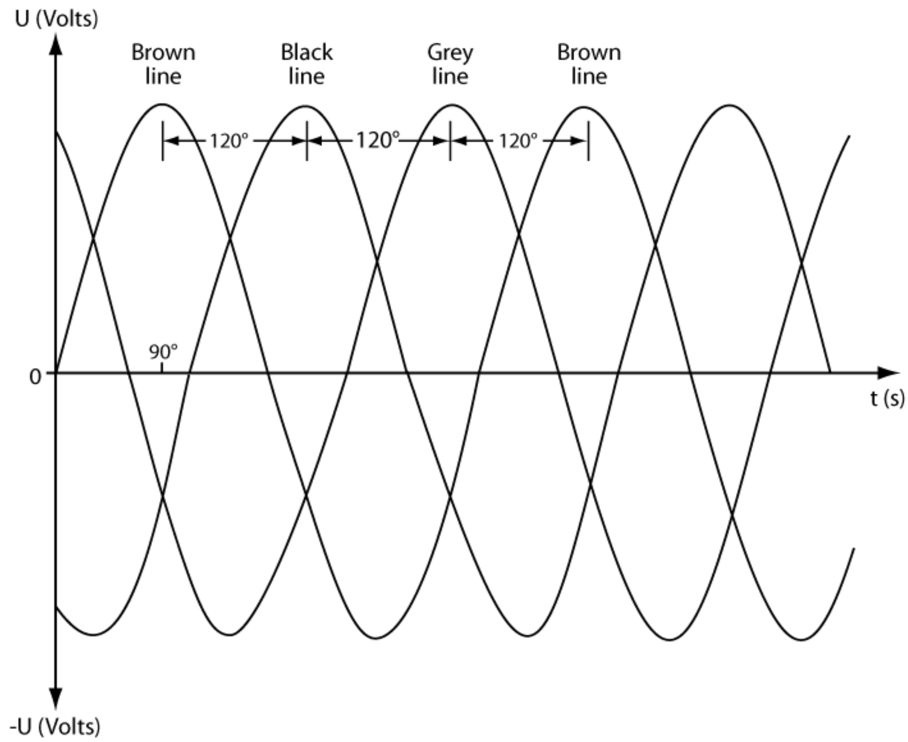
We now move on to consider a.c. machines, and in many ways the three-phase motor is the easier one to start with.

The key problem has always been, ‘how do we get the motor to self-start?’ We need at least two magnetic fields interacting for rotation to be produced, and into this comes the idea of a rotating magnetic field.

You are already aware that electrical power is generated as an alternating waveform (a.c.). It is therefore easier to drive a.c. motors rather than d.c. machines. We will begin by looking at the three-phase induction motors.

It would be worthwhile just clarifying what is meant by **three-phase**. A generator consists of three distinct electrical windings, effectively three coils. When the rotor is turned within a magnetic field these windings, which are placed 120º away from each other, produce an emf (induced emf).

Three windings will naturally produce a three-phase supply. The reason for this is that the induced emf in each winding is always rising or falling at different points in the a.c. cycle, compared to the other windings. This seems a little complex so have a look at the diagram below.



You can see that there are three a.c. waveforms. If the generator had six electrical windings then we would get a six-phase supply separated by 60°. As it is, we get three phases separated by 120°.

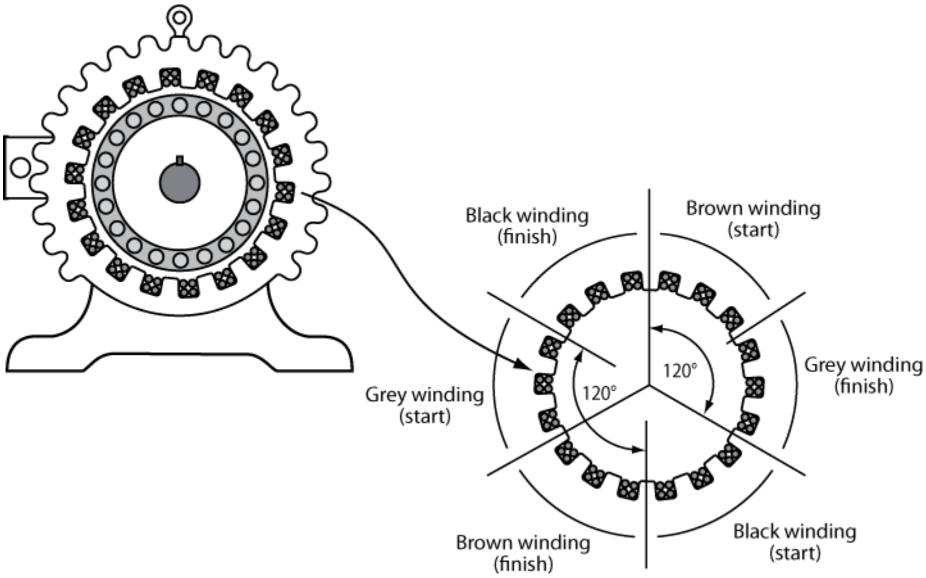
There are very real benefits to this. The main ones however are that three-phase supplies allow for smaller machines and cables, as the loading can be spread across each of the phases.

There are two general types of **three-phase induction motors**. These are:

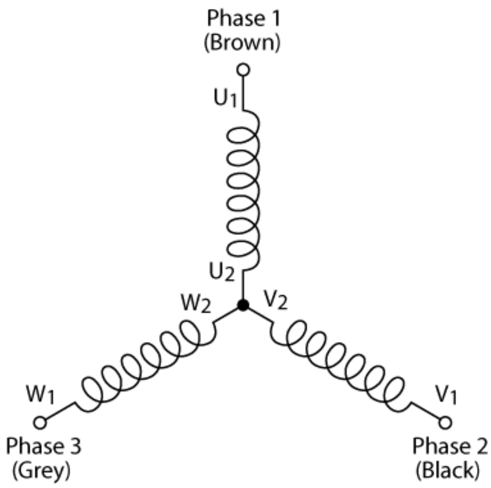
1) **wound rotor**
2) **squirrel cage**.

We'll look at the wound rotor constructions in a later session. But for now let us concentrate on the squirrel cage motor as this is by far the most common motor used today.

A supply is connected to the ***stator*** of the motor. The stator is just the electrical windings around the outside (non-moving) of the motor.



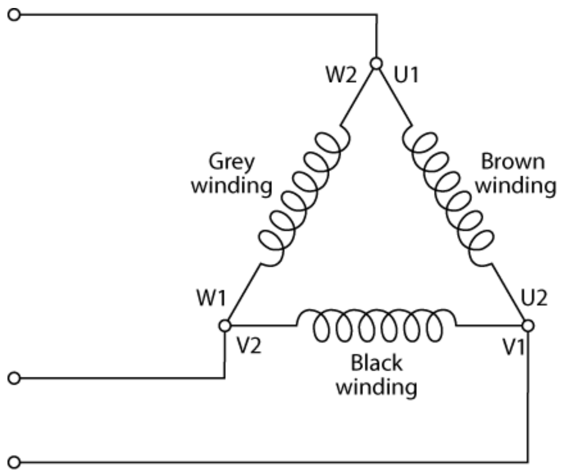
These windings are fixed and don't rotate. The supply can be connected in any one of two ways. These two ways are called ***star*** and ***delta***. Have a look at the diagram below.



This is a star-connected arrangement. There are three sets of windings here. Here they are labelled U_1, U_2; V_1, V_2; W_1, W_2. However, you may see them labelled U, U_1; V, V_1 etc.

The supply to the windings is labelled ***brown***, ***black*** and ***grey*** phase. If we connect the end of each winding together so that U_2, V_2 and W_2 are connected together, then we produce a star shape, hence the name. This is not the shape that you see when you look at the windings themselves, but an electrical representation of what is happening.

Have a look at the diagram below. Again there are three sets of windings here, labelled **U_1**, **U_2**; **V_1**, **V_2**; **W_1**, **W_2.**



The supply to the windings is labelled ***brown***, ***black*** and ***grey*** phase, as before.

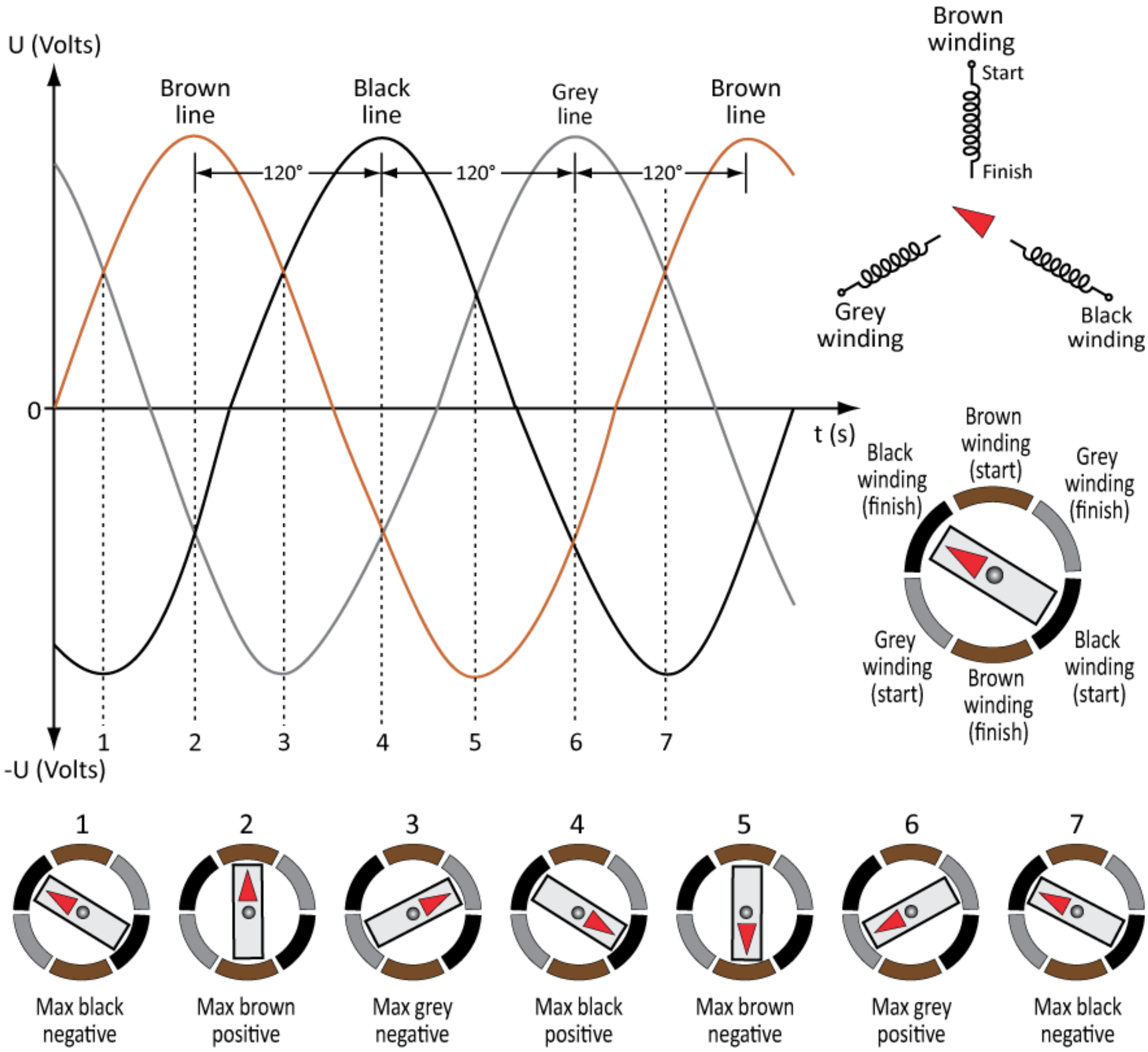
Now if we connect the end of each winding to the beginning of the next winding, so that **U_2** is connected to **V_1**, **V_2** is connected to **W_1**, and **W_2** is connected to **U_1**, then we have connected our winding in a delta (Greek letter shaped like a triangle) shape, hence the name.

This is not the shape that you see when you look at the windings themselves, but an electrical representation of what is happening in terms of their connection.

I'll go through simply what happens when a supply is connected to a squirrel cage motor.

When the supply is turned on, a three-phase supply is connected across the three sets of windings. Because the windings are set 120° apart then the magnetic field in each winding is rising or falling at three different times. This produces, what is known as a ***rotating magnetic field***.

The diagram below shows the idea of apparent movement.



The three sine waves are rising and falling at different times, this gives us the rotation.

The numbers relate to specific points in time when we have one of the phases at a maximum.

In the above diagram we are looking at the first '***snap-shot***' of time (1). It can be seen that the black phase is carrying the maximum current but is in the negative half cycle and is therefore producing a peak magnetising force but pointing away from itself.

Looking at position 2, you will see that when the brown phase is at a maximum in the positive cycle, then the grey and black phases are at half their maximum value. The arrow shows the overall or resultant magnetising force direction.

This shows that the resultant magnetic field has moved in a clockwise direction by 60°. You should be able to see a pattern forming now.

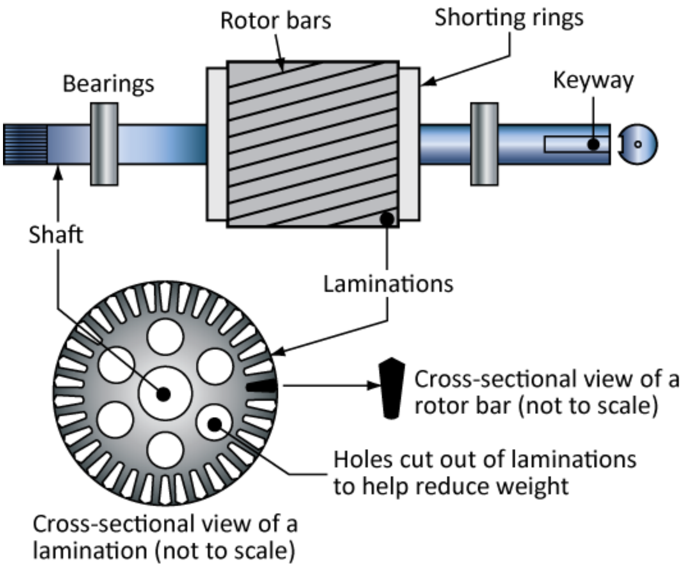
This process is continually repeated and the resultant field will continually move in a particular direction. It doesn't have to be a clockwise direction. Change any two of the windings and the direction of the magnetic field will suddenly become anti-clockwise.

These magnetic fields rise and fall at the same frequency as the supply, and so we state that the magnetic field 'rotates' at the ***synchronous speed***.

The synchronous speed also depends on the number of poles that the particular motor has. You have been introduced to the idea of poles on a machine, and you should know that we are talking about the number of magnetic north and south poles that we have.

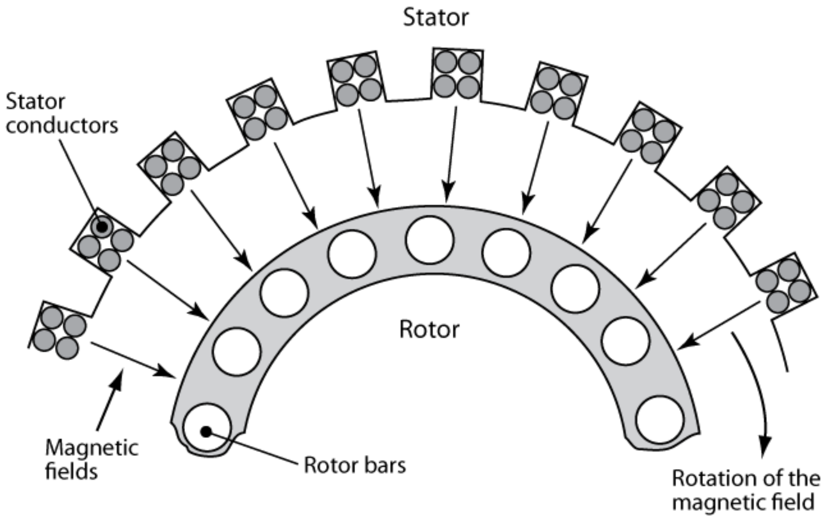
In our squirrel cage motor, we now have our supply and our rotating magnetic field, running at synchronous speed.

The ***rotor*** shown below, of this type of machine is made up of thick bars of aluminium shorted at the ends by aluminium rings.



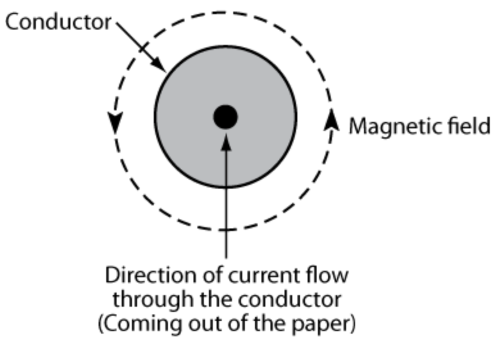
You should be able to see where this particular motor gets its name. The bars and end rings form a shape similar to that used by mice etc. in their exercise wheels. The name was initially given by Nikolai Tesla, who was said to have seen squirrels using the exercise wheels.

The rotor also has a laminated steel core, which concentrates the magnetic field. Let's take a brief look at how the torque is produced in this type of motor. Have a look at the diagram below.

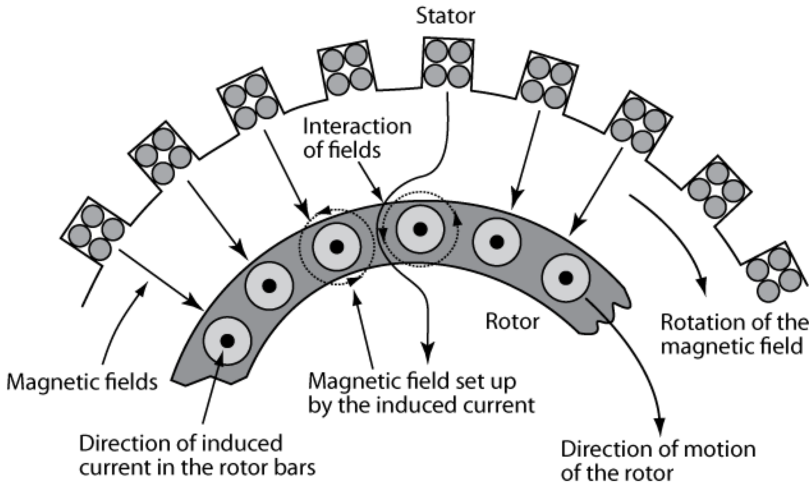


If we assume that we know the direction of the rotating magnetic field is to the right, and that the magnetic field is '***flowing***' from the stator to the rotor. This will create an induced emf in the conductor. This induced emf will create an induced current that is flowing out of the page. We can determine this using Fleming's light-hand rule because we are considering the direction of motion in a motor.

Because we know the direction of the current in the conductor, we can determine the direction of the magnetic field surrounding it.



Below, we can see that the force on the conductor is going to act to 'push' the rotor in the same direction as the rotating magnetic field.



The field becomes weak on the right hand side because the main field and the field set up by the current in the rotor bars are moving in opposite directions. The overall field on the left hand side is strong, because both fields are moving in the same direction.

We can now see that the combination of the two magnetic fields must produce an interaction, and this force is multiplied by the number of conductors that are placed within the magnetic field.

> 'As the rotating magnetic field passes by each of the rotor bars, an induced emf is created in each of the bars. This induced emf in turn creates an induced current. To create the necessary large magnetic field in the rotor the bars are shorted out at each end creating a circulating current. The interaction of the rotating magnetic field and the magnetic field surrounding the rotor bars causes the rotor to turn in the same direction as the rotating magnetic field.'

Things are obviously a little more complicated than this, but this is fundamentally, what happens in a three-phase squirrel cage induction motor.

Exercise 4

1. How is a rotating magnetic field created within a three-phase induction motor?

2. Name the main elements of an induction motor.

3. Why are the rotor bars skewed and not straight?

4. Why is the ac induction motor used more often than other types?

5. In considering the rotor of an induction motor, why is it laminated and how are they separated from each other. What other piece of plant is similarly constructed.

5: Speed, poles, frequency, emf and magnetic field strength

In this session the student will:

- Gain an understanding of the effect of poles, frequency and the like on the nature of an induction motors.

In the last session we considered in some detail the basic principles of operation of three-phase induction motors. In this session we are going to look in a little more detail at the various factors that affect the way in which the various motors work.

Frequency, slip and poles

The rate at which the rotor turns depends on two things:

- the synchronous speed of the rotating magnetic field:
  - this depends on the frequency
  - pairs of poles
- the amount of slip.

Synchronous speed

The speed of the rotating magnetic field is directly related to two specific items, the frequency and the number of pairs of poles.

The equation linking the terms is; $n_s = \frac{f}{p} \, rev \, per \sec$

Where $n_s = synchronous\,speed\ (rs^{-1}),\ f = frequency\ (Hz)\ and\ p = pairs\ of\ poles$

In many ways frequency is the obvious choice, after all the frequency tells us how many times that the supply changes direction in a second. So why should the number of pairs of poles have an effect?

Let's consider the difference between a two-pole and a four-pole motor. In a two-pole motor the poles will be separated by 180°. In a four-pole motor the poles will be set 90° apart. In a two-pole motor the flux changes direction every half cycle and so on a 50 Hz supply the time taken is:

Using $n_s = \frac{f}{p} rps$ (remember p is in pairs of poles).

Therefore the speed of the rotating magnetic field in a two-pole motor is;

$$n_s = \frac{50}{1} = 50 rps \qquad or\ 3000 rpm$$

In a four-pole motor the flux moves 90°and takes four half cycles (two cycles) to make a complete turn.

Using $n_s = \frac{f}{p} rps$

Therefore the speed of the rotating magnetic field in a four-pole motor is;

$$n_s = \frac{50}{2} = 25 rps \qquad or\ 1500 rpm$$

So changing the number of poles has a very significant effect on the speed of the machine.

Slip

Consider the effect of the rotor moving at the same speed as the rotating magnetic field:

> If the rotor were to speed up to synchronous speed, then there would be no difference between rotating magnetic field and the rotor and there could be no induced emf. If there is no induced emf then there is no induced current, and with no induced current there can be no second magnetic field.

The basic rule is

No interaction between magnetic fields = No movement

Slip, therefore is the difference between the speed of the rotating magnetic field and the speed of the rotor.

It is worthwhile therefore looking at speed and slip now. I've already stated that the synchronous speed depends on the speed of the rotating magnetic field and the number of poles that exist. We therefore already know the speed of the rotating magnetic field as this is directly related to our supply, and as our supply is at a frequency of 50 Hz, then our speed should be at 50 Hz.

Synchronous speed is labelled as $\boldsymbol{n_s}$ (small n) and is measured in revolutions per second $\left({}^{r}\!/\!{}_{s} \text{ or } rps \text{ or } rs^{-1} \right)$. Frequency is labelled as $\boldsymbol{f}$ (small f) and is measured in Hertz (Hz). The numbers of poles that exist are considered as pairs of poles. This means that a six-pole motor has three pairs of poles.

Slip is the difference between the synchronous speed and the rotor speed. Without slip there can be no torque developed. The rotor will always run slightly behind the rotating magnetic field which we are calling synchronous speed.

As you would expect there is an equation to consider.

$$s = \frac{n_s - n_r}{n_s} \times 100\%$$

The slip however, is usually expressed as a percentage but can be left at a per unit value.

Let us try some examples.

1). A motor has a speed of 500 rpm. If the frequency of the supply is 50 Hz, what will be the number of pairs of poles?

$$n_s = \frac{f}{p} \text{ } \textit{transpose for p}$$

$$p = \frac{f}{n_s} = \frac{50}{500} = \frac{50}{8.333} = 6 \text{ pairs of poles}$$

Notice that you should convert revolutions per minute into revolutions per second before carrying out the rest of the calculation. Effectively, rs^{-1} is the base unit and all things should relate to that.

We'll work through a couple more of examples to get a feel of what is happening.

2). An a.c. induction motor has a synchronous speed of 50 rs^{-1}. The shaft of the motor is running at 48 rs^{-1}. What is the per unit and percentage slip?

$$s = \frac{n_s - n_r}{n_s} = \frac{50-48}{50} = 0.04\,p.u.\ \ or\ 4\%$$

It is common to have such a level of slip in an induction motor.

3). A six-pole induction motor is connected to a 50 Hz a.c. supply and has a slip of 6 %. Determine the speed of the motor.

$$n_s = \frac{f}{p} = \frac{50}{3} = 16.667\,rs^{-1}$$

$$s = \frac{n_s - n_r}{n_s}\ \ transpose\ for\ n_r$$

$$n_r = n_s - 0.06n_s = n_s(1-0.06) = 16.667 \times (1-0.06) = 15.67\,rs^{-1}\ \ or\ 940\,rpm$$

I only put in the speed per minute to give some idea of the rate of rotation that people can commonly relate to. It is normal to leave your answers in rs^{-1} form.

4). An eight-pole a.c. induction motor is running at 11 rps when it is connected to a 50 Hz supply. What is the value of slip?

$$n_s = \frac{f}{p} = \frac{50}{4} = 12.5\,rs^{-1}$$

$$s = \frac{n_s - n_r}{n_s} = \frac{12.5-11}{12.5} = 0.12\,p.u.\ or\ 12\%$$

The slip calculated above is quite large. This would tend to show that the motor is coming under excessive loading: the lower the slip, the lower the load on the motor; the higher the slip, the higher the loading on the motor.

Change in emf

Any change in voltage to a three-phase induction motor can alter the torque significantly.

There is a direct relationship between the applied voltage and the torque developed by the motor, however this relationship is not linear.

$$T \propto U^2$$

This can be proved; however at present what you need to be conscious of is that for a voltage reduction to 80% of full voltage, then the torque will fall by $0.8^2 = 0.64$ of final value.

Magnetic field strength

In any a.c. induction motor there are a series of conditions that are met. These are:

- a voltage is induced in each rotor conductor while it is being cut by the flux. This induced voltage produces an induced current that flows around the rotor windings or bars since it is a squirrel cage.
- the induced voltage produces an induced current that flows around the rotor windings
- the rotating magnetic field and the magnetic field generated within the rotor experience a mechanical force
- the force always acts in a direction to drag the rotor conductors along with the rotating magnetic field.

Now going back to the start of this list we can see that if the magnetic flux density were to change then there would be a significant change in the force exerted on the conductors.

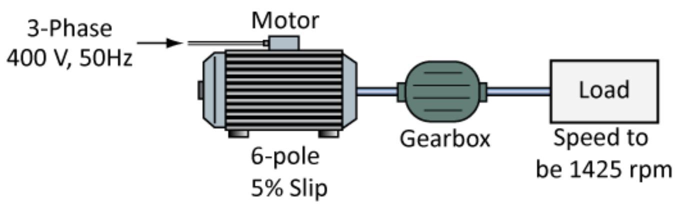
Exercise 5

1. What determines the amount of slip in an induction motor?

2. A three-phase 15 kW 6-pole induction motor is connected to a 400 V 50 Hz supply.
   i) What is the synchronous speed?
   ii) If the voltage were to fall to 380V would the synchronous speed change?

3. A four-pole 400 V, 60 Hz three-phase induction motor is loaded so that there is a slip of 2 rps. What is the speed of the rotor?

4. A motor/load arrangement is shown below. Determine;
   i) The synchronous speed
   i) The output speed of the motor
   ii) The gear ratio of the gearbox.



6: Types of three-phase induction motors

In this session the student will:

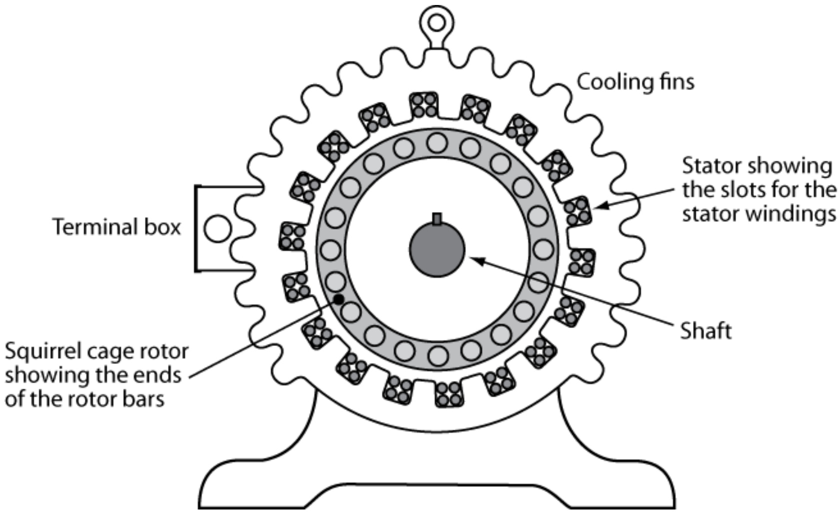
- Gain an understanding of the different types of three phase induction motors.

In the last session we considered the effects of frequency, poles, voltage and magnetic flux to the way in which the three-phase induction motor works. In this session we will consider the basic types of three-phase induction motors that exist and where they are used.

There are two general types of **three-phase induction motors**. These are:

- wound rotor
- squirrel cage.

We'll look at their respective constructions. This will enable us to use the correct terminology, and be able to separate a.c. machine theory from that of d.c. machine theory.



The diagram above shows the general layout of a three-phase squirrel cage a.c. induction motor.

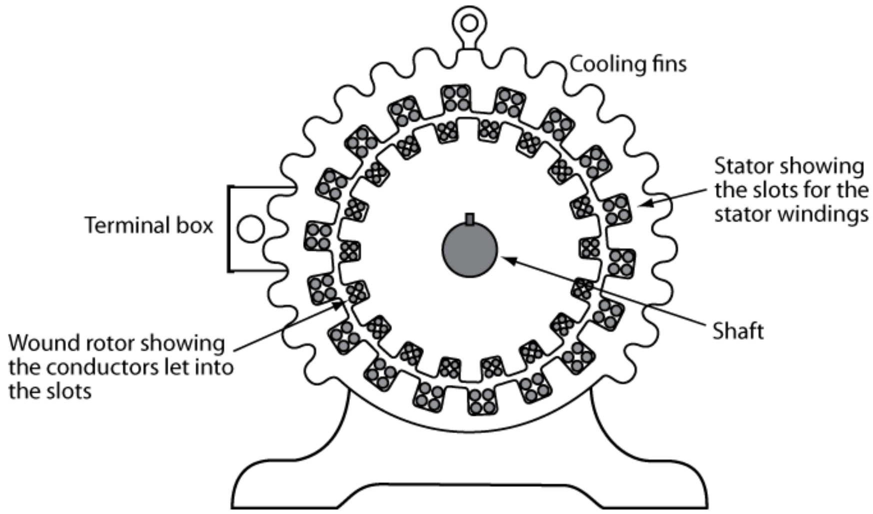
The squirrel cage induction motor is the most commonly used type of three-phase induction motor. This is because of ease of manufacture and cost. With the squirrel cage induction motor there is no way in which the induced current can be altered in the rotor as the shorted conductors are set in the manufacturing process.

Electronic speed control can take place but this doesn't act directly on the rotor. This means that when the motor is turned on there is no control of speed or loading. This has consequences that we will look at when we look at the different ways in which these motors can be started.

However, there is a second type of three-phase induction motor.

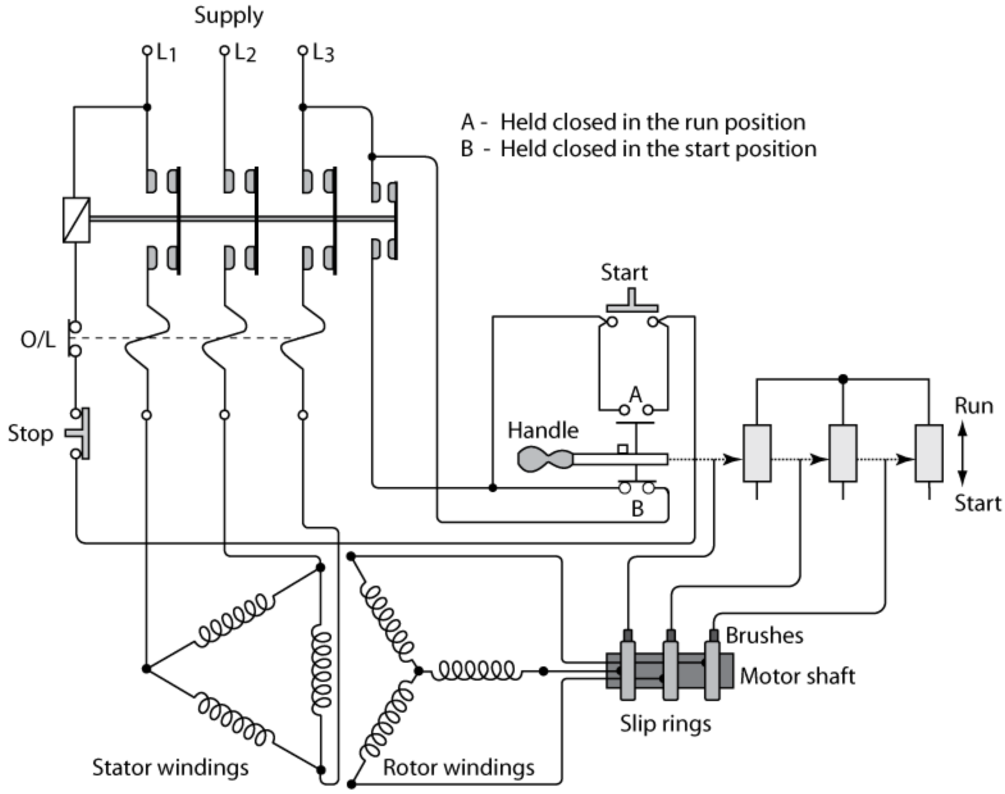
Wound rotor induction motor

The diagram below shows a three-phase wound rotor induction motor.



With the wound rotor motor however there is the ability to control the speed and the loading of the rotor.

With the wound rotor motor, the supply is connected directly to the stator, which is connected in delta. The rotor however, is made up of windings rather than solid aluminium bars shorted out at each end. The rotor windings are connected in star and the ends of the windings are connected to a set of slip rings. These slip rings are then connected to a bank of external resistors connected in series with the windings. Have a look at the diagram over the page.



This type of induction motor operates in much the same way as the squirrel cage induction motor. The same rotating magnetic field is created, and there is the same interaction between the magnetic field created by the stator and the rotor.

So, what is the difference? There are three specific areas in industry where wound rotor motors are useful:

- start up of heavy loads
- variable speed drives
- frequency converters.

Start-up against load

When a squirrel-cage induction motor starts up against heavy loads then the rotor winding gets very hot; it acts like a short-circuited transformer. With a wound rotor motor the heat is generated within the external resistors which can be cooled down externally: this keeps the rotor cool

In addition the external resistors can be varied as the motor picks up speed and it therefore allows the motor to develop its maximum torque while it accelerates. This limits the start-up time.

Variable speed drives

Varying the resistors will vary the speed of the motor. The external resistors act to control the current providing some crude speed control. This speed control can be improved on, and we will consider this in a later session.

Frequency converter

Here the wound rotor motor is ‘driven’ by a separate squirrel-cage induction motor and acts as a three-phase generator. To get this effect however the rotor must be driven in the opposite direction to the rotating magnetic field.

Exercise 6

1. How does a wound rotor induction motor differ from a squirrel cage induction motor?

2. What type of three-phase induction motor would you choose to use for:
   i) a lathe
   ii) a variable speed pump.

3. In simple terms what is a basic use of a frequency converter

4. Think about what would happen if one of the phases were to be lost on a three-phase induction motor. Sketch a circuit diagram and write an explanation.

Now move on to the next session.

7: Single-phase induction motors

In this session the student will:

- Gain an understanding of the different types of single phase induction motors.
- Gain an understanding of how single phase induction motors operate.
- Gain an understanding of the problems associated with starting of single phase induction motors.

From a previous session, you learnt that with the three-phase induction motors, the rotating magnetic field is created in the stator. This magnetic field then '**cuts**' the conductors in the rotor. This cutting of the rotor bars creates an induced emf in the rotor, which in turn creates an induced current that then goes on to produce a second magnetic field. It is the interaction between the rotating magnetic field and the magnetic field created in the rotor that causes the rotor to turn.

Therefore, with our three-phase motors, we were able to use the three phases to create a rotating magnetic field. This makes them self-starting.
With the single-phase machines, we have to be a little more creative in providing the necessary variation in the magnetic fields to give them the necessary starting torque.

There are a number of different types of single-phase a.c. induction motor. However, with this type of motor, only one phase is provided to the motor. It is **not** self-starting

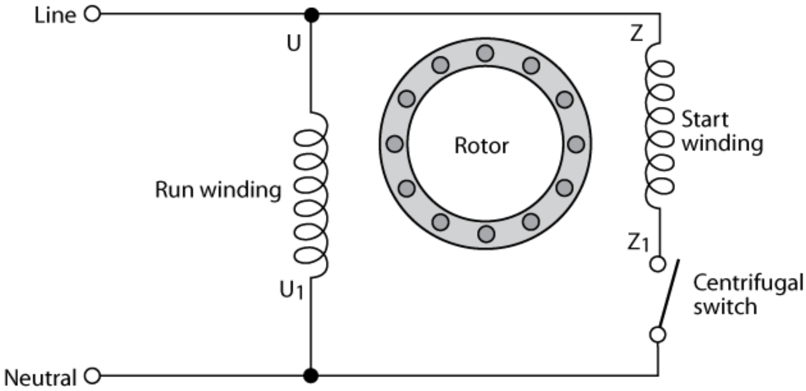
The single-phase supply creates a '**pulsating magnetic field**' rather than the rotating one of the three-phase supply. Unless we can somehow get a second magnetic field to rise and fall at a different time to the one created by the supply, we will get no starting torque or rotation.

What needs to be created is some type of '***false***' second rotating magnetic field.

The three types of single-phase induction motor have very different ways of creating this second magnetic field.

Single-phase split-phase induction motor

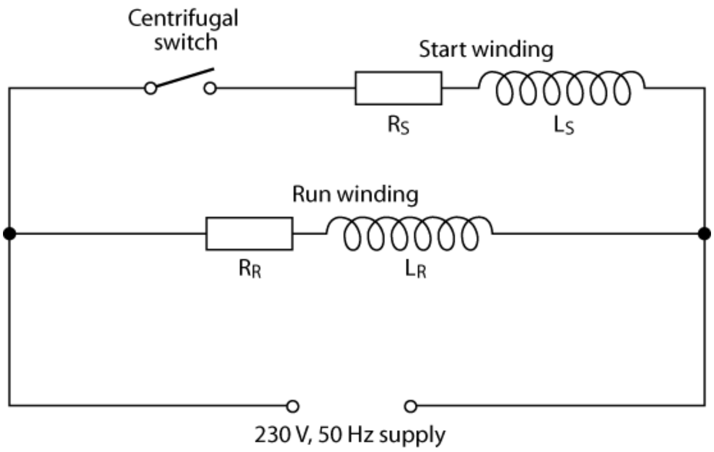
Have a look at the diagram below.



This is a very much-simplified diagram; however, it is good enough for our purposes.

We have our main run winding. This is effectively a large coil of wire. When current flows through the coil a pulsating magnetic field is created around it.

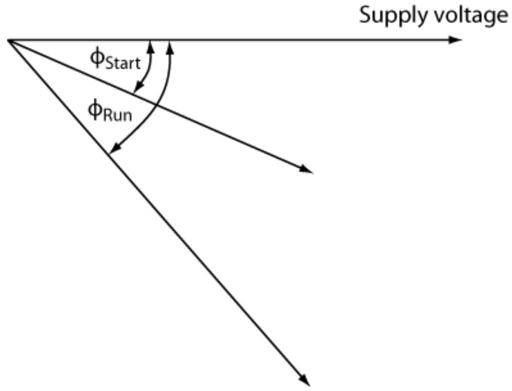
We also have a second winding. This second winding is connected in parallel with the run winding.



The windings have been broken down into their two component parts; their resistance and inductance.

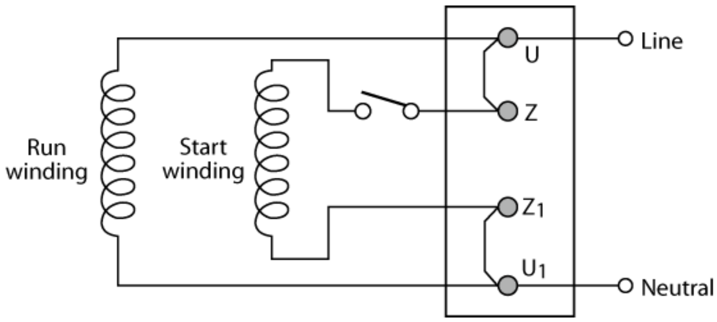
The length, and hence the inductance and resistance, of start winding is different to the run winding. This difference in resistance and inductance creates a difference in impedance and so we get a different phase angle between the run and start windings.

Have a look at the phasor diagram below.



You can see that because of the variation in resistance and hence impedance between the two windings, there is a difference in phase angle between the two windings. This difference in the phase angle caused by the two windings means that the magnetic fields that they produce will be rising and falling at different times.

The variation in the two magnetic fields is sufficient for the motor to self-start. We have in effect created a type of rotating magnetic field, although admittedly it is a poor one. Have a look at the connection diagram of this type of motor.



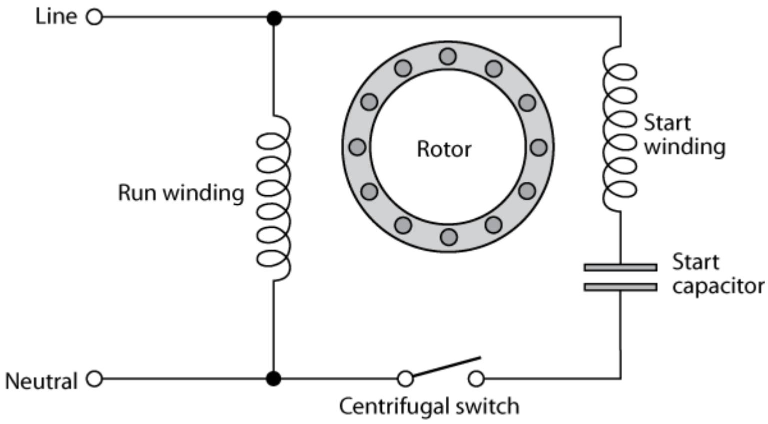
At a certain speed, the centrifugal switch opens and the start winding is open circuited (taken out of the system). This type of motor has good starting torque, usually 1.5 times the full load torque.

If you wanted to reverse the direction of this type of motor, all you have to do is reverse either the start winding connections or the run winding connections; never both at the same time!

Single-phase capacitor-start induction motor

The same problem of self-starting still occurs. Remember that every type of single-phase induction motor is just trying to get over the problem of self-starting.

With the split-phase motor, we have the use of two different windings, with this creating sufficient difference between the magnetic fields to create a variation on the rotating (pulsating) magnetic field. The capacitor start motor has a slight variation on this theme. Have a look at the diagram below.

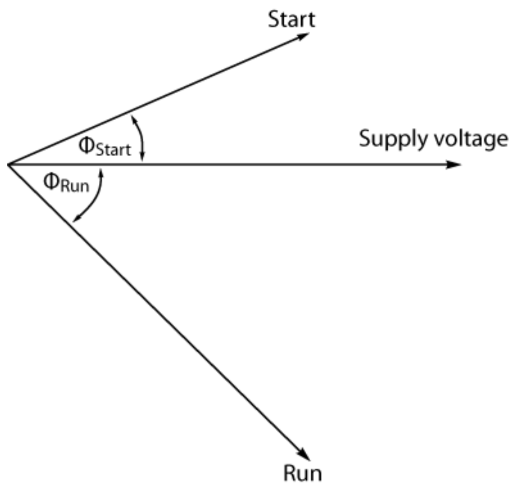


The only difference between this and the split-phase motor is the addition of a capacitor connected in series with the start winding.

You will be aware that a capacitor acts on the supply exactly opposite to the way an inductor behaves. A pure inductor lags the supply by 90° whereas a pure capacitor leads the supply by 90°.

If we therefore, place a capacitor in series with the start winding, the angle between the start and run windings will increase.

Have a look at the phasor diagram.



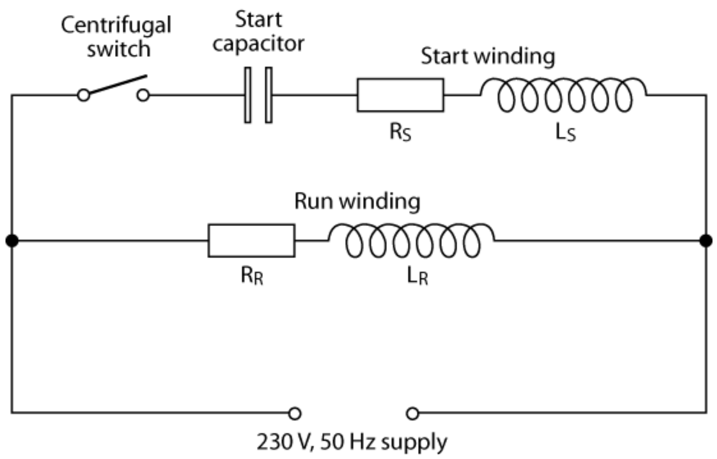
When compared to the phasor diagram of the split-phase motor, you should notice that the difference in angle is much greater. This provides a much smoother starting torque. The smoothness of the torque is solely due to the increase in the difference in phase angle between the start and run windings. The two magnetic fields have been separated that little bit more.

There are two types of capacitor-start motor. One type has a centrifugal switch, switching out the capacitor and start winding at an appropriate point. The other type is called a '***capacitor-start and capacitor-run***'.

Capacitor start

The reason for using a capacitor is to improve the starting torque.

Considering the circuit below, when the motor has run up to speed, the capacitor is switched out of the circuit, along with the start winding by the centrifugal switch.

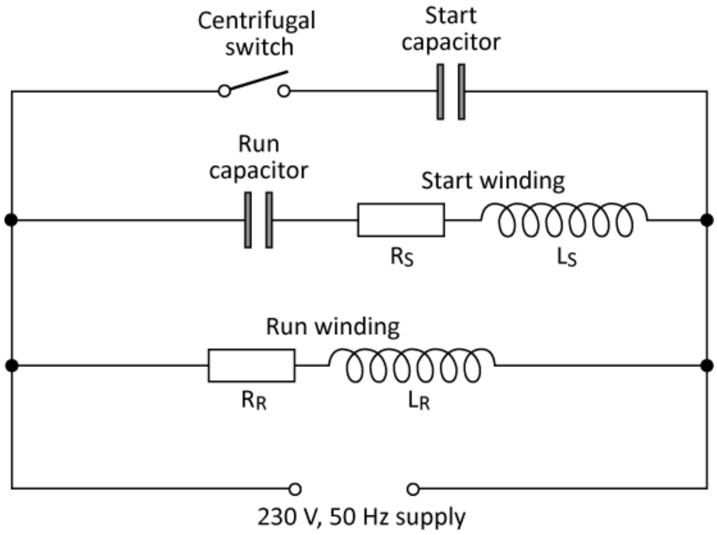


Capacitor start and run

This type of motor has two capacitors connected during the start period which improves the starting torque even further than if it just had the one capacitor as mentioned above.

The start capacitor switches out, via a centrifugal switch when the motor has reached a certain speed.

Have a look at the diagram below.



When running normally the run capacitor and start winding are still connected, this improves the running efficiency when connected to a load.

The diagram shows what is happening electrically. You can see that this is a parallel a.c. circuit.

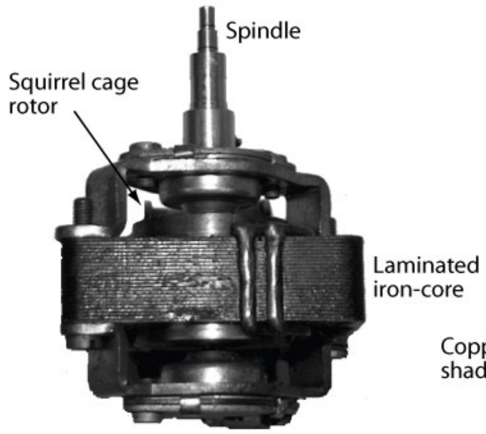
This motor can be reversed the same way as the split-phase motor. Swap over the start or run winding, but not both.

Generally the single-phase motors are smaller than 1 kW, although there have been some built which are 40 kW rating.

Single-phase motors of whatever type are generally less efficient than three-phase motors.

Single-phase shaded pole induction motor

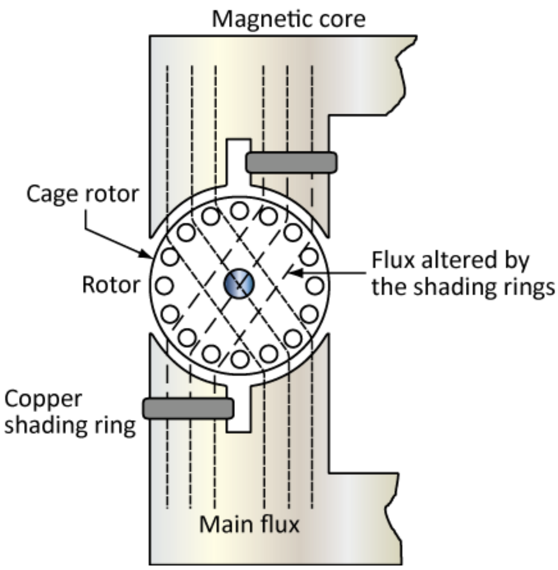
Again, we are still dealing with the problems of self-starting. Have a look below.



This is the simplest single-phase a.c. motor. There is a coil, a core and a rotor. The coil has current flowing in it, and this creates our pulsating magnetic field. This magnetic field is focussed in the laminated iron core.

As with our other motors, this would be of absolutely no use, unless we could create a second magnetic field. This is where the shading rings come in.

Shading rings are solid pieces of copper, looped around part of the core. These pieces of copper have a very low resistance and a large area. The shading rings create a different path for the magnetic flux, and so two effective magnetic fluxes are created.



The two fluxes are sufficiently out of phase with each other and now link with the rotor. This enables the rotor to turn. This diagram shows the path that the flux takes through the core and the rotor.

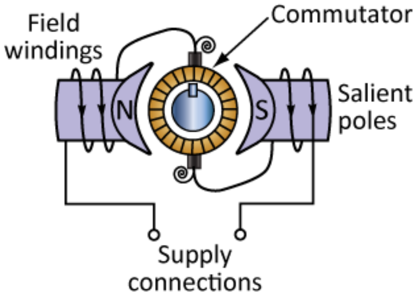
It is this variation in the magnetic fields that create the self-starting.

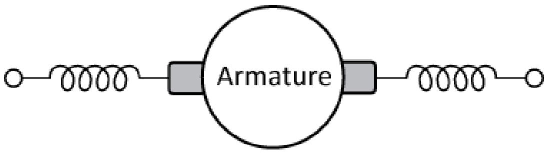
This type of motor has very poor efficiency and a low power factor. However, it is also very quiet. They are often used in fans for cooling power supplies and in the older type of cheap record players. They are however not good at speed control and are used less and less.

Universal Motor

A universal motor is one that operates on either single-phase ac or dc supply. These motors are normally made in sizes ranging from about 4 W to 300 W.

They are available in larger sizes for special conditions. The low power ratings are used on vacuum cleaners, sewing machines, food mixers, and power hand tools.





To change direction of rotation, simply change the connections to the armature

The salient-pole type is the most popular type of universal motor. The salient-pole type consists of a stator with two concentrated field windings, a wound rotor, a commutator, and brushes. The stator and rotor windings in this motor are connected in series with the power source. There are two carbon brushes that remain on the commutator at all times. These two brushes are used to connect the rotor windings in series with the field windings and the power source.

The universal motor does not operate at a constant speed. The motor runs as fast as the load permits; i. e., low speed with a heavy load and high speed with a light load. Universal motors have the highest power-to-weight ratio of all the types of electric motors.

The operation of a universal motor is much like a series dc motor. Since the field winding and armature are connected in series, both the field winding and armature winding are energized when voltage is applied to the motor. Both windings produce magnetic fields which react to each other and cause the armature to rotate.

Exercise 7

1. Why does a single-phase motor require a second winding?

2. What is the main difference between a split-phase and a capacitor start/run induction motor?

3. A capacitor start capacitor run motor when turned on runs up to speed and then cuts out. After a further period of time the motor runs up to speed again and then cuts out. Eventually, the overload operates. Where would you start looking for the problem?

4. How can the direction of rotation in a split-phase induction motor be reversed?

5. Investigate the type of motor used in household refrigerators. What type and rating are they? What are they used for?

8: Starting of machines

In this session the student will:

- Gain an understanding of how a.c. and d.c. machines are started.

In this session we are going to deal with the starting of a.c. three-phase motors and d.c. motors. Both require special ways of starting, although for very different reasons.

Starting of three-phase motors

When a three-phase induction motor is first turned on there is a large short-term overload. This is because of the large amount of inrush current (current due purely to the resistive effect of the windings) and because the induced emf has not created a large enough induced current to oppose the supply.

What this means, is that when the motor is initially turned on then a current much larger than the normal (*run*) current is delivered. With an induction motor, this can be between five and ten times greater than the run current. Although this doesn't damage the machine, generally, the supply authorities are not altogether impressed by this sudden 'glitch' on their supply.

There are no strict rules regarding the requirement of starting mechanisms for three-phase induction motors. The actual type of control mechanisms will vary from installation to installation. A reasonable '*ball park*' figure is 5 kW. Any motor rated at more than 5 kW should have some means of controlling the initial starting current. There are further requirements however that are of more immediate concern, and these relate to BS 7671 (IEE Wiring Regulations). Chapter 55, Section 552 deals with rotating machinery.

The gist of Regulations 552.1.1 and 552.1.2 is:

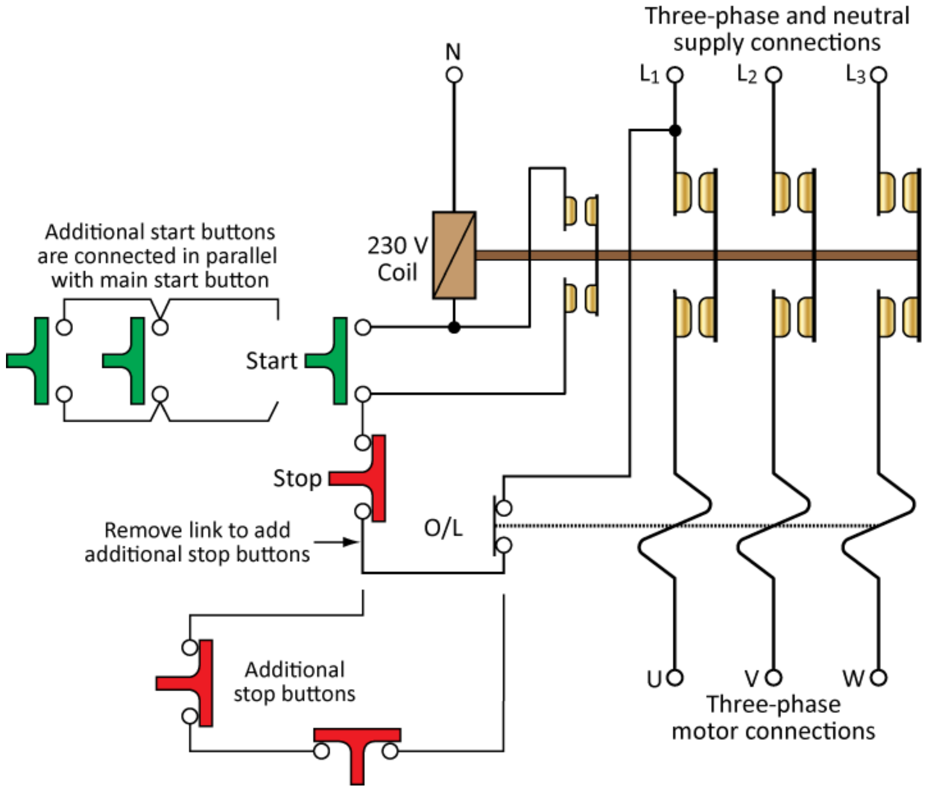
- the starting and running of motors heats them up. The motors, control gear and cables must be capable of handling the generated heat
- motors rated above 370 W must have some means of overload protection.

Four types of starting have generally been used on three-phase induction motors, although these are not the only ones. We will only consider the four. These are:

- direct-on-line starter
- star-delta starter
- auto-transformer starter
- rotor resistance starter.

Direct-on-line starter

Have a look at the diagram below.



This is the most common type of starter for motors generally smaller than 5 kW. In the diagram on the previous page, only the contactor and its overloads are shown.

There are two aspects to the DOL starter:

- supply and overload arrangements
- under-voltage arrangements.

Both are necessary.

The control circuit consists of an operating coil, a start button (normally open), a stop button (normally closed) a set of hold-on contacts and some means of the overload breaking the circuit.

Try to follow the description of what happens whilst looking at the diagram above.

We have a 230 V coil and so we require a separate neutral. We could just as easily use a 400 V coil and leave out the neutral. Some companies use 110 V coils for electrical safety reasons.

The ***start button*** is a ***normally open*** contact, it is pressed to make, not pressed to break. The ***stop button*** and the ***overload switch*** are ***normally closed*** contacts. The stop button/s and the overload switch are connected in series with each other.

If you follow the diagram above: when the start button is pressed current flows through the made contact, through the coil, and then on through the stop button and overload to form our circuit. The coil attracts a contact (switch) and the contactor makes; connecting the supply to the load.

However, when the start button is released, without the use of a hold-on contact the circuit is broken and the coil is de-energised, breaking the contact between the supply and the load.

This contact is connected in parallel with the start button.

This contact effectively shorts out the start button and so the coil remains energised even when the start button opens the circuit.

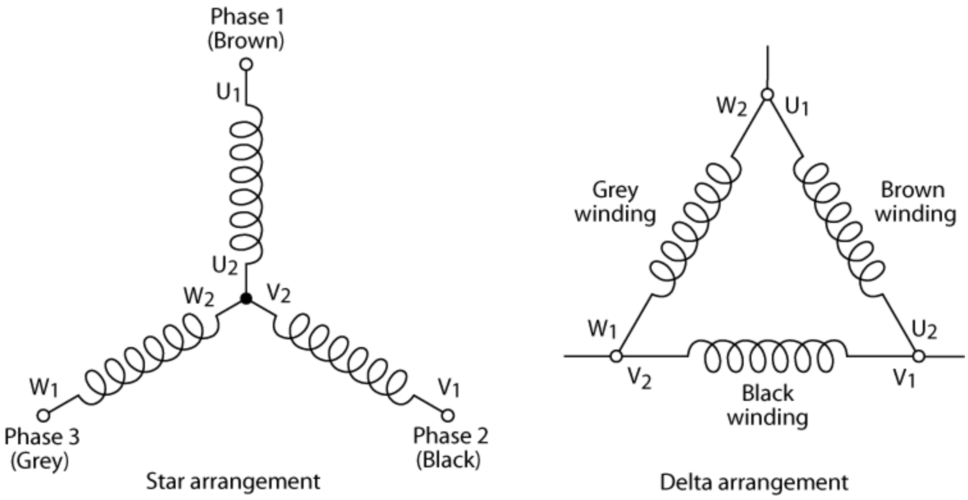
We get our under-voltage protection here as well. If the overload operates, then the current in the coil circuit ceases to flow and the coil de-energises. This is something to check when you complete a Schedule of Inspections.

Even if the overload were then to reset, because the hold-on contact has opened, it would require someone to press the start button again to make sure that the motor started. The motor would be unable to start up on its own.

To add additional stop and start buttons is simple. If you require additional start buttons, just connect more normally open contacts (start buttons) in parallel with the start button. If you require more stop buttons, just connect more normally closed contacts (stop buttons) in series with the stop button.

Star-delta starters

Direct on line starters provide large starting currents (five to ten times the run current) which are fine for the smaller type of three-phase induction motor. For larger three-phase induction motors, this is not acceptable. This is not because of any inherent damage that could be done to the motor, but because any large current demand sets a bit of a problem for the distributors. It also has a dramatic effect on the consumer's electricity bill!



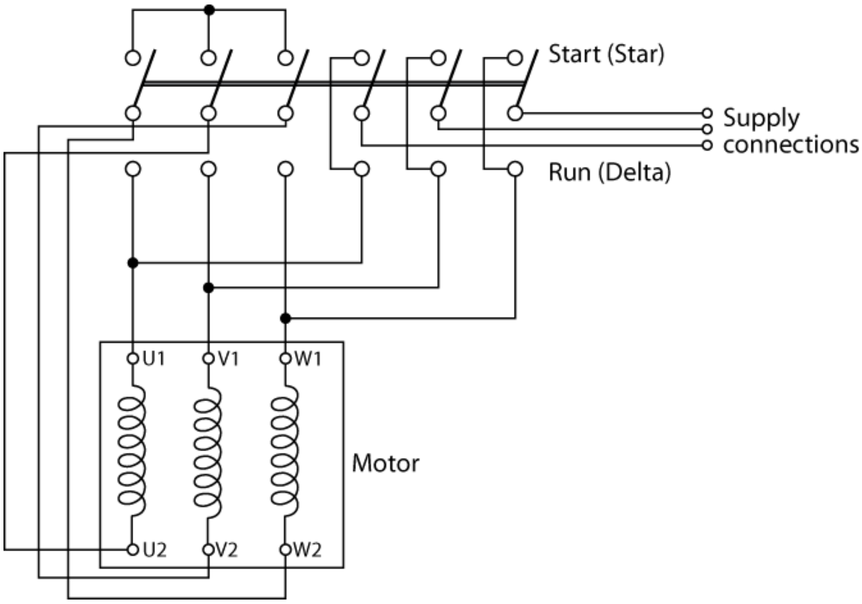
The star-delta starter reduces this starting current. The star-delta starter does just what its name suggests. It connects the motor windings first in star and then in delta.

With the star-delta arrangement, the motor windings are effectively extended and brought to a remote control point outside of the motor.

One end of the motor winding is connected to the supply. The opposite end of the winding is initially connected in such a way as to short them out, thus providing us with a star arrangement. Once the motor is up to speed, the connections are then altered to connect them in delta.

The connection is made via two bars of brass running the length of the starter with appropriate gaps left to create the star/delta effect.

Have a look at the diagram below. This is the arrangement of a hand-operated star-delta starter.



When you look at the diagram things may seem a little bewildering. Take care to notice how the connections are made in delta (have a look at the diagram of star and delta windings on the previous page). The end of the brown phase is connected to the beginning of the grey phase; the end of the black phase is connected to the beginning of the brown phase; and the end of the grey phase is connected to the beginning of the black phase.

This should match the starter shown above. The switches are all linked, and so when the handle is moved from star to delta, all the switches move.

With the hand-operated starter, there are three positions, '***OFF***', '***STAR***' and '***DELTA***'. The mid position is the off position.

There are not too many hand-operated star-delta starters left nowadays. More often there is an automatic star-delta starter.

To start the motor you would push the handle down. The starter has now connected the motor windings in star. When the motor has reached an appropriate speed, you'll know this by the change in sound made (a bit like a car engine sound change as you change gear), you would move the handle sharply up through the off position into the delta position (pointing upwards).

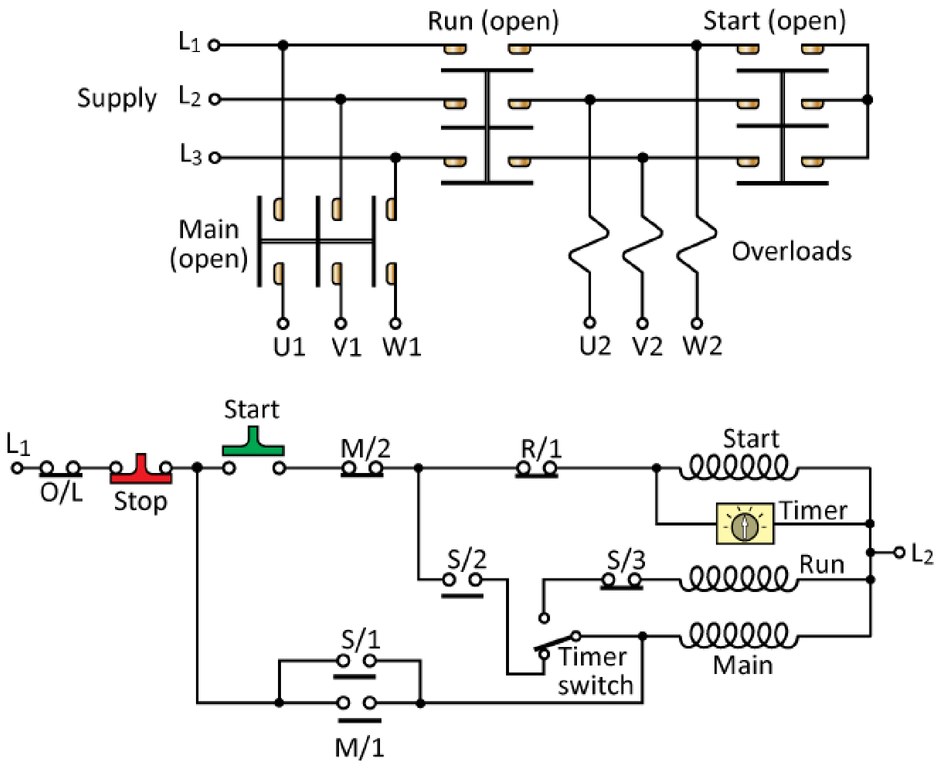
Automatic star-delta starter

Typical control mechanism for an automatic star-delta starter.

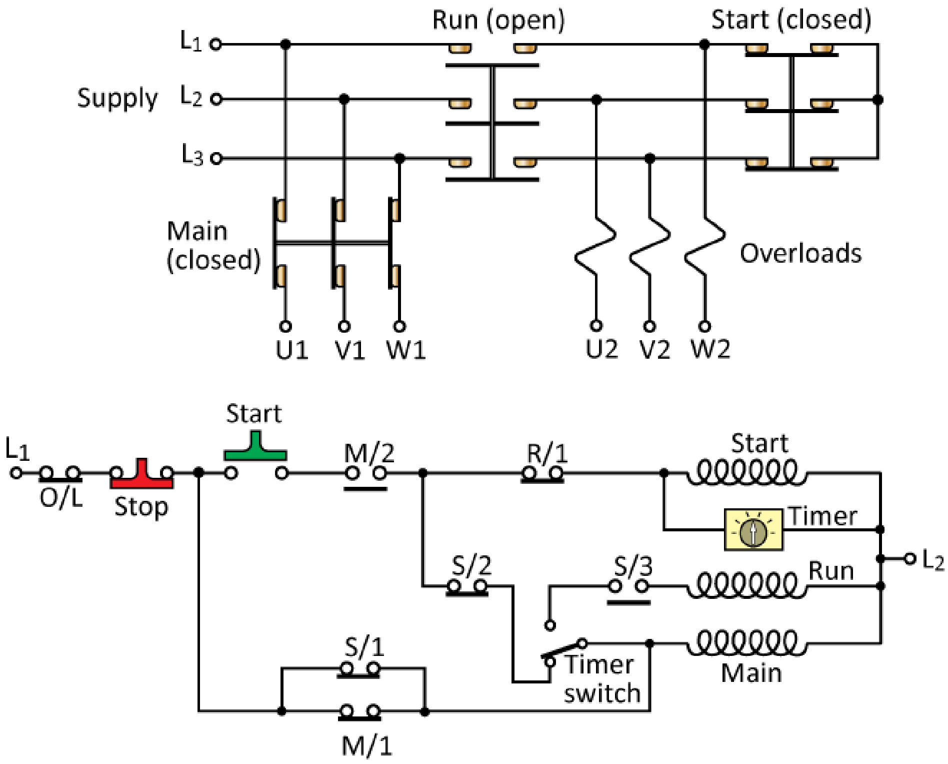
The timer control which switches from star to delta connections is quite noticeable as being the round control knob on the left hand side of the starter.

It is a little awkward to follow, but remember that the key features are the shorting of the ends of the windings in star and then the connecting of the ends of the windings in delta. Have a look at the series of diagrams over the next few pages.

In this diagram, the motor has no supply. You can see in the top part of the diagram that all the contactors are open. If you look at the bottom line diagram, you can follow the line and see that there is no supply on to the coils.

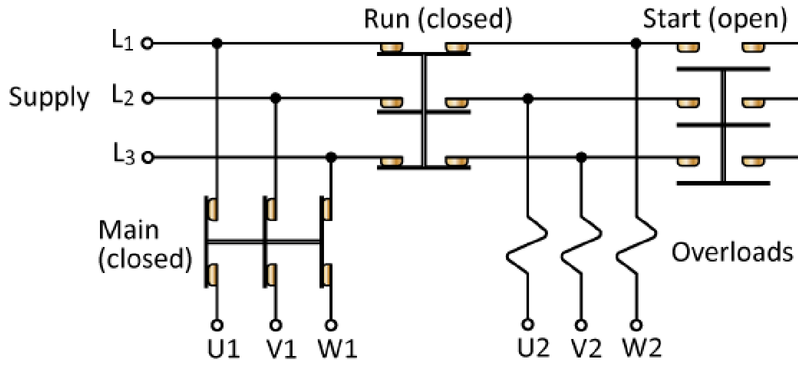


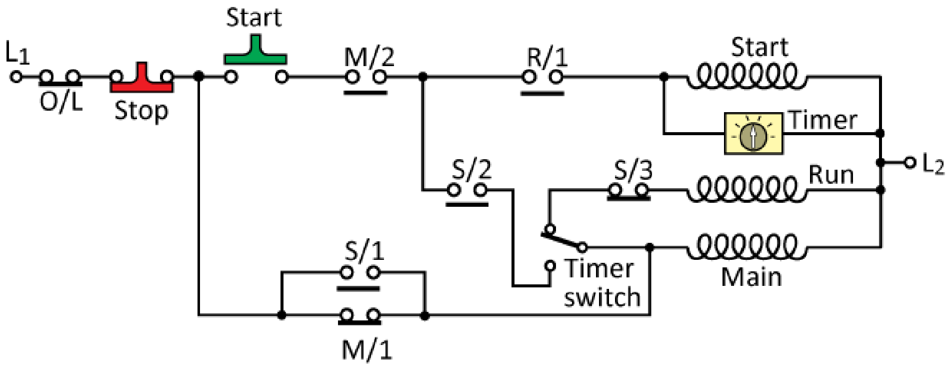
Here, assume the start button has been pressed and a supply has been put onto the main coil via ***M/2***, ***S/2*** and the timer switch. The main contactor pulls in with contact ***M/2*** opening and ***M/1*** closing. ***M/1*** is acting as a hold-on contact.



At the same time as this is happening a supply is put onto the start contactor coil and this contactor pulls in. As this pulls in the hold-on contact ***S/1*** closes and the start coil is held on via the timer switch. ***S/2*** is now closed contact as is ***R/1***. The timer is also energised to start its countdown. The motor is now connected in star.

When the timer has run its course, it operates a switch and the supply to the start coil is removed, although the main contactor is still held on via ***M/1***.





The current now flows through the timer switch, onto the coil of the run contactor, through the now closed auxiliary contact ***S/3***. The start winding can no longer be pulled in, as ***R/1*** is now open.

To reset everything the overloads would need to operate or the stop button would need to be pressed. The motor is now running in delta.

Don't try to memorise this, there is always a diagram given inside the starter whether it be a simple DOL, or a more complicated star-delta starter.

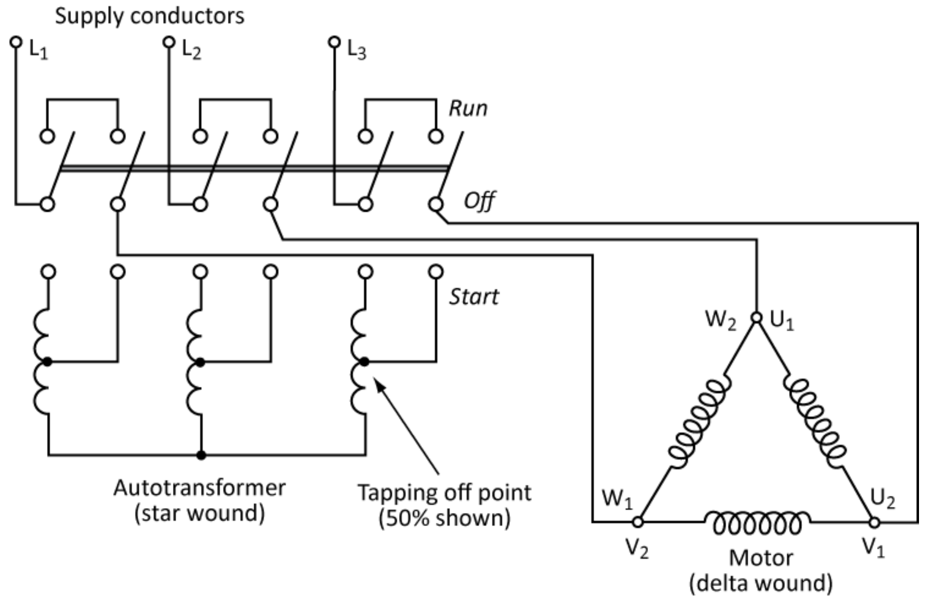
This starter still has the same types of overload protection as the DOL starter. The key feature is however, that it reduces the start voltage to approximately 58 % of its full load value. It therefore limits the starting current to between two and four times the full load current, rather than the five to ten times for the DOL starter. It also has the effect of reducing the starting torque to about 50 % of its full load torque.

This type of starter is commonly used on the larger types of motor; usually between 5 and 20kW. It is relatively cheap and effective. However, this type of starter should only be used where the motor is to be started against either light or no-load.

Autotransformer starter

This type of starter is used where you want or need to limit the start current, but only have a three terminal motor and not a six terminal as would be needed for star-delta starting.

Have a look at the diagram below first.



With this type of starter, the motor is permanently connected in delta. The reduction in starting current is produced by '***tapping***' off the supply to the motor from the transformer. This tapping off reduces the effective supply voltage to the motor.

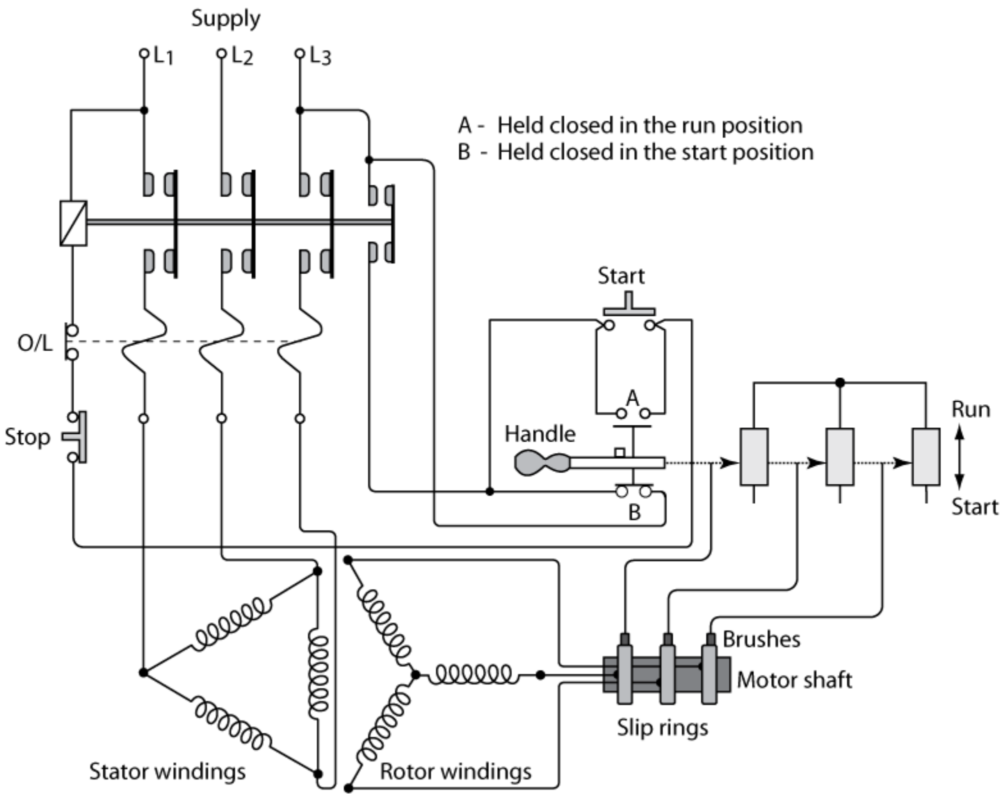
The transformer is connected in star. As the motor builds up in speed, the tapped supply is altered. This leaves part of the winding of the transformer in series with the motor. This acts as a choke, reducing the current. Eventually the motor is connected directly to the supply.

The usual tap-off points on the transformer are set at 40 %, 60 % and 75 % of the supply voltage. These settings will provide an initial starting torque of 16 %; 36 % or 56 % of full-load torque when compared to what a DOL supply will provide.

These first three types of starter are used for the squirrel-cage induction motor. The last type of starter that we'll look at is used for the wound rotor motor, and is called the rotor resistance starter.

Rotor resistance starter

This type of motor can be started up against heavy loads and the control of the torque and speed is gained by '**extending**' the resistance of the rotor to an external bank of resistors. Have a look at the diagram below.



When the start button is pressed, a supply is connected to the coil and the stator winding has a supply. The contact at ***B*** is made and there is the maximum resistance connected across the rotor winding via the external resistors.

As the handle is moved and the resistors are shorted out the contact ***A*** is made and the DOL starter is held 'ON' until the stop button is pressed or the overloads operate.

When all the resistance is connected in the rotor circuit, the maximum torque is developed at standstill. As the speed increases the torque drops until it is balanced by the load. When some resistance is taken out of the rotor circuit, the speed increases until it levels out. This sequence is repeated until all the resistors in the rotor circuit have been removed and the motor is then running at full speed. The slip rings are then short-circuited and the motor runs as a squirrel cage motor would run.

This type of motor and starter allows for a more gradual change in torque with no '***hiccup***' as the starter moves from star to delta or on switch on.

This type of motor and starter, as already stated, does provide some limited speed control, although it is at a cost of loss in efficiency.

Other types of starter

There are other types of starters available for the squirrel cage motors. These are ***soft start*** and ***variable frequency inverter***.

Both of these methods use electronics to gain the control necessary and have their own particular advantages.

The soft start will overtake the star/delta starter in its use. This type of starter provides a nice smooth increase in current and torque and provides a large degree of control. It makes use of thyristors fired at particular points in the a.c. cycle, which reduces the amount of energy in the circuit. The major drawback with this type of arrangement is that it will place a d.c. '***spike***' onto the supply and other sensitive equipment could be affected, such as computers.

The variable frequency inverter controls the frequency applied to the motor and so can vary the speed dramatically. Obviously things are a little more complicated than this, however it is useful to know that there are other types of starter available, not just the ones previously listed.

Starting of d.c. motors

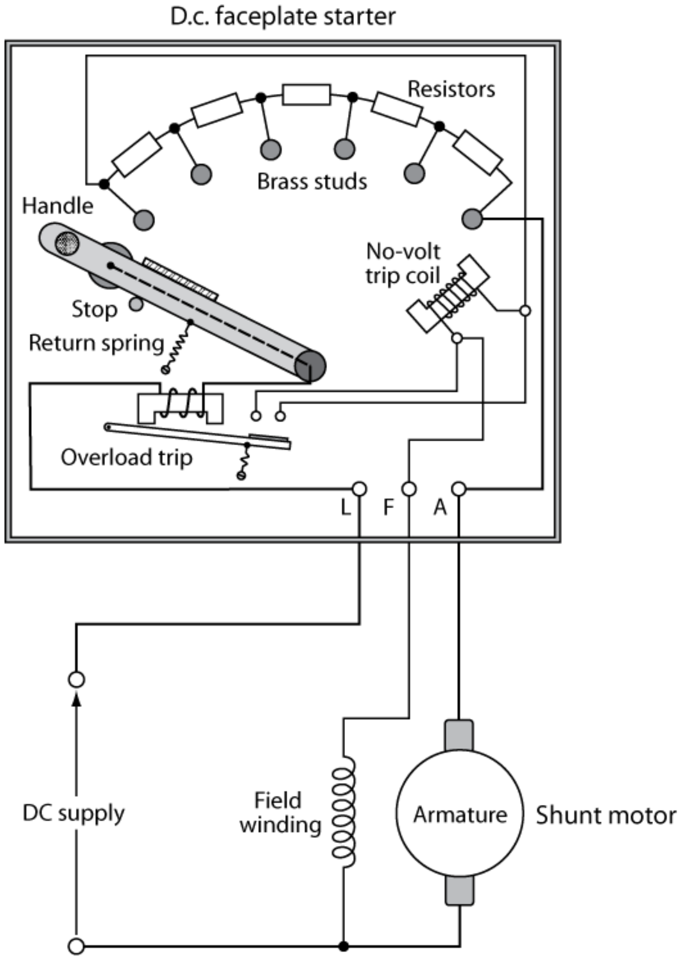
All d.c. motors require some means of starting. The armature of a d.c. machine has a very low resistance, commonly around 0.2 Ω. Now imagine that we have a 200 V supply. When the supply is first turned on to the motor, the current in the armature is very high.

$$U = IR \quad \text{transpose}$$
$$I = \frac{U}{R}$$
$$I = \frac{200}{0.2} = \underline{\underline{1000\text{A}}}$$

As you can see, at the instance of turning on the supply there would be a massive current flowing in the armature. This is unacceptable.

If we can reduce the initial starting current by inserting some resistance in line with the armature then the current would fall, and then as the speed built up then so would the induced emf (back emf). This effect would then take over from the resistors and they could be steadily cut out of the circuit.

Below shows the type of starter commonly used for d.c. machines. It is called a '***face plate starter***'.



The supply is connected through a magnetic overload to the starting arm. This starting arm is part of the circuit and is spring loaded:

- as the arm begins to move to the first resistor stud, the motor begins to rotate (not at full speed) and the supply is also connected directly to the field winding
- as the motor builds up speed, the arm is steadily moved across the other resistors studs. This movement actually takes each resistor out of the circuit until full speed is reached.
- when the motor is at full speed, the starting arm is held in place by the hold on contact. If, however, there is an overload then the contact at the overload shorts the contacts and the hold on contact is shorted out. This provides a simple '***no volt release***' mechanism.

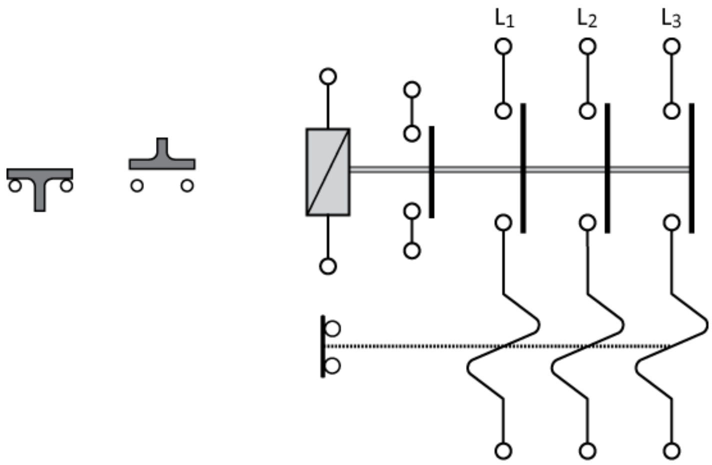
The other method of starting a d.c. machine is via the use of electronics.

The use of resistors in starting is expensive in both maintenance and power loss terms. The use of silicon-controlled rectifiers (SCRs), allows for the control of the current to a very fine degree. This is often called '***soft-start***'.

The use of electronics also controls the speed and so we will look at this in more detail in a later session.

Exercise 8

1. Draw a line diagram of the control circuit for the motor starter shown below.



2. At what level must overloads be used?

3. Why does a d.c. motor require a starter?

4. The following motors need installing. For each of the situations choose an appropriate type of starter:
   a) 3 kW squirrel-cage induction motor
   b) 20 kW squirrel-cage induction motor
   c) 35 kW wound rotor induction motor
   d) 150 kW squirrel-cage induction motor
   e) d.c. shunt motor;

5. A three-phase induction motor is controlled by an automatic star/delta starter with overloads. Detail what would happen if one of the windings in a three-phase motor open-circuited?

6. Using three triple-pole contactors and a timer show how a star-delta motor can be connected.

9: Speed control of machines

In this session the student will:

- Gain an understanding of how the speed of a.c. and d.c. machines are managed.

Before the use of electronics to control the speed and torque of machines, the choice of motors where limited to the speed required, in which case is was mainly d.c. motors being the best choice.

A.c. speed control

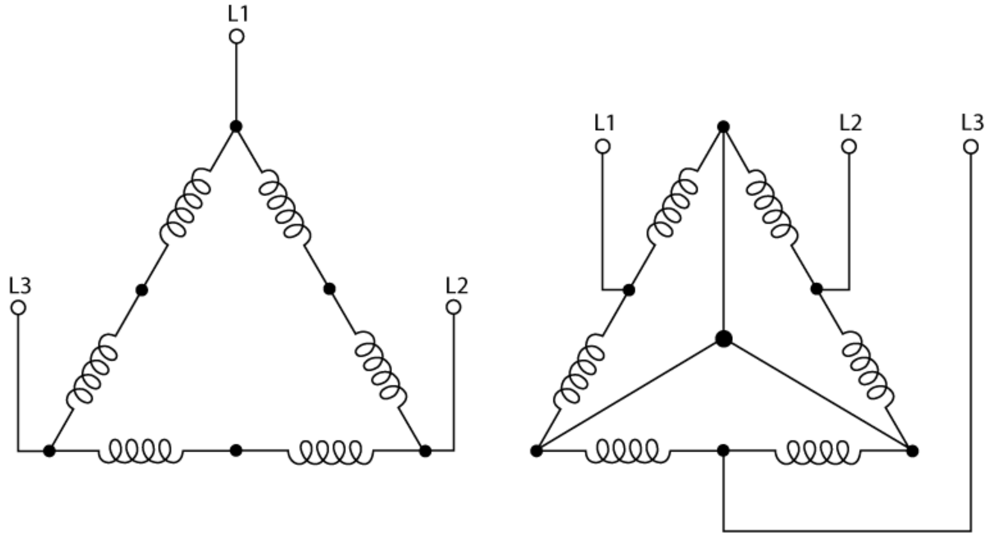
There are varieties of ways of gaining speed control in a.c. motors which are so much better than using wound rotor starters etc. These are:

- pole changing
- electronics.

Pole changing

We are already aware from the work that we did with determining the speed of a motor, that the speed of the rotating magnetic field is dependent of frequency and the number of pairs of poles. If therefore some means can be created of altering the number of pairs of poles then the rotating magnetic field can be altered.

This can be done. It is possible with special connections to make use of one winding to create two or even three poles. Have a look at the connections of the pole changing winding.



The winding is effectively 'tapped' at the centre to double the number of poles; very simple, yet effective.

Electronic speed control

The use of electronics to control the speed of an a.c. motor uses a variety of means. The types available are:

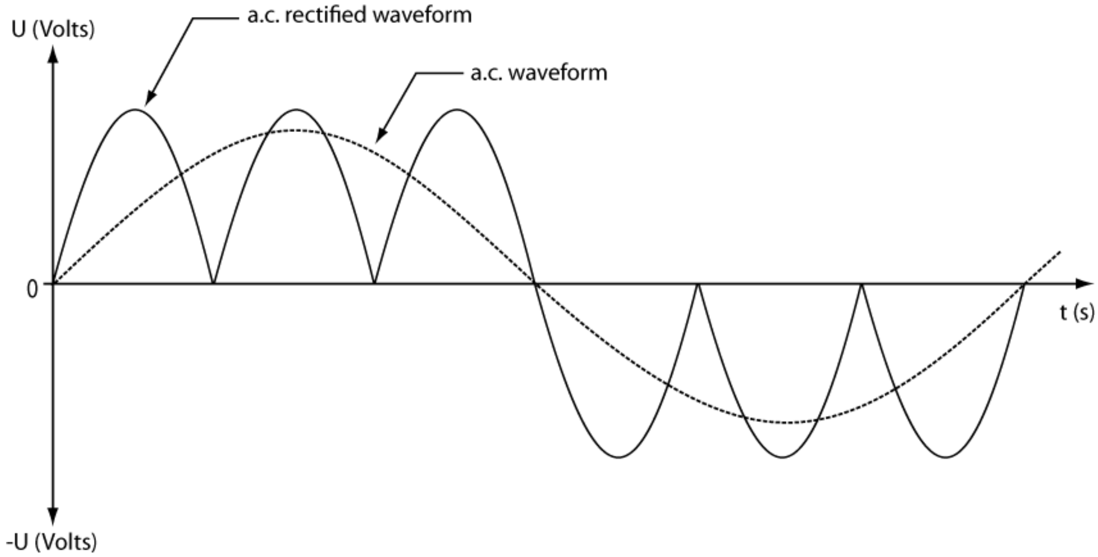
- static frequency changers
- static voltage controllers
- pulse-width modulation (PWM)
- pulse-amplitude modulation (PAM).

We will briefly look at each area

Static frequency changer

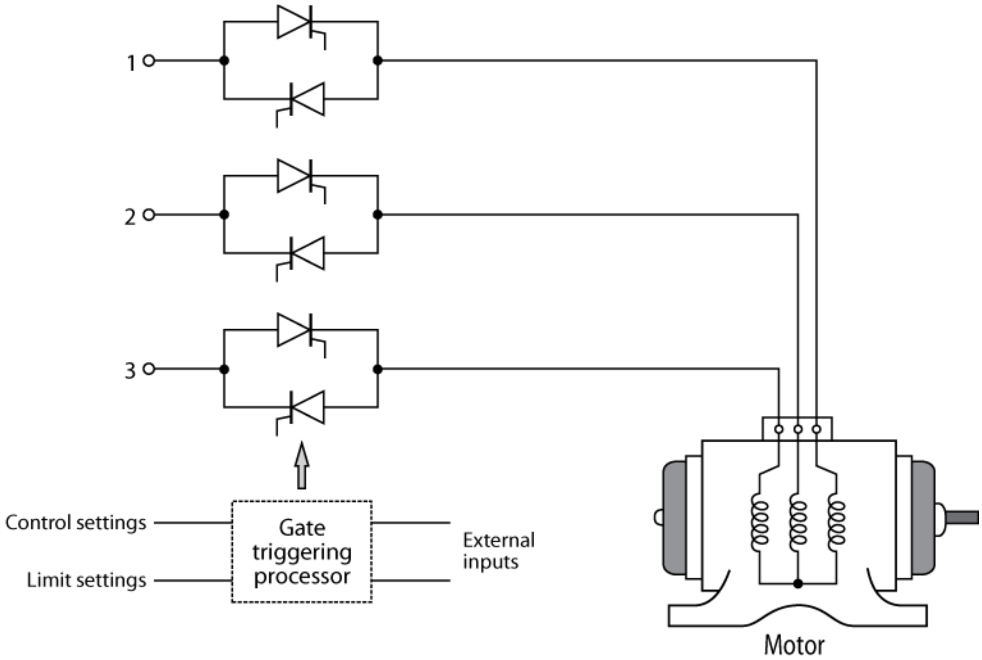
In a cyclo-converter the alternating voltage at supply frequency is converted directly to a low frequency output voltage, without any intermediate d.c. stage. The operating principle of this converter was developed in the early 1930s when the grid controlled mercury arc rectifiers became popular.

Effectively thyristors are fired in a certain order allowing for a 'type' of doctored sine wave to be generated. Have a look at the generated waveform of a cyclo-converter where the frequency has been reduced from 50 Hz to $16\frac{2}{3}$ Hz .



Static voltage controllers

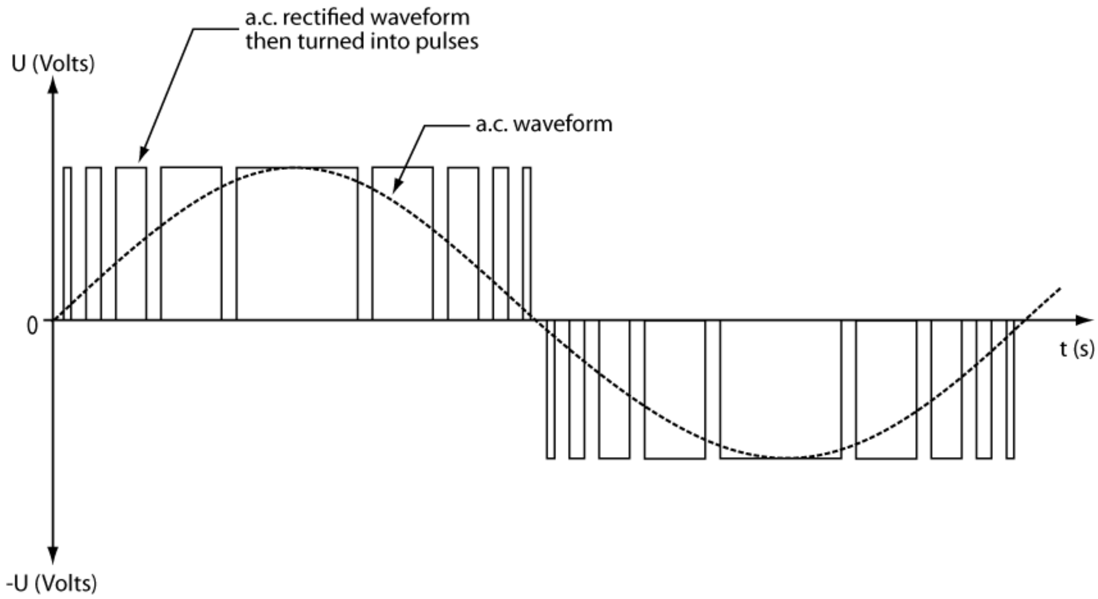
These enable speed and torque control by varying the a.c. supply, and it is this that we understand by 'soft-start'. By changing the stator voltage we directly affect the torque developed.



The thyristors are fired at set points depending on whether the motor is starting, running, or slowing down.

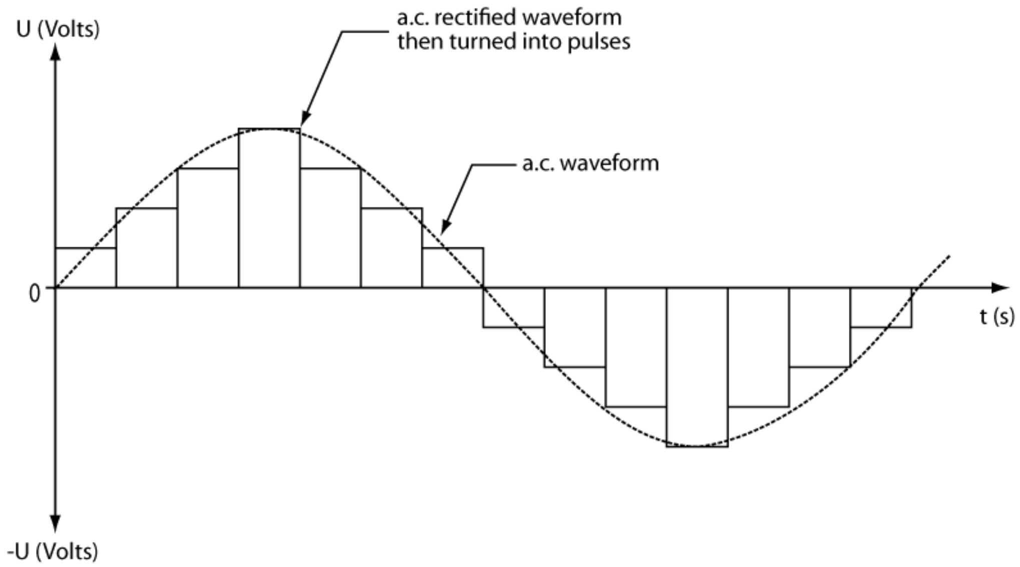
Pulse Width Modulation (PWM)

With PWM the a.c. supply is rectified to d.c. which is then turned into a series of signals. The length of the signal directly (length of the ON and OFF time) affects the average voltage, and by varying the pulses we can also create changes in frequency.



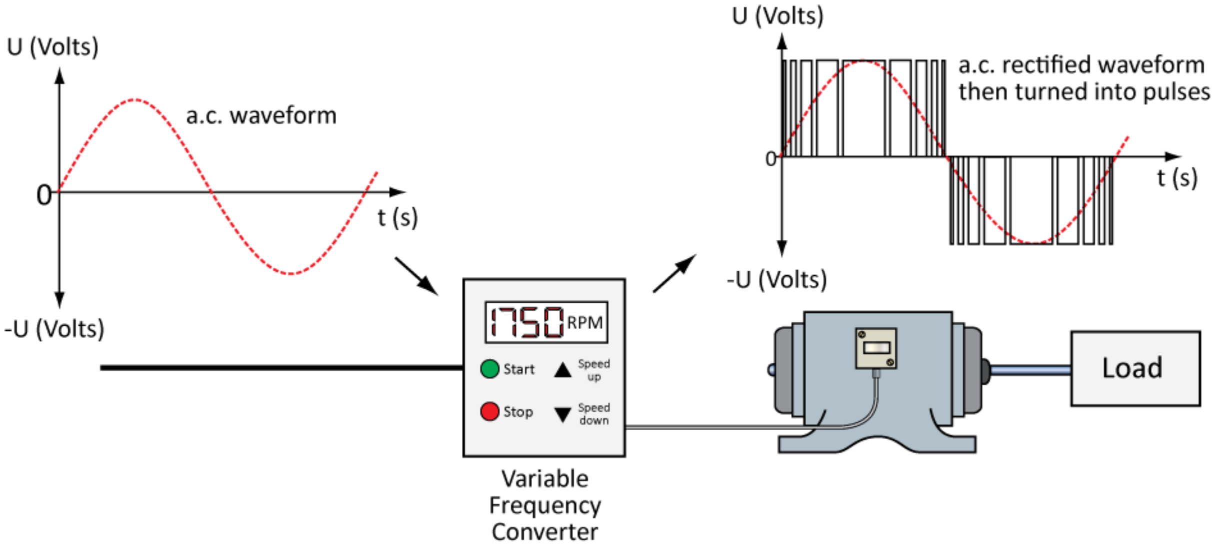
Pulse Amplitude Modulation (PAM)

PAM still rectifies a.c. to d.c., but then rather than changing the length of time that a signal exists for, changes the amplitude of the signal, and so we can get our altered waveform.



Variable frequency drives. (VFDs)

The speed of standard induction motors can be controlled by variation of the frequency of the voltage applied to the motor. Due to flux saturation problems with induction motors, the voltage applied to the motor must alter with the frequency. The induction motor is generally considered to be a constant speed machine. The running speed is set by the frequency applied to it and is independent of load torque provided the motor is not over loaded. This is achieved by the use of VFDs.



AC motor frequency inverters use digital circuitry to produce an alternating current. They have high speed switches that can be turned on and off thousands of times a second. These on and off signals add up to make an electric wave which is then sent to the motor. By turning the switches on and off at different rates, the inverter can generate different frequencies.

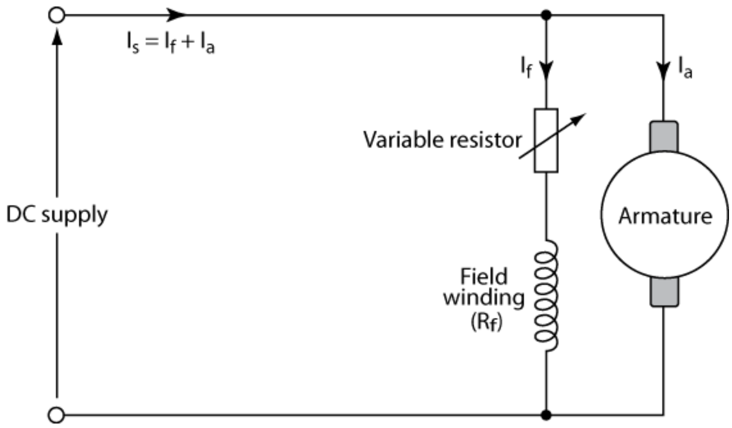
D.c. speed control

As with a.c. motors, there are a range of ways in which d.c. motors can be controlled:

- variation of the field winding
- electronics.

Variation of field winding

To get some level of speed control a variable resistor is connected in series with the field coil. This affects the current through the coil and so affects the flux.



With the motor, the addition of a resistor in series with the field winding will lead to a reduction in the current flowing in the field.

This reduction in current will lead to a reduction in the strength of the magnetic field and the induced emf Because of these reductions, the armature current and the torque increase. This causes the armature to accelerate until the generated emf is nearly equal to the applied voltage.

This method of speed control allows for a three to fourfold increase in speed, although never a reduction.

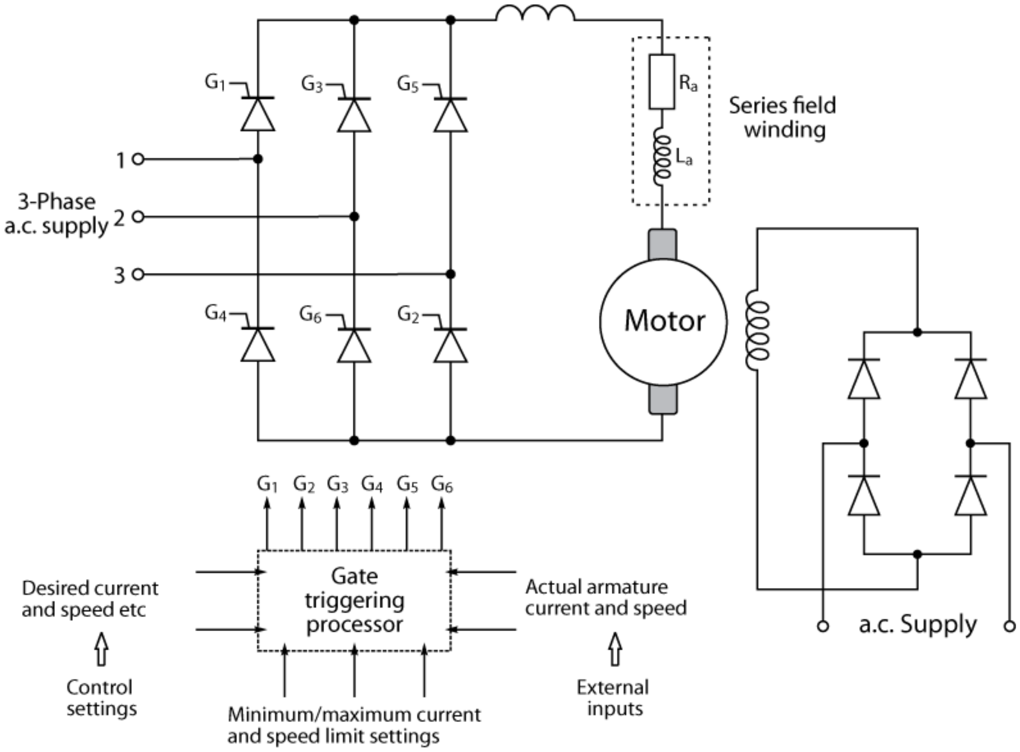
- Decrease the flux and you will increase the speed.

For a series motor, an additional resistor connected in series with the field and armature winding will reduce the current flow and have a voltage dropped across it, reducing the speed of the motor.

Electronics

Electronics are used to manage the speed and torque of d.c. motors by managing the supply to the motor. In effect an a.c. supply is provided to a controlled rectifier, and it is this that is used to manage the voltage levels to the motor.

The diagram below shows a relatively simple way in which a d.c. motor might be controlled.



The firing of the thyristors is controlled depending on the various inputs and limits. The benefits of this simple arrangement are:

- starting is more efficient as no limiting resistors are needed – this reduces the power losses
- thyristors have small power losses attached to them
- poor use cannot cause damage as the limits are pre-set.

There are a wide range of other control options available, but all are more complex.

Exercise 9

1. List two methods of achieving speed control for a d.c. motor and state any advantage or disadvantages they might have.

2. List some of the common methods used to control the speed of induction motors.

3. How is the speed of small a.c. motors controlled?

B&B Training Associates

Engineering Learning Materials

Attempt all questions.

All marks are shown in the right-hand margin.

You should aim to pass with an 85 % minimum mark.

Anything less than this mark should lead you to re-read the text.

1.	What is the function of a commutator?	2
2.	When should carbon brushes be replaced, and why is carbon used?	2
3.	What are the differences between a shunt and a series d.c. motor?	6
4.	Why should a series motor always be connected to a load?	2
5.	How is a rotating magnetic field created in a three-phase induction motor?	6
6.	What are the two types of three-phase a.c. induction motor?	2
7.	A three-phase, four-pole squirrel-cage induction motor is supplied from a 50 Hz supply. If the percentage slip is 5 % determine the synchronous speed and the speed of the rotor.	4
8.	Where would you use the two main types of three-phase induction motor?	4
9.	What is the particular problem of single-phase induction motors? How is this problem overcome?	4
10.	Name four different types of single-phase induction motor.	4
11.	A single-phase induction motor is turned on and simply hums. How can we quickly determine whether it is the run or the start winding that is the problem?	4
12.	What are the main types of starter used for a.c. motors? What rating of motor does each cover?	6
13.	Why is a faceplate starter used for some types of d.c. motor?	2
14.	What happens when the number of poles is doubled on an a.c. machine?	2
	Total marks	50

