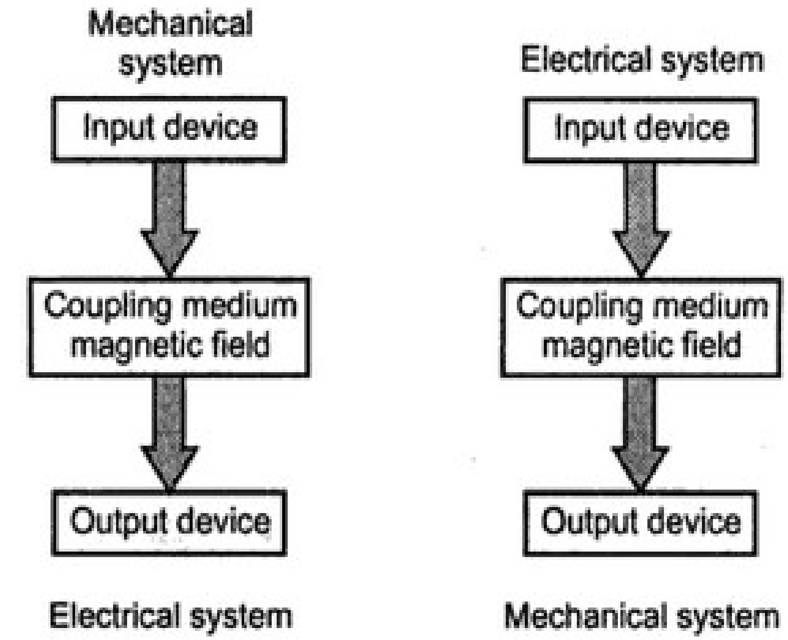
UNIT IV

Electrical Machines: Principle of operation, construction and applications of DC machines, transformers, induction motors, synchronous generators, stepper motor, Brushless DC (BLDC) motor

DC Machines

In practice, three types of electromechanical energy conversion devices are in use.

1. The various transducers such as microphones, loudspeakers, strain guage, thermocouples etc. These devices handle low energy signals. These devices mostly operate on vibrating motion.
2. The devices which produce the mechanical force or torque based on translatory motion such as electromagnets, relays, solenoids, actuators etc. These devices handle large energy signals than the transducers.
3. The devices used for continuous energy conversion using rotational motion such as generators, motors etc. These devices handle very large energy signals.



a) Generating device   b) Motoring device

$$\begin{bmatrix}\text{Electrical energy}\\ \text{input from}\\ \text{electrical system}\end{bmatrix} = \begin{bmatrix}\text{Mechanical}\\ \text{transformed}\\ \text{output energy}\end{bmatrix} + \begin{bmatrix}\text{Change}\\ \text{energy}\\ \text{stored}\end{bmatrix} + \begin{bmatrix}\text{Total energy loss}\\ \text{i.e. energy dissipated}\\ \text{in the form of heat}\end{bmatrix}$$

... For motor (1)

$$\begin{bmatrix}\text{Mechanical energy}\\ \text{input from}\\ \text{mechanical system}\end{bmatrix} = \begin{bmatrix}\text{Electrical}\\ \text{transformed}\\ \text{energy output}\end{bmatrix} + \begin{bmatrix}\text{Change in}\\ \text{energy}\\ \text{stored}\end{bmatrix} + \begin{bmatrix}\text{Total energy loss}\\ \text{i.e. energy}\\ \text{dissipated}\end{bmatrix}$$

... For generator (2)

General Construction of a Rotation machine

It is known that whenever there is relative motion between a conductor and the flux, the e.m.f. is induced in the conductor. This is the principle of a generator. While whenever a current carrying conductor is placed in a magnetic field then it experiences a mechanical force, which is the principle of a motor. Hence every rotating machine must posses following parts,

1. Stationary member called stator.
2. Rotating member called rotor.
3. Shaft
4. Slip ring, brush assembly
5. Bearings

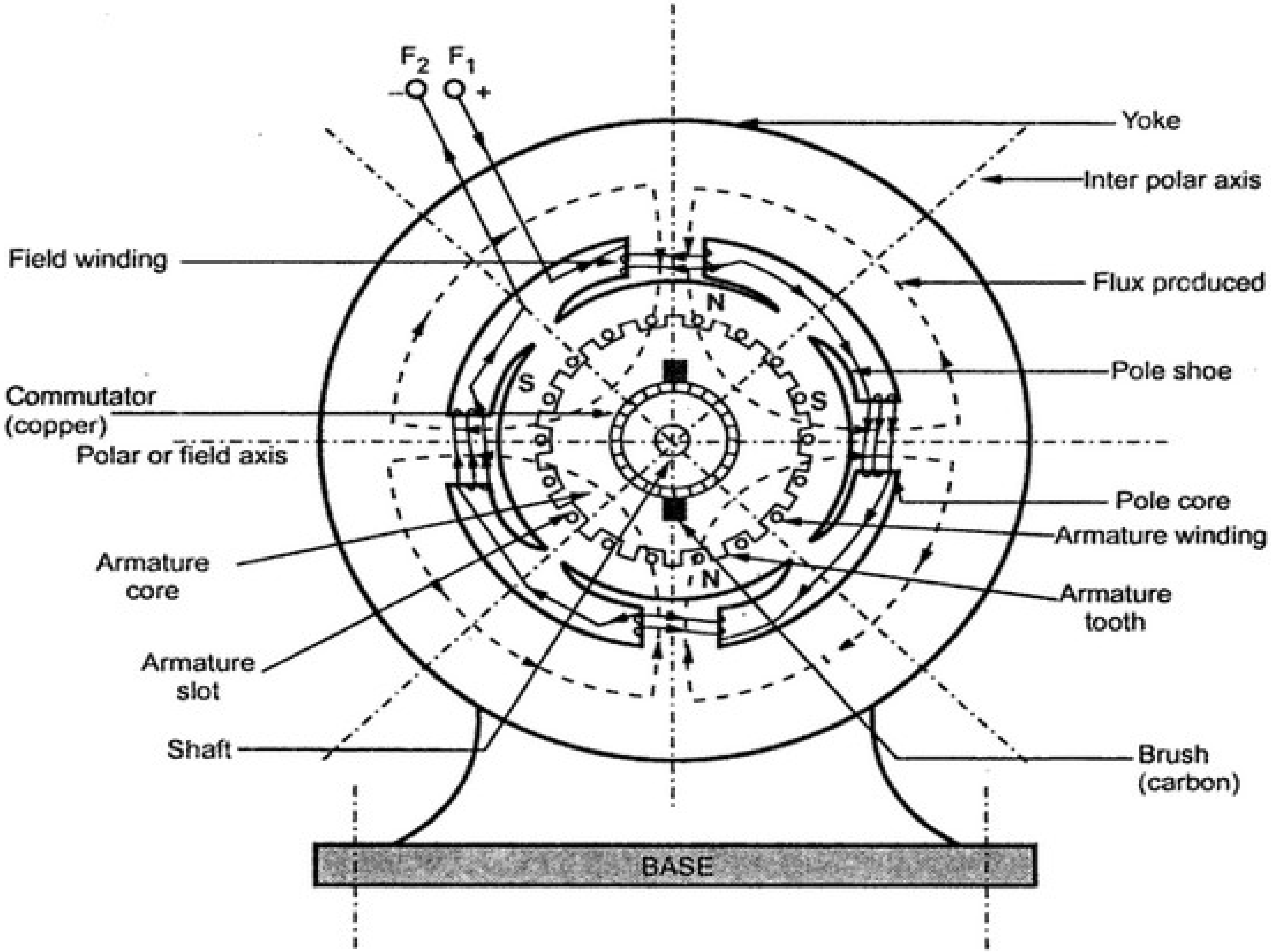
Now these are the mechanical parts which machine must possess. In addition to these a machine has,

1. An arrangement of winding which is used as a primary source of flux when current is passed through it. This is called **field winding or exciting winding.**
2. An arrangement of conductors to form a winding in which e.m.f. is induced. This is called an **armature winding.**

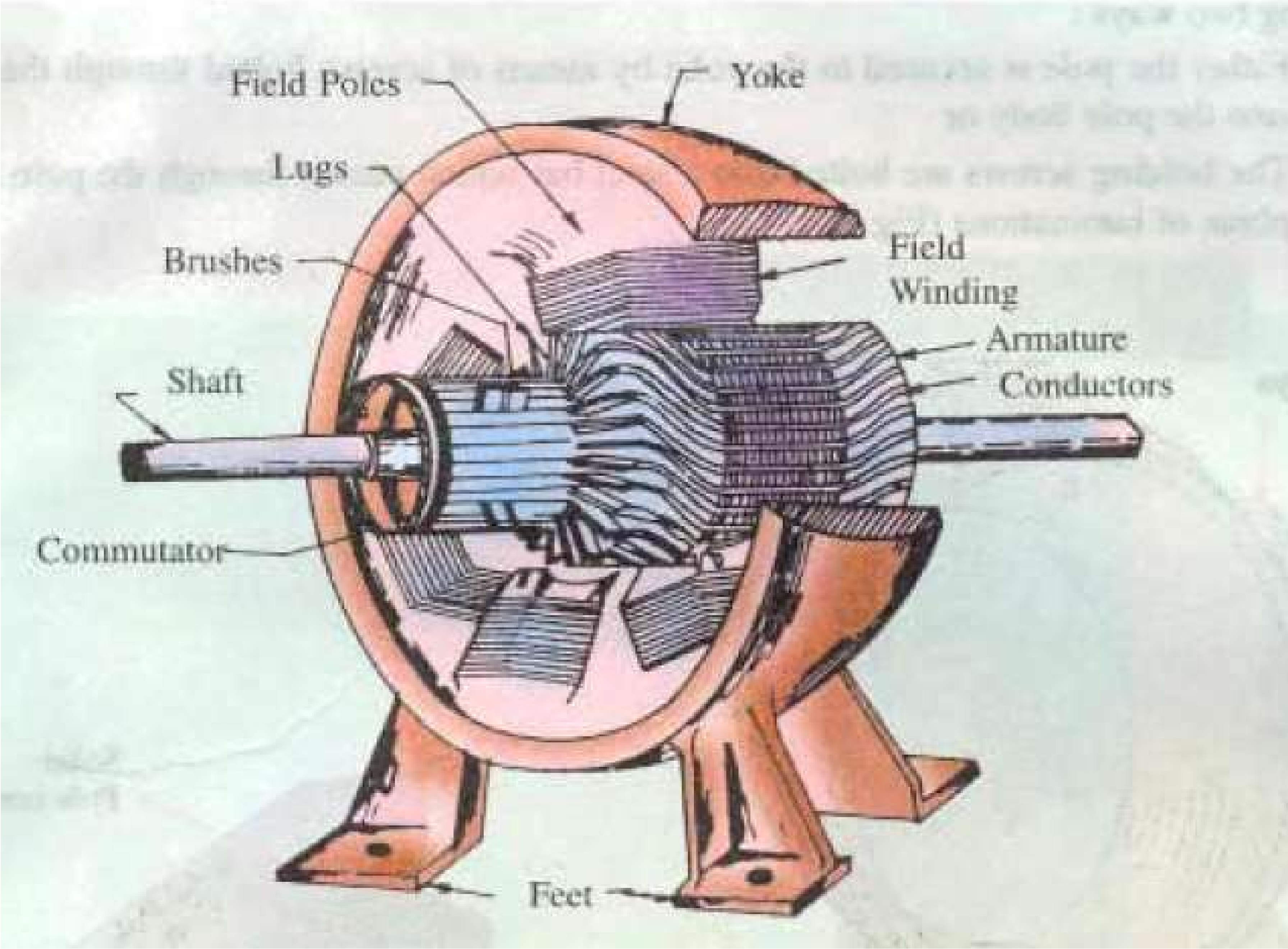
The current flowing through the field winding, used to produce main flux is called **magnetizing current, exciting current or field current.**

The current flowing through the armature winding varies as the load on the machine varies. So it is called a **load current** or an **armature current.**

The current in the field winding is always d.c. There is an appropriate air gap between a stator and a rotor of the machine. In most of machines armature winding is placed on the stator while the field winding is placed on the rotor from practical convinience point of view.



A cross-section of typical d.c. machine



Field Poles
Yoke
Lugs
Brushes
Field
Winding
Armature
Conductors
Shaft
Commutator
Feet

Yoke

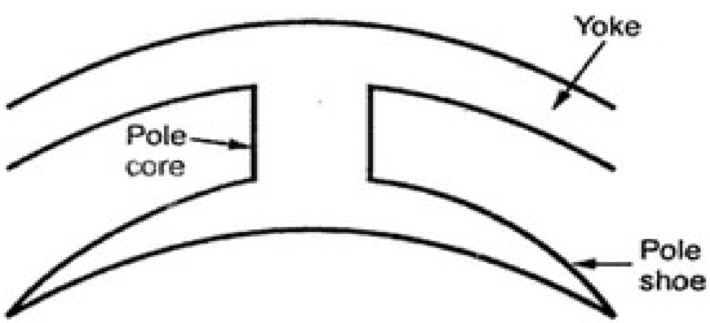
a) Functions :

1. It serves the purpose of outermost cover of the d.c. machine. So that the insulating materials get protected from harmful atmospheric elements like moisture, dust and various gases like SO_2 , acidic fumes etc.
2. It provides mechanical support to the poles.
3. It forms a part of the magnetic circuit. It provides a path of low reluctance for magnetic flux. The low reluctance path is important to avoid wastage of power to provide same flux. Large current and hence the power is necessary if the path has high reluctance, to produce the same flux.

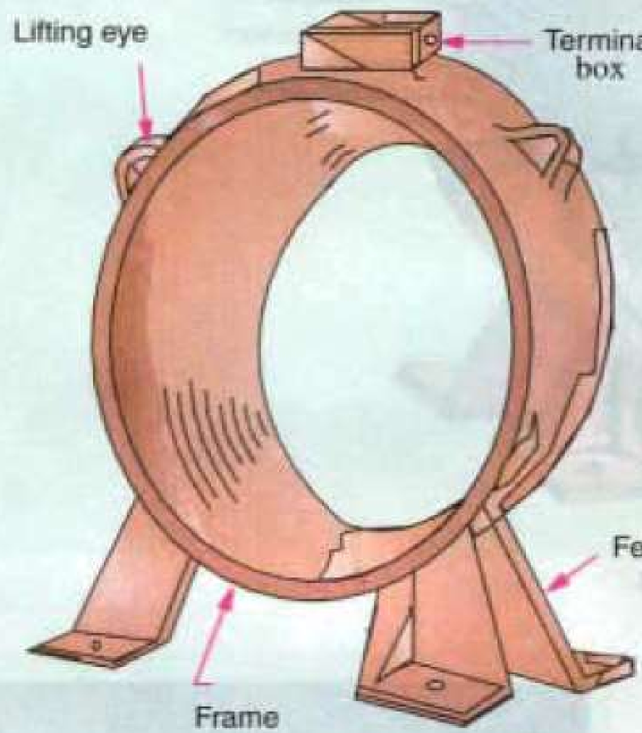
b) Choice of material : To provide low reluctance path, it must be made up of some magnetic material. It is prepared by using cast iron because it is cheapest. For large machines rolled steel, cast steel, silicon steel is used which provides high permeability i.e. low reluctance and gives good mechanical strength.

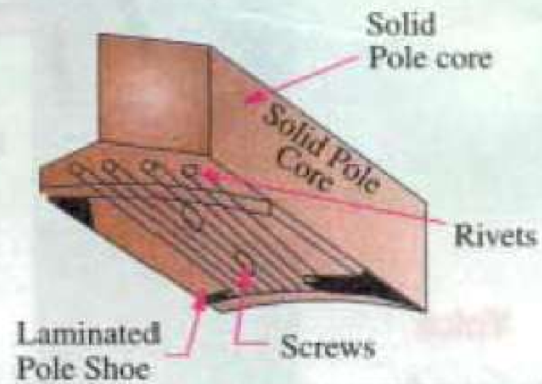
Poles

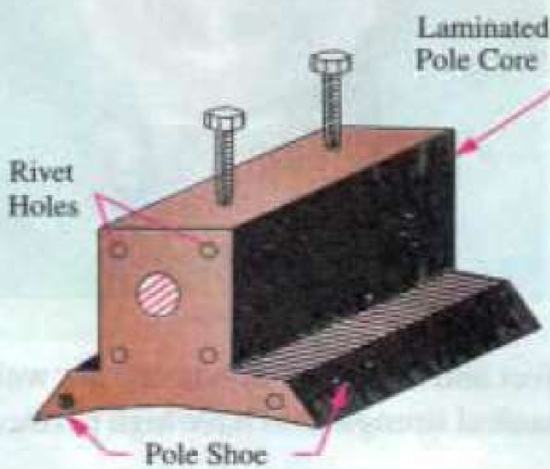
Each pole is divided into two parts namely, I) Pole core and II) Pole shoe

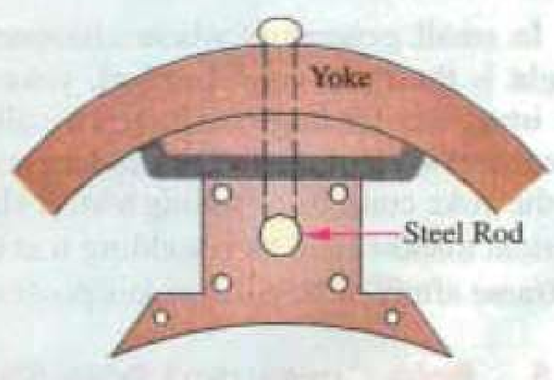


Pole structure


Lifting eye
Terminal box
Feet
Frame


Solid Pole core
Solid Pole Core
Rivets
Laminated Pole Shoe
Screws


Laminated Pole Core
Rivet Holes
Pole Shoe


Yoke
Steel Rod

a) Functions of pole core and pole shoe :

1. Pole core basically carries a field winding which is necessary to produce the flux.
2. It directs the flux produced through air gap to armature core, to the next pole.
3. Pole shoe enlarges the area of armature core to come across the flux, which is necessary to produce larger induced e.m.f. To achieve this, pole shoe has been given a particular shape.

b) Choice of material : It is made up of magnetic material like cast iron or cast steel.

As it requires a definite shape and size, laminated construction is used. The laminations of required size and **shape are** stamped **together** to get a pole which is then bolted to the yoke.

Field Winding (F1 - F2)

The field winding is wound on the pole core with a definite direction.

a) Functions : To carry current due to which pole core, on which the field winding is placed behaves as an electromagnet, producing necessary flux.

As it helps in producing the magnetic field i.e. exciting the pole as an electromagnet it is called **Field winding** or **Exciting winding.**

b) Choice of material : It has to carry current hence obviously made up of some conducting material. So aluminium or copper is the choice. But field coils are required to take any type of shape and bend about pole core and copper has good pliability i.e. it can bend easily. So copper is the proper choice.

Key Point: *Field winding is divided into various coils called field coils. These are connected in series with each other and wound in such a direction around pole cores, such that alternate 'N' and 'S' poles are formed.*

By using right hand thumb rule for current carrying circular conductor, it can be easily determined that how a particular core is going to behave as 'N' or 'S' for a particular winding direction around it. The direction of winding and flux can be observed in the Fig.

Armature

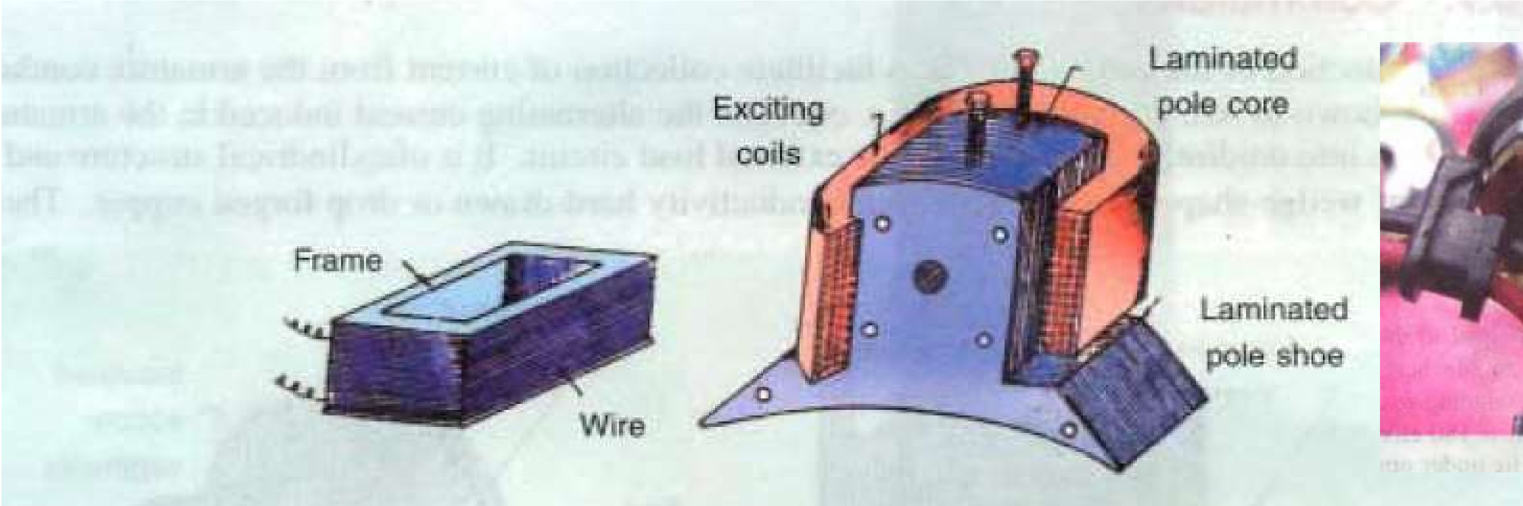
It is further divided into two parts namely,

I) Armature core and II) Armature winding.

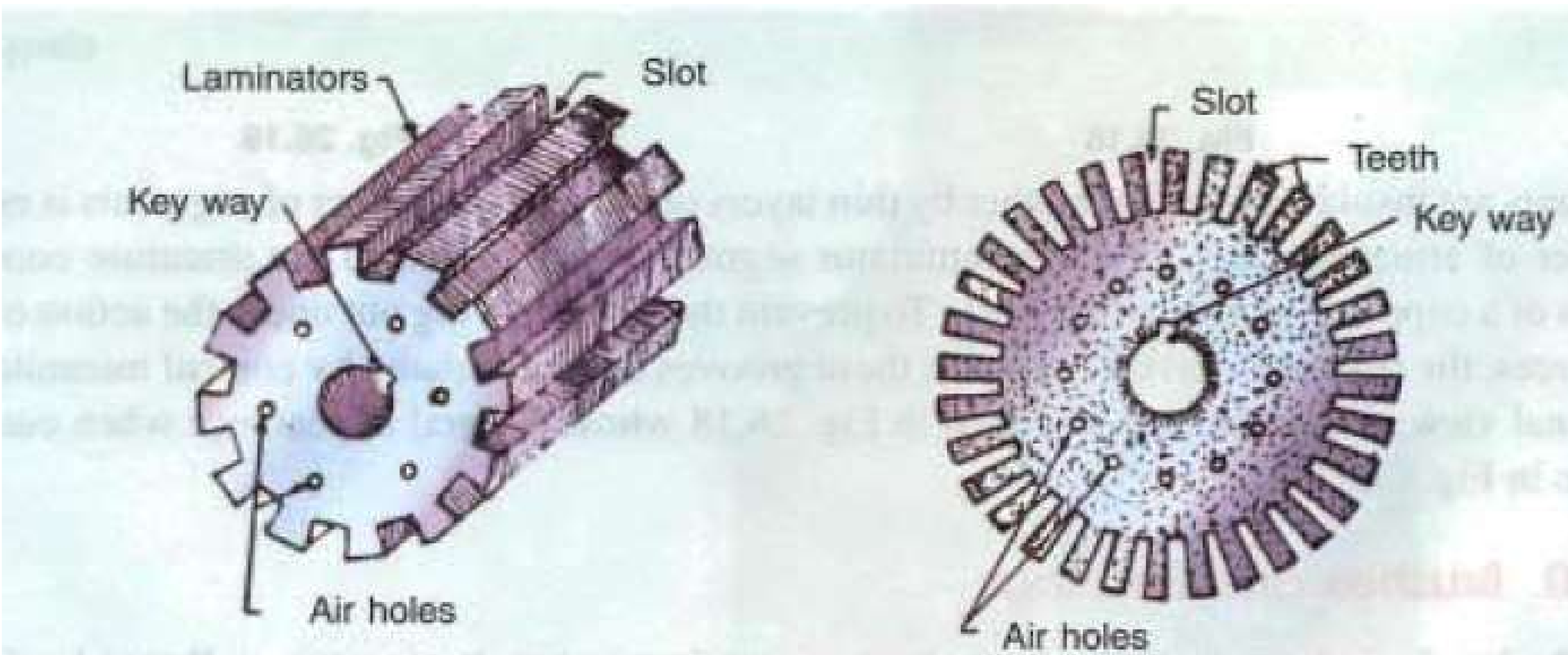
I) Armature core : Armature core is cylindrical in shape mounted on the shaft. It consists of slots on its periphery and the air ducts to permit the air flow through armature which serves cooling purpose.

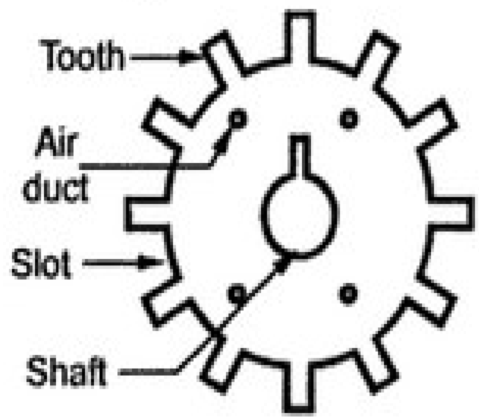
a) Functions :

1. Armature core provides house for armature winding i.e. armature conductors.
2. To provide a path of low reluctance to the magnetic flux produced by the field winding.




Armature winding





Single circular lamination of armature core

b) Choice of material : As it has to provide a low reluctance path to the flux, it is made up of magnetic material like cast iron or cast steel.

It is made up of laminated construction to keep eddy current loss as low as possible. A single circular lamination used for the construction of the armature core is shown in the Fig.

II) Armature winding : Armature winding is nothing but the interconnection of the armature conductors, placed in the slots provided on the armature core periphery. When the armature is rotated, in case of generator, magnetic flux gets cut by armature conductors and e.m.f. gets induced in them.

a) Functions :

1. Generation of e.m.f. takes place in the armature winding in case of generators.
2. To carry the current supplied in case of d.c. motors.
3. To do the useful work in the external circuit.

b) Choice of material : As armature winding carries entire current which depends on external load, it has to be made up of conducting material, which is copper.

Armature winding is generally former wound. The conductors are placed in the armature slots which are lined with though insulating material.

Commutator

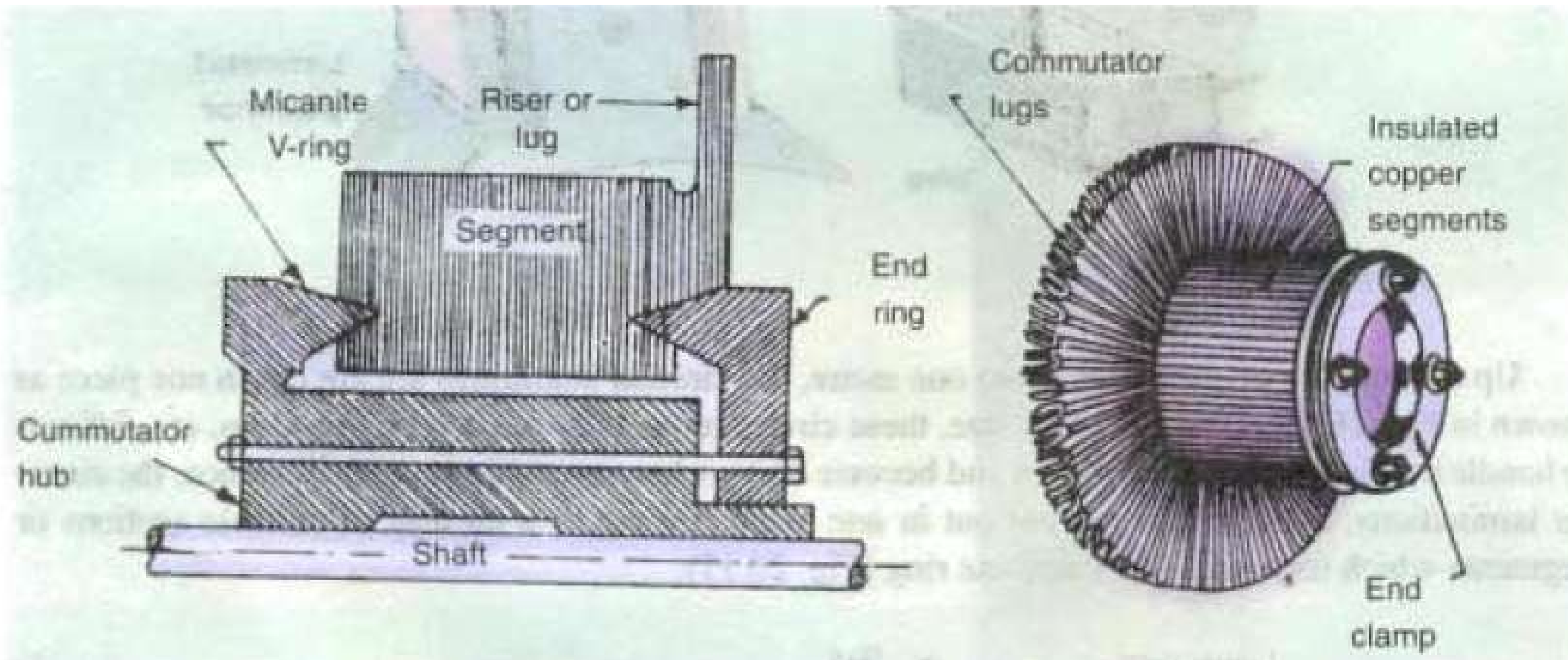
We have seen earlier that the basic nature of e.m.f. induced in the armature conductors is alternating. This needs rectification in case of d.c. generator, which is possible by a device called commutator.

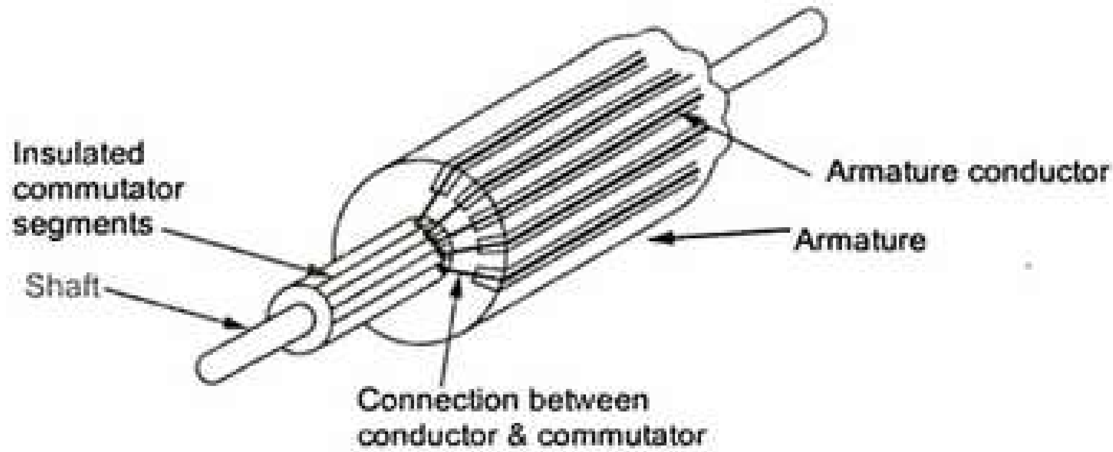
a) Functions :

1. To facilitate the collection of current from the armature conductors.
2. To convert internally developed alternating e.m.f. to unidirectional (d.c.) e.m.f.
3. To produce unidirectional torque in case of motors.

b) Choice of material : As it collects current from armature, it is also made up of copper segments.

It is cylindrical in shape and is made up of wedge shaped segments of hard drawn, high conductivity copper. These segments are insulated from each other by thin layer of mica. Each commutator segment is connected to the armature conductor by means of copper lug or strip. This connection is shown in the Fig.


Micanite
V-ring
Riser or
lug
Segment
End
ring
Cummutator
hub
Shaft
Commutator
lugs
Insulated
copper
segments
End
clamp



Commutator

Brushes and Brush Gear

Brushes are stationary and resting on the surface of the commutator.

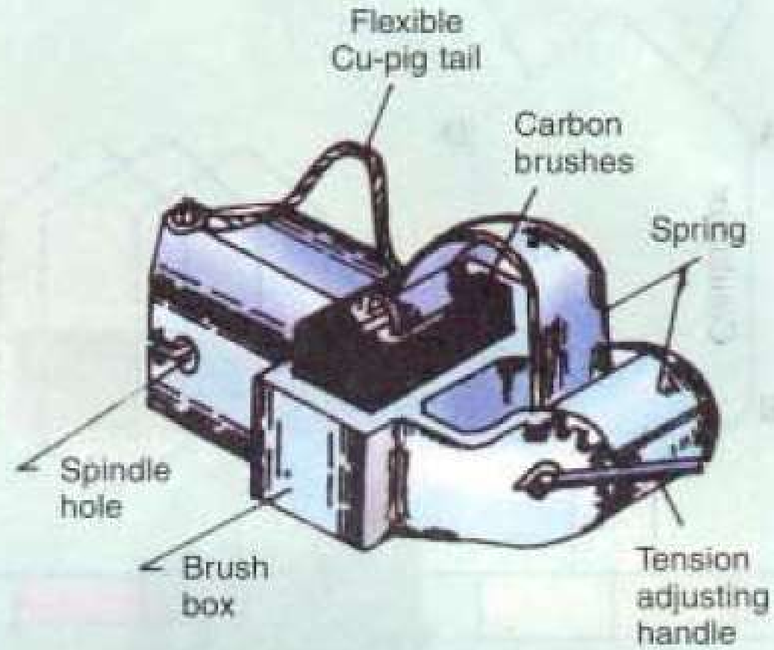
a) Function : To collect current from commutator and make it available to the stationary external circuit.

b) Choice of material : Brushes are normally made up of soft material like carbon.

Brushes are rectangular in shape. They are housed in brush holders, which are usually of box type. The brushes are made to press on the commutator surface by means of a spring, whose tension can be adjusted with the help of lever. A flexible copper conductor called **pig tail** is used to connect the brush to the external circuit. To avoid wear and tear of commutator, the brushes are made up of soft material like carbon.

Bearings

Ball-bearings are usually used as they are more reliable. For heavy duty machines, roller bearings are preferred.

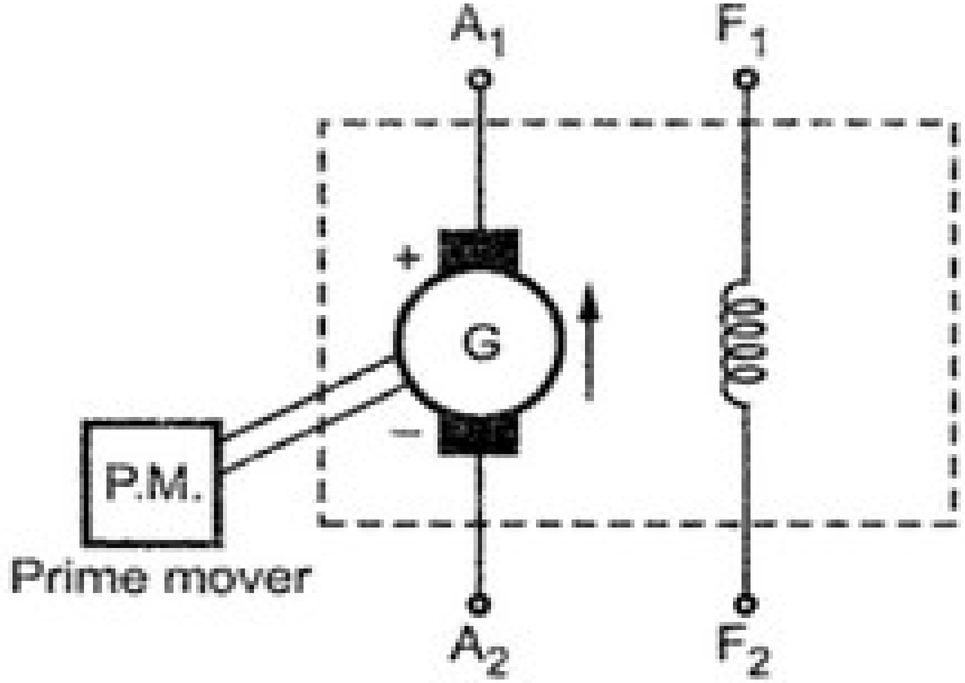

Flexible
Cu-pig tail
Carbon
brushes
Spring
Spindle
hole
Brush
box
Tension
adjusting
handle

Working principle

- A generator works on the principles of Faraday's law of electromagnetic induction

- Whenever a conductor is moved in the magnetic field , an emf is induced and the magnitude of the induced emf is directly proportional to the rate of change of flux linkage.

- This emf causes a current flow if the conductor circuit is closed .



Symbolic representation of d.c. generator

Methods of Excitation

The magnetic field required for the operation of a d.c. generator is produced by an electromagnet. This electromagnet carries a field winding which produces required magnetic flux when current is passed through it.

Key Point : *The field winding is also called* ***exciting winding*** *and current carried by the field winding is called an* ***exciting current.***

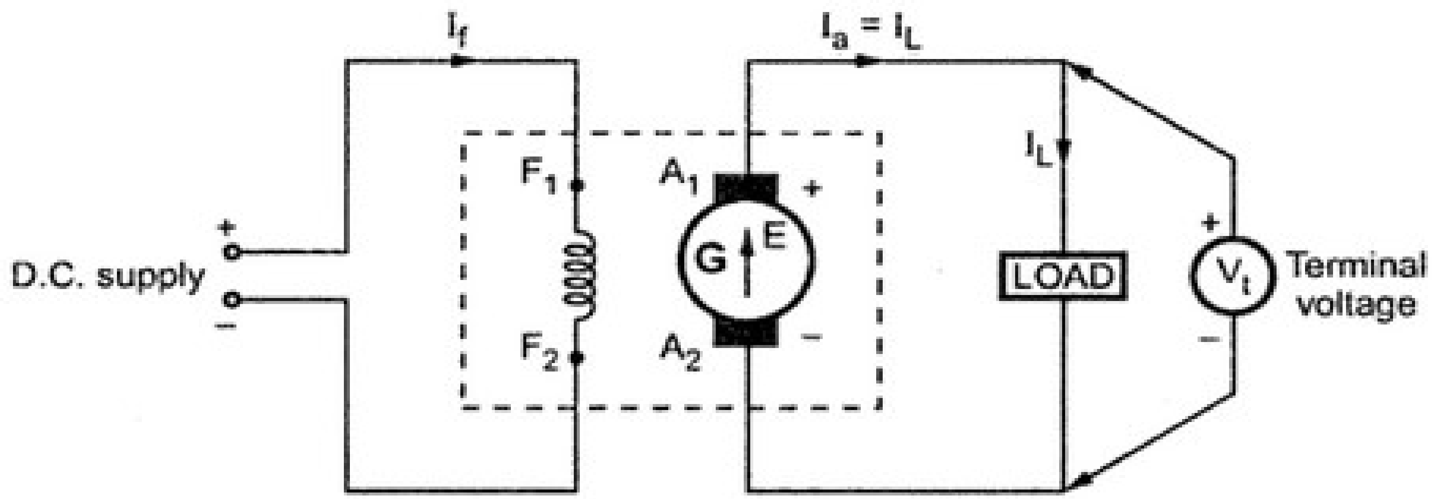
Thus supplying current to the field winding is called excitation and the way of supplying the exciting current is called **method of excitation.**

There are two methods of excitation used for d.c. generators,

1. Separate excitation 2. Self excitation.

Depending on the method of excitation used, the d.c. generators are classified as,

1. Separately excited generator 2. Self excited generator.



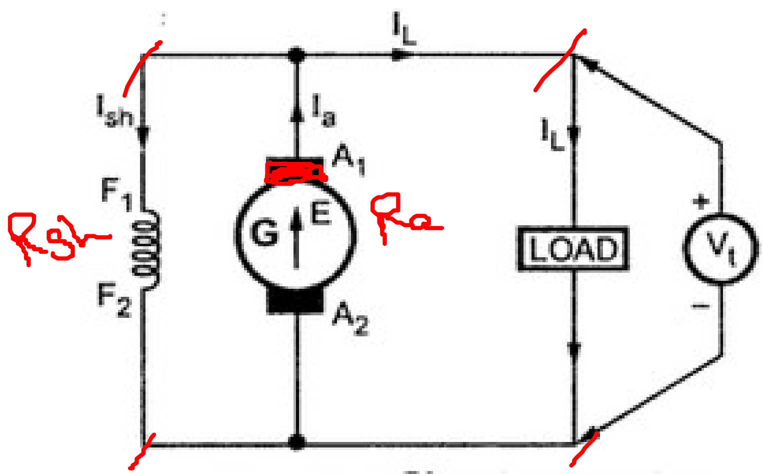
Separately excited generator

Based on how field winding is connected to the armature to derive its excitation, this type is further divided into following three types.

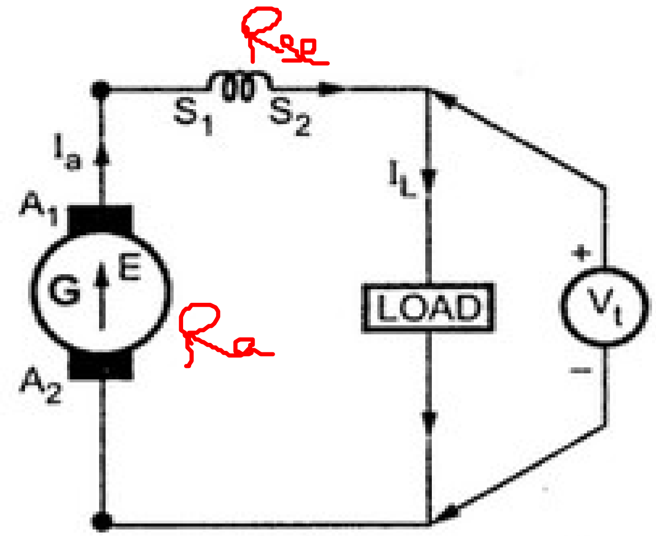
i) Shunt generator

ii) Series generator

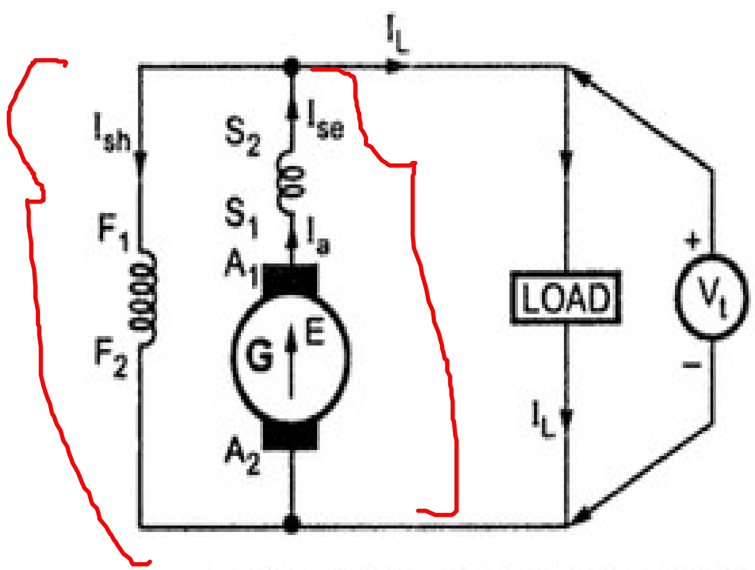
iii) Compound generator



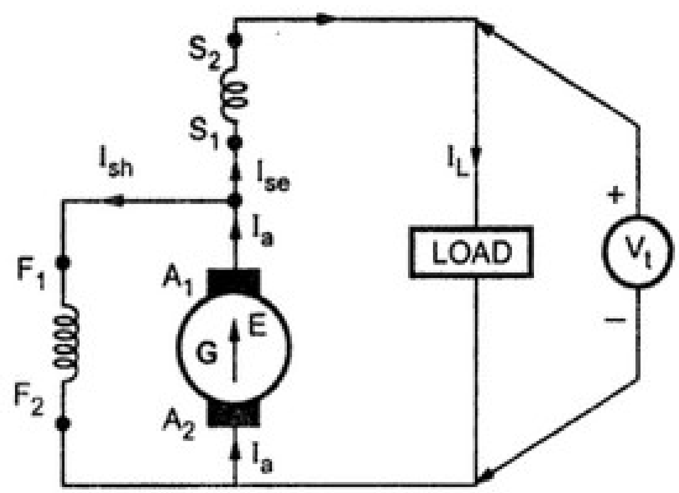
Shunt generator



Series generator



Long shunt compound generator



Short shunt compound generator

shunt gr $\quad I_a = I_{sh} + I$ $\quad I_L = \frac{P_L}{V_L} = \frac{V_L}{R_L}$

$E_g = V_L + I_a R_a + BCD$

$I_{sh} = \frac{V_L}{R_{sh}}$

BCD → Brush Contact drop

Series $\quad I_a = I_{se} = I_L = \frac{P_L}{V_L}$

$E_g = I_a R_a + V_L + I_{se} R_{se} + BCD$

$I_L = \frac{P_L}{V_L} = \frac{V_L}{R_L}$

Long shunt $\quad I_a = I_{se} = I_{sh} + I$

$E_g = V_L + I_a R_a + I_{se} R_{se} + BCD$

(or)

$V_L + I_{sh} R_{sh} + BCD$

Short shunt $\quad I_a = I_{sh} + I_{se}$

$I_{se} = I_L = \frac{P_L}{V_L} = \frac{V_L}{R_L}$

$E_g = V_L + I_a R_a + I_{se} R_{se} + BCD$

EMF equation:-

$\phi \rightarrow$ flux per pole in webers

Z = Total number of armature conductors

P = no of Poles; A = no of Parallel Paths

N = Speed of armature in RPM

$$e = \frac{d\phi}{dt}$$

1 Rev = $P\phi$

Flux Cut by one conductor per sec

$$= P\phi \times \frac{\text{no of Rev of ar}}{\text{Sec}}$$

$$\frac{d\phi}{dt} = P\phi \times \frac{N}{60}$$

Average emf induced in one conductor $= \frac{\phi P N}{60}$

No of arm conductor / Parallel path $= \frac{Z}{A}$

Total Emf generated across the terminals

$$\boxed{E = \frac{\phi P N}{60} \times \frac{Z}{A}}$$ Volts

Emf $\propto \phi$ → Direction of mag. field

$\propto N$ → " of Rotation

Emf

Gr → E_g

motor → Back emf → E_b

Lap wdg → $A = P$ → $E_g = \frac{\phi Z N}{60}$ volts

Wave wdg → $A = 2$ → $E_g = \frac{\phi P Z N}{120}$ volts

i) A 4 Pole wave wound DC generator has 50 slots and 24 Conductors/slot. The flux per pole is 10 mWb. Determine the induced emf in the armature if it is rotating at a speed of 600 rpm.

$P = 4$; no of slots $= 50$, conductors/slot $= 24$.

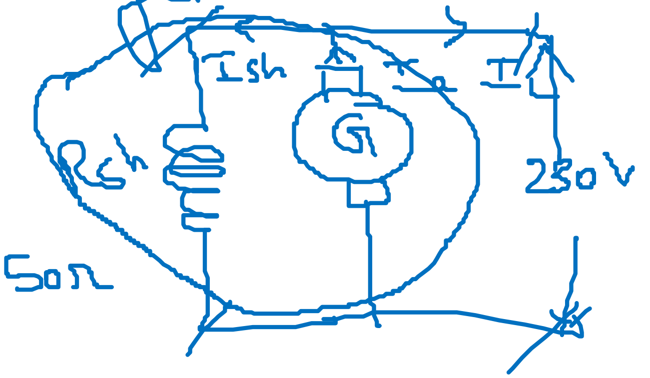
Total conductors $= 24 \times 50$; $N = 600$ rpm ; $\phi = 10$ mWb $\times 10^{-3}$

$A = 2$

$$E_g = \frac{\phi Z P N}{60 \times A} = \frac{10 \times 10^{-3} \times 24 \times 50 \times 4 \times 600}{60 \times 2}$$

$= 240$ volt.

2) A Shunt generator rated, delivers 450A at 230V & the resistance of shunt field and armature are 50Ω and 0.03Ω Find the generated EMF



$$E_g = V_L + I_a R_a + \cancel{B_{CD}}$$

$$I_a = I_{sh} + I_L$$

$$\begin{cases} R_{sh} = 50\Omega \\ R_a = 0.03\Omega \end{cases}$$

$$I_{sh} = \frac{V_L}{R_{sh}} = \frac{230}{50}$$

$$I_a = \frac{230}{50} + 450$$

$$= 454.6A$$

$$I_L = 450A$$

$$E_g = 230 + (454.6 \times 0.03) = 243.6V$$

Applications of Various Types of Generators

Separately Excited Generators :

As a separate supply is required to excite field, the use is restricted to some special applications like electro-plating, electro-refining of materials etc.

Shunt Generators :

Commonly used in battery charging and ordinary lighting purposes.

Series Generators :

Commonly used as boosters on d.c. feeders, as a constant current generators for welding generator and arc lamps.

Cumulatively Compound Generators :

These are used for domestic lighting purposes and to transmit energy over long distance.

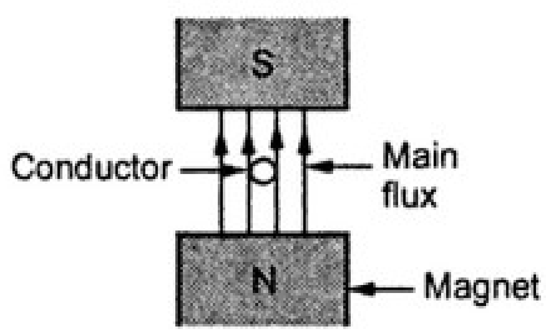
Differential Compound Generators :

The use of this type of generators is very rare and it is used for special application like electric arc welding.

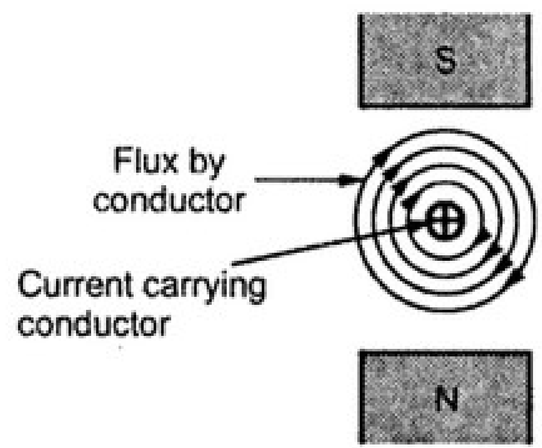
Principle of Operation of a D.C. Motor

The principle of operation of a d.c. motor can be stated in a single statement as 'when a current carrying conductor is placed in a magnetic field; it experiences a mechanical force'. In a practical d.c. motor, field winding produces a required magnetic field while armature conductors play a role of a current carrying conductors and hence armature conductors experience a force. As conductors are placed in the slots which are on the periphery, the individual force experienced by the conductors acts as a twisting or turning force on the armature which is called a **torque**. The torque is the product of force and the radius at which this force acts. So overall armature experiences a torque and starts rotating. Let us study this motoring action in detail.

Consider a single conductor placed in a magnetic field as shown in the Fig. (a). The magnetic field is produced by a permanent magnet but in a practical d.c. motor it is produced by the field winding when it carries a current.



(a) Conductor in a magnetic field

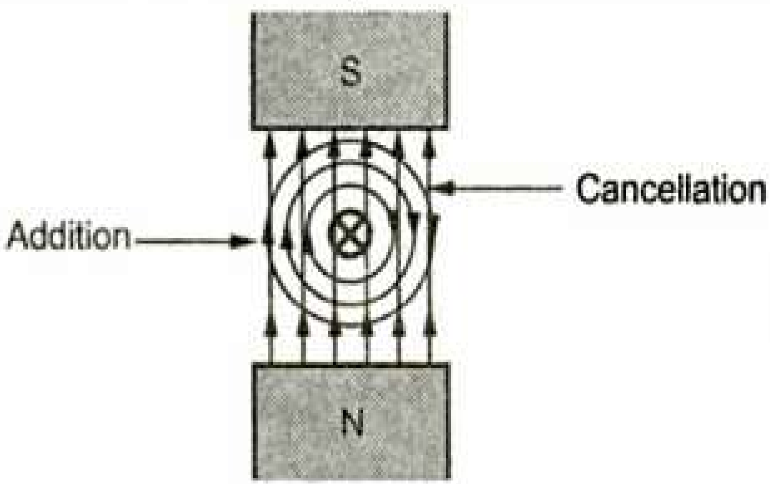


(b) Flux produced by current carrying conductor

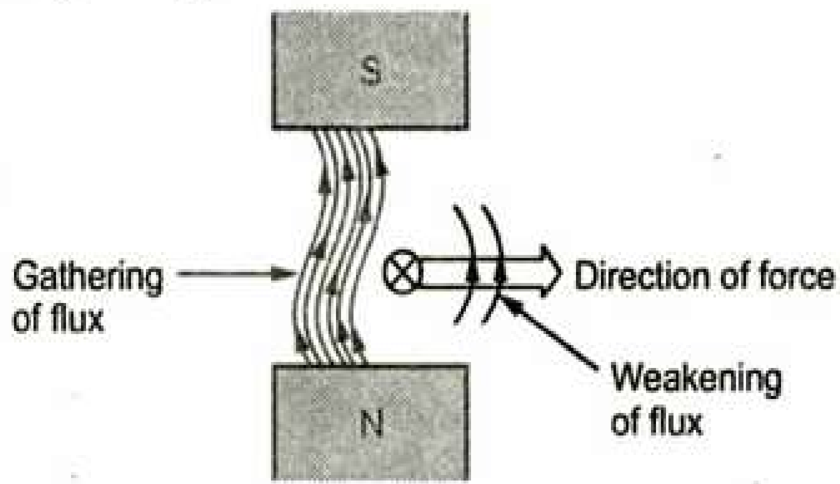
Now there are two fluxes present,

1. The flux produced by the permanent magnet called main flux.
2. The flux produced by the current carrying conductor.

These are shown in the Fig. (a). From this, it is clear that on one side of the conductor, both the fluxes are in tne same direction. In this case, on the left of the conductor there is gathering of the flux lines as two fluxes help each other. As against this, on the right of the conductor, the two fluxes are in opposite direction and hence try to cancel each other. Due to this, the density of the flux lines in this area gets weakened. So on the left, there exists high flux density area while on the right of the conductor there exists low flux density area as shown in the Fig. (b).

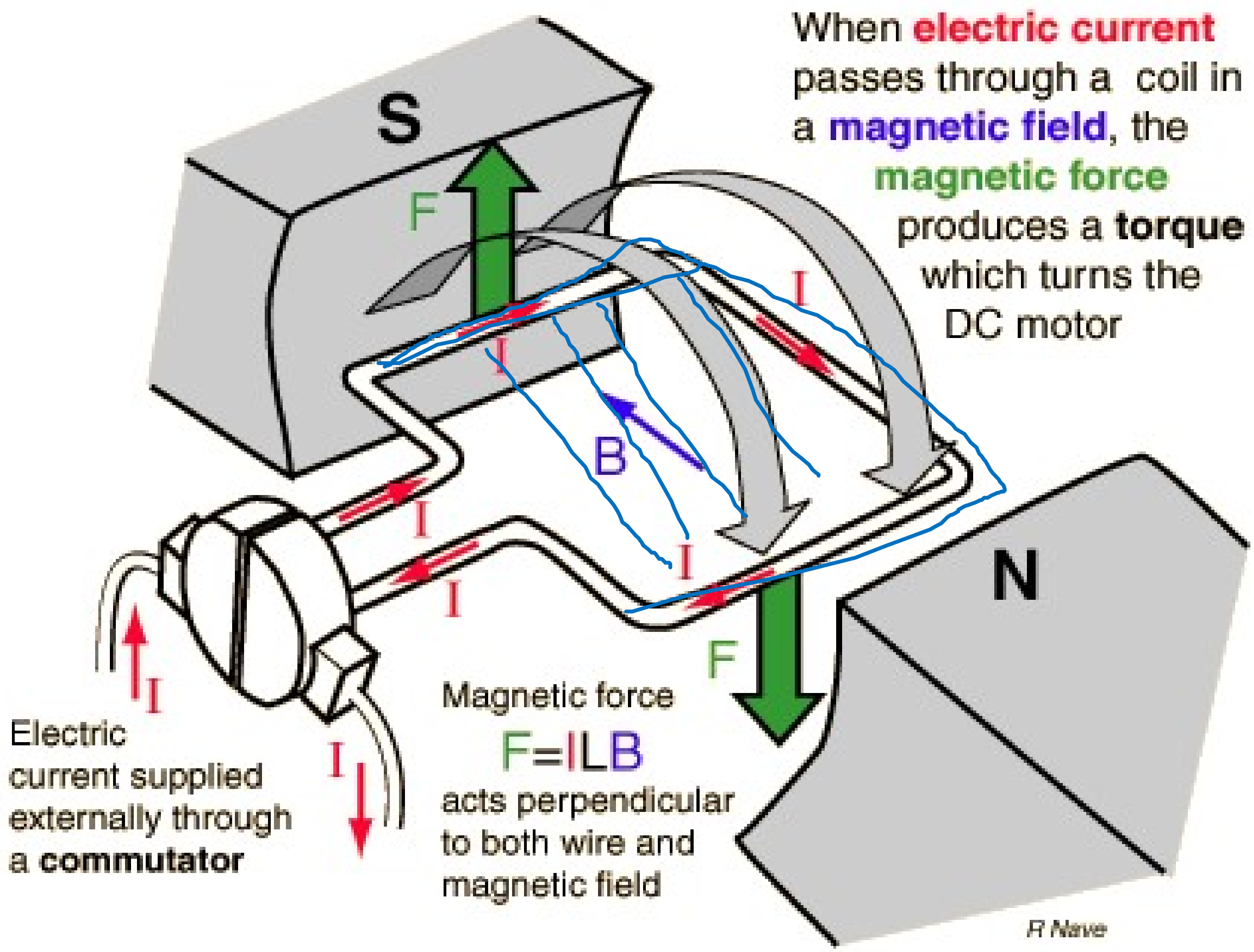


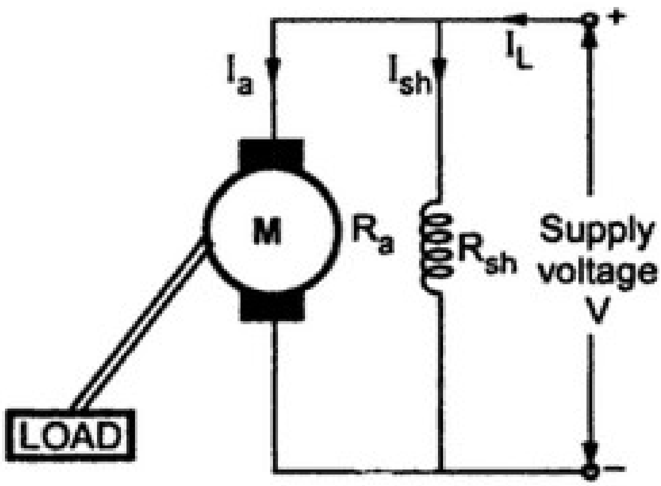
(a) Interaction of two fluxes



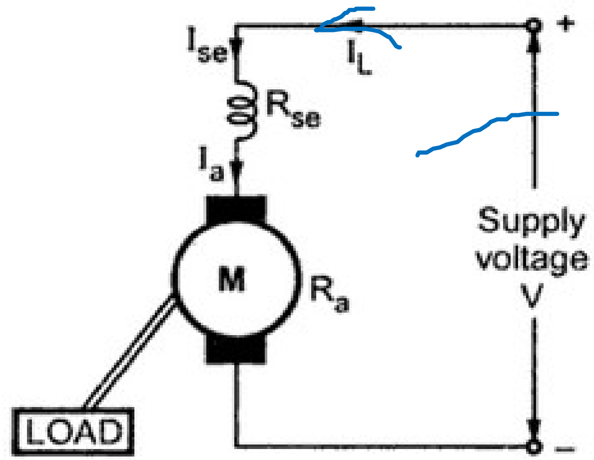
(b) Force experienced by the conductor

Working principle of DC motor

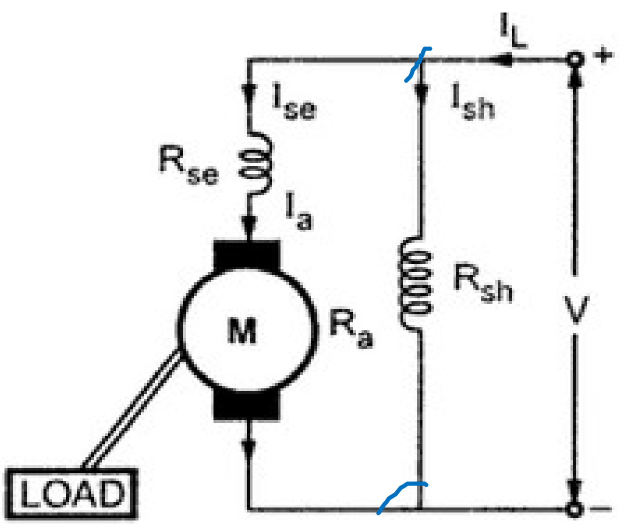




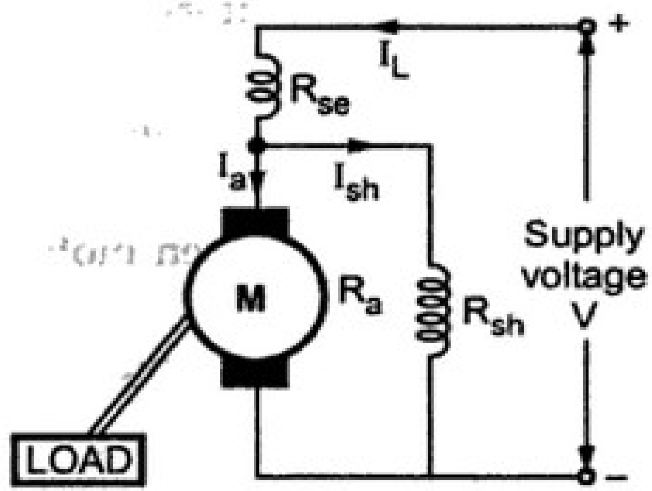
D.C. shunt motor



D.C. Series motor



Long shunt compound motor



Short shunt compound motor

Comparison between Shunt and Series Field Winding

Sr. No.	Shunt field winding	Series field winding
1.	The resistance is high.	Resistance is low.
2.	The cross-sectional area is small thus wire is thin.	The cross-sectional area is more thus wire is thick.
3.	The length is more thus has large number of turns.	The length is small thus has less number of turns.
4.	The current rating is low.	The current rating is high.
5.	Always connected in parallel with the armature.	Always connected in series with the armature.

Type of motor	Characteristics	Applications
Shunt	Speed is fairly constant and medium starting torque.	1) Blowers and fans 2) Centrifugal and reciprocating pumps 3) Lathe machines 4) Machine tools 5) Milling machines 6) Drilling machines
Series	High starting torque. No load condition is dangerous. Variable speed.	1) Cranes 2) Hoists, Elevators 3) Trolleys 4) Conveyors 5) Electric locomotives
Cumulative compound	High starting torque. No load condition is allowed.	1) Rolling mills 2) Punches 3) Shears 4) Heavy planers 5) Elevators
Differential compound	Speed increases as load increases.	Not suitable for any practical application.

EMF equation

Let,

- Ø= flux per pole in weber
- Z = Total number of conductor
- P = Number of poles
- A = Number of parallel paths
- N =armature speed in rpm
- Eg = emf generated in any on of the parallel path

EMF equation

Flux cut by 1 conductor
in 1 revolution $= P * \phi$

Flux cut by 1 conductor in
60 sec $= P \phi N / 60$

Avg emf generated in 1
conductor $= P\phi N/60$

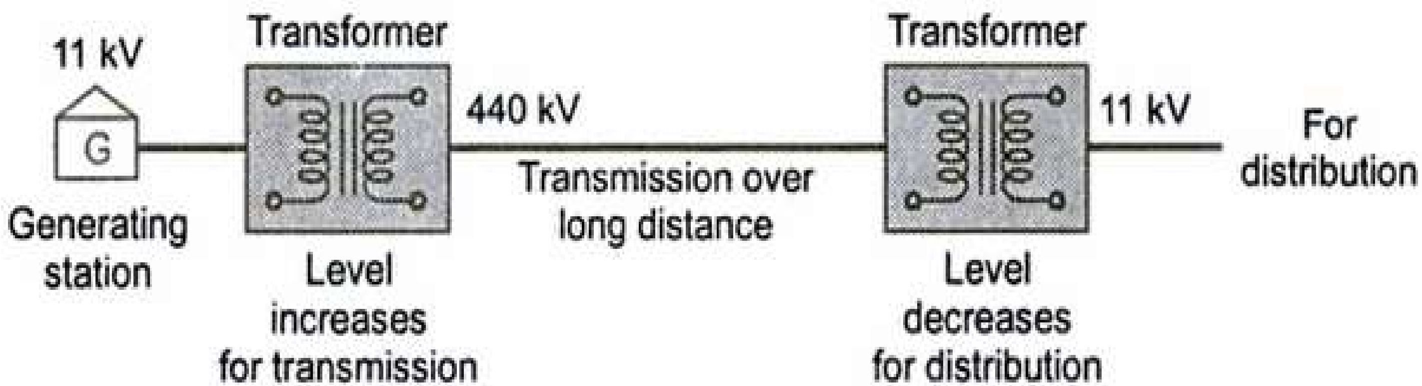
Number of conductors in
each parallel path $= Z / A$

$E_g = P\phi NZ/60A$

Transformers

The transformer is a static piece of apparatus by means of which an electrical power is transformed from one alternating current circuit to another with the desired change in voltage and current, without any change in the frequency.

The use of transformers in transmission system is shown in the Fig.




Principle of Working

The principle of **mutual induction** states that when two coils are inductively coupled and if current in one coil is changed uniformly then an e.m.f. gets induced in the other coil. This e.m.f. can drive a current, when a closed path is provided to it. The transformer works on the same principle. In its elementary form, it consists of two inductive coils which are electrically separated but linked through a common magnetic circuit. The two coils have high mutual inductance.

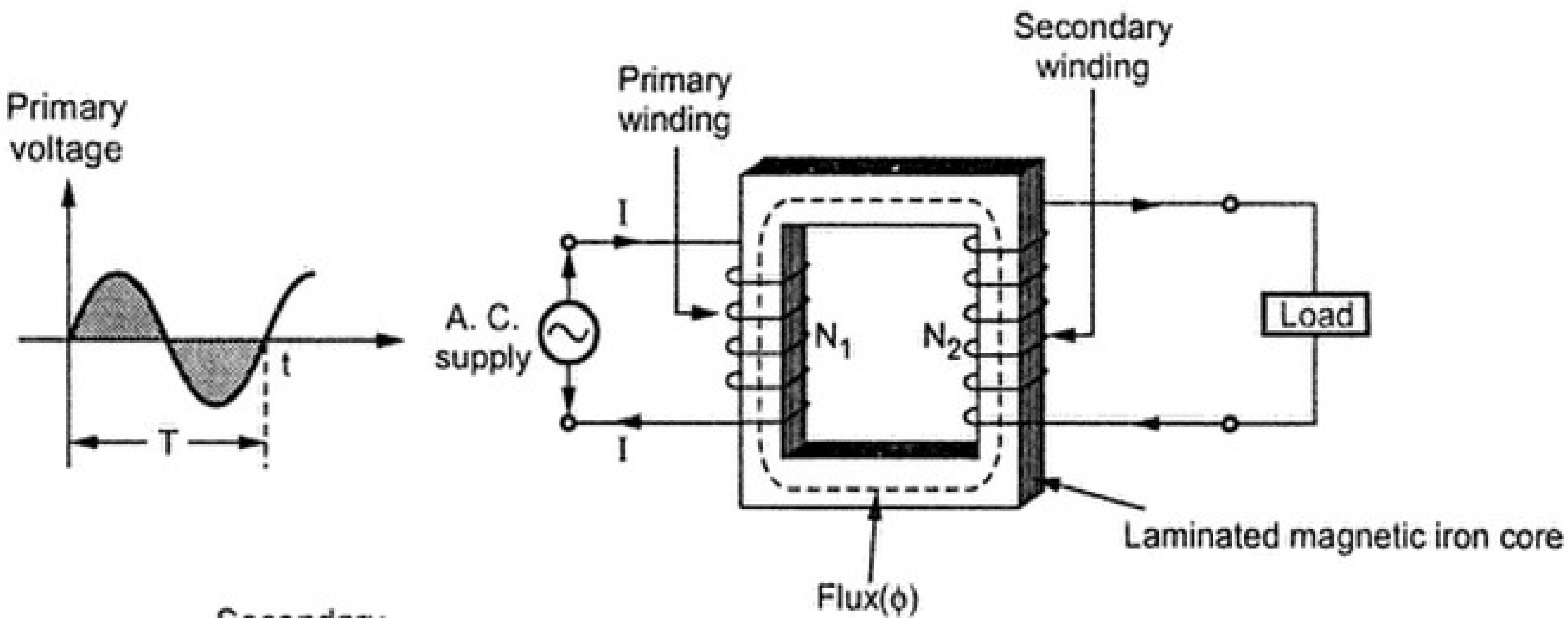
One of the two coils is connected to a source of alternating voltage. This coil in which electrical energy is fed with the help of source is called **primary winding (P)**. The other winding is connected to load. The electrical energy transformed to this winding is drawn out to the load.

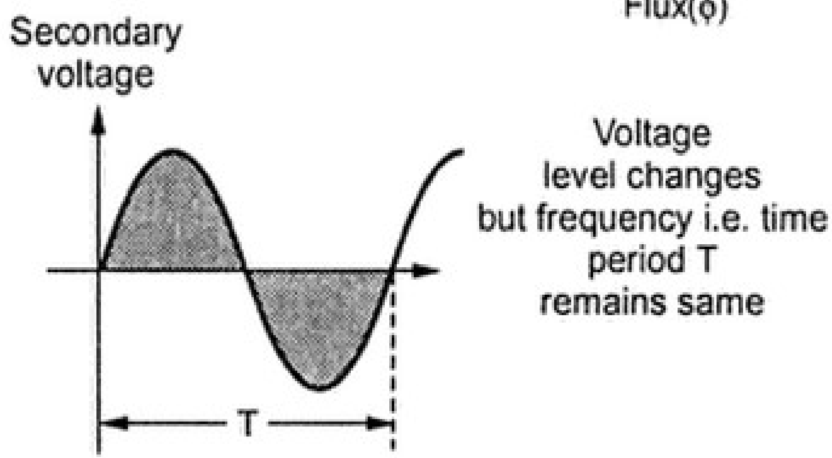
What is a Transformer?

- A static device which can transfer electrical energy from one circuit to another circuit without change of frequency.

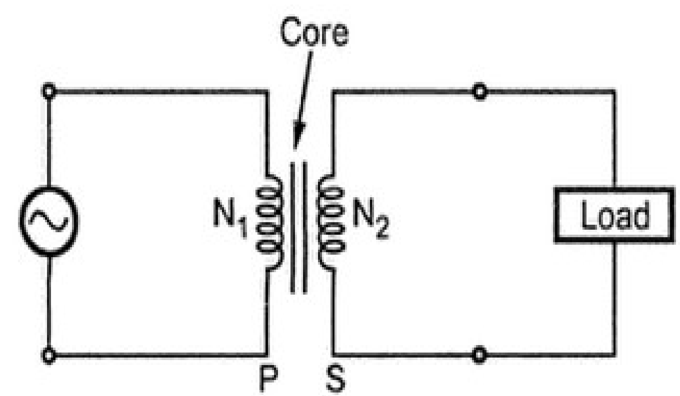
- Can increase or decrease the voltage but with a corresponding decrease or increase in current.

- Works on the principle of **Mutual Induction**.





Basic transformer



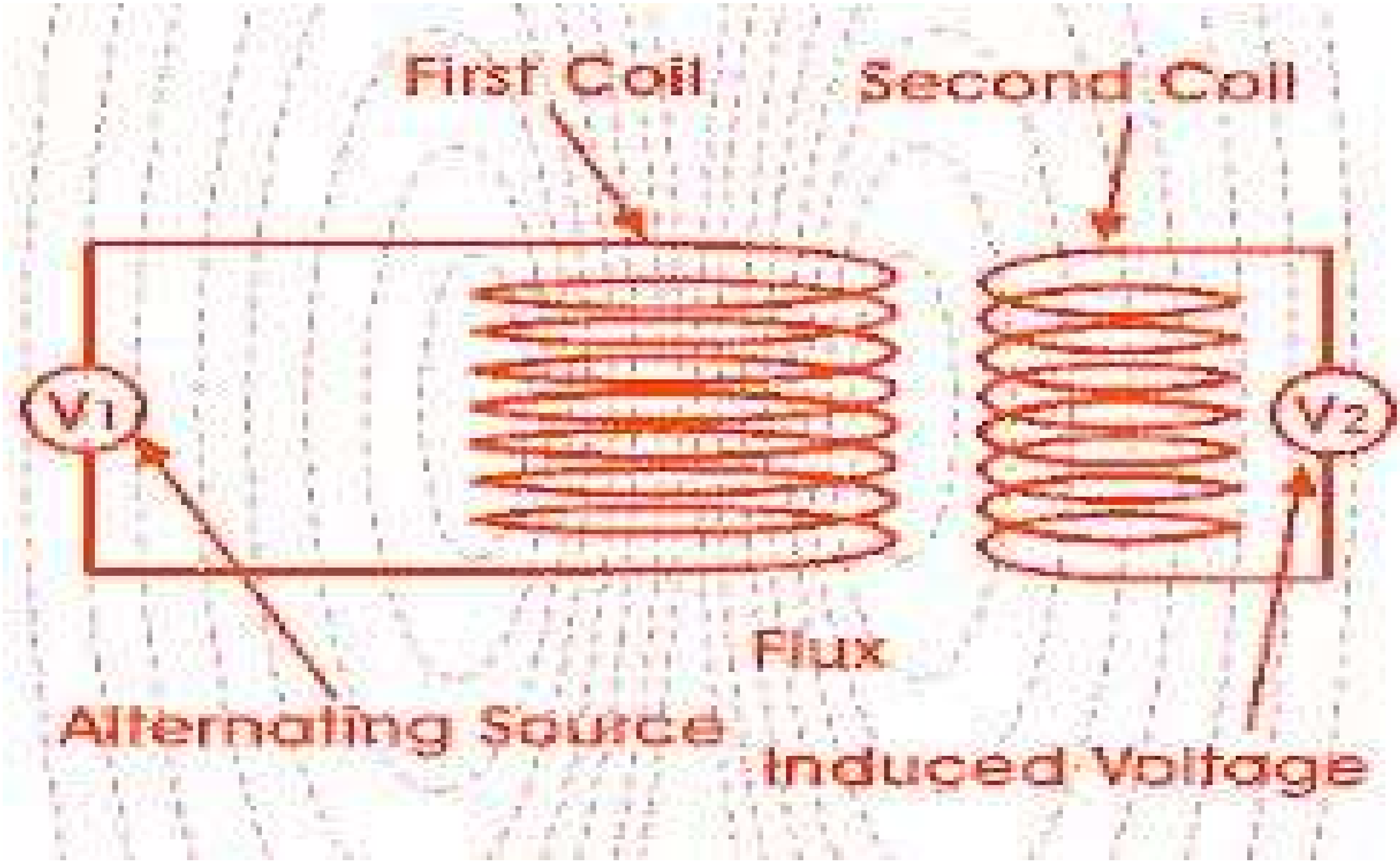
Symbolic representation

What is Mutual Induction?

- Phenomenon in which a change of current in one coil causes an induced emf in another coil placed near to the first coil.

- The coil in which current is changed is called **primary coil** and the coil in which emf is induced is called **secondary coil**.

Mutual Induction (cont.)



Mutual Induction (cont.)

- Consider two coils placed near each other .
- When current is passed through the primary coil, magnetic flux is produced. This magnetic flux is also linked with the secondary coil.
- If the current is changed by varying the resistance in the primary circuit, the magnetic flux also change. As this changing flux is linked with the secondary coil, it induces an emf in it.
- This phenomenon of inducing emf in a coil by changing current in another coil is known **Mutual Induction**.

Working Principle of a Transformer

- When an alternating voltage V_1 is applied to the primary winding, an alternating current I_1 flows in it producing an alternating flux in the core.

- By Faraday's law, an emf e_1 is induced in the primary winding.

$$\mathbf{e_1 = -N_1 (d\Phi/dt)}$$

where N_1 is the number of turns in the primary winding.

- The induced emf in the primary winding is nearly equal and opposite to the applied voltage V_1.

Working Principle of a Transformer (cont.)

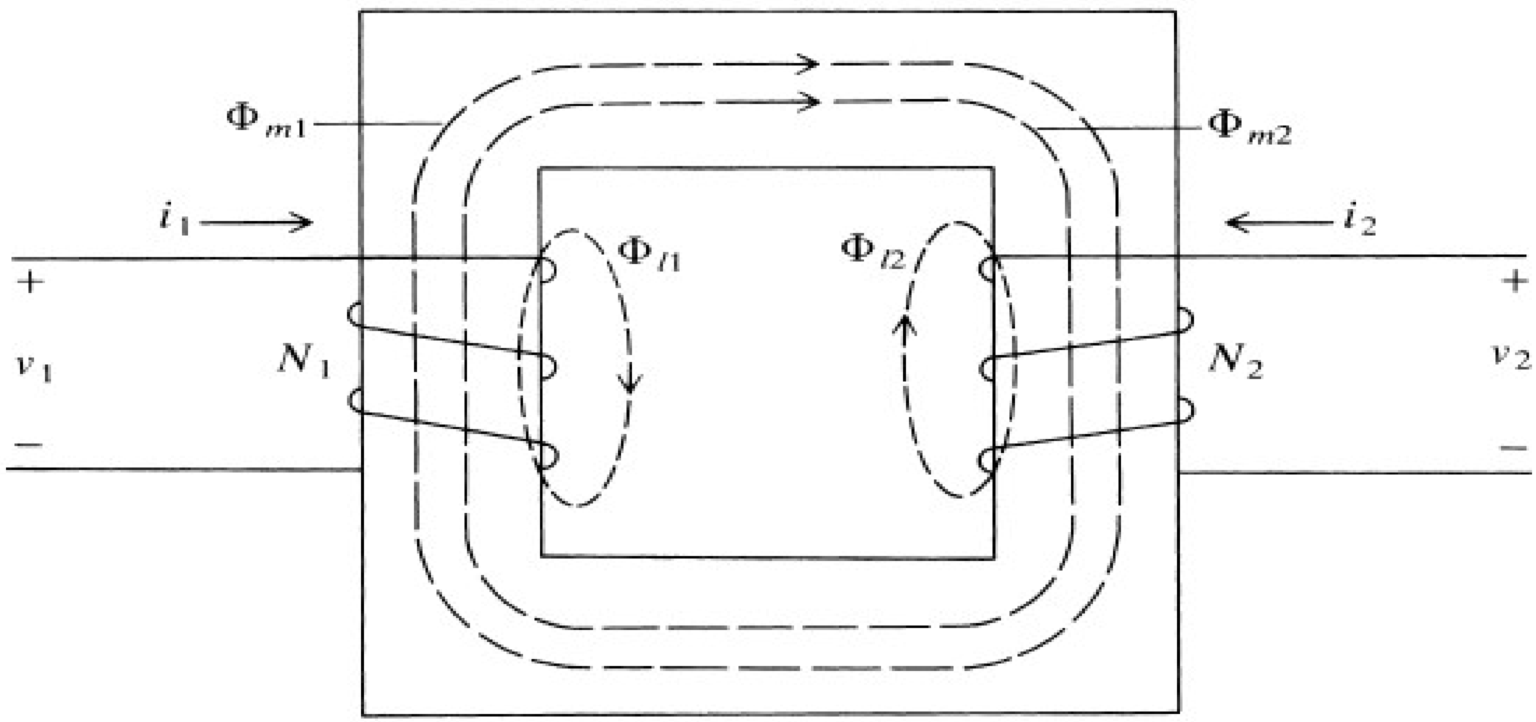
- Assuming leakage flux to be negligible, almost the whole flux produced in primary winding links with the secondary winding.

$$\mathbf{e_2 = -N_2\ (d\Phi/dt)}$$

where N_2 is the number of turns in the secondary winding.

- If the secondary circuit is closed through the load, a current I_2 flows in the secondary winding.
- Thus energy is transferred from the primary winding to the secondary winding.

Working Principle of a Transformer (cont.)



Construction of a Transformer

- A transformer mainly consists of two coils or windings placed on a common core.

- **Core** -- Soft iron or steel
  --Made of laminations to provide a continuous magnetic path

- Windings – **Primary and Secondary**

  Primary winding – Electrical energy is fed
  Secondary winding – Connected to Load
  Insulated copper conductors in the form of round wire or strip.
  Placed around the limbs of the core.

Can D.C. Supply be used for Transformers ?

The d.c. supply can not be used for the transformers.

The transformer works on the principle of mutual induction, for which current in one coil must change uniformly. If d.c. supply is given, the current will not change due to constant supply and transformer will not work.

Practically winding resistance is very small. For d.c., the inductive reactance X_L is zero as d.c. has no frequency. So total impedance of winding is very low for d.c. Thus winding will draw very high current if d.c. supply is given to it. This may cause the burning of windings due to extra heat generated and may cause permanent damage to the transformer.

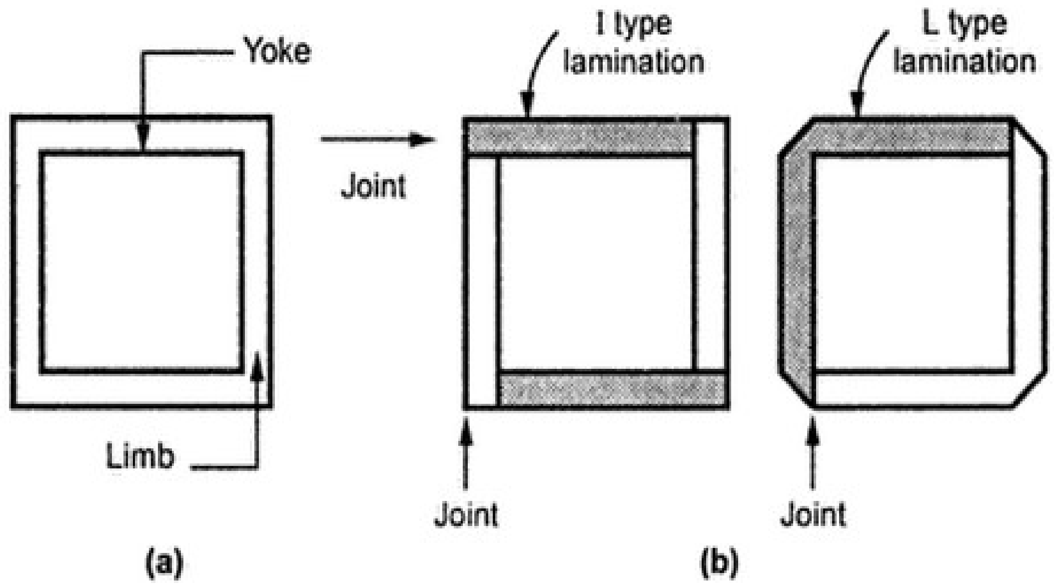
There can be saturation of the core due to which transformer draws very large current from the supply when connected to d.c.

Thus d.c. supply should not be connected to the transformers.

Construction

There are two basic parts of a transformer i) Magnetic Core ii) Winding or Coils.

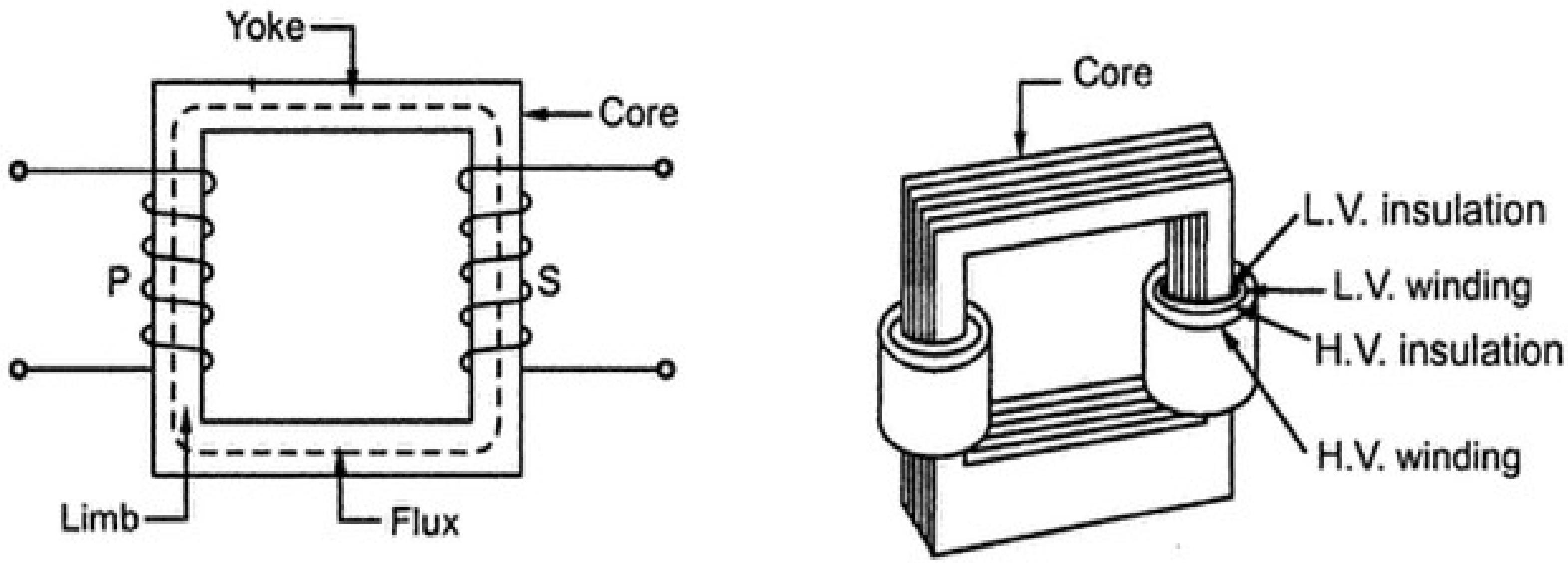
The core of the transformer is either square or rectangular in size. It is further divided into two parts. The vertical portion on which coils are wound is called **limb** while the top and bottom horizontal portion is called **yoke** of the core. These parts are shown in the Fig. (a).



Construction of Single Phase Transformers

The various constructions used for the single phase transformers are,

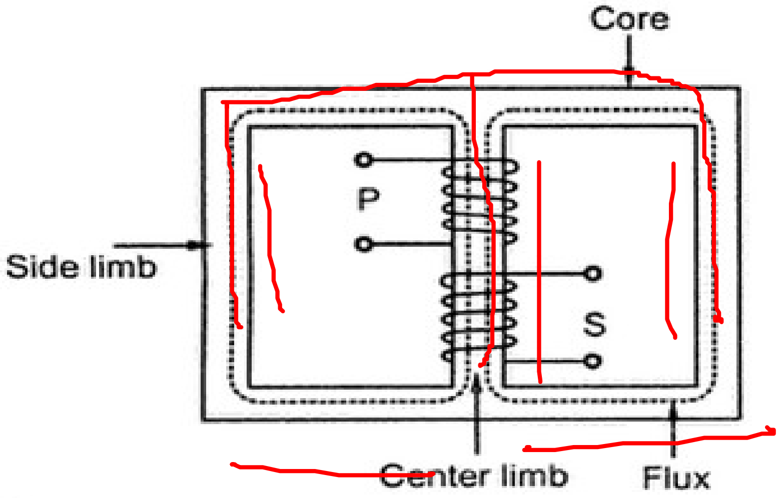
1. Core type   2. Shell type



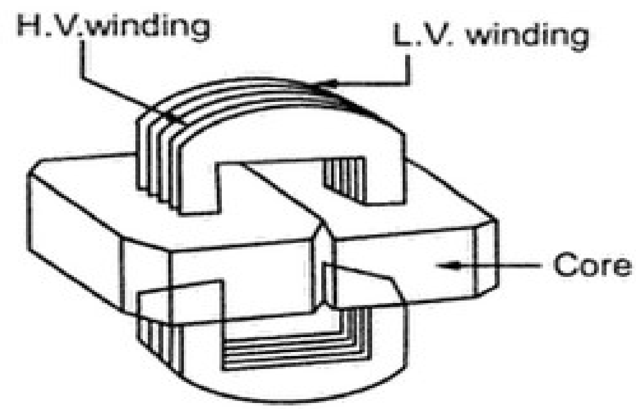
(a) Representation

(b) Construction

Core type transformer



(a) Representation



(b) Construction

Shell type transformer

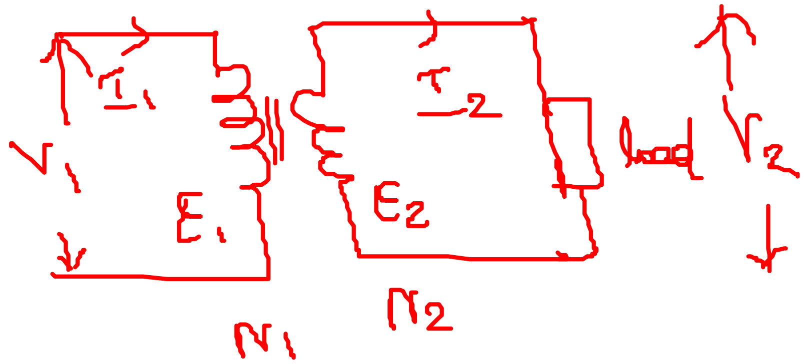
Sr. No.	Core Type	Shell Type
1.	The winding encircles the core.	The core encircles most part of the windings.
2.	The cylindrical type of coils are used.	Generally, multilayer disc type or sandwich coils are used.
3.	As windings are distributed, the natural cooling is more effective.	As windings are surrounded by the core, the natural cooling does not exist.
4.	The coils can be easily removed from maintenance point of view.	For removing any winding for the maintenance, large number of laminations are required to be removed. This is difficult.
5.	The construction is preferred for low voltage transformers.	The construction is used for very high voltage transformers.
6.	It has a single magnetic circuit.	It has a double magnetic circuit.
7.	In a single phase type, the core has two limbs.	In a single phase type, the core has three limbs.

EmF eqn :-

$\phi_m \to wb$

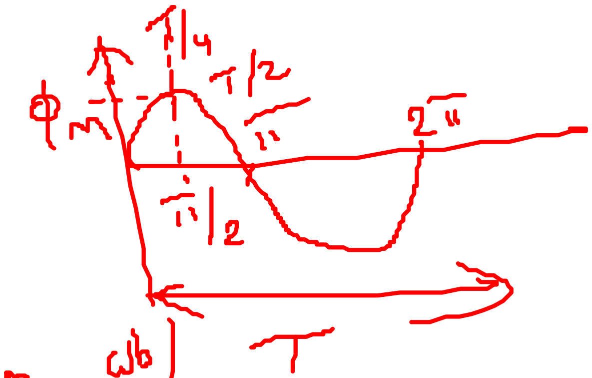
$B_m \to wb/m^2$

$A \to m^2$, $f = Hz$, $T = \frac{1}{f}$



Average rate of change of flux

$$= \frac{\phi_m}{1/4f} = 4f\phi_m \ wb/sec$$



Average value of EmF induced in 1 turn $= 4f\phi_m$ Volts

Form factor (Kf) $= \frac{\text{Rms}}{\text{Average}} = 1.11$

$e \propto \frac{d\phi}{dt}$

N

Rms value of EmF induced in 1 turn

$= 1.11 \times 4f\phi_m$

$= 4.44 f\phi_m$ volts

RmS value of EMF induced in Entire primary winding $\Big\}$ $E_1 = 4.44 f \phi_m N_1$ Volts

″ Secondary $\Big\}$ $E_2 = 4.44 f \phi_m N_2$ volts

$\downarrow$

$4.44 f B_m A N_2$

$$B_m = \frac{\phi_m}{A}$$

Transformer Ratio (K)

For ideal Tr $(N_1 = N_2)$

$V_1 = E_1$; $V_2 = E_2$

$V_1 I_1 = V_2 I_2$

$$\boxed{K = \frac{N_2}{N_1}}$$

$$\boxed{\frac{E_2}{E_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1}} \leftarrow \frac{V_2}{V_1} = \frac{I_1}{I_2}$$

instrumental Transformer (IT)

$\downarrow$ CT

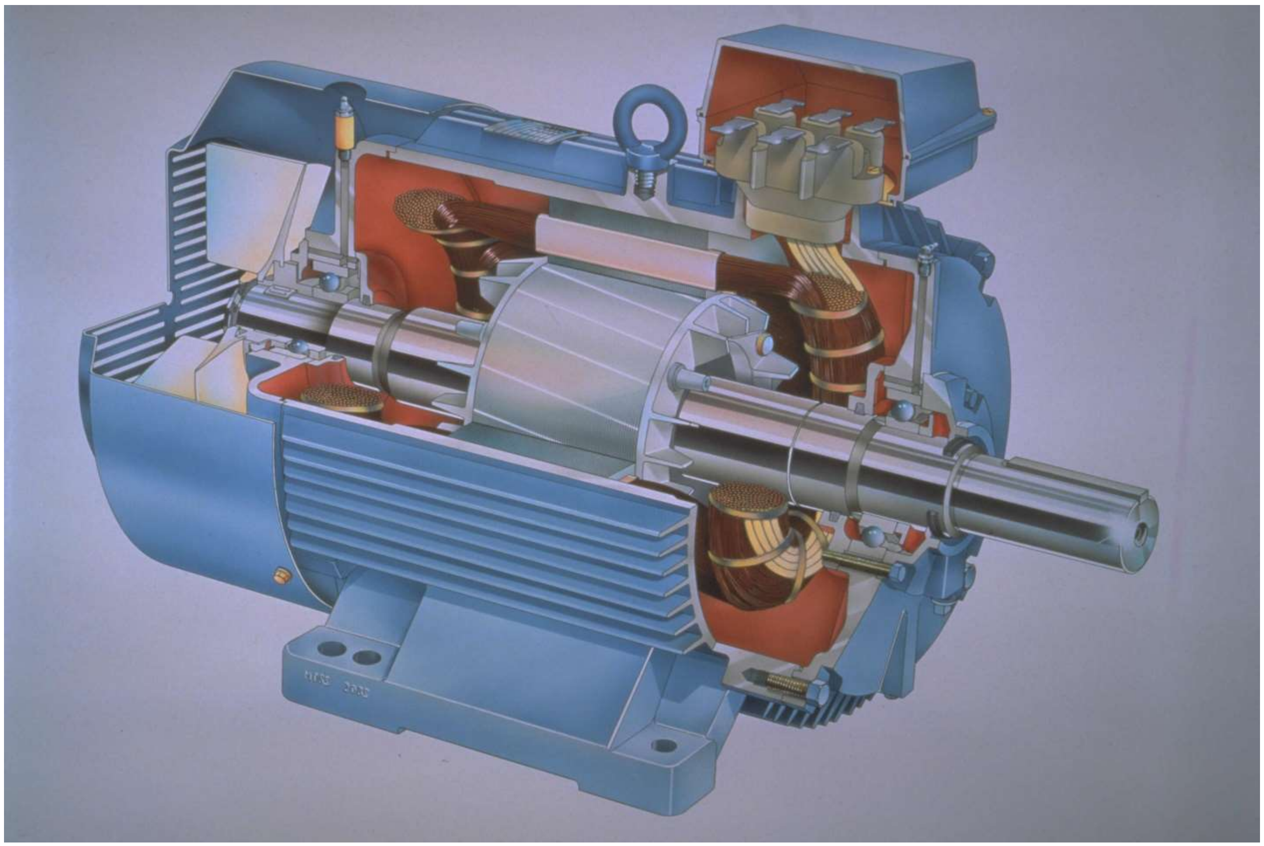
PT

Applications

- Major application is to increase voltage before transmitting electrical energy over long distances through wires and to reduce voltage at places where it is to be used.

- Used in electronic circuits to step down the supply voltage to a level suitable for low voltage circuits they contain.

Induction Motors



Introduction

- Three-phase induction motors are the most common and frequently encountered machines in industry
  - simple design, rugged, low-price, easy maintenance
  - wide range of power ratings: fractional horsepower to 10 MW
  - run essentially as constant speed from no-load to full load
  - Its speed depends on the frequency of the power source
    - not easy to have variable speed control
    - requires a variable-frequency power-electronic drive for optimal speed control

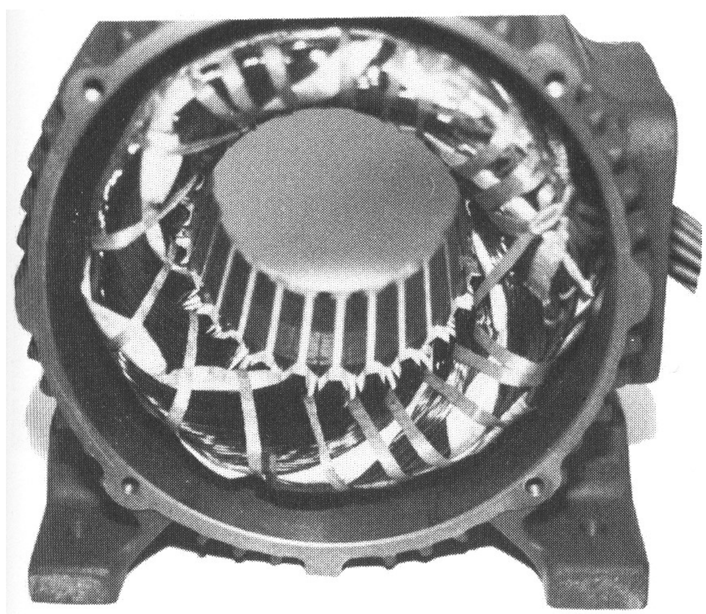
For lightning and general purposes in homes, offices, shops, small factories single phase system is widely used as compared to three phase system as the single phase system is more economical and the power requirement in most of the houses, shops, offices are small, which can be easily met by single phase system.

The single phase motors are simple in construction, cheap in cost, reliable and easy to repair and maintain.

Due to all these advantages the single phase motor finds its application in vacuum cleaner, fans, washing machine, centrifugal pump, blowers, washing machine, small toys etc.

Construction

- An induction motor has two main parts
  - a stationary stator
    - consisting of a steel frame that supports a hollow, cylindrical core
    - core, constructed from stacked laminations (why?), having a number of evenly spaced slots, providing the space for the stator winding



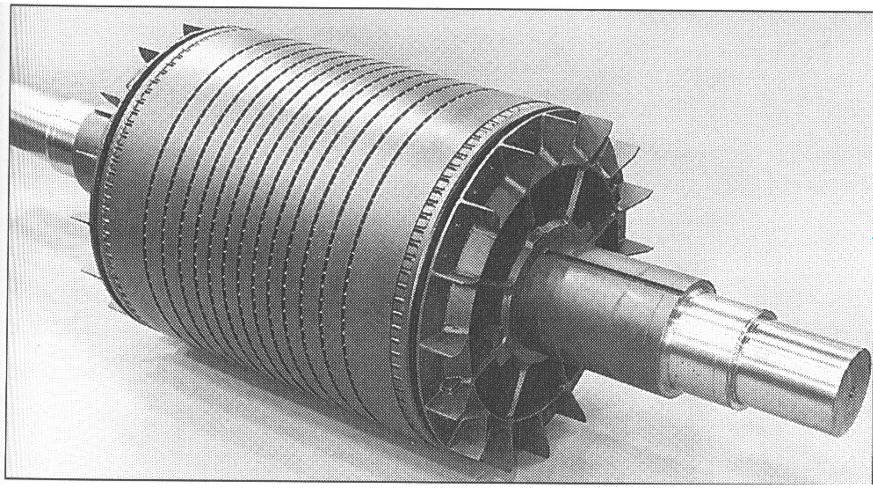
Stator of IM

Construction

- a revolving rotor
  - composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding
  - one of two types of rotor windings
  - conventional 3-phase windings made of insulated wire (wound-rotor) » similar to the winding on the stator
  - aluminum bus bars shorted together at the ends by two aluminum rings, forming a squirrel-cage shaped circuit (squirrel-cage)

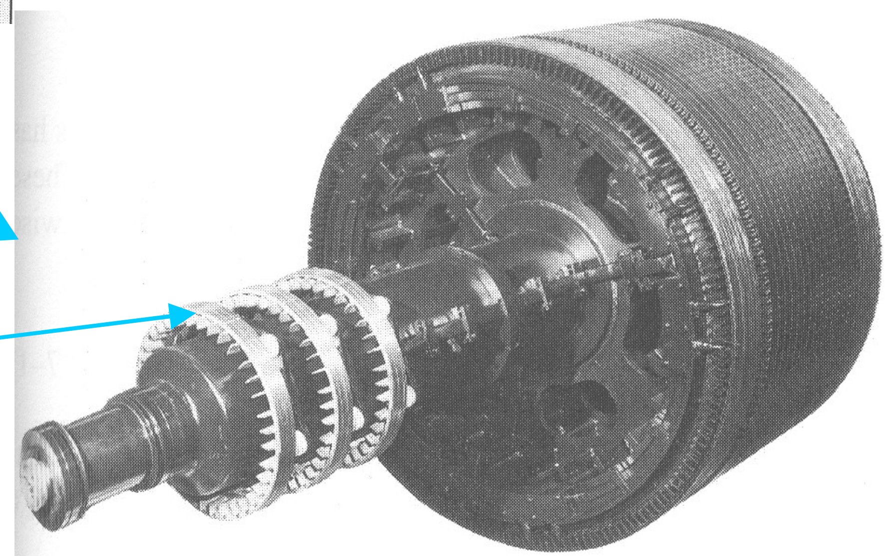
- Two basic design types depending on the rotor design
  - squirrel-cage: conducting bars laid into slots and shorted at both ends by shorting rings.
  - wound-rotor: complete set of three-phase windings exactly as the stator. Usually Y-connected, the ends of the three rotor wires are connected to 3 slip rings on the rotor shaft. In this way, the rotor circuit is accessible.

Construction



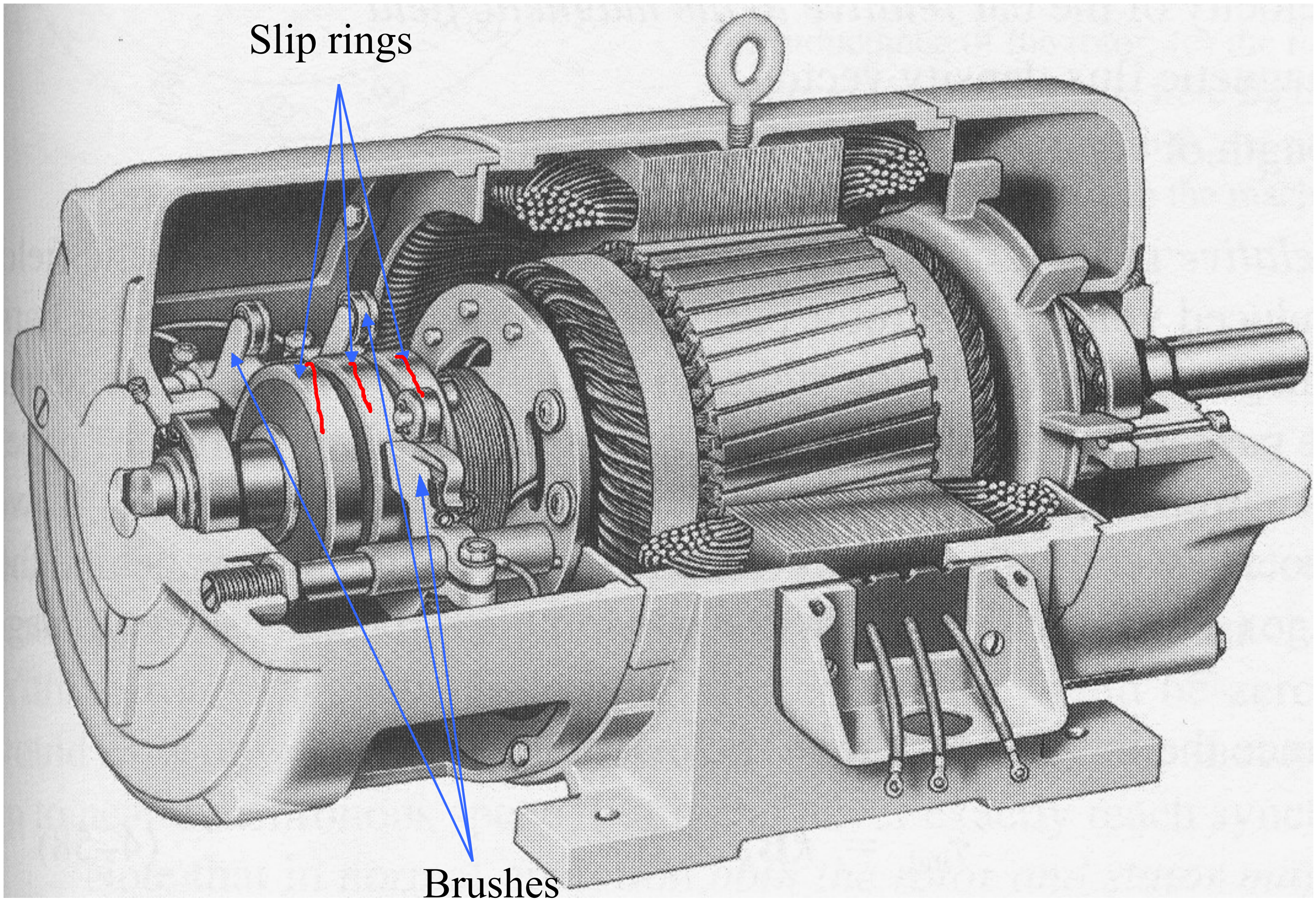
Squirrel cage rotor

Wound rotor



Notice the slip rings

Construction

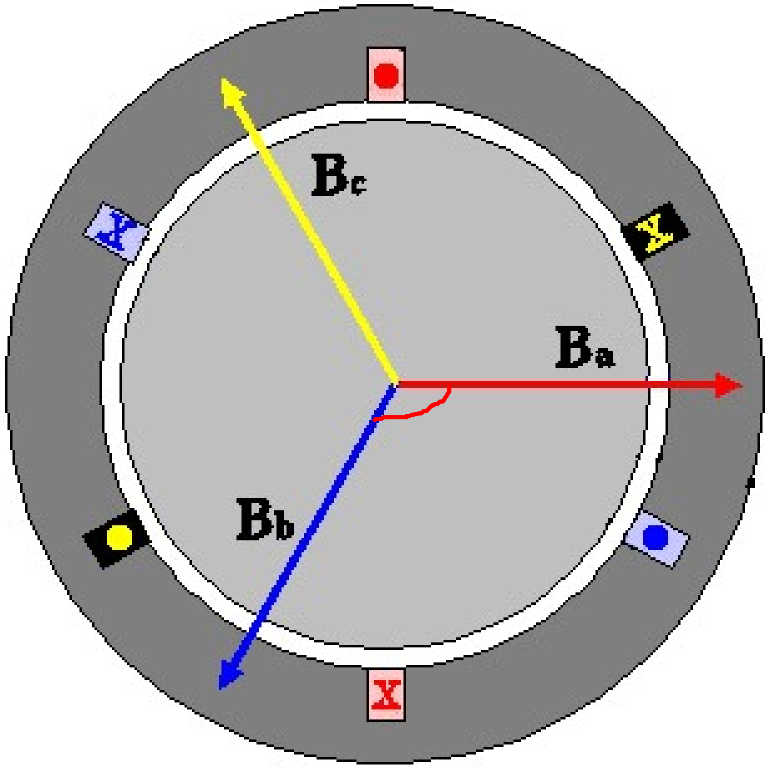


Cutaway in a typical wound-rotor IM. Notice the brushes and the slip rings

Rotating Magnetic Field

- Balanced three phase windings, i.e. mechanically displaced 120 degrees form each other, fed by balanced three phase source
- A rotating magnetic field with constant magnitude is produced, rotating with a speed

$$\boxed{n_{sync} = \frac{120 f_e}{P} \quad rpm}$$



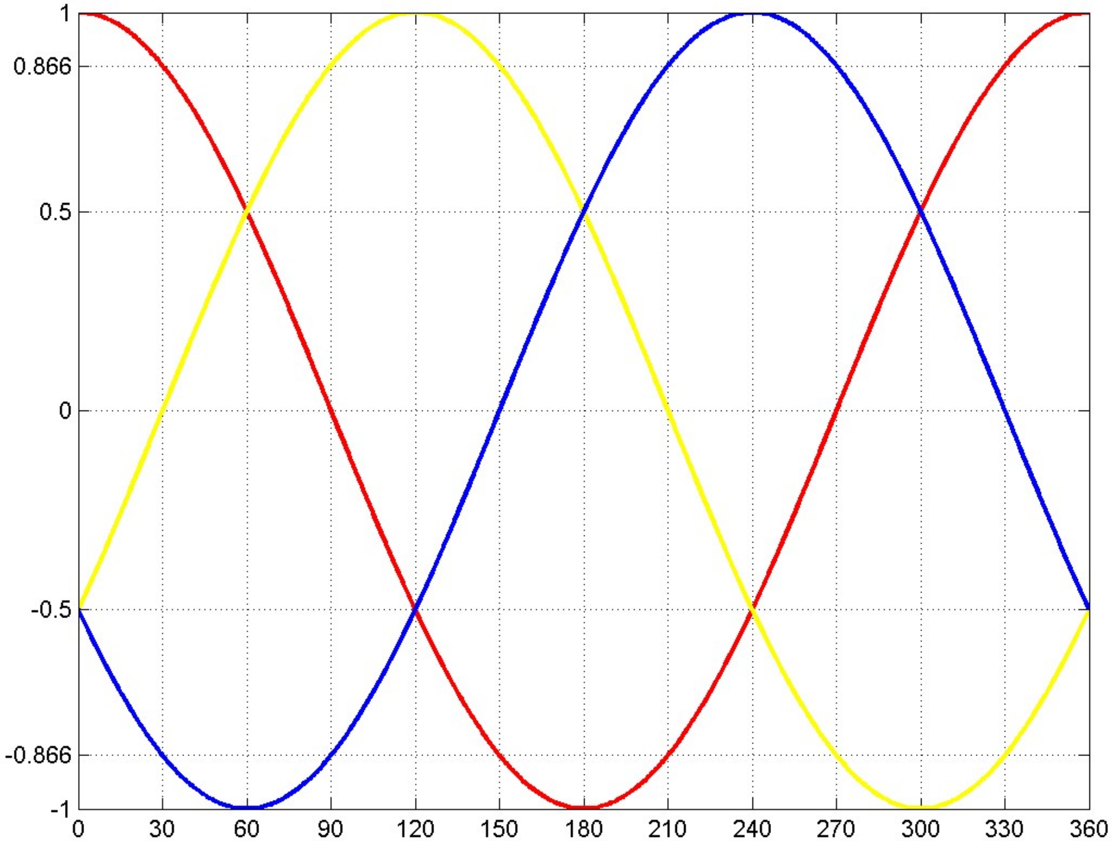
Where f_e is the supply frequency and

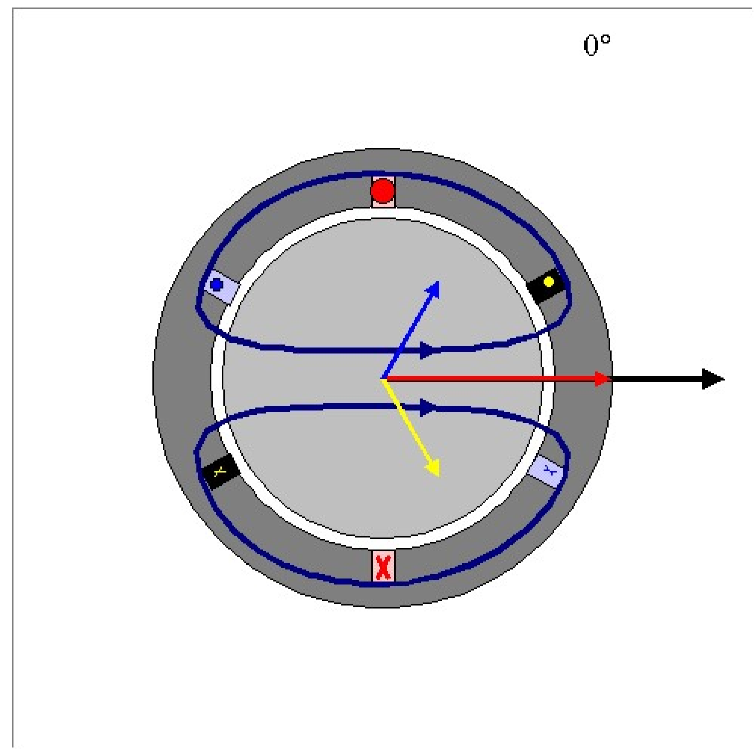
P is the no. of poles and n_{sync} is called the synchronous speed in *rpm* (revolutions per minute)

Synchronous speed

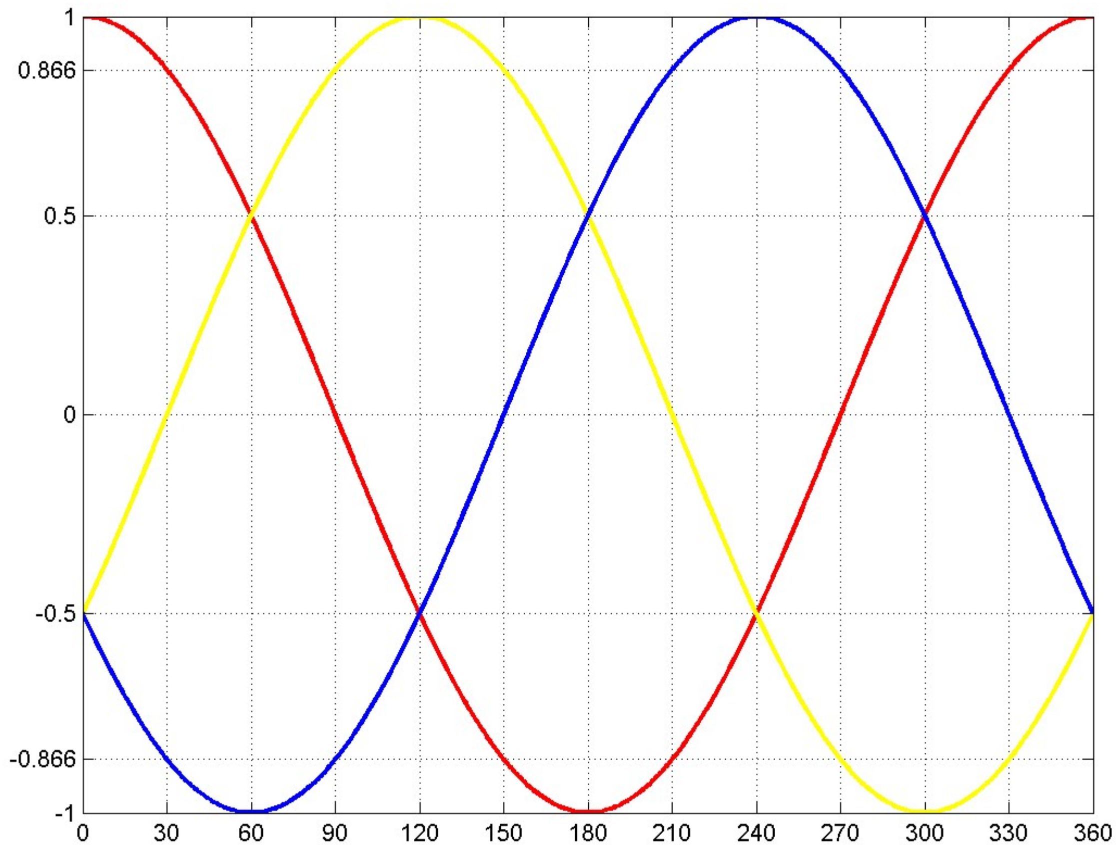
P	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

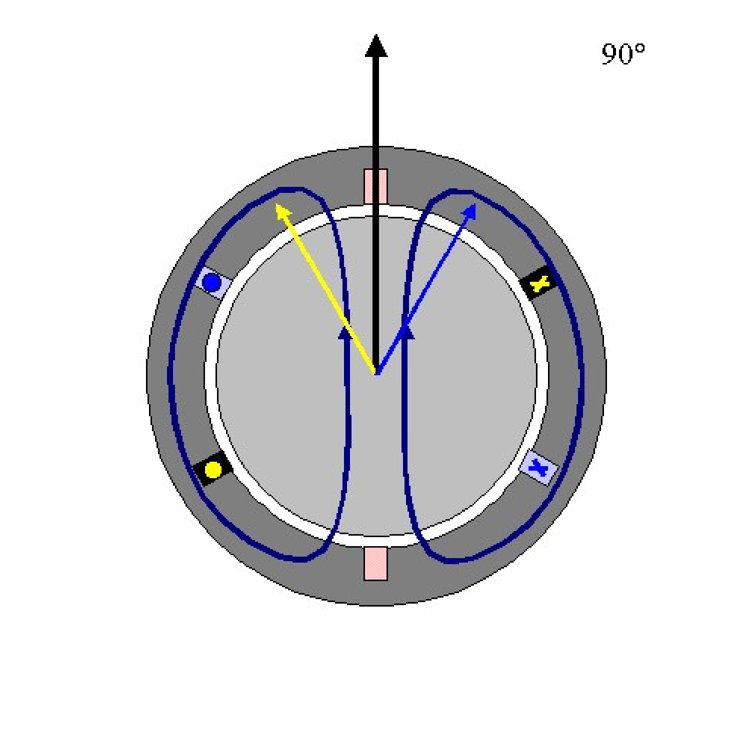
Rotating Magnetic Field





Rotating Magnetic Field





Rotating Magnetic Field

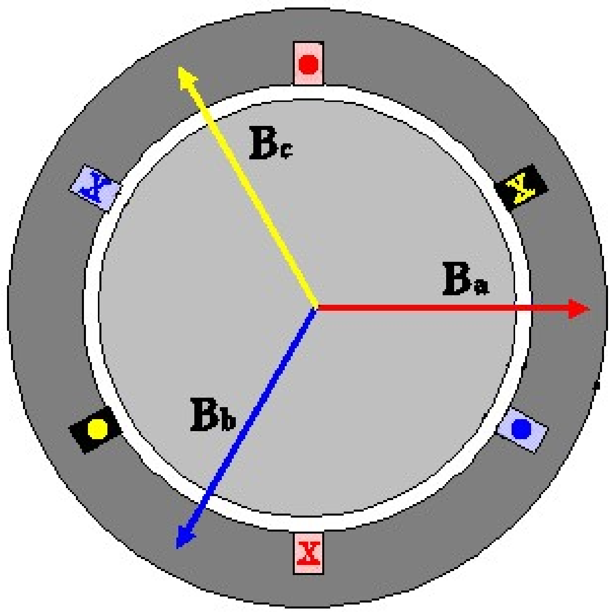
$$B_{net}(t) = B_a(t) + B_b(t) + B_c(t)$$

$$= B_M \sin(\omega t)\angle 0° + B_M \sin(\omega t - 120°)\angle 120° + B_M \sin(\omega t - 240)\angle 240°$$

$$= B_M \sin(\omega t)\hat{\mathbf{x}}$$

$$-[0.5B_M \sin(\omega t - 120°)]\hat{\mathbf{x}} - [\frac{\sqrt{3}}{2} B_M \sin(\omega t - 120°)]\hat{\mathbf{y}}$$

$$-[0.5B_M \sin(\omega t - 240°)]\hat{\mathbf{x}} + [\frac{\sqrt{3}}{2} B_M \sin(\omega t - 240°)]\hat{\mathbf{y}}$$



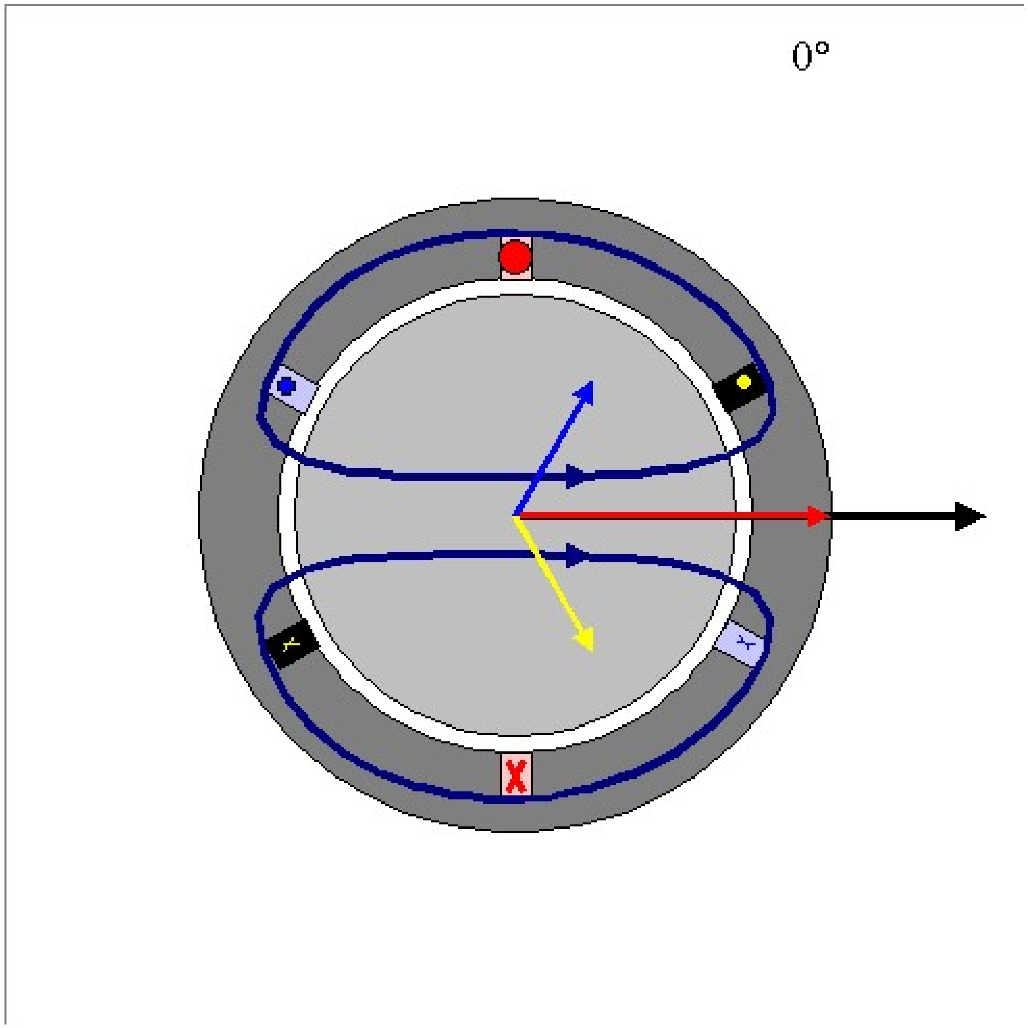
Rotating Magnetic Field

$$B_{net}(t) = [B_M \sin(\omega t) + \frac{1}{4} B_M \sin(\omega t) + \frac{\sqrt{3}}{4} B_M \cos(\omega t) + \frac{1}{4} B_M \sin(\omega t) - \frac{\sqrt{3}}{4} B_M \cos(\omega t)]\hat{\mathbf{x}}$$

$$+[-\frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t) + \frac{\sqrt{3}}{4} B_M \sin(\omega t) - \frac{3}{4} B_M \cos(\omega t)]\hat{\mathbf{y}}$$

$$= [1.5 B_M \sin(\omega t)]\hat{\mathbf{x}} - [1.5 B_M \cos(\omega t)]\hat{\mathbf{y}}$$

Rotating Magnetic Field



Principle of operation

- This rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings
- Due to the fact that the rotor windings are short circuited, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings
- The rotor current produces another magnetic field
- A torque is produced as a result of the interaction of those two magnetic fields

$$\tau_{ind} = kB_R \times B_s$$

Where τ_{ind} is the induced torque and B_R and B_S are the magnetic flux densities of the rotor and the stator respectively

Induction motor speed

N_s

- At what speed will the IM run?
  - Can the IM run at the synchronous speed, why?
  - If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed
  - When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced

Induction motor speed

- So, the IM will always run at a speed lower than the synchronous speed
- The difference between the motor speed and the synchronous speed is called the *Slip*

$$\boxed{n_{slip} = n_{sync} - n_m}$$

Where n_{slip}= slip speed

n_{sync}= speed of the magnetic field

n_m = mechanical shaft speed of the motor

The Slip

$$\boxed{s = \frac{n_{sync} - n_m}{n_{sync}}}$$

Where s is the *slip*

Notice that : if the rotor runs at synchronous speed

$$s = 0$$

if the rotor is stationary

$$s = 1$$

Slip may be expressed as a percentage by multiplying the above eq. by 100, notice that the slip is a ratio and doesn't have units

Induction Motors and Transformers

- Both IM and transformer works on the principle of induced voltage
  - Transformer: voltage applied to the primary windings produce an induced voltage in the secondary windings
  - Induction motor: voltage applied to the stator windings produce an induced voltage in the rotor windings
  - The difference is that, in the case of the induction motor, the secondary windings can move
  - Due to the rotation of the rotor (the secondary winding of the IM), the induced voltage in it does not have the same frequency of the stator (the primary) voltage

Frequency

- The frequency of the voltage induced in the rotor is given by

$$f_r = \frac{P \times n}{120}$$

Where f_r = the rotor frequency (Hz)

P = number of stator poles

n = slip speed (rpm)

$$f_r = \frac{P \times (n_s - n_m)}{120}$$

$$= \frac{P \times sn_s}{120} = sf_e$$

Frequency

- What would be the frequency of the rotor's induced voltage at any speed n_m?

$$\boxed{f_r = s\, f_e}$$

- When the rotor is blocked (s=1) , the frequency of the induced voltage is equal to the supply frequency
- On the other hand, if the rotor runs at synchronous speed (s = 0), the frequency will be zero

Torque

- While the input to the induction motor is electrical power, its output is mechanical power and for that we should know some terms and quantities related to mechanical power
- Any mechanical load applied to the motor shaft will introduce a Torque on the motor shaft. This torque is related to the motor output power and the rotor speed

$$\boxed{\tau_{load} = \frac{P_{out}}{\omega_m} \quad N.m}$$

and

$$\boxed{\omega_m = \frac{2\pi n_m}{60} \quad rad/s}$$

Horse power

- Another unit used to measure mechanical power is the horse power
- It is used to refer to the mechanical output power of the motor
- Since we, as an electrical engineers, deal with watts as a unit to measure electrical power, there is a relation between horse power and watts

$$\boxed{hp = 746\ watts}$$

Example

A 208-V, 10hp, four pole, 60 Hz, Y-connected induction motor has a full-load slip of 5 percent

1. What is the synchronous speed of this motor?
2. What is the rotor speed of this motor at rated load?
3. What is the rotor frequency of this motor at rated load?
4. What is the shaft torque of this motor at rated load?

Solution

1. $$n_{sync} = \frac{120 f_e}{P} = \frac{120(60)}{4} = 1800\ rpm$$

2. $$n_m = (1-s)n_s$$
$$= (1-0.05)\times 1800 = 1710\ rpm$$

3. $$f_r = sf_e = 0.05\times 60 = 3Hz$$

4. $$\tau_{load} = \frac{P_{out}}{\omega_m} = \frac{P_{out}}{2\pi \frac{n_m}{60}}$$
$$= \frac{10\,hp \times 746\,watt/hp}{1710\times 2\pi \times (1/60)} = 41.7\ N.m$$

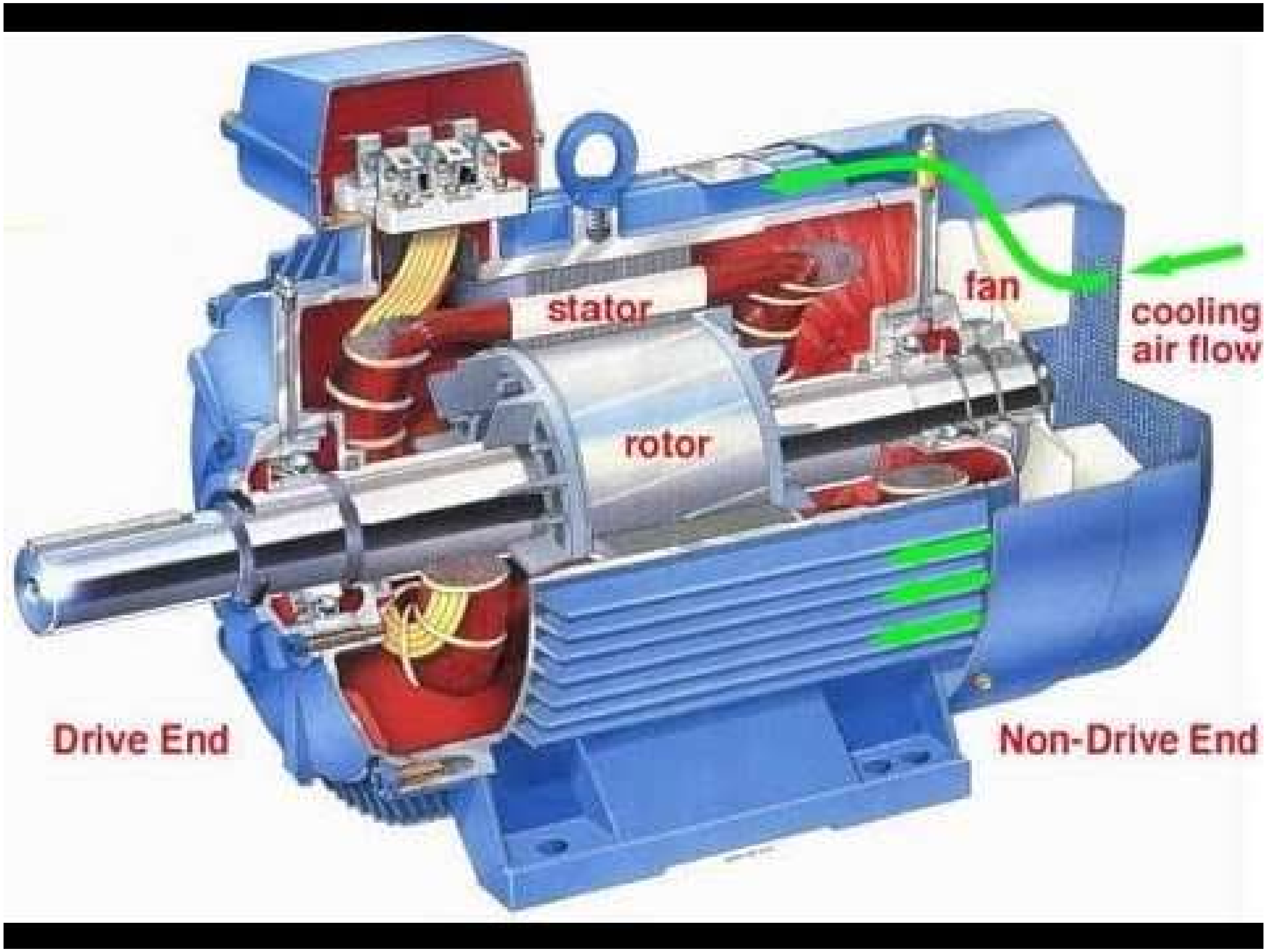
Introduction

- An electrical motor - electromechanical device which converts electrical energy into a mechanical energy.
- In case of **three phase AC operation**, most widely used motor is Three phase induction motor. (also known as an asynchronous motor)
- These motors do not require any starting device or they are **self starting** induction motor.

- Due to the lag between the flux current in the rotor and the flux current in the stator, the rotor will never reach its rotating magnetic field speed (i.e. the synchronous speed).

Characteristics

- Simple and rugged construction.
- Low cost and minimum maintenance.
- Needs no additional starting.


stator
fan
cooling
air flow
rotor
Drive End
Non-Drive End

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.

- When 3-phase stator winding is energized from a 3-phase supply, a rotating magnetic field is set up which rotates round the stator at synchronous speed N_s (= 120 f/P).
- The rotating field passes through the air gap and cuts the rotor conductors, which as yet, are stationary.

Applications of 3phase IM

- Lifts
- Cranes
- Hoists
- Large capacity exhaust fans
- Driving lathe machines
- Crushers
- Oil extracting mills
- Textile and etc.