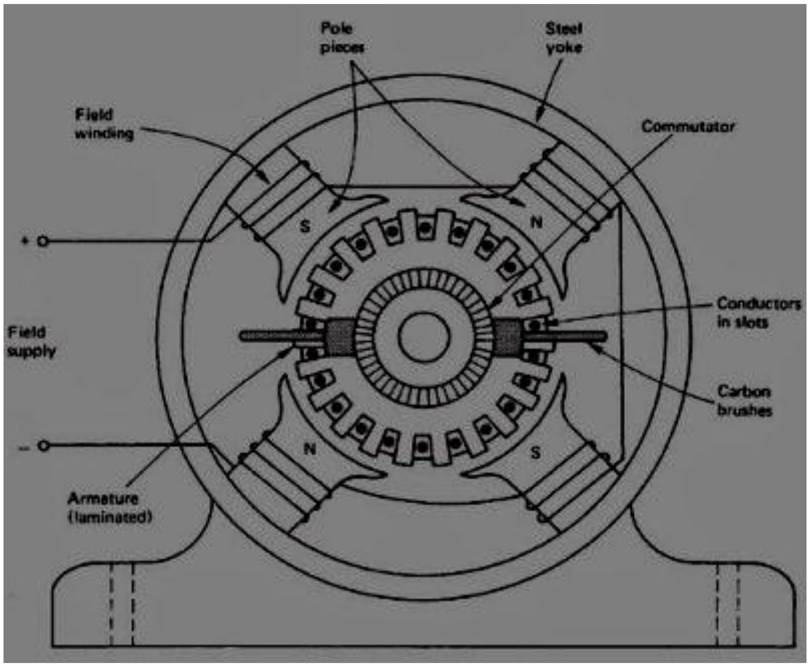
Chapter -1 DC(Direct Current) Machines

Construction of DC Machine:



Constructional Diagram of 4-pole DC Machine

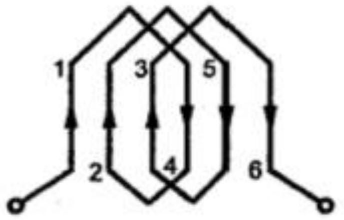
Parts of DC Machine:

- **STATOR & ROTOR-**
- All conventional electrical machines consist of a stationary member called the stator separated by an air gap from a rotating member called rotor.
- In d.c machines the stator usually consists of salient poles with coils wound round them so as to produce a magnetic field.
- The rotor is familiarly called the armature and consists of a series of coils located in slots around its periphery and connected to a commutator**.**
- **Yoke/Frame-**
- Yoke is the outer frame dc m/c. It carries the magnetic flux provided by the pole and acts as a protecting shield for the entire machine.
- **Field magnet-**
- It is a strong permanent magnet (in case of a small dc machine) or an electromagnet (in case of large dc machine) of intense magnetic field.
- The field magnet has two parts**- Pole core and Pole Shoe**.
- **Pole core** is made of cast steel or cast iron with laminated pole shoes screwed on to the holes in the yoke.
- **Pole shoes** spread out the flux in the air gap and reduce the reluctance of the magnetic path due to its large cross-section. Poles shoes support the exciting coils.
- **Field winding-**
- These are fine copper wire (or strip) wound around the pole pieces.
- The flux produced by the winding is cut by the revolving armature.
- **ARMATURE CORE-**
- It houses armature coils in the slots. It is cylindrical or drum shaped.
- Armature is placed in between the two poles of field magnet and is rotated about its central axis mechanically (by a prime mover)
- **ARMATURE WINDING-**
- It is made up of copper.
- It consists of large no. of insulated coils, each coil having one or more turns.
- Armature conductors are placed in armature slots.

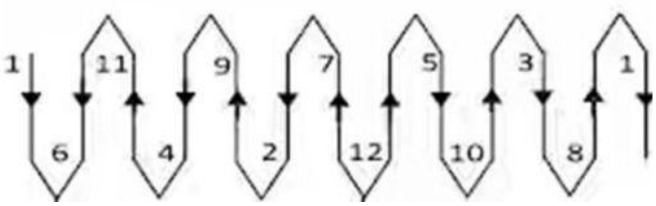
- **Commutator-**
- It converts the alternating current produced in the armature conductors into direct current in case of dc generator and alternating torque into unidirectional torque in case of dc motor.
- It consists of wedge shaped copper segments (Insulated from either side to form a ring).
- It facilitates the collection of current from the armature conductors.
- **Brushes-**
- They are fixed on the commutator by pressure springs.
- They are usually made of a high grade carbon or graphite and are in the shape of rectangular block.
- They collect the current from the commutator.

Types of Armature Winding:

- These are of two types : i. Lap winding
  ii. Wave winding



Lap Winding



Wave Winding

- **Comparison:**

Lap Winding	Wave Winding
No. of parallel paths (A) = no. of poles(P)	No of parallel path(A) = 2
Used for high current & low voltage.	Used for low current & high voltage.

DC Generators:

- **Working Principle-**
- A dc generator is a machine which converts mechanical energy into electrical energy.
- It is based on the principle of dynamically induced emf. i.e Whenever a conductor cuts magnetic flux, dynamically induced emf is produced as per faraday's laws of electromagnetic induction.

- **EMF equation of a DC Generator-**

Let P = Number poles of the generator.
ϕ = Flux produced by each pole in weber.
N = Speed of armature revolution in r.p.m.
Z = Total number of armature conductors.
A = Number of parallel paths in which the 'Z' number of conductors are divided.

According to faraday's law of electromagnetic induction, Average value of emf induced in each armature conductor is given by, $e = Rate\ of\ cutting\ the\ flux = \frac{d\phi}{dt}$ $---------(1)$

In one revolution, armature conductor will cut total flux produced by all the poles i.e $d\phi = \phi \times P$.

While time required completing one revolution is $dt = \frac{60}{N}\ seconds,\ \ as\ speed\ is\ in\ r.p.m$

From equation (1), Hence emf induced in one conductor $= \frac{d\phi}{dt} = \frac{\phi P}{\frac{60}{N}} = \frac{\phi PN}{60}$

Now the conductors in one parallel path are always in series.

There are total 'Z' conductors with 'A' parallel paths, hence $\frac{Z}{A}$ number of conductors is always in series and emf remains same across all the parallel paths.

Hence total emf can be expressed as, $E = \frac{\phi P N}{60} \times \frac{Z}{A}$

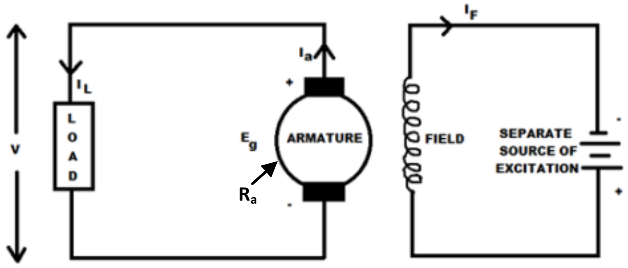
$$\boxed{or\ E = \frac{P\phi Z N}{60A}\ volts}$$

Note:

- ***For lap wound armature, $A = P$ and for wave wound armature, $A = 2$***
- ***In above expression of emf, for any dc generator $\frac{PZ}{60A} = constant = K$,***
  Hence, $E = K\phi N$, i.e E is directly proportional to ϕ and N

Types of DC Generator:

1. **Separately Excited DC Generator-**
   - A dc generator whose field winding is excited form an independent external dc source, such as battery is called a separately excited dc generator.
   - There is no physical connection between the armature and the field windings. The armature is driven mechanically by a prime mover.
   - The field current produces magnetic flux which is cut by rotating armature conductors and emf is induced.



Separately excited DC generator

Where, $I_a = armature\ current$ $\quad I_L = load\ current$ $\quad V = terminal\ voltage\ or\ load\ voltage$

$E_g = generated\ or\ induced\ emf = \frac{P\phi Z N}{60A} - - - 1$

Equations- form above diagram,

$I_a = I_L = I - - - - 2$

$V = E_g - I_a R_a = E_g - I R_a \ - - - - - 3$

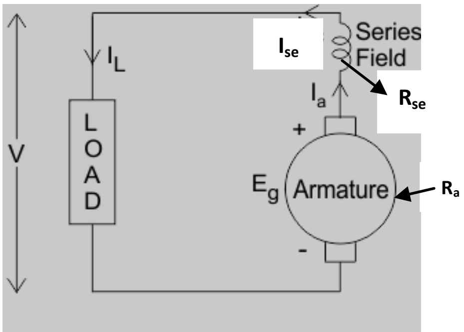
$Power\ developed = E_g I_a \ - - - - 4$

$Power\ developed = V I_L \ - - - - - 5$

2. **Self Excited DC Generator:** A dc generator whose field winding is excited by the current supplied by the generator itself is called a Self Excited DC Generator.

It further classified as follow-

i. **Series Wound Generator-** In series generator the field winding is connected in series with the armature winding.



Series Wound Generator

$R_{se} = resistance\ of\ series\ field\ winding$

$I_{se} = current\ in\ series\ field\ winding$

Equations- $I_a = I_{se} = I_L \ - - - - - 1$

$V = E_g - I_a R_a - I_{se} R_{se}$

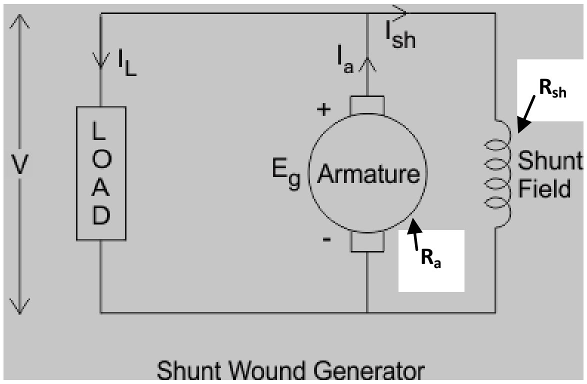
$V = E_g - I_a (R_a + R_{se}) \ - - - - 2$

$Where, E_g = \frac{P\phi Z N}{60A}$

$Power\ Developed = E_g I_a \ - - - - 3$

$Power\ delivered = V I_L \ - - - - - 4$

ii. **Shunt Wound Generator-** In shunt wound generator the field winding is connected across (in parallel) the armature winding.



Shunt Wound Generator

$R_{sh} = resistance\ of\ shunt\ field\ winding$

$I_{sh} = current\ of\ shunt\ field\ winding$

Equations:

$$I_{sh} = \frac{V}{R_{sh}} \qquad ------1$$

$$I_a = I_L + I_{sh} \qquad ---2$$

$$V = E_g - I_a R_a \qquad ----3 \qquad Where, E_g = \frac{P\phi ZN}{60A}$$

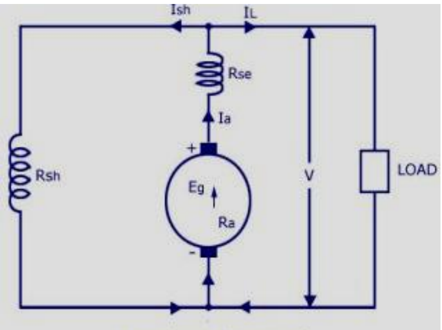
$$Power\ Developed = E_g I_a \qquad ----4$$

$$Power\ delivered = VI_L \qquad -----5$$

iii. **Compound Wound Generator:** In compound wound generator, there are two field windings, One of them with many turns of fine wire is connected across the armature and other with few turns of thick wire is connected in series with the armature winding.

A compound wound generator may be classified as-

a. **Long Shunt Compound Wound Generator-** The shunt field winding is connected in parallel with the combination of both armature and series field winding.



Long Shunt Compound

$$I_{sh} = \frac{V}{R_{sh}} \qquad ------1$$

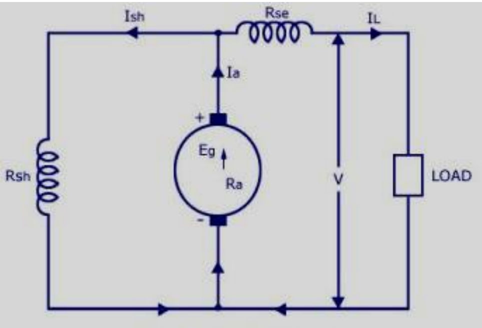
$$I_a = I_{se} = I_L + I_{sh} \qquad ---2$$

$$V = E_g - I_a(R_a + R_{se}) \qquad ----3 \qquad Where, E_g = \frac{P\phi ZN}{60A}$$

$$Power\ Developed = E_g I_a \qquad ----4$$

$$Power\ delivered = VI_L \qquad -----5$$

b. **Short Shunt Compound Wound Generator-** The shunt field winding is connected in parallel with armature winding.



Short Shunt Compound

$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}} \qquad -----1$$

$$I_a = I_L + I_{sh} \qquad ---2$$

$$V = E_g - I_a R_a + I_L R_{se}) \qquad ----3 \qquad Where, E_g = \frac{P\phi ZN}{60A}$$

$$Power\ Developed = E_g I_a \qquad ----4$$

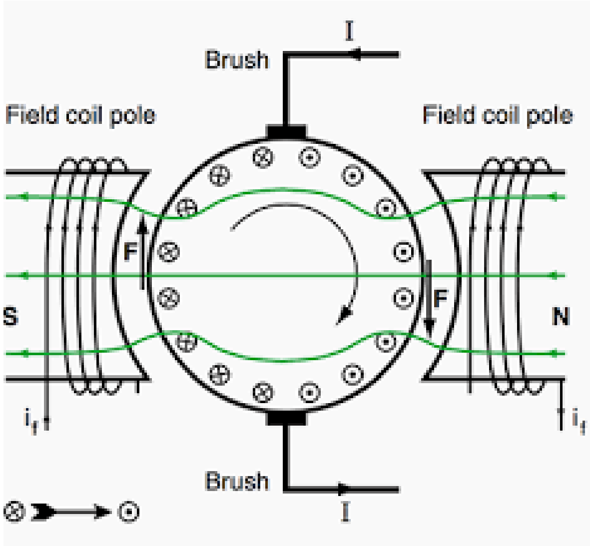
$$Power\ delivered = VI_L \qquad -----5$$

DC Motor:

Principle of Working- If a current carrying conductor is placed in a magnetic field, mechanical force experienced on the conductor, magnitude of which is given by, $F = BiL\,newton$, and the direction of which is given by Fleming's left hand rule.

Working-

- When motor is connected to d.c supply mains, a dc current passes through the brushes and commutator to the armature winding.
- While it passes through commutator it is converted into ac so that group of conductors under successive field poles carries current in opposite direction.
- A resultant rotor field is produced. It tries to come in line with the main field and torque develops. Thus motor rotates.

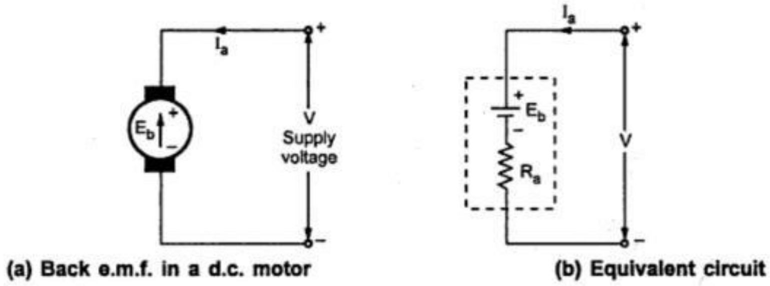


Back EMF:

- The rotating conductors of armature between poles of magnet, in a dc motor cut magnetic flux; there by developing an induced emf, which opposes the applied voltage as per Lenz's law.
- This induced emf set up in the coil of dc motor, opposing the current flowing through the armature conductors, when armature rotates, is called back emf.
- Magnitude of back emf is given by: $E_b = \frac{P\phi ZN}{60A}$ volts

  Since, $\frac{PZ}{60A} = constant = K$

  $E_b = K\phi N$, Hence back emf depends on the speed of the rotation of the armature and flux per pole.



(a) Back e.m.f. in a d.c. motor (b) Equivalent circuit

- Due to presence of back emf the dc motor becomes a regulating machine i.e motor adjusts itself to draw the armature current just enough to satisfy the load demand. The basic principle of this fact is that the $E_b \alpha N$
- When load is suddenly put on to the motor, motor tries to slow down. So speed of the motor reduces due to which back emf also decreases, which allows to motor draw more armature current, hence the torque on the armature increases.
- The motor speed stops decreasing when the armature current is just enough to produce torque demanded by the new load.

- When load on the motor is suddenly decreased, the speed of the motor tries to increase. Hence back emf increases, which reduce the current drawn by the armature. The motor speed stops increasing when the armature current is just enough to produce the less torque required by the new load.

Torque Equation of a DC Motor

The torque is produced in DC Motor, due to electromagnetic effect of current; hence it is called as electromagnetic torque.

Let, $T_a = Torque\ developed\ by\ armature\ in\ newton - meter$
$I_a = armature\ current\ in\ ampere$
$n = no\ of\ revolution\ of\ armature\ in\ r.p.s$
$\omega = angular\ velocity\ of\ revolution\ of\ armature\ in\ rad/sec$

Since; motor is a machine, which converts input electrical power into mechanical power at output.

Electrical power developed at the armature of dc motor $= E_b I_a$ $\quad ------1$

Mechanical power developed at the armature of dc motor $= T_a \omega$ $\quad ------2$

Hence for energy balance equation (1) must equal to equation (2),

i.e $\quad T_a\omega = E_b I_a$

Or $\quad T_a = \frac{E_b I_a}{\omega}$

Since, $E_b = \frac{P\phi ZN}{60A} = \frac{P\phi Zn}{A}$ $\qquad n = no\ of\ revolution\ of\ armature\ in\ r.p.s$

Put this value in above equation we have,

$$T_a = \frac{P\phi Zn}{A} \times \frac{I_a}{2\pi n} \qquad since\ \omega = 2\pi n$$

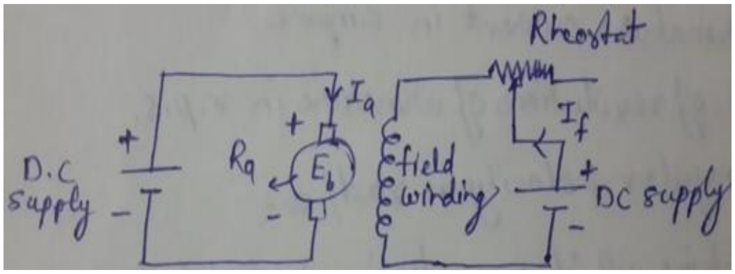
$$\boxed{\boldsymbol{T_a = \frac{PZ}{2\pi A} \times \phi I_a} \qquad newton - meter}$$

Since, $\frac{PZ}{2\pi A} = constant = K$

$$T_a = K\phi I_a \qquad i.e\ T_a \alpha\ \phi I_a$$

Types of DC Motor

1. **Separately-Excited DC Motor-** A dc motor whose field winding is excited by separate source of excitation is called Separately-Excited D C Motor.

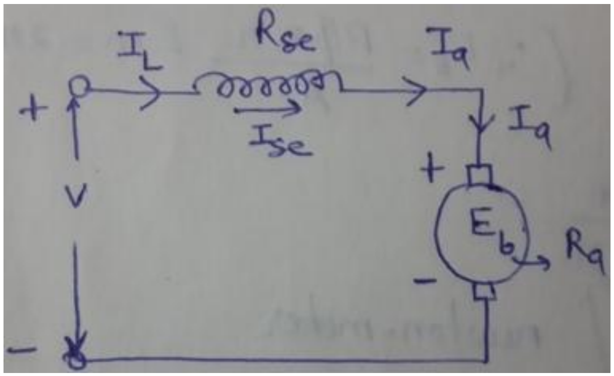


Separately excited DC Motor

$E_b = \frac{P\phi ZN}{60A} = back\ emf$
$I_f = field\ current, \quad I_a = armature\ current$
$R_a = armature\ resistance, \quad V = terminal\ voltage$
$V = E_b + I_a R_a$

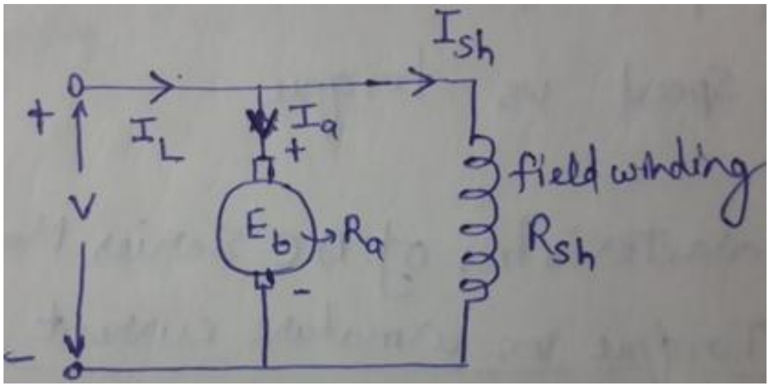
2. Self-Excited DC Motor-

i. **Series Wound Motor-** Field winding is connected in series with the armature winding.



$I_L = Line\ current \quad V = terminal\ volatge$
$R_{se} = resistance\ of\ field\ winding$
$R_a = armature\ resisytance$
$I_{se} = current\ in\ field\ winding$
$I_a = armature\ current$
$E_b = \frac{P\phi ZN}{60A} = back\ emf$
$I_L = I_{se} = I_a \quad ----1$
$V = E_b + I_a(R_a + R_{se})$
$Power\ input\ = VI_L \qquad Mechanical\ Power\ Developed = T_a\omega$

ii. **Shunt Wound Motor-** Field winding is connected in parallel with armature winding.

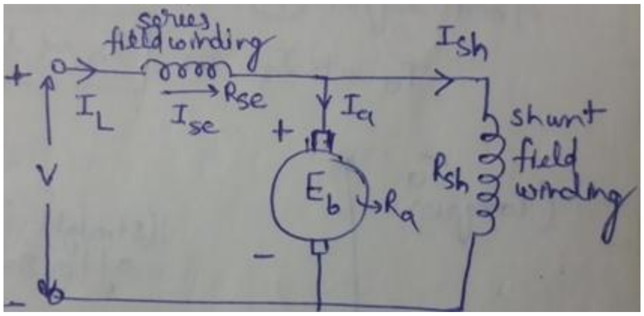


$I_L = Line\ current \quad V = terminal\ volatge$
$R_{sh} = resistance\ of\ field\ winding$
$R_a = armature\ resisytance$
$I_{sh} = current\ in\ field\ winding$
$I_a = armature\ current$
$E_b = \frac{P\phi ZN}{60A} = back\ emf \qquad I_{sh} = \frac{V}{R_{sh}} \quad ---1$
$I_L = I_{sh} + I_a \quad ----2$
$V = E_b + I_aR_a$ ---3
$Power\ input\ = VI_L \qquad Mechanical\ Power\ Developed = T_a\omega$

iii. **Compound Motor:** Shunt and series field winding are both present in compound motor, compound motor are further of two types, namely, cumulative compound and differential compound.

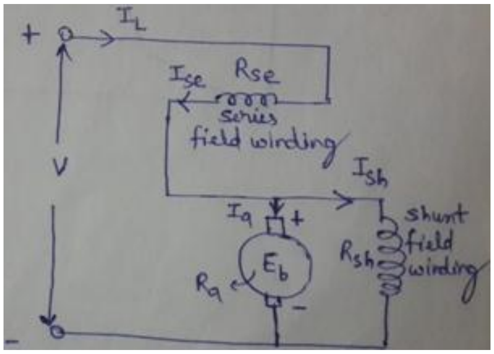
a) **Cumulative Compound Motor-**

- The field winding is connected in such a way that direction flow of current is same in both the field winding as shown in figure.
- Series field flux strengthens the field due to shunt field winding.



b) **Differential Compound Motor-**

- The series and shunt field windings are connected in such a way that the direction of flow of current is opposite to each other in them as shown in figure.
- The flux due to series field winding weakens the field due to shunt field winding.



Application of DC Motor:

- **DC Series Motor-** It has high starting torque; they are used in**-** hoist, cranes, trolley cars, conveyors, electric-locomotives, elevators, vacuum cleaners etc.
- **DC Shunt Motor-** It has constant speed applications, they are used in – lathes, centrifugal pumps, reciprocating pumps, fans, blowers, printing press, spinning and weaving machine.

Three-Phase Induction Motor (3-ϕ Induction Motor)

Types of 3-ϕ I.M: Types of 3-ϕ I.M is depend upon type of rotor is used. On the basis of construction, rotor is of two types; hence 3-ϕ I.M is of two types.

1. Squirrel Cage Rotor:

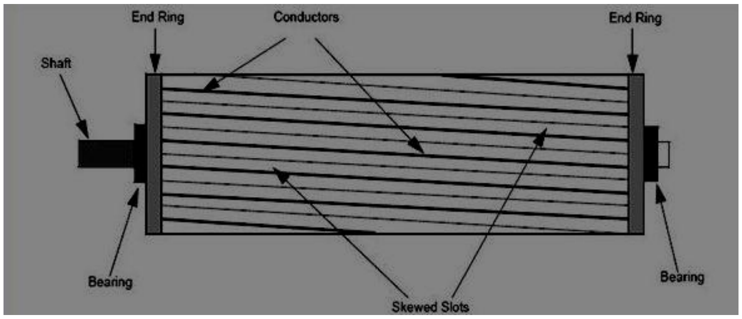


Figure 1 Squirrel Cage Rotor

- When higher starting torque is not the requirement, the rotor is constructed in a very simple manner.
- The bars and the end rings together look like a cage and hence such a rotor is called as cage rotor or squirrel cage rotor.

Advantage of Squirrel cage rotor:

i. Simple construction.
ii. Frequent maintenance is not required since slip rings and brushes are absent.
iii. Less rotor copper loss so high efficiency.

Disadvantages:

i. Small starting torque.
ii. It is not possible to connect any external resistance to the rotor so starting torque can not be adjusted.
iii. Rotor resistance starter cannot be used.
iv. Rotor resistance based speed control cannot be used.

Applications: Squirrel cage rotors are preferred for applications such as lathe machines, fans, water pumps, blowers etc. which do not require high starting torque.

2. **Wound Rotor or Slip Ring type Rotor**:

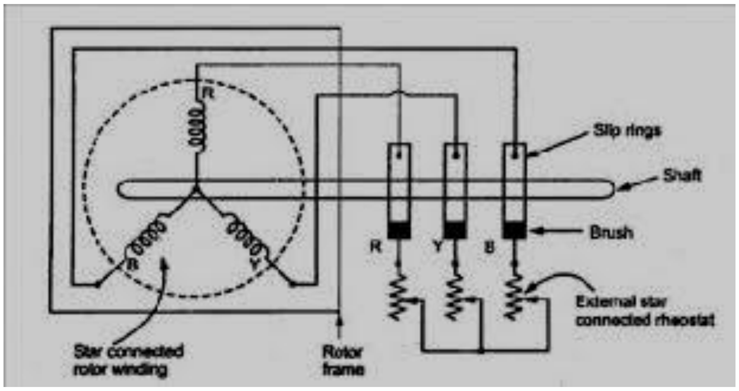


Figure 2 Slip ring rotor

- The rotor winding is connected in the star connection like a normal three phase star connected transformer.
- The slip rings are continuously in contact with three brushes which pressed against the slip rings.
- External resistances are added with the help of slip rings and brushes to provide variable speed and high starting torque.

Disadvantages:

i. More wear and tear so frequent maintenance.
ii. Increased loss in rotor so reduced efficiency.
iii. Poor power factor at full load.
iv. Needs a rotor resistance starter.
v. Low pull out torque.

Advantages:

i. External resistance can be connected to rotor. So it is possible to adjust starting torque.
ii. High starting torque can be obtained.
iii. Speed control using rotor resistance control is possible to achieve.

Applications: slip ring rotors are preferred for application such as cranes, elevators, lifts, and compressors etc. which need high starting torque.

Principle of operation of 3-phase Induction Motor:

- The stator winding of 3-ϕ I.M is connected to 3-ϕ balanced ac supply. The flow of 3-ϕ ac current in the 3-ϕ stator windings produces a rotating magnetic field.
- The speed of rotating field is the synchronous speed, $N_s = \frac{120f}{P}$ r.p.m.
- The rotating flux waves cuts the stationary rotor conductors, PN_s times per second and therefore emfs are induced in the rotor conductors.
- As the rotor circuit is short circuited, these induced emfs give rise to current in the rotor conductors.
- The interaction of these rotor currents with rotating flux wave produces torque in the rotor of a 3-ϕ I.M and as a consequence, rotor begins to rotate.
- According to Lenz's law effect opposes the cause. Here effect is the developed torque and cause is the flux cutting by rotor conductors. Therefore, as per Lenz's law, the developed torque must oppose (or minimize) the cause, that is flux cutting action.
- This is possible only if the developed torque forces the rotor to rotate in the direction of rotating field.

Note: 3-ϕ I.M is also known as asynchronous motor, because it runs slightly less than synchronous speed.

Concept of Slip: The difference between the synchronous speed and the rotor speed expressed as a fraction of (or percent) synchronous speed is known as slip.

Let, N_s = synchronous speed & N_r = rotor speed, then

slip (s) = $\frac{N_s - N_r}{N_s}$ or $\boxed{\% s = \frac{N_s - N_r}{N_s} \times 100}$

$\boxed{\text{or } N_r = N_s(1 - s)}$

Note:

- when rotor is stationary, i.e at standstill or at starting, rotor speed will be zero, i.e $N_r = 0$

$$\Rightarrow s = \frac{N_s - 0}{N_s} = 1$$

- if rotor runs at synchronous speed then, $N_r = N_s$

$$\Rightarrow s = \frac{N_s - N_s}{N_s} = 0$$

i.e. value of slip varies between 0 & 1.

Frequency of rotor current or emf:

- When the rotor is stationary, the frequency of rotor current is the same as the supply frequency.
- But when the rotor starts revolving, then the frequency depends upon the relative speed or on slip speed.

$$\text{Slip speed} = N_s - N_r = \frac{120\, f_r}{P} --------(i)$$

$$\text{also, } N_s = \frac{120\, f}{P} --------(ii)$$

divide equation (i) and (ii), we have,

$$\frac{f_r}{f} = \frac{N_s - N_r}{N_s}$$

$\frac{f_r}{f} = s \qquad (s = \frac{N_s - N_r}{N_s})$

Or $f_r = s\,f$

Where f_r= frequency of rotor current of emf,

f = frequency of supply

Torque Equation of a 3-ϕ I.M:

It is expressed as, $T = \frac{k\ s\ E_2^2 R_2}{R_2^2 + (sX_2)^2} \qquad N - m$

Where, k = constant, E_2 = rotor emf, R_2 = rotor circuit resistance, X_2 = Rotor circuit reactance.

Since at starting, s = 1

Hence, $T_{\text{starting}} = \frac{k\ E_2^2 R_2}{R_2^2 + (X_2)^2} \qquad N - m$

Torque-Slip Characteristics of 3-ϕ Induction Motor:

Since torque of 3-ϕ I.M is given by,

$$T = \frac{k\ s\ E_2^2 R_2}{R_2^2 + (sX_2)^2} \qquad N - m \qquad ----- (i)$$

For constant supply voltage, the value of E_2 is also constant, assuming R_2 as constant.

Hence from equation (i), $T \ \alpha \frac{s}{R_2^2 + (sX_2)^2} \qquad -------- (ii)$

- At synchronous speed, slip is zero, hence torque is zero.
- At stand still the slip, s = 1, consequently, the torque-slip curves start from origin (i.e s = 0) and ends at s = 1.

Case –I: When slip is very low;

When the speed is very near to synchronous speed N_s i.e when slip is very low, then: $(sX_2)^2 << R_2^2$ (from equation -ii)

Hence $(sX_2)^2$ can be neglected, in comparison to R_2^2 in denominator of equation (ii)

i.e equation (ii) becomes, $T \ \alpha \ \frac{s}{R_2^2}$---------- (iii)

From equation (iii) it is clear that torque is directly proportional to slip, for low value of slip.

Since R_2 is constant, Hence for low value of slip, the torque-slip curve is approximately a straight line. (as show in fig.3)

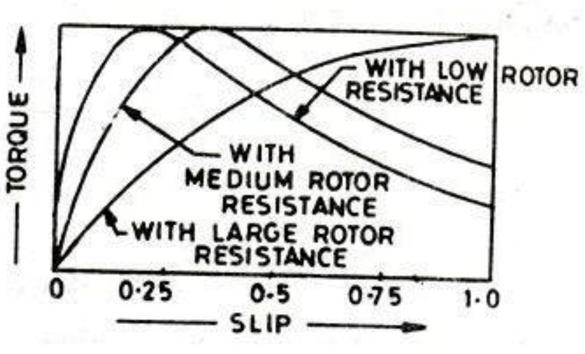


Figure 3 torque-slip characteristics of 3-phase I.M

Case –II: When slip is very High:

Slip is very high, i.e at the time of starting. then : $(sX_2)^2 >> R_2^2$ (from equation - ii)

Hence R_2^2 can be neglected in comparison to $(sX_2)^2$ in the denominator of equation (ii)

Now equation (ii) becomes, T $\alpha \frac{s}{(sX_2)^2}$ or T$\alpha \frac{1}{sX_2{}^2}$ $-----(iv)$

From equation (iv) it is clear that torque is inversely proportional to slip, since X_2 is constant.
Hence for higher value of slip, torque-slip curve will be a rectangular hyperbola. (As shown in fig3)

SINGLE-PHASE INDUCTION MOTOR (1-ϕ I.M)

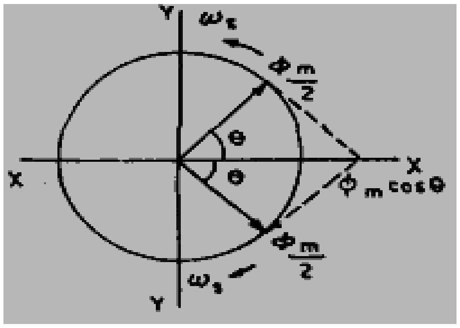
Why it is not a self starting motor:
A 1-ϕ I.M is very similar to a 3-ϕ squirrel cage I.M . It has (i) a squirrel-cage rotor (ii) a single-phase winding on the stator.
The 1-ϕ stator winding produces a magnetic field that pulsates in strength in a sinusoidal manner. The field polarity reverses after each half cycle but the field does not rotate. Consequently, the alternating flux cannot produce rotation in a stationary squirrel-cage rotor.

How to make it self start:
However, if the rotor of a single-phase motor is rotated in one direction by some mechanical means, it will continue to run in the direction of rotation.
As a matter of fact, the rotor quickly accelerates until it reaches a speed slightly below the synchronous speed. Once the motor is running at this speed, it will continue to rotate even though 1-ϕ current is flowing through the stator winding.

The above phenomenon can be explained by "Double Revolving Field Theory".

Working Principle: **Double Revolving Field Theory**

This theory is based on the fact that an alternating sinusoidal flux ($\phi = \phi_m \cos \omega t$) can be represented by two revolving fluxes, each equal to one-half of the maximum value of alternating flux (i.e.$\phi_m/2$) and each rotating at synchronous speed ($N_s = \frac{120f}{P}$) in opposite directions.



$where, \theta = \omega t$

With the help of double revolving field theory working of 1-ϕ I.M can explain as:

(i)Rotor at standstill:

- When rotor is stationary and the stator winding is connected to a single-phase supply. The alternating flux produced by the stator winding can be represented as the sum of the two rotating fluxes ϕ_1 and ϕ_2, each equal to one half of the maximum value of alternating flux and each rotating at synchronous speed ($N_s = \frac{120f}{P}$) in opposite directions.(as shown in fig.) Let the $\phi_1$rotate in anticlockwise direction and ϕ_2 in clockwise direction.
- The ϕ_1 will produce torque T_1 in the anticlockwise direction and ϕ_2 will produce torque T_2 in clockwise direction.
- At standstill, these two torques are equal and opposite and the net developed torque is zero. Therefore, 1-ϕ I.M is not self starting.

(ii) Rotor Running:

- If the rotor is started by spinning the rotor or by using auxiliary circuit, in say clockwise direction.
- The flux rotating in clockwise direction is the forward rotating flux (ϕ_f) and that in the other direction is the backward rotating flux(ϕ_b). The slip $w.r.t$ to forward flux will be

$$s_f = \frac{N_s - N_r}{N_s} = s$$

WhereN_s = synchronous speed
N_r = speed of the rotor in the direction of the forward flux

The rotor rotates opposite to the rotation of the backward flux. Therefore, the slip *w.r.t* the backward flux will be

$$s_b = \frac{N_s - (-N_r)}{N_s} = \frac{N_s + N_r}{N_s} = \frac{2N_s - N_s + N_r}{N_s}$$
$$= \frac{2N_s}{N_s} - \frac{(N_s - N_r)}{N_s} = 2 - s$$
$$s_b = 2 - s$$

- Thus for forward rotating flux, slip is “s” (less than unity) and for backward rotating flux, the slip is “2 – s” (greater than unity).
- Since for usual rotor resistance/reactance ratios, the torque at slip of less than unity are greater than those of slips of more than unity, the resultant torque will be in the direction of the forward flux.
- Thus if the motor once started, it will develop net torque in the direction in which it has been started and will function as a motor.

Methods of Starting or Types of Single-Phase Induction Motor:

- It is undesirable to start a single-phase induction motor by mechanical means.
- Hence for producing a revolving stator magnetic field, 1-ϕ supply is converted into a two phase supply through the use of starting winding in addition to the main single phase winding on the stator slots.
- The two windings are located 90^0 electrical apart.
- The resistance and reactance (inductive or capacitive) of the circuits of the two windings are made such that when connected across 1-ϕ supply, the currents flowing through the windings have sufficient phase difference.
- This result in production of 2-phase currents. Thus a rotating magnetic field is produced which will develop torque on the rotor of the motor.

Hence according to the method employed to make them self-starting, single-phase induction motor is classified as: (Methods of starting and types of single-phase induction motor)

(i) Split-Phase or Resistance Start Induction motor
(ii) Capacitor-Start Motor
(iii) Capacitor-start Capacitor-run Motor
(iv) Permanent-split or Permanent capacitor Motor
(v) Shaded-pole Motor

i. Split-Phase or Resistance Start Induction motor:

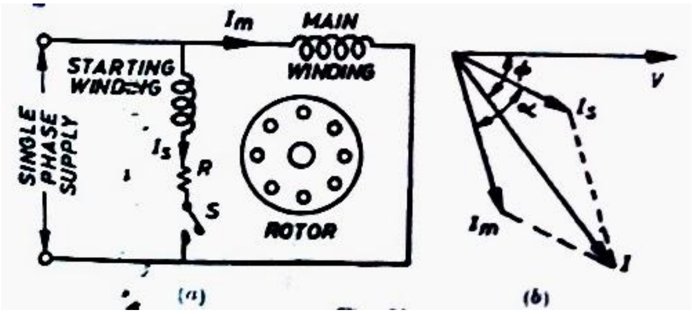


Figure 4 Split-Phase I.M

- It has a single- cage rotor and its stator has two windings- a main stator winding and a starting winding (auxiliary winding).
- The main winding and starting winding are displaced 90^0in space.

- The main winding has very low resistance and high inductive reactance.
- Thus, the current I_M in the main winding lags behind the supply voltage "V" by nearly 90^0. The starting winding has a resistor connected in series with it. It has a high resistance and low inductive reactance so that the current I_A in the starting winding is nearly in phase with the supply voltage.
- Thus, there is time phase difference between the currents in the two windings.
- The time phase difference ϕ is not 90^0but usually of the order of 30^0.
- This phase difference is enough to produce a rotating magnetic field.
- The starting winding is disconnected from supply automatically when the motor reaches speed about 70 to 80% of synchronous speed.

Applications: The common applications are, washing machines, air-conditioning fans, food mixers, floor polishers, blowers, centrifugal pumps, small drill etc.

- **Capacitor motors**: Capacitor motors are 1-ϕ I.M that employs a capacitor in the starting winding circuit to produce a greater phase difference between the current in the main winding and starting winding.

ii. Capacitor-start Motor:

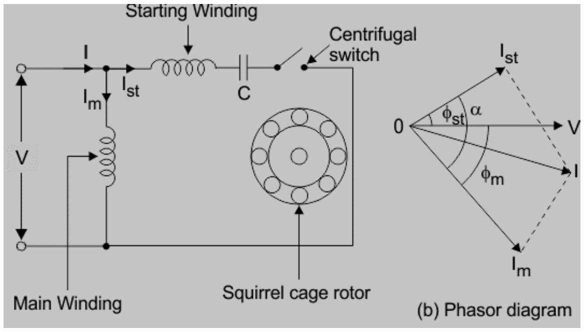


Figure 5 Capacitor-start Motor

- The two windings are displaced 90^0 in space. A capacitor C is connected in series with the starting winding.
- By choosing a capacitor of the proper rating the current I_M in the main winding may be made to lag behind I_{st} in the starting winding by 90^0 .
- Thus a single phase current is split into two phases to be applied to the stator windings. Thus the windings are displaced 90^0 electrical and their mmf's are equal in magnitude but 90^0 apart in time phase.
- Therefore motors acts like a balanced two-phase motor.
- As the motor approaches its rated speed, the starting winding and the starting capacitor C are disconnected automatically by switch 'S'.
- The motor is so named because it uses the capacitor only for the purpose of starting.

Applications: It is used for load of higher inertia where frequent starts are required. These motors are most suitable for pumps and compressors and therefore they are widely used in refrigerators and in air conditioner compressors.

iii. Capacitor-start Capacitor-run Motor:

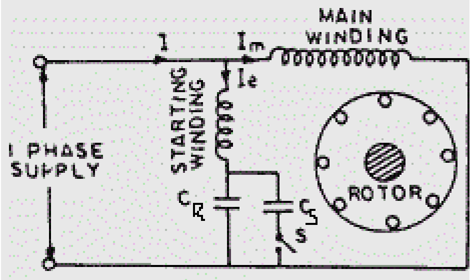


Figure 6 Capacitor-start Capacitor- run I.M

- The two windings are displaced 90^0 in space. The motor uses two capacitors C_S and C_R. The capacitors are connected in parallel at starting.
- The capacitor C_S is called starting capacitor. In order to obtain a high starting torque, a large current is required. For this purpose, the capacitive reactance in the starting winding should be low. Since $X_s = \frac{1}{2\pi f C_S}$, the value of C_S should be large.
- During normal operation, the rated line current is smaller than the starting current. Hence the capacitive reactance should be large. Since $X_R = \frac{1}{2\pi f C_R}$ the value of C_R should be small.
- As motor approaches synchronous speed, the capacitor C_S disconnected by switch.
- Since one capacitor C_S is used only at starting and C_R for continues running, this motor is called capacitor-start capacitor-run motor.

Applications: It is used for loads of higher inertia requiring frequent starts where the maximum pull out torque and efficiency required are higher. They are used in pumping equipment, refrigeration, air compressors etc.

iv. Permanent-Split Capacitor Motor:

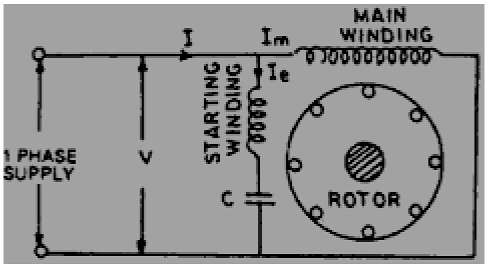


Figure 7 Permanent Capacitor Motor

- Since the capacitor “C” is always in the circuit, this type of motor has no starting switch.
- The starting winding is always in the circuit and therefore this motor operates in the same way as a two-phase motor.
- Consequently, it produces a uniform torque. The motor is therefore less noisy during operations.

Advantages: (a) No switch is required.
(b) It has higher efficiency.
(c) It has higher power factor because of permanently connected capacitor.
(d) It has a higher maximum torque.

Applications: It is used in ceiling fan, blowers in heaters and air conditioner and to drive refrigerator compressors.

v. Shaded-pole motor:

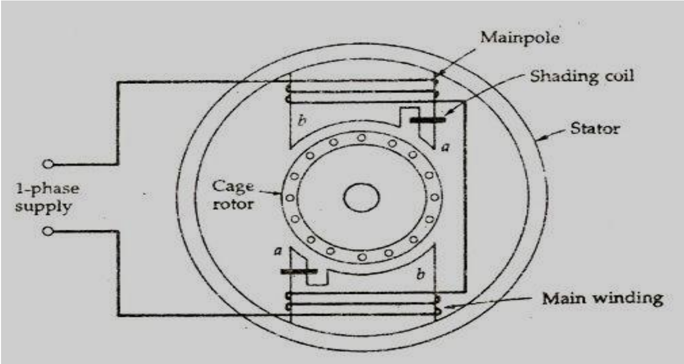


Figure 8 Shaded-Pole motor

- It consists of a stator and a cage type rotor.
- The stator is made up of salient poles. Each pole is slotted on side and a copper ring is fitted on the smaller part “a” as shown in fig 8. This part is called shaded pole.
- This ring is usually a single turn coil and is known as shading coil.

Working:

- When field current flows in the field winding, an alternating flux is produced in the field core. A portion of this flux links with the shading coil, which behaves as a short circuited secondary of transformer.
- A voltage is induced in the shading coil, and this voltage circulates a current in it.
- This induced current produces a flux, which opposes the main core flux. The shading coil thus causes the flux in the shading portion “a” to lag behind the flux in the unshaded portion “b” of the pole.
- At the same time, the main flux and the shaded pole flux are displaced in space. This space displacement is less than 90^0.
- Since there is time and space displacement between the two fluxes, the condition for setting up a rotating magnetic field is produced.
- Under the action of the rotating flux a starting torque is developed on the cage rotor.

Application: Shaded pole motor is very cheap. The starting torque developed by a shaded pole motor is very low. The losses are high and the power factor is low. Consequently the efficiency is low.

The most common applications are table fans, exhaust fans, hair driers, record players, tape recorders, slide projectors etc.

Three-Phase Synchronous Machine (3-ϕ Synchronous Machine)

Types of Rotor:

i. **Salient Type Rotor:** This type of rotor has a large number of projecting (salient) poles (shown in fig 9).

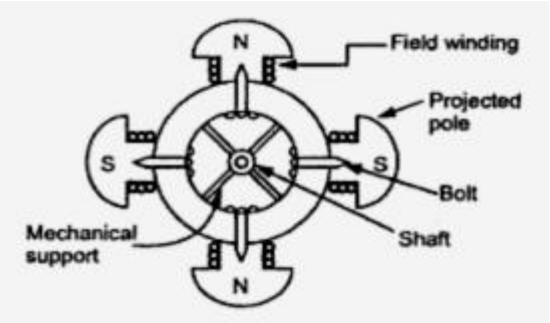


Figure 9 Salient pole rotor

It has following features:-
(a) Salient pole machines are larger in diameter but smaller in axial length.
(b) Poles of these rotors are laminated in order to reduce eddy current loss.
(c) These machines are suitable for medium speed. (i.e 500 rpm)
Example: Hydropower Plant.

ii. **Cylindrical Rotor:** A cylindrical rotor is consists of a smooth solid forged steel, cylinder having a number of slots for accommodating field coils.

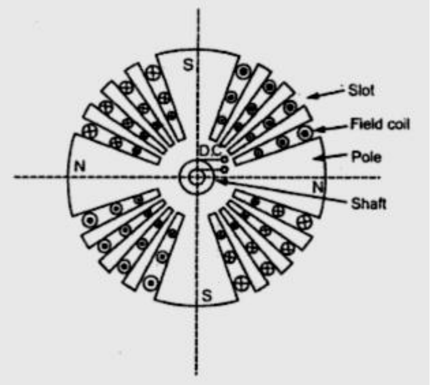
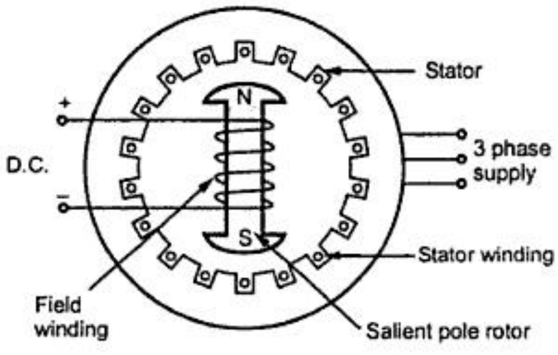


Figure 10 cylindrical rotor

It has following features:-
(a) They are smaller in diameter and larger in axial length.
(b) Usually number of poles on the rotor is two.
(c) Mechanically they are more balanced.
(d) These machines are suitable for speed from 1000 to 3000 rpm.
Example: Thermal power plant.

Three-Phase Synchronous Generator (Alternator):



Working Principle**:**

- The rotor of the alternator is provided DC supply and is rotated by means of some prime mover.
- The flux generated in the rotor conductor, sweeps past the air gap cuts the stator conductor.
- According to faraday's law an emf is induced in the stator (or armature) conductor. If the stator circuit is closed, the 3-ϕ alternating current will be start flowing in the circuit.
- The frequency of the output will be same as that of the rotor speed.

  i.e $f = \frac{PN_S}{120}\ Hz$

Three-Phase Synchronous Motor:

Working:

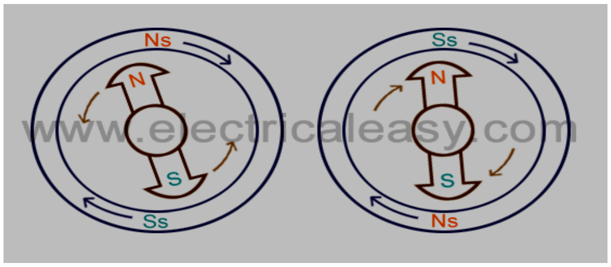


Figure 11 (a) and (b)

- As the rotor of Synchronous motor is excited from d.c supply, so the poles of the rotor retain the same polarity throughout but the polarity of the stator poles changes as it is connected to an a.c supply.
- Fig(a), At this instant, the rotor N- pole is repelled by the stator, N_S pole and therefore, the rotor tends to rotate in anticlockwise direction.

- After half a period, the polarity of stator poles is reversed but the polarity of the rotor poles remains the same (fig. b). As this instant, rotor N- pole is attracted to the stator , S_S pole and therefore, the rotor tends to rotate in clockwise direction.
- Hence due to continuous and rapid rotation of stator poles, the rotor is subjected to a torque which is rapidly reversing.
- Owing to rotor large inertia, the rotor can not instantaneously respond to such quickly-reversing torque, with the result that rotor remains stationary.

Starting of Synchronous Motor:

First Method:

- Use auxillary d.c motor or petrol, diesel engine and coupled to prime mover.
- Start auxillary machine, Bring it to rated speed and at same time, give 3-phase supply to stator.
- Keep field winding open.
- Bring auxillary machine at synchronous speed, start in the same direction in the direction of rotating field of stator.
- Give d.c supply to rotor and try to increase field cuurent, there will be a jurk in machine.
- Disconnect prime mover.
- Now motor will run at synchronous speed. i.e. Synchronous motor will start.

Second Method: By use of Damper winding-

- The damper windings consist of short-circuited copper bars embedded in the face of field poles.
- AC supply given to the stator produces a rotating magnetic field which causes the rotor to rotate, therefore, in the beginning synchronous motor provided with damper winding start as a squirrel cage induction motor.
- The exciter moves along the rotor. When the motor attains 95% of synchronous speed, the rotor is magnetically locked by the rotating magnetic field of the stator and the motor runs as a synchronous speed.

Applications of Synchronous Motor:

i. They are used in power house and substation in parallel to the bus-bars to improve power factor. For this purpose they are run with out mechanical load and overexcited.
ii. Such motors are also used to regulate the voltage at end of transmission lines.
iii. Because of higher efficiency possible with synchronous motors,they can be empolyed advantageously for the loads where constant speed is required. They are used to drive such as fans,blowers,d.c generators,centrifugal pumps,compressors,rubber and paper mill etc.