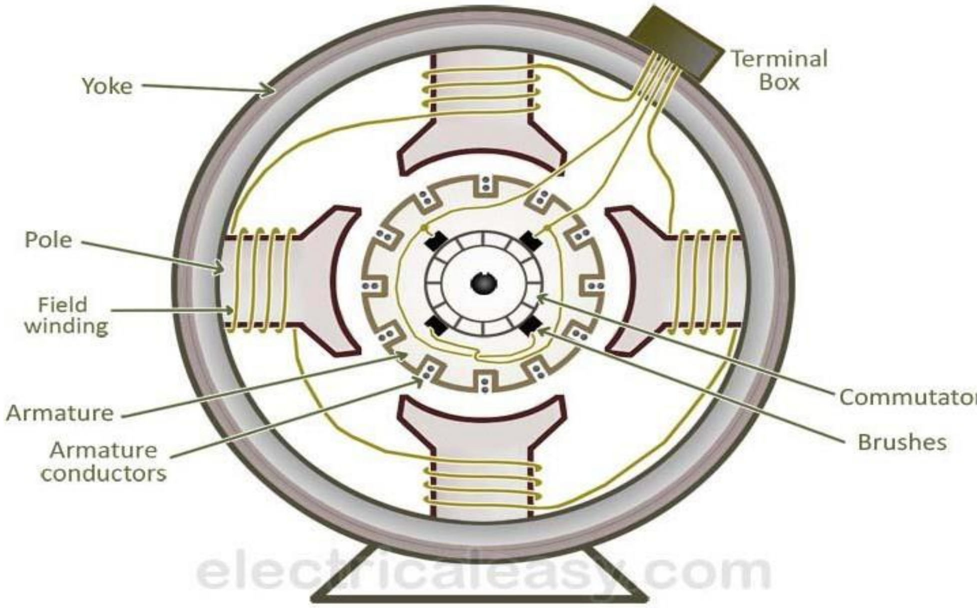
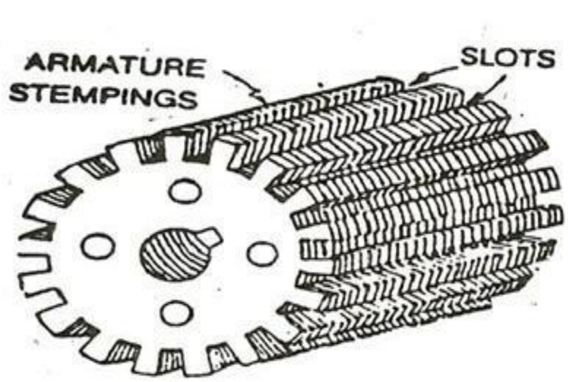
CONSTRUCTION OF A DC MACHINE



The above figure shows constructional details of a simple **4-pole DC machine**. A DC machine consists of two basic parts; Field system and Armature assembly. Basic constructional parts of a DC machine are described below.

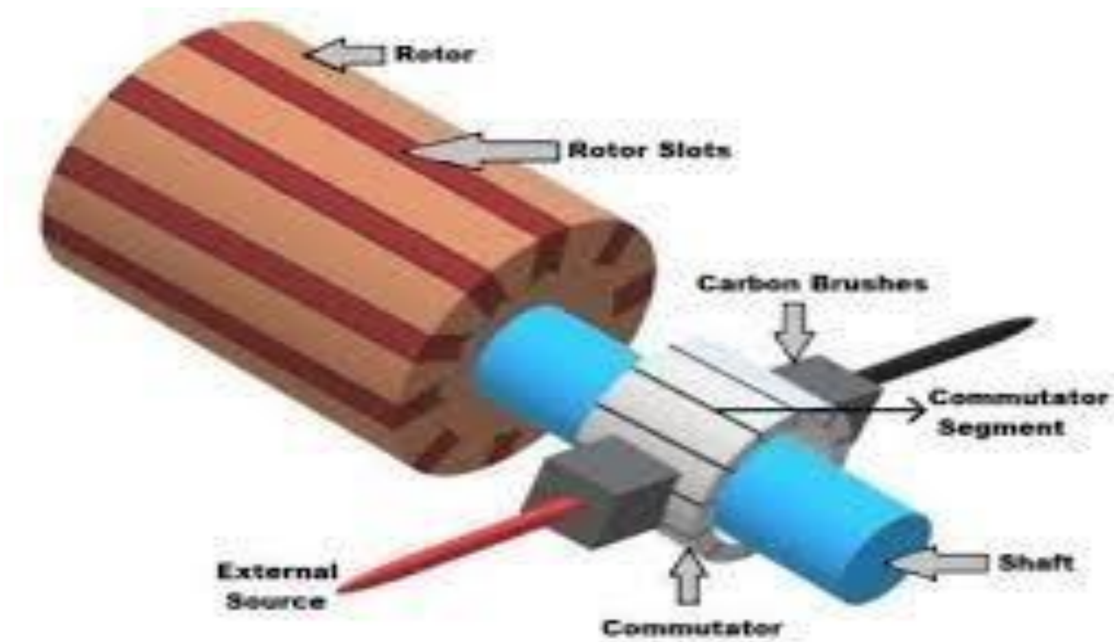
1. **Yoke:** The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.
2. **Poles and pole shoes:** Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in air gap uniformly.
3. **Field winding:** They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.

4. **Armature core:** Armature core is the rotor of a dc machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.



5. **Armature winding:** It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding.
6. **Commutator and brushes:** Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a dc generator, is to collect the current generated in armature

conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors. A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft. Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

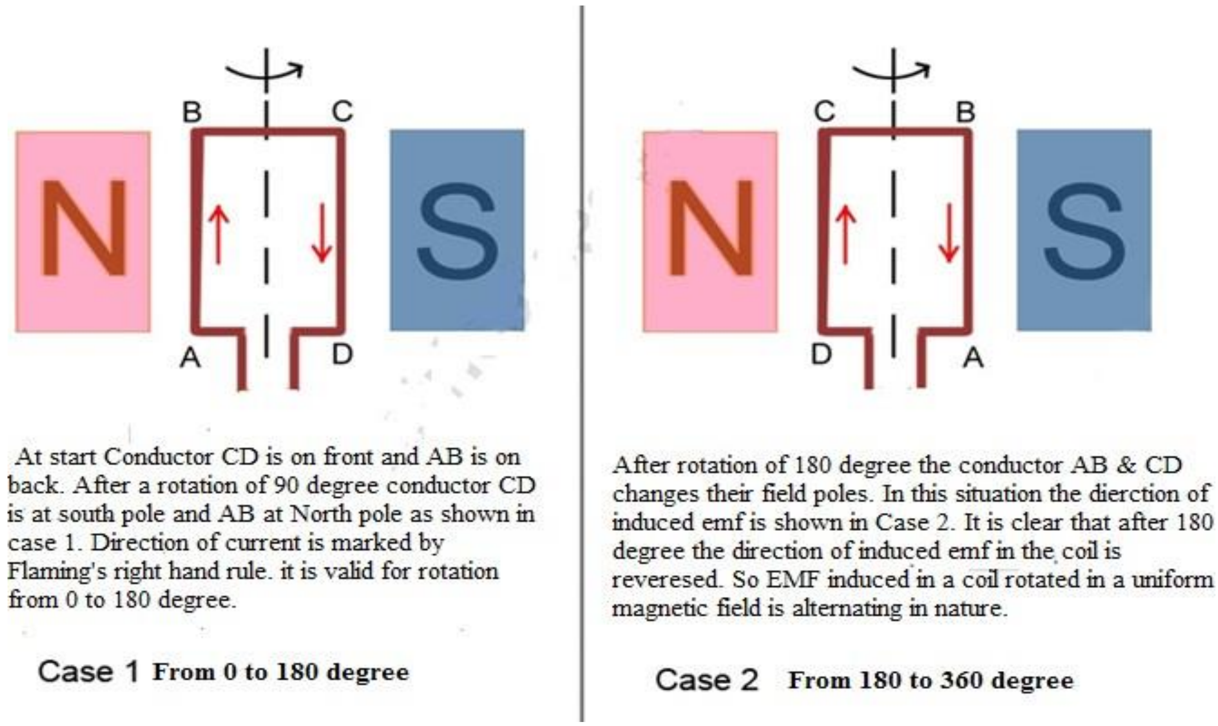


DC GENERATOR WORKING

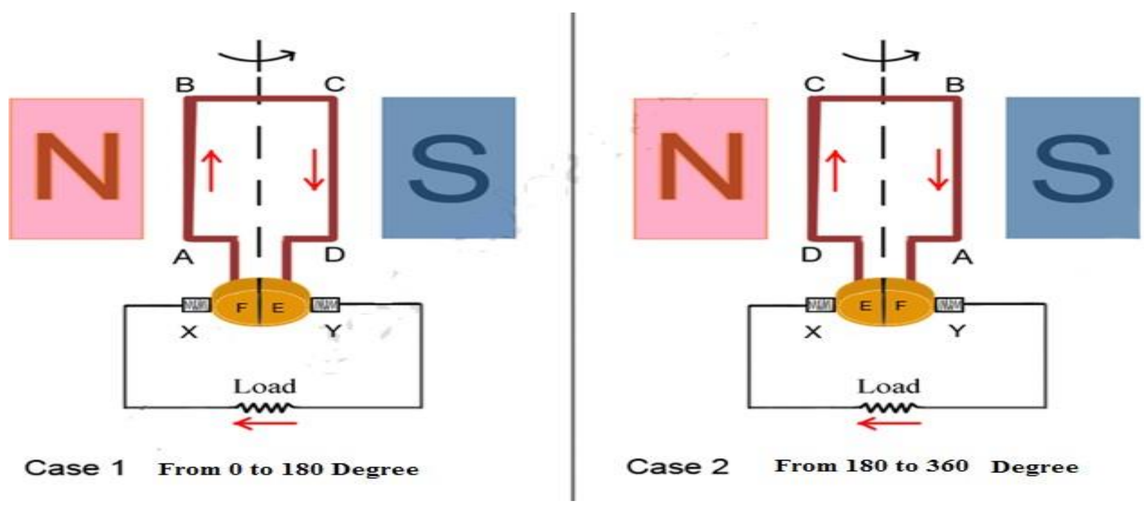
DC Generator Operating Principle: Whenever a rotating conductor is placed in a uniform magnetic field due to rotation of conductor the flux linkages of conductor gets changed and an emf is induced in the conductor whose direction is given by Fleming's right-hand rule. AS conductor is moving so generator is a case of dynamically induced EMF.

Flaming's Right Hand Rule: Fleming's right-hand rule gives the direction of induced EMF or current . The **right hand is** held with the thumb, index finger and middle finger mutually perpendicular to each other such that thumb **is** pointed in the direction of the motion of the conductor, index finger in the direction of the magnetic field then central finger gives the direction of induced current.

Working of a single turn generator: Consider a coil or single turn of winding having 2 conductors AB and CD is being rotated in a uniform magnetic field as shown in fig.



From this discussion it is clear that EMF induced in the coil of single turn generator is alternating in nature. This alternating EMF can be converted in direct current by using split ring and brush arrangement. In next fig. we can see that coil ends are connected to split ring **F** and **E**. These split rings are free to rotate with coil and on outer surface of these split ring stationary brushes **X** and **Y** are placed through which external load resistance $\mathbf{R_L}$ is connected to the generator. Now due to rotation as the direction of induced current is reversed in the coil the split rings also changes their brushes and in external circuit we maintain load current from brush **Y** to brush **X** for all cases.



So in single turn generator we get a unidirectional pulsating current across the load.

NOTE: In practical generator the magnitude of output current is kept constant by increasing the number of coils. A coil remain in contact with the brushes only for time interval in which the induced current in coil is maximum and then due to rotation it is replaced by the next coil.

Commutator Action : in DC Generator the commutator

(i) Act as mechanical rectifier convert induced AC armature current in to DC current at load terminal

(ii) Collect armature conductor current and supplied it to the load. Provides stationary contacts to connect load in form of brushes.

DC Generators are classified on the basis of their excitation system (i.e. working flux is produced). There are three methods of excitation, and thus three main **types of DC generators**:

1. Permanent Magnet DC Generators – Pieces of permanent magnet are placed around armature to develop working flux. No Field poles or coils are required hence compact in size but still rarely used in industry due to constant field strength and low rating. Used in vehicles as dynamo for charging battery and in techometers.

2. Separately Excited DC Generators – In separately excited dc machines, the field winding is supplied from a separate power source. That means the field winding is electrically separated from the armature circuit. Shown in Fig. 1

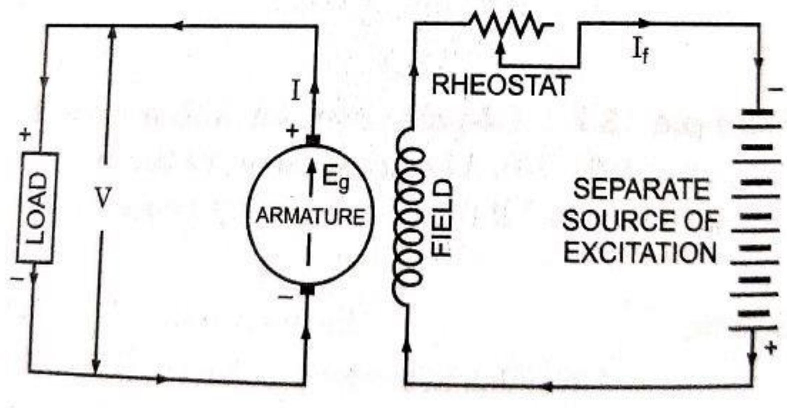


Fig. 1 Separately Excited DC Generators

3. Self Excited DC Generators –In a **self-excited type of DC generator**, the field winding is energized by the current produced by themselves. A small amount of flux is always present in the poles due to the residual magnetism. So, initially, current induces in the armature conductors of a dc generator only due to the residual magnetism. The field flux gradually increases as the induced current starts flowing through the field winding.

Self-excited machines can be further classified as –

- **Series wound dc machines** – In this type, field winding is connected in **series with the armature winding**. Therefore, the field winding carries whole of the load current (armature current). That is why series winding is designed with **few turns of thick wire** and the resistance is kept very low (about 0.5 Ohm**). Fig.2**

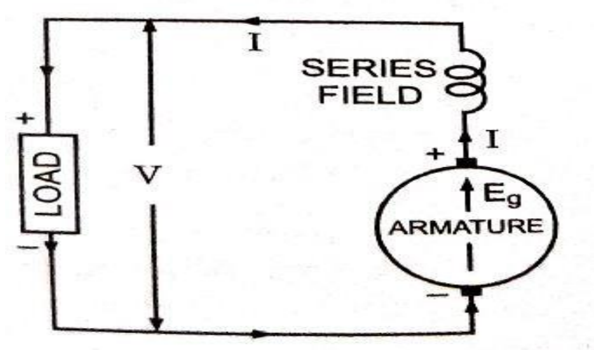


Fig. 2 Series Wound DC Generators

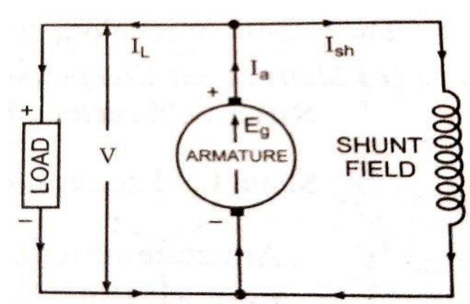
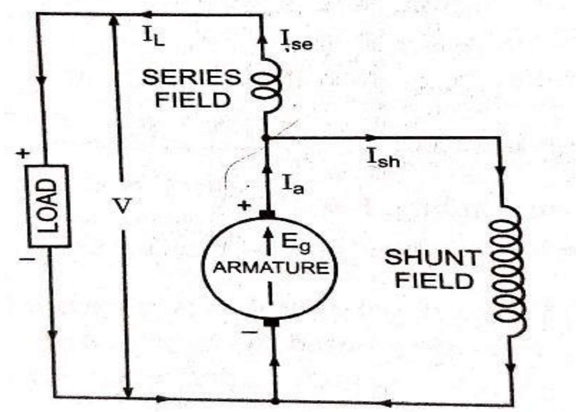


Fig. 3 Shunt Wound DC Generators

- **Shunt wound dc machines** – Here, field winding is connected in parallel with the armature winding. Hence, the full voltage is applied across the field winding. Shunt winding is made with a large number of turns of a wire having cross-sectional area very small **(Thin wire**). The resistance is kept very high (about 100 Ohm). It takes only small current which is less than 5% of the rated armature current. Fig.3
- **Compound wound dc machines** – In this type, there are two sets of field winding. One is connected in series and the other is connected in parallel(Shunt) with the armature winding. Depending upon connection of shunt or parallel field winding Compound wound machines are further divided as -
  - **Short shunt** – field winding is connected in parallel with only the armature winding. **(Fig.4)**



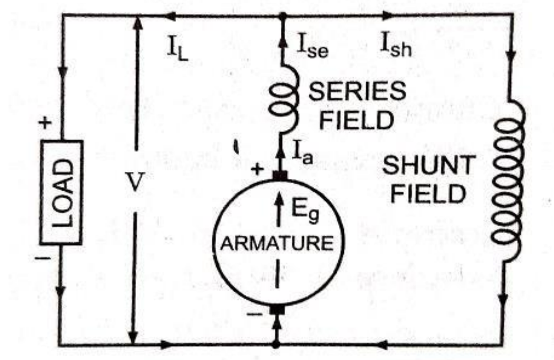


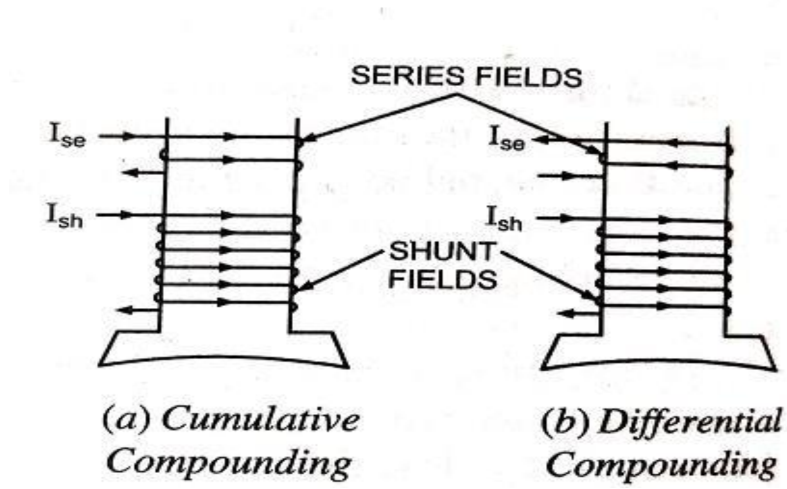
Fig.4 Short Shunt Compound Generator **Fig.5 Short Shunt Compound Generator**

- **Long shunt** – field winding is connected in parallel with the combination of series field winding and armature winding **(Fig.5)**

Note:- Depending upon the interaction between series field and shunt field winding flux the compound generators can be classified as Cumulative compound and differential compound.

Cumulative Compound Generator : In these generators the shunt and series field carries current in same direction so their flux is additive in nature. With increase in load or armature current net flux in machine increases

Differential Compound Generator : In these generators the shunt and series field carries current in opposite direction so their flux act opposite to each other. The net flux is difference in shut field flux and series field flux. With the increase in load or armature current net flux in machine decreases.



EMF equation of a DC generator

Consider a DC generator with the following parameters,

P = number of field poles , ϕ = flux produced per pole in Wb (weber)

Z = total no. of armature conductors

A = no. of parallel paths in armature

N = rotational speed of armature in revolutions per min. (rpm)

Now, Average emf generated per conductor is given by $\frac{d\phi}{dt}$ …..(eq. 1)

Flux cut by one conductor in one revolution = $d\phi = P\phi$ webers

Number of revolutions per second (speed in RPS) = $\frac{N}{60}\ rps$

Therefore, time for one revolution =dt = $\frac{60}{N}\ sec$

From eq. 1, emf generated per conductor = $\frac{d\phi}{dt} = \frac{P\phi N}{60}$ Volts …..(eq. 2)

Above equation-2 gives the emf generated in one conductor of the generator. If Z is total number of armature conductor then EMF generated in total armature conductors is given by $E = \frac{P\phi ZN}{60}$ Volts,

The conductors are connected in series as per parallel path, and the emf across the generator terminals is equal to the generated emf across any parallel path. Therefore,

$$E_g = \frac{\text{EME induced in armature}}{\text{Number of parallel paths}} = \frac{P\phi ZN}{60\ A} \quad \text{Volts}$$

For simplex lap winding, number of parallel paths is equal to the number of poles (i.e. A=P),

Therefore, for simplex lap wound dc generator, Generated EMF is given by $E_g = \frac{\phi ZN}{60}$ Volts

For simplex wave winding, number of parallel paths is equal to 2 (i.e P=2),

Therefore, for simplex wave wound dc generator, Generated EMF is given by $E_g = \frac{P\phi ZN}{120}$ Volts

Also from above equation it is clear that output of a given generator directly proportional to flux and armature speed. $E_g\ \alpha\ \phi N$. We can reverse the polarity of brushes of generator either by changing direction of magnetic flux ϕ or direction of rotation of armature.

DC Motor Operating principle: A machine that converts DC electrical power into mechanical power is known as a DC motor**.** DC motor working is based on the principle that when a current carrying conductor is placed in a Uniform 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 Newtons Where,**

B = magnetic flux density, I = current and L = length of the conductor in the magnetic field.

Fleming's left hand rule: If we stretch the first finger, Central finger and thumb of our left hand to be perpendicular to each other, and the direction of magnetic field is represented by the first finger, direction of the current is represented by the second finger, then the thumb represents direction of the force experienced by the current carrying conductor.

Working of a single turn motor:- Consider a single turn motor at which DC supply is connected at brushes. The Split ring **a** is connected to positive brush and Split ring **b** is connected to negative brush. The coil end 1 under south pole carrying current in **inward direction** (represented by +) and coil end 2 under north pole carrying current in **outward direction** (represented by *). In this condition motor armature will experience torque of force in **Clockwise direction** calculated by Fleming Left hand rule.(**Fig.1**)

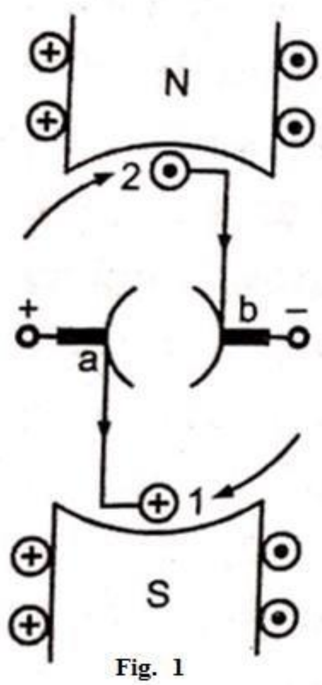


Fig. 1

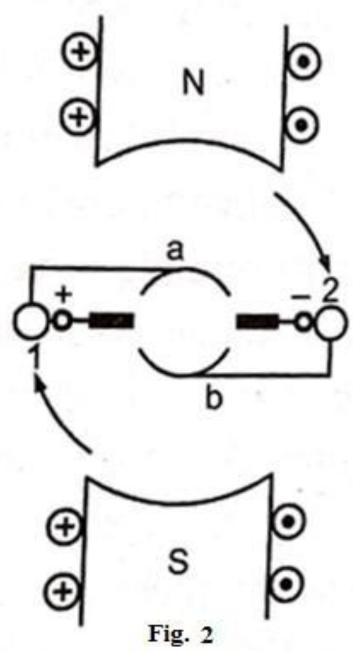


Fig. 2

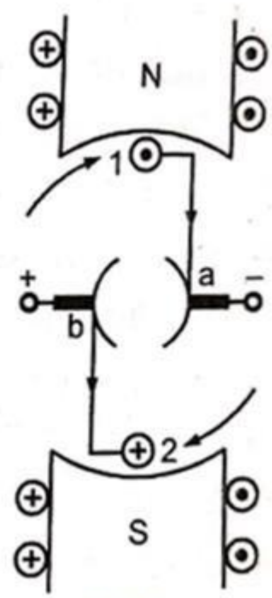


Fig. 3

In Fig.2 due to rotation in clockwise direction the split ring **a** in no longer in contact with positive brush and similarly split ring **b** is not in contact with negative brush. In this condition the coil is not taking any current from brushes and also it is not developing any torque. Due to inertia armature is continue to rotate in initial clockwise direction.

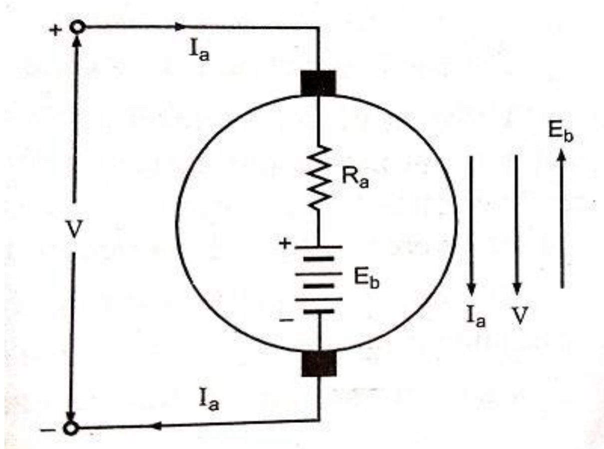
In Fig.3 as coil ends changes their field poles 1 goes under north pole and 2 goes under south pole, the split rings also changed their brushes. So direction of current in coil is reversed and armature will again develop torque in clockwise direction. This is how a single turn motor operates.

Function of Commutator : In DC Motor the commutator convert the supplied DC current in to AC current. By reversing current in each conductor as it passes from one pole to another, it helps to develop a **continuous and unidirectional torque** in DC Motor.

Back Emf:- Back EMF is the EMF induced in the armature of a DC Motor due to simultenous generator action. When a Machine act as DC Motor then it has rotating conductor and a magnetic field associated with it. Thus while running as a motor, the armature of a DC machine simultenously fullfill all the requirement of generator action. So a generator action automatically induced in the motor armature and due to generator action an emf is induced in the armature conductors. The direction of this induced EMF is given by Flaming's Right hand rule. The magnitude of back EMF is given by :-

$$\mathbf{E_b = P\phi\, Z\, N / (60*A)\ \ Volts}$$

The Direction of back EMF is opposite to the supply voltage. So to continue Motor operation a part of supply has to overcome the back emf. Thus the amount of supply used in overcoming the back emf is directly proportional to the mechanical power developed in motor armature. (P_{mech}).



Line Diagram of Motor Armature.

$$V = E_b + I_a R_a$$ **Voltage Equation**

Supply voltage = Back EMF + Drop in Armature

$$V I_a = E_b I_a + I_a^2 R_a$$ **Power Equation**

Supply Power = Pmech. + Armature cu losses

Significance of back EMF: The presence of back EMF is necessary for energy conversion in motors. The Mechanical power developed in motor armature P_{mech} is directly proportional to back EMF.

$$P_{mech} = E_b I_a$$

Also the back EMF act as a governor for armature current. The armature current of DC Motor is given by

$$I_a = (V-E_b) / R_a$$

Now, When machine at no load the value of motor speed or back EMF is high, So Armature current is small.

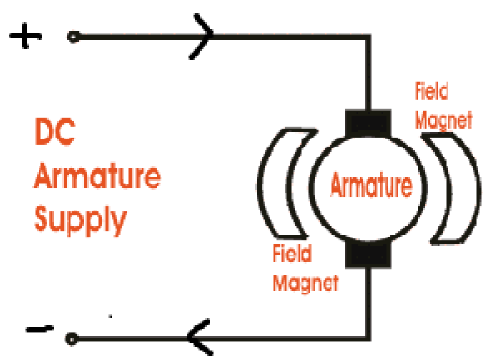
Similarly on application of load the motor speed decreases which reduces Back EMF or increases Armature current. So the motor always draw as much Armature current as required to satisfy the torque requirement of load. Thus Presence of Back **EMF makes a motor self regulating** so that excess armature current is avoided and motor losses can be reduced.

The **Mechanical power in armature P_{mech} is Maximum** when back EMF is half of applied voltage. (E_b = V/2). This condition is never achieved in practice because equal amount of power is wasted in the form of Armature Cu losses. So the overall efficiency of motor after considering other losses is well below 50 %

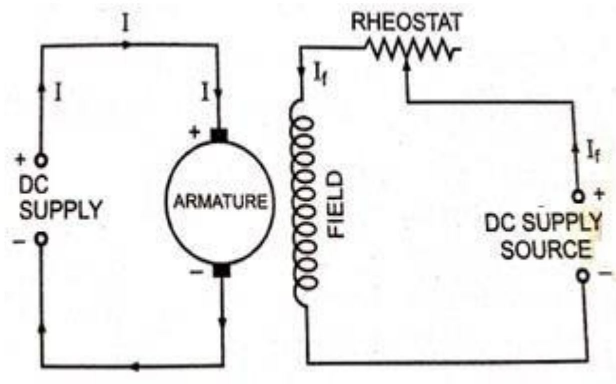
Classification of DC Motors:- The DC Motors are classified in to following categories :

- Permanent Magnet DC Motor (PMDC Motor)
- Separately Excited DC Motor
- Shunt Wound DC Motor
- Series Wound DC Motor
- Compound Wound DC Motor

(i) **Permanent Magnet DC Motor** : It consists of an armature winding as in case of an usual motor, but does not necessarily contain the field windings. In these types of DC motor are such that, permanent magnets are mounted on the inner periphery of the stator to produce the field flux. In these motors torque of DC Motor can only be changed by controlling the armature supply because of constant flux.



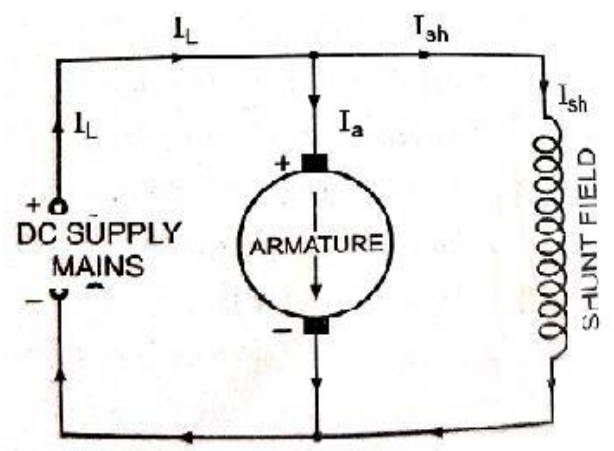
Permanent Magnet DC Motor



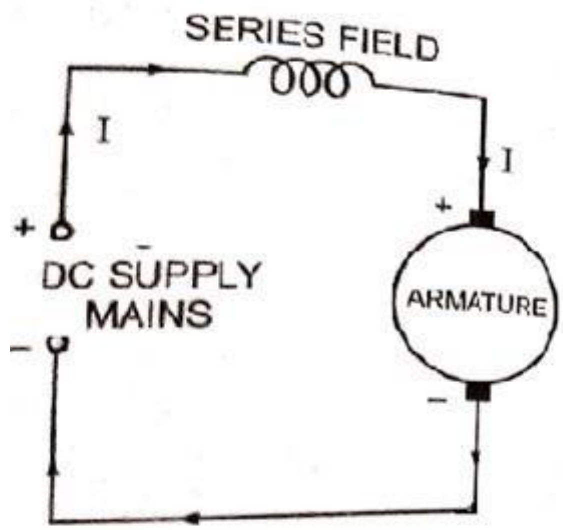
Seperately Excited DC Motor

(ii) **Separately Excited DC Motor:** In case of a separately excited DC motor the separate supply is given to the field and armature windings. The main distinguishing fact in these types of DC motor is that, the armature current does not flow through the field windings, as the field winding is energized from a separate external source of DC current as shown in the figure beside.

(iii) **Shunt Wound DC Motor:** In case of a shunt wound DC motor the field windings are exposed to the entire terminal voltage as they are connected in parallel to the armature winding as shown in the figure below. In these motors the magnetic flux practically remains constant as the value of shunt field current is constant.



DC Shunt Wound Motors



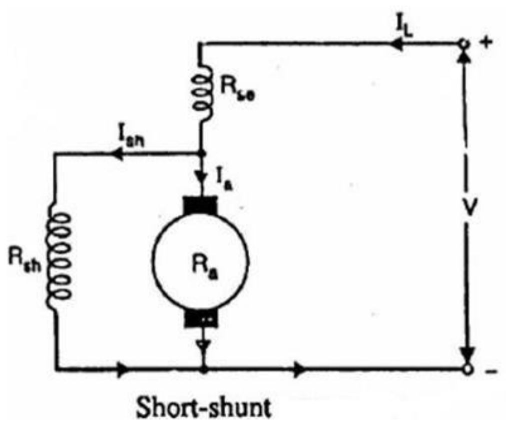
Series Wound DC Motor

(iv) **Series Wound DC Motor:** In case of a series wound DC motor the entire armature current flows through the field winding as its connected in series to the armature winding. In these motors ($I_L = I_a = I_f$) Line , armature and field current are same as all are in series

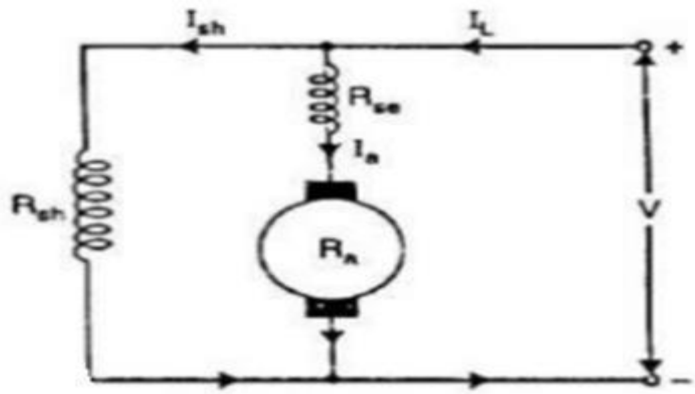
(v) **Compound Wound DC Motor:** In compound motors the field winding is divided in to two parts one is series field and other is shunt field. Depending upon connection of shunt field winding the compound wound motors are of two types.

Short shunt motor : Shunt windings are only connected across armature.

Long shunt motor : Shunt windings are connected across armature as well as across the series field windings



Short-shunt

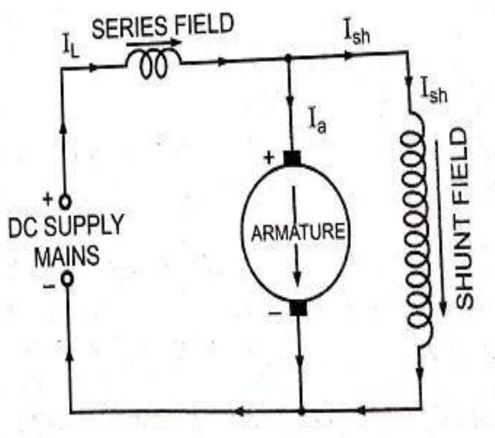


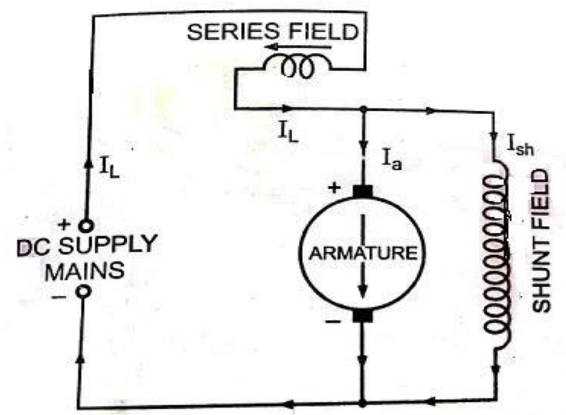
Long-shunt

Depending upon interaction of Shunt and series field winding flux the compound motors are of two types

Cumulative compound motor : Both winding flux act in same direction. Net flux increases with load current.

Differential compound motor : Both winding flux act in opposite direction. Net flux decreases with load current.





Cumulative compound Short shunt motor

Differential compound Short shunt motor

TORQUE EQUATION FOR DC MOTOR

ARMATURE TORQUE: As we know the relation between torque and power for a rotating body is given by

$$T = \frac{P}{\omega} = \frac{P}{2\pi\, n_{rpm}} = \frac{60}{2\pi}\frac{P}{N} \quad \text{where N is in RPM} \quad = \quad 9.55\,\frac{P}{N} \quad \text{Nm}\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

In dc motor the power developed in motor armature is given by $P = E_b I_a$. So corresponding to this power we define armature torque using equation (i) as $T_a = 9.55\frac{E_b I_a}{N}$. As we know as $E_b = \frac{P\phi Z N}{60\ A}$ so using this

$$T_a = 9.55\frac{P\phi Z\ N\ I_a}{N\ \ 60A} = 0.159\ P\phi Z\frac{I_a}{A}\ \ \text{Nm}$$

From above equation it is clear that motor torque is directly proportional to flux and armature current. $T \alpha\ \phi I_a$

SHAFT TORQUE : From the total power developed in motor armature a small power is lost in the form of iron and friction losses and rest power is delivered to the load connected at the motor shaft as motor output. The shaft torque is defined corresponding to this motor output.

$$T_{SH} = \frac{9.55}{N}\ (\text{Motor Output in watt}) = \frac{9.55}{N}(\text{Powerdeveloped in armature} - \text{Iron \& Friction losses})$$

$T_{SH} = \frac{9.55}{N}(\text{Powerdeveloped in armature}) - \frac{9.55}{N}(\text{Iron \& Friction losses}) = (T_a - T_f)$ where T_f is known as Frictional torque. The three torques can be related as

$$T_a = T_{SH} + T_f$$

THREE PHASE AND SINGLE PHASE INDUCTION MOTOR.

A 3 phase Induction motor have two main parts namely rotor and stator

1. **Stator:** As its name indicates stator is a stationary part of induction motor. A stator winding is placed in the stator of induction motor and the three phase supply is given to it.

CONSTRUCTIONAL DETAILS

Stator:- The stator is the outer stationary part of the motor, which consists of the outer cylindrical frame of the motor, which is made either of welded sheet steel, cast iron or cast aluminum alloy. The main function of the stator core is to carry the alternating flux. In order to reduce the eddy current and hysteresis loss, the stator core is made up of high grade, low loss silicon steel stampings. The thickness of these stampings varies from 0.35 to 0.65 mm. All the stamping are stamped together to form stator core, which have slots along its inner periphery.

The stator carries a 3-phase winding and is fed from a 3-phase supply. It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed. The number of poles are higher, lesser the speed and vice-versa. The stator winding, when supplied with a 3-phase currents, produce a magnetic flux, which is of constant magnitude but which revolves at synchronous speed ($N_s = 120 \times f / p$).This revolving magnetic flux induces emf in rotor by mutual induction.

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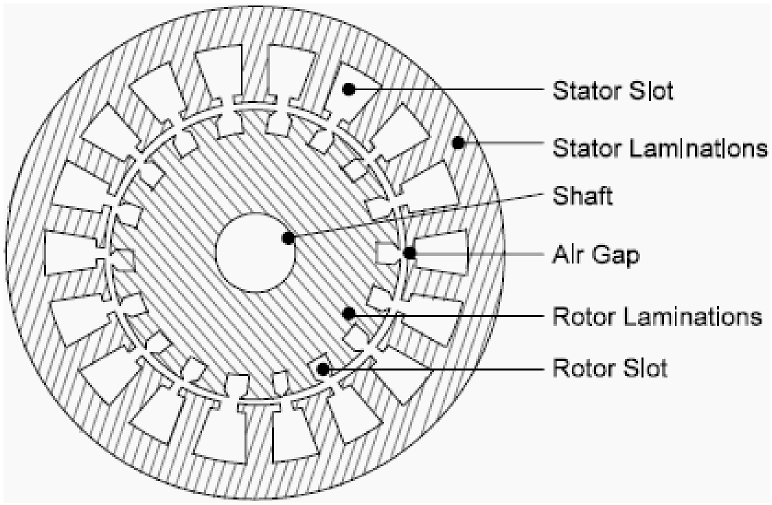


Fig. Stator and Rotor Lamination

2. **Rotor:** The rotor is a rotating part of induction motor. The rotor is connected to the mechanical load through the shaft. There are two types of 3-phase induction motor based on the type of rotor used:
(i) Squirrel cage induction motor (ii) Slip ring induction motor or Phase wound motor

(i) SQUIRREL CAGE ROTOR: Almost 90 % of induction motors are squirrel-cage type, because this type of rotor has the simplest, economical rugged and almost indestructible design. The Rotor consists of cylindrical laminated core with slightly skewed rotor slots on its outer periphery for carrying the rotor conductors which is in the form of heavy bars of copper, aluminium or alloys. One bar is placed in each slot. The rotor bars are brazed or electrically welded or bolted to two heavy and stout short circuiting end-rings, thus giving us, what is called a squirrel cage construction

The rotor slots are not quite parallel to the shaft but are purposely given a slight skew. This is useful in two ways. It helps to make the motor run quietly by reducing the magnetic hum and It helps in reducing the locking tendency of the rotor. i.e. the tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between the two.

The only drawback of this type of rotor construction is poor starting torque of motor due to low rotor resistance.

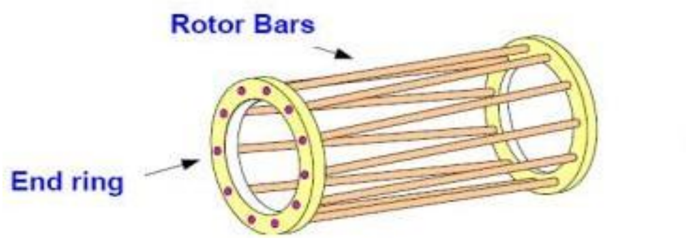


Fig. A squirrel cage rotor.

(ii) PHASE WOUND OR SLIP RING ROTOR :- In this type of three phase induction motor the rotor is wound for the same number of poles as that of the stator. The rotor consists of numbers of slots and star connected rotor winding are placed inside these slots. The three terminals are connected together to form a star point which is connected internally to rotor shaft and the other three terminals are connected to three slip rings which are mounted on the rotor shaft. The external resistance can be easily connected through the brushes and slip rings and hence used for speed controlling and improving the starting torque of three phase induction motor. At starting, the resistance is connected to the rotor circuit and is gradually cut out as the rotor pick up its speed. When the motor is running the slip ring are shorted by connecting a metal collar, which connects all slip ring together, and the brushes are also removed. This reduces the wear and tear of the brushes. Due to the presence of slip rings and brushes the rotor construction becomes somewhat complicated therefore it is less used as compare to squirrel cage induction motor.

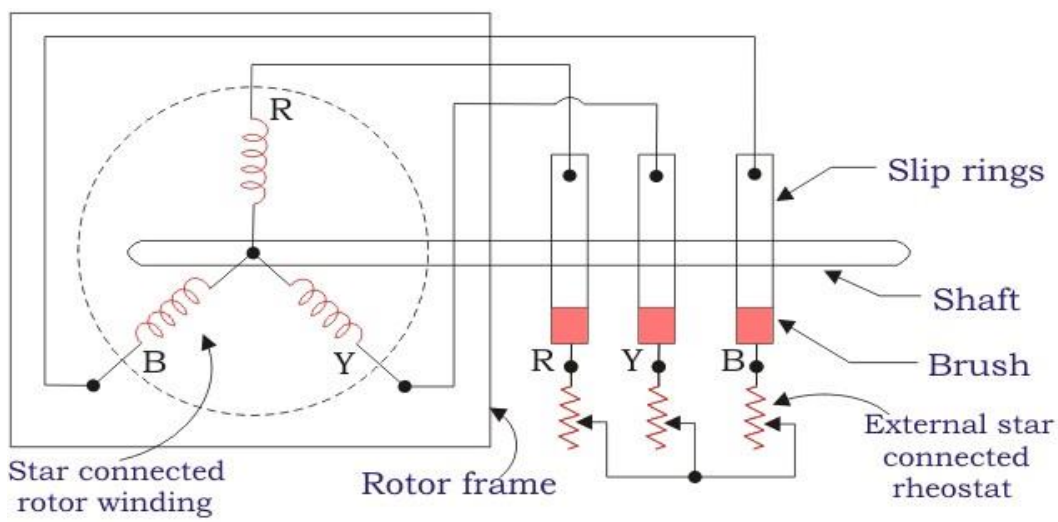


Fig. A phase wound or slip ring rotor

Difference between Slip Ring and Squirrel Cage Induction Motor

Slip ring or phase wound Induction motor	Squirrel cage induction motor
Construction is complicated due to presence of slip ring and brushes	Construction is very simple
The rotor winding is similar to the stator winding	The rotor consists of rotor bars which are permanently shorted with the help of end rings
We can easily add rotor resistance by using slip ring and brushes	Since the rotor bars are permanently shorted, its not possible to add external resistance
Due to presence of external resistance high starting torque can be obtained	Staring torque is low and cannot be improved

Slip ring and brushes are present	Slip ring and brushes are absent
Frequent maintenance is required due to presence of brushes	Less maintenance is required
The construction is complicated and the presence of brushes and slip ring makes the motor more costly	The construction is simple and robust and it is cheap as compared to slip ring induction motor
This motor is rarely used only 10% industry uses slip ring induction motor	Due to its simple construction and low cost. The squirrel cage induction motor is widely used
Rotor copper losses are high and hence less efficiency	Less rotor copper losses and hence high efficiency
Speed control by rotor resistance method is possible	Speed control by rotor resistance method is not possible
Slip ring induction motor are used where high starting torque is required i.e in hoists, cranes, elevator etc	Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc

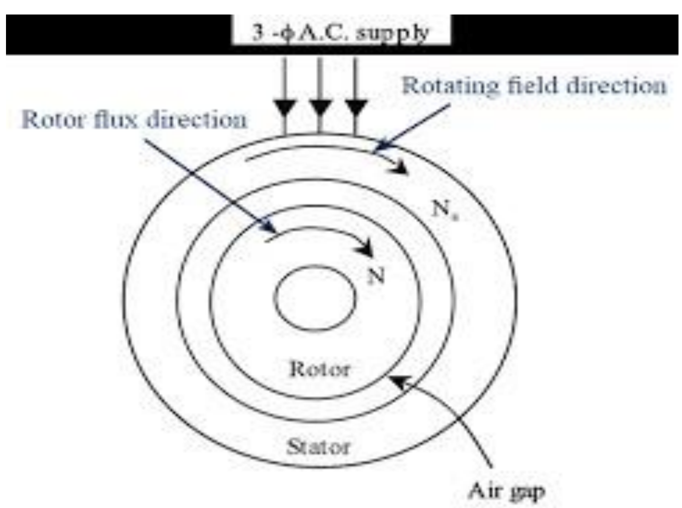
Principle of operation three phase Induction Motor

The three phase stator winding gets energized **when** a three phase supply is given to the stator winding, a rotating magnetic field is produced which revolves round the stator with synchronous speed (N_s= 120f/p) and magnitude of this field 1.5 times the maximum value of flux produced by any individual stator phase.

The rotating magnetic field moves through the air gap and cuts the conductor of rotor, which is at rest. Because of the relative motion between the stationary rotor and the synchronously rotating stator flux, EMF's are induced in the conductors of rotor. Since the rotor circuit is short circuited the current start flows in the rotor conductors**.** The current carrying conductors of rotor are positioned in the magnetic field created by the stator. As a result, mechanical forces act on the conductors of rotor.

The rotation in the rotor is explained as per the Lenz's law. According to this lenz's law, the directions of current in the rotor will be such that they incline to oppose the source producing them. At the moment, the cause generating the rotor currents is the relative speed amongst the rotating magnetic field and the stationary rotor conductor. Therefore to decrease the relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it.

An induction motor always runs at a speed less than synchronous speed because the current induced in the rotor circuit is due to relative motion between stator magnetic field and rotor conductors. As the rotor is speed up the relative motion decreases which reduces the induced current and the developed torque in rotor conductors, so the rotor will never reach to the synchronous speed and it will settle down at a speed less than synchronous speed.



What will happen if the induction motor runs at synchronous speed? When rotor of induction motor is made to run at synchronous speed by some external means still the motor is not going to work at synchronous speed because at this speed the stator magnetic field will appear stationary to the rotor conductor. So no current will induced in the rotor and motor will not going to develop any torque.

Slip Slip is the difference between the synchronous speed of the stator magnetic field and the actual speed of rotor. It isexpressed as the ratio of synchronous speed.

$$Slip\,(s) = \frac{N_s - N_r}{N_s}$$

The quantity Ns - N is sometimes called slip speed.

(i) When the rotor is stationary (i.e., $N_r = 0$), slip, s = 1 or 100 %.
(ii) When the rotor is at synchronous speed (i.e., $N_r = N_s$), slip, s = 0 or 0 %.
In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.

Rotor Current Frequency When in induction motor, the rotor is stationary, rotor, conductors are cut by the rotating flux at synchronous speeds N_s. Therefore the frequency of rotor current is the same as that of supply frequency, so

$$N_s = \frac{120f}{P} \ldots\ldots\ldots\ldots \quad (1)$$

When rotor start revolving, the rate at which the rotor conductors are being cut by the rotating flux depends upon the relative speed between the rotor and stator revolving magnetic field, called the slip speed. The frequency of the rotor emf induced by the relative motion between rotor conductors and the stator revolving magnetic field is given by :

$$N_s - N_r = \frac{120\,f'}{P} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where f' frequency of rotor currents under running condition. Now taking ratio of (2)/(1) we get

$$f' = sf$$

Thus the frequency of rotor emf in an induction motor is given by the product of slip(*s)* and the supply frequency (*f*).

Slip Torque Characteristics of induction Motor

As the induction motor is loaded from no load to full load, its speed decreases hence slip increases. Due to the increased load, motor has to produce more torque to satisfy load demand. The behavior of motor can be easily judged by sketching a curve obtained by plotting torque produced against slip of induction motor. The curve obtained by plotting torque against slip from s = 1 (at start) to s = 0 (at synchronous speed) is called torque-slip characteristics of the induction motor. The expression of torque at any slip s is given by

$$T = \frac{ksE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

Where s = Slip,
E_2 = Per phase stand still induced EMF in rotor,
R_2= Per phase value of stand still rotor resistance
X_2= Per phase value of stand still rotor reactance
K = Constant equals to $3/2\pi\, n_s$ where n_s = synchronous speed in R.P.S

The torque slip characteristic curve is divided roughly into two regions. They are given below.

- High slip region
- Low slip region

High slip region In this region, slip is high i.e. slip value is near to one. Here it can be assumed that the term R_2^2 is very very small as compared to $(s\,X_2)^2$. Hence neglecting from the denominator, we get

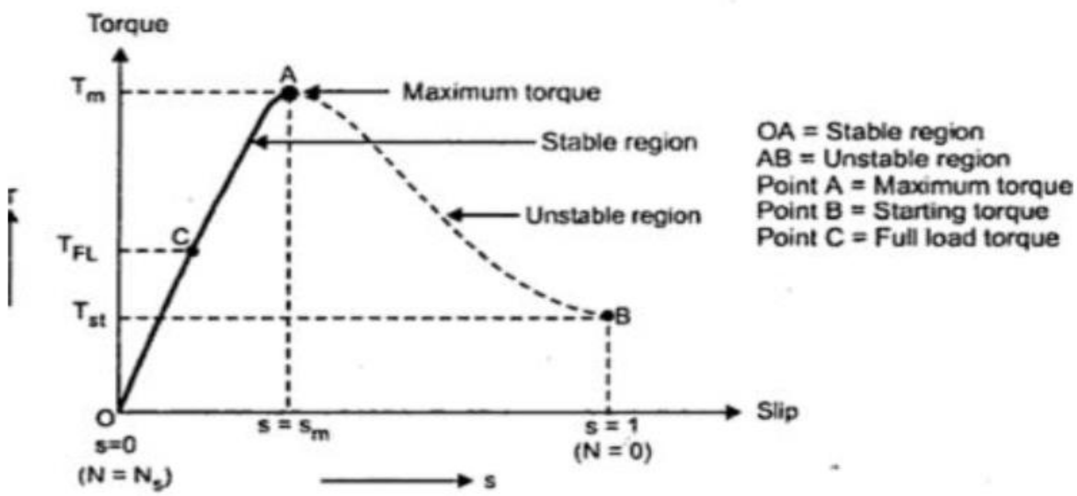
$$T \propto 1/S$$

In high slip region torque is inversely proportional to the slip. Hence its nature is like rectangular hyperbola. In high slip region as T α 1/S torque decreases as slip increases. But torque must increases to satisfy the load demand. In high slip region as speed of motor decreases, due to increase in load, the decrease in speed causes increase in slip which reduces motor torque. Due to reduction in torque the speed further decreases which further increases slip. Again torque further decreases as T α1/S hence same load acts as an extra load due to reduction in torque produced. Hence speed further drops. Eventually motor comes to standstill condition. Thus motor can not continue to rotate at any point in this high slip region. Hence this region is called unstable region of operation.

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 $(SX_2)^2$ is negligible in comparison with R_2. Therefore, torque is directly proportional to slip. The torque slip curve is a straight line.

$$T \propto S$$

In low slip region when load is connected to motor the motor speed decreases or the value of slip increases there by increasing the motor torque. This region is called the stable region of operation Normally induction motor is operated in this region.
In low slip region, as load increases, slip increases and torque also increases linearly. Every motor has its own limit to produce a torque. The maximum torque, the motor can produces as load increases is T_m which occurs at $S = S_m$ which is given by $S_m=R_2/X_2$. So linear behavior or stable region of motor continues from S = 0 to $S= S_m$. If load is increased beyond this limit, motor slip acts dominantly pushing motor into high slip region. Due to unstable conditions in high slip region, motor comes to standstill condition. The unstable region of motor continues from $s = s_m$ to s = 1.
Hence i.e. maximum torque which motor can produce is also called breakdown torque or pull out torque.



Slip Torque of 3-Phase induction motor

Effect of rotor resistance on motor torque:-
(1) The magnitude of maximum torque T_m is independent of rotor resistance.
(2) Rotor resistance control the value of slip or speed at which maximum torque is available. By increasing rotor circuit resistance we get maximum torque at a higher value of slip or at lower value of speed
(3) The starting torque is directly proportional to rotor resistance. By increasing rotor resistance we can increase starting torque of motor. Even maximum torque can be obtained at starting by making rotor resistance equal to rotor reactance. $(R_2 =X_2)$.

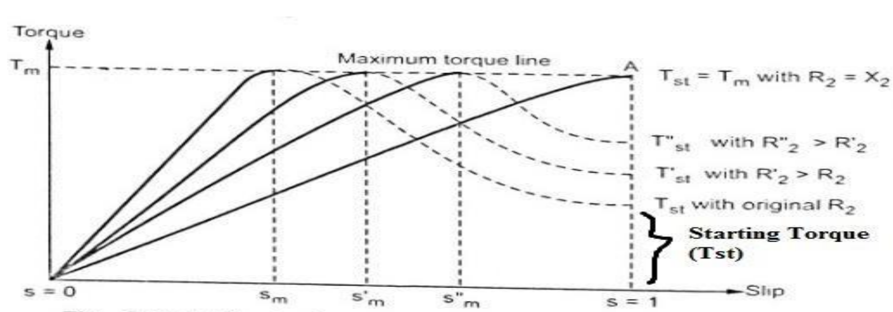


Fig. 5.14.1 Effect of rotor resistance on torque-slip curves

SINGLE PHASE INDUCTION MOTOR

A **Single Phase Induction Motor** consists of a single phase winding which is mounted on the stator of the motor and a cage winding placed on the rotor. A pulsating magnetic field is produced, when the stator winding of the single-phase induction motor is energized by a single phase supply.

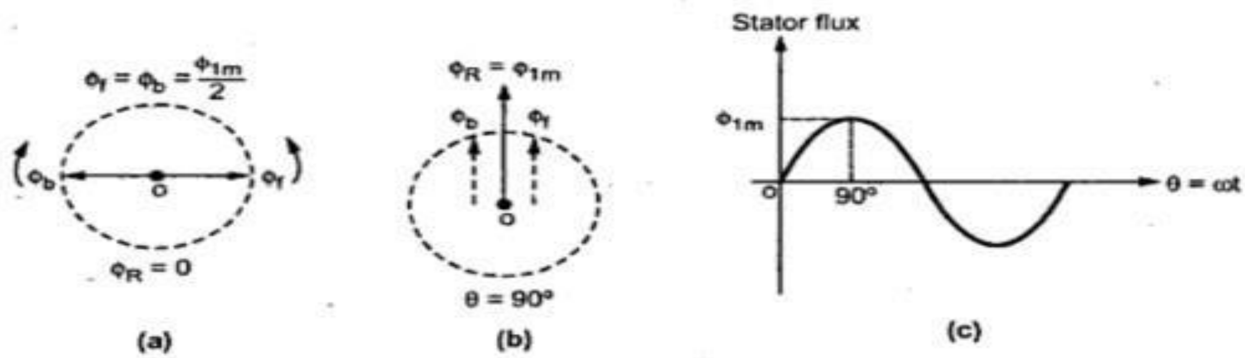
The word Pulsating means that the field builds up in one direction falls to zero and then builds up in the opposite direction. Under these conditions, the rotor of an induction motor does not rotate. Hence, a single phase induction motor is not self-starting. It requires some special starting means.

The behavior of the single phase induction motor is explained by Double Revolving Field Theory.

Double Revolving Field Theory. According to this theory, any alternating field can be resolved into two synchronously rotating fields which rotate in opposite directions and each having magnitude as half of the maximum magnitude of the alternating field

In case of single phase induction motors, the stator winding produces an alternating magnetic field having maximum magnitude of Φ_{1m}.According to double revolving field theory, consider the two components of the stator flux, each having magnitude half of maximum magnitude of stator flux i.e. ($\Phi_{1m}/2$). Both these components are rotating in opposite directions at the synchronous speed N_s which is dependent on frequency and stator poles.

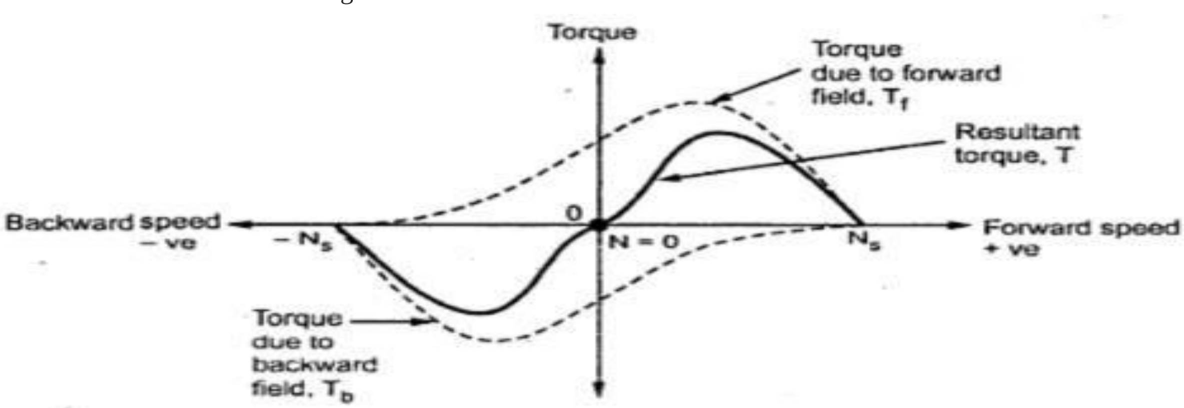
Let Φ_f is forward component rotating in anticlockwise direction while Φ_b is the backward component rotating in clockwise direction. The resultant of these two components at any instant gives the instantaneous value of the stator flux at that instant. So resultant of these two is the original stator flux.



The Fig.shows the stator flux and its two components Φ_f and Φ_b. At start both the components are shown opposite to each other in the Fig.1(a). Thus the resultant $\Phi_R = 0$. This is nothing but the instantaneous value of the stator flux at start. After 90^o , as shown in the Fig. 1(b), the two components are rotated in such a way that both are pointing in the same direction. Hence the resultant Φ_R is the algebraic sum of the magnitudes of the two components. So $\Phi_R = (\Phi_{1m}/2) + (\Phi_{1m}/2) = \Phi_{1m}$. This is nothing but the instantaneous value of the stator flux at $\theta = 90^o$ as shown in the Fig 1(c). Thus continuous rotation of the two components gives the original alternating stator flux.

Both the components are rotating and hence get cut by the motor conductors. Due to cutting of flux, e.m.f. gets induced in rotor which circulates rotor current. The rotor current produces rotor flux. This flux interacts with forward component Φ_f to produce a torque in one particular direction say anticlockwise direction. While rotor flux interacts with backward component Φ_b to produce a torque in the clockwise direction. So if anticlockwise torque is positive then clockwise torque is negative.

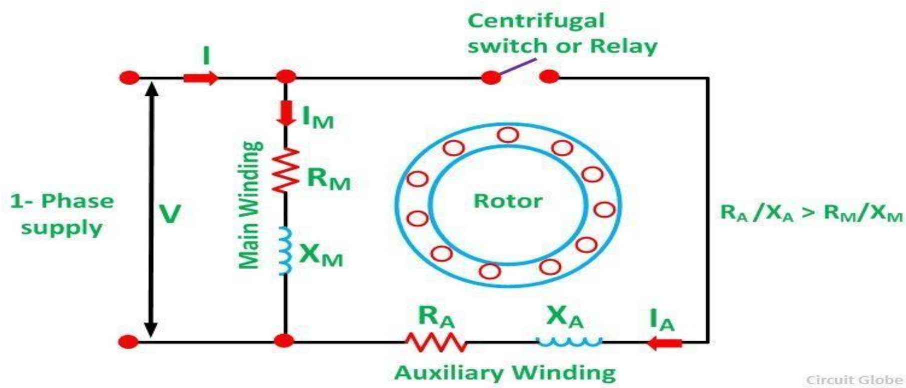
At start these two torques are equal in magnitude but opposite in direction. Each torque tries to rotate the rotor in its own direction. Thus net torque experienced by the rotor is zero at start. And hence the single phase induction motors are not self starting. The two oppositely directed torques and the resultant torque can be shown effectively with the help of torque-speed characteristics. It is shown in the Fig.2.



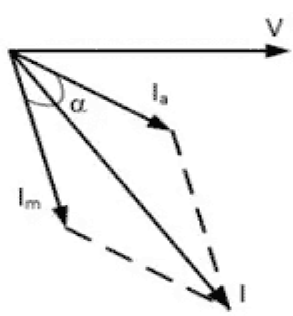
Starting Methods of a Single Phase Induction Motor The Single Phase Motor is not self starting and hence needs an auxiliary means of starting. The motor is started temporarily converting it into two phase motor. Single phase Induction motors are usually classified according to the auxiliary means used to start the motor. They are classified according to the starting methods.

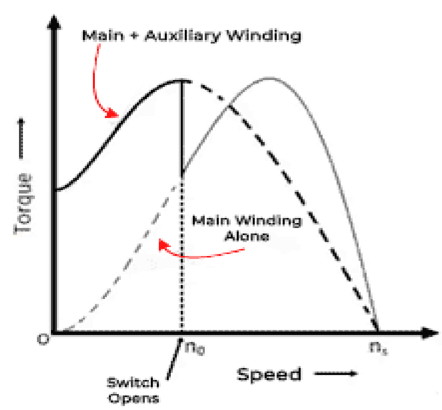
- Split Phase or Resistance Start Motor
- Capacitor Start Motor
- Permanent Split Capacitor (PSC) or Single value capacitor motor
- Capacitor Start Capacitor Run Motor or Two value capacitor motor
- Shaded Pole Motor.

(1) **Split Phase or Resistance Start Motor** It has a single cage rotor, and its stator has two windings known as main winding and starting winding or auxiliary winding. Both the windings are displaced 90 degrees in space. The main winding has very low resistance and a high inductive reactance whereas the starting winding has high resistance and low inductive reactance. The Connection Diagram of the motor is shown below.



The phasor diagram of the Split Phase Induction Motor is shown below.

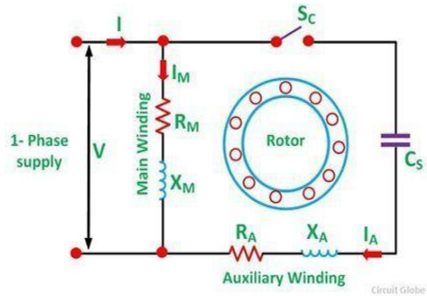


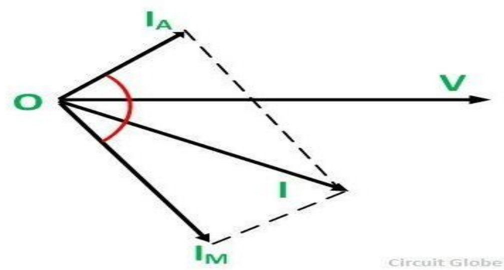


The current in the main winding (I_M) lag behind the supply voltage V almost by the 90-degree angle. The current in the auxiliary winding I_A is approximately in phase with the line voltage. Thus, there exists a phase difference between the currents of the two windings. The time phase difference ϕ is not 90 degrees, but of the order of 30 degrees. This phase difference is enough to produce a rotating magnetic field. Due to this rotating field motor develop its starting torque.

As soon as the motor reaches the speed of about 70 to 80 % of the synchronous speed the starting winding is disconnected automatically from the supply mains by centrifugal switch. It is used to disconnect the starting winding from the supply. The drawback of this type of motors is poor starting torque and low power factor under running conditions

2) **Capacitor Start Motor** ACapacitor Start Motorsare a single phase Induction Motor that employs a capacitor in the auxiliary winding circuit to produce a greater phase difference between the current in the main and the auxiliary windings. The name capacitor starts itself shows that the motor uses a capacitor for the purpose of the starting. The figure below shows the connection diagram of a Capacitor Start Motor.



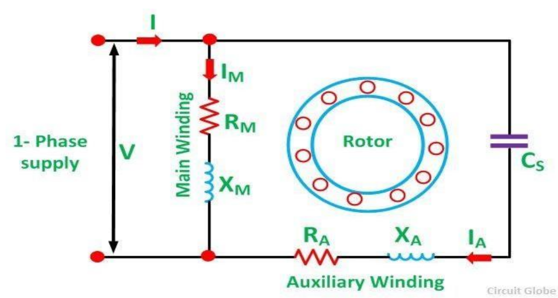


I_M is the current in the main winding which is lagging the auxiliary current I_A by almost 90 degrees as shown in the phasor diagram. Thus, a single phase supply current is split into two phases. The motor acts as a balanced two-phase motor. As the motor approaches its rated speed, the auxiliary winding and the starting capacitor is disconnected automatically by the centrifugal switch provided on the shaft of the motor.

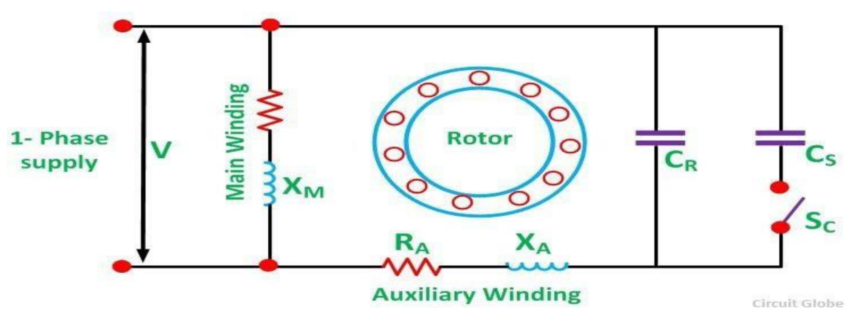
The capacitor starts motor develops a much higher starting torque than resistance start motor of the order of 3 to 4.5 times of the full load torque. To obtain a high starting torque the Starting capacitor value must be large and the valve of the starting winding resistance must be low.

The electrolytic capacitors of the order of the 250 µF are used in starting winding which is suitable for short time operations.

3) **Permanent Split Capacitor (PSC) or Single value capacitor motor:** The **Permanent Split Capacitor** motor also has a cage rotor and the two windings named as main and auxiliary windings. It has a capacitor connected in series with the starting winding. The capacitor C is permanently connected in the circuit both at the starting and the running conditions so this type of motor does not contain any centrifugal switch. The auxiliary winding is always there in the circuit. Therefore, the motor operates as the balanced two-phase motor. The motor produces a uniform torque and has noise free operation and higher power factor. The paper capacitor is used in the motor as an Electrolytic capacitor cannot be used for continuous running. The cost of the paper capacitor is higher, and size is also large as compared to the electrolytic capacitor of the same ratings. As a single capacitor is used so neither starting nor running characteristics are optimum.



4) **Capacitor Start Capacitor Run Motor or Two value capacitor motor :** The Capacitor Start Capacitor Run Motor has a cage rotor, and its stator has two windings known as Main and Auxiliary Windings. There are two capacitors in this method. So this motor is also known as Two Value Capacitor Motor. Connection diagram of the Two valve Capacitor Motor is shown below



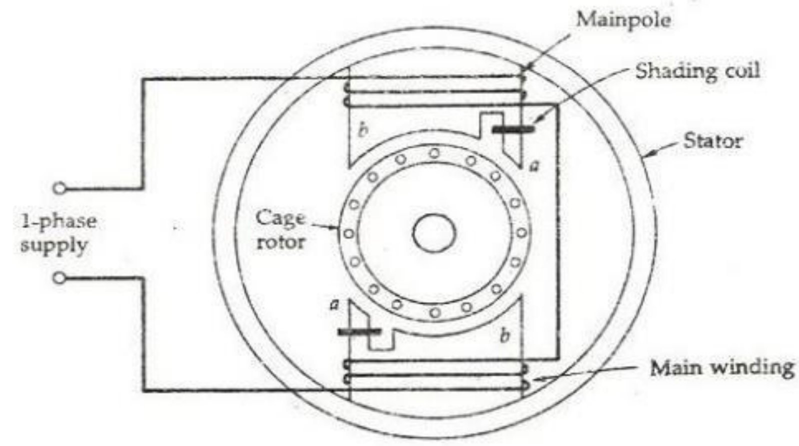
Capacitor Start Capacitor Run Motor or Two value capacitor motor

There are two capacitors in this motor represented by C_S and C_R. At the starting, the two capacitors are connected in parallel. The Capacitor Cs is the Starting capacitor is short time rated. It is electrolytic type.

As the motor reaches the synchronous speed, the starting capacitor Cs is disconnected from the circuit by a centrifugal switch Sc. The capacitor C_R is connected permanently in the circuit and thus it is known as RUN Capacitor. The run capacitor is long time rated and is made of oil filled paper.

This type of motor is quiet and smooth in running develop uniform torque. They have higher efficiency than the motors that run on the main windings or on single capacitor. They are used for loads of higher inertia requiring frequent starts where the maximum pull-out torque and efficiency required are higher. The Two Value Capacitor Motors are used in pumping equipment, refrigeration, air compressors, etc.

5) Shaded Pole Motor



2 Pole Shaded Pole Motor

A shaded pole motor may be 2 pole or 4 pole. Here we are considering a 2 pole shaded pole motor shown in fig. The stator has salient poles. Usually 2 to 4 poles are used. Each of the poles has its own exciting coil. A part of each pole is wrapped by a copper coil. The copper coil forms a closed loop across each pole. This loop is known as the shading coil.

The operation of the motor can be understood by referring to figure shown below. The fig. shows one pole of the motor with a shading coil. Considering a cycle of alternating current applied to the stator winding we will explain the working of shaded pole motor

- *<u>During the portion OA</u>*

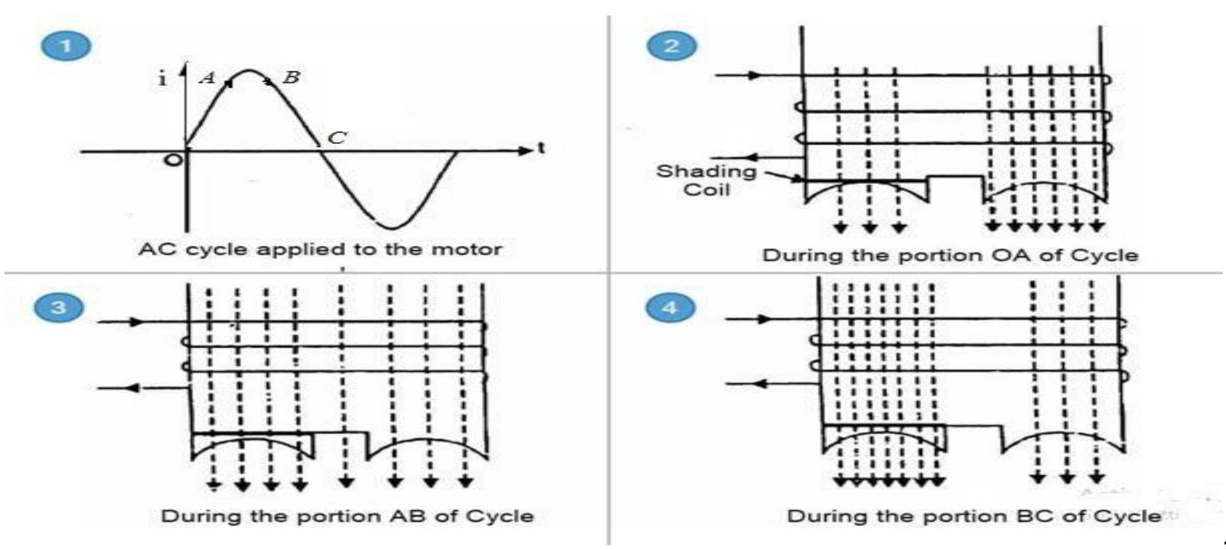
During the portion OA of the alternating-current cycle, the flux begins to increase [See Fig 1] and an e.m.f. is induced in the shading coil. The resulting current in the shading coil will be in such a direction (Lenz's law) so as to oppose the change in flux. Thus the flux in the shaded portion of the pole is weakened while that in the unshaded portion is strengthened as shown in figure 2.

- *<u>During the portion AB</u>*

During the portion AB of the alternating-current cycle, the flux has reached almost maximum value and is not changing. Consequently, the flux distribution across the pole is uniform [See Fig 3] since no current is flowing in the shading coil.

- *<u>During the portion BC</u>*

As the flux decreases (portion BC of the alternating current cycle), current is induced in the shading coil so as to oppose the decrease in current. Thus the flux in the shaded portion of the pole is strengthened while that in the unshaded portion is weakened as shown in Fig 4.



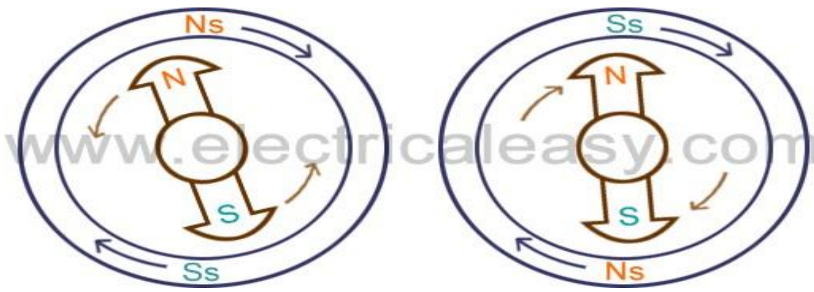
The effect of the shading coil is to cause the field flux to shift across the pole face from the un-shaded to the shaded portion. This shifting flux is like a weak rotating field moving in the direction from un-shaded portion to the shaded portion of the pole. Due to this field motor develop its torque like an induction motor and start rotating.

In absence of centrifugal switch the design of motor is very simple economical and maintenance free. The drawback of these motor are poor starting torque, low power factor and poor efficiency. Also the direction of rotation of these motors can not be reversed.

Due to low power these motors are suitable for toys, small fan, hairdryers, photocopy machine and other small business machines.

SYNCHRONOUS MOTOR

Synchronous motor is a doubly excited machine which operates on the principle of magnetic locking. Its stator consists of armature winding which is three-phase winding connected to three phase AC supply. The Rotor consists of Field winding to which dc Supply is given. As the 3 phase stator armature winding carrying 3 phase currents produces 3 phase rotating magnetic field (RMF). The rotor Field winding carrying DC supply also produces a constant flux. Consider a two pole synchronous machine as shown in figure below.



- Now, the stator poles are revolving with synchronous speed (lets say clockwise).Their polarity will change with each half cycle of supply. Let for positive half of stator supply, N pole of the rotor is near the N pole of the stator (as shown in first schematic of above figure), then the poles of the stator and rotor will repel each other, and the *torque produced will be anticlockwise*.
- For negative half cycle of supply the polarity of stator poles will reverse but polarity of Field pole on rotor will remain unchanged. In this case, N pole of rotor will be attracted by S pole of the stator and *the torque produced will be clockwise.*
- Hence, the rotor will undergo to a rapidly reversing torque, and the motor will not start.
  So the synchronous motor is not **self starting**.

Principle of Operation Synchronous Motor

When the rotor is rotated up to the synchronous speed by some external force (in the direction of revolving field of the stator), and then rotor field is excited by DC supply the poles of rotor will be attracted by the stator pole and both the magnetic field will lock each other. As the rotor is also rotating at synchronous speed so this magnetic locking will continue even when the polarity of stator poles is reversed. As the polarity of stator poles is changed in half cycle, the rotor also moves through a distance of one pole pitch (to the next pole)and the magnetic drag of stator field continue to attract the rotor. So when external force is removed from rotor the motor will continue to rotate at synchronous speed due to locking between stator and rotor fields. This is how a synchronous motor operates.

Characteristic Features Of A Synchronous Motor

- Synchronous motor will run either at synchronous speed or will not run at all.
- The only way to change its speed is to change its supply frequency. (As Ns = 120f / P)
- Synchronous motors are not self starting. They need some external force to bring them near to the synchronous speed.
- They can operate under any power factor, lagging as well as leading. Hence, synchronous motors can be used for power factor improvement.

Synchronous Motor Starting Methods

The various methods to start the synchronous motor are,

1. Using pony motors
2. Using damper winding

3. Using small d.c. machine coupled to it.

Using Pony motors In this method, the rotor is brought to the synchronous speed with the help of some external device like small induction motor. Such an external device is called 'pony motor'. Once the rotor attains the synchronous speed, the d.c. excitation to the rotor is switched on. Once the synchronism is established pony motor is decoupled. The motor then continues to rotate as synchronous motor.

Using damper winding In a synchronous motor, in addition to the normal field winding, the additional winding consisting of copper bars placed in the slots in the pole faces. The bars are short circuited with the help of end rings. Such an additional winding on the rotor is called damper winding. This winding as short circuited, acts as a squirrel cage rotor winding of an induction motor.

Once the stator is excited by a three phase supply, the motors starts rotating as an induction motor at sub synchronous speed. Then d.c. supply is given to the field winding. At a particular instant motor gets pulled into synchronism and starts rotating at a synchronous speed. As rotor rotates at synchronous speed, the relative motion between damper winding and the rotating magnetic field is zero. Hence when motor is running as synchronous motor, there can not be any induced e.m.f. in the damper winding. So damper winding is active only at start, to run the motor as an induction motor at start. Afterwards it is out of the circuit

Using small d.c. machine Many a times, a large synchronous motor are provided with a coupled d.c. machine. This machine is used as a d.c. motor to rotate the synchronous motor at a synchronous speed. Then the excitation to the rotor is provided. Once motor starts running as a synchronous motor, the same d.c. machine acts as a d.c. generator called exciter. The field of the synchronous motor is then excited by this exciter itself.

Applications:

- Synchronous motors are used in generating stations and in substations connected to the busbars to improve the power factor. For this purpose they are run without mechanical load on them and in over-excited condition. These motors used for power factor correction applications can also be termed as "synchronous condensers". Advantage of synchronous condensers compared to shunt capacitors is that shunt capacitors generate constant reactive power whereas on the other hand synchronous condensers can able to deliver different reactive power levels by varying the excitation of machine.
- Because of the higher efficiency compared to induction motors they can be employed for loads which require constant speeds. Some of the typical applications of high speed synchronous motors are such drives as fans, blowers, dc generators, line shafts, centrifugal pumps, compressors, reciprocating pumps, rubber and paper mills
- Synchronous motors are used to regulate the voltage at the end of transmission lines
- In textile and paper industries synchronous motors are employed to attain wide range of speeds with variable frequency drive system.

15. COMPARISON OF 3-PHASE SYNCHRONOUS AND INDUCTION MOTORS

S. No.	*Synchronous Motors*	*Induction Motors*
1	It has got no self starting torque and some external means is required for its starting.	It has got self starting torque and no special means is required for its starting.
2	Its average speed is constant and independent of load.	Its speed falls with the increase in load and is always less than synchronous speed.
3	It can be operated under a wide range of power factor, both lagging and leading.	It operates at only lagging power factor, which becomes very poor at light loads.
4	It requires dc excitation so it is a doubly excited machine.	It requires no dc excitation so it is a singly excited machine.
5	No speed control is possible.	Speed can be controlled but to small extent.
6	It is used for supplying mechanical load as well as for power factor improvement.	It is used for supplying mechanical load only.
7	Its torque is less sensitive to change in supply voltage.	Its torque is more sensitive to change in supply voltage.
8	Breakdown torque is proportional to the supply voltage.	Breakdown torque is proportional to the square of the supply voltage.
9	It is more complicated and costs more comparatively.	It is more simple and costs less comparatively.

Principle of Operation Synchronous Alternator

The synchronous generator or alternator is an electrical machine which converts the mechanical power from a prime mover into an AC electrical power at a particular voltage and frequency. The principle of operation of synchronous generator is electromagnetic induction which states that If there exists a relative motion between the flux and conductors, then an emf is induced in the conductors whose direction can be determined by using Fleming's right hand rule.

From construction point of view, a synchronous machine consists of two main parts: Stationary part known as ***Stator*** and Rotating part known as ***Rotor***.

There are mainly two types of rotor used in **construction of alternator**,

1. Salient pole type.
2. Cylindrical rotor type.

Salient Pole Type

The term salient means projecting. The salient pole type of rotor is generally used for slow speed machines having large diameters and relatively small axial lengths. The poles, in this case, are made of thick laminated steel sections riveted together and attached to a rotor with the help of joint.

Cylindrical Rotor Type

The cylindrical rotor is generally used for very high speed operation and employed in steam turbine driven alternators like turbo generators. The machines are built in a number of ratings from 10 MVA to over 1500 MVA. The cylindrical rotor type machine has a uniform length in all directions, giving a cylindrical shape to the rotor thus providing uniform flux cutting in all directions. The rotor, in this case, consists of a smooth solid steel cylinder, having a number of slots along its outer periphery for hosting the field coils.

The cylindrical rotor alternators are generally designed for 2-pole or 4 pole for speed 3000 or 1500 rpm.

$$N_s = \frac{(120 \times f)}{P} = \frac{(120 \times 50)}{2} = 3000\ rpm \quad . \quad N_s = \frac{(120 \times f)}{P} = \frac{(120 \times 50)}{4} = 1500\ rpm$$

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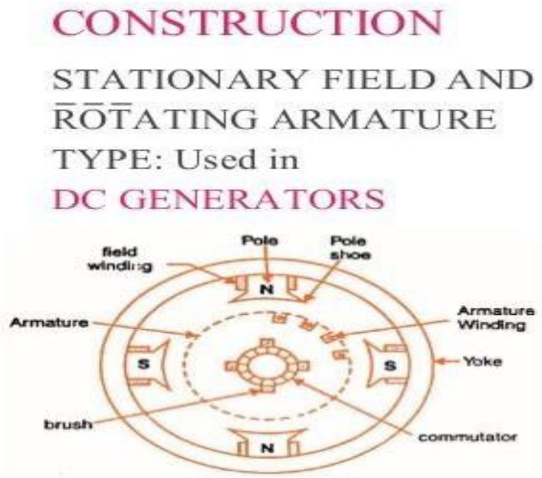
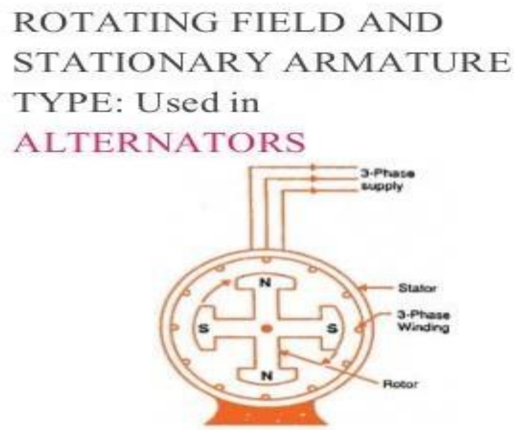
In synchronous alternator depending upon the arrangement of armature and field winding synchronous machines are classified into two types: Stationary field &Rotating Armature type and Rotating Field & stationary armature type.

- In rotating armature type, the armature winding is housed in the rotor and the DC excited field winding is placed on stator The emf generated in armature is supplied to the load via slip ring and carbon brush assembly. This type of synchronous machine is only built for small rating machine. This same arrangement is similar to DC generators with rotating brushes.
- In rotating field type synchronous machine, filed winding is wound on the rotor. DC supply is extended to the field winding by assembly of slip ring and carbon brush. Electrical power is developed in armature windings placed at stator and supplied to the load using stationary terminals mounted on the stator. This type is more famous and widely used in large sized synchronous machine.

  The advantages of rotating field type synchronous alternator are as follows

1. It is easier to insulate stationary winding for high voltages for which the alternators are usually designed. Ii is because they are not subjected to centrifugal forces and also extra space is available due to the stationary arrangement of the armature.
2. As the armature winding are on outer side of machine the ventilation and cooling is better in this type of arrangement
3. The stationary 3-phase armature can be directly connected to load without going through large, unreliable slip rings and brushes.
4. Only two slip rings are required for d.c. supply to the field winding on the rotor. Since the exciting current is small, the slip rings and brush gear required are of light construction.
5. Due to simple and robust construction of the rotor, higher speed of rotating d.c. field is possible. This increases the output obtainable from a machine of given dimensions.





<u>EMF equation of alternator</u>.

Let, P be the number of poles , Φ is Flux per pole in Webers

N is the speed in revolution per minute (r.p.m)

f be the frequency in Hertz

Z_{ph} is the number of conductors connected in series per phase

T_{ph} is the number of turns connected in series per phase, K_c is the coil span factor

K_d is the distribution factor

Flux cut by each conductor during one revolution is given as **Pϕ** Weber.

Time taken to complete one revolution is given by **60/N** sec

Average EMF induced per conductor will be given by the equation shown below

$$\frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts}$$

Average EMF induced per phase will be given by the equation shown below

$$\frac{P\varphi N}{60} \times Z_{ph} = \frac{P\varphi N}{60} \times 2T_{ph} \quad \text{and}$$

$$T_{ph} = \frac{Z_{ph}}{2}$$

$$\text{Average EMF} = 4 \times \varphi \times T_{ph} \times \frac{PN}{120} = 4\varphi f T_{ph}$$

The average EMF equation is derived with the following assumptions given below.

- Coils have got the full pitch.
- All the conductors are concentrated in one stator slot.

Root mean square (R.M.S) value of the EMF induced per phase is given by the equation shown below.

E_{ph} = Average value x form factor

Therefore,

$$E_{ph} = 4\varphi f T_{ph} \times 1.11 = 4.44\ \varphi\ f\ T_{ph} \quad \text{volts}$$

If the coil span factor K_c and the distribution factor K_d , are taken into consideration than the Actual EMF induced per phase is given as

$$E_{ph} = 4.44\ K_c K_d \varphi\ f\ T_{ph} \quad \text{volts} \ \ldots \ldots . (1)$$

Equation (1) shown above is the EMF equation of the Synchronous Generator.

<u>Coil Span Factor</u>

The Coil Span Factor is defined as the ratio of the induced emf in a coil when the winding is short pitched to the induced emf in the same coil when the winding is full pitched.

<u>Distribution Factor</u>

Distribution factor is defined as the ratio of induced EMF in the coil group when the winding is distributed in a number of slots to the induced EMF in the coil group when the winding is concentrated in one slot.