Module 3: Electrical Machines

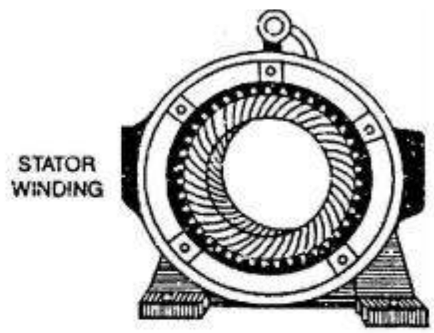
Construction and working of a three-phase induction motor

The three phase induction motors are simple in construction, rugged, low cost and easy to maintain. They run at a constant speed from no-load to the full load. Therefore, these motors are frequently used in industry.

Construction of Three Phase Induction Motor:

A Three phase induction motor has two main parts (i) stator and (ii) rotor. The rotor is separated from the stator by a small air-gap which ranges from 0.4 mm to 4 mm, depending on the power of the motor.

1. **Stator:**



It consists of a steel frame which encloses a hollow, cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current losses. A number of evenly spaced slots are provided on the inner periphery of the laminations. The insulated connected to form a balanced 3-phase star or delta connected the circuit.

The 3-phase stator winding is wound for a definite number of poles as per requirement of speed. Greater the number of poles, lesser is the speed of the motor and vice-versa. When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced. This rotating field induces currents in the rotor by electromagnetic induction.

2. Rotor:

The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding) may be one of the following two types:

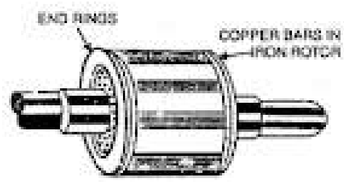
(i) Squirrel cage type (ii) Wound type

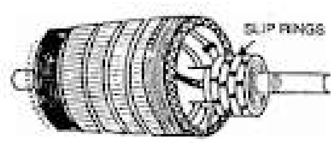
(i) Squirrel cage rotor: It consists of a laminated cylindrical core having parallel slots on its outer periphery. One copper or aluminum bar is placed in each slot. All these bars are joined at each end by metal rings called end rings.

This forms a permanently short circuited winding which is indestructible. The entire construction (bars and end rings) resembles a squirrel cage and hence the name. The rotor is not connected electrically to the supply but has current induced in it by transformer action from the stator.

Those induction motors which employ squirrel cage rotor are called squirrel cage induction motors. Most of 3 phase induction motors use squirrel cage rotor as it has a remarkably simple and robust construction enabling it to operate in the most adverse circumstances.

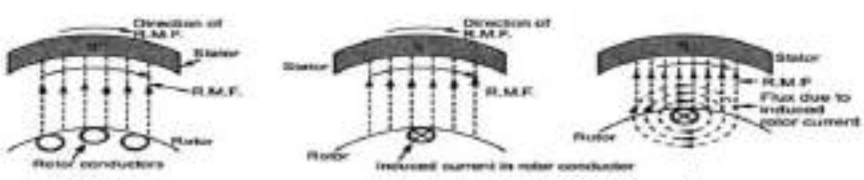
However, it suffers from the disadvantage of a low starting torque. It is because the rotor bars are permanently short-circuited and it is not possible to add any external resistance to the rotor circuit to have a large starting torque.





(ii) Wound rotor: It consists of a laminated cylindrical core and carries a 3-phase winding, similar to the one on the stator .The rotor winding is uniformly distributed in the slots and is usually star-connected. The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring. The three brushes are connected to a 3-phase star-connected rheostat . At starting, the external resistances are included in the rotor circuit to give a large starting torque. These resistances are gradually reduced to zero as the motor runs up to speed.

Principle of Operation of 3-Phase Induction Motor



When the stator is excited with three-phase supply, three-phase stator winding produce a rotating magnetic field at constant magnitude, which rotates at synchronous speed (N_s). This changing magnetic field cuts the rotor conductors and induces a current in them according to the principle of Faraday's laws of electromagnetic induction. As these rotor conductors are shorted, the current starts to flow through these conductors.

In the presence of magnetic field of stator, rotor conductors are placed, and therefore, according to the Lorentz force principle, a mechanical force acts on the rotor conductor. Thus, force is exerted on the rotor conductors which produce torque in the rotor which tends to move it in the same direction of rotating magnetic field.

This rotor conductor's rotation can also be explained by Lenz's law which tells that the induced currents in the rotor oppose the cause for its production, here this opposition is rotating magnetic field. This result the rotor starts rotating in the same direction of the stator rotating magnetic field. If the rotor speed is equal to the stator speed, then no current will induce in the rotor because the reason for rotor rotation is the relative speed of the rotor and stator magnetic fields. This stator magnetic field speed and the rotor speed difference is called as slip. This is how 3-phase motor is called as asynchronous machine due to this relative speed difference between the stator and the rotors.

The relative speed between the stator field and the rotor conductors causes to rotate the rotor in a particular direction. Hence, for producing the rotation, the rotor speed Nr must always be less than the stator field speed Ns, and the difference between these two parameters depends on the load on the motor

Slip Speed in an induction motor

Definition: The slip in an induction motor is the difference between the main flux speed and their rotor speed. The symbol S represents the slip. It is expressed by the percentage of synchronous speed. Mathematically, it is written as

$$\%S = \frac{N_s - N}{N_s} \times 100$$

The value of slip at full load varies from 6% in case of small motor and 2% in the large motor.

The induction motor never runs at synchronous speed. The speed of the rotor is always less than that of the synchronous speed. If the speed of the rotor is equal to the synchronous speed, no relative motion occurs between the stationary rotor conductors and the main field.

Then, no EMF induces in the rotor and zero current generates on the rotor conductors. The electromagnetic torque is also not induced. Thus, the speed of the rotor is always kept slightly less than the synchronous speed. The speed at which the induction motor work is known as the slip speed.

The speed of the rotor is slightly less than the synchronous speed. Thus, the slip speed expresses the speed of the rotor relative to the field.

- If N_s is the synchronous speed in revolution per minute
- N_r is the actual rotor speed in revolution per minute.

The slip speed of the induction motor is given as

$$S = N_s - N_r \dots\dots\dots (1)$$

The fraction part of the synchronous speed is called the Per Unit Slip or Fractional Slip. The per unit slip is called the Slip. It is denoted by s.

$$S = \frac{N_S - N_r}{N_S} \text{ per unit (p.u)} \dots\dots\dots (2)$$

$$\text{Percentage slip} = \frac{N_s - N_r}{N_s} \times 100 \dots\dots\dots (3)$$

Therefore, the rotor speed is given by the equation shown below.

$$N_r = N_S (1 - S)$$

Alternatively, if

- n_s is the synchronous speed in revolution per second
- n_r is the actual rotor speed in revolution per second.

Then,

$$S = \frac{n_s - n_r}{n_s} \text{ per unit (p. u)} \dots \dots . . (4)$$

The percentage slip in revolution per second is given as shown below.

$$\text{Percentage slip} = \frac{n_s - n_r}{n_s} \text{ x } 100 \dots \dots . . (5)$$

Also,

$$s = \frac{\omega_s - \omega_r}{\omega_s} \dots \dots \dots . (5)$$

Importance of Slip

Slip plays an essential role in Induction motor. As we know, the slip speed is the difference between the synchronous and rotor speed of the induction motor. The emf induces in the rotor because of the relative motion, or we can say the slip speed of the motor. So,

$$e_2 \propto N_s - N_r$$

The rotor current is directly proportional to the induced emf.

$$i_2 \propto e_2$$

The torque is directly proportional to the rotor current.

$$T \propto i_2$$

Therefore,

$$T = K(N_s - N_r) \text{ or } T = KN_s\left(\frac{N_s - N_r}{N_s}\right) \text{ or } T = K_1 S$$

Hence, torque is directly proportional to slip.

$$T \propto S$$

The above equation show that the torque induces on the rotor is directly proportional to the slip of the induction motor. The high value of slip induces the emf in the rotor. This EMF develops the heavy torque on the rotor conductors.

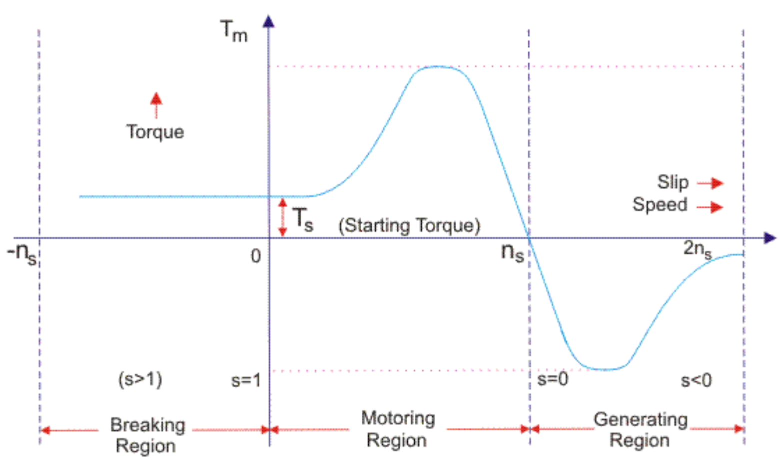
The value of the slip is adjusted by considering the load on the motor. For full-load, the high value of torque is required. This can be achieved by increasing the amount of the slip and reducing the speed of the rotor. The slip of the motor is kept low when the induction motor is running at no-load. The small slip produces the small torque on the motor.

The value of the induction motor slip is adjusted according to the requirement of the driving torque at the normal working condition.

Torque Slip Characteristics of Three Phase Induction Motor

The torque slip curve for an induction motor gives us the information about the variation of torque with the slip. The slip is defined as the ratio of difference of synchronous speed and actual rotor speed to the synchronous speed of the machine. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.

The curve can be described in three modes of operation



Torque Slip Curve for Three Phase Induction Motor

The torque-slip characteristic curve can be divided roughly into three regions:

- Low slip region

- Medium slip region
- High slip region

The torque equation of the induction motor is given below.

$$T = \frac{k\,s\,R_2 E_{20}^2}{R_2^2 + (sX_{20})^2} \dots\dots\dots\dots (1)$$

Low Slip Region

At the synchronous speed, s = 0, therefore, the torque is zero. When the speed is very near to synchronous speed. The slip is very low and $(sX_{20})^2$ is negligible in comparison with R_2. Therefore,

$$T = \frac{k_1 s}{R_2}$$

If R_2 is constant, the torque becomes

$$T = k_2 s \dots\dots (2)$$

When $k_2 = k_1/R_2$

From the equation (1) shown above, it is clear that the torque is proportional to slip. Hence, in the normal working region of the motor, the value of the slip is small. The torque slip curve is a straight line.

Medium Slip Region

As the slip increases, the speed of the motor decreases with the increase in load. The term $(sX_{20})^2$ becomes large. The term R_2^2 may be neglected in comparison with the term $(sX_{20})^2$ and the torque equation becomes as shown below.

$$T = \frac{k_3 R_2}{sX_{20}^2} \dots\dots\dots (3)$$

At the standstill condition, the torque is inversely proportional to the slip.

High Slip Region

Beyond the maximum torque point, the value of torque starts decreasing. As a result, the motor slows down and stops. At this stage, the overload protection must immediately disconnect the motor from the supply to prevent damage due to overheating of the motor.

The motor operates for the values of the slip between s = 0 and s = s_M. Where, s_M is the value of the slip corresponding to the maximum torque. For a typical induction motor, the pull-out torque is 2 to 3 times the rated full load torque. The starting torque is about 1.5 times the rated full load torque.The curve shown below shows the Torque Slip Characteristic of the Induction Motor

Losses in induction motors:

The losses in induction motor are broadly categorized into two classes, namely

1. Constant losses
2. Variable losses.

Constant losses in Induction Motor

These losses do not depend on the load hence they are known as constant losses. These can be further categorized as under:

1. Core losses: These include eddy current and hysteresis losses in stator as well as in rotor magnetic core. Iron losses in rotor core are negligible since rotor current frequency is very small in the order of 0.5 to 2 Hz.
   These losses of induction motor are constant since these depend upon voltage and frequency which is practically constant.
   The hysteresis losses can be reduced by selecting a high permeability material for the core. The eddy current losses can be reduced by using the laminated cores instead of solid ones.
2. Friction and windage losses: These losses are also constant losses as these losses depend upon the speed of the induction motor. The speed of the induction motor is approximately constant.
   The no-load test is performed on induction motor to determine the constant losses in the induction motor.

Variable Losses of Induction Motor

These are:

1. Copper losses (I^2R losses) in the stator winding.
2. Copper losses (I^2R losses) in the rotor winding.

These losses occur due to the resistance of rotor winding as well as the resistance of stator winding. These losses are also called copper losses.

These are proportional to the square of stator and rotor currents respectively. As these currents depend on the load, copper losses vary with the change in load.

Hence these are known as variable losses. The blocked rotor test is performed on induction motor to determine the variable losses.

Speed Control Methods of Induction Motor

1 Speed control with respect to stator side of induction motor.
2 Speed control with respect to rotor side of induction motor.

1 <u>Speed control with respect to stator side of induction motor.</u>

a. By changing supply voltage of motor

b. Changing no of poles(Stator) of motor

c. Changing frequency of supply

1(a) By changing the applied voltage:

The torque developed in induction motor is given by

$$T = \frac{k\,s\,R_2 E_{20}^2}{R_2^2 + (sX_{20})^2} \;\dots\dots\dots\dots(1)$$

Rotor resistance R_2 is constant and if slip s is small then $(sX_{20})^2$ is so small that it can be neglected. Therefore, $T \propto sE_{20}^2$ where E_2 is rotor induced emf and $E_{20} \propto V$ Thus, $T \propto sV^2$, which means, if supplied voltage is decreased, the developed torque decreases. Hence, for providing the same load torque, the slip increases with decrease in voltage, and consequently, the speed decreases.

This method is the easiest and cheapest, still rarely used, because

1. Large change in supply voltage is required for relatively small change in speed.
2. Large change in supply voltage will result in a large change in flux density, hence, this will disturb the magnetic conditions of the motor.

1(b) Changing number of poles (Stator) of motor:

The synchronous speed of induction motor is given by $N_s = \frac{120f}{P}$

$$N_s \; \alpha \; \frac{1}{P}$$

Adding or removing the poles can vary the speed.

Pole changing can be used to achieve different speed in induction motor by switching the configuration of electrical stator winding in the ratio of 2:1

For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles.

for supply frequency of 50 Hz

i) synchronous speed when 4 pole winding is connected, Ns = 120*50/4 = 1500 RPM

ii) synchronous speed when 6 pole winding is connected, Ns = 120*50/6 = 1000 RPM

The no of stator poles can be changed by providing, multiple stator winding.

We provide two separate windings in the stator. These two stator windings are electrically isolated from each other and are wound for two different numbers of poles. Using a switching arrangement, at a time, supply is given to one winding only and hence speed control is possible.

Disadvantages of this method are that the smooth speed control is not possible. This method is more costly and less efficient as two different stator windings are required.

1 (c) Changing frequency of supply

The frequency of power supply is constant, therefore, to control the speed of induction motor by this method, the induction motor is connected to alternator(generator) operating independently.

To control the speed, the frequency of alternator is changed.

This is costly method.

2 Speed control with respect to rotor side of induction motor

a. Adding external resistance into rotor side of motor
b. Apply cascade connection
c. Injecting emf into rotor side of motor

2 (a) Adding external resistance into rotor side of motor

This method is applicable only to phase wound induction motor.

The equation of torque for three phase induction motor is given by

$$T = \frac{k\, s\, R_2 E_{20}^2}{R_2^2 + (sX_{20})^2} \dots\dots\dots\dots (1)$$

The three-phase induction motor operates in a low slip region. In low slip region term $(sX_{20})^2$ becomes very very small as compared to R_2. So, it can be neglected and also E_2 is constant. So the equation of torque after simplification becomes,

$$T \alpha \frac{s}{R2}$$

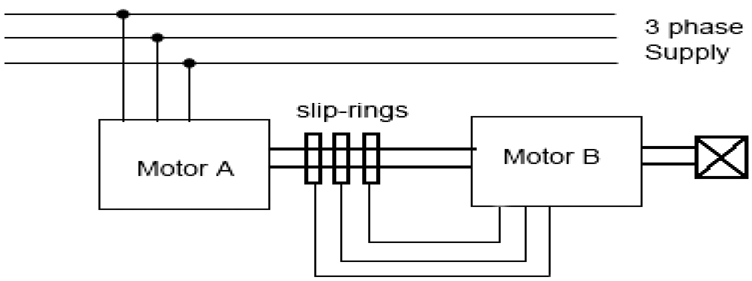
Now if we increase rotor resistance R_2 , torque decreases but we have to supply the same load torque. So, we increase slip, which will further result in the decrease in rotor speed. Thus by adding additional resistance in the rotor circuit, we can decrease the speed of the three-phase induction motor. The main advantage of this method is that with an addition of external resistance starting torque increases

But this method of speed control of three phase induction motor also suffers from some disadvantages:

1. The speed above the normal value is not possible
2. Large speed change requires a large value of resistance, and if such large value of resistance is added in the circuit, it will cause large copper loss and hence reduction in efficiency.
3. This method cannot be used for squirrel cage induction motor.

2 (b) Apply cascade connection:

In this method of speed control, two motors are used. Both are mounted on a same shaft so that both run at same speed. One motor is fed from a 3phase supply and the other motor is fed from the induced emf in first motor via slip-rings. The arrangement is as shown in following figure



In this method of speed control of three phase induction motor, four different speeds can be obtained.

When only main induction motor work, having speed corresponds to

$$N_s = \frac{120f}{P1}$$

When only auxiliary induction motor work, having speed corresponds to

$$N_s = \frac{120f}{P2}$$

When cumulative cascading is done, then the complete set runs at a speed of

$$N_s = \frac{120f}{P1+P2}$$

When differential cascading is done, then the complete set runs at a speed of

$$N_s = \frac{120f}{P1-P2}$$

2(c) Injecting emf into rotor side of motor

In this method, speed of an induction motor is controlled by injecting a voltage in rotor circuit. It is necessary that voltage (emf) being injected must have same frequency as of the slip frequency. However, there is no restriction to the phase of injected emf. If we inject emf which is in opposite phase with the rotor induced emf, rotor resistance will be increased. If we inject emf which is in phase with the rotor induced emf, rotor resistance will decrease. Thus, by changing the phase of injected emf, speed can be controlled.

The main advantage of this method is a wide range of speed control (above normal as well as below normal) can be achieved.

Starting Methods of Three Phase Induction Motors

The three phase induction motors are self-starting due to rotating magnetic field. But the motors show tendency to draw very high current at the time of starting. Such a current can be 6 to 8 times of full load or rated current and it can damage the motor winding. Hence there should be a device which can limit such high starting current. Such a device which limits high starting current is called a starter.

NECESSITY OF STARTER

In a 3 phase induction motor, the magnitude of an induced emf in the rotor circuit depends on the slip of the induction motor. Thus induced emf effectively decides the magnitude of the rotor current. The rotor current in the running condition is given by:

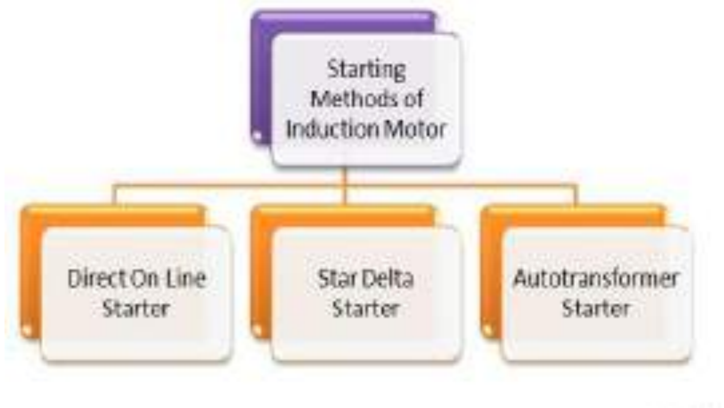
$$I_{2r} = s\, E_2^{\,2} / (R^2{}_2 + sX^2{}_2)$$

1. At starting time, the speed of the motor is zero and slip is at its maximum i.e. unity. So magnitude of rotor induced emf is very large at start. As rotor conductors are short-circuited, the large induced emf circulates very high current through rotor at start.
2. The condition is exactly similar to a transformer with short-circuited secondary. Such a transformer when excited by a rated voltage circulates a very high current through short-circuited secondary. As secondary current is large, Primary current also draws very large current from the supply line.
3. Similarly in a 3 phase induction motor, when rotor current is high, consequently the stator draws a very high current from the supply line. Due to such increment in line current ⇒ Voltage starts increasing. ⇒ Whole system can collapse. ⇒Hence even 3 Hp rating induction motor is not allowed without Starter.
4. Due to such heavy in rush current at start
   There is Possibility of damage of the motor windings. It causes large line voltage drop.

Thus other appliances connected to the same line may be subjected to voltage spikes which may affect their working. So to avoid such affects, it is necessary to limit the current drawn by the motor at start. The starter is a device which is basically used to limit the starting current by supplying reduced voltage to the motor at the time of starting.

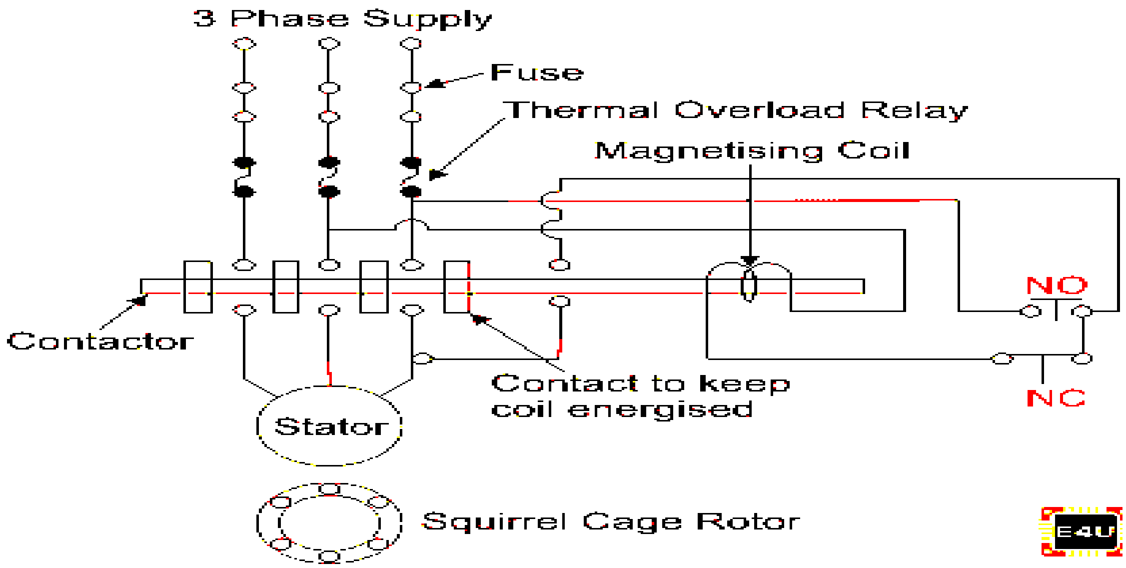
There are three main methods of Starting Cage Induction Motor. They are as follows.

- Direct –On– line (DOL) starters for less than 10 Kw motors.
- Star–Delta starters for large motors. The stator winding is initially connected in a star configuration and later on changed over to a Delta connection, when the motor reaches rated speed.
- Auto transformer.



DIRECT ON LINE STARTER

A DOL starter (or Direct On Line starter or across the line starter) is a method of starting of a 3 phase induction motor. In DOL Starter an induction motor is connected directly across its 3-phase supply, and the DOL starter applies the full line voltage to the motor terminals. Despite this direct connection, no harm is done to the motor. A DOL motor starter contains protection devices, and in some cases, condition monitoring. A wiring diagram of a DOL starter is shown below:



Since the DOL starter connects the motor directly to the main supply line, the motor draws a very high inrush current compared to the full load current of the motor (up to 5-8 times higher). The value of this large current decrease as the motor reaches its rated speed.

A direct on line starter can only be used if the high inrush current of the motor does not cause an excessive voltage drop in the supply circuit. If a high voltage drop needs to be avoided, a star delta starter should be used instead. Direct on line starters are commonly used to start small motors, especially 3 phase squirrel cage induction motors.

As we know, the equation for armature current in the motor.

$$I_a = \frac{(V - E)}{R_a}$$

The value of back emf (E) depends upon speed (N), i.e. E is directly proportional to N.

At starting, the value of E is zero. So starting current is very high. In a small rating motor, the rotor has more considerable axial length and small diameter. So it gets accelerated fastly. Hence, speed increases and thus the value of armature current decreases rapidly. Therefore, small rating motors smoothly run when it is connected directly to a 3-phase supply. If we connect a large motor directly across 3-phase line, it would not run smoothly and will be damaged, because it does not get accelerated as fast as a smaller motor since it has short axial length and larger diameter more massive rotor. However, for large rated motors, we can use an oil immersed DOL starter.

DOL Starter Working Principle

The working principle of a **DOL starter** begins with the connection to the 3-phase main with the motor. The control circuit is connected to any two phases and energized from them only. When we press the start button, the current flows through contactor coil (magnetizing coil) and control circuit also. The current energises the contactor coil and leads to close the contacts, and hence 3-phase supply becomes available to the motor. If we press the stop button, the current through the contact becomes discontinued, hence supply to the motor will not be available, and the similar thing will happen when the overload relay operates. Since the supply of motor breaks, the machine will come to rest. The contactor coil (Magnetizing Coil) gets supply even though we release start button because when we release start button, it will get supply from the primary contacts as illustrated in the diagram of the **Direct Online Starter**.

Advantages of DOL Starter

The advantages of a DOL starter include:

1. Simple and most economical starter.
2. More comfortable to design, operate and control.
3. Provides nearly full starting torque at starting.
4. Easy to understand and troubleshoot.

Disadvantages of DOL Starter

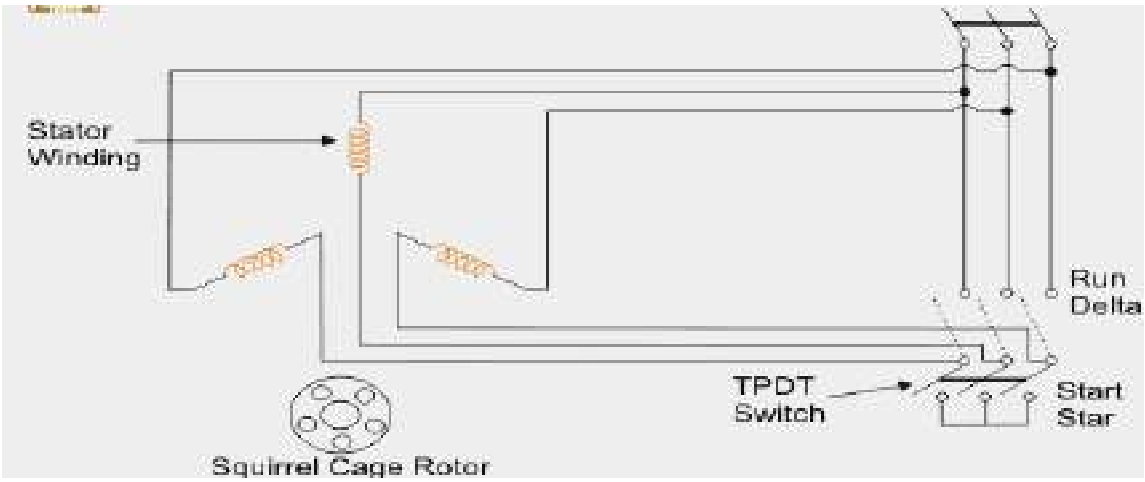
The disadvantages of a DOL starter include:

1. High starting current (5-8 times of full load current).
2. DOL Starter causes a significant dip in voltage, hence suitable only for small motors.
3. DOL Starter reduces the lifespan of the machine.
4. Mechanically tough.

STAR DELTA STARTER

A star delta starter is the most commonly used method for the starting of a 3 phase induction motor. In star delta starting an induction motor is connected in through a star connection throughout the starting period. Then once the motor reaches the required speed, the motor is connected in through a delta connection

A star delta starter will start a motor with a star connected stator winding. When motor reaches about 80% of its full load speed, it will begin to run in a delta connected stator winding. A star delta starter is a type of reduced voltage starter. We use it to reduce the starting current of the motor without using any external device or apparatus.

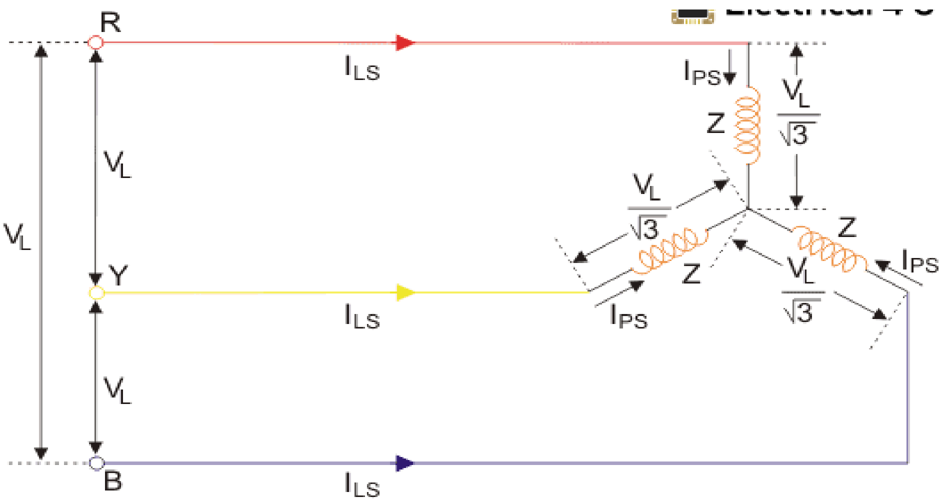


This is a big advantage of a star delta starter, as it typically has around 1/3 of the inrush current compared to a DOL starter.

The starter mainly consists of a TPDP switch which stands for Triple Pole Double Throw switch. This switch changes stator winding from star to delta. During starting condition stator winding is connected in the form of a star. Now we shall see how a star delta starter reduces the starting current of a three-phase induction motor.

For that let us consider,

V_L = Supply Line Voltage, I_{LS} = Supply Line Current and, I_{PS} = Winding Current per Phase and Z = Impedance per phase winding at stand still condition.



As the winding is star connected, the winding current per phase (I_{PS}) equals to supply line current (I_{LS}).

$$I_{PS} = I_{LS}$$

As the winding is star connected, the voltage across each phase of the winding is

$$\frac{V_L}{\sqrt{3}}$$

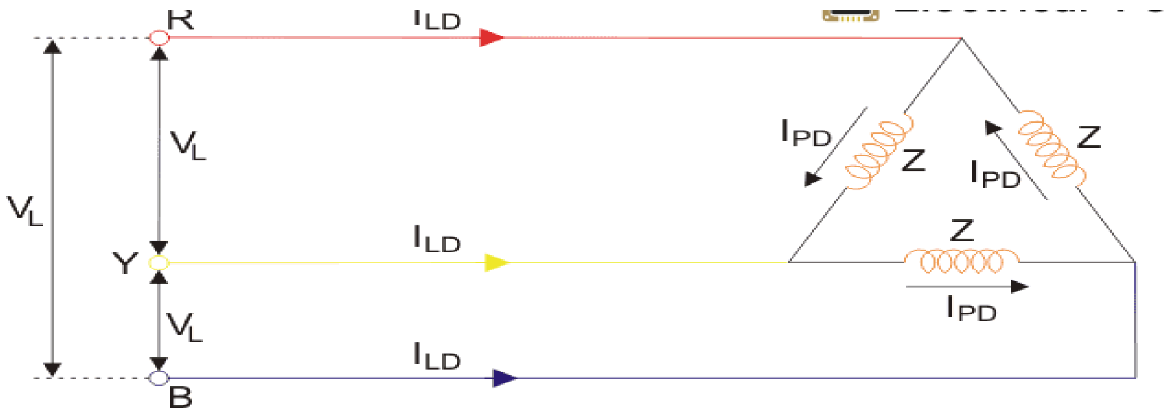
Hence, the winding current per phase is

$$I_{PS} = \frac{V_L}{\sqrt{3}Z}$$

Since here, the winding current per phase (I_{PS}) equals to the supply line current (I_{LS}), we can write,

$$I_{PS} = \frac{V_L}{\sqrt{3}Z} \Leftrightarrow I_{LS} = \frac{V_L}{\sqrt{3}Z}$$

Now, let us consider the situation where the motor gets started with delta connected stator winding from same three phase supply points,



Here, I_{LD} = Supply Line Current and, I_{PD} = Winding Current per Phase and Z = Impedance per phase winding at stand still condition.

As the winding is delta connected, supply line current (I_{LD}) is root three times of the winding current per phase (I_{PD})

$$I_{LD} = \sqrt{3}\ I_{PD}$$

As the winding is delta connected, the voltage across each phase of the winding is

$$V_L$$

Hence, the winding current per phase is

$$I_{PD} = \frac{V_L}{Z}$$

Now, we can write,

$$I_{LD} = \sqrt{3}\ I_{PD} = \frac{\sqrt{3}\ V_L}{Z}$$

Now, by comparing supply line currents drawn by an induction motor with star and delta connected winding, we get

$$\frac{I_{LD}}{I_{LS}} = \frac{\frac{\sqrt{3}\ V_L}{Z}}{\frac{V_L}{\sqrt{3}\ Z}} = 3 \Rightarrow I_{LS} = \frac{1}{3} I_{LD}$$

Thus we can say that the starting current from the mains in case of star delta is one-third of direct switching in the delta. Again, we know that the starting torque of an induction motor is proportional to the square of the voltage applied to the winding per phase.

$$\frac{Starting\ torque\ in\ star\ connected\ stator\ winding\ motor}{Starting\ torque\ in\ delta\ connected\ stator\ winding\ motor}$$

$$= \frac{\left(\frac{V_L}{\sqrt{3}}\right)^2}{{V_L}^2} = \frac{1}{3}$$

The equation shows that star delta starter reduces the starting torque to one-third of that produced by DOL starter. The star-delta starter is equivalent to an autotransformer with a 57.7% tapping.

Advantages of Star Delta Starter

The advantages of star delta starters include:

1. Inexpensive
2. No heat is produced, or tap changing device needs to be used, hence efficiency increases.
3. Starting current reduced to 1/3 of direct online starting current.
4. Produce high torque per ampere of line current.

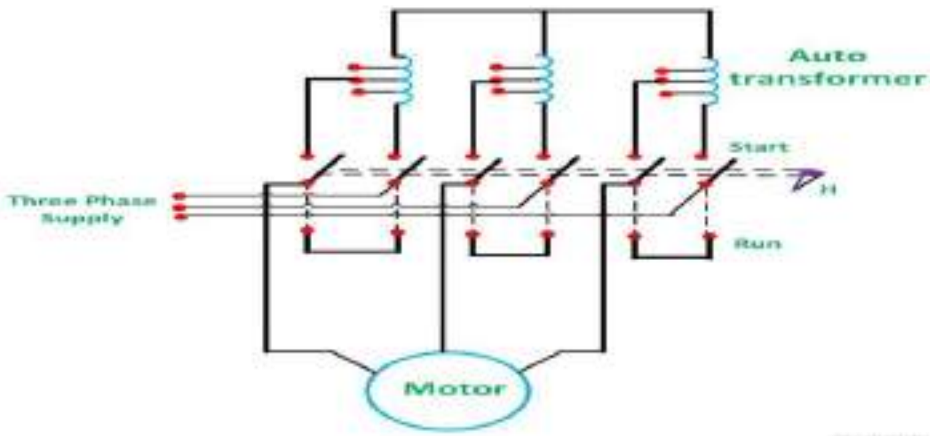
Disadvantages of Star Delta Starter

The disadvantages of star delta starters include:

1. Starting torque is reduced to 1/3 of full load torque.
2. A particular set of motors required.

AUTO TRANSFORMER STARTER

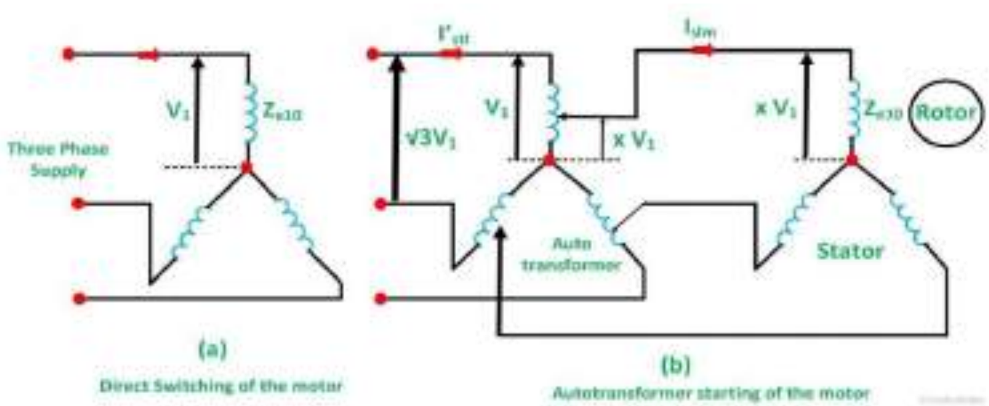
An Auto transformer Starter is suitable for both star and delta connected motors. In this method, the starting current is limited by using a three-phase auto transformer to reduce the initial stator applied voltage. The figure below shows the motor with the Auto transformer starter.



It is provided with a number of tapings. The starter is connected to one particular tapping to obtain the most suitable starting voltage. A double throw switch S is used to connect the auto transformer in the circuit for starting. When the handle H of the switch S in the START position. The primary of the auto transformer is connected to the supply line, and the motor is connected to the secondary of the auto transformer.

When the motor picks up the speed of about 80 percent of its rated value, the handle H is quickly moved to the RUN position. Thus, the auto transformer is disconnected from the circuit, and the motor is directly connected to the line and achieve its full rated voltage. The handle is held in the RUN position by the under voltage relay.

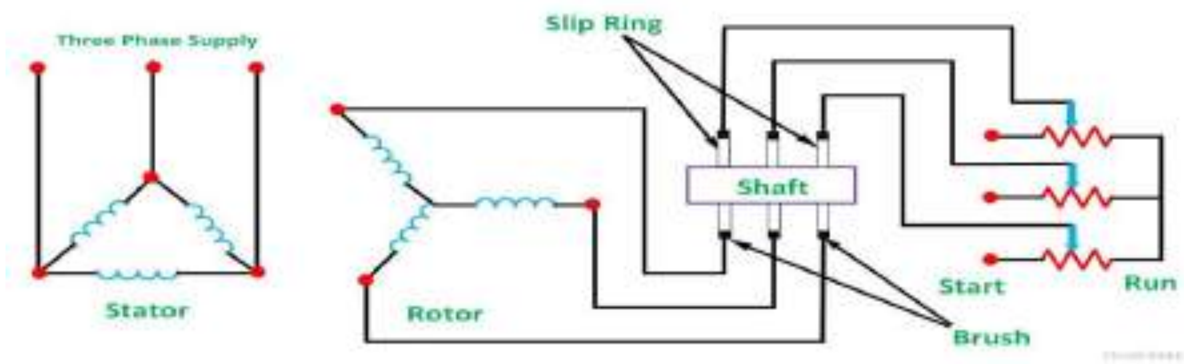
If the supply voltage fails or falls below a certain value, the handle is released and returns to the OFF position. Thermal overload relays provide the overload protection.



Star delta starter is equivalent to an auto transformer starter of the ratio
x = 0.58. A Star Delta starter is much cheaper than an auto transformer starter and is commonly used for both small and the medium size motors.

Slip Ring Induction Motor Starter Method of Starting Induction Motor

In the **Slip Ring Induction Motor** starter, the full supply voltage is connected across the starter. The connection diagram of the slip ring starter induction motor is shown below.



Full starting resistance is connected and thus the supply current to the stator is reduced. The rotor begins to rotate, and the rotor resistances are gradually cut out as the speed of the motor increases. When the motor is running at its rated full load speed, the starting resistances are cut out completely, and the slip rings are short-circuited.

Single Phase Induction Motor

The main characteristic of single-phase inductions motor is the same as that of a three-phase. This motor starts automatically (self) but a 1-phase Induction motor will not start automatically because it cannot expand starting torque. 3-phase expands starting torque through a rotating magnetic field. For reason of economy, most houses, offices and also rural areas are supplied with single phase a.c, as power requirements of individual load items are rather small. Single phase motors are simple in construction, reliable, easy to repair and comparatively cheaper in cost and therefore, used in domestic purposes like fans, refrigerators, vacuum cleaners, washing machines, other kitchen equipment, tools, blowers, centrifugal pumps, small farming appliances etc.

Construction of Single-Phase induction motor:

Single phase induction motor is very simple and robust in construction. Like other ac motors, single-phase induction motor has two main parts, one rotating and other stationary. The stationary part in single-phase induction motors is Stator and the rotating part is Rotor.

The stator carries a distributed winding in the slots cut around the inner periphery. The stator conductors have low resistance and they are winding called Starting winding is also mounted on the stator. This winding has high resistance and its embedded deep inside the stator slots, so that they have considerable inductance. The rotor is invariably of the squirrel cage type. In practice, in order to convert temporarily the single-phase motor into two-phase motor, auxiliary conductors are placed in the upper layers of stator slots. The auxiliary winding has a centrifugal switch in series with it. The function of the switch is to cut off the starting winding, when the rotor has accelerated to about 75% of its rated speed. In capacitor start motors, an electrolytic capacitor of suitable capacitance value is also incorporated in the starting winding circuit.

The main stator winding and auxiliary (or starting) winding are joined in parallel, and there is an arrangement by which the polarity of only the starting winding can be reversed. This is necessary for changing the direction of rotation of the rotor.

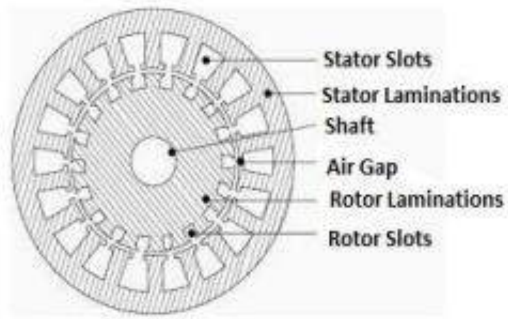


Fig 1

A single-phase induction motor is similar to a 3-phase squirrel cage induction motor in physical appearance. The rotor is same as that employed in 3-phase squirrel cage induction motor. There is uniform air gap between stator and rotor but no electrical connection between them.

Although single phase induction motor is simpler in construction and is cheaper than a 3-phase induction motor of the same frame size, it is less efficient and it operates at lower power factor.

Working of Single-phase induction motor:

A single-phase induction motor is inherently not self-staring can be shown easily.

Consider a single-phase induction motor whose rotor is at rest. Let a single phase a.c. source be connected to the stator winding (it is assumed that there is no starting winding). Let the stator be wound for two poles.

When power supply for the stator is switched on, an alternating current flow through the stator winding. This sets up an alternating flux. This flux crosses the air gap and links with the rotor conductors. By electromagnetic induction e.m.f.'s is induced in the rotor conductors. Since the rotor forms a closed circuit, currents are induced in the rotor bars. Due to interaction between the rotor induced currents and the stator flux, a torque is produced. It is readily seen that if all rotor conductors in the upper half come under a stator N pole, all rotor conductors in the lower half come under a stator S pole. Hence the upper half of the rotor is subjected to a torque which tends to rotate it in one direction and the lower half of the rotor is acted upon by an equal torque which tends to rotate it in the opposite direction. The two equal and opposite torques cancel out, with the result that the net driving torque is zero. Hence the rotor remains stationary. Thus, the single-phase motor fails to develop starting torque.

This argument holds good irrespective of the number of stator poles and the polarity of the stator winding. The net torque acting on the rotor at standstill is zero.

If, however, the rotor is in motion in any direction when supply for the stator is switched on, it can be shown that the rotor develops more torque in that direction. The net torque then, would have non-zero value, and under its impact the rotor would speed up in its direction.

The analysis of the single-phase motor can be made on Double revolving field theory.

Double Revolving Field Theory:

This theory for single phase states that a stationary pulsating magnetic field can be resolved into two RMF, each of equal magnitude but rotating in the opposite direction.

It makes use of the idea that an alternating uni-axial quantity can be represented by two oppositely-rotating vectors of half magnitude. Accordingly, an alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously ($Ns = 120\ f/\ P$) in opposite direction.

As shown in figure: (2a) let the alternating flux have a maximum value of ϕ_m. Its component fluxes A and B will each equal to $\phi_m/2$ revolving in anti-clockwise and clockwise directions respectively. After some time, when A and B would have rotated through angle +ϴ and – ϴ, as in figure: (2b), the resultant flux would be

$$= 2 * \phi_m/2 \cos 2\Theta/2 = \phi_m \cos \Theta$$

After a quarter cycle of rotation, fluxes A and B will be oppositely-directed as shown in figure: (2c) so that the resultant flux would be zero.

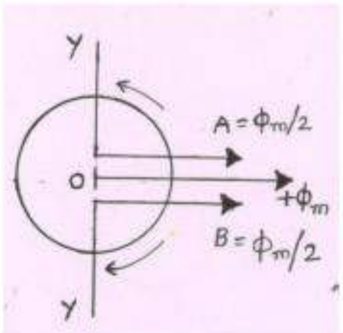


Fig 2a

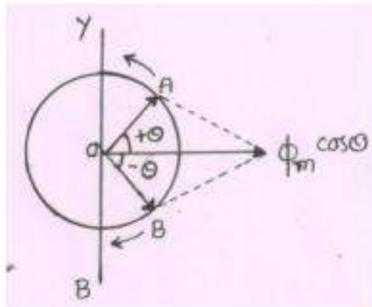


Fig 2b

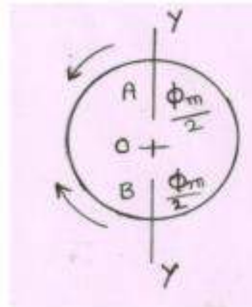


Fig 2c

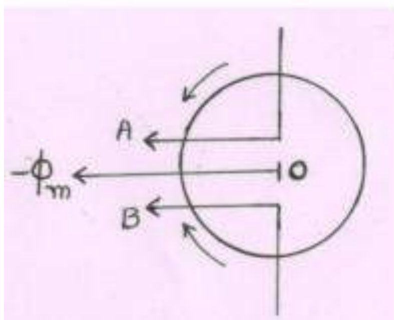


Fig 2d

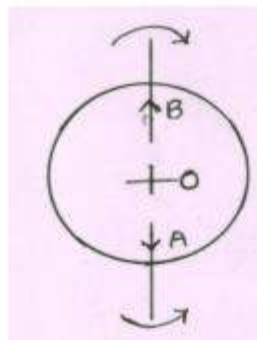


Fig 2e

After half a cycle, fluxes A and B will have a resultant of -2* ϕ_m /2 = -ϕ_m. After three quarters of a cycle, again the resultant is zero, as shown in figure: (2e) and so on. If we plot the values of resultant flux against Θ between limits $\Theta=0^0$ to $\Theta=360^0$, then a curve similar to the one shown in figure: (3) is obtained. That is why an alternating flux can be looked upon as composed of two revolving fluxes, each of half the value and revolving synchronously in opposite directions.

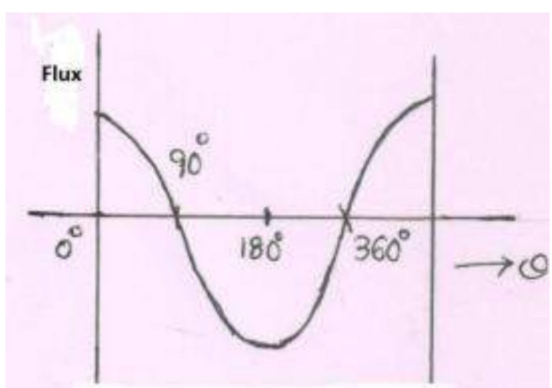


Fig 3

Starting Methods of Single-Phase Induction Motors:

A single-phase induction motor with main stator winding has no inherent starting torque, since main winding introduces only stationary, pulsating air-gap flux wave. For the development of starting torque, rotating air-gap field at starting must be introduced. Several methods which have been developed for the starting of single-phase induction motors, may be classified as follows:

a) Split-phase starting.

b) Shaded-pole starting.

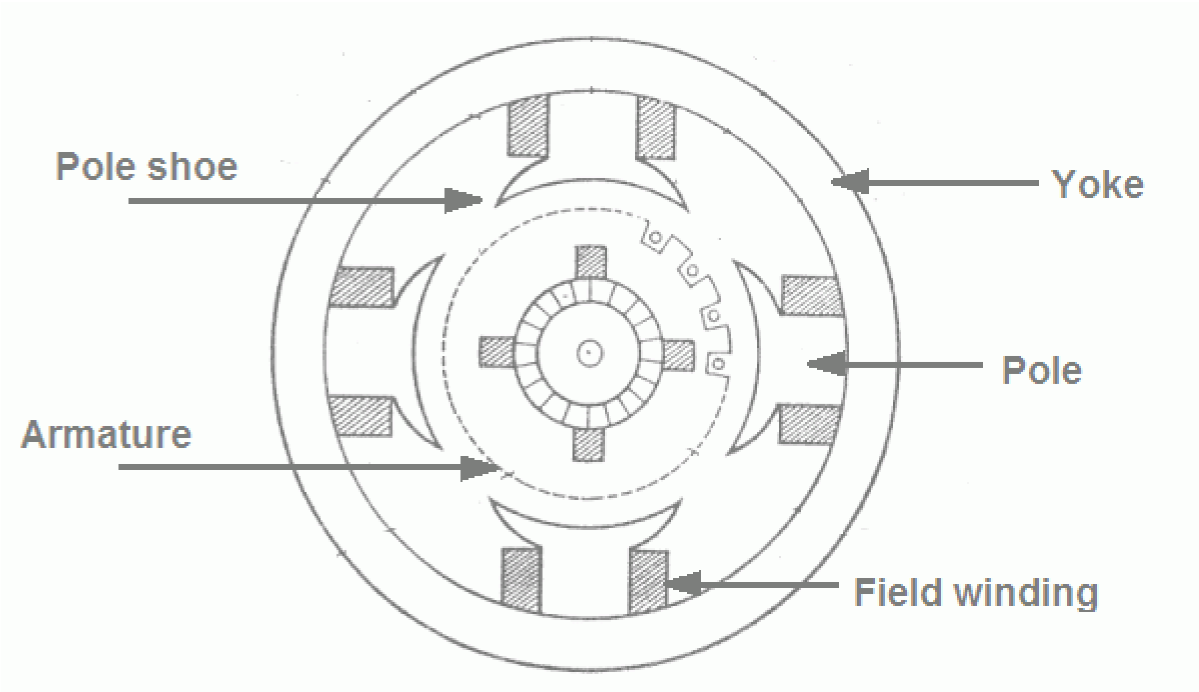
c) Repulsion-motor starting

d) Reluctance starting.

DC MOTOR

A DC motor is any of a class of rotary electrical motors that converts direct current electrical energy into mechanical energy. A DC motor or a DC machine consists of two windings namely field winding and armature winding. The field winding is stationary and armature winding can rotate. The field winding produces a magnetic flux in the air gap between the armature and field windings and the armature is placed in this magnetic field.

Construction of DC Motor

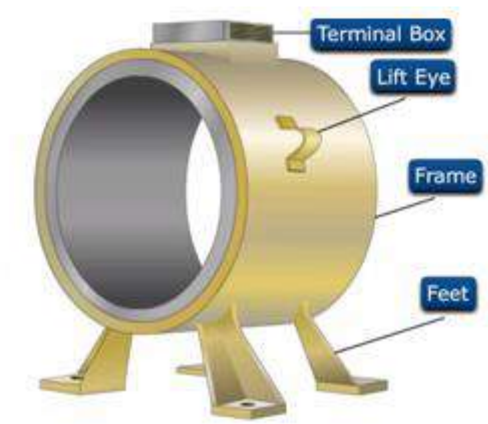


Construction of a DC Motor

The main parts used in the construction of a DC motor are the yoke, poles, field winding, commutator, carbon brushes bearings etc. A brief description of the various parts is as follows:

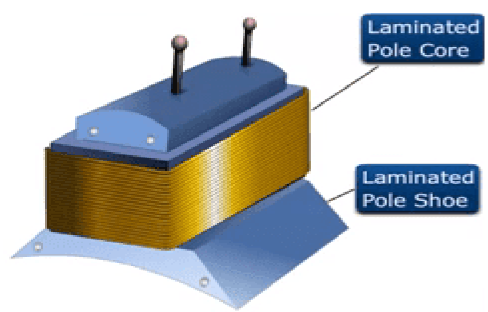
1.Yoke

The yoke acts as the outer cover of a DC motor and it is also known as the frame. The yoke is an iron body, made up of low reluctance magnetic material such as cast iron, silicon steel, rolled steel etc. Yoke serve two purposes, firstly it provides mechanical protection to the outer parts of the machine secondly it provides low reluctance path for the magnetic flux.



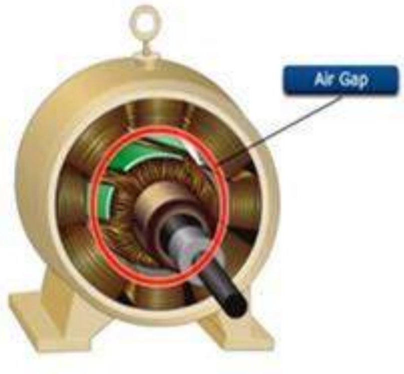
2. **<u>Poles and Pole Shoe</u>**

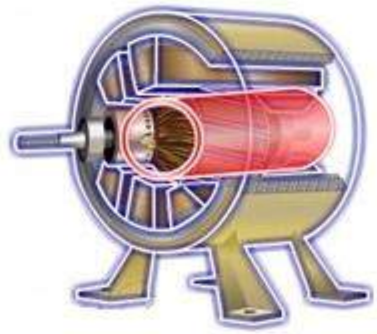
The pole and pole shoe are fixed on the yoke by bolts. These are made of thin cast steel or wrought iron laminations which are riveted together. Poles produce the magnetic flux when the field winding is excited. Pole shoe is an extended part of a pole. Due to its shape, the pole area is enlarged and more flux can pass through the air gap to the armature.



<u>3.Field Winding</u>

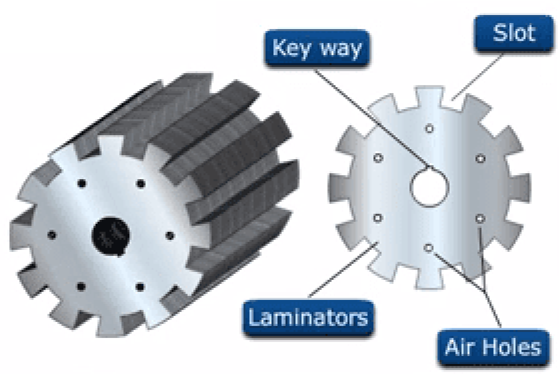
The coils around the poles are known as field (or exciting) coils and are connected in series to form the field winding. Copper wire is used for the construction of field coils. When the DC current is passed through the field windings, it magnetizes poles which produce magnetic flux.





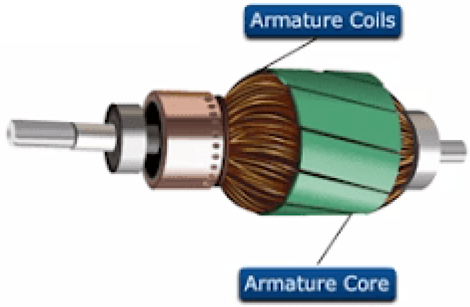
4. **<u>Armature Core</u>**

It is a cylindrical drum and keyed to the rotating shaft. A large number of slots are made all over its periphery, which accommodates the armature winding. Low reluctance, high permeability material such as cast iron and cast steel are used for armature core. The laminated construction is used to produce the armature core to minimize the eddy current losses. The air holes are also provided on the armature core for the air circulation which helps in cooling the motor.



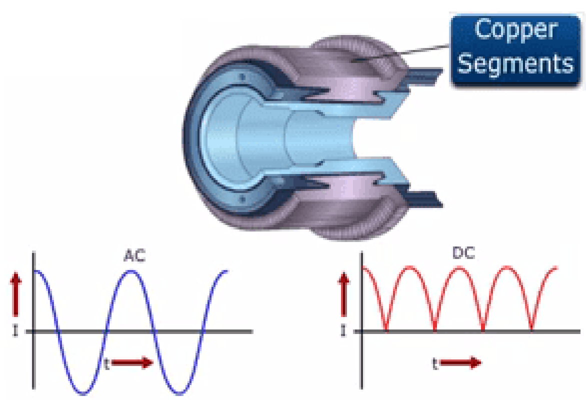
5. **<u>Armature Winding</u>**

The armature winding plays very important role in the construction of a DC motor because the conversion of power takes place in armature winding. On the basis of connections, there are two types of armature windings name.

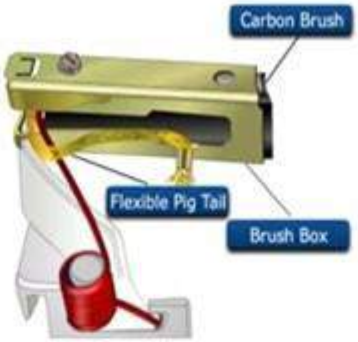


6.Commutator

It is a mounted on the shaft. It is made up of a large number of wedge-shaped segments of hard drawn copper, insulated from each other by a thin layer of mica. The commutator connects the rotating armature conductor to the stationary external circuit through carbon brushes. It converts alternating torque into unidirectional torque produced in the armature.



7. <u>Carbon Brushes</u>



The current is conducted from voltage source to armature by the carbon brushes which are held against the surface of commutator by springs. They are made of high-grade carbon steel and are rectangular in shape.

8. Bearings

The ball or roller bearings are fitted in the end housings. The friction between stationary and rotating parts of the motor is reduced by bearing. Mostly high carbon steel is used for making the bearings as it is very hard material.

WORKING PRINCIPLE OF DC MOTOR

A machine that converts DC electrical power into mechanical power is known as a Direct Current motor.

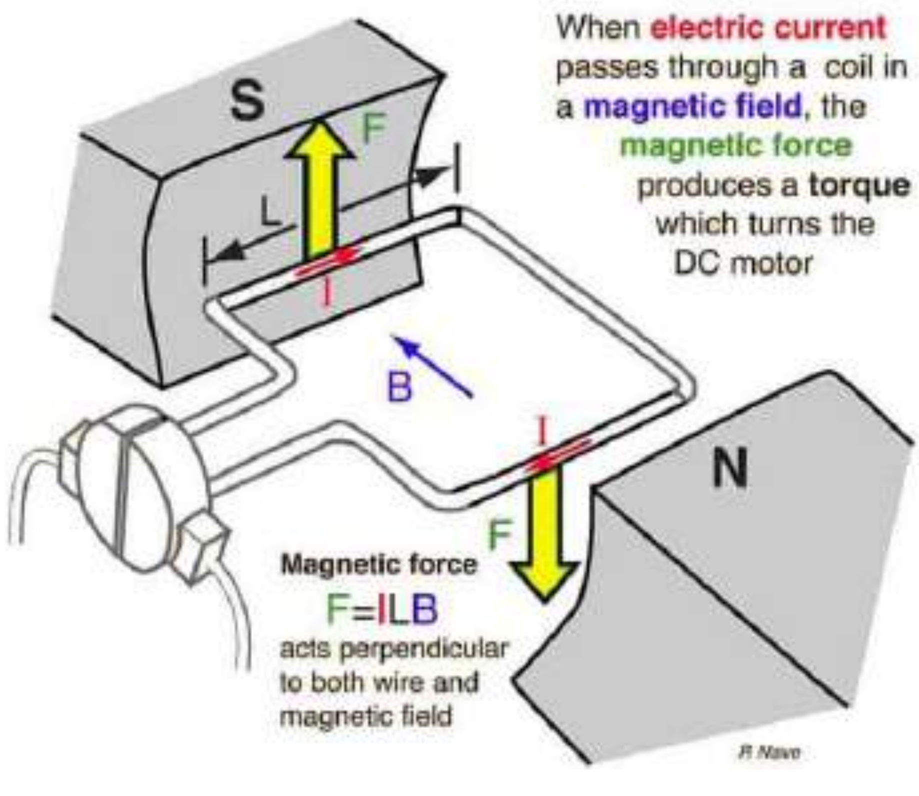
DC motor working is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.

The direction of this force is given by Fleming's left-hand rule and magnitude is given by;

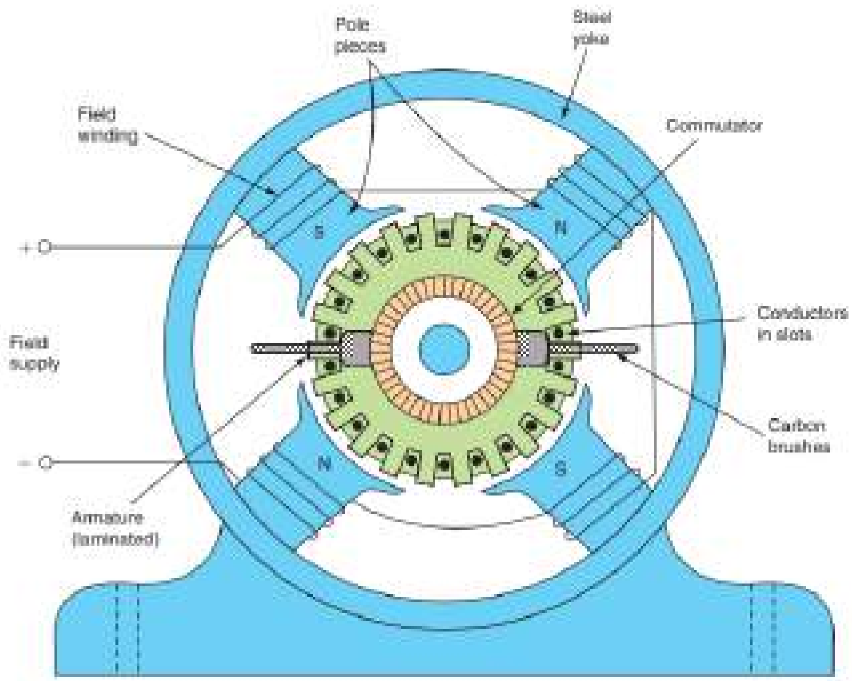
$$F = BIL \text{ Newtons}$$

According to Fleming's left-hand rule when an electric current passes through a coil in a magnetic field, the magnetic force produces a torque that turns the DC motor.

The direction of this force is perpendicular to both the wire and the magnetic field.

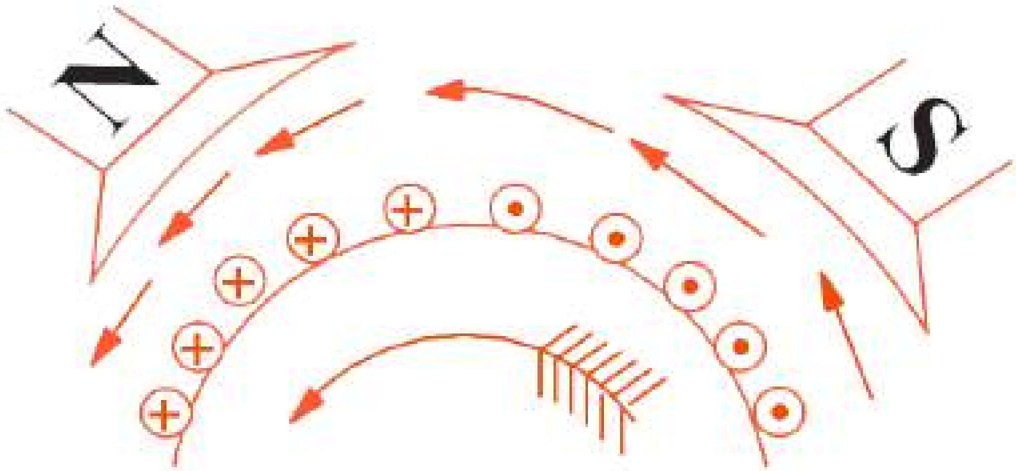


Basically, there is no constructional difference between a DC motor and a DC generator. The same DC machine can be run as a generator or motor.



Consider a part of a multipolar DC motor as shown in the figure below. When the terminals of the motor are connected to an external source of DC supply:

- the field magnets are excited developing alternate North and South poles
- the armature conductors carry currents.



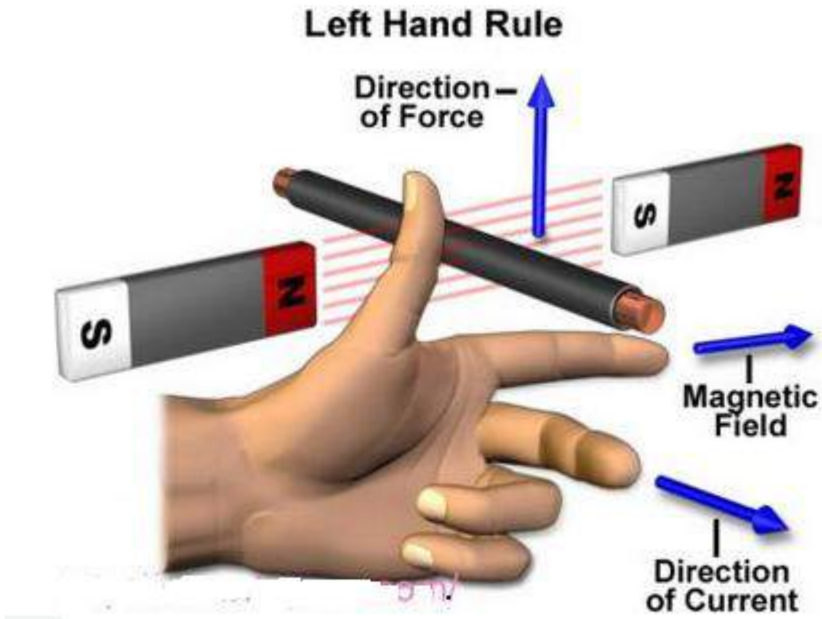
Part of a Multi-polar DC Motor

All conductors under North-pole carry currents in one direction while all the conductors under South-pole carry currents in the opposite direction.

The armature conductors under N-pole carry currents into the plane of the paper (denoted as ⊗ in the figure). And the conductors under S-pole carry currents out of the plane of the paper (denoted as ⊙ in the figure).

Since each armature conductor is carrying current and is placed in the magnetic field, a mechanical force acts on it.

On applying Fleming's left-hand rule, it is clear that force on each conductor is tending to rotate the armature in the anticlockwise direction. All these forces add together to produce a driving torque which sets the armature rotates.



When the conductor moves from one side of a brush to the other, the current in that conductor is reversed. At the same time, it comes under the influence of the next pole which is of opposite polarity. Consequently, the direction of the force on the conductor remains the same.

It should be noted that the function of a commutator in the motor is the same as in a generator. By reversing current in each conductor as it passes from one pole to another, it helps to develop a continuous and unidirectional torque.

Characteristics of separatedly excited DC motors/ dc shunt motor

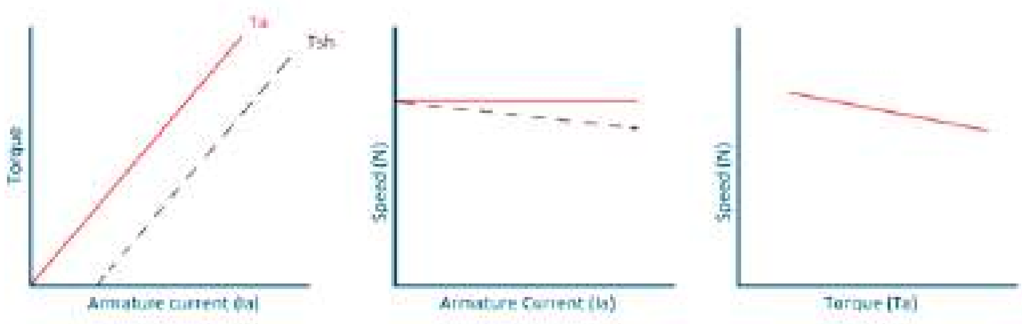
Torque vs. armature current (Ta-Ia)

In case of separately excited dc motors, we can assume the field flux ϕ to be constant. Though at heavy loads, ϕ decreases in a small amount due to increased armature reaction. As we are neglecting the change in the flux ϕ, we can say that torque is proportional to armature current Hence, the Ta-Ia characteristic for a dc shunt motor will be a straight line through the origin.

Speed vs. armature current (N-Ia)

As flux ϕ is assumed to be constant, we can say N ∝ Eb. But, as back emf is also almost constant, the speed should remain constant. But practically, ϕ as well as Eb decreases with increase in load. Back emf Eb decreases slightly more than ϕ, therefore, the speed decreases slightly. Generally, the speed decreases only by 5 to 15% of full load speed. Therefore, **motor**

can be assumed as a constant speed motor. In speed vs. armature current characteristic in the following figure, the straight horizontal line represents the ideal characteristic and the actual characteristic is shown by the dotted line.



Torque vs. speed (T-Na)

the corresponding speed $N_0=V_a/(K_e\Phi)$ is the no-load speed. The motor speed decreases as the torque developed increases, resulting in a drooping characteristic. The speed-torque curves are shown in Fig. 1.3. The figure clearly shows a speed drop of 2 to 3% as the torque varies from no-load to full load.

Synchronous Generator

The electrical machine can be defined as a device that converts electrical energy into mechanical energy or mechanical energy into electrical energy. Anelectrical generator can be defined as an electrical machine that converts mechanical energy into electrical energy. An electrical generator typically consists of two parts; stator and rotor. There are various types of electrical generators such as direct current generators, alternating current generators, vehicular generators, human powered electrical generators, and so on.

Synchronous Generators

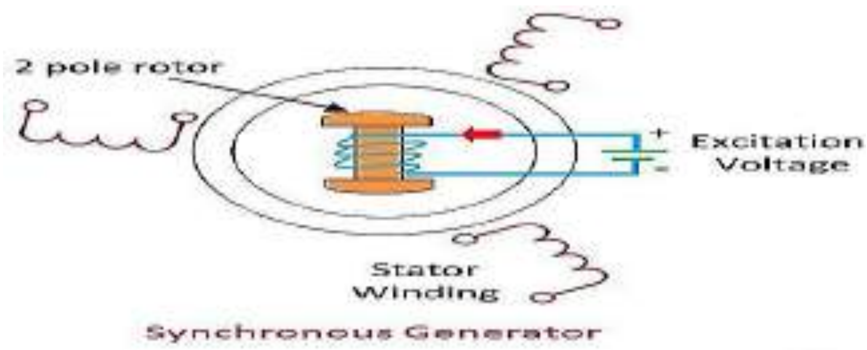
Definition: The synchronous generator or alternator is an electrical machine that converts the mechanical power from a prime mover into an AC electrical power at a particular voltage and frequency. The synchronous motor always runs at a constant speed called synchronous speed.

Construction of Synchronous Generator

The rotor and stator are the rotating and the stationary part of the synchronous generator. They are the power generating components of the synchronous generator. The rotor has the field pole, and the stator consists the armature conductor. The relative motion between the rotor and the stator induces the voltage between the conductors. The rotor or stator of electrical machines acts as a power-producing component and is called as an armature. The electromagnets or permanent magnets mounted on the stator or rotor are used to provide magnetic field of an electrical machine. The generator in which permanent magnet is used instead of coil to provide excitation field is termed as permanent magnet synchronous generator or also simply called as synchronous generator. The rotation of field poles in the presence of armature conductors induces an alternating voltage which results in electrical power generation.

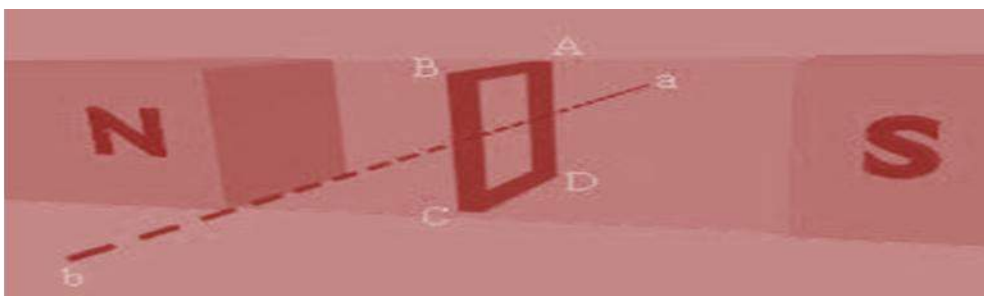
$$N_s = \frac{120f}{P}$$

Where, ‘f’ indicates alternating current frequency and ‘P’ indicates number of poles.

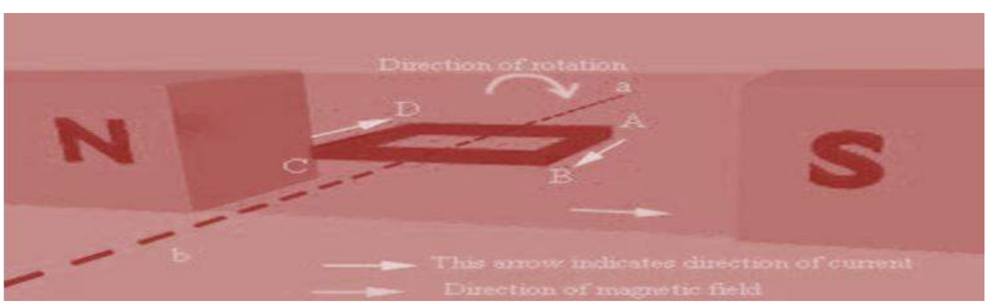


Working Principle of Synchronous Generator

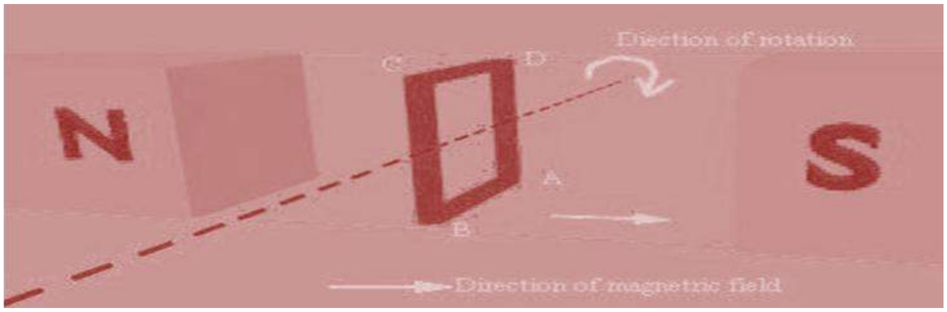
The principle of operation of synchronous generator is electromagnetic induction. If there exists a relative motion between the flux and conductors, then an emf is induced in the conductors. To understand the synchronous generator working principle, let us consider two opposite magnetic poles in between them a rectangular coil or turn is placed as shown in the below figure.



If the rectangular turn rotates in clockwise direction against axis a-b as shown in the below figure, then after completing 90 degrees rotation the conductor sides AB and CD comes in front of the S-pole and N-pole respectively. Thus, now we can say that the conductor tangential motion is perpendicular to magnetic flux lines from north to south pole.

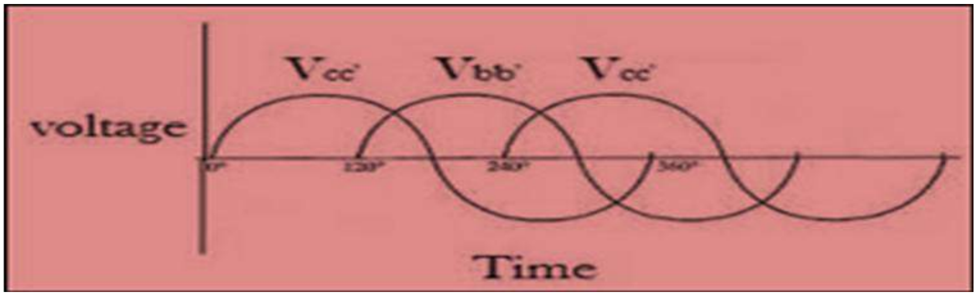


So, here rate of flux cutting by the conductor is maximum and induces current in the conductor, the direction of the induced current can be determined using Fleming's right hand rule. Thus, we can say that current will pass from A to B and from C to D. If the conductor is rotated in a clockwise direction for another 90 degrees, then it will come to a vertical position as shown in the below figure.



Now, the position of conductor and magnetic flux lines are parallel to each other and thus, no flux is cutting and no current will be induced in the conductor. Then, while the conductor rotates from clockwise for another 90 degrees, then rectangular turn comes to a horizontal position as shown in the below figure. Such that, the conductors AB and CD are under the N-pole and S-pole respectively. By applying Fleming's right hand rule, current induces in conductor AB from point B to A and current induces in a conductor CD from point D to C. Thus, for one complete revolution of rectangular turn the current in the conductor reaches to maximum & reduces to zero and then in the opposite direction it reaches to maximum & again reaches to zero. Hence, one complete revolution of rectangular turn produces one full sine wave of current induced in the conductor which can be termed as the generation of alternating current by rotating a turn inside a magnetic field.

The synchronous generator rotor and shaft or turbine blades are mechanically coupled to each other and rotate at synchronous speed. Thus, the magnetic flux cutting produces an induced emf which causes the current flow in armature conductors. Thus, for each winding the current flows in one direction for the first half cycle and current flows in the other direction for the second half cycle with a time lag of 120 degrees (as they displaced by 120 degrees). Hence, the output power of synchronous generator can be shown as below figure.



Applications of Synchronous Generator

The three-phase synchronous generators have many advantages in generation, transmission and distribution. The large synchronous generators use in the nuclear, thermal and hydropower system for generating the voltages. The synchronous generator with 100MVA power rating uses in the generating station. The 500MVA power rating transformer use in the super thermal power stations. The synchronous generators are the primary source of the electrical power. For the heavy power generation, the stator of the synchronous generator design for voltage ratings between 6.6 kV to 33 kV.