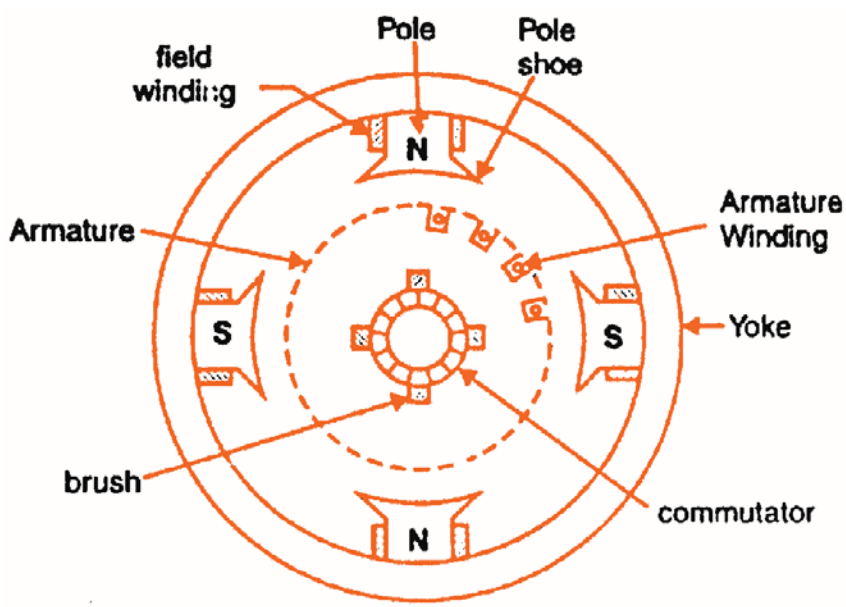
DC MACHINES

Constructional details of a DC Machine:

• A DC machine can be used as a DC generator or a DC motor without any constructional changes. Thus, a DC generator or a DC motor can be broadly termed as a DC machine.

• when the machine is being assembled, we do not know whether it is a dc generator or motor. Any dc generator can be run as a dc motor and vice-versa.

• The following figure shows the constructional details of a simple **4-pole** DC machine



A DC machine consists of two basic parts, stator and rotor.

The other important parts are described below.

1. Yoke:

- The outer frame of a D.C Machine (Generator or Motor) is called as yoke. Yoke is made up of cast iron or steel.
- Yoke provides mechanical strength for whole assembly of the D.C Machine
- It also carries the magnetic flux produced by the poles.

2. Poles:

- Poles are to support field windings or coils which are wound around it.
- Poles are joined to the yoke with the help of screws or welding.

3. Pole shoe:

- Pole shoe is an extended part of the pole which serves two purposes,
  (i) To prevent field coils from slipping and
  (ii) To spread out the flux in air gap uniformly.

4. Field winding:

- Field winding is wound on poles and connected in series or parallel with armature winding.
- Field coils are mounted on the poles and carry the dc exciting current.
- The field coils are connected in such a way that adjacent poles have opposite polarity.

5. Armature core and Armature winding:

- Armature core is the rotor of a D.C Machine.
- Armature core is cylindrical in shape on which slots are provided to carry armature winding.
- The armature core is laminated to reduce the eddy current loss.
- Armature winding can be wound by one of the two methods known as
  Lap winding (A=P) and Wave winging (A=2)

6. Commutator:

- In DC Generator, commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes.
- In DC Motor, commutator acts as mechanical inverter which converts direct voltage into alternating voltage.
- The commutator is made of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine.

7. Brushes:

- The purpose of brushes is to ensure electrical connections between the rotating commutator and stationary external load circuit.
- The brushes are made of carbon and rest on the commutator.
- Thus brushes are physically in contact with armature conductors hence wires can be connected to brushes.

D.C GENERATOR

An electrical Generator is a machine which converts mechanical energy (or power) into electrical energy (or power).

Principle of Operation of D.C Generator:

According to Faraday's Laws of Electromagnetic Induction

"Whenever a conductor cuts magnetic flux, dynamically induced e.m.f. is produced in it".

The magnitude of the EMF is given by

$$E = Bl\upsilon \text{ (Volts)}$$

Where, B= Magnetic filed

l = Effective length of conductor

υ = Velocity of conductor in magnetic field

The direction of the induced emf / current is given by Fleming's Right Rule

Fleming's Right Rule:

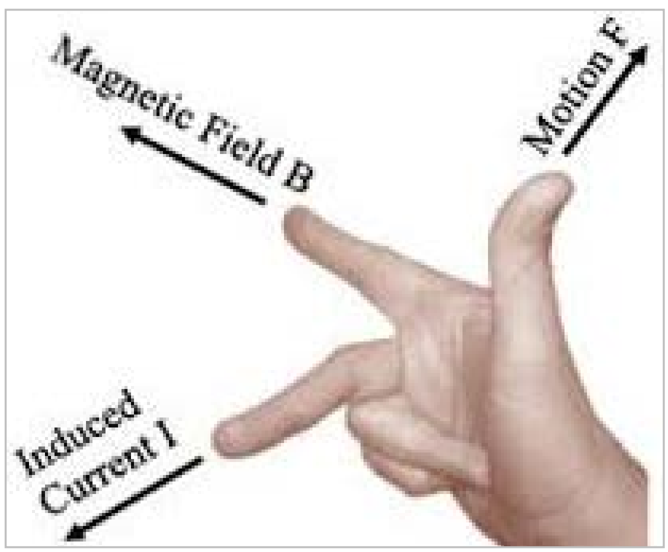
Stretch the thumb, fore finger and centre finger of Right hand in mutually perpendicular directions such that

When

- The Thumb represents the direction of the Motion of the Conductor (F).
- The Fore finger represents the direction of the magnetic Field (B).

Then

- The Centre finger represents the direction of the Current (I).



EMF Equation of D.C Generator:

Let P = Number of poles of the generator

Φ = Flux produced by each pole in webers (Wb)

N = Speed of armature in r.p.m.

Z = Total Number of Armature Conductors

A = Number of parallel paths in which the 'Z' number of conductors are divided

So A = P for lap type of winding

A = 2 for wave type of winding

Now e.m.f. gets induced in the conductor according to Faraday's law of electromagnetic induction.

Hence average value of e.m.f. induced in each armature conductor is,

$$e = \textbf{Rate of cutting the flux} = \frac{d\phi}{dt}$$

Now consider one revolution of conductor.

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

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

$$\therefore \quad e = \frac{\phi P}{\frac{60}{N}} = \phi P \frac{N}{60}$$

This is the e.m.f. induced in one conductor.

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 are always in series and e.m.f. remains same across all the parallel paths.

Total e.m.f. generated in d.c. generator is, $\therefore \quad E = \phi P \frac{N}{60} \times \frac{Z}{A} \ Volts$

The e.m.f. equation of d.c. generator is $E = \frac{\phi P N Z}{60 A} \quad Volts$

$$E = \frac{\phi N Z}{60} \quad Volts \qquad for\ Lap\ Type\ as \quad A = P$$

$$E = \frac{\phi\, P\, N\, Z}{120} \quad Volts \qquad for\;\; Lap\;\; Type\;\; as \quad A = 2$$

Example: A **4 pole**, **lap** wound, d.c. generator has a useful flux of **0.07 Wb per pole**. Calculate the generated e.m.f. when it is rotated at a speed of **900 r.p.m**. with the help of prime mover. Armature consists of **440 number of conductors**. Also calculate the generated e.m.f. if **lap wound armature is replaced by wave** wound armature.

Solution:

Given that

Number of poles of the generator P = 4

Total Number of Armature Conductors Z = 440

Flux produced by each pole in webers Φ = 0.07 Wb

Speed of armature in r.p.m. N = 900 r.p.m.

The e.m.f. equation of d.c. generator $E = \frac{\phi\, P\, N\, Z}{60\, A} \quad Volts$

i) For lap wound, A = P = 4

$$\therefore \qquad E = \frac{\phi\, P\, N\, Z}{60\, A} = \frac{0.07 \times 4 \times 900 \times 440}{60 \times 4} = 462\; Volts$$

ii) For wave wound A = 2

$$\therefore \qquad E = \frac{\phi\, P\, N\, Z}{60\, A} = \frac{0.07 \times 4 \times 900 \times 440}{60 \times 2} = 924\; Volts$$

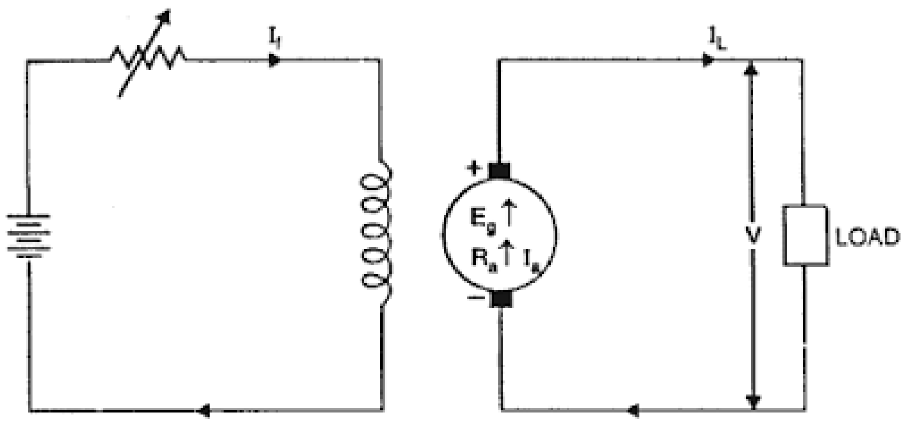
Types of DC Generators:

Generators are generally classified according to the methods of field excitation.

1. Separately excited dc generators and 2.Self excited dc generators

Separately excited dc generators:

A dc generator whose field winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator.



Armature current, $I_a = I_L$

Terminal voltage, $V = E_g - I_a R_a$

Electric power developed $= E_g I_a$

Self-Excited D.C. Generators:

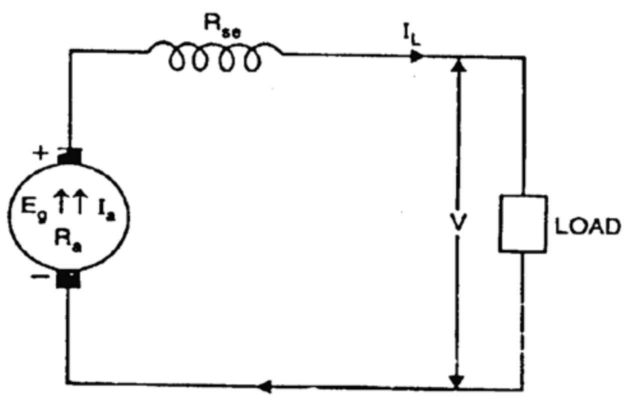
A D.C. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator.

There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

- Series generator
- Shunt generator
- Compound generator

Series generator:

- In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load.
- Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance.
- Series generators are rarely used except for special purposes e.g., as boosters.



Armature current, $I_a = I_{se} = I_L = I$

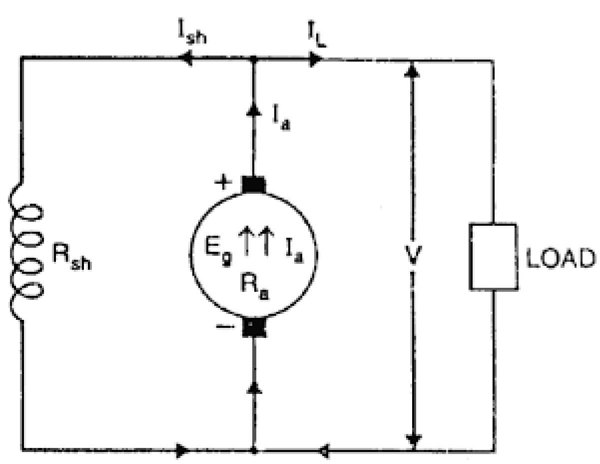
Terminal voltage, $V = E_g - I\,(R_a + R_{se})$

Electric power developed $= E_g I_a$

Power delivered to load $= V\,I$

Shunt generator:

- In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it.
- The shunt field winding has many turns of fine wire having high resistance.
- Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load.



Shunt field current, $I_{sh} = \dfrac{V}{R_{sh}}$

Armature current, $I_a = I_L + I_{sh}$

Terminal voltage, $V = E_g - I\,R_a$

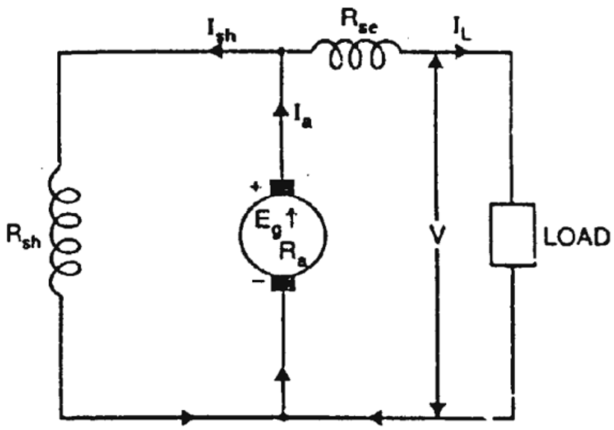
Electric power developed $= E_g I_a$

Power delivered to load $= V\,I_L$

Compound generator:

- In a compound-wound generator, there are two sets of field windings on each pole - one is in series and the other in parallel with the armature.
- A compound wound generator may be:

Short Shunt in which shunt field winding is in parallel only with the armature winding.



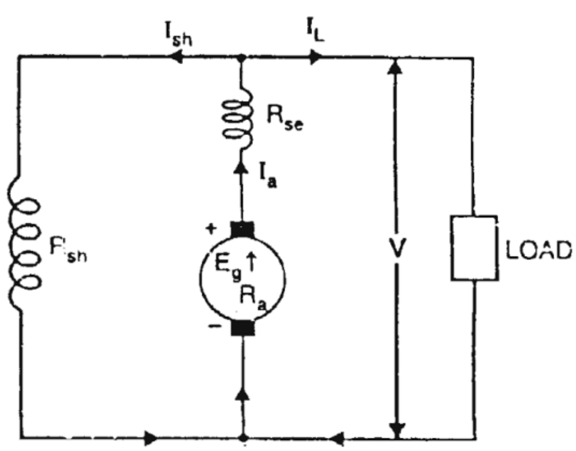
Series field current, $I_{se} = I_L$

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

Electric power developed $= E_g I_a$

Power delivered to load $= V I_L$

Long Shunt in which shunt field winding is in parallel with both series field and armature winding. **Long shunt:**



Series field current, $I_{se} = I_a = I_L + I_{sh}$

Shunt field current, $I_{sh} = \dfrac{V}{R_{sh}}$

Terminal voltage, $V = E_g - I(R_a + R_{se})$

Electric power developed $= E_g I_a$

Power delivered to load $= V I_L$

DC MOTORS

A DC motor is a machine which converts electric energy into mechanical energy.

Principle of Operation DC Motor:

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

The direction of mechanical force is given by Fleming's Left-hand Rule and its magnitude is given by

$$F = B\, I\, l \text{ Newton.}$$

Where B = Magnetic field

I = Current flowing through the conductor

l = Effective length of conductor

Fleming's Left-hand Rule:

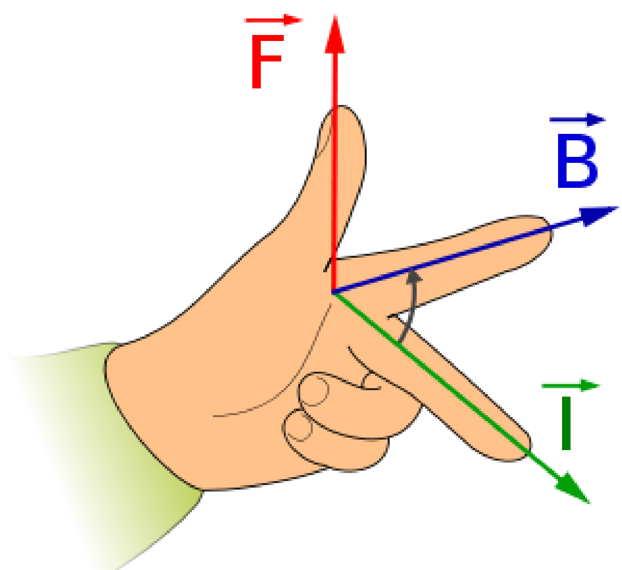
Stretch the thumb, fore finger and centre finger of left hand in mutually perpendicular directions such that

When

- The Fore finger represents the direction of the magnetic Field (B).
- The Centre finger represents the direction of the Current (I).

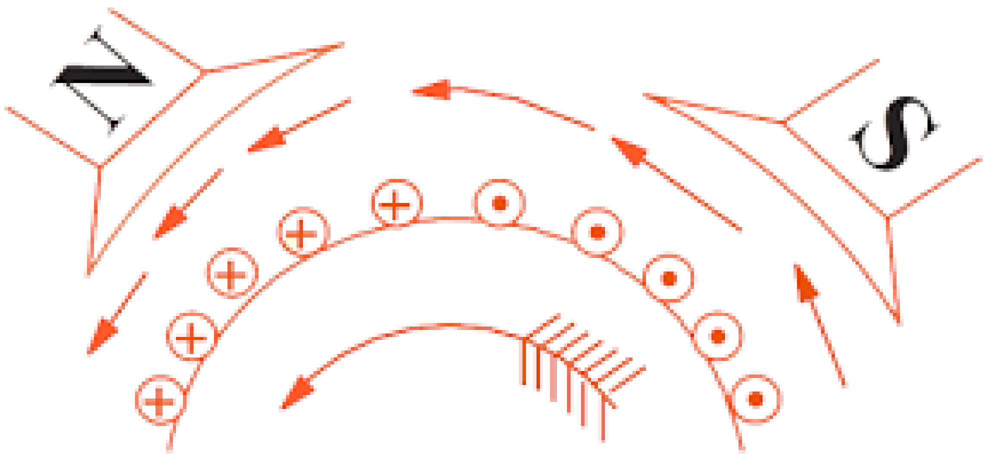
Then

- The Thumb represents the direction of the Motion of the Conductor (F).



Working of DC Motor

Consider a part of a D.C motor as shown in Figure below.



When the terminals of the motor are connected to an external source of d.c. supply:

- The field magnets are excited developing alternate N and S poles.
- The armature conductors carry currents.
- All conductors under N-pole carry currents in one direction while all the conductors under S-pole carry currents in the opposite direction.
- Suppose the conductors under N-pole carry currents into the plane of the paper and those under S-pole carry currents out of the plane of the paper as shown in Figure.
- Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force acts on it.
- On applying Fleming's left hand rule, it is clear that force on each conductor is tending to rotate the armature in anticlockwise direction.
- All these forces add together to produce a driving torque which sets the armature rotating.

Torque Equation of DC Motor:

The mechanical power that is required to produce the desired torque of dc machine is given by, $P_m = E_b\, I_a$

The mechanical power P_m is related to the electromagnetic torque T_g as,

$P_m = T_g\, \omega$ Where ω is speed in rad/sec.

Now equating we get, $E_b\, I_a = T_g\, \omega$

Now for simplifying the torque equation of dc motor we substitute.

$$E_b = \frac{\phi P N Z}{60\, A} \quad Volts$$

Where,

P = Number of poles of the generator

Φ = Flux produced by each pole in webers (Wb)

Z = Total Number of Armature Conductors

N = Speed of the D.C. motor in r.p.m.

A = Number of parallel paths in which the 'Z' number of conductors are divided

So A = P for lap type of winding

A = 2 for wave type of winding

From $E_b\, I_a = T_g\, \omega$ $\quad T_g = \dfrac{E_b\, I_a}{\omega}$, we know that $\omega = \dfrac{2\pi N}{60} \quad rad/\sec$

We get

$$T_g = \frac{\left(\dfrac{\phi P N Z}{60\, A}\right) I_a}{\left(\dfrac{2\pi N}{60}\right)} = \frac{\phi P Z I_a}{2\,\pi\, A}$$

This is the torque equation of dc motor. It can be further simplified as:

$$T_g = k_a\, \phi\, I_a$$

Where

$$k_a = \frac{P Z}{2\,\pi\, A}$$

Which is constant for a motor and therefore the torque of dc motor varies with only flux **φ** and armature current $\mathbf{I_a}$

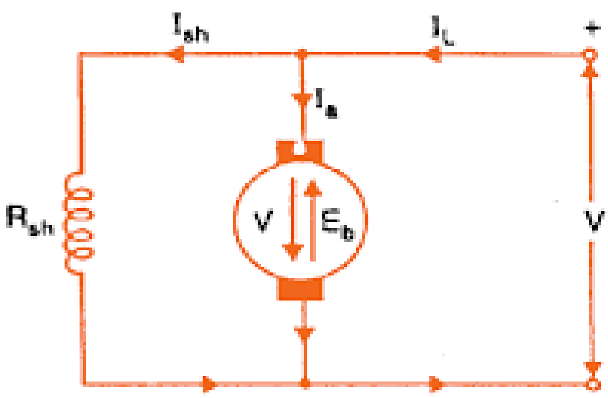
Types of DC Motors:

Like generators, there are three types of d.c. motors characterized by the connections of field winding in relation to the armature. They are

1. Shunt Wound DC Motor
2. Series Wound DC Motor
3. Compound Wound DC Motor
    - Short Shunt Connection
    - Long Shunt Connection

Shunt DC Motor

Shunt-wound motor in which the field winding is connected in parallel with the armature.



Shunt field current, $I_{sh} = \dfrac{V}{R_{sh}}$

Armature current, $I_L = I_a + I_{sh}$

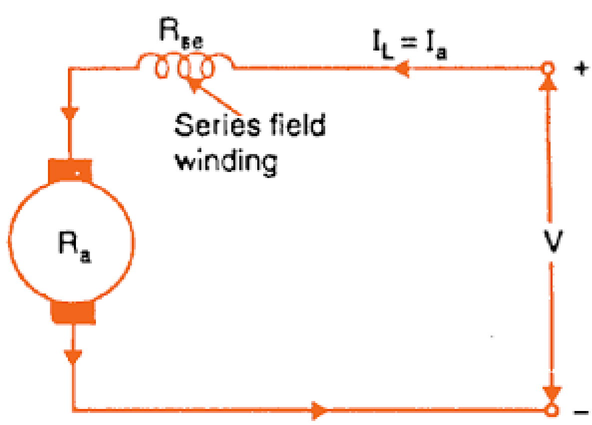
Terminal voltage, $V = E_b + I_a R_a$

Electric power developed $= E_b I_a$

Power delivered to load $= V I_L$

Series DC Motor

Series-wound motor in which the field winding is connected in series with the armature.



Armature current, $I_a = I_{se} = I_L = I$

Terminal voltage, $V = E_b + I(R_a + R_{se})$

Electric power developed $= E_b I_a$

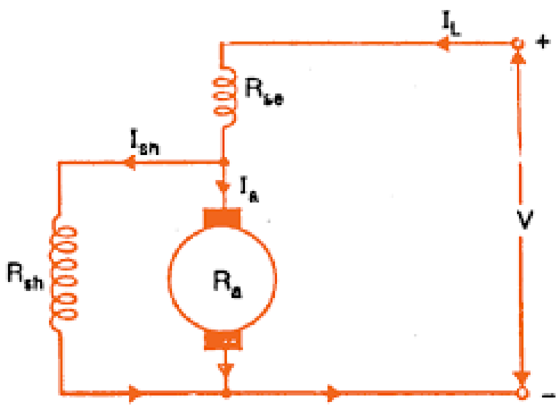
Power delivered to load $= V I$

Compound Wound DC Motor

Compound-wound motor which has two field windings; one connected in parallel with the armature and the other in series with it.

There are two types of compound motor connections (like generators).

Short Shunt in which shunt field winding is in parallel only with the armature winding.



Short-shunt connection

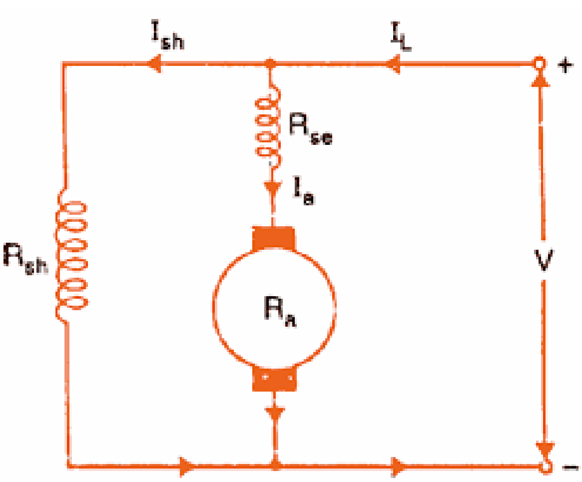
Series field current, $I_{se} = I_L$

Terminal voltage, $V = E_b + I_a R_a + I_L R_{se}$

Electric power developed = $E_b I_a$

Power delivered to load $= V I_L$

Long Shunt in which shunt field winding is in parallel with both series field and armature winding.



Long-shunt connection

Series field current, $I_{se} = I_a = I_L - I_{sh}$

Shunt field current, $I_{sh} = \dfrac{V}{R_{sh}}$

Terminal voltage, $V = E_b + I_a (R_a + R_{se})$

Electric power developed $= E_b I_a$

Power delivered to load $= V I_L$

THREE PHASE INDUCTION MOTOR

Introduction: Three-phase induction motors are the most widely used electric motors in industry. Speed of this motors are frequency dependent. The induction motor may be considered to be a **transformer with a rotating secondary**

Advantages

- It has simple and rugged construction.
- It is relatively cheap.
- It requires little maintenance.
- It has high efficiency and reasonably good power factor.
- It has self starting torque.

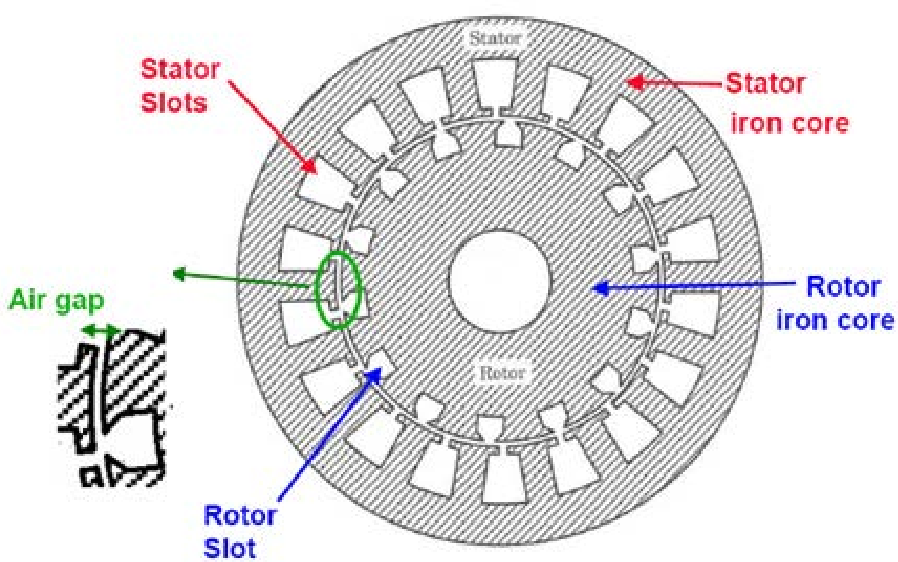
Disadvantages

- It is essentially a constant speed motor and its speed cannot be changed easily.
- Its starting torque is inferior to d.c. shunt motor.

Constructional Details of A Three Phase Induction Motor

A typical motor consists of two parts namely stator and rotor like other type of motors.

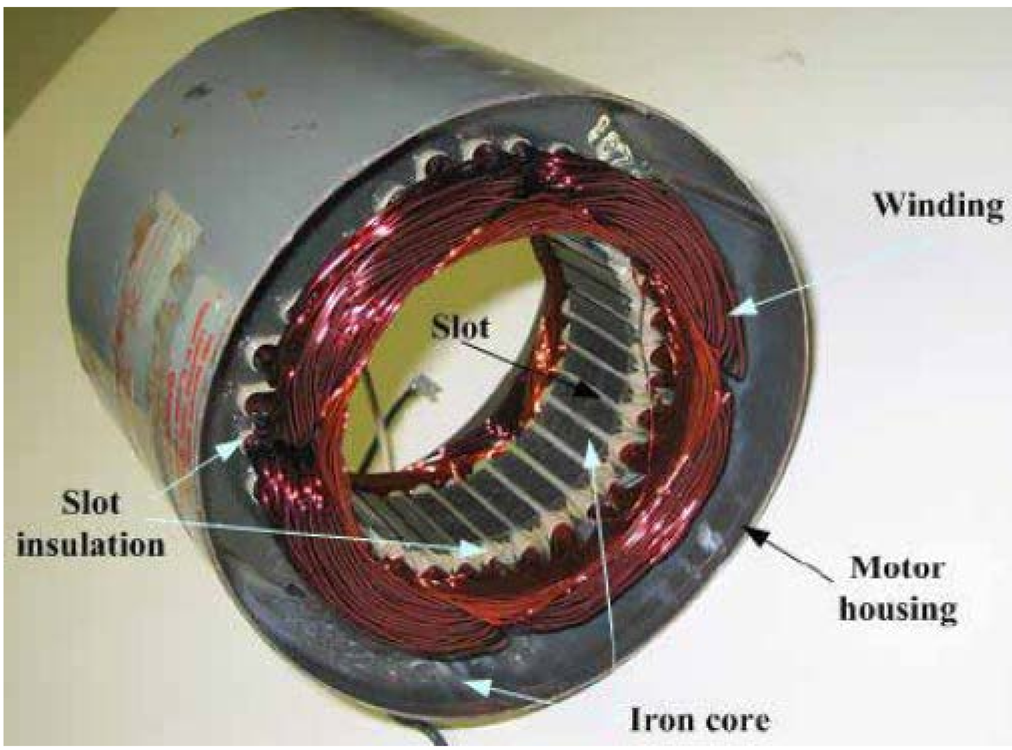
1. **Stator:** An outside stationary stator having coils supplied with AC current to produce a rotating magnetic field
2. **Rotor:** An inside rotor attached to the output shaft that is given a torque by the rotating field.



Stator:

- It consists of a steel frame which encloses a hollow, cylindrical core made up of thin laminations of silicon steel
- A number of evenly spaced slots are provided on the inner periphery of the laminations for providing 3 phase winding.
- The 3-phase stator winding is wound for a definite number of poles as per requirement of speed.
- When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude (1.5 ϕ_m) is produced.

This rotating field induces currents in the rotor by electromagnetic induction



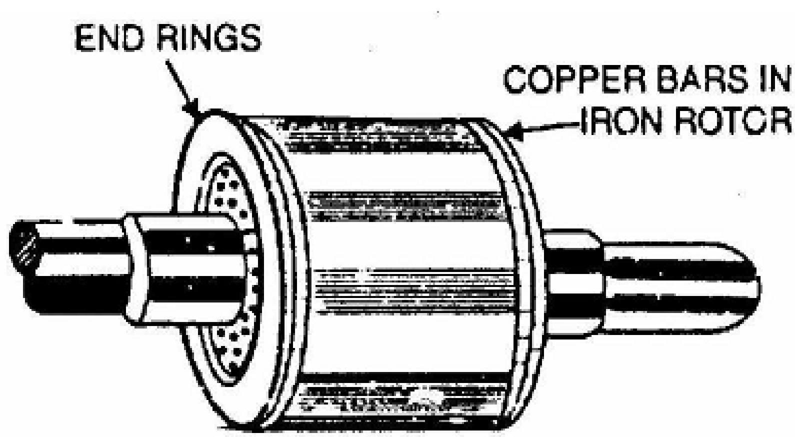
Rotor:

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

(i) Squirrel cage type (ii) Wound type

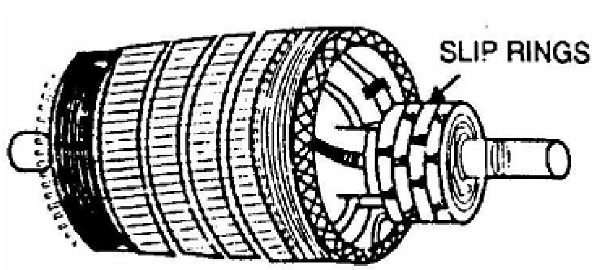
Squirrel cage type

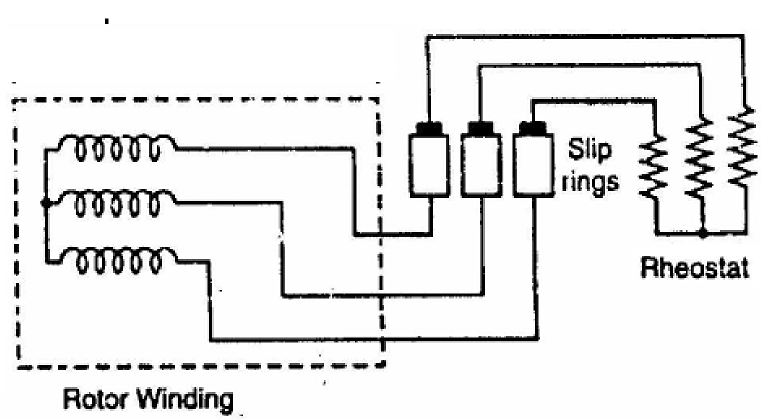
- Most of 3-phase induction motors use squirrel cage rotor.
- It has a remarkably simple and robust construction.
- The rotor winding consists of single copper or aluminum bars placed in the slots and short-circuited by end-rings on both sides of the rotor.
- It suffers from the disadvantage of a low starting torque.

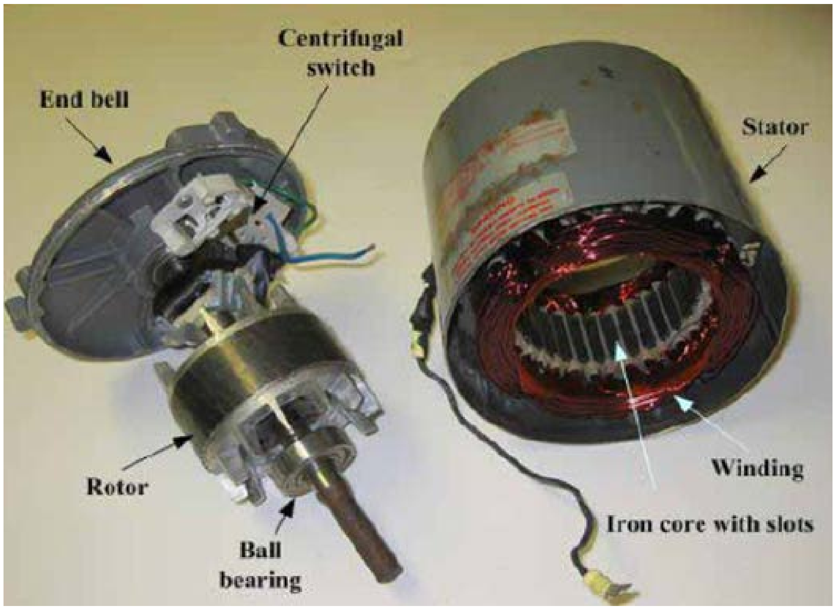


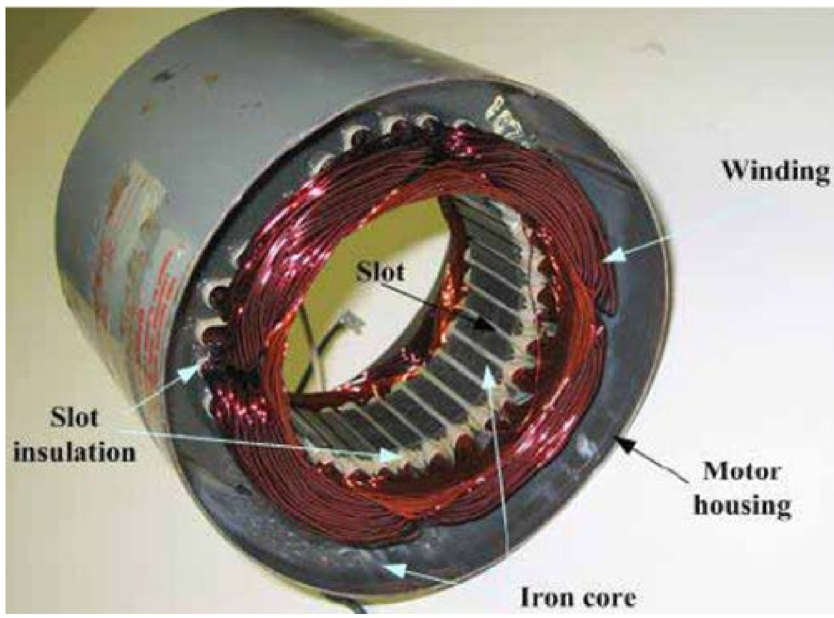
Wound type

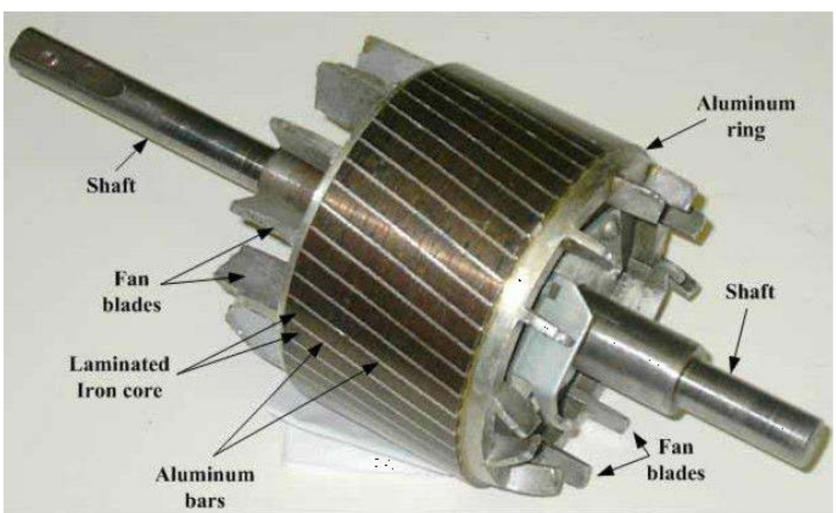
- In the wound rotor, an insulated 3-phase winding similar to the stator winding wound for the same number of poles as stator, is placed in the rotor slots.
- The ends of the star-connected rotor winding are brought to three slip rings on the shaft so that a connection can be made to it for starting or speed control.
- At the time of starting, the external resistances are included in the rotor circuit to give a large starting torque.
- These resistances are gradually reduced to zero as the motor runs up to speed.





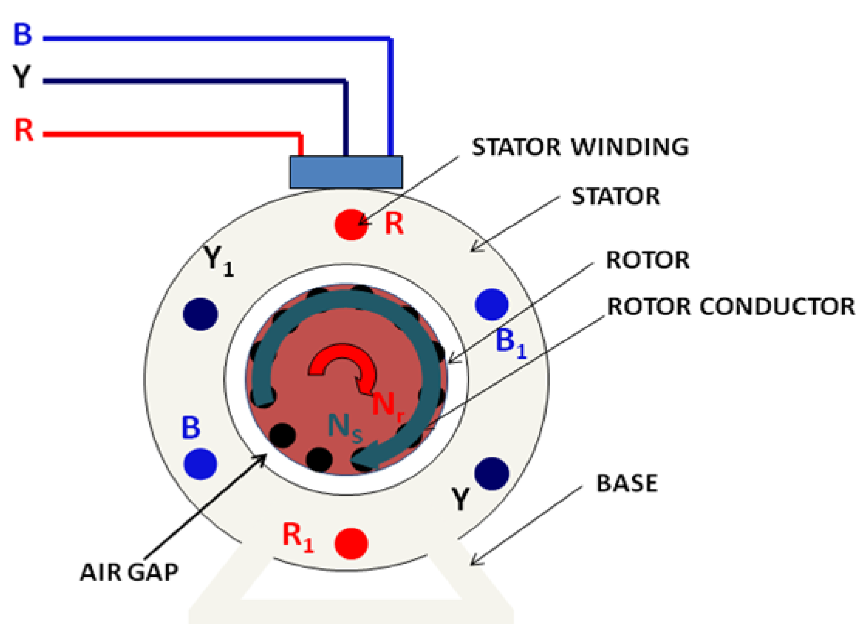

Centrifugal switch
End bell
Stator
Rotor
Winding
Iron core with slots
Ball bearing


Winding
Slot
Slot insulation
Motor housing
Iron core


Aluminum ring
Shaft
Fan blades
Shaft
Laminated Iron core
Fan blades
Aluminum bars

Principle of operation of three phase induction motors

- When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced.
- The speed at which stator magnetic field rotates is called **synchronous speed (N_S).**
- Magnitude of this rotating magnetic field is constant and is equal to 1.5 φ_m
- The rotating field passes through the air gap and cuts the rotor conductors, which as yet, are stationary.
- According to Faraday's laws of electromagnetic induction current flows through the short circuited conductors.
- The interaction of the rotating flux and the rotor current generates a force that drives the motor and a torque is developed consequently.
- Mechanical force acts on the rotor conductors and rotor start to rotate in the direction of rotating magnetic field.
- The torque is proportional with the flux density and the rotor
- The motor speed is less than the synchronous speed.
- The direction of the rotation of the rotor is the same as the direction of the rotation of the revolving magnetic field in the air gap



Slip (s)

- In practice, the rotor can never reach the speed of stator flux ,Because of friction and windage losses makes the rotor to slow down.
- Hence, the rotor speed (N_r) is always less than the stator flux speed (N_s).
- **The difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed Nr is called slip.**

It is usually expressed as a percentage of synchronous speed

i.e.,The quantity N_s - N_r is called slip speed.

When the rotor is stationary (i.e., N_r = 0), slip, s = 1 or 100 %

$$\%\ Slip = \frac{N_s - N_r}{N_s} * 100\%$$

Rotor Frequency(f_r)

- The frequency of a **voltage or current induced** due to the relative speed between rotor conductor and rotating magnetic field can be calculated by

$$f_r = \frac{(N_s - N_r)\ P}{120}$$

where $(N_s - N_r)$= Relative speed between magnetic field and the armature winding

P = Number of poles

- For a rotor speed (N_r), the relative speed between the rotating flux (N_s) and the rotor is $(N_s - N_r)$.

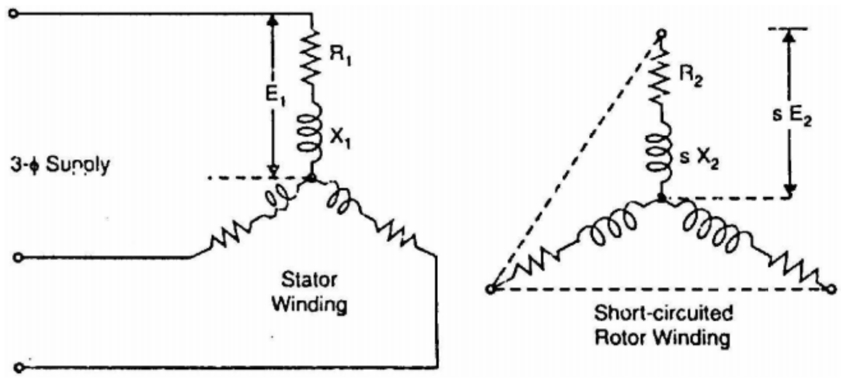
The frequency of supply voltage (stator rotating flux) is $f = \frac{N_s\ P}{120}$

$$\frac{f_r}{f} = \frac{\frac{(N_s - N_r)\ P}{120}}{\frac{N_s\ P}{120}} = \frac{N_s - N_r}{N_s} = s\ f$$

Problems:

1. A three phase induction motor is wound for 4 poles and is supplied from 50Hz system. Calculate (i) the synchronous speed (ii) the speed of the motor when slip is 4% and (iii) the motor rotor current frequency when the motor runs at 600 r.p.m.
2. A 6 pole, 3phase, 50 Hz induction motor is running at full load with a slip of 4%. The rotor is star connected and its resistance and stand still reactance are 0.25 Ω and 1.5 Ω per phase. The e.m.f between slip rings is 100V. Find the rotor current per phase and power factor, assuming the slip rings are short circuited.

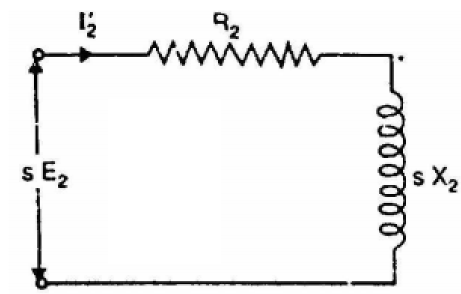
Rotor Current



- The e.m.f induced in rotor windings at standstill (s=1) is $E_2 = \sqrt{2}\,\pi\, f\, N_2\, \phi_m$
- The e.m.f induced in rotor windings under running condition is

$$E_2' = \sqrt{2}\,\pi\, f_r\, N_2\, \phi_m = \sqrt{2}\,\pi\,(s\ f\,)N_2\,\phi_m = s\ E_2$$

Torque Equation of 3-Phase Induction Motor



Rotor equivalent circuit diagram for a 3-ph induction motor

$$Rotor\ Current\ induced\ /\ phase\quad I_2 = \frac{e.m.f\ induced\ /\ phase}{Z_2}$$

Rotor power factor $= Cos\ \phi_2 = \dfrac{R_2}{Z_2}$

At standstill Slip s=1

$$Rotor\ Current\ /\ phase\quad I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

When running at slip s

$$Rotor\ Current\ /\ phase\quad I_2' = \frac{E_2'}{Z_2} = \frac{s\,E_2}{Z_2} = \frac{s\,E_2}{\sqrt{R_2^2 + (s\,X_2)^2}} \quad \text{and} \quad \cos\ \phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

Torque T developed is directly proportional to rotor flux , rotor current and power factor

$$T\ \alpha\ \phi_2\, I_2' \cos\ \phi_2 \qquad \text{and} \qquad \phi_2\ \alpha\ E_2$$

$$\therefore \quad T\ \alpha\ E_2\, I_2' \cos\ \phi_2 = k\, E_2\, I_2' \cos\ \phi_2$$

$$T = k\ E_2 \frac{s\,E_2}{\sqrt{R_2^2 + (s\,X_2)^2}} \frac{R_2}{\sqrt{R_2^2 + (s\,X_2)^2}} \qquad T = k\ \frac{s\,E_2^2}{R_2^2 + (s\,X_2)^2}$$

Starting torque **s=1** $\quad T = k\ \dfrac{E_2^2}{R_2^2 + X_2^{\ 2}}$

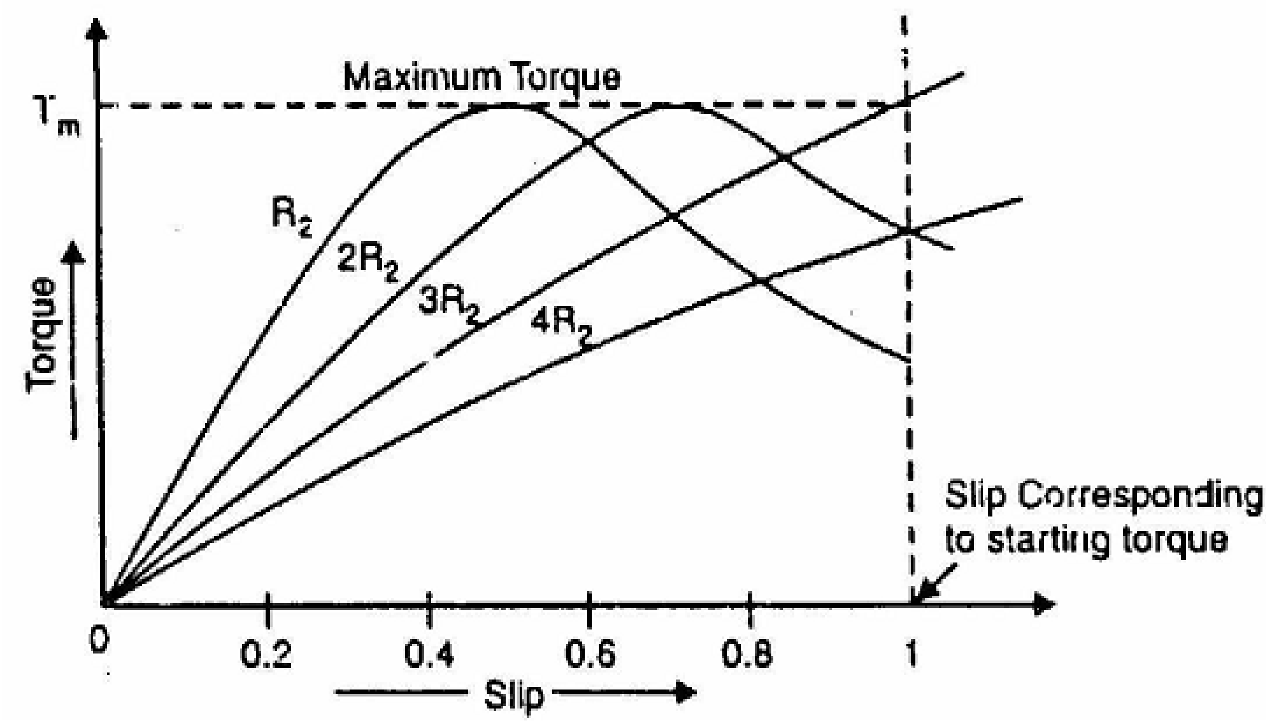
Torque Slip Characteristics

If a curve is drawn between the torque and slip for a particular value of rotor resistance R_2, the graph thus obtained is called torque-slip characteristic.

At s = 0, T = 0 so that torque-slip curve starts from the origin

At normal speed, slip is small so that sX_2 is negligible $T \alpha s$ and the torque increases and becomes maximum at $s = \frac{R_2}{X_2}$

For high values of slip R_2 value is less compared to sX_2 value so $R_2^2 \approx 0$ and $T \alpha \frac{1}{s}$



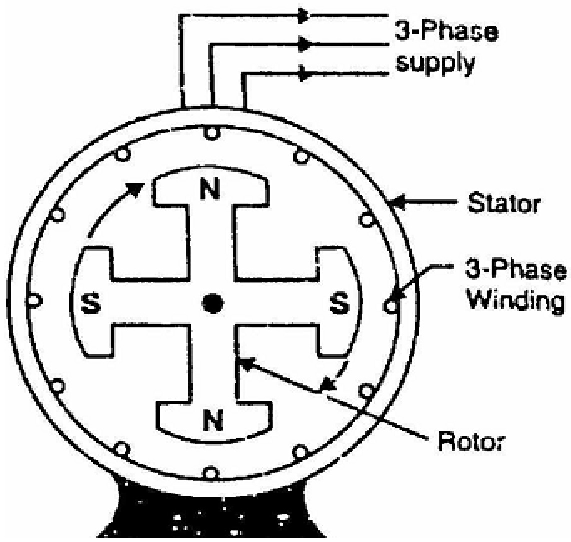
SYNCHRONOUS MACHINES

Introduction

- Rotates at synchronous speed.
- The machine which produces 3-phase power from mechanical power is called an alternator or synchronous generator.
- An alternator has 3-phase winding on the stator and a d.c. field winding on the rotor. They convert mechanical energy into a.c. energy.

Constructional details of synchronous machines

Like any machine a synchronous machine has two parts. a) Stator b) Rotor



Stator

- It is the stationary part of the machine and is built up of sheet-steel laminations having slots on its inner periphery
- A 3-phase winding is placed in these slots and serves as the armature winding of the alternator
- The armature winding is always connected in star and the neutral is connected to ground.

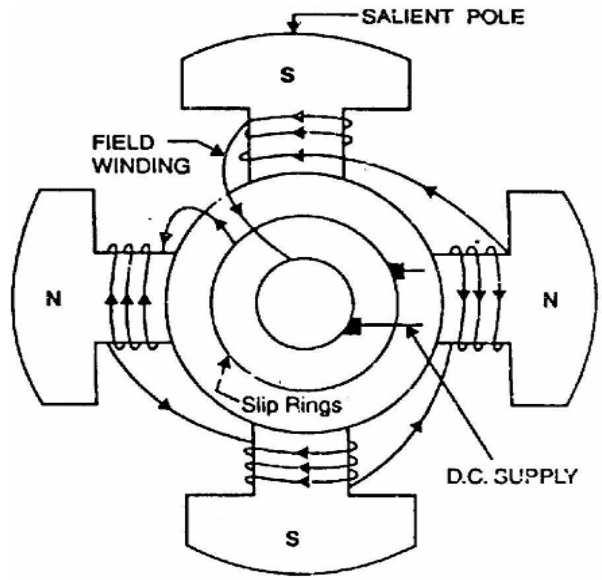
Rotor

- The rotor carries a field winding which is supplied with direct current through two slip rings by a separate d.c. source.
- Rotor construction is of two types,

  (i) Salient (or projecting) pole type (ii) Non-salient (or cylindrical) pole type

Salient pole type

- Salient or projecting poles are mounted on a large circular steel Frame which is fixed to the shaft of the alternator
- These are used in Low and medium-speed alternators (120-400 r.p.m.)
- Due to excessive windage loss if driven at high speed and would tend to produce noise.
- At higher speeds they may be subjected to Mechanical stresses



Non-salient pole type (cylindrical type)

- In this type, the rotor is made of smooth solid forged-steel radial cylinder having a number of slots along the outer periphery.
- The field windings are embedded in these slots and are connected in series to the slip rings through which they are energized by the d.c. exciter.
- These are used in High-speed alternators