# BASIC ELECTRICAL ENGINEERING

by

**S Reddy Ramesh**
**Assistant Professor**
Dept of Electrical & Electronics Engineering
Aditya College of Engineering & Technology
Surampalem.

# Unit- I DC Machines

- Principle of operation of DC generator
- EMF equation
- Types of DC machines
- Torque equation of DC motor
- Applications
- Three point starter
- Losses and efficiency
- Swinburne’s test
- Speed control methods
- OCC of DC generator
- Brake test on DC Shunt motor
- Numerical problems

# Overview of Direct Current Machines:

- Direct-current (DC) machines are divided into dc generators and dc motors.

- Most DC machines are similar to AC machines: i.e. they have AC voltages and current within them.

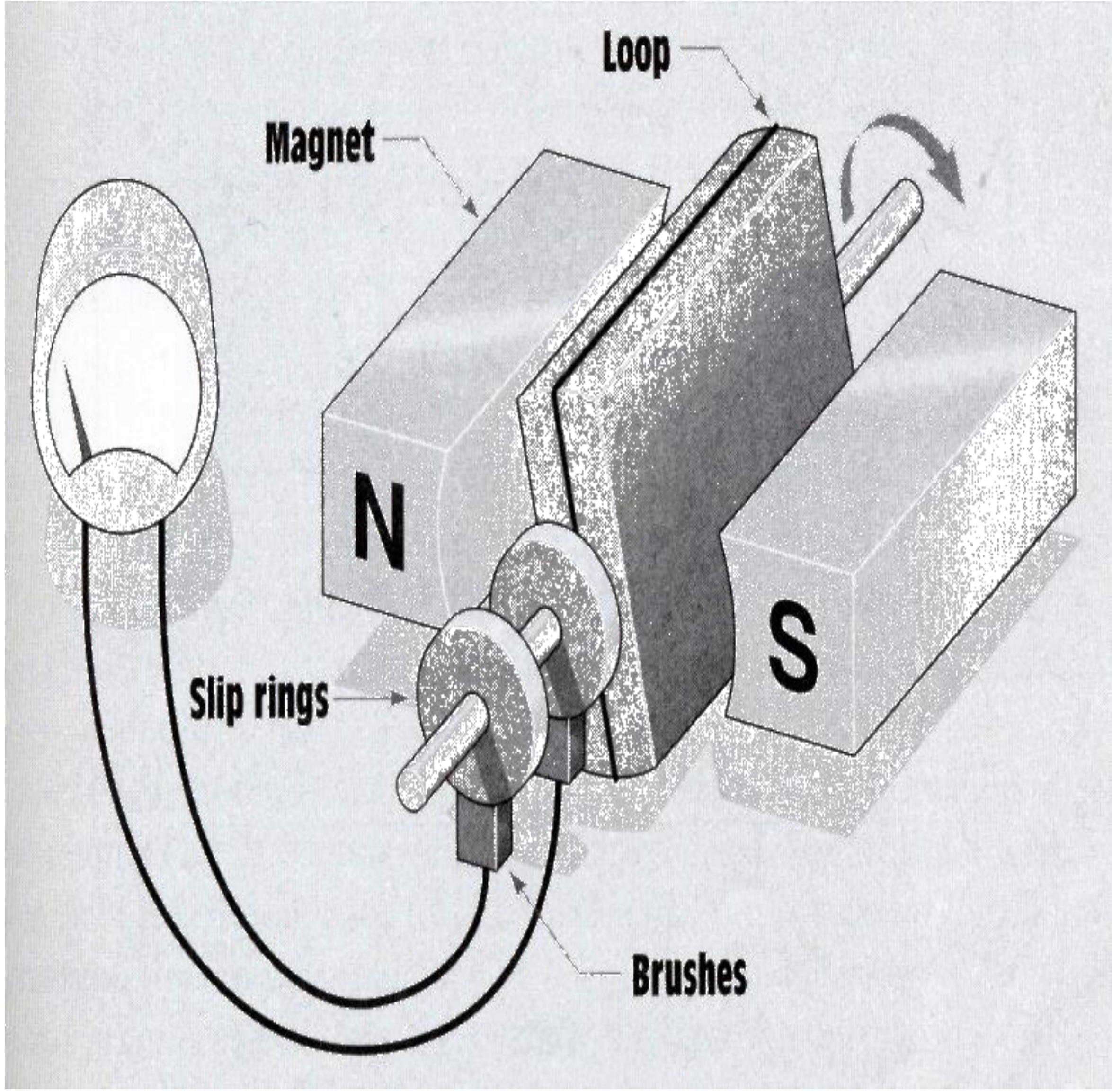
- DC machines have DC outputs just because they have a mechanism converting AC voltages to DC voltages at their terminals.

- This mechanism is called a commutator; therefore, DC machines are also called commutating machines.

- DC generators are not as common as they used to be, because direct current, when required, is mainly produced by electronic rectifiers.

# DC Generator:

- A dc generator is a machine that converts mechanical energy into electrical energy (dc voltage and current) by using the principle of magnetic induction.
- In this example, the ends of the wire loop have been connected to two slip rings mounted on the shaft, while brushes are used to carry the current from the loop to the outside of the circuit.



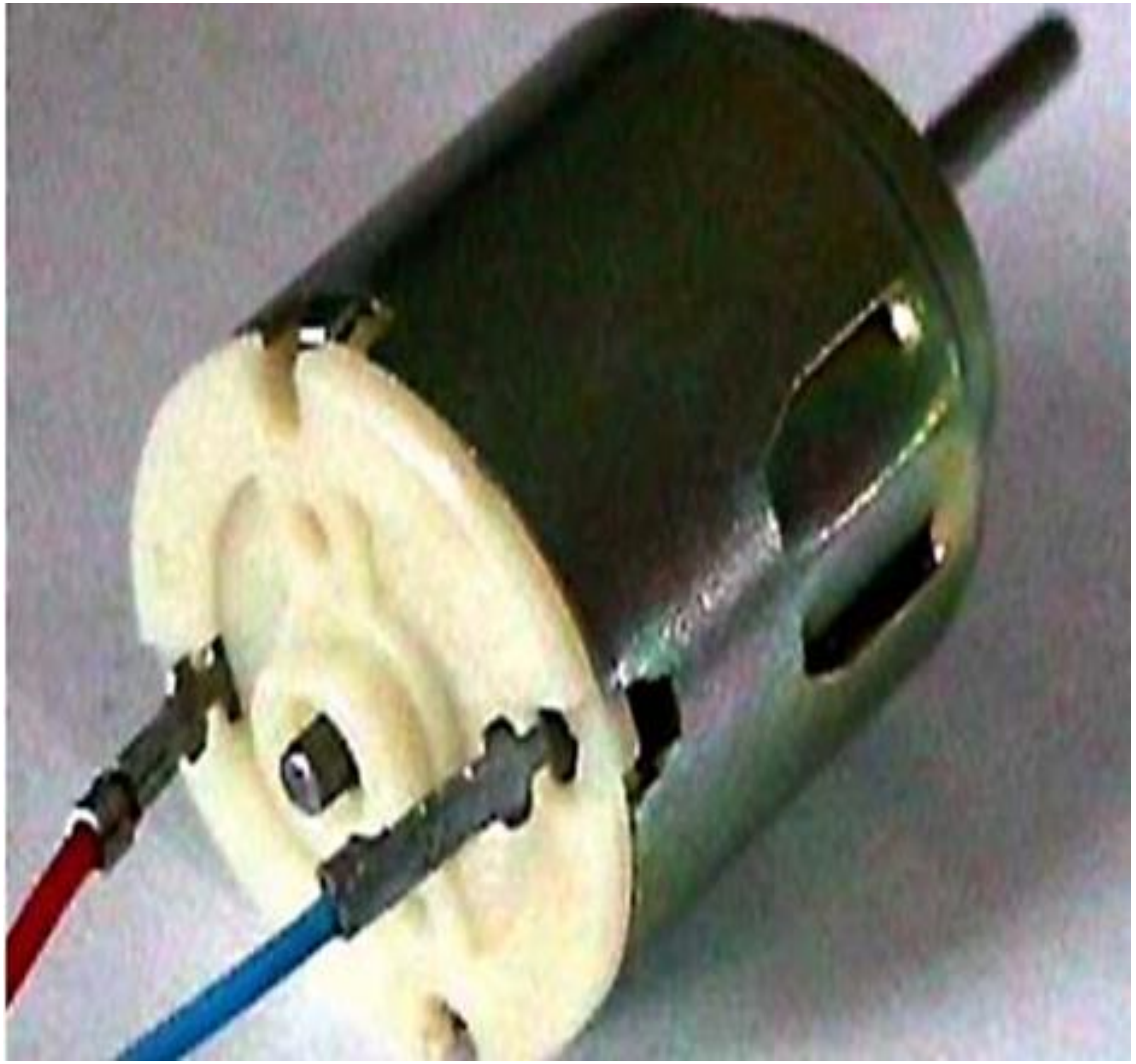

Principle of magnetic induction in DC machine

# DC Motor

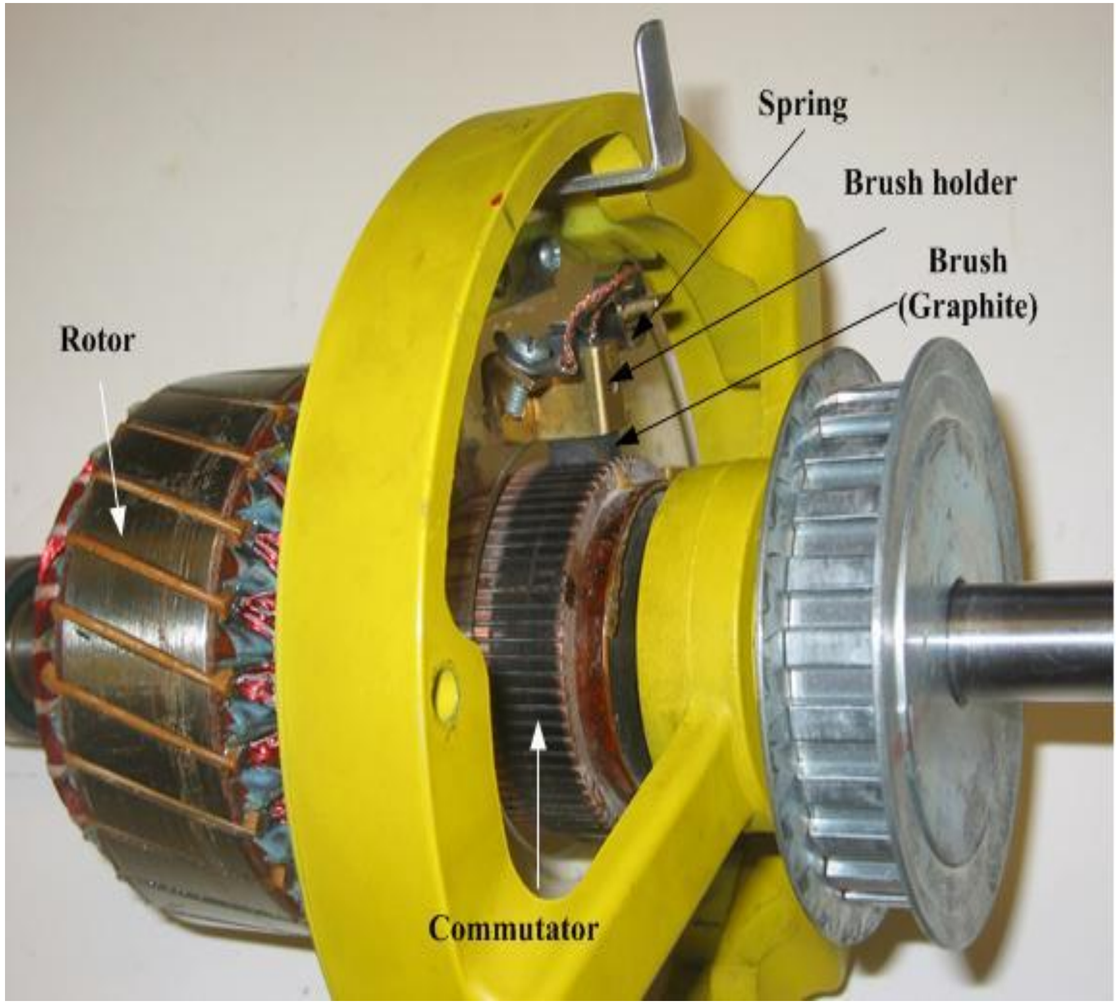
- DC motors are everywhere! In a house, almost every mechanical movement that you see around you is caused by an DC (direct current) motor.

- An dc motor is a machine that converts electrical energy into mechanical energy by supplying a dc power (voltage and current).

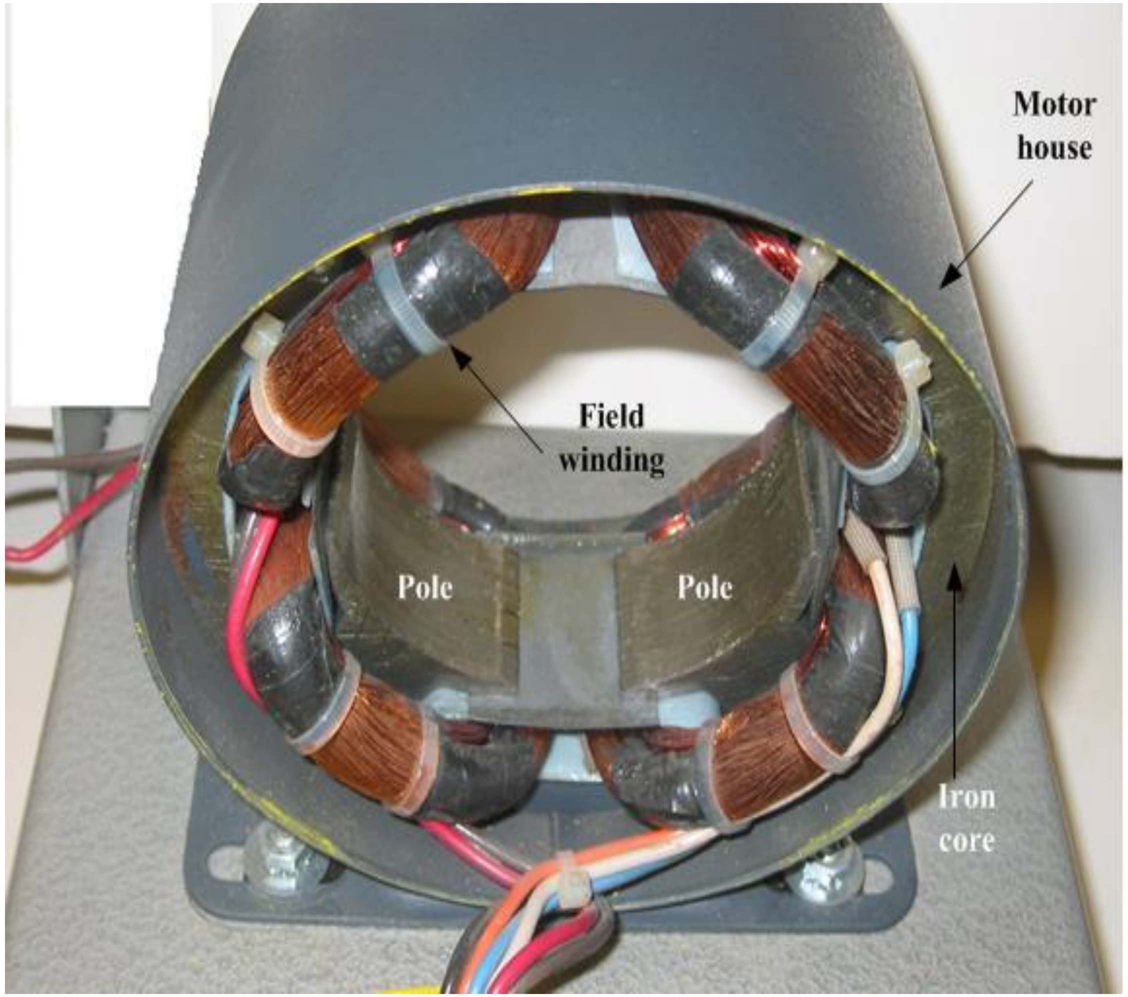
- An advantage of DC motors is that it is easy to control their speed in a wide dispersion.



# Construction of DC Machine

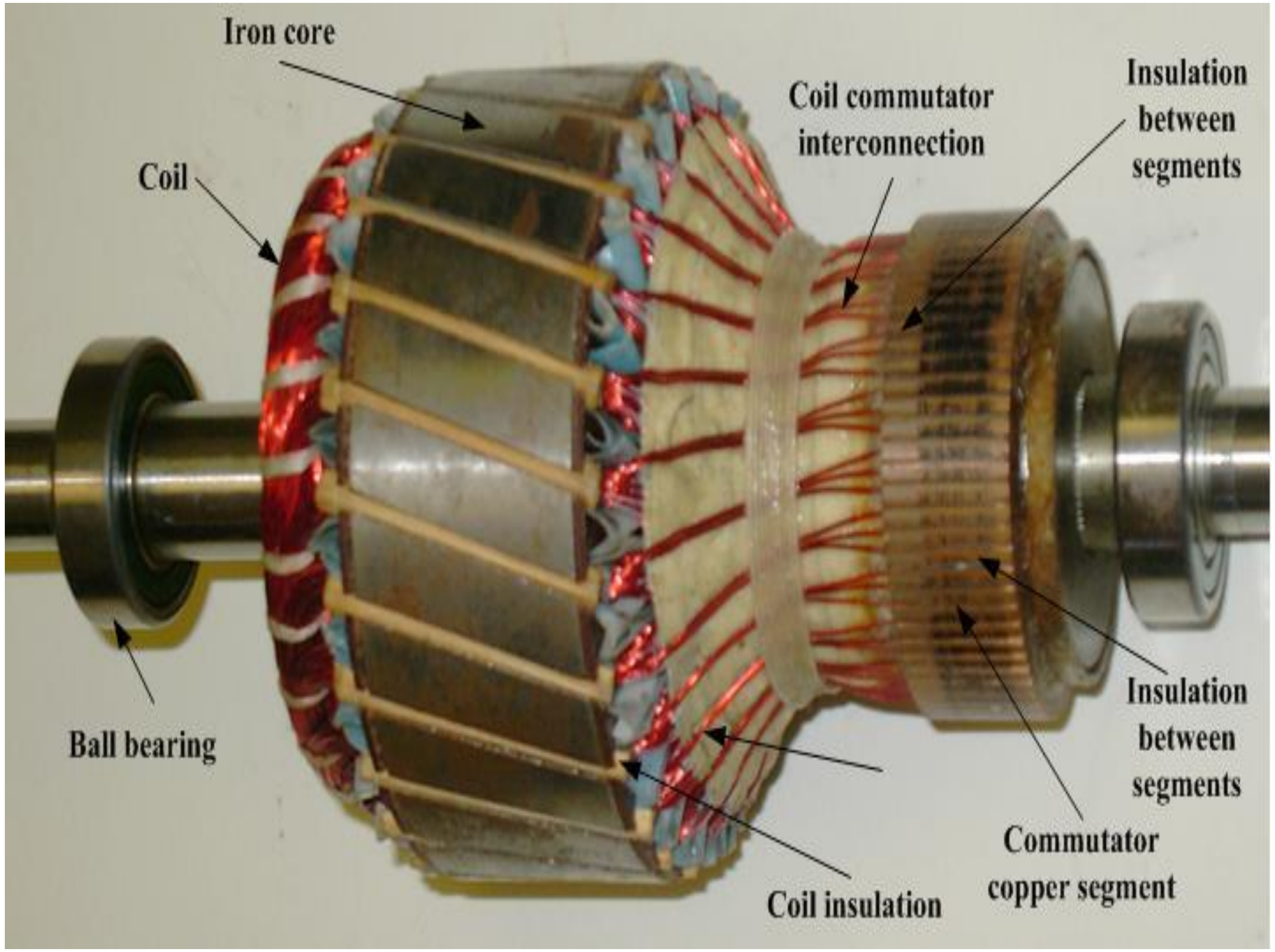


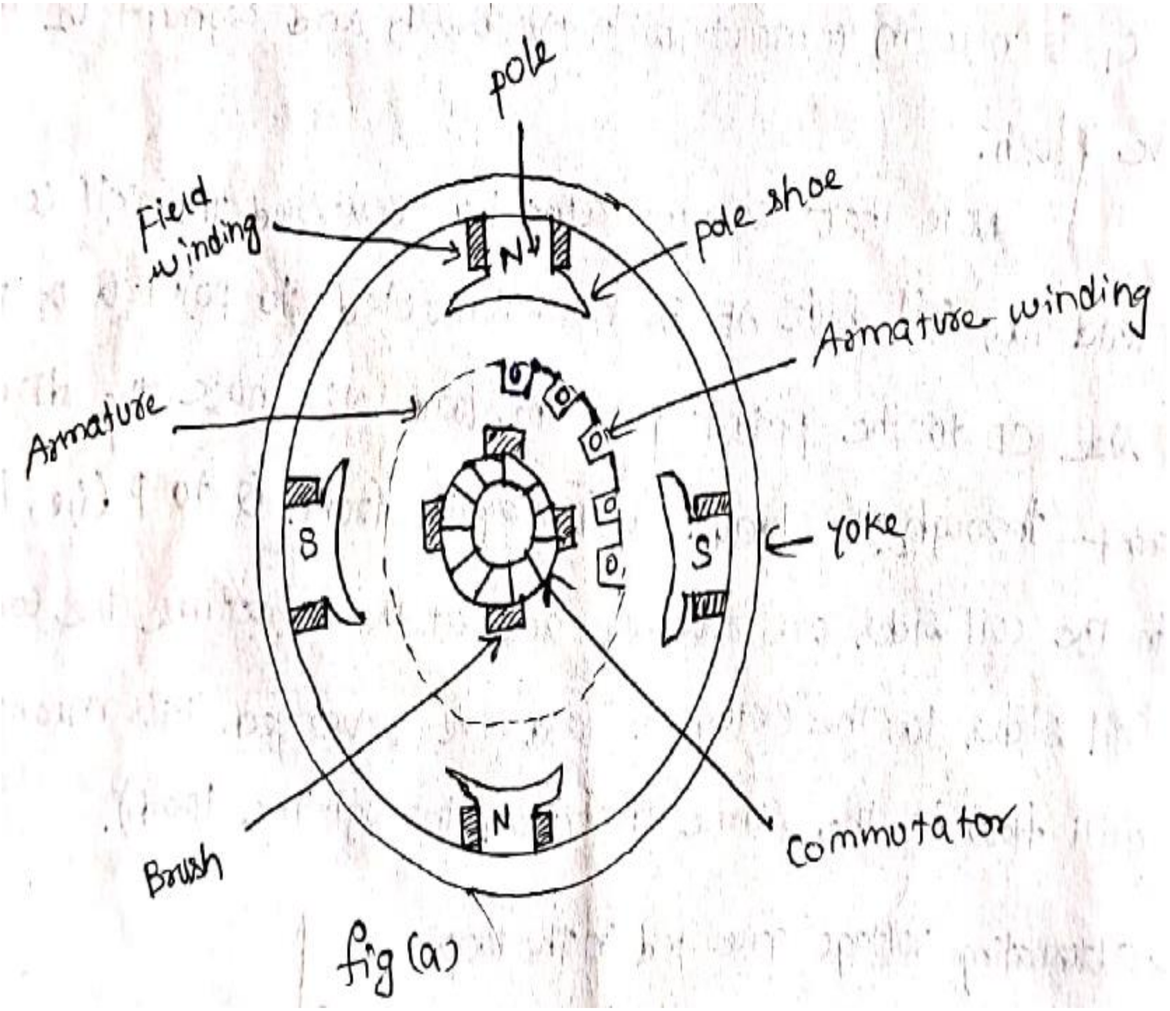

Cutaway view of DC motor




Stator with poles visible

# Construction of DC Machine:

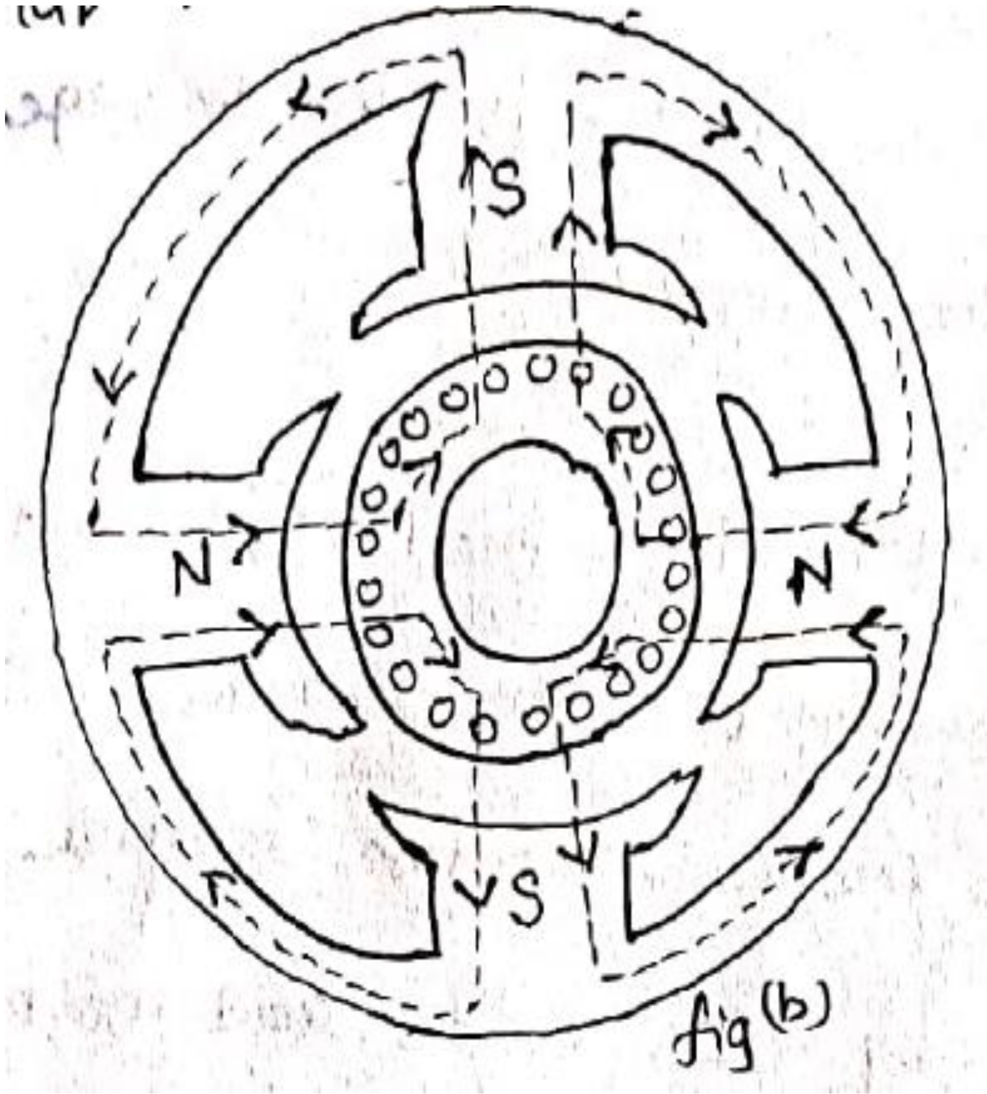



Rotor or armature of a DC Motor

# Armature:

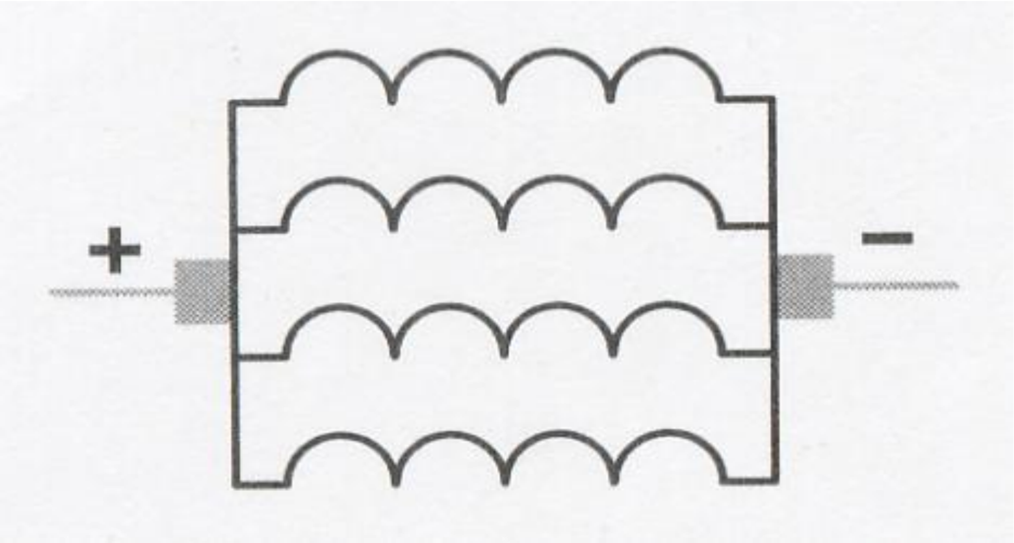
- More loops of wire = higher rectified voltage
- In practical, loops are generally placed in slots of an iron core
- The iron acts as a magnetic conductor by providing a low-reluctance path for magnetic lines of flux to increase the inductance of the loops and provide a higher induced voltage.
- The commutator is connected to the slotted iron core.
- The entire assembly of iron core, commutator, and windings is called the armature.
- The windings of armatures are connected in different ways depending on the requirements of the machine.

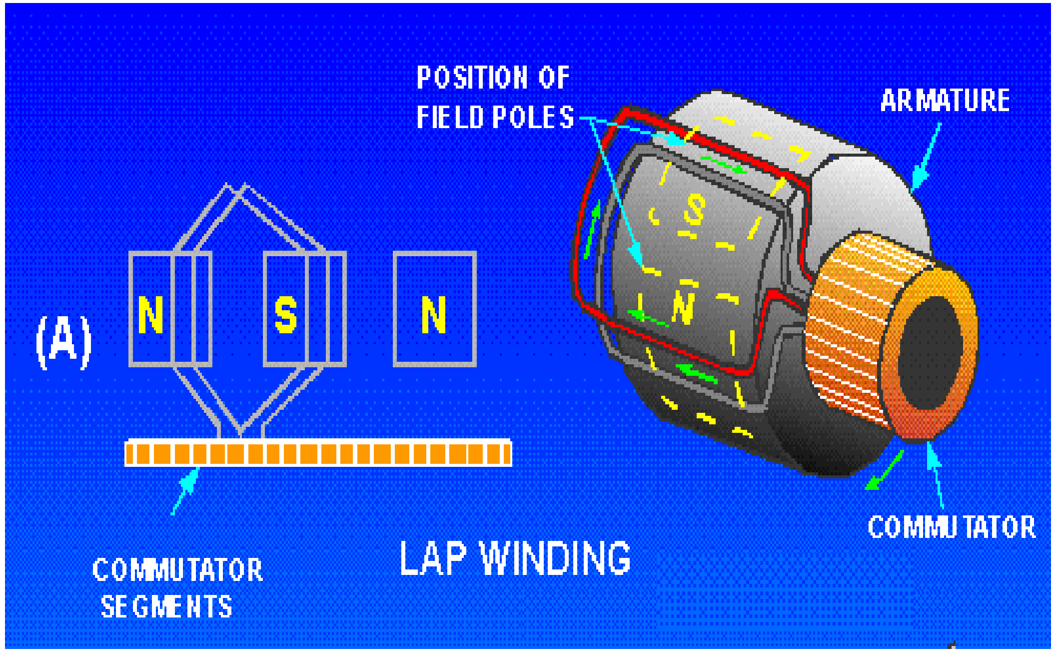



**Rotor is rotating part - armature**
**Stator is stationary part - field**

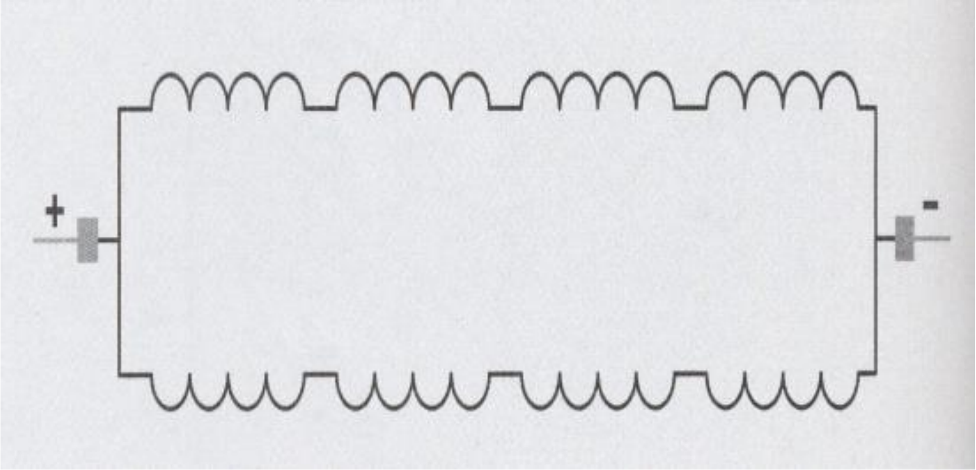
# Armature Windings:

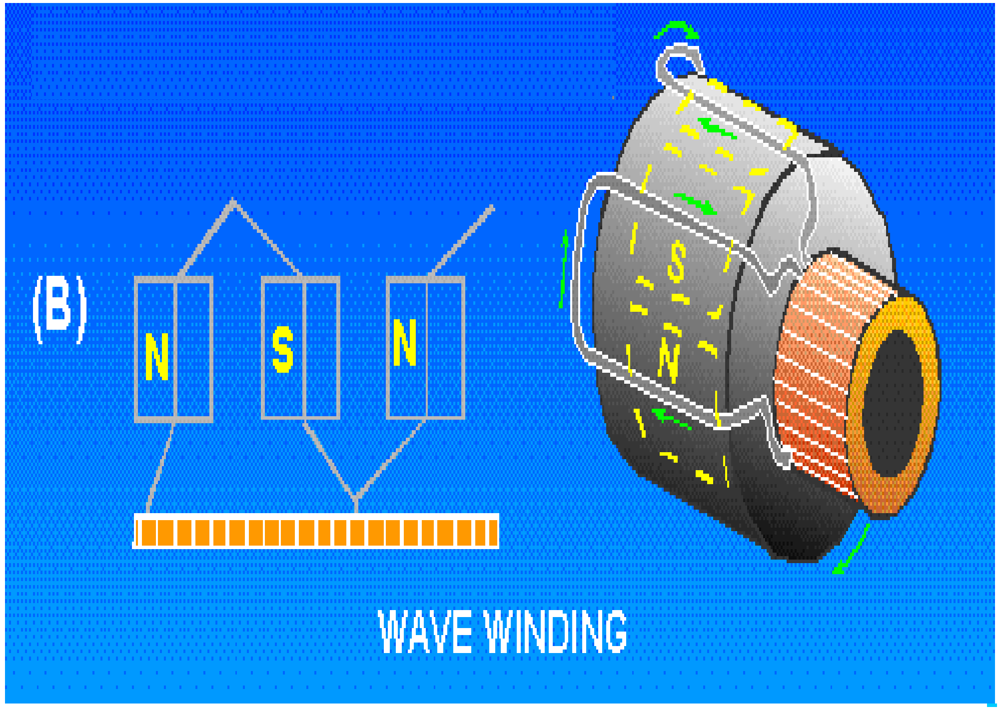
- **Lap Wound Armature:**
  - are used in machines designed for low voltage and high current
  - armatures are constructed with large wire because of high current
  - Eg: - These are used in the starter motor of almost all automobiles
  - The windings of a lap wound armature are connected in parallel. This permits the current capacity of each winding to be added and provides a higher operating current
  - No of current path, **C=2p** ; p=no of poles



- **Wave Wound Armature:**
  - are used in machines designed for high voltage and low current
  - their windings connected in series
  - When the windings are connected in series, the voltage of each winding adds, but the current capacity remains the same
  - are used is in the small generator in hand-cranked meg ohmmeters.
  - No of current path, C=2



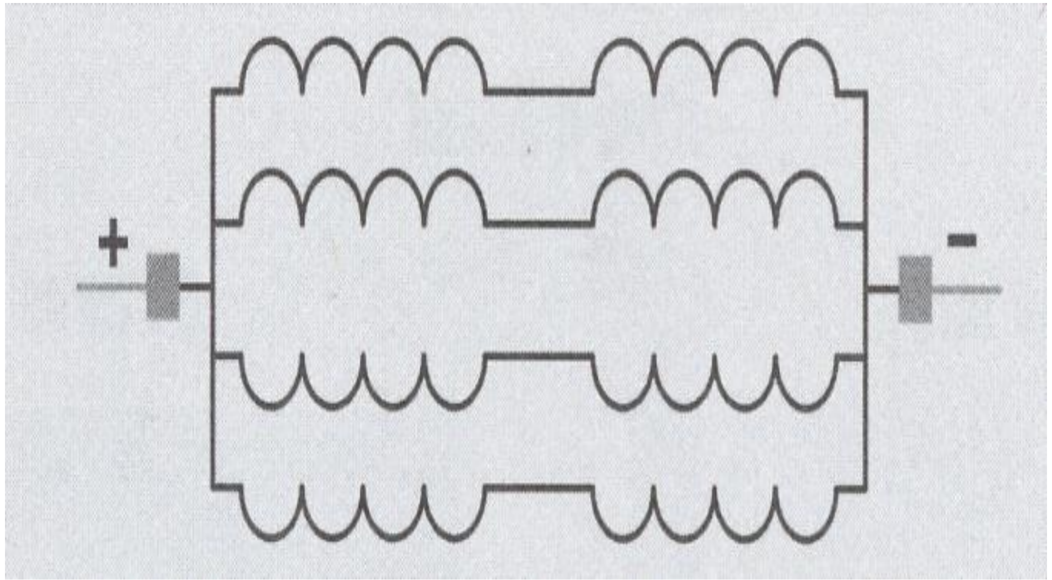



# Frog leg Wound Armatures:

designed for use with moderate current and moderate armature voltages.

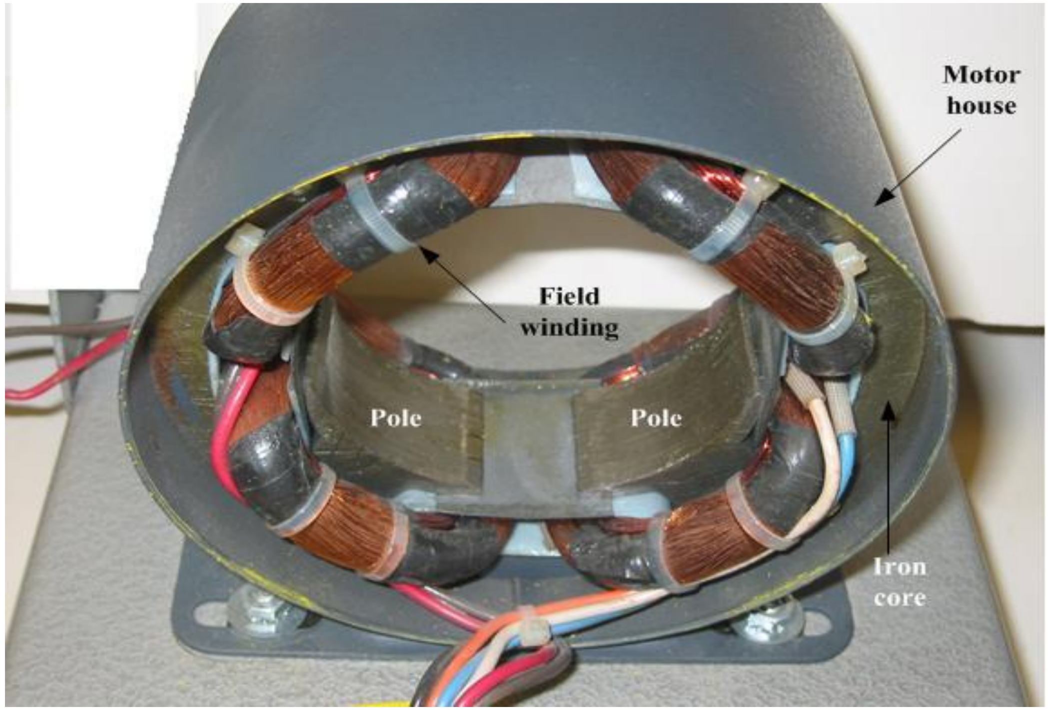
the windings are connected in series parallel.

Most large DC machines use frog leg wound armatures.




## Field Windings:

- Most DC machines use wound electromagnets to provide the magnetic field.
- Two types of field windings are used :
  - series field
  - shunt field

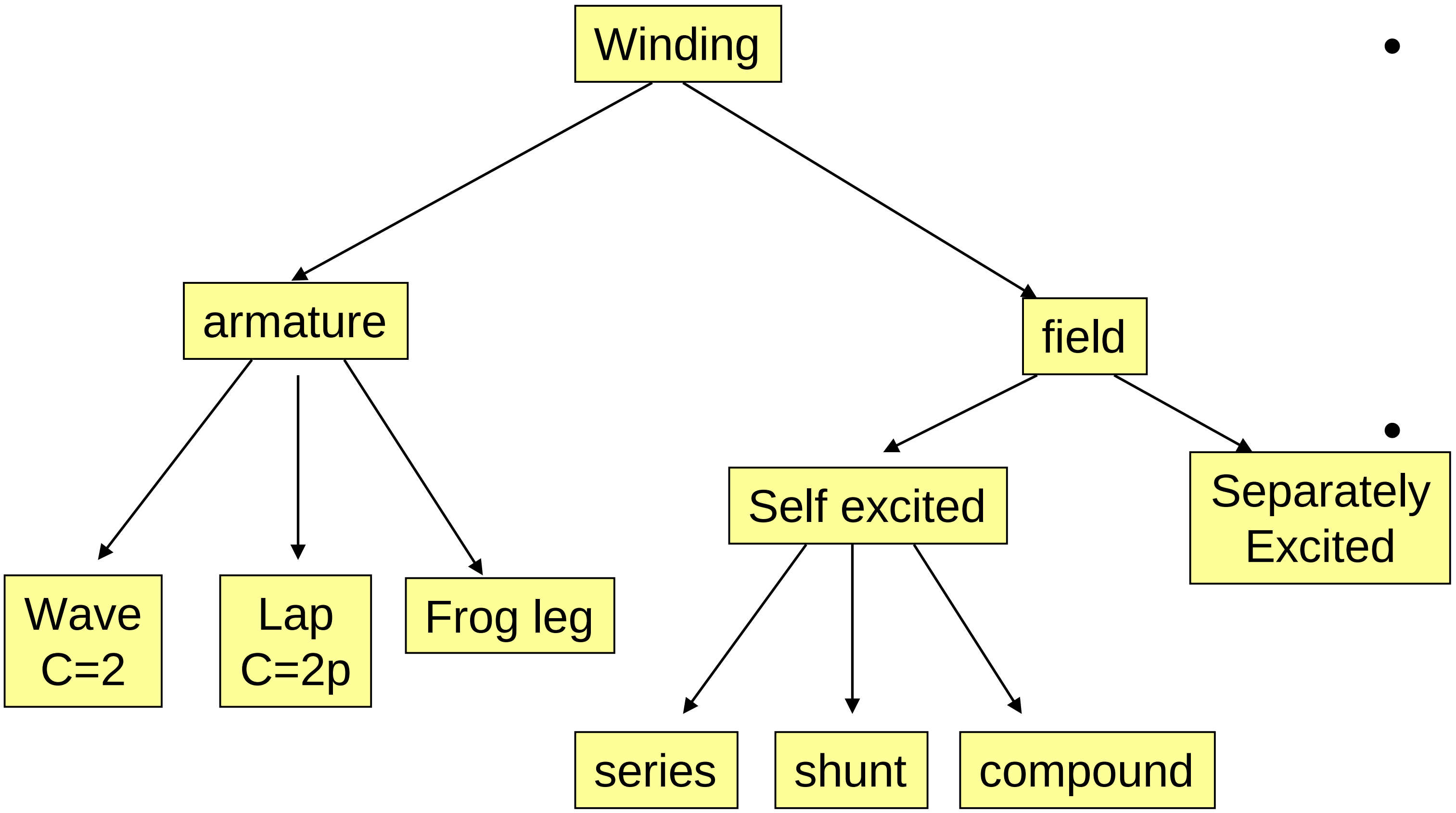


# Field Windings:

- **Series field winding:**
  - are so named because they are connected in series with the armature
  - are made with relatively few windings turns of very large wire and have a very low resistance
  - usually found in large horsepower machines wound with square or rectangular wire.
  - The use of square wire permits the windings to be laid closer together, which increases the number of turns that can be wound in a particular space

- **Shunt field winding:**
  - is constructed with relatively many turns of small wire, thus, it has a much higher resistance than the series field.
  - is intended to be connected in parallel with, or shunt, the armature.
  - high resistance is used to limit current flow through the field.
- When a DC machine uses both series and shunt fields, each pole piece will contain both windings.
- The windings are wound on the pole pieces in such a manner that when current flows through the winding it will produce alternate magnetic polarities.

# MACHINE WINDINGS OVERVIEW:



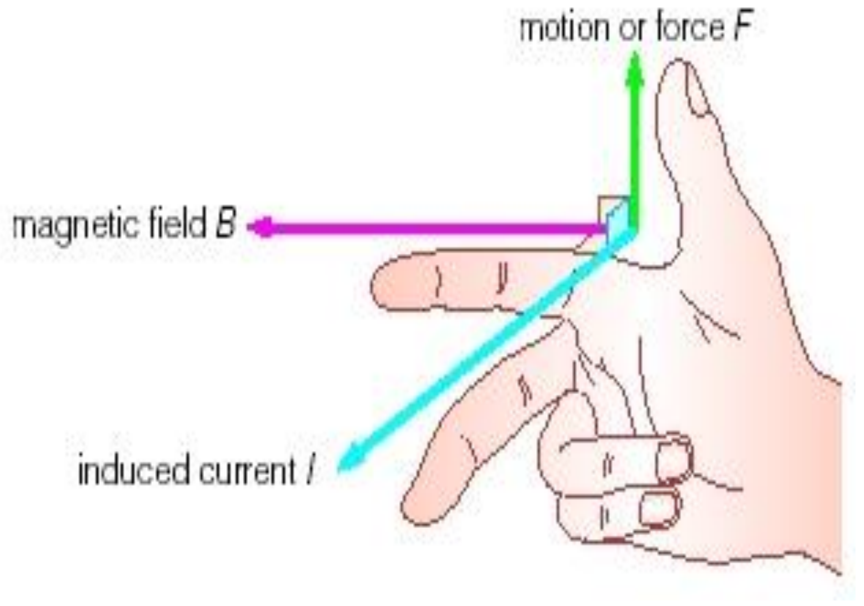

# Principle of operation of DC Generator:

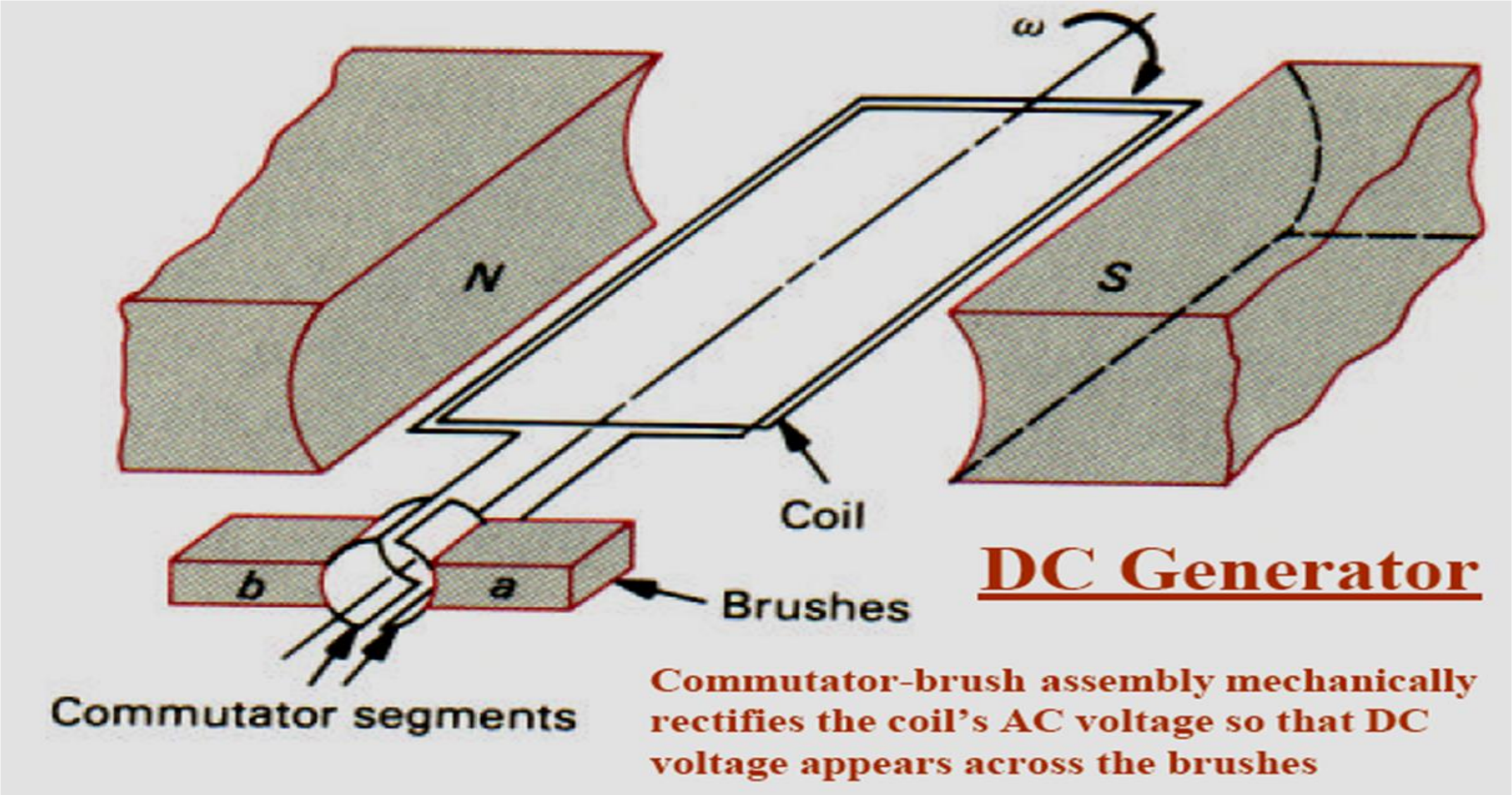
- Whenever a conductor is moved within a magnetic field in such a way that the conductor cuts across magnetic lines of flux, voltage is generated in the conductor.
- The amount of voltage generated depends on:

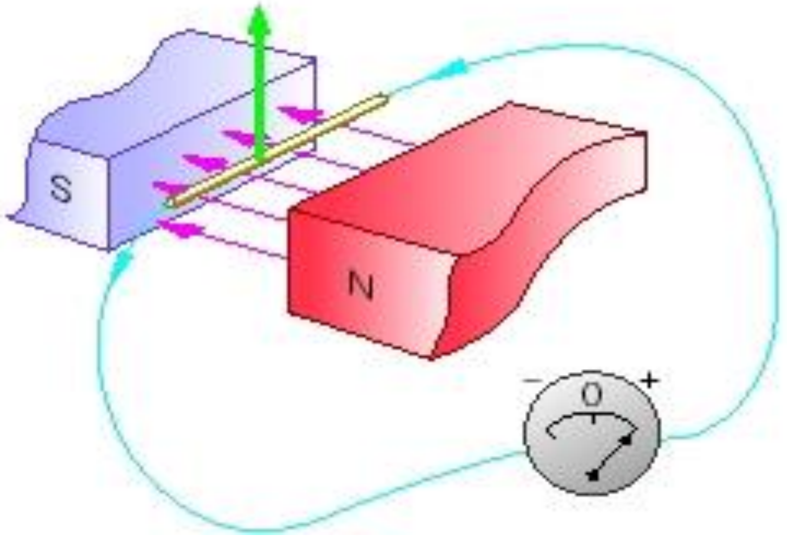
i. the strength of the magnetic field,
ii. the angle at which the conductor cuts the magnetic field,
iii. the speed at which the conductor is moved, and
iv. the length of the conductor within the magnetic field

# Fleming's Right Hand Rule(Generator rule):

- Use: To determine the direction of the induced emf /current of a conductor moving in a magnetic field.
- The polarity of the voltage depends on the direction of the magnetic lines of flux and the direction of movement of the conductor.

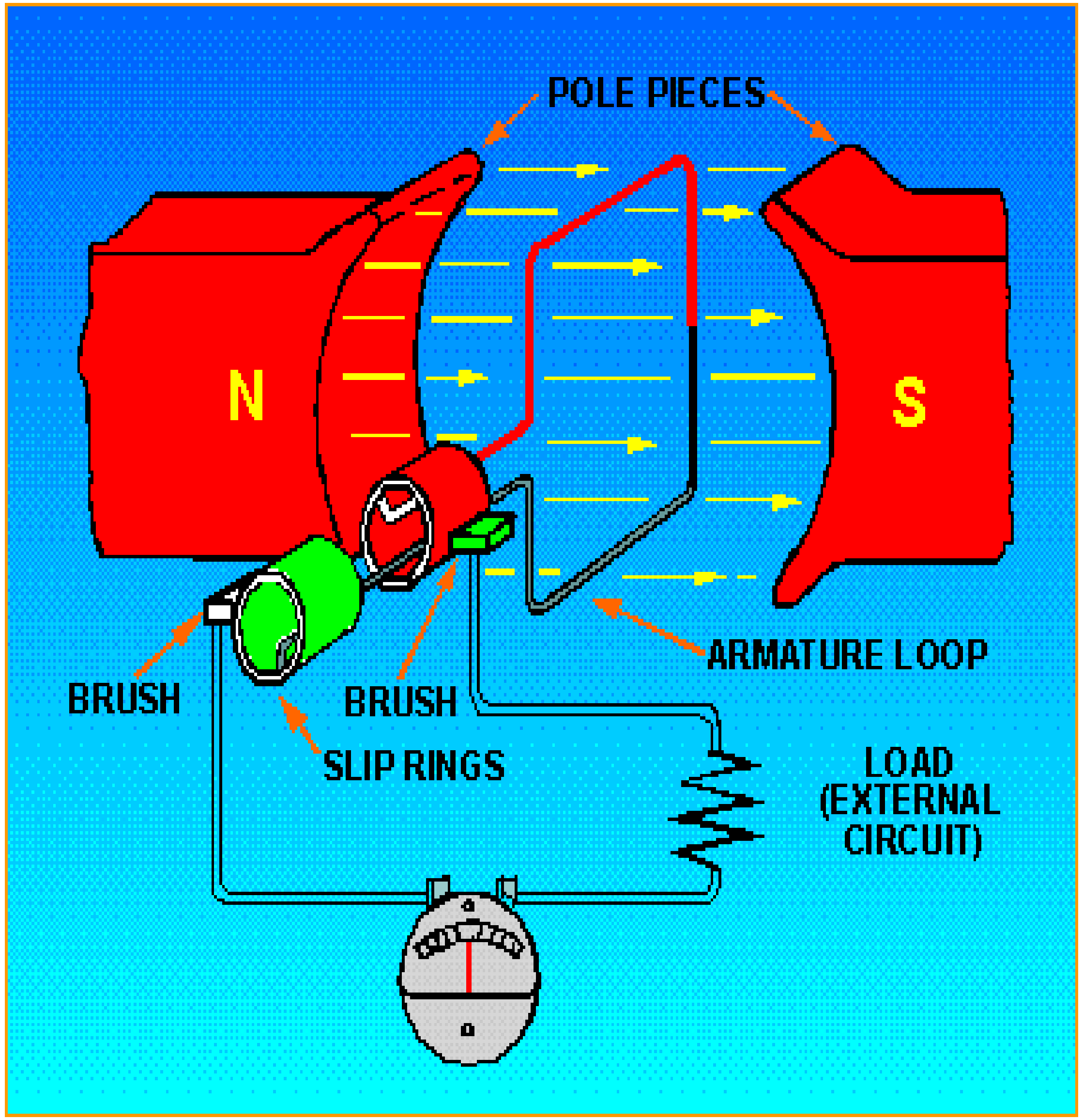


# Elementary Generator:

- The simplest elementary generator that can be built is an ac generator.
- Basic generating principles are most **easily explained** through the use of the elementary ac generator.
- For this reason, the ac generator will be discussed first. The dc generator will be discussed later.
- An elementary generator consists of a wire loop mounted on the shaft, so that it can be rotated in a stationary magnetic field.
- This will produce an induced emf in the loop.
- Sliding contacts (brushes) connect the loop to an external circuit load in order to pick up or use the induced emf.



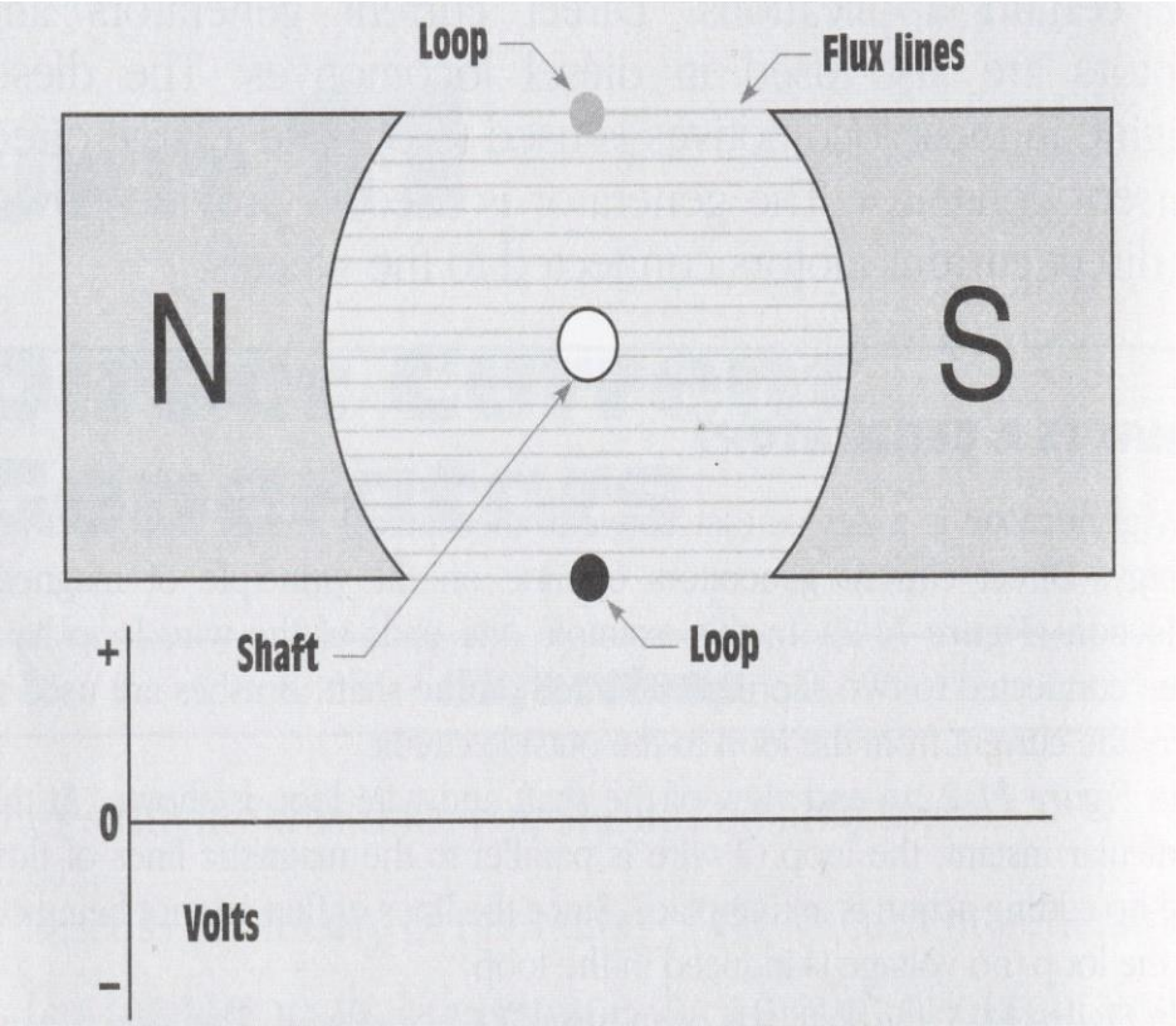
- The pole pieces (marked N and S) provide the magnetic field. The pole pieces are shaped and positioned as shown to concentrate the magnetic field as close as possible to the wire loop.

- The loop of wire that rotates through the field is called the ARMATURE. The ends of the armature loop are connected to rings called SLIP RINGS. They rotate with the armature.

- The brushes, usually made of carbon, with wires attached to them, ride against the rings. The generated voltage appears across these brushes. (These brushes transfer power from the battery to the commutator as the generator spins.

# Elementary Generator(A):

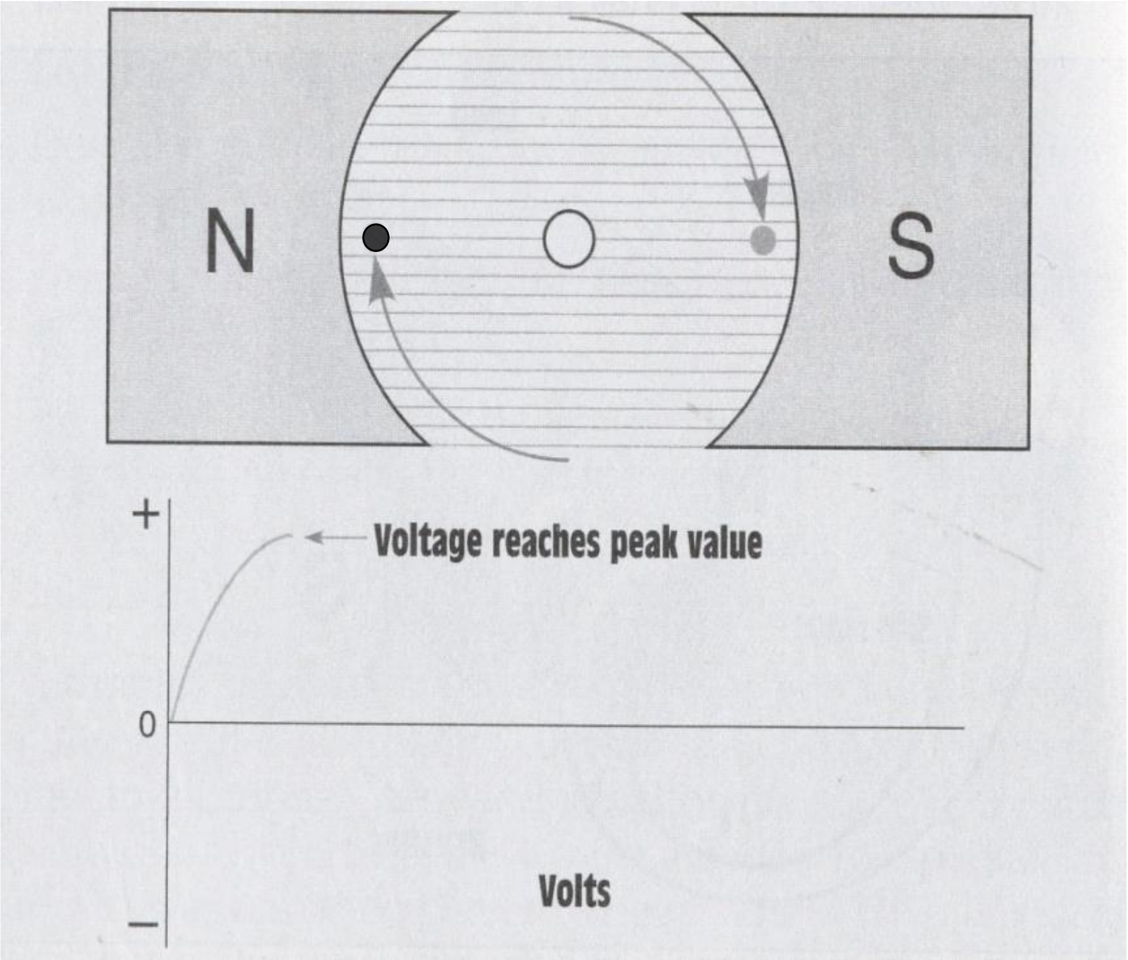
- An end view of the shaft and wire loop is shown.
- At this particular instant, the loop of wire (the black and white conductors of the loop) is parallel to the magnetic lines of flux, and no cutting action is taking place.
- Since the lines of flux are not being cut by the loop, no emf is induced in the conductors, and the meter at this position indicates zero.
- This position is called the NEUTRAL PLANE.




$0^0$ Position (Neutral Plane)

# Elementary Generator(B):

- The shaft has been turned $90^0$ clockwise, the conductors cut through more and more lines of flux, and voltage is induced in the conductor.
- at a continually increasing angle , the induced emf in the conductors builds up from zero to a maximum value or peak value.
- Observe that from $0^0$ to $90^0$, the black conductor cuts down through the field.
- At the same time the white conductor cuts up through the field.
- The induced emf's in the conductors are series-adding.



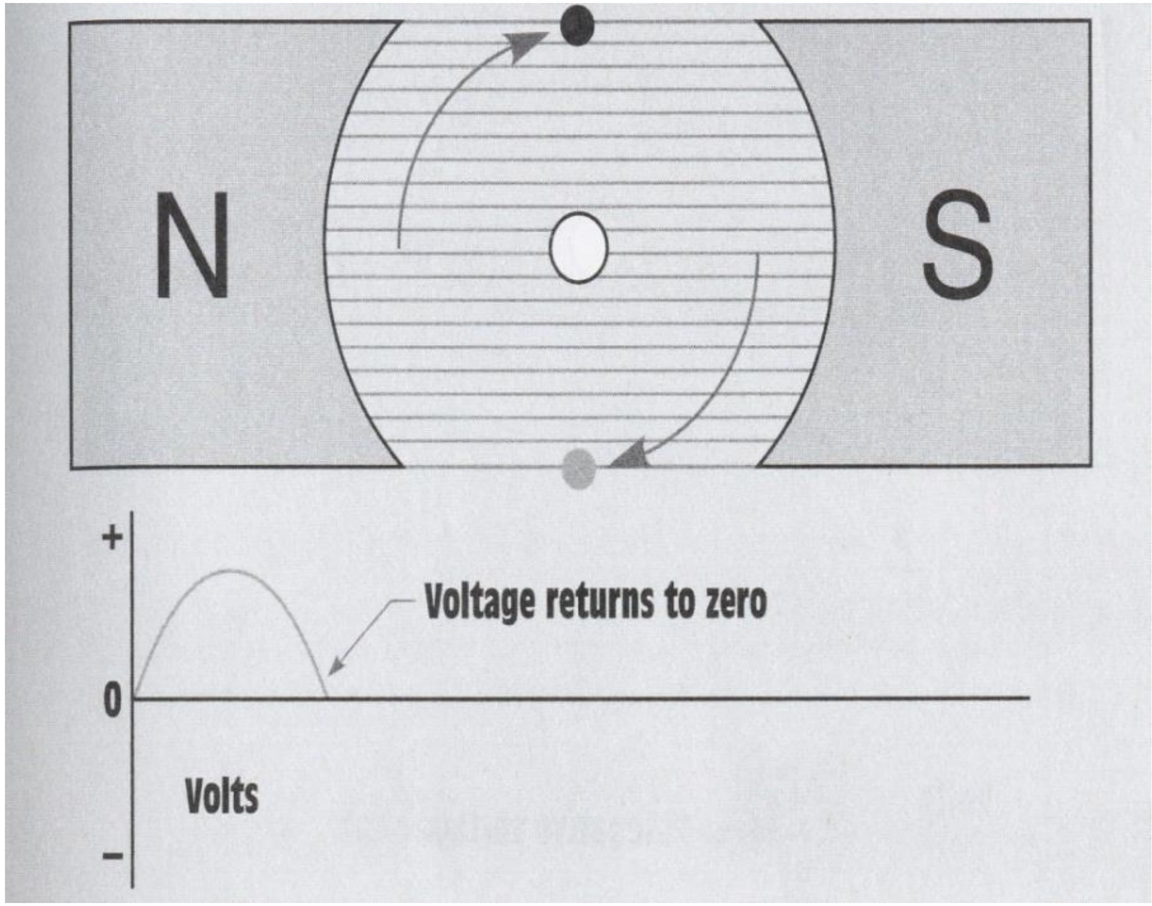

$90^o$ Position

- The meter at position B reads maximum value.

- This means the resultant voltage across the brushes (the terminal voltage) is the sum of the two induced voltages.

# Elementary Generator(C):

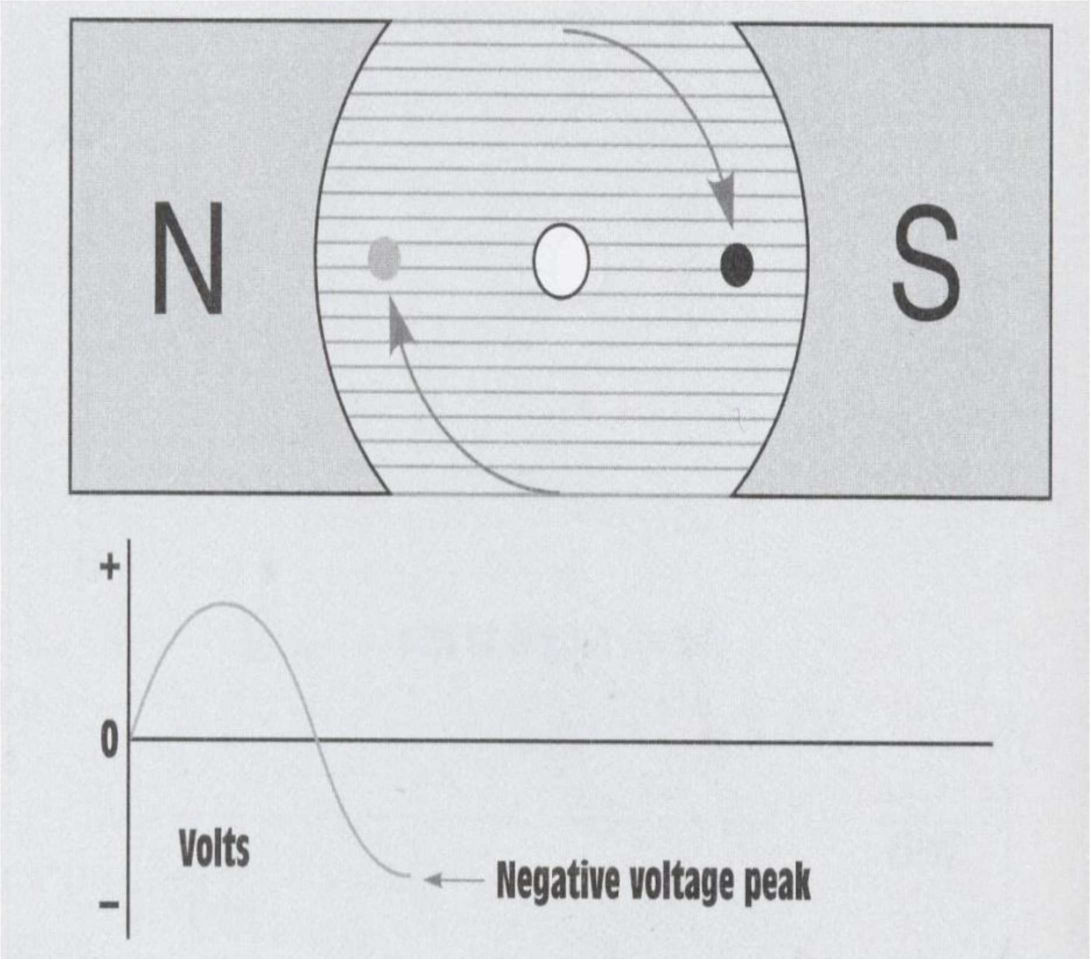
- After another $90^0$ of rotation, the loop has completed $180^0$ of rotation and is again parallel to the lines of flux.
- As the loop was turned, the voltage decreased until it again reached zero.
- Note that : From $0^0$ to $180^0$ the conductors of the armature loop have been moving in the same direction through the magnetic field.
- Therefore, the polarity of the induced voltage has remained the same




$180^o$ Position

# Elementary Generator(D):

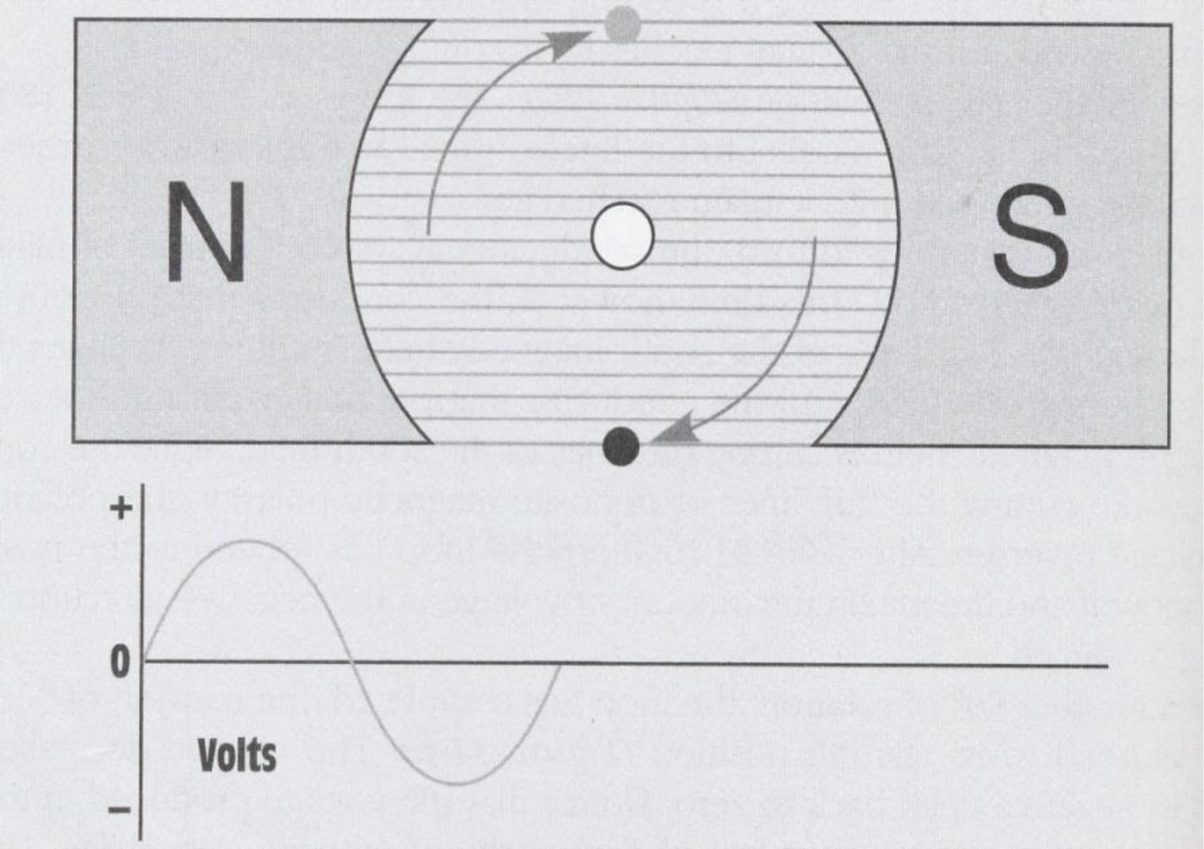
- As the loop continues to turn, the conductors again cut the lines of magnetic flux.
- This time, however, the conductor that previously cut through the flux lines of the south magnetic field is cutting the lines of the north magnetic field, and vice-versa.
- Since the conductors are cutting the flux lines of opposite magnetic polarity, the polarity of the induced voltage reverses.
- After 270º of rotation, the loop has rotated to the position shown, and the maximum terminal voltage will be the same as it was from A to C except that the polarity is reversed.




270º Position

# Elementary Generator(A):

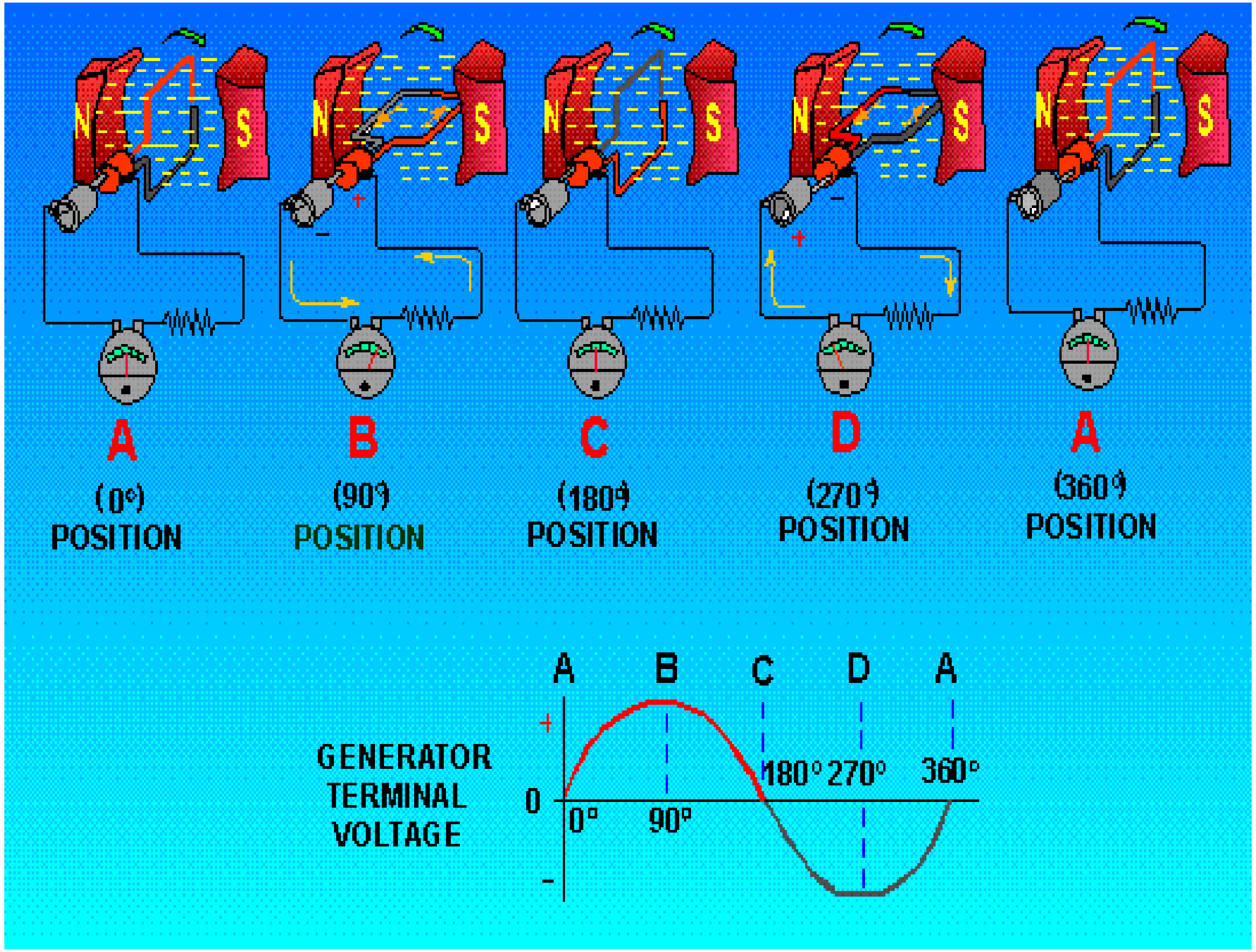
- After another $90^0$ of rotation, the loop has completed one rotation of $360^0$ and returned to its starting position.
- The voltage decreased from its negative peak back to zero.
- Notice that the voltage produced in the armature is an alternating polarity. The voltage produced in all rotating armatures is alternating voltage.




$360^o$ Position

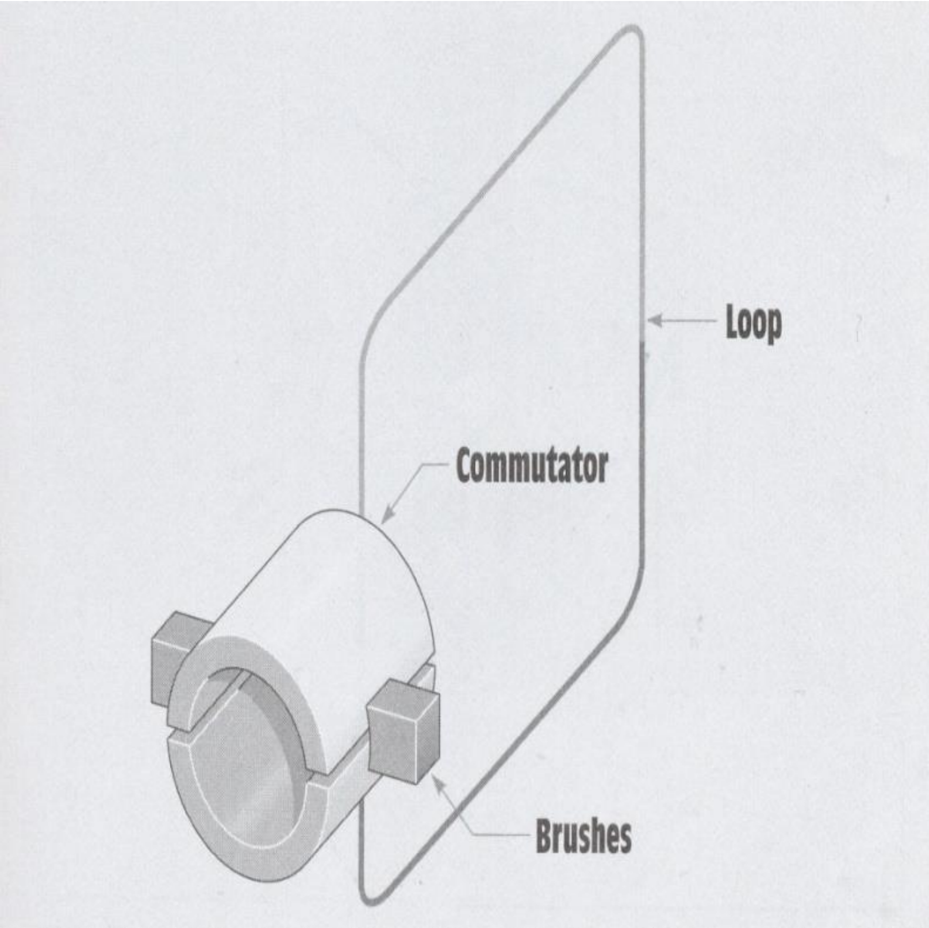
# Elementary Generator(Conclusion):

- Observes
  - The meter direction
  - The conductors of the armature loop
  - Direction of the current flow



# Elementary DC Generator:

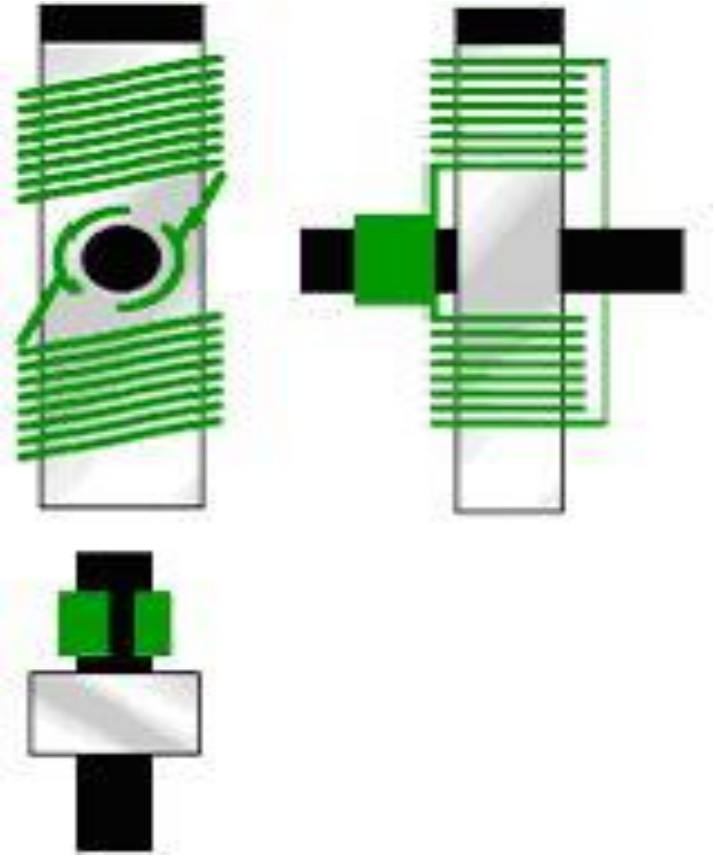
- Since DC generators must produce DC current instead of AC current, a device must be used to change the AC voltage produced in the armature windings into DC voltage.
- This job is performed by the **commutator.**
- The commutator is constructed from a copper ring split into segments with insulating material between the segments (See next page).
- Brushes riding against the commutator segments carry the power to the outside circuit.




- The commutator in a dc generator replaces the slip rings of the ac generator. This is the main difference in their construction.
- The commutator mechanically reverses the armature loop connections to the external circuit.

# Armature:

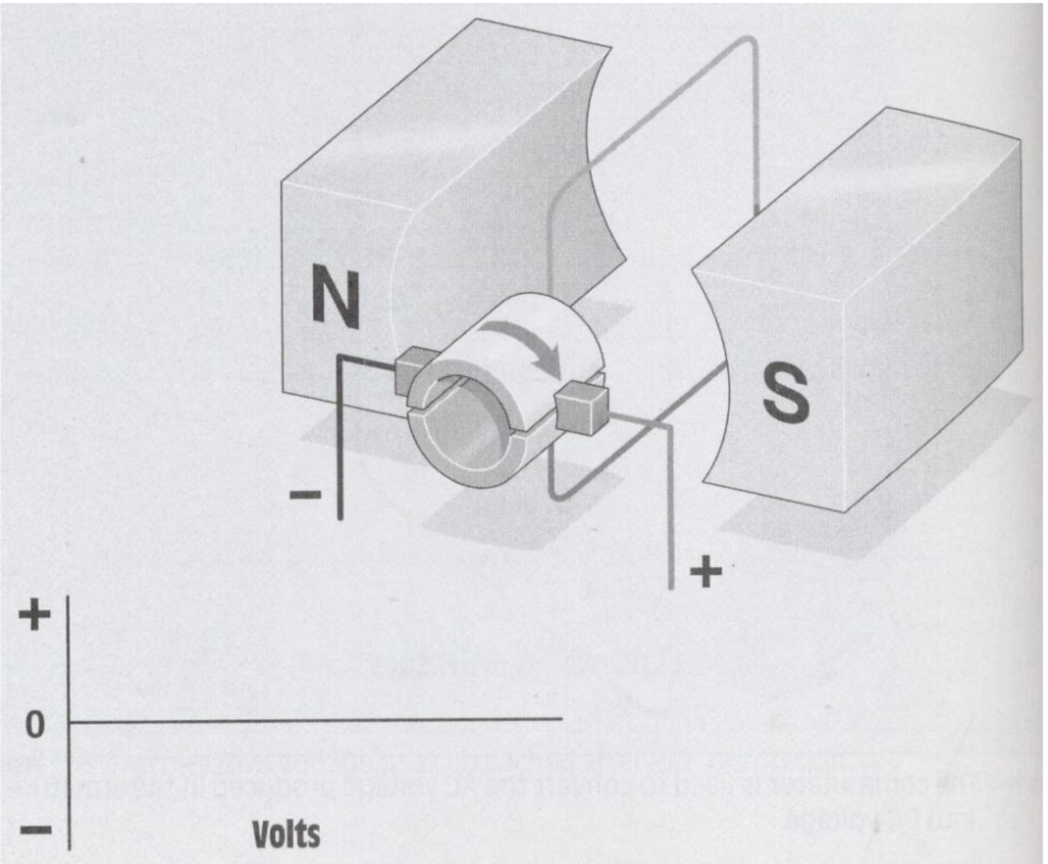
- The armature has an **axle**, and the commutator is attached to the axle.
- In the diagram to the right, you can see three different views of the same armature: front, side and end-on.
- In the end-on view, the winding is eliminated to make the commutator more obvious.
- We can see that the commutator is simply a pair of plates attached to the axle.
- These plates provide the two connections for the coil of the electromagnet.



Armature with commutator view

# Elementary DC Generator:

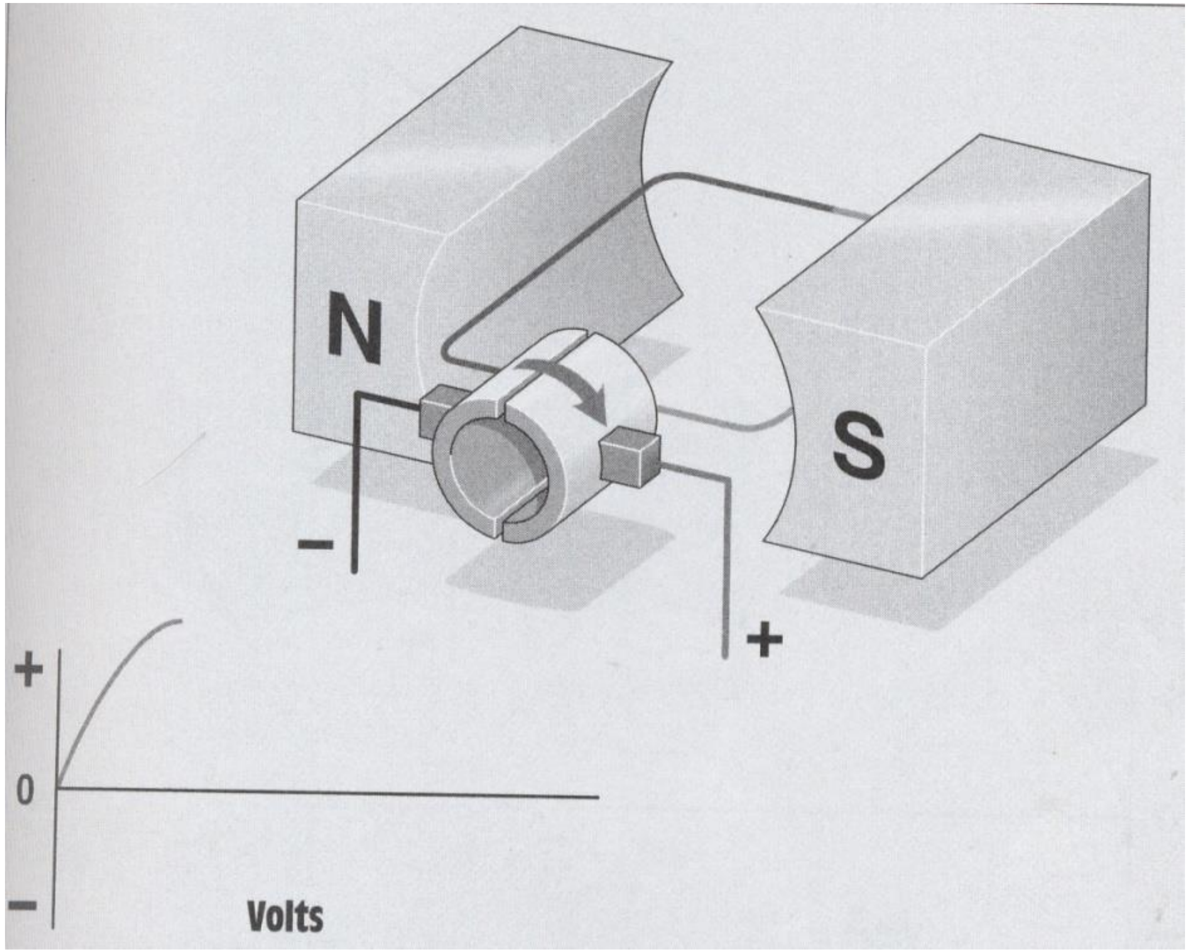
- The loop is parallel to the magnetic lines of flux, and no voltage is induced in the loop
- Note that the brushes make contact with both of the commutator segments at this time. The position is called neutral plane.




0º Position(DC Neutral plane)

# Elementary DC Generator:

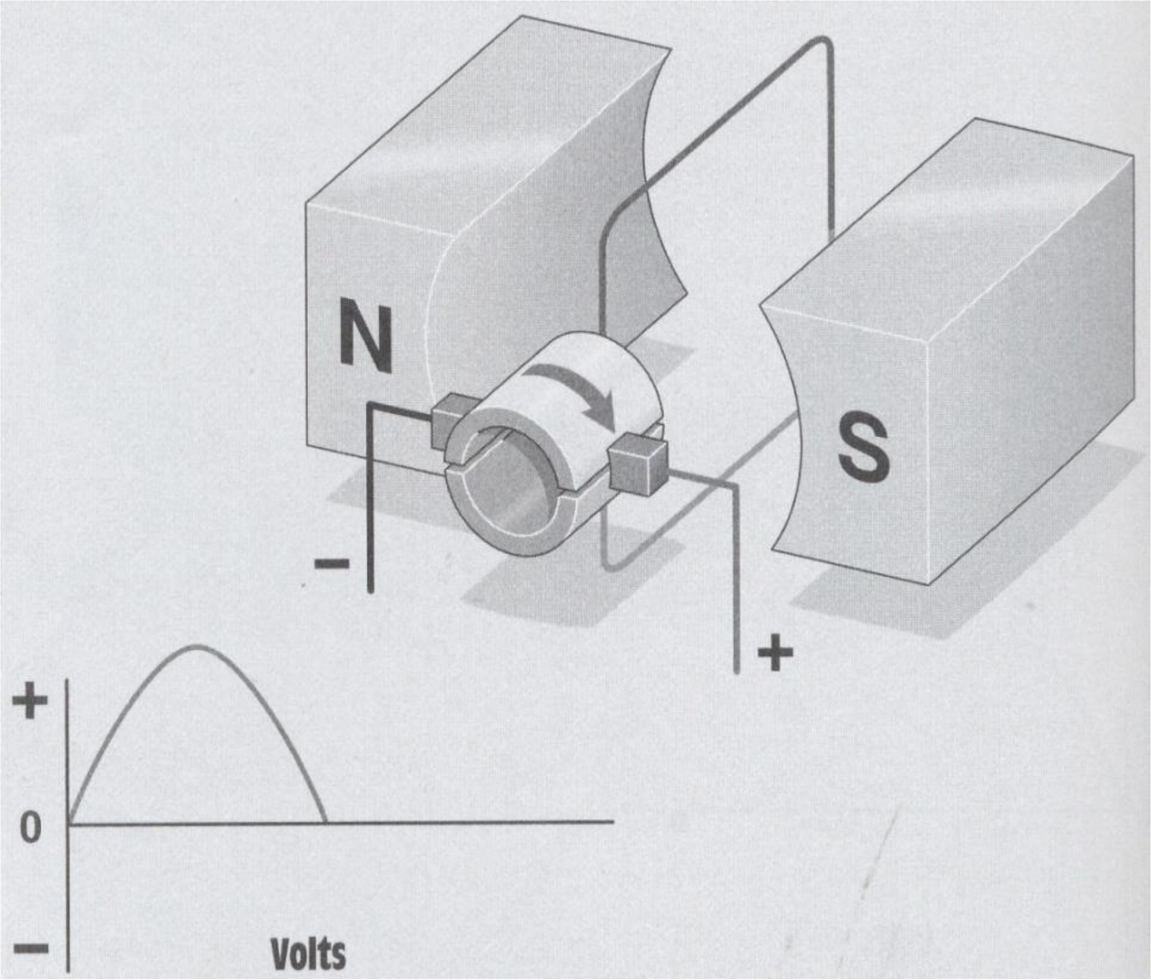
- As the loop rotates, the conductors begin to cut through the magnetic lines of flux.
- The conductor cutting through the south magnetic field is connected to the positive brush, and the conductor cutting through the north magnetic field is connected to the negative brush.
- Since the loop is cutting lines of flux, a voltage is induced into the loop.
- After $90^0$ of rotation, the voltage reaches its most positive point.




$90^o$ Position

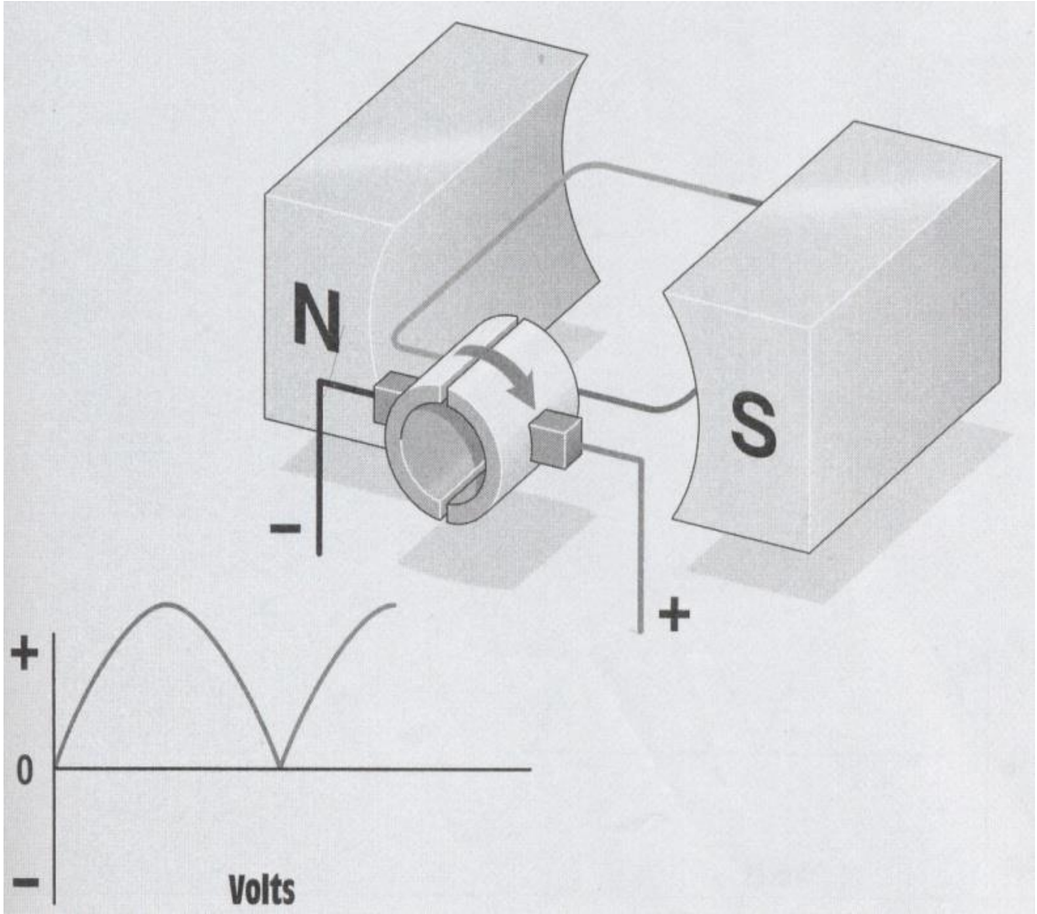
# Elementary DC Generator:

- As the loop continues to rotate, the voltage decreases to zero.
- After $180^0$ of rotation, the conductors are again parallel to the lines of flux, and no voltage is induced in the loop.
- Note that the brushes again make contact with both segments of the commutator at the time when there is no induced voltage in the conductors




180$^o$ Position(DC)

- During the next $90^0$ of rotation, the conductors again cut through the magnetic lines of flux.
- This time, however, the conductor that previously cut through the south magnetic field is now cutting the flux lines of the north field, and vice-versa. .
- Since these conductors are cutting the lines of flux of opposite magnetic polarities, the polarity of induced voltage is different for each of the conductors. The commutator, however, maintains the correct polarity to each brush.
- The conductor cutting through the north magnetic field will always be connected to the negative brush, and the conductor cutting through the south field will always be connected to the positive brush.
- Since the polarity at the brushes has remained constant, the voltage will increase to its peak value in the same direction.

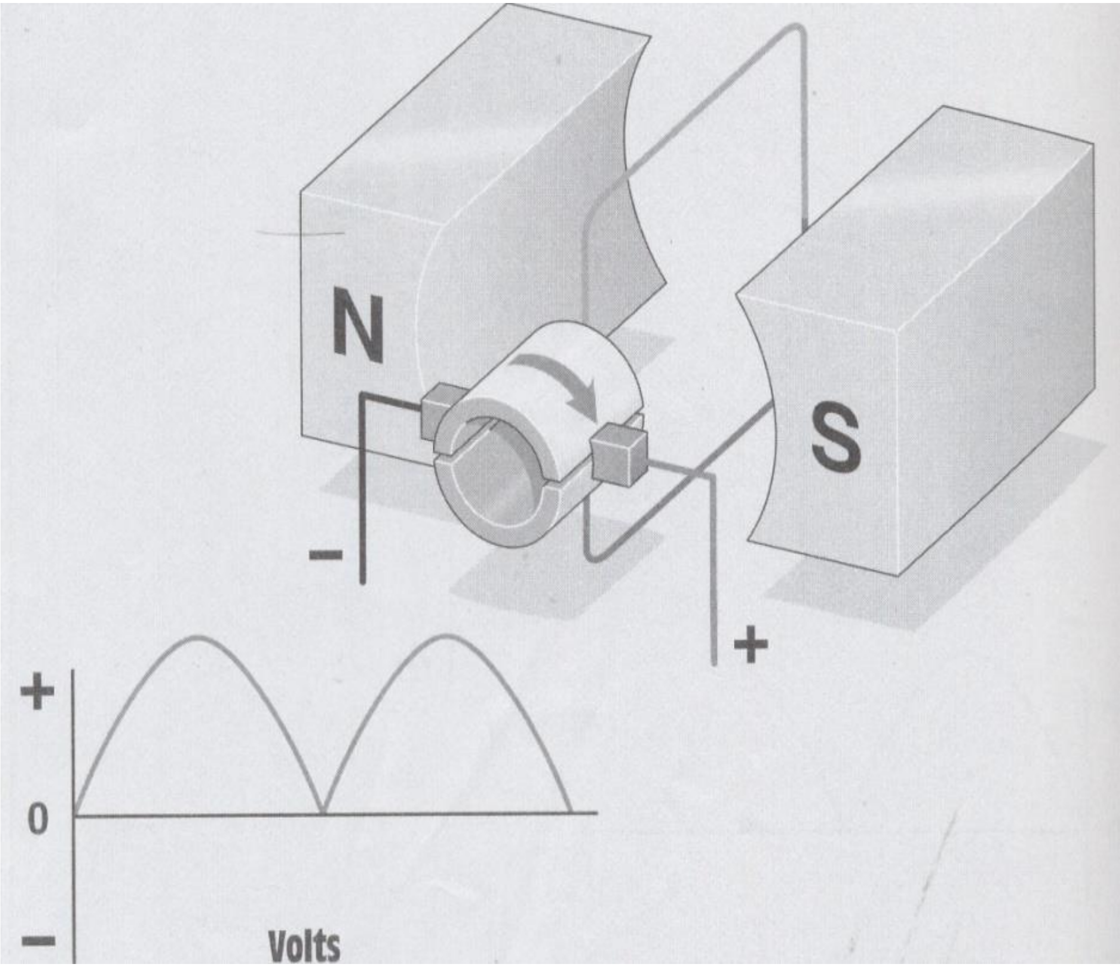



$270^o$ Position(DC)

**Elementary DC Generator**

# Elementary DC Generator:

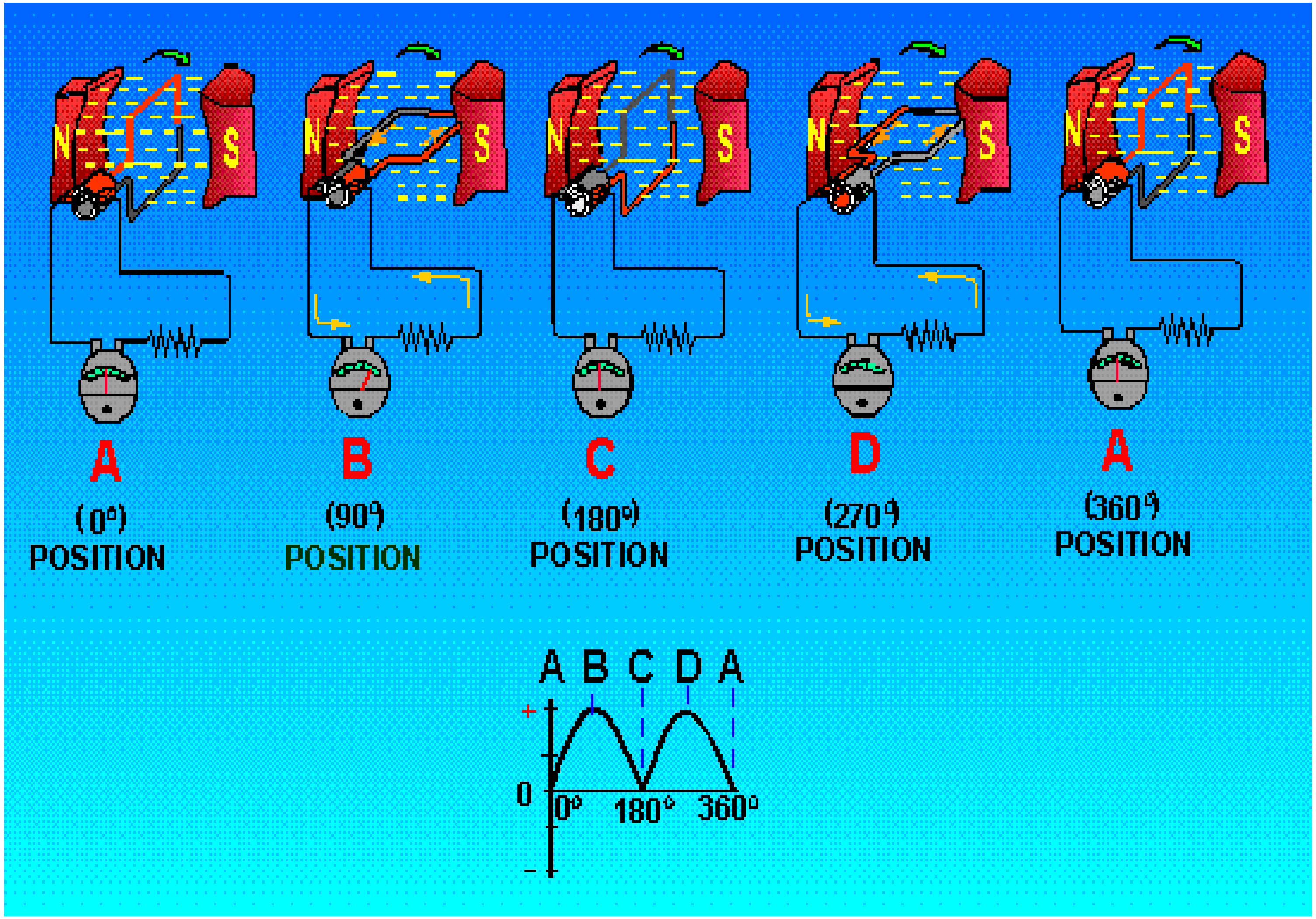
- As the loop continues to rotate, the induced voltage again decreases to zero when the conductors become parallel to the magnetic lines of flux.
- Notice that during this $360^0$ rotation of the loop the polarity of voltage remained the same for both halves of the waveform. This is called rectified DC voltage.
- The voltage is pulsating. It does turn on and off, but it never reverses polarity. Since the polarity for each brush remains constant, the output voltage is DC.




$0^o$ Position(DC Neutral Plane)

## Elementary DC Generator(Conclusion):

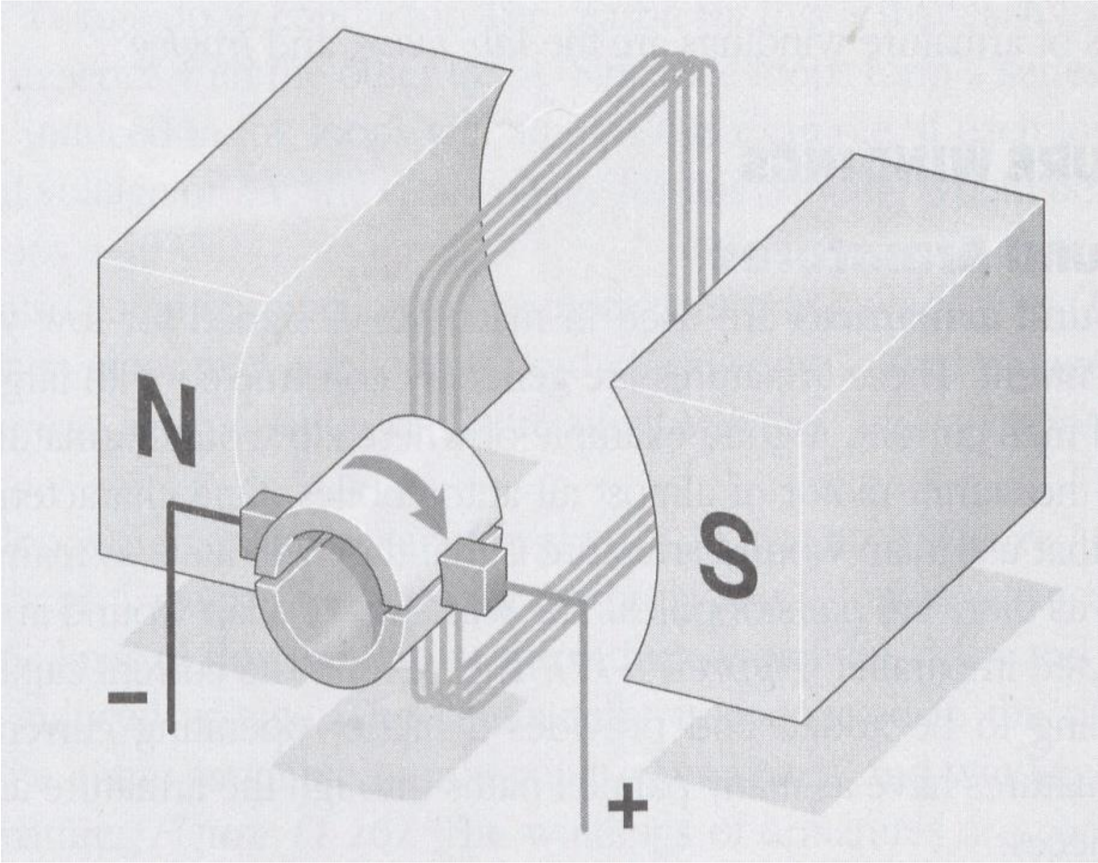
- Observes
  - The meter direction
  - The conductors of the armature loop
  - Direction of the current flow



# Effect of additional turns:

- To increase the amount of output voltage, it is common practice to increase the number of turns of wire for each loop.
- If a loop contains 20 turns of wire, the induced voltage will be 20 times greater than that for a single-loop conductor.
- The reason for this is that each loop is connected in series with the other loops. Since the loops form a series path, the voltage induced in the loops will add.
- In this example, if each loop has an induced voltage of 2V, the total voltage for this winding would be 40V.

(2V x 20 loops = 40 V)




Effect of additional turns

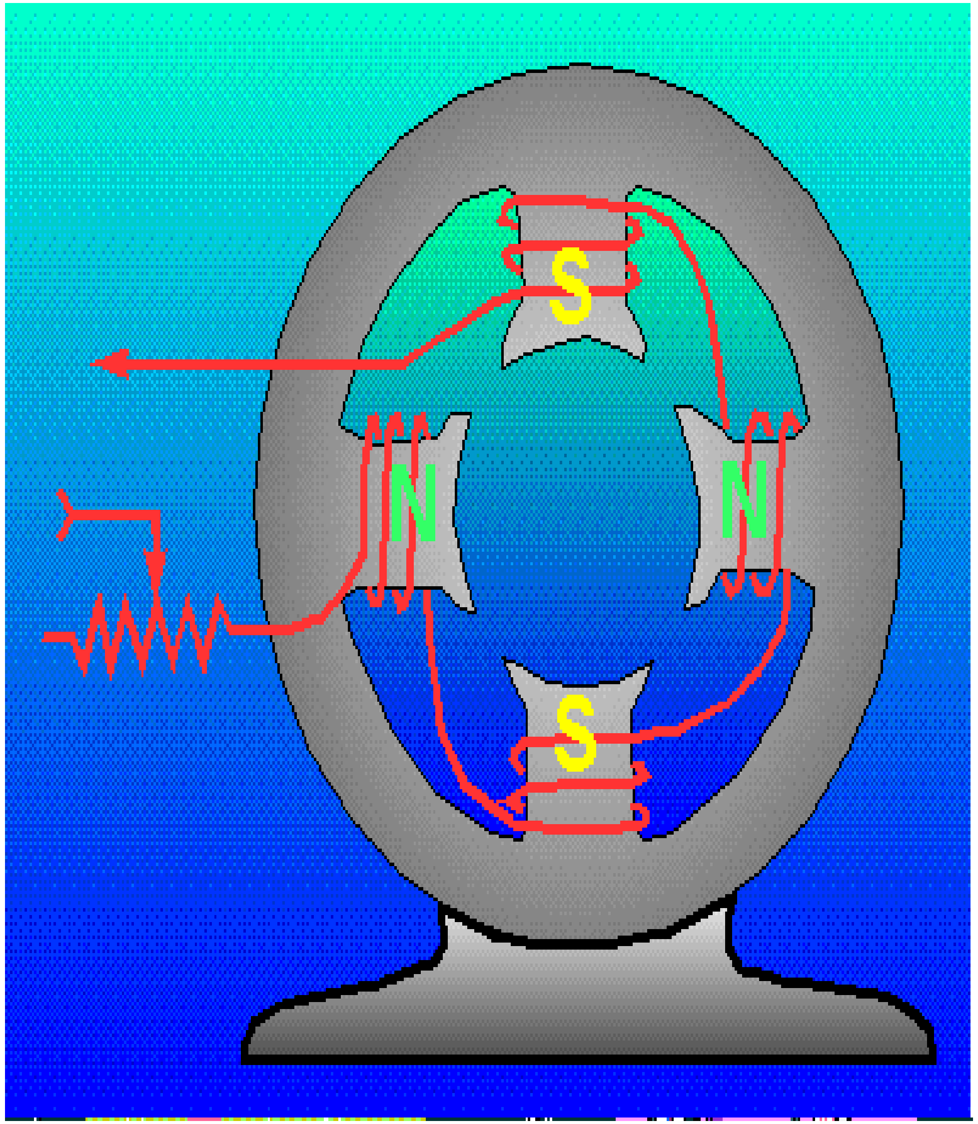
# Practical DC Generator:

- The actual construction and operation of a practical dc generator differs somewhat from our elementary generators
- Nearly all practical generators use electromagnetic poles instead of the permanent magnets used in our elementary generator
- The main advantages of using electromagnetic poles are:

  (1) increased field strength and

  (2)possible to control the strength of the fields. By varying the input voltage, the field strength is varied.

By varying the field strength, the output voltage of the generator can be controlled.



Four-pole generator(without armature)

The DC Generators and DC Motors have the same general construction. In fact, when the machine is being assembled, we usually do not know whether it is DC Generator or DC Motor. All the DC Machines have 5 principle components, i.e.,

i. Field system
ii. Armature core
iii. Armature winding
iv. Commutator
v. Brushes

## (i)Field system:

The function of the field system is to produce uniform magnetic field within which the armature rotates.

It consists of a number of salient poles(even number) bolted to the inside of circular frame(yoke).

The yoke is usually made of cast steel(solid) whereas the pole pieces are composed of stacked laminations. 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.

The mmf developed by the field coil produces a magnetic flux that passes through the pole pieces, the air gap, the armature as shown in fig(b).

By reducing the length of air gap, we can reduce the size of field coils(no of turns).

## (ii) Armature core:

The armature core is keyed to the machine shaft and rotates between the field poles. It consists of slotted soft-iron laminations(about 0.4 mm to 0.6 mm thick) that are stacked to form a cylindrical core.

The laminations are individually coated with a thin insulating film so that they do not come in electrical contact with each other.

The purpose of laminating the core is to reduce the eddy current losses.

The laminations are slotted to accommodate and provide mechanical security for the armature winding and to give shorter air gap for the flux to cross between the pole face and the armature teeth.

## (iii) Armature winding:

The slots of the armature core holds insulated conductors that are connected in a suitable manner. This is known as armature winding. This is the winding in which working emf is induced.

The armature conductors are connected in series-parallel. The conductors being connected in series so as to increase the voltage and in parallel paths so as to increase the current.

## (iv) Commutator:

A commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct current across the brushes.

The commutator is made up of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine.

The armature conductors are slotted to the commutator segments in a suitable manner to give rise to armature winding.

Greater care is taken in building the commutator because any eccentricity will cause the brushes to bounce, produce unacceptable sparking.

The sparks may burn the brushes and overheat and carbonise the commutator.

## (v) Brushes:

The purpose of brushes is to ensure electrical connections between the rotating commutator and stationary external load circuit.

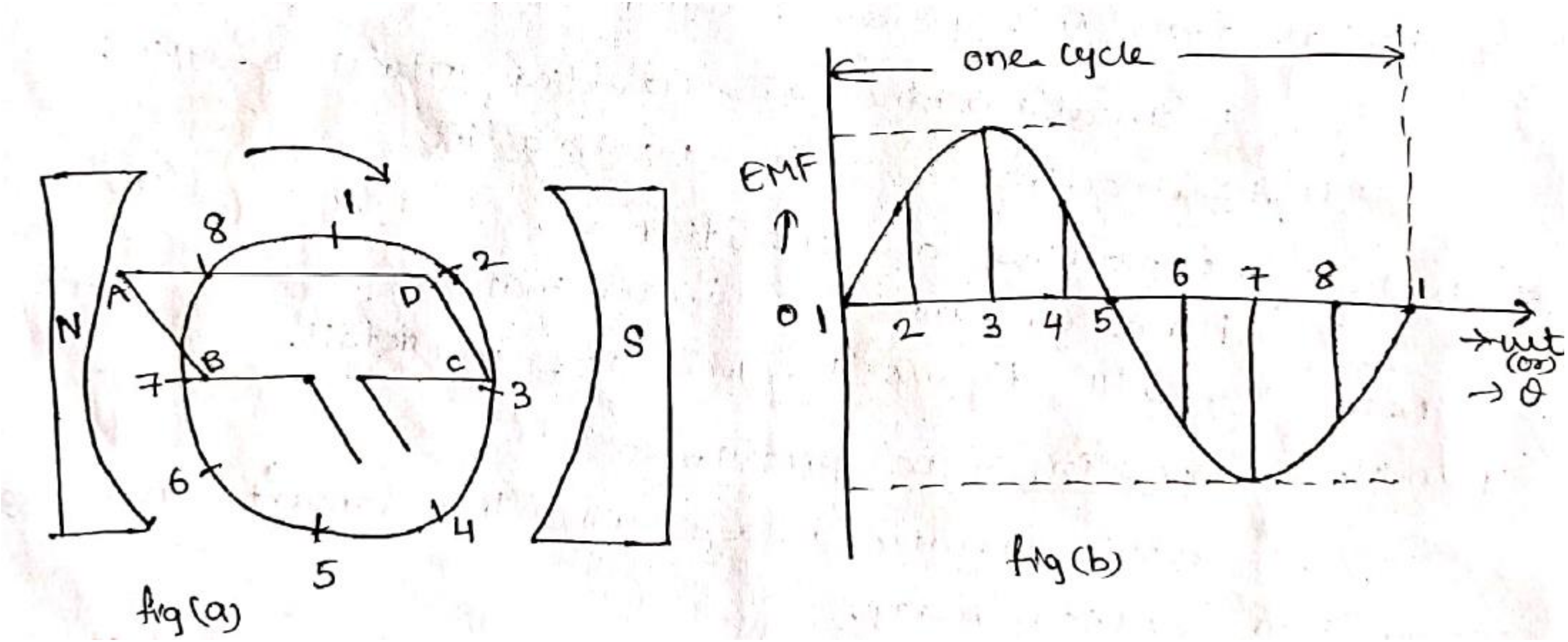
When the machine is acting as a generator, the brushes carry current from the commutator to the external stationary load.

In case, the machine is acting as a motor, they feed supply current to the commutator.

The brushes are made up of carbon and rest on the commutator.

As we go round the commutator, the successive brushes have +ve and –ve polarities. Brushes having the same polarity are connected together so that we have two terminals i.e., +ve and –ve terminal

# Simple Loop Generator:




Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in figure(a). As the loop rotates the magnetic flux linking the coil sides AB & CD changes continuously.

Hence the emf induced in these coil sides also changes but the emf induced in one coil side adds to that induced in the other.

It is because the coil sides always remain under the influence of opposite poles i.e., if one coil side is under the influence of the N-Pole, then the other coil side will be under the influence of S-Pole and vice-versa.

i. When the loop is in position no:1(see fig(a)), then the generated emf is zero, because the coil sides(AB & CD) are cutting no magnetic flux but are moving parallel to it.
ii. When the loop is in position no:2, the coil sides are moving at an angle to the magnetic flux and therefore, a low emf is generated as indicated by point 2 in fig(b).
iii. When the loop is in position no:3, the coil sides(AB & CD) are at right angles to the magnetic flux, and therefore cutting the flux at a maximum rate. Hence, at this instant the generated emf is maximum as indicated by point 3 in fig(b).
iv. At position 4, the generated emf is less because the coil sides are cutting the magnetic flux at an angle.
v. At position 5, no magnetic lines are cut and hence induced emf is zero as indicated by point 5 in fig(b).

(vi) At position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated emf is reversed. The maximum emf in this direction(reverse direction, see fig(b)) will be when the loop is at position 7 and zero when at position 1.

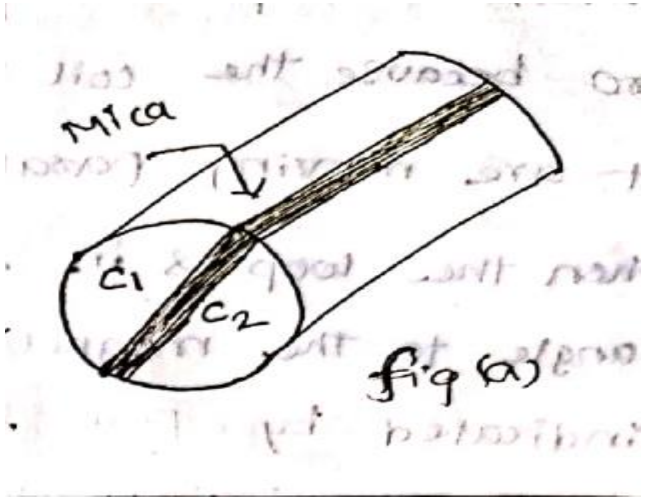
This cycle repeats with each revolution of the coil.

Note that emf generated in the loop is alternating one. It is because any coil side say AB, has emf in one direction when under the influence of N-pole and in the other direction when under the influence of S-pole.

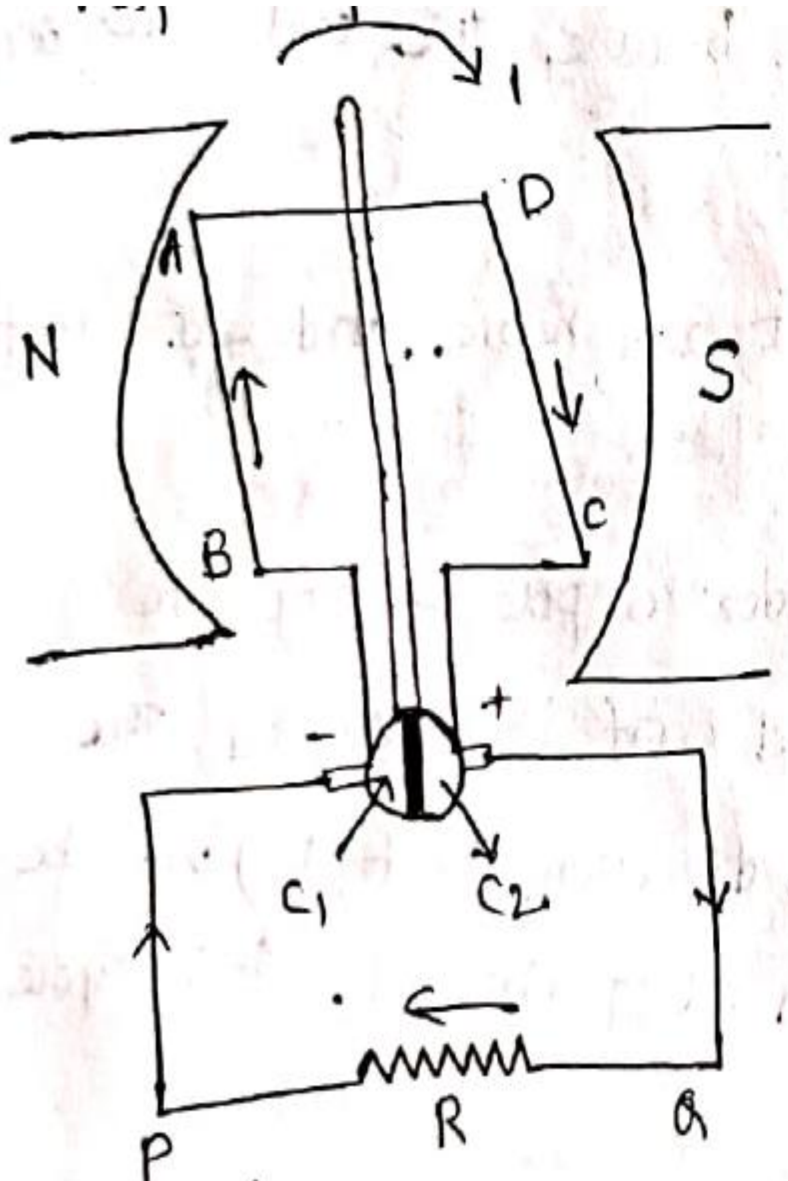
If a load is connected across the ends of the loop, then alternating current will flow through the load. The alternating voltage generated in the loop can be converted into DC by a device called commutator. In fact, commutator is a mechanical rectifier.

**Commutator:**

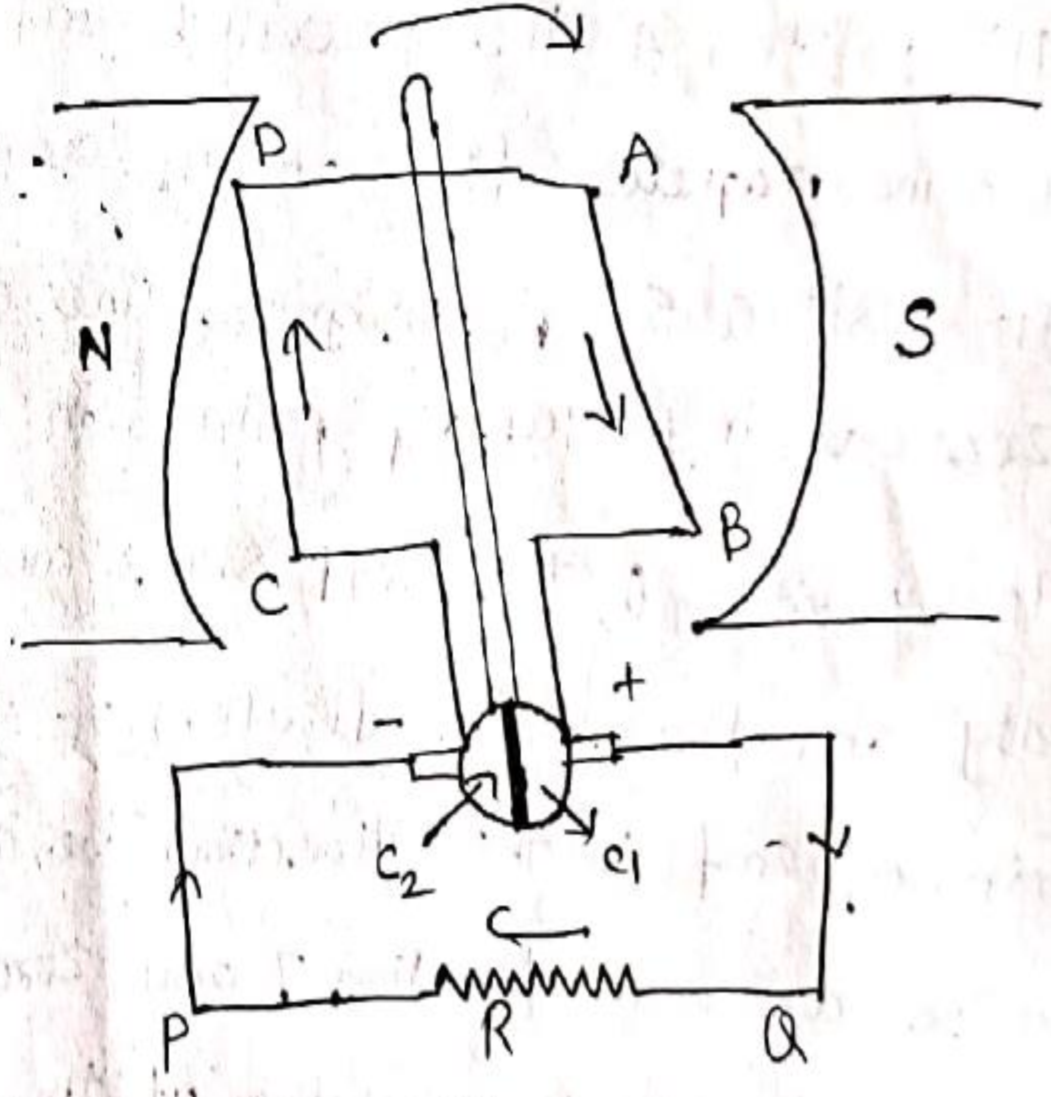
If some by means, connection of coil side to the external load is reversed and at the same instant the current in the coil side reverses, the current through the load will be DC.




Fig(a) shows a commutator having two segments $C_1$ & $C_2$. It consists of a cylindrical metal ring cut into two halves or segments $C_1$ & $C_2$ respectively separated by thin sheet of mica.




fig(b)




fig(c)

The commutator is mounted on, but insulated from the rotor shaft. The ends of coil sides AB & CD are connected to the segments $C_1$ & $C_2$ respectively as shown in fig(b). Two stationary carbon brushes rest on the commutator and lead current to the external load. With this arrangement, the commutator at all times connects the coil side under S-pole to the +ve brush and that under N-pole to the –ve brush.

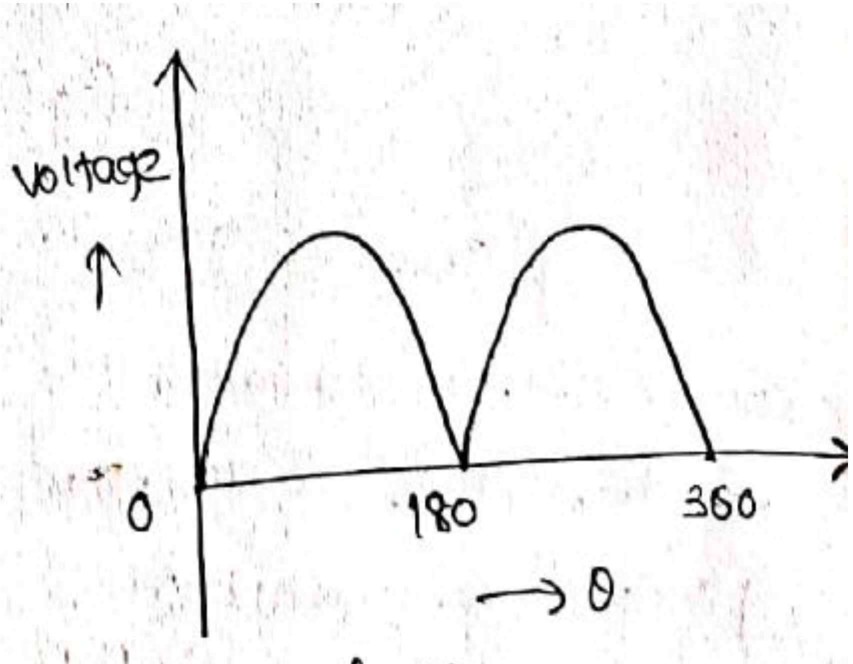
(i) In fig(b), the coil sides AB & CD are under N-pole and S-pole respectively. Note that segment $C_1$ connects the coil side AB to point P of the load resistance R and the segment $C_2$ connects the coil side CD to point Q of the load. Also note the direction of current through load. It is from Q to P.

(ii) After half a revolution of the loop(180$^o$ rotation), the coil side AB is under S-pole and the coil side CD under N-pole as shown in fig(c). The current in the coil sides now flow in the reverse direction but the segments $C_1$&$C_2$ have also moved through 180$^o$ i.e., segment C1 is now in contact with +ve brush and segment C2 in contact with –ve brush.

Note that commutator has reversed the coil connections to the load i.e., coil AB is now connected to point Q of the load and coil side CD to the point P of the load.

Also note the direction of current through the load. It is again from Q to P(i.e., the current in the coil sides are reversed and at the same time the connections of the coil sides to the external load are reversed. This means that

current will flow in the same direction through the load.
Thus the alternating voltage generated in the loop will appear as direct voltage across the brushes.
Note that emf generated in the armature winding of a DC Generator is AC. The purpose of brushes is simply to lead current from the rotating loop or winding to the external stationary load.
The variation of voltage across the brushes with the angular displacement of the loop is shown in fig(d).



fig(d)

This is not a steady direct voltage but has a pulsating character. It is because the voltage appearing across the brushes varies from zero to maximum value and back to zero twice for each revolution of the loop.
A pulsating direct voltage produced by a single loop is not suitable for use. This can be achieved by using a large number of coils connected in series. The resulting arrangement is known as armature winding.

# EMF Equation of DC Generator:

Let $\phi$ = magnetic flux/pole in webers

Z = Total no: of armature conductors

P = No: of poles

A = No: of parallel paths

2 for wave winding

P for Lap winding

N = Speed of armature in rpm

Eg = EMF of the generator

Magnetic flux cut by one conductor in one revolution of the armature $d\phi = p\phi$ webers

Time taken to complete one revolution

$dt = 60/N$ sec

EMF generated/conductor = $d\phi/dt = P\phi/60/N$

$P\phi N/60$ Volts

EMF of generator =

Eg = (Emf/conductor) * no: of conductors/parallel path

$(P\phi N/60) * (Z/A)$

**Eg = $\phi ZNP/60A$ volts**

Where A = 2 for wave winding

A = P for Lap winding

## Armature Resistance:

The resistance offered by the armature circuit is known as armature resistance(Ra) and includes:

Resistance of armature winding

Resistance of brushes

The armature resistance depends upon the construction of machine. Except for small machines its value is generally less than 1Ω.

## Types of DC Generators:

The magnetic field in a DC Generator is normally produced by electromagnets rather than permanent magnets. Generators are generally classified according to their method of field excitation.

On this basis DC Generators are divided into two classes:

Separately excited DC Generators

Self excited DC Generators

The behavior of DC Generator on load depends upon the method of field excitation adopted.

# Separately Excited DC Generators:

A DC Generator whose field winding magnet is supplied from an independent external DC source is called separately excited DC generator. Fig(a) shows the connections of a separately excited DC Generator. The voltage output depends upon the speed of rotation of armature and the field current($E_g$=ϕZNP/60A) The greater the speed and the field current, greater is the generated emf. Separately excited DC Generators are rarely used in practice. The DC generators are normally of Self-excited type.

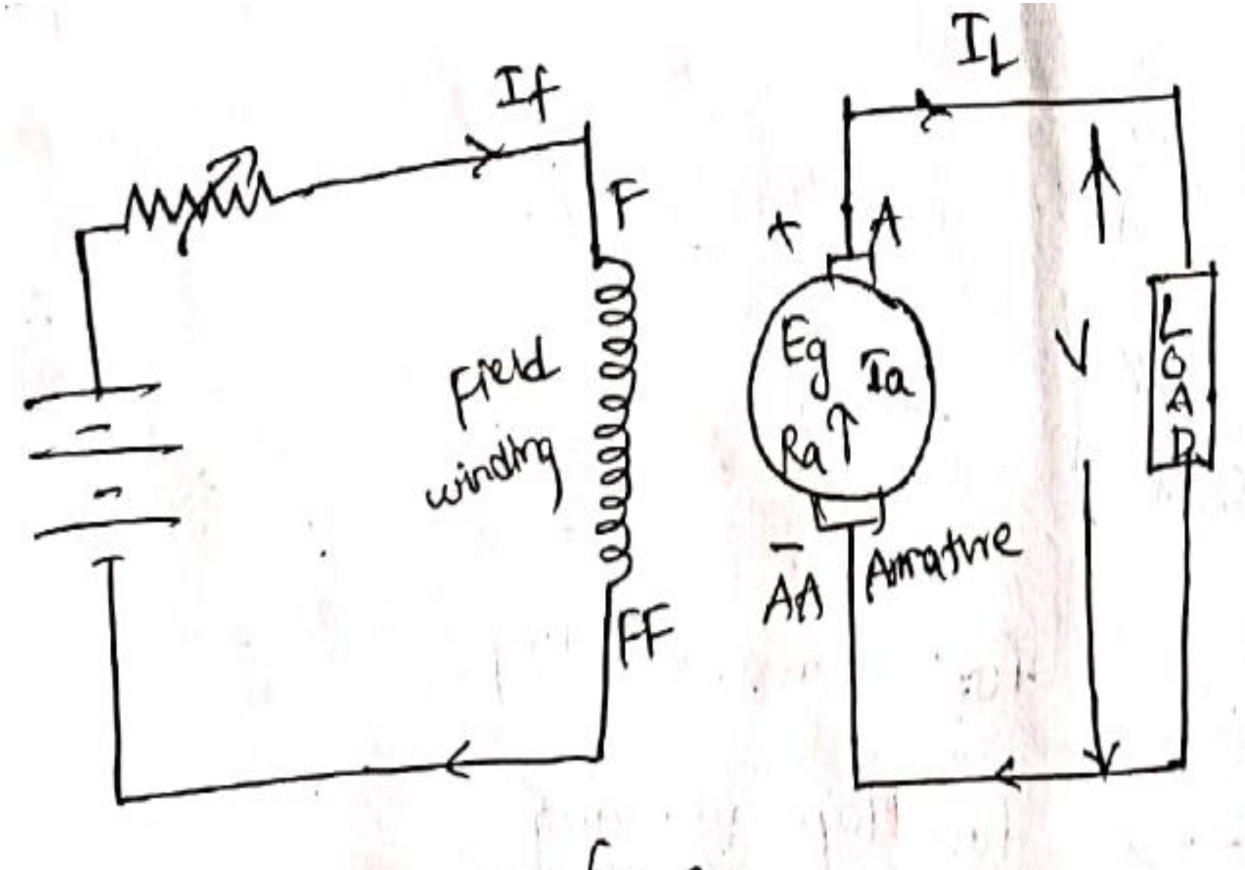


fig (a)

Armature current = $I_a = I_L$

Terminal voltage = $V = E_g - I_a R_a$

Electric power Developed = $E_g I_a$

power delivered to load = $E_g I_a - I_a^2 R_a = I_a(E_g - I_a R_a) = V I_a$

## Self excited DC Generators:

A DC Generator whose field winding magnet is supplied current from the output of the generator itself is called self excited DC Generator.

When the armature is rotated, a small voltage is induced in the armature winding due to **Residual Magnetic Flux** in the poles. This voltage produces a small field current in the field winding and causes the flux/pole increases. The increased flux increases the induced voltage which further increases the field current. This event takes place rapidly and the generator builds up to the rated generated voltage. There are 3 types of self excited DC Generators depending upon the matter in which the field winding is connected to the armature, namely:

i. Series Generator
ii. Shunt Generator
iii. Compound Generator

## (i) Series Generator:

In a series wound generator the field winding is connected in series with the armature winding so that the whole armature current flows through the field winding as well as the load.

Fig(a) shows the connections of a series wound generators. Since the field winding carries the whole of the load current; it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes i.e., as boosters.

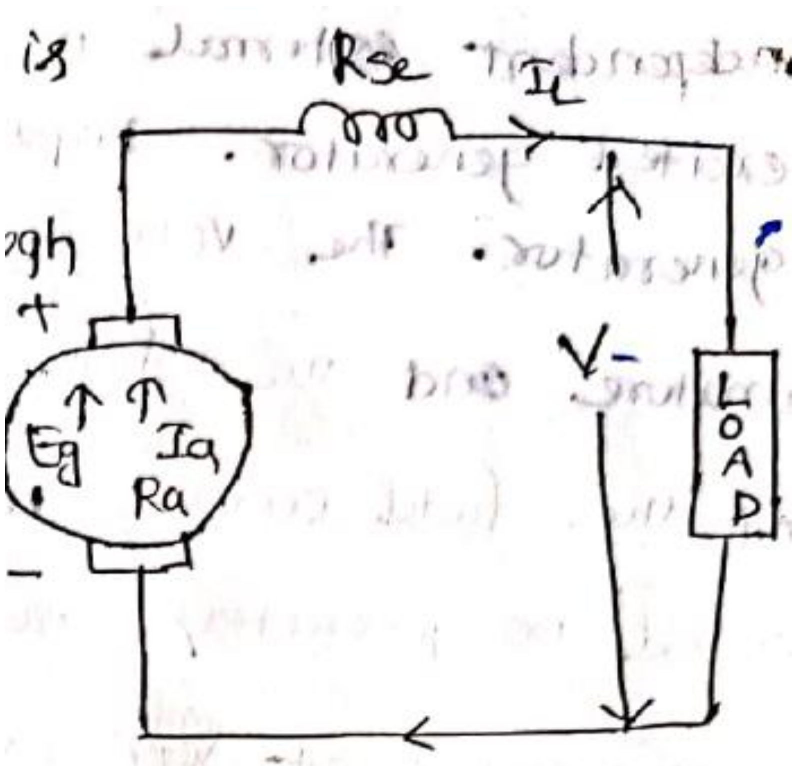



fig (a)

Armature current $= I_a = I_{se} = I_L = I$ (say)

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

power Developed in Armature $= E_g I_a$

power delivered to load $= E_g I_a - I_a^2 (R_a + R_{se})$.

$I_a [E_g - I_a(R_a + R_{se})] = V I_a$ or $V I_L$

# (ii) Shunt Generator:

In DC 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. Fig(a) shows the connections of a shunt wound generator.

Shunt field current $= I_{sh} = V/R_{sh}$

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

Terminal voltage $= V = E_g - I_a R_a$

power developed in armature $= E_g I_a$

power delivered to load $= V I_L$

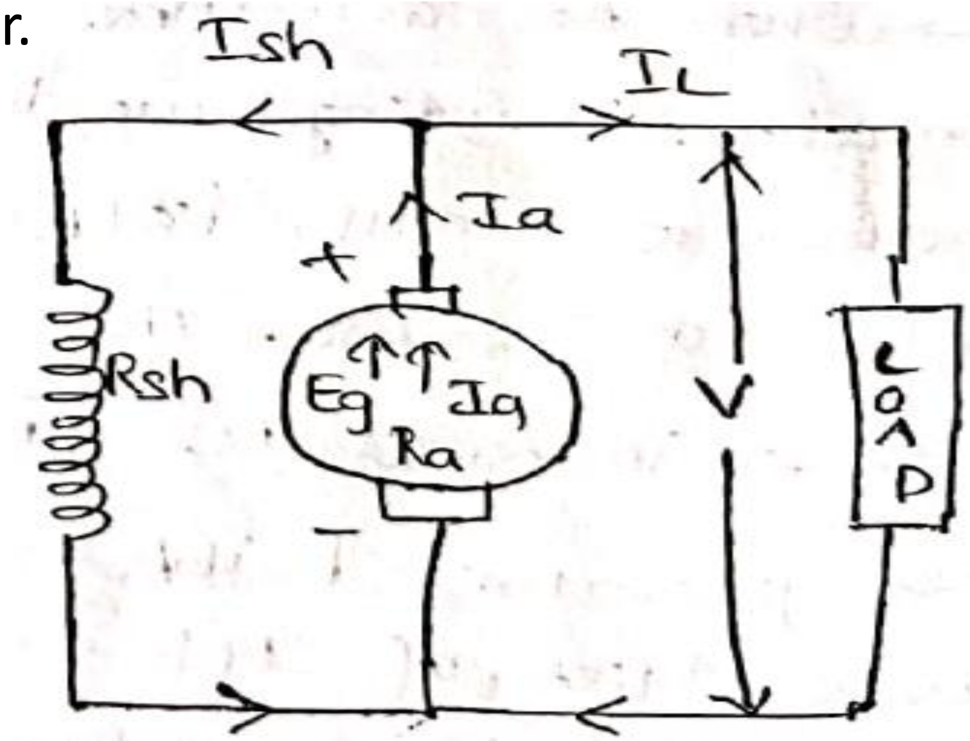


fig (a)

# (iii) Compound Generator:

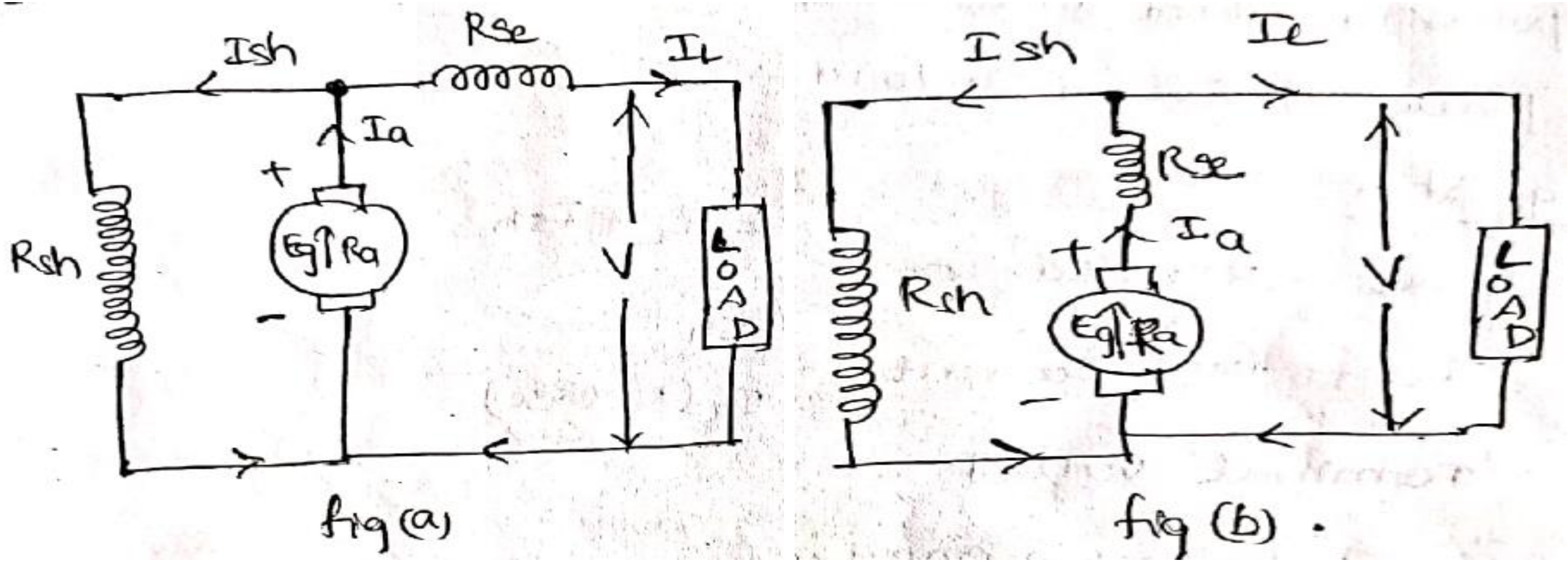


fig (a) fig (b).

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 generator may be:

(a) Short shunt in which only shunt field winding is in parallel with the armature winding as in fig(a).

(b) Long shunt in which shunt field winding is in parallel with both series field and armature winding.

Normally, the majority of mmf is provided by the shunt field. The two windings may be connected to aid each other(cumulative compounding) or they oppose each other(differential compounding).

**Short Shunt :-**

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

Shunt field current = $I_{sh} = \frac{V_t \; I_{se} R_{se}}{R_{sh}}$

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

power developed in armature = $E_g I_a$

power delivered to load = $V I_L$

**Long Shunt :-**

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

Shunt field current = $I_{sh} = V / R_{sh}$

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

power developed in Armature = $E_g I_a$

power delivered to load = $V I_L$

# Losses in a DC Machine:

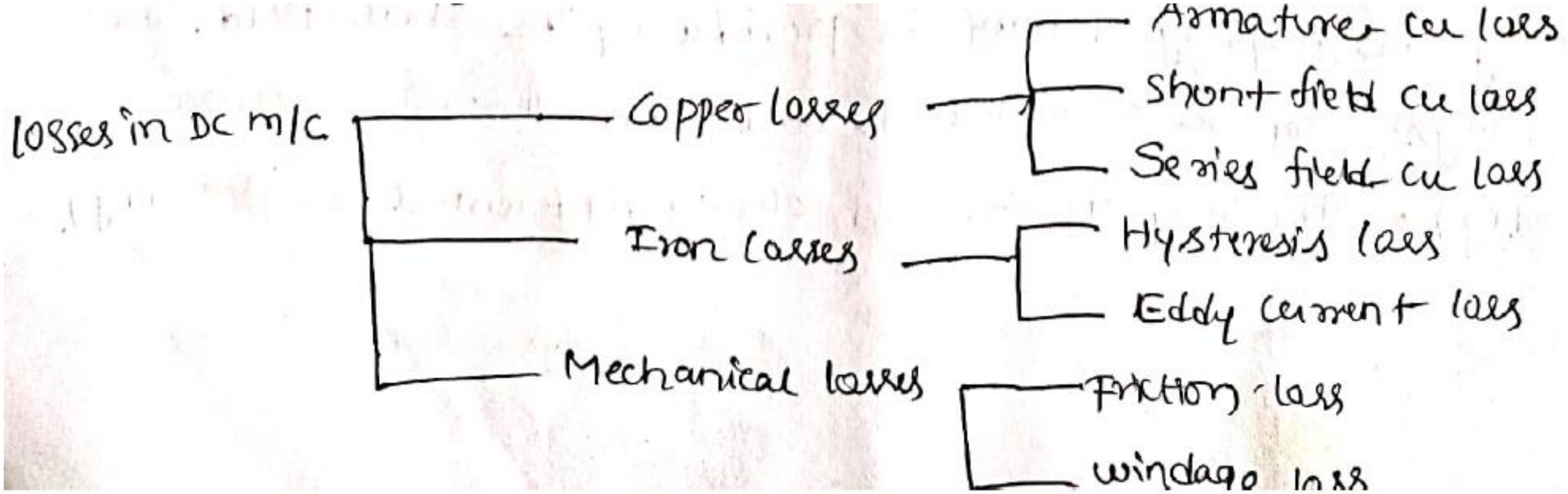
The losses in a DC Machine(Generator or Motor) may be divided into three classes viz.,

i. Copper losses

ii. Iron or core losses

iii. Mechanical losses

- All these losses appear as heat and thus raise the temperature of the machine. They also lower the efficiency of the machine.



## (i) Copper losses:

These losses occur due to currents in the various windings of the machine.

Armature copper loss = $I_a^2 R_a$

Shunt field copper loss = $I_{sh}^2 R_{sh}$

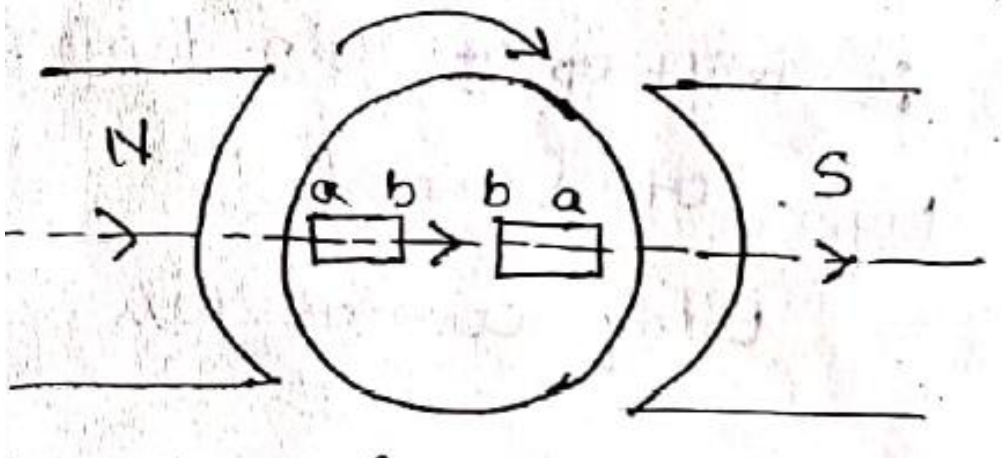
Series field copper loss = $I_{se}^2 R_{se}$

## (ii) Iron or Core losses:

These losses occur in the armature of a DC Machine and are due to the rotation of armature in the magnetic field of the poles. They are two types viz
(a) Hysteresis loss
(b) Eddy current loss

### (a) Hysteresis Loss:

These losses occur in the armature of a DC Machine since any given part of the armature is subjected to magnetic field reversals as it passes under successive poles.



fig(a)

Fig(a) shows an armature rotating in two-pole machine. Consider a small piece ab of the armature. When the piece ab is under N-pole, the magnetic lines pass from a to b. Half a revolution later, the same piece of iron is under S-pole and the magnetic lines pass from b to a so that magnetism in the iron is reversed. In order to reverse continuously the molecular magnets in

The armature core, some amount of power has to spent which is called hysteresis loss and is given by

**$P_h = \eta B_{max}^{1.6} f V$ Watts**

$B_{max}$ = max: magnetic flux density in armature

f = frequency of magnetic reversals

= NP/120 where N is in rpm

V = volume of armature in $m^3$

H = steinmetz hysteresis coefficient

In order to reduce this loss in a DC Machine armature core is made of such materials which have a low value of steinmetz hysteresis coefficient e.g., Silicon Steel.

**(b) Eddy Current Loss:**

When armature rotates in the magnetic field of poles, an emf is induced in it which Circulates eddy currents in the armature core. The power loss due to these eddy currents is called eddy current loss. In order to reduce this loss, the armature core is made up of thin laminations insulated from each other by a thin layer of varnish.

**Eddy current loss=$P_e = K_e B_{max}^2 f^2 t^2 V$ Watts**

Where $K_e$ = constant

$B_{max}$ = max: magnetic flux density

f = frequency of magnetic reversal

t = thickness of laminations

v = volume of material in $m^3$

It may be noted that eddy current loss depends upon the square of lamination thickness. For this reason, lamination thickness should be kept as small as possible.

## (iii) Mechanical losses:

These losses are due to friction & windage

(a) Friction loss i.e., bearing friction, brush friction.

(b) Windage loss i.e., air friction of rotating armature.

These losses depend upon the speed of the machine. But for a given speed, they are practically constant.

Iron losses & Mechanical losses together are called Stray losses.

## Constant & Variable losses:

The losses in a DC Generator or a DC Motor may be sub-divided into:

(a) Constant losses

(b) Variable losses

## (a) Constant losses:

The losses in a DC Generator which remains constant at all loads are known as constant losses. The constant losses in a DC Generator are:

- Iron losses
- Mechanical losses
- Shunt field losses

## (b) Variable losses:

The losses in a DC Generator which vary with load are called variable losses. The variable losses in a DC Generator are:

Copper loss in the armature winding($I_a^2R_a$)

Copper loss in series field winding($I_{se}^2R_{se}$)

**Total loss = Constant loss + Variable loss**

# Power Stages:

The various power stages in a DC Generator are represented diagrammatically shown in fig(a).

(i) Mechanical Efficiency

$$\eta_{mech} = \frac{B}{A} = \frac{E_g I_a}{\text{Mechanical power Input}}$$

(ii) Electrical efficiency

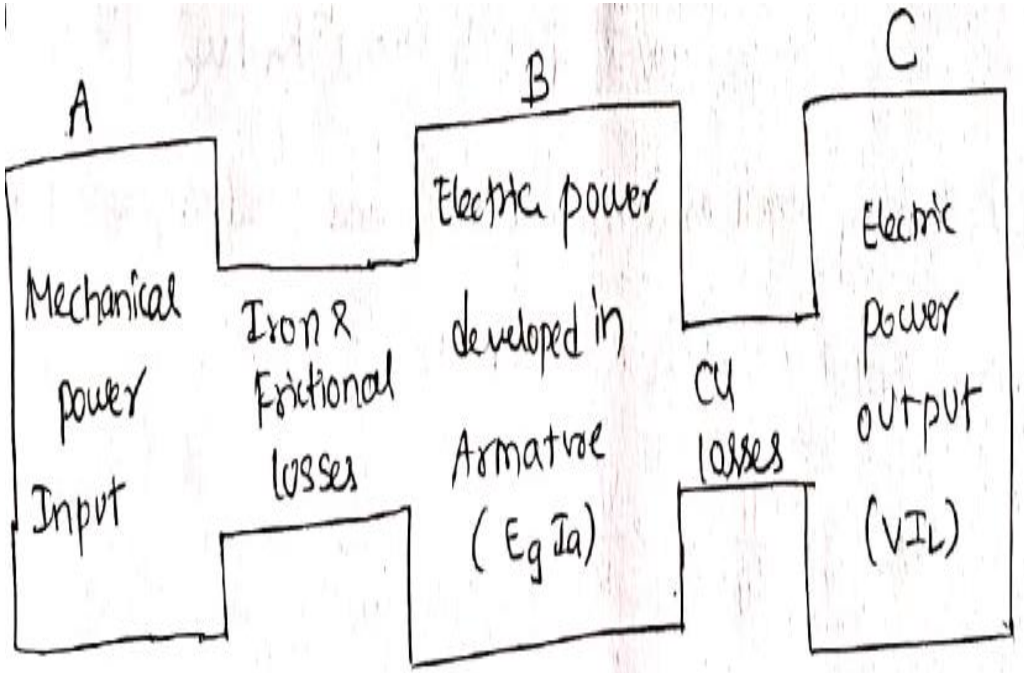
$$\eta_{elec} = \frac{C}{B} = \frac{V I_L}{E_g I_a}$$

(iii) Commercial or Overall efficiency

$$\eta_{comm} = \frac{C}{A} = \frac{V I_L}{\text{Mechanical power Input}}$$

So, $\eta_{comm} = \eta_{mech} \times \eta_{elec}$

$$\eta_{comm} = \frac{C}{A} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}}$$




fig(a)

A − B = Iron & Frictional losses

B − C = Copper losses

# Condition for maximum efficiency:

The efficiency of a DC Generator is not constant but varies with load. Consider a DC shunt generator delivering a load current $I_L$ at a terminal voltage V.

Generator output = $V*I_L$

Generator input = Output + Total losses

= $V*I_L$ + Variable losses + Constant losses

= $V*I_L + I_a^2*R_a + W_c$

= $V*I_L + (I_L+I_{sh})^2*R_a + W_c$ [Ia=IL+Ish]

The $I_{sh}$ is generally small as compared to $I_L$ and therefore neglected;

Generator input = $V*I_L + I_L^2*R_a + W_c$

$\eta$ = output/input

= $V*I_L/ V*I_L + I_L^2*Ra + W_c$

= $1/(1+(I_LR_a/V)+(W_c/VI_L))$ -------(1)

The η will be maximum when the denominator of eqn (1) is minimum

$$\frac{d}{dI_L}\left(\frac{I_L R_a}{V} + \frac{W_c}{V I_L}\right) = 0$$

(or) $$\frac{R_a}{V} - \frac{W_c}{V I_L^2} = 0$$

$$\frac{R_a}{V} = \frac{W_c}{V I_L^2}$$

$I_L^2 R_a = W_c$ i.e., $I_a^2R_a = W_c$

i.e., Variable loss = Constant loss

Then load current corresponding to $\eta_{max}$ is given

$$I_L = \sqrt{\frac{W_c}{R_a}}$$

Hence, the efficiency of a DC Generator will be maximum when the load current is such that variable loss is equal to the constant loss.

## Numerical Problems

1. Calculate the emf generated by 4-pole wave wound generator having 65 slots with 12 conductors/slot when driven at 1200 rpm. The flux per pole is 0.02 webers.
2. An 8-pole, lap-wound armature rotated at 350 rpm is required to generate 260V. The useful magnetic flux/pole is 0.05 wb. If the armature has 120 slots. Calculate the no: of conductors/slot.
3. A 6-pole lap wound DC Generator has 600 conductors on its armature. The flux per pole is 0.02 wb. Calculate;

i. The speed at which the generator must be run to generate 300V.

ii. What would be the speed if the generator were wave wound.

4. The armature of a 6-pole, 600 rpm lap wound generator has 90 slots. If each coil has 4 turns, calculate the flux/pole required to generate an emf of 288 V.

5. A 100kW, 240V DC Shunt generator has a field resistance of 55Ω and armature resistance of 0.067 Ω. Find the full load generated voltage?

6. A 4-pole DC Shunt generator with a wave wound armature has to supply a load of 500 lamps each of 100W at 250V. Allowing 10V for the voltage drop in the connecting leads between the generator and the load and drop of 1V per brush. Calculate the speed at which the generator should be driven. The magnetic flux per pole is 30mwb and the armature and shunt field resistances are respectively 0.05 Ω & 65 Ω. The no: of armature conductors is 390.

7. A 30kW, 300V DC Shunt generator has armature & field resistances of 0.05 Ω & 100 Ω respectively. Calculate the total power developed by the armature when it delivers full load output.

8. A 4-pole DC shunt generator with a shunt field resistance of 100 Ω and armature resistance of 1 Ω has 378 wave connected conductors in its armature. The flux/pole is 0.02 wb. If a load resistance of 10 Ω is connected across the armature terminals and the generator is driven at 1000 rpm, calculate the power absorbed by the load.

9. A DC Compound generator is to supply a load of 250 lamps, each rated at 100W, 250V The armature, series & shunt windings have resistances of 0.06 Ω, 0.04 Ω & 50 Ω respectively. Determine the generated emf when the machine is connected in
i. Long shunt ii. Short shunt
Take drop/brush as 1V.

10. A DC Shunt generator supplies 96A at a terminal voltage of 200V. The armature & shunt field resistances are 0.1 Ω and 50 Ω respectively. The iron & frictional losses are 2500W. Find i. emf generated ii. Copper losses iii. Commercial efficiency

11. A DC shunt generator delivers full load current of 200A at 240V. The shunt field resistance is 60 Ω and full load efficiency is 90%. The stray losses are 800W. Find
i. Armature resistance ii. Current at which maximum efficiency occurs.

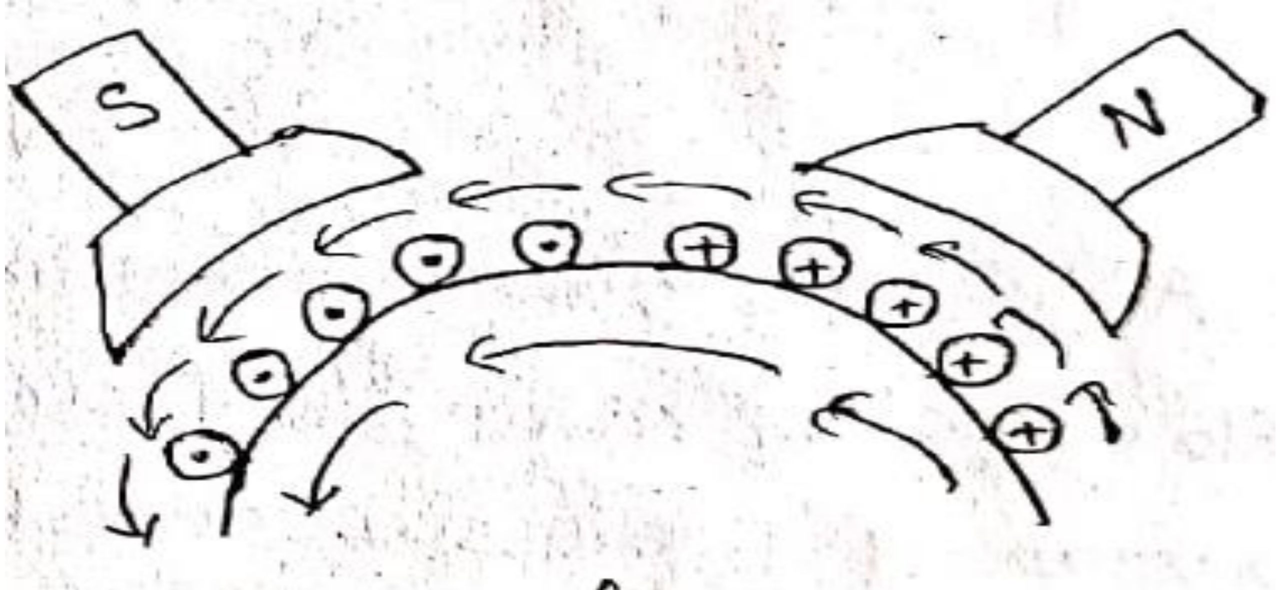
12. A 75kW DC Shunt generator is operated at 230V. The stray losses are 1810W and shunt field circuit draws 5.35A. The armature circuit has a resistance of 0.035 Ω and brush drop is 2.2V. Calculate:
i. Total losses ii. Input of prime mover iii. η at rated load

# DC Motors

## Principle:

A machine that converts DC power into mechanical power is known as DC motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experience a mechanical force. The direction of this force is given by Fleming's Left hand rule and magnitude is given by: F = B I L Newtons

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



fig(a)

## Working of DC Motor:

Consider a part of DC motor as shown in fig(a). When the terminals of the motor are connected to the external source of DC supply:

The field magnets are excited developing alternate N & 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 fig(a). Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force acts on it. If applying Fleming's left hand rule, it is clear that force on each conductor is tending to rotate the armature in anti-clockwise direction.

All these forces add together to produce a driving torque which sets the armature rotating.

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

## Back EMF or Counter EMF:

When the armature of a DC motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence emf is induced in them as in a DC Generator.

The induced emf acts in opposite direction to the applied voltage V and is known as Back or counter emf ($E_b$). According to Lenz's law, **the direction of induced emf is such that it opposes the cause producing it. The cause producing the back emf Eb is the applied voltage V.** Hence $E_b$ opposes the applied voltage V.

The back emf ($E_b$=ϕZNP/60A) is always less than the applied voltage V, although this difference is small when the motor is running under normal conditions.

Consider a shunt wound motor shown in fig (a) when DC voltage V is applied across the motor Terminals, the field magnets are excited and armature conductors are supplied with current. Therefore, driving torque acts on the armature which begins to rotate. As the armature rotates, Eb is induced which opposes the applied voltage V. The V has to force current through the armature against the Eb.

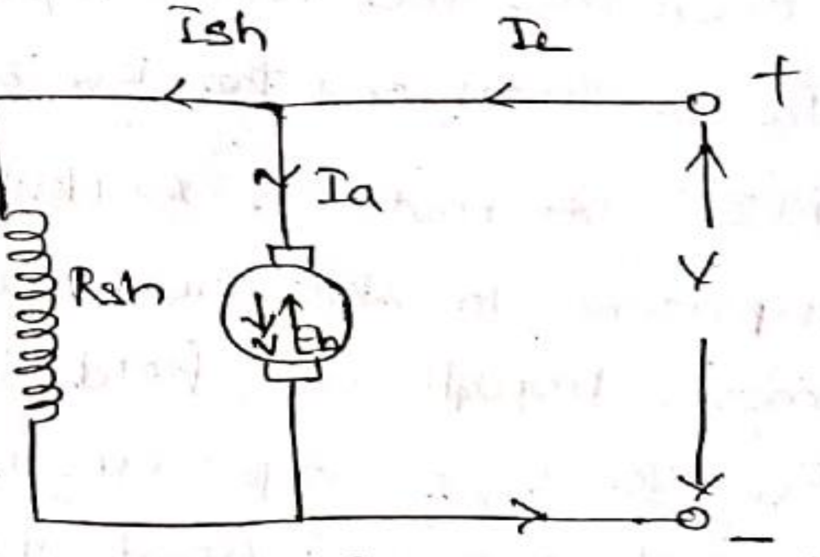


fig (a)

The electric work done in overcoming and causing the current to flow against $E_b$ is converted into mechanical energy developed in the armature. Therefore, the energy conversion in a DC motor is only possible due to the production of $E_b$.

Net voltage across armature circuit $= V - E_b$

If $R_a$ is the armature circuit resistance, then $I_a = \frac{V - E_b}{R_a}$

Since $V$ and $R_a$ are usually fixed, the value of $E_b$ will determine the current drawn by the motor. If the speed of the motor is high, then $E_b$ is large and hence the motor will draw less $I_a$ and vice versa.

# Significance of Back EMF:

The presence of back emf makes the DC Motor a self-regulating machine, i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load. $I_a = V – E_b / Ra$

i When the motor is running on No-load, small torque is required to overcome the friction & windage losses. Therefore, the armature current $I_a$ is small and the $E_b$ is nearly equal to the applied voltage.

ii If the motor is suddenly loaded, the first effect is to cause the armature to slow down. Therefore, the speed at which the armature conductors move through the field is reduced and hence the $E_b$ falls. The decreased $E_b$ allows a larger current to flow through the armature and larger current means increased driving torque. Thus, the driving torque increases as the motor slows down. The motor will stop slowing down when the $I_a$ is just sufficient to produce the increased torque required by the load.

iii. If the load on the motor is decreased, the driving torque is momentarily in excess of the requirement so that armature is accelerated. As the armature speed increases, the $E_b$ also increases and causes the $I_a$ to decrease. The motor will stop accelerating when the $I_a$ is just sufficient to produce the reduced torque required by the load.

It follows that $E_b$ in a DC Motor regulates the flow of $I_a$ i.e., **it automatically changes the armature current to meet the load requirement.**

## Voltage Equation of DC Motor :-

let

$V$ = applied voltage

$E_b$ = Back emf

$R_a$ = armature resistance

$I_a$ = armature current

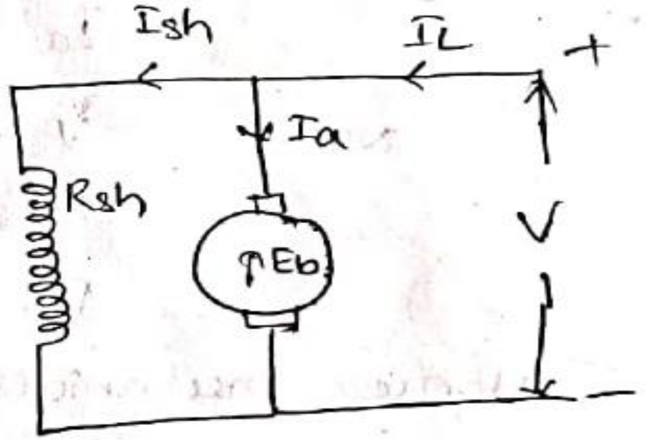



fig (a)

Since $E_b$ acts in opposition to the applied voltage $V$, the net voltage across the armature circuit is $V - E_b$. The $I_a$ is given by:

$$I_a = \frac{V - E_b}{R_a} \quad \text{(or)}$$

$$V = E_b + I_a R_a \quad \text{--- (1)}$$

This is known as voltage equation of the DC motor.

$$V = E_b + I_aR_a \longleftarrow (1)$$

This is known as voltage equation of the DC motor.

## power Equation :-

multiply eqn (1) by $I_a$ throughout. we get

$$VI_a = E_bI_a + I_a^2R_a \longleftarrow (2)$$

This is known as power equation of DC motor.

$VI_a$ = electric power supplied to armature (armature input)

$E_bI_a$ = power developed by armature (armature output)

$I_a^2R_a$ = electric power wasted in armature (armature cu loss)

Out of the armature input, a small portion of about 5% is wasted as $I_a^2*R_a$ and the remaining portion $E_b*I_a$ is converted into mechanical power within the armature.

## Condition for Maximum power :-

The mechanical power developed by the motor is $P_m = E_b I_a$

Now $P_m = VI_a - I_a^2 R_a$ ∵ from eqn (2)

Since V and $R_a$ are fixed, power developed by the motor depends upon armature current. For maximum power, $dP_m/dI_a$ should be zero.

$$\frac{dP_m}{dI_a} = V - 2I_aR_a = 0$$

$$I_aR_a = V/2$$

Now

$$V = E_b + I_aR_a$$

$$= E_b + \frac{V}{2}$$

$$E_b = \frac{V}{2} \quad \text{——— (3)}$$

Hence, mechanical power developed by the motor is maximum when $E_b$ is equal to half of the applied voltage.

# Types of DC Motors:

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

(i) shunt wound motor :- The motor in which the field winding is connected in parallel with the armature as shown in fig (a) The current through the shunt field winding is not the same as the armature current. shunt field windings are designed to produce the necessary mmf by means of a relatively large no: of turns of wire having high resistance. Therefore. shunt field current is relatively small compared with Ia.

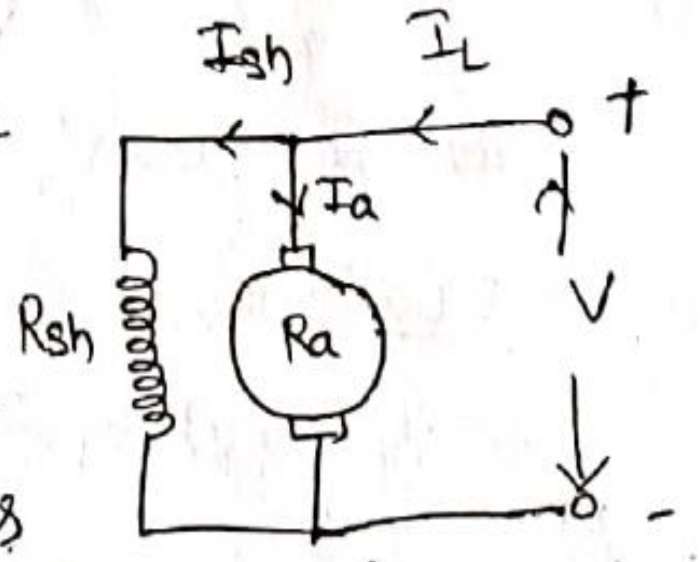
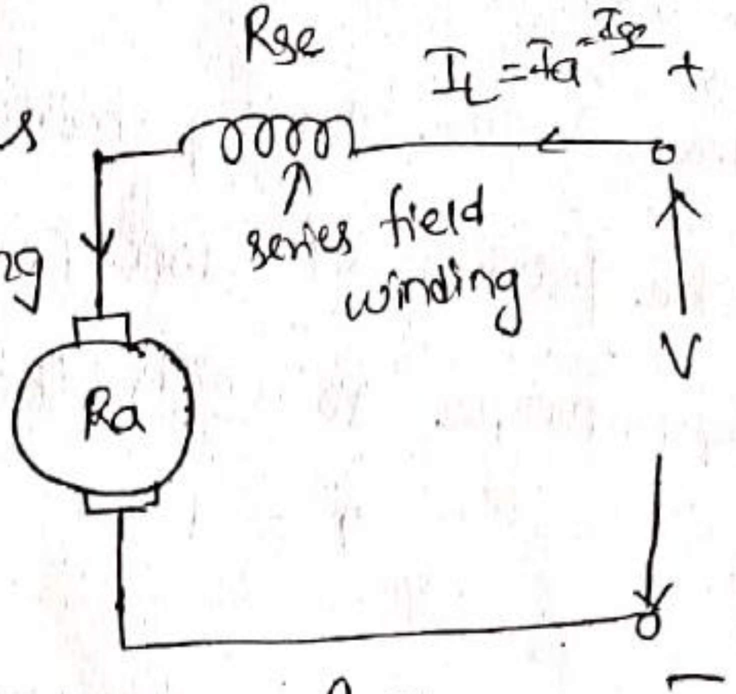


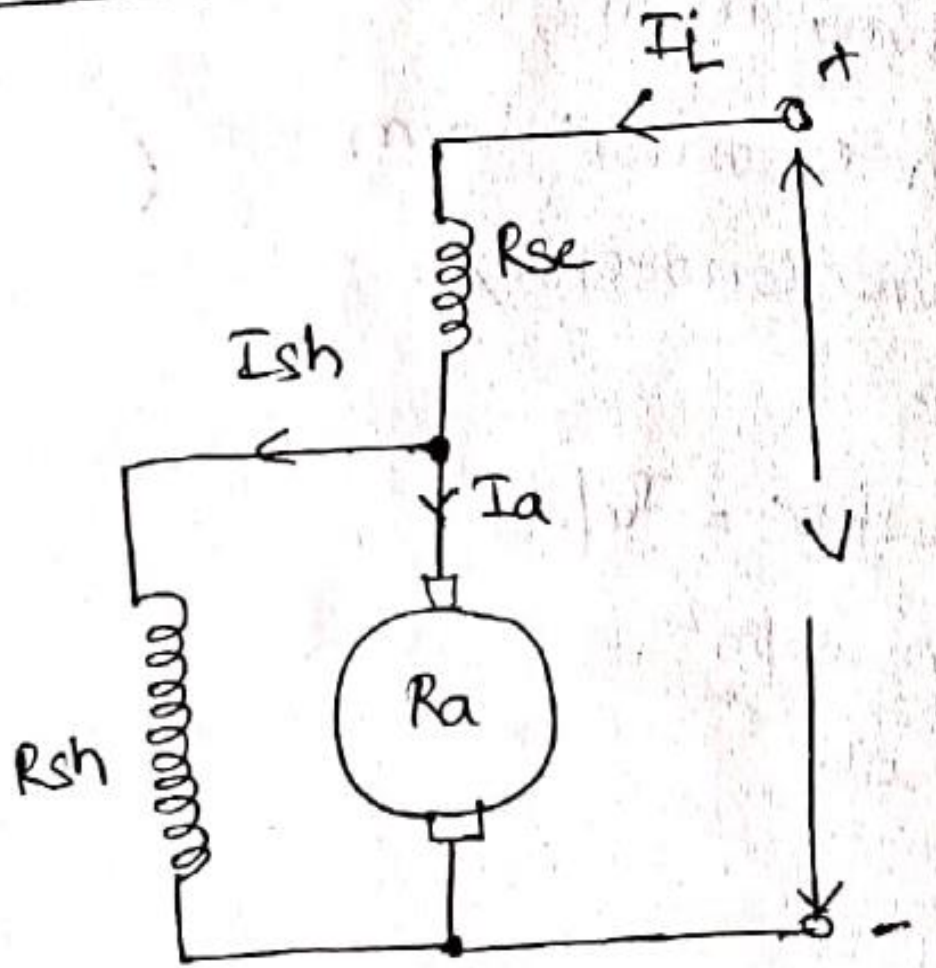
fig (a)

(ii) Series wound motor :- The motor in which the field winding is connected in series with the armature. Therefore, series field winding carries the armature current. Since the current passing through a series field winding is the same as the armature current, series field winding must be designed with much fewer turns than shunt field windings for the same mmf. Therefore, a series field winding has a relatively small no: of turns of thick wire and therefore will possess a low resistance.

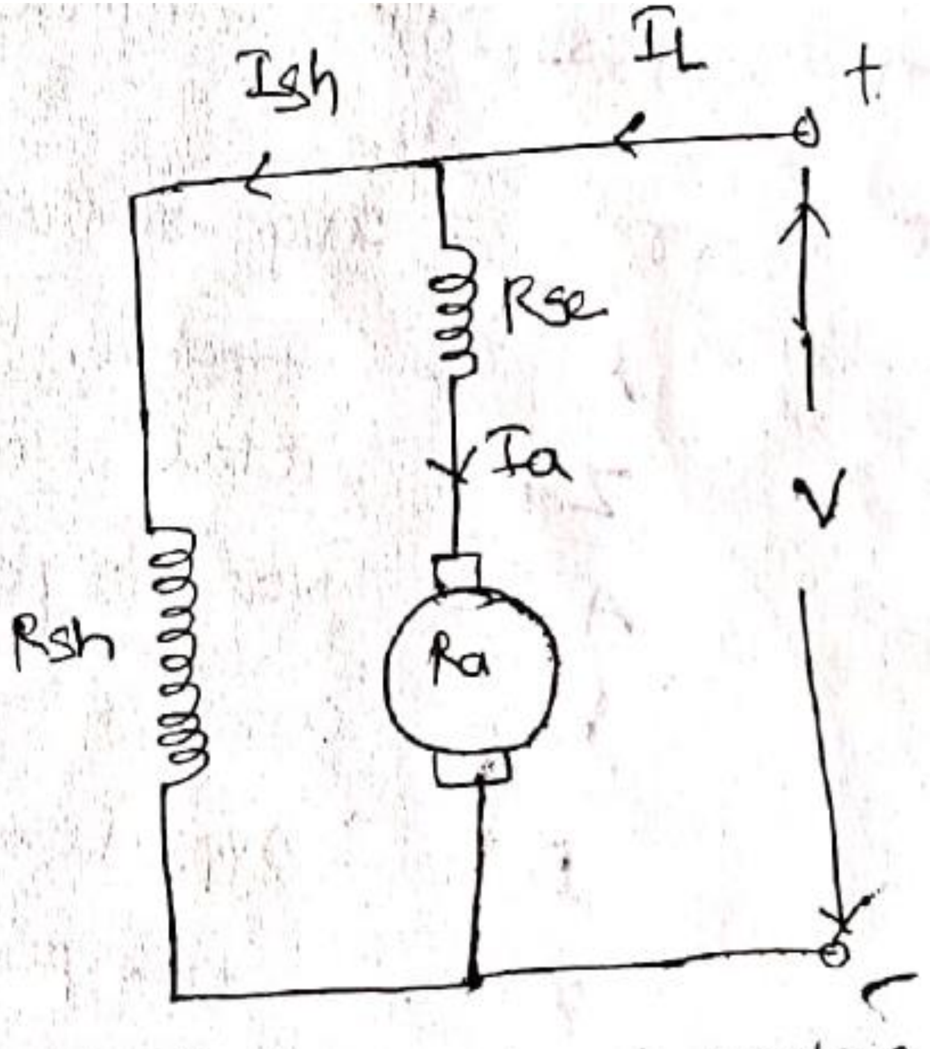



fig(a)

## (iii) compound wound motor :-




Fig(a) Short shunt motor



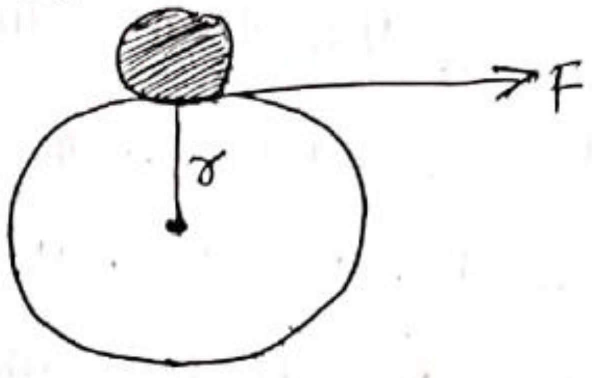

fig(b) Long-shunt motor

fig (a) short-shunt motor

The motor in which having 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). when the shunt field winding is directly connected across the armature terminals as shown in fig(a) it is called short-shunt. when the shunt winding is so connected that it shunts the series combination of armature & series field as shown in fig(b), it is called long shunt.

## Torque Equation of a DC motor :-

Torque is the turning moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts i.e.,



fig(a)

$$T = F \times r$$

In a DC motor, each conductor is acted upon by a circumferential force F at a distance, r, the radius of the armature (fig(a)). Therefore each conductor exerts a force, tending to rotate the armature. The sum of the torques due to all armature conductors is known as gross or armature Torque (Ta).

let $r$ = avg radius of armature in m

$l$ = effective length of each conductor in m

$Z$ = Total no: of armature conductors

$A$ = No: of parallel paths

$i$ = current in each conductor = $I_a/A$

$B$ = Avg: flux density in $wb/m^2$

$\phi$ = flux per pole in wb

$P$ = no: of poles

Force on each conductor = $F = Bil$ newtons

Torque due to one conductor = $F \times r$ N-m

Total armature Torque = $T_a = ZFr$ N-m

$= ZBilr$ N-m.

Now $i_a = I_a/A$; $B = \frac{\phi}{a}$ where $a$ is the cross-Sectional area of flux path at radius $r$. clearly $a = \frac{2\pi rl}{P}$

$$T_a = Z \times \left(\frac{\phi}{a}\right) \times \left(\frac{I_a}{A}\right) \times l \times r$$

$$= Z \times \frac{\phi}{2\pi rl/P} \times \frac{I_a}{A} \times l \times r$$

$$= \frac{Z \phi I_a P}{2\pi A}$$

(or) $T_a = 0.159\, Z\phi I_a \left(\frac{P}{A}\right)$ N-m —— (1)

Since $Z, P$ and $A$ are fixed for a given m/c.

$$T_a \propto \phi I_a \quad \text{—— (2)}$$

Hence Torque in a DC motor is directly proportional to flux/pole and armature current

For a DC Shunt Motor, flux ϕ is practically constant $T_a \propto I_a$ --------(3)

For a DC Series Motor, flux ϕ is directly proportional to armature current and provided saturation does not takes place.

$T_a \propto I_a^2$ --------(4) up to magnetic saturation

Alteanative expression for Ta

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

$$\frac{P\phi Z}{A} = \frac{60 \times E_b}{N}$$

From eqn ①

$$T_a = 0.159 \times \left(\frac{60 \times E_b}{N}\right) \times I_a$$

$$\boxed{T_a = 9.55 \frac{E_b I_a}{N}} \text{ N-m} \quad \text{—⑤}$$

**Shaft Torque :-**

The Torque which is available at the motor shaft for doing useful work is known as shaft Torque (Tsh).

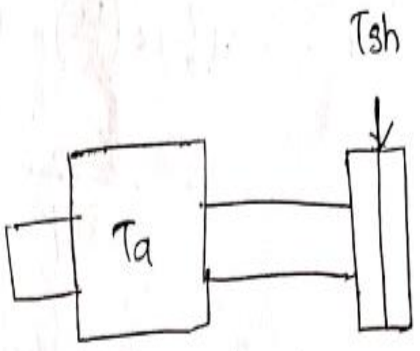



fig (a)

From fig (a). we can illustrate the concept of shaft Torque. The Total Torque Ta developed in armature of a motor is not available at the shaft as a part of it is lost in overcoming the Iron and frictional losses in the motor. Therefore, Tsh is somewhat less than the total armature Torque Ta. The difference Ta−Tsh is known as lost Torque.

$$T_{sh} = 9.55 \times \frac{\text{output}}{N} \text{ N-m} \quad \text{—①}$$

The horse power developed by the $T_{sh}$ is known as Brake Horse power (BHP). If the motor is running at N rpm and the shaft Torque is $T_{sh}$ N-m, then

$$W.D/revolution = force \times distance\ moved\ in\ 1\ revolution$$

$$= F \times 2\pi r = 2\pi T_{sh}$$

$$W.D/minute = 2\pi N T_{sh}$$

$$W.D/sec = \frac{2\pi N T_{sh}}{60}\ watts$$

$$= \frac{2\pi N T_{sh}}{60 \times 746}\ HP$$

$$Useful\ output\ power = \frac{2\pi N T_{sh}}{60 \times 746}\ H.P$$

$$(or)\quad BHP = \frac{2\pi N T_{sh}}{60 \times 746}$$

## Speed of a DC motor :

$$E_b = V - I_a R_a \quad —(1)$$

$$E_b = \frac{\phi Z N P}{60 A} \quad —(2)$$

$$\frac{P \phi Z N}{60 A} = V - I_a R_a \quad —(3)$$

$$N = \frac{(V - I_a R_a)\, 60 A}{\phi Z P}$$

(or)

$$N = K \cdot \frac{(V - I_a R_a)}{\phi} \quad \text{where } K = \frac{60 A}{P Z}$$

But $V - I_a R_a = E_b$

$$N = K \frac{E_b}{\phi}$$

$$N \propto \frac{E_b}{\phi} \quad —(4)$$

Therefore, in a DC motor, speed is directly proportional to $E_b$ and inversely proportional to flux per pole $\phi$.

## Speed relations :-

If a DC motor has initial values of speed, flux per pole and Eb as $N_1$, $\phi_1$ and $E_{b1}$ respectively and the corresponding final values are $N_2$, $\phi_2$ and $E_{b2}$, then;

$$N_1 \propto \frac{E_{b1}}{\phi_1} \quad \text{and} \quad N_2 \propto \frac{E_{b2}}{\phi_2}$$

$$\therefore \frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \times \frac{\phi_2}{\phi_1} \quad \text{--- (5)}$$

(i) For a shunt motor, flux practically remains constant so that $\phi_1 = \phi_2$.

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \quad \text{--- (6)}$$

(ii) For a Series motor, $\phi \propto I_a$ prior to saturation.

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \times \frac{I_{a2}}{I_{a1}} \quad \text{--- (7)}$$

where $I_{a1}$ = initial armature current

$I_{a2}$ = final armature current

## Speed Regulation :-

The speed regulation of a motor is the change in speed from full-load to no-load and is expressed as a percentage of the speed at full load.

i.e.,

$$\%\ \text{Speed regulation} = \frac{\text{NL Speed} - \text{FL Speed}}{\text{FL Speed}} \times 100$$

$$= \frac{N_0 - N}{N} \times 100 \quad \text{—— (8)}$$

where $N_0$ = No-load Speed

$N$ = Full-load Speed.

## Losses in a DC motor :-

The losses occuring in a DC motor are the same as DC generator losses.

These are (i) copper losses

(ii) mechanical losses

(iii) iron losses

All these losses cause (a) an increase of Temperature and

(b) reduction in $\eta$ of the DC motor.

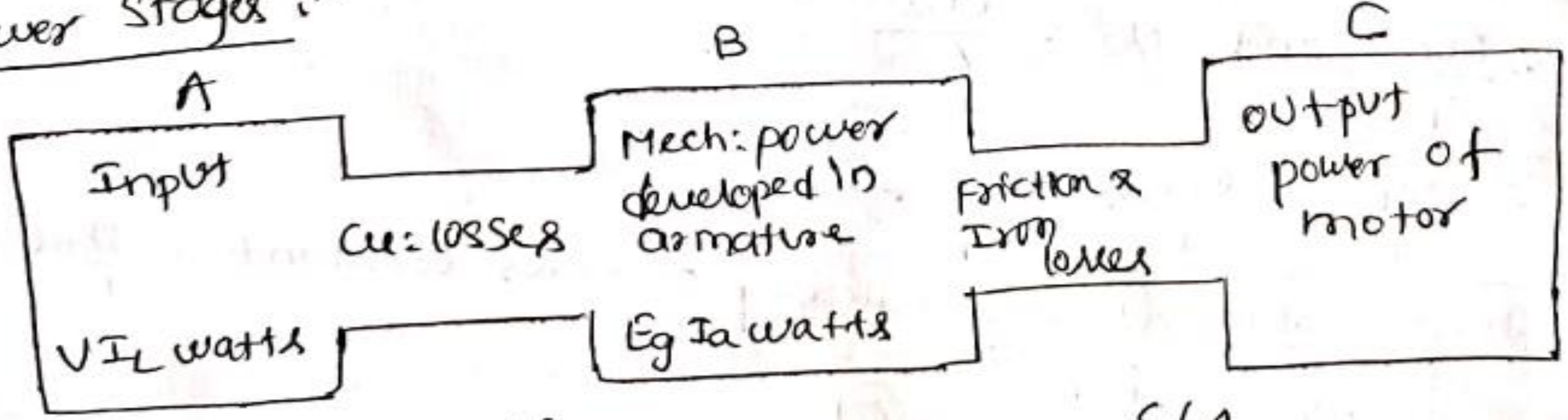
## Efficiency of DC motor :-

$$\eta = \frac{\text{output}}{\text{Input}} \times 100 = \frac{\text{output}}{\text{output} + \text{losses}} \times 100$$

Like DC generator, the $\eta$ of DC motor will be maximum when

variable losses = constant losses.

## power stages :-




Commercial (or) Overall efficiency = $\eta_c$ = C/A

Electrical efficiency = $\eta_e$ = B/A

Mechanical efficiency = $\eta_m$ = C/B

## Applications of DC motors:-

1) **Shunt motors:-** The characteristics of a shunt motor reveal that it is an approximately constant speed motor. It is therefore used

(i) where the speed is required to maintain almost constant from no-load to full load.

(ii) where the load has to be driven at a no:of speeds and any one of which is required to remain nearly constant.

**Industrial use:-** Lathes, drills, boring mills, shapers, spinning and weaving machines etc.,

2) **Series motors:-** It is a variable speed motor i.e., speed is low at high torque and vice-versa. However, at light or no load, the motor tends to attain dangerously high speed. The motor has a high $T_{st}$. It is therefore used

It is

(i) where large starting Torque is required i.e., in elevators and electric Traction

(ii) Where the load is subjected to heavy fluctuations and the speed automatically required to reduce at high Torques & vice-versa.

Industrial use :- Electric Traction, cranes, elevators, air compressors, vaccum cleaners, Sewing machines etc.,

3) Compound Motors :- Differential compound motors are rarely used because of their poor Torque characteristics. However cummulative compound motors are used with a fairly constant speed is required with irregular loads or suddenly applied heavy loads

Industrial use :- presses, Shears, reciprocating machines etc.,

## Speed Control of DC motors :-

The speed of a DC motor is given by :

$$N \propto \frac{E_b}{\phi}$$

(or)

$$N = K \frac{(V - I_a R)}{\phi} \text{ rpm} \quad — (1)$$

where $R = R_a$ — for shunt motor

$R = R_a + R_{se}$ — for series motor

from eqn (1) it is clear that there are two methods of controlling the speed of a DC motor.

(i) By varying the flux per pole $\phi$, known as flux control method.

(ii) By varying the resistance in the armature circuit, this is known as armature control method.

## Speed control of DC shunt motors :-

The speed of DC shunt motor can be changed by
(i) flux control method
(ii) Armature control method.

### i) Flux control method :-

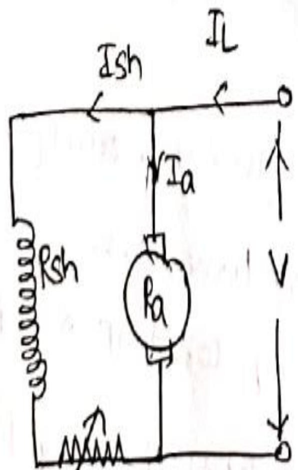


fig (a)

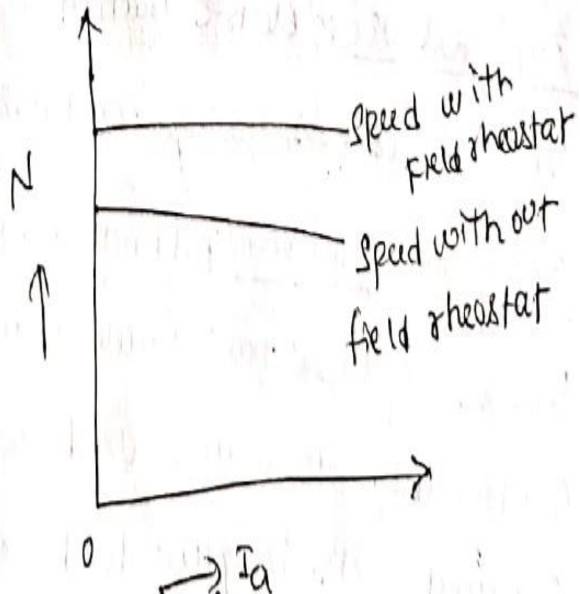


fig (b)

By varying the flux $\phi$, the motor speed ($N \propto \frac{1}{\phi}$) can be changed and hence the name flux control method. In this method, a variable resistance (known as shunt field rheostat) is placed in series with shunt field winding shown in fig (a).

The shunt field rheostat reduces the $I_{sh}$ and hence the flux $\phi$. Therefore, we can only raise the speed of the motor above the normal speed shown in fig (b).

**Advantages :-**

1) Easy and convenient method.
2) Inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of $I_{sh}$.
3) Speed control by this method is independent of the load on the m/c.

## Disadvantages :-

1) only speeds higher than the normal speeds can be obtained since the total field circuit Ω cannot be reduced below Rsh.

2) There is a limit to the maximum speed obtainable by this method. It is because if the flux is too much weakened, commutation becomes poorer.

## 2) Armature control method :-

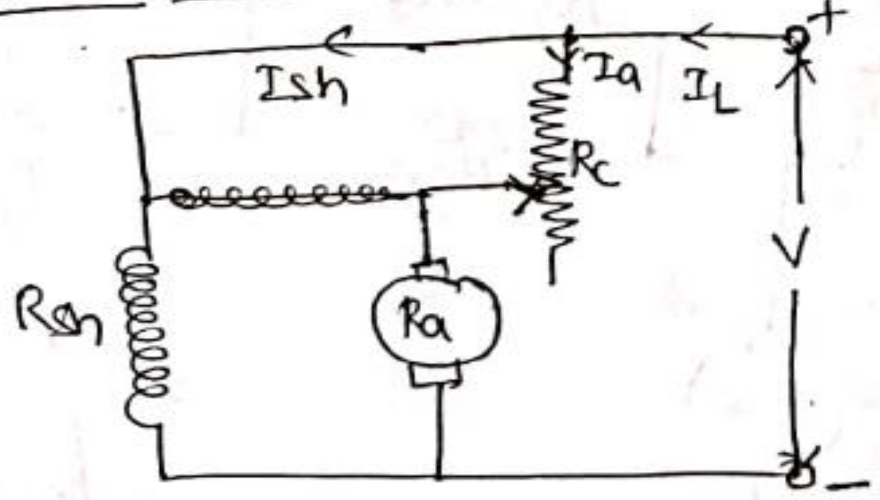



fig (a)

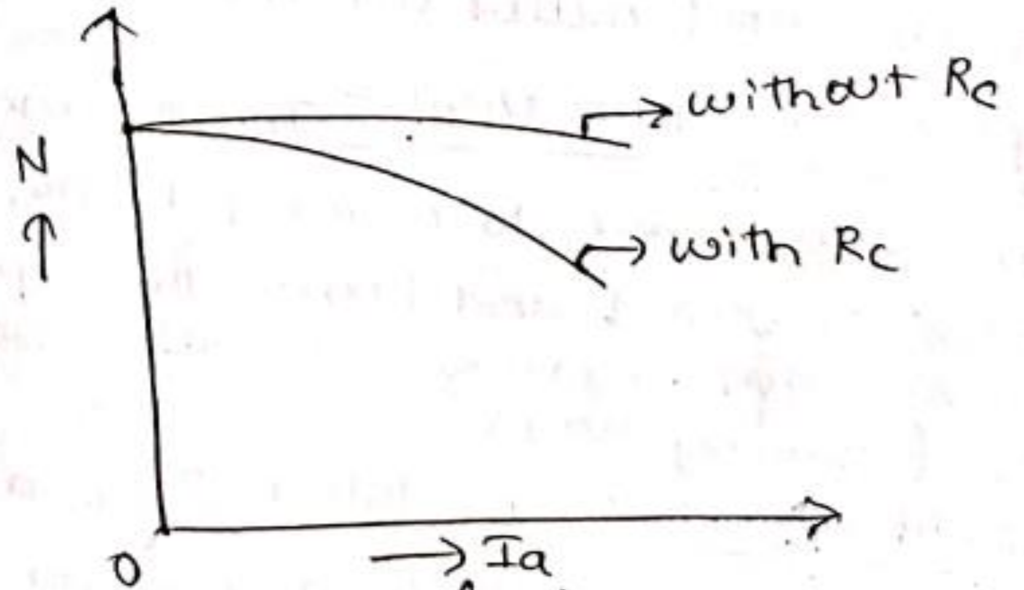



fig (b)

By varying the voltage available across the armature, the $E_b$ and hence the speed of the motor can be changed. This is done by inserting a variable resistance $R_c$ (known as controller resistance) in series with the armature shown in fig (a).

$$N \propto V - I_a(R_a + R_c)$$

where $R_c$ = controller resistance.

Due to voltage drop in $R_c$, the $E_b$ is decreased.

$\therefore E_b = V - I_a(R_a + R_c)$. Since V is constant, $E_b$ will decrease. Since $N \propto E_b$, the speed of the motor is reduced. The highest speed obtainable is that corresponding to $R_c = 0$, i.e., normal speed. Hence, this method can only provide speeds below the normal speed (fig (b)).

**Disadvantages :-**

1) A large amount of power is wasted in the $R_C$ since it carries full Ia.
2) The output and η of the motor are reduced
3) This method results in poor speed regulation.

**Speed control of DC Series motors :-**

Speed control is obtained by two methods
(i) Flux control method (ii) Ra control method.

**1. Flux control method :-** In this method, The flux ~~proportional~~ to produced by the series motor is varied and hence the speed. The variation of flux can be achieved in the following ways:

**(i) Field Diverters :-** In this method, a variable resistance (called field diverter) is connected in parallel with series field winding as shown in fig (a).

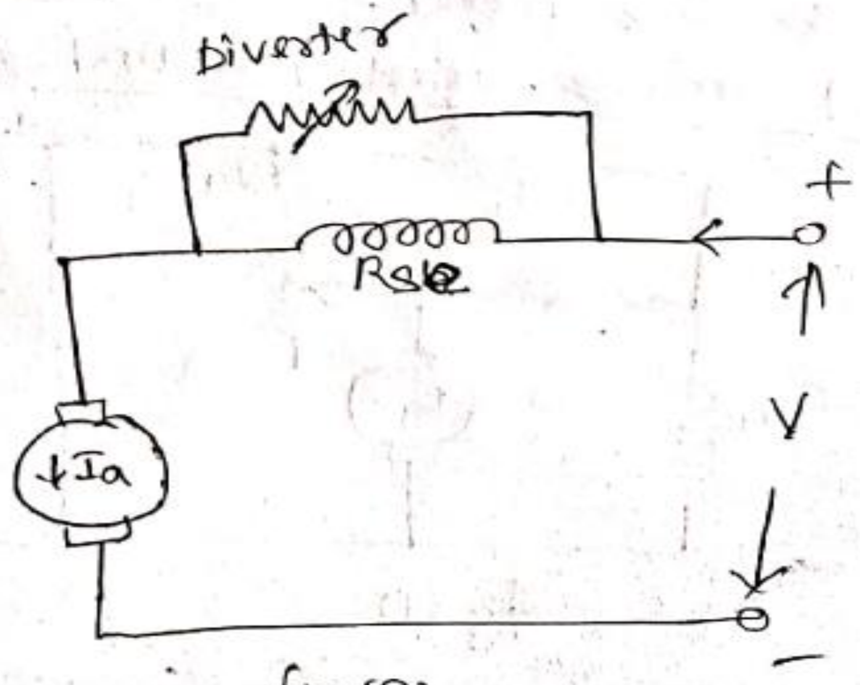


fig (a)

Its effect is to shunt some portion of the line current from the series field winding, thus weakening the field and increasing the speed ($N \propto \frac{1}{\phi}$). The lowest speed obtainable is that corresponding to zero current in the diverter (i.e., diverter is open). obviously, the lowest speed obtainable is the normal speed of the motor. consequently, this method can only provide speeds above the normal speed. The series field diverter method is often employed in traction work.

(ii) Armature Diverter:-

In order to obtain speeds below the normal speed, a variable resistance (called armature diverter) is connected in parallel with the armature as shown in fig (a). The diverter shunts some of the line current, thus reducing the armature current. Now for a

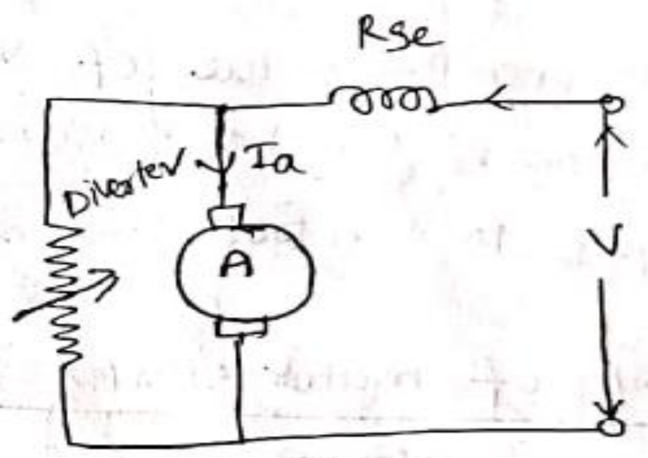


fig (a)

given load, if $I_a$ is decreased, the flux $\phi$ must increase ($\because T \alpha \phi I_a$). since $N \alpha \frac{1}{\phi}$, the motor speed is decreased. By adjusting the armature diverter, any speed lower than the normal speed can be obtained.

(iii) Tapped field control:-

In this method, the flux is reduced (and hence speed is increased) by decreasing the no. of turns of the series field winding as shown in fig (a). The switch S can short circuit any part of the field winding, thus decreasing the flux and raising the speed. With full turns of the field winding, the motor runs at normal speed and as the field turns are cut out, speeds higher than normal speeds are achieved.

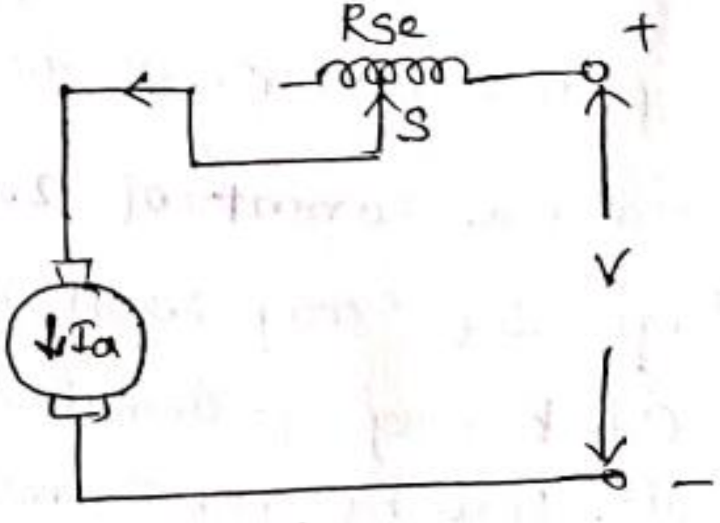


fig (a)

(2) Armature resistance control:-

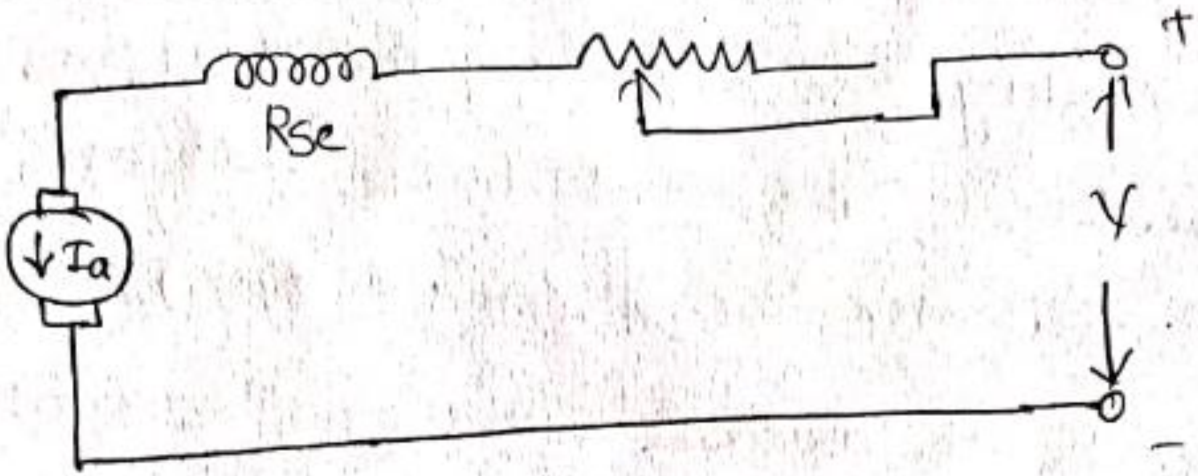


fig (a)

In this method, a variable resistance is directly connected in series with the supply to the complete motor as shown in fig (a). This reduces the voltage available across the armature and hence the speed falls. By changing the value of variable resistance, any speed below the normal speed can be obtained. This is the most common method employed to control the speed of the DC Series motor.

## Necessity of motor starters :-

At starting when the motor is stationary, there is no $E_b$ in the armature. Consequently, if the motor is directly switched on the mains, the armature will draw a heavy current ($I_a = \frac{V}{R_a}$) because of small armature resistance. As an example, 5 HP, 220 V DC shunt motor has a full load current of 20 A and an armature resistance of about 0.5 Ω. If this motor is directly switched on to supply, it would take an armature current of 220/0.5 = 440 A, which is 22 times the $I_{FL}$. This High $I_{st}$ may result in :

(i) burning of armature due to excessive heating effect.
(ii) damaging the commutator and brushes due to heavy sparking
(iii) excessive voltage drop in the line to which the motor is connected,

In order to avoid excessive current at starting, a variable resistance(known as starting resistance) is inserted in series with the armature circuit. This resistance is gradually reduced as the motor gains speed(and hence $E_b$ increases) and eventually it is cutout completely when the motor has attained full speed.

Fig(a) shows the schematic diagram of a shunt motor starter with protective devices. It consists of starting resistance divided into several sections and connected in series with the armature. The tapping points of the starting resistance are brought out to a no: of studs, one end of shunt field winding is connected to the first stud and the other end to the far side of the supply, included in

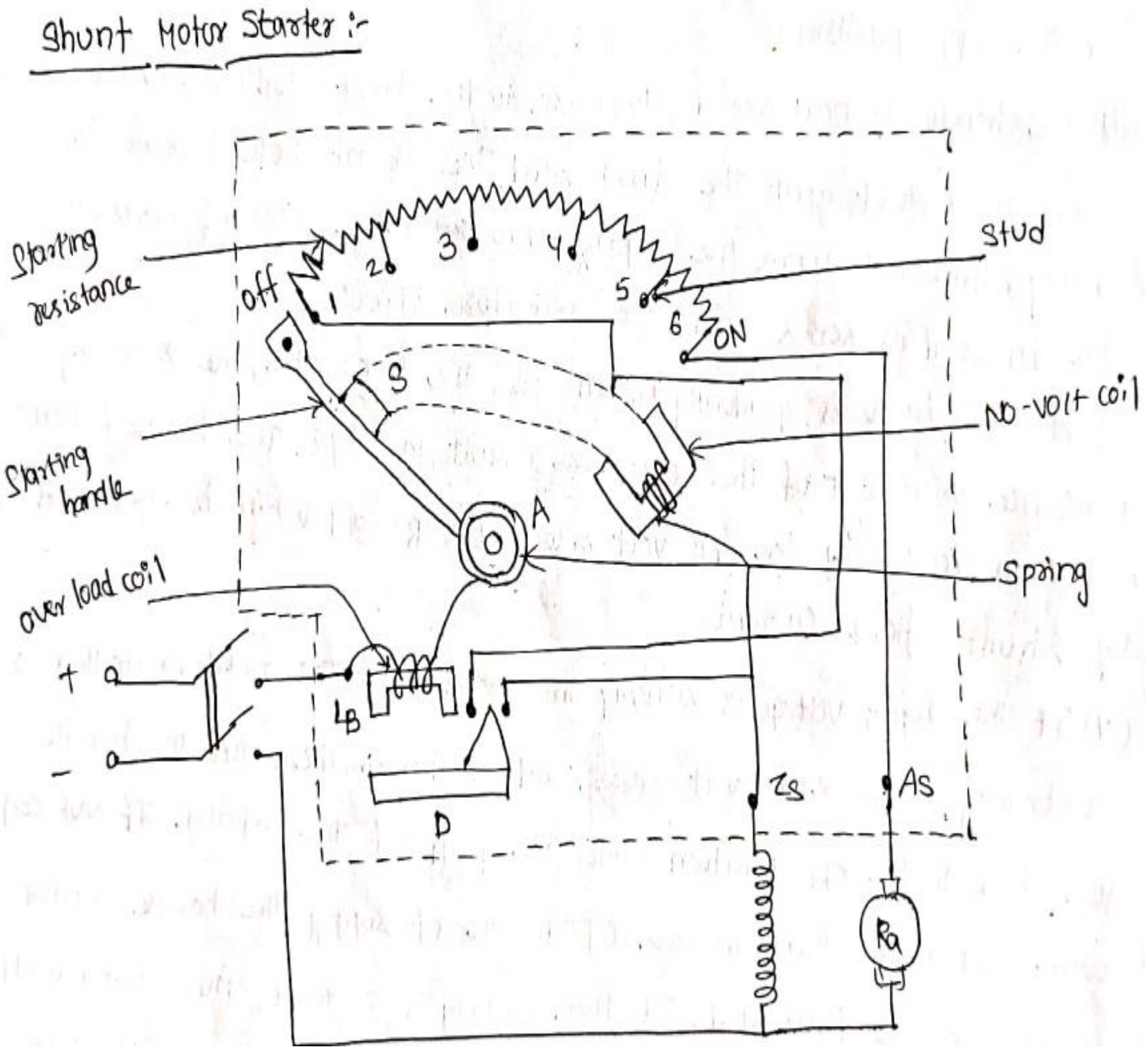



Fig: 3-point starter

this circuit is the **No-Volt Release coil.** One end of the starting handle A is connected to one side of supply through **Over Load Release coil.** The other end of starting handle moves against spring and makes contact with each stud during starting operation, cutting out more and more starting resistance as it passes over each stud in clockwise direction.

Operation :-

(i) To start with the DC supply is switched on with starting handle in the OFF position.

(ii) The handle is now moved clockwise to the first stud. As soon as it comes in contact with the first stud, the shunt field winding is directly connected across the supply, while the whole starting resistance is inserted in series with the armature circuit.

(iii) As the handle is gradually moved over the final stud, the starting resistance is cut out of the armature circuit in steps. The handle is now held magnetically by the No-volt release (NVR) coil which is energised by shunt field current.

(iv) If the supply voltage is suddenly interrupted or if the field excitation is accidentally cut, the no-volt release coil is demagnetized and the handle goes back to the OFF position under the pull of the spring. If NVR coil were not used, then in case of failure of supply, the handle would remain on the final stud. If then supply is restored, the motor will be directly connected across the supply, resulting in an excessive armature current.

(v) If the motor is overloaded, it will draw excessive current from the supply. This current will increase the ampere-turns of the OLR coil and pull the armature D, thus short-circuiting the No-volt release coil. The NVC is demagnetized and the starting handle is pulled to the OFF position by the spring. Thus, the motor is automatically disconnected from the supply.

## Swinburne's Test :- (No-load Test or Losses method) :-

In this method the losses are measured separately and efficiency at any desired load is predetermined. The Iron and friction losses are determined by measuring the input to the machine on no-load, the machine being run as a motor at Normal voltage and speed. the copper losses are calculated from measured values of the various resistances. the method may be applied to compound and Shunt motors. the fig (a) shows the connection diagram for determining the no load losses of a DC shunt machine

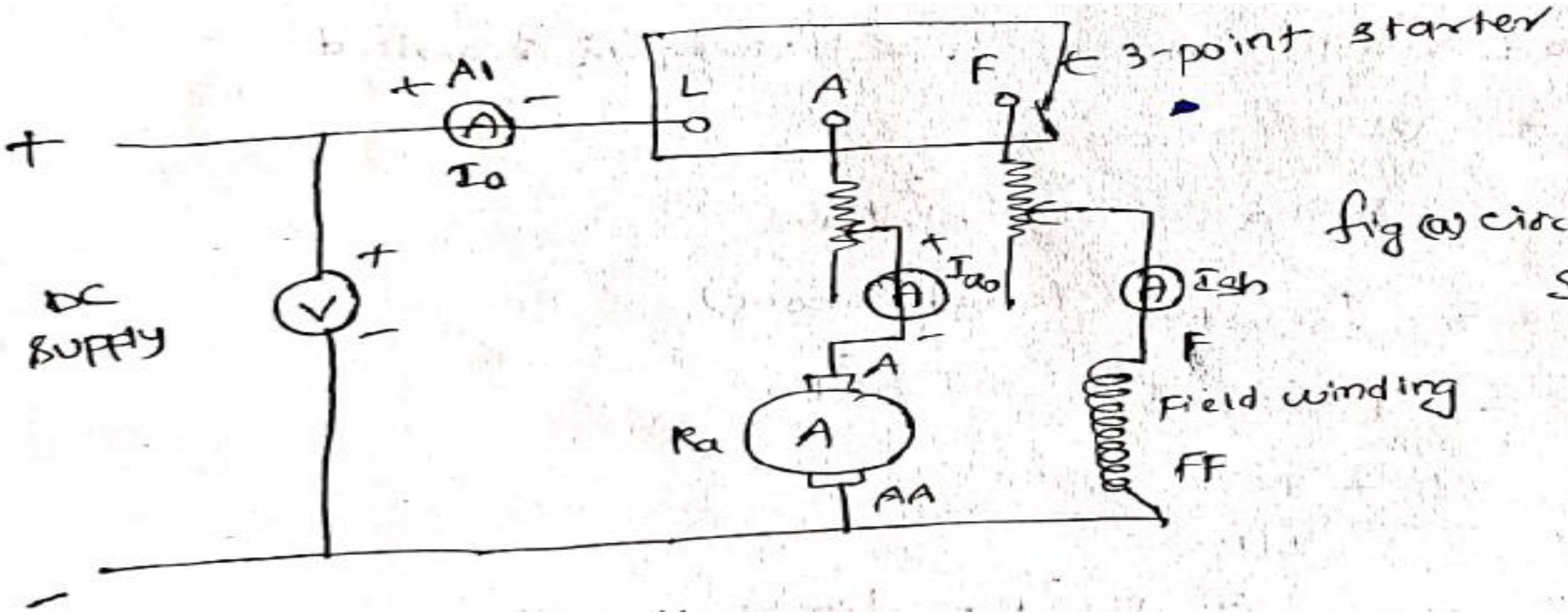



fig (a) circuit Diagram for Swinburne's Test let $V$ = Supply voltage

$I_0$ = Initial Armature current at No-load

$I_{sh}$ = Shunt Field current

No-load armature current = $I_{a0} = I_0 - I_{sh}$

No-load Input = $VI_0$ watts

power I/p to the armature = $V(I_0 - I_{sh})$

power I/p to shunt = $VI_{sh}$

No-load power Input to the machine supplies the following:

(i) Iron losses in core

(ii) Frictional losses

(iii) Windage losses

(iv) Armature copper loss

Constant losses $P_{const}$ = No-load I/p − No-load armature copper loss

$$= VI_0 - (I_0 - I_{sh})^2 R_a$$

By knowing the constant losses of a machine, its efficiency at any other load can be determined as given below:

**Efficiency when running as a motor :-** $I_a = I - I_{sh}$

where $I$ is the load current at which efficiency is required

Motor input $= VI$

Armature copper loss $= I_a^2 R_a = (I - I_{sh})^2 R_a$

Constant losses $= P_{const}$ (found above)

Total losses $= P_{const} + (I - I_{sh})^2 R_a$

$$\eta_{motor} = \frac{I/p - \text{Total Losses}}{I/p}$$

$$= \frac{VI - (I - I_{sh})^2 R_a - P_{const}}{VI} \quad \text{--- (1)}$$

**Efficiency when running as a generator :-**

$I_a = I + I_{sh}$

Generator output $= VI$

Armature copper loss $= (I + I_{sh})^2 R_a$

Constant losses $= P_{const}$ (found above)

Total losses $= (I + I_{sh})^2 R_a + P_{const}$

$$\eta_{gene} = \frac{o/p}{o/p + \text{Total losses}}$$

$$= \frac{VI}{VI + (I + I_{sh})^2 R_a + P_{const}} \quad \text{--- (2)}$$

## Advantages :-

1) It is convenient and economical method of testing of DC machine since power required to test a large machine is small.
2) The efficiency can be predetermined at any load because constant losses are known.

## Disadvantages :-

1) Since the test is not conducted at full-load. It is not possible to know whether at full load commutation would be satisfactory and the temperature rise would be within the specified limit (or) not.
2) This test cannot be applied to series motors because the speed of a series motor being very high at no-load, it is not possible to run a DC series motor on no-load.

# Brake Test on DC Shunt Motor:

## SWINBURNE'S TEST

- This test is the simplest Indirect method for finding out the efficiency of dc machine.
- In this method of testing , constant losses are determined experimentally by operating the dc machine as motor running at no load .
- This test is applicable to dc machines in which flux is practically constant i.e. shunt and compound machines .

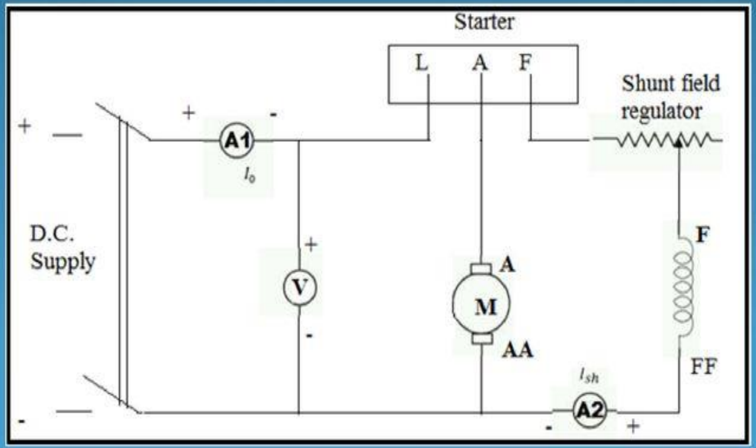



fig (A) circuit diagram of Swinburne's test on dc shunt motor

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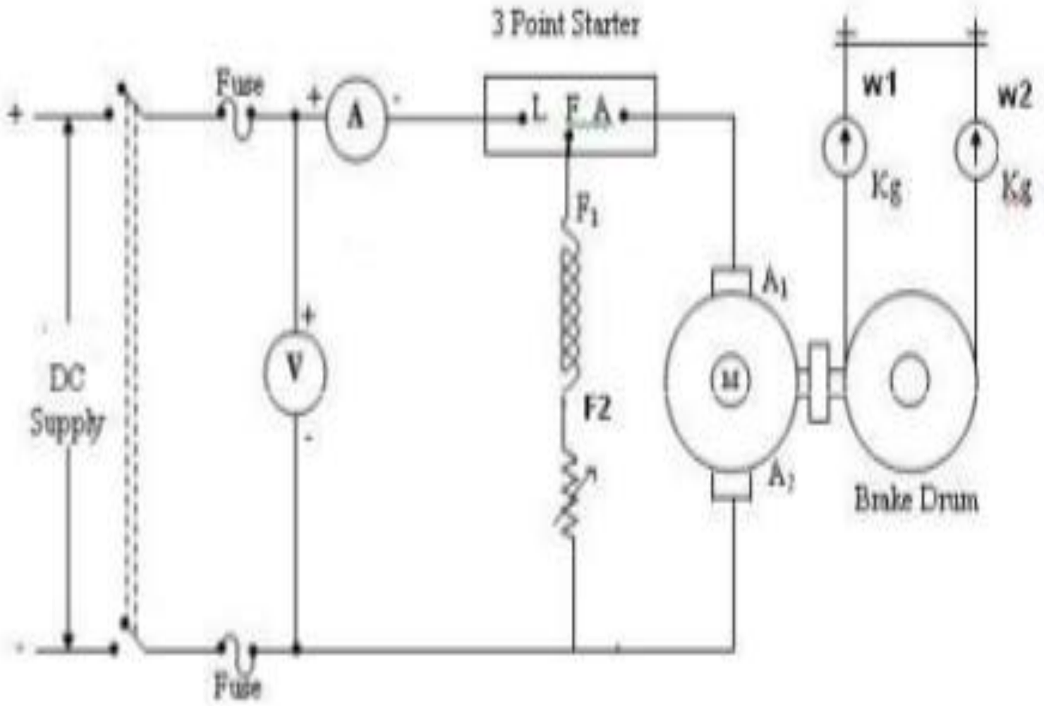



**Precaution:** While performing this test with series machines care should be taken that brake applied is tight failing Which the motor will attain dangerously high speed and get damaged

DC Machines can be tested by three different methods namely Direct Method, Indirect Method and Regenerative Method. Direct Method of testing of DC Machine, also known as Brake Test (if carried out for a DC Motor) will be discussed here.

Direct method is suitable for small DC machines. In Direct Method, the DC machine is subjected to rated load and the entire output power is wasted. The ratio of output power to the input power gives the Efficiency of DC Machine. For a DC Generator the output power is wasted in resistor.

Direct Method of testing when conducted on a motor is also known as Brake Test. Brake Test of DC Motor is carried out as shown in figure above.

Let

$S_1$ = Readings on spring balance 1 in Kgf.wt.

$S_2$ = Readings on spring balance 2 in Kgf.wt.

The net force applied on the brake drum is $(S_1 - S_2)$ Kgf.Wt.

If R = radius of the pulley in meters &

N = Motor speed in rpm then,

Shaft torque, T, developed by the motor is:

$T = 9.81 \times (S_1 - S_2) \times R$ Nm

Output power = $(2\times \Pi \times N \times T) / 60$ Watts

Input power = $V (I_a + I_{sh})$ Watts

Efficiency = Output power / Input power

## Procedure:

1. The connections are made as per the circuit diagram.
2. Initially the starter is in off position.
3. The field rheostat is in minimum position.
3. 220 DC supply is applied by closing the DPST Switch.
4. The DC motor is started slowly with the starter and brought to the rated speed.
5. Load is applied on the drum gradually in steps by tightening the belt around it.
6. The readings of the ammeter & voltmeter, two spring balances and the speed at every step are noted.
7. Drum is cooled through out the loading period by pouring water.
8. The experiment is continued till the full load on the motor is impressed.
9. The machine is switched of by opening the DPST switch.

# Advantages of Brake Test On DC Shunt Motor:

1. The actual efficiency of the motor under working conditions can be found out.
2. Brake test is simple and easy to perform.
3. It is not only for dc shunt motor, also can be performed on any type of DC Motor(except DC Series motor).

# Disadvantages of Brake Test On DC Shunt Motor:

1. In brake test due to the belt friction lot of heat will be generated and hence there is the large dissipation of energy.
2. The cooling arrangement is necessary to minimize the heat. Mostly in our laboratories, we use water as the cooling liquid.
3. Convenient only for small rated machines due to limitations regarding heat dissipation arrangements.
4. The power developed gets wasted hence brake test method is little expensive.
5. The efficiency observed is on the lower side.

# Problems on DC Motors



**Example 31.2(a).** *The following readings are obtained when doing a load test on a d.c. shunt motor using a brake drum :*

| | | | |
|---|---|---|---|
| *Spring balance reading* | *10 kg and 35 kg* | *Diameter of the drum* | *40 cm* |
| *Speed of the motor* | *950 r.p.m.* | *Applied voltage* | *200 V* |
| *Line current* | *30 A* | | |

*Calculate the output power and the efficiency.* **(Electrical Engineering, Madras Univ. 1986)**

**Solution.** Force on the drum surface $F = (35 - 10) = 25$ kg wt $= 25 \times 9.8$ N

Drum radius $R = 20$ cm $= 0.2$ m ; Torque $T_{sh} = F \times R = 25 \times 9.8 \times 0.2 = 49$ N

$N = 950/60 = 95/6$ r.p.s. ; $\omega = 2\pi\,(95/6) = 99.5$ rad/s

Motor output $= T_{sh} \times \omega$ watt $= 49 \times 99.5 = 4{,}876$ W

Motor input $= 200 \times 30 = 6000$ W ; $\eta = 4876/6000 = 0.813$ or 81.3%

1 A 250V shunt motor takes a total current of 20A. The shunt field and armature resistances are 200Ω and 0.3Ω respectively. Determine i) value of back emf ii) gross mechanical power in the armature.

2 A 230V motor has an armature circuit resistance of 0.6Ω. If the full-load armature current is 30A and no-load armature current is 4A, find the change in the back emf from no-load to full-load.

3 A 4-pole motor is fed at 440V and takes an armature current of 50A. The resistance of the armature circuit is 0.28Ω. The armature winding is wave connected with 888 conductors and useful flux/pole is 0.023 wb. Calculate speed of the motor.

4 The counter emf of a shunt motor is 227V, the field resistance is 160Ω and field current is 1.5A. If the line current is 39.5A, find armature resistance. Also find the armature current when the motor is stationary.

5 A 20kW, 250V DC shunt generator has armature and field resistances of 0.1Ω & 125Ω respectively. Calculate the total armature power developed when running

i) As a generator delivering 20kW output

ii) As a motor taking 20kW input.

6 Find the useful flux/pole on no-load of 250V, 6-pole shunt motor having wave connected armature winding with 110 turns. The armature resistance is 0.2 Ω. The armature current is 13.3A at a no-load speed of 908rpm.

7 A 440V shunt motor has armature resistance of 0.8 Ω and field resistance of 200 Ω. Determine the back emf when giving an output of 7.46kW at 85% efficiency.

8 Calculate the value of torque established by the armature of a 4-pole motor having 774 conductors, 2 paths in parallel, 24mWb flux/pole, when the total armature current is 50A.

9 An armature of a 6-pole machine 75cm in diameter has 664 conductors each having an effective length of 30cm and carrying a current of 100A. If 70% of total conductors lie simultaneously in the field of average flux density 0.85 Wb/m2, calculate

i) Armature torque ii) Horse power output at 250 rpm

10 A 230V DC Shunt motor takes a current of 40A and runs at 1100rpm. If armature & shunt field resistance are 0.25 Ω & 230 Ω respectively. Find the torque developed by the armature.

11 A DC motor takes an armature current of 110A at 480V. The armature circuit resistance is 0.2 Ω the machine has 6-pole and armature is lap connected with 864 conductors. The flux/pole is 0.05 Wb. Calculate i) the speed and ii) the gross torque developed by the motor.

12 A 240V, 4-pole shunt motor running at 1000rpm gives 15 HP with an armature current of 50A and field current of 1A. The armature winding is wave connected and has 540 conductors. The armature resistance is 0.1 Ω and the drop at each brush is 1V. Find i) useful torque ii) The total torque iii) useful flux/pole and
iv) Iron & frictional losses

13 A 4-pole DC series motor has 944 wave connected armature conductors. At a certain load the flux/pole is 34.6m Wb and the total mechanical torque developed is 209 N-m. Calculate the line current taken by the motor and the speed at which it will run. The applied voltage is 500V and total motor resistance is 3 Ω.

14 A 200V, 14.92kW DC shunt motor when tested by the Swinburne method gave the following results:
Running light: armature current was 6.5A and field current 2.2A. With the armature locked, the current was 70A when a potential difference of 3V was applied to the brushes. Estimate the efficiency of the motor when working under full-load conditions

# BASIC ELECTRICAL ENGINEERING

by

**S Reddy Ramesh**
**Assistant Professor**
Dept of Electrical & Electronics Engineering
Aditya College of Engineering & Technology
Surampalem.

# Unit-II TRANSFORMERS

- Principle of operation of single phase transformer
- constructional features
- EMF equation
- Losses and efficiency of transformer
- Regulation of transformer
- OC & SC test
- Predetermination of efficiency and regulation
- Sumpner’s test
- Numerical Problems.

# TRANSFORMERS

## Introduction:

A Transformer is a static equipment used for raising or lowering the voltage of an AC supply with a corresponding decrease or increase in current. It is essentially consists of two windings, the primary and secondary wound on a common laminated magnetic core.

(or)

A transformer is a device that transfers electrical energy from one electrical circuit to another electrical circuit by electromagnetic induction (transformer action).

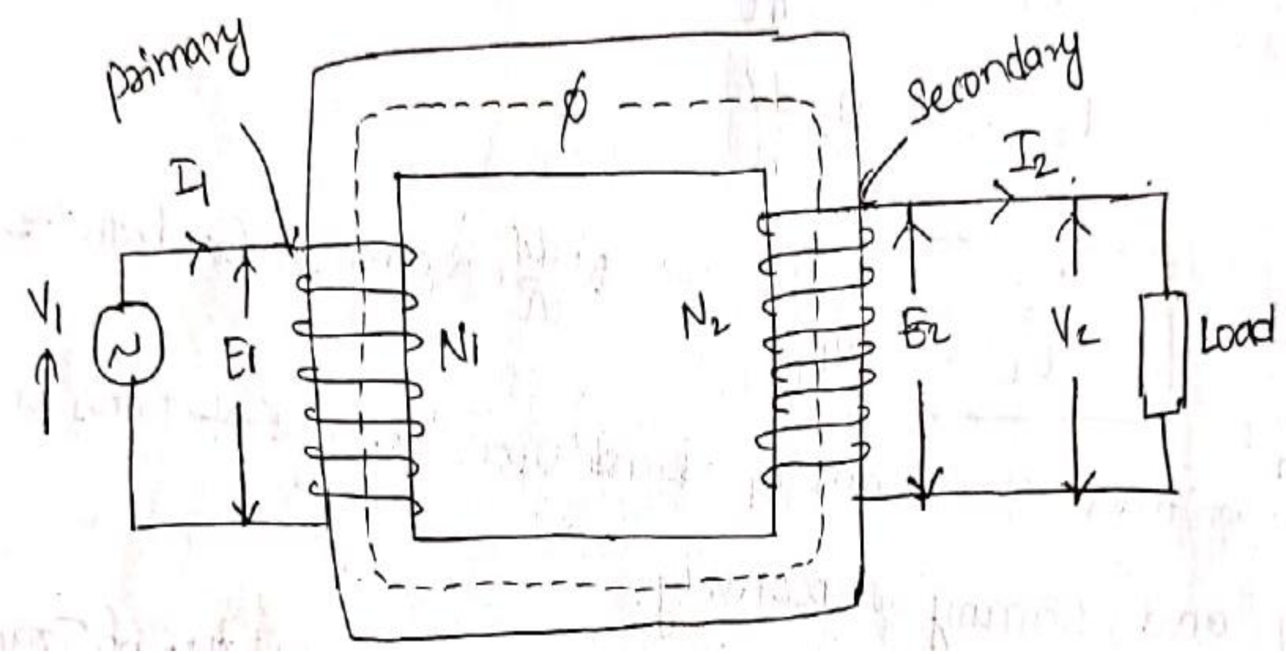
A transformer mainly has two windings wound on the two limbs of the transformer, namely, the primary winding and the secondary winding. Primary winding connected with the supply, secondary winding connected with load.

(or)

An A.C. device used to change high voltage low current A.C. into low voltage high current A.C. and vice-versa without changing the frequency.

In brief,

1. Transfers electric power from one circuit to another circuit.
2. It does so without a change in frequency.
3. It accomplishes this by electromagnetic induction.
4. Where the two electric circuits are in mutual inductive influence of each other.



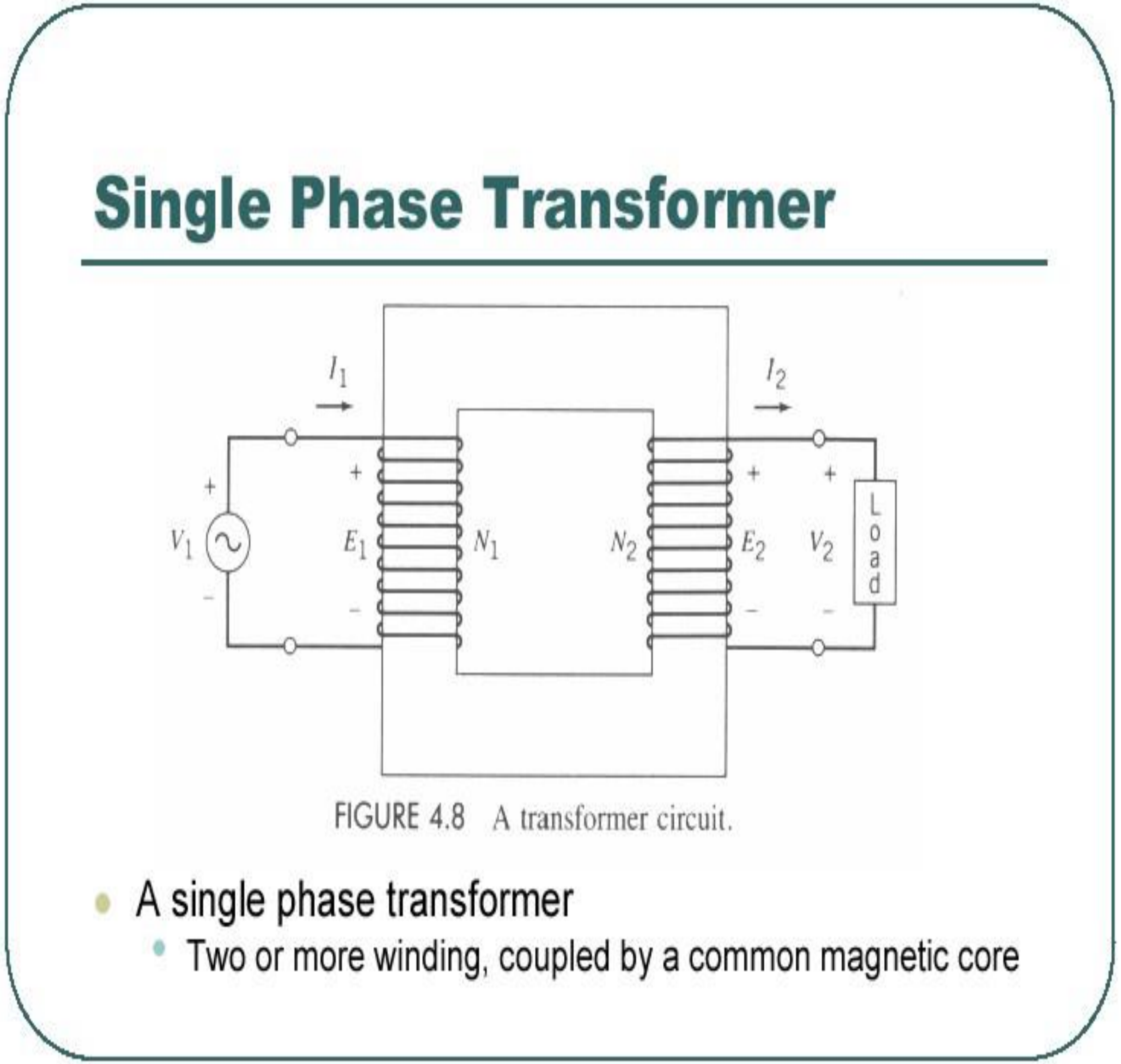



FIGURE 4.8 A transformer circuit.

The winding connected to the ac source is called primary winding and the one connected to load is called Secondary winding. The alternating voltage $V_1$ whose magnitude is to be changed is applied to the primary. Depending upon the no: of turns of the primary ($N_1$) and Secondary ($N_2$), an alternating emf $E_2$ is induced in the secondary. The induced emf $E_2$ in the Secondary causes a Secondary current $I_2$. Consequently, terminal voltage $V_2$ will appear across the load. If $V_2 > V_1$, it is called a step-up Transformer. On the other hand, if $V_2 < V_1$, it is called a step-down Transformer.

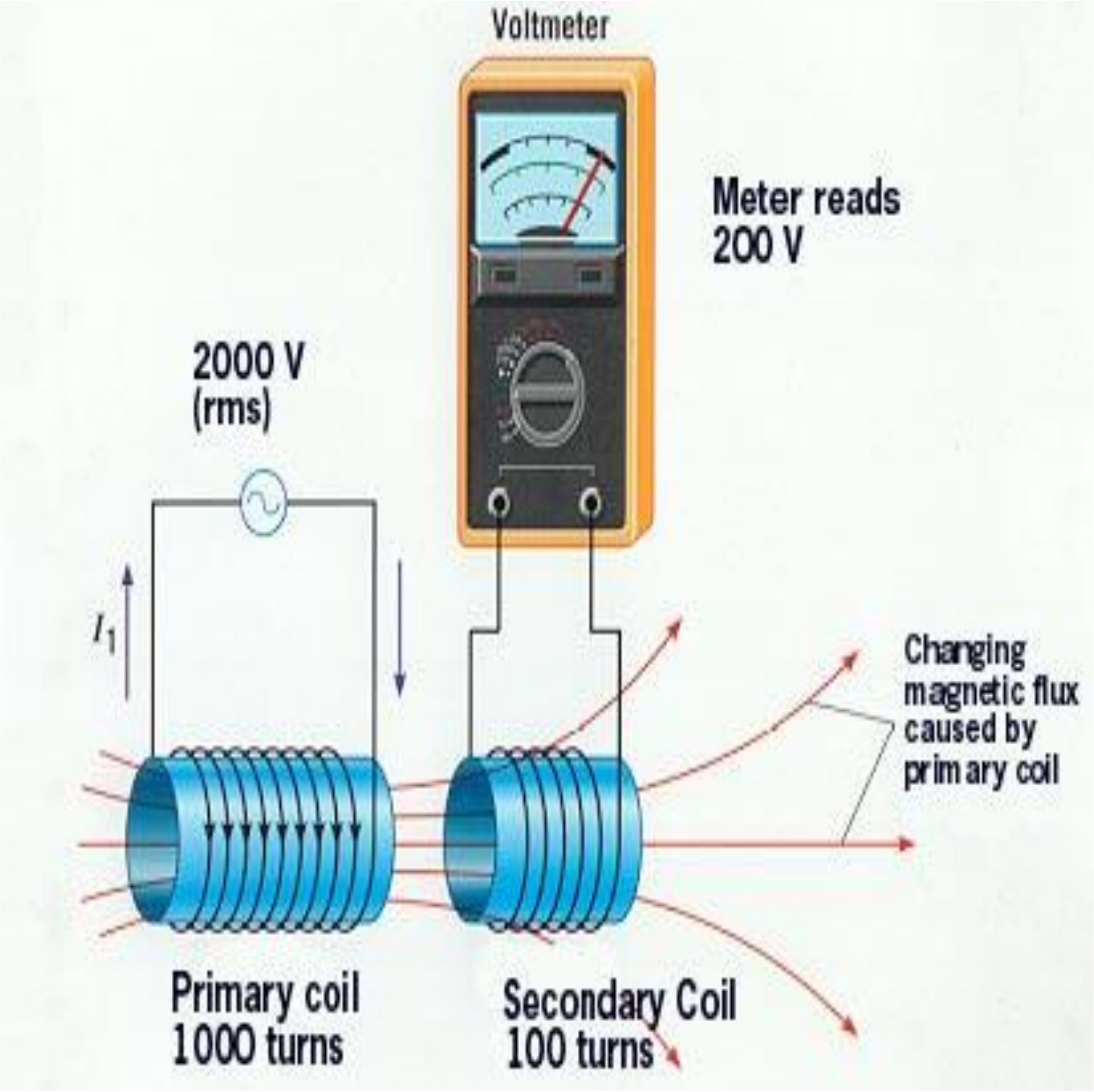
→ The Two windings are electrically seperable and magnetically coupled

# Principle of operation:

It is based on principle of **MUTUAL INDUCTION.** According to which an e.m.f. is induced in a coil when current in the neighbouring coil changes.

The primary of the transformer having $N_1$ turns is fed from an AC supply of $V_1$ volts. The current $I_1$ will flow through the primary coil. The current through the primary will set up a flux ϕ in the core. This flux, when linked with the primary winding, will produce an induced e.m.f., $E_1$, in the primary.

The flux ϕ will pass through the core and link with the secondary winding to induce an e.m.f., $E_2$, in the secondary winding.



Because of this induced e.m.f., a current $I_2$ will flow through the load connected with the secondary winding. The load terminal voltage is $V_2$.

If the input voltage $V_1$ is greater than the output voltage $V_2$, then it is called the step-down transformer. If the input voltage $V_1$ is less than the output voltage $V_2$, then it is called the step-up transformer.

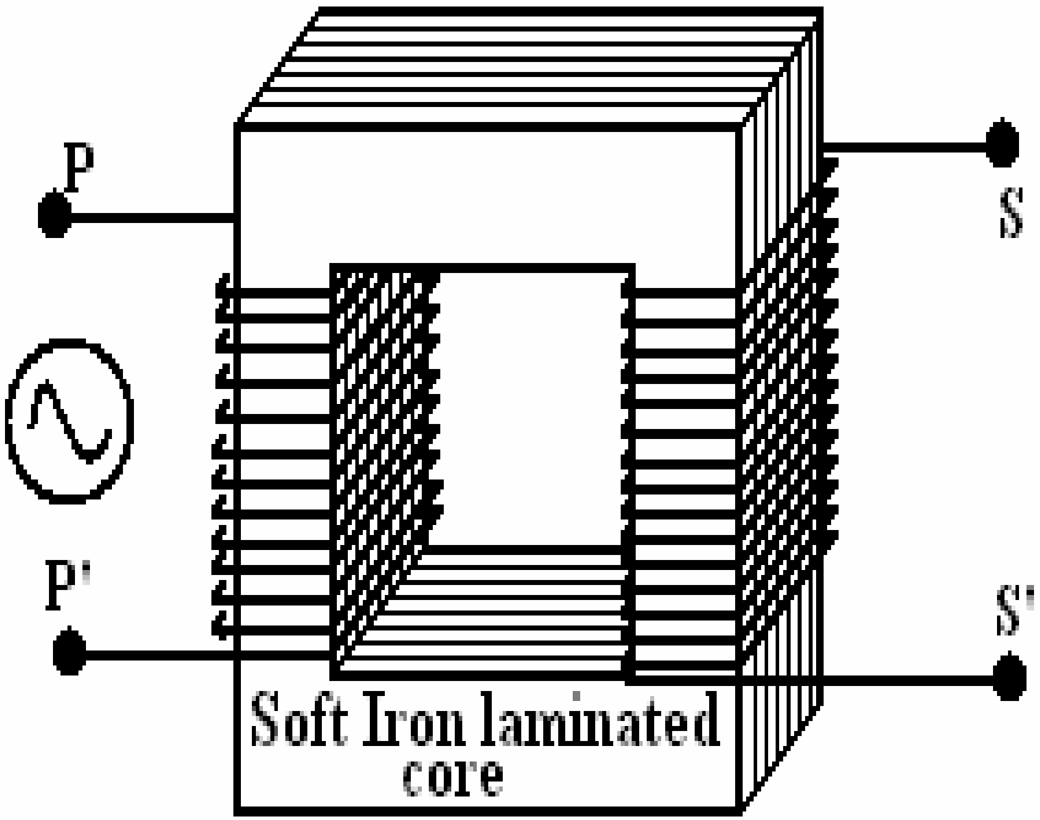
## Transformation Ratio:

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

Where, $N_1$ and $N_2$ is the number of turns of primary and secondary, $I_1$ and $I_2$ is the primary and secondary current respectively, $V_1$ and $V_2$ are the primary and secondary voltage respectively, and $E_1$ and $E_2$ are the primary and secondary EMF respectively.

# Working of a transformer

1. When current in the primary coil changes being alternating in nature, a changing magnetic field is produced
2. This changing magnetic field gets associated with the secondary through the soft iron core
3. Hence magnetic flux linked with the secondary coil changes.
4. Which induces e.m.f. in the secondary.



**working :-** when an alternating voltage $V_1$ is applied to the primary, an alternating flux $\phi$ is set up in the core. The alternating flux links both the windings and induces emf $E_1$ and $E_2$ in them according to Faraday's law of electromagnetic induction. The emf $E_1$ is termed as primary emf and emf $E_2$ is termed as secondary emf.

So,

$$E_1 = -N_1 \frac{d\phi}{dt}$$

$$E_2 = -N_2 \frac{d\phi}{dt}$$

$$\therefore \boxed{\frac{E_2}{E_1} = \frac{N_2}{N_1}} \qquad \because \frac{d\phi}{dt} \text{ is common for both the windings}$$

The magnitudes of $E_2$ and $E_1$ depend upon the no: of turns on the secondary and primary respectively.

If $N_2 > N_1$, then $E_2 > E_1$ (or $V_2 > V_1$) and we get step-up Transformer.
on the other hand, if $N_2 < N_1$, then $E_2 < E_1$ (or $V_2 < V_1$) and we get Step-down T/F.

If load is connected across the secondary winding, the secondary emf $E_2$ will cause a current $I_2$ to flow through the load. Thus a T/F enables us to transfer ac power from one circuit to another with a change in voltage level.

The following points may be noted:

1) The Transformer action is based on the laws of electromagnetic induction.
2) There is no electrical connection between the primary and secondary. The AC power is transferred from primary to secondary through magnetic flux.
3) There is no change in frequency i.e., output power has the same frequency as the input power.
4) The losses that occur in a Transformer are:
   a) ~~copper~~ core losses — eddy current and hysteresis losses
   b) copper losses — in the resistance of the windings

# Classification of Transformers:

i) Classification based on application
- Step-up transformer
- Step-down transformer

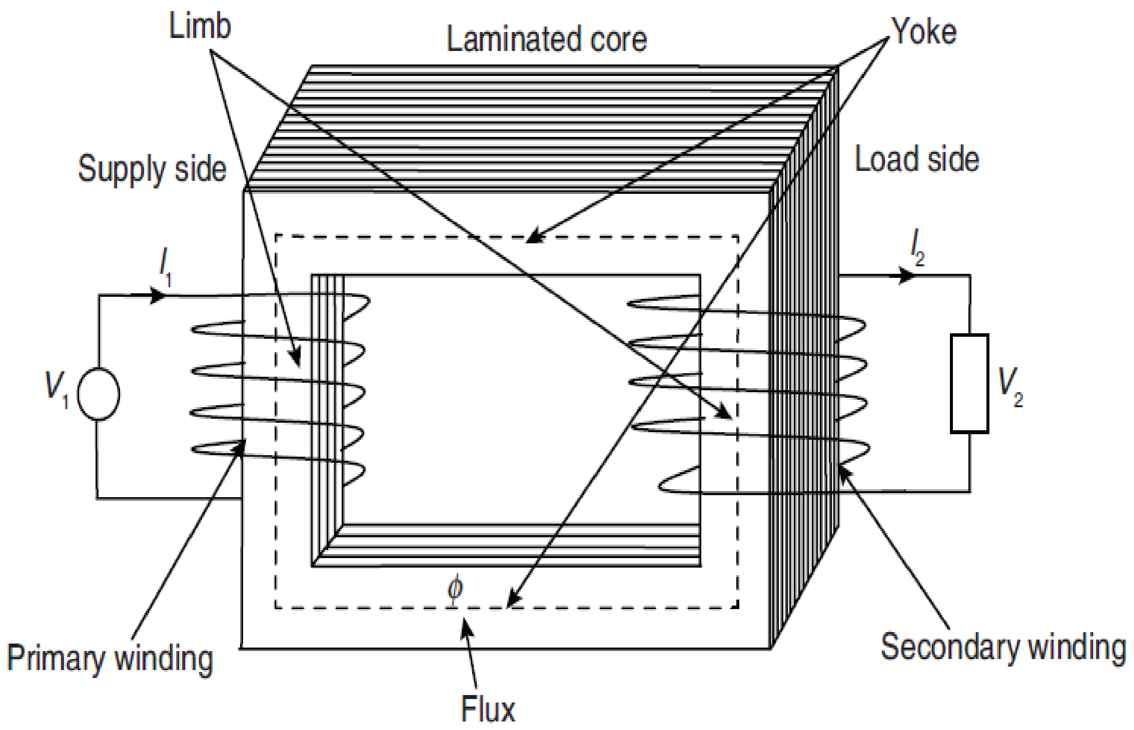
ii) Classification based on construction
- Core type transformer
- Shell type transformer

iii) Classification based on number of phases
- Single-phase transformer
- Three-phase transformer

iv) Classification based on the location of transformer
- Indoor type transformer
- Outdoor type transformer
- Station transformer

# Transformer Construction:

The different parts of the transformer are shown in Figure given below.

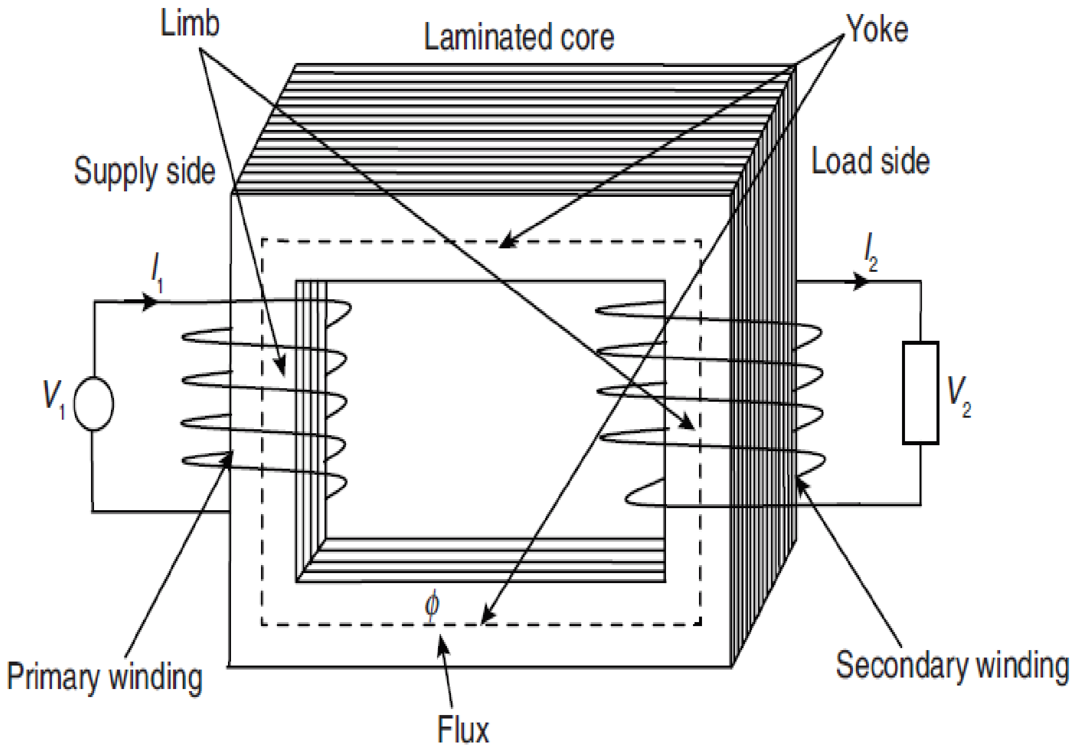


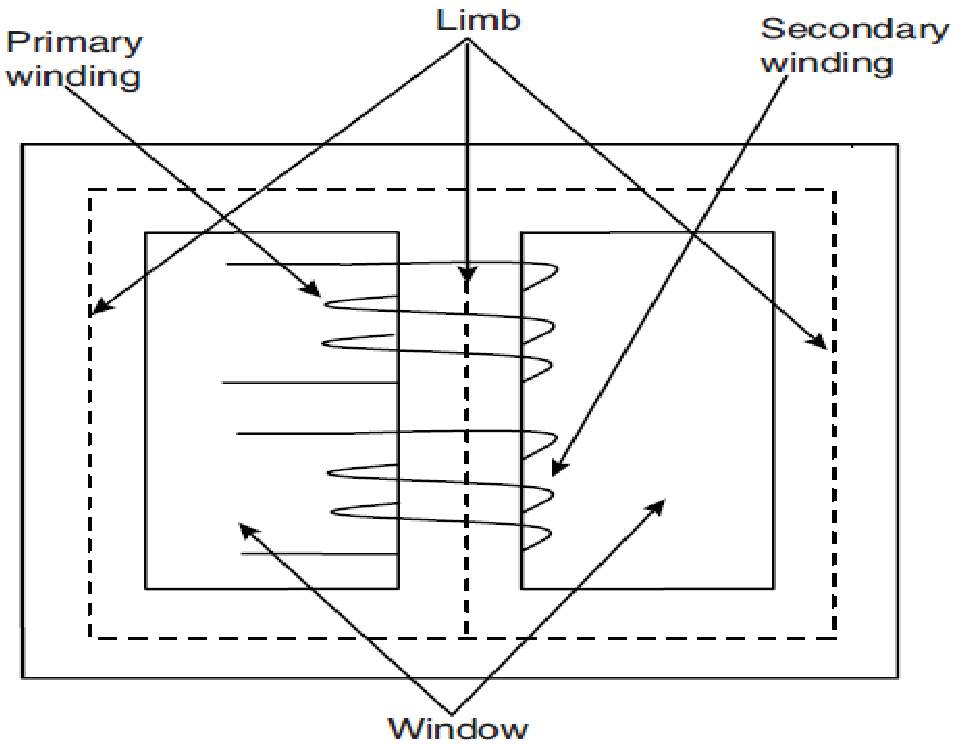
## Core-type Transformer:

A core-type transformer has a single path for the magnetic flux to flow in the transformer. The core can be in the form of a rectangle or a square.

## Shell type Transformer:

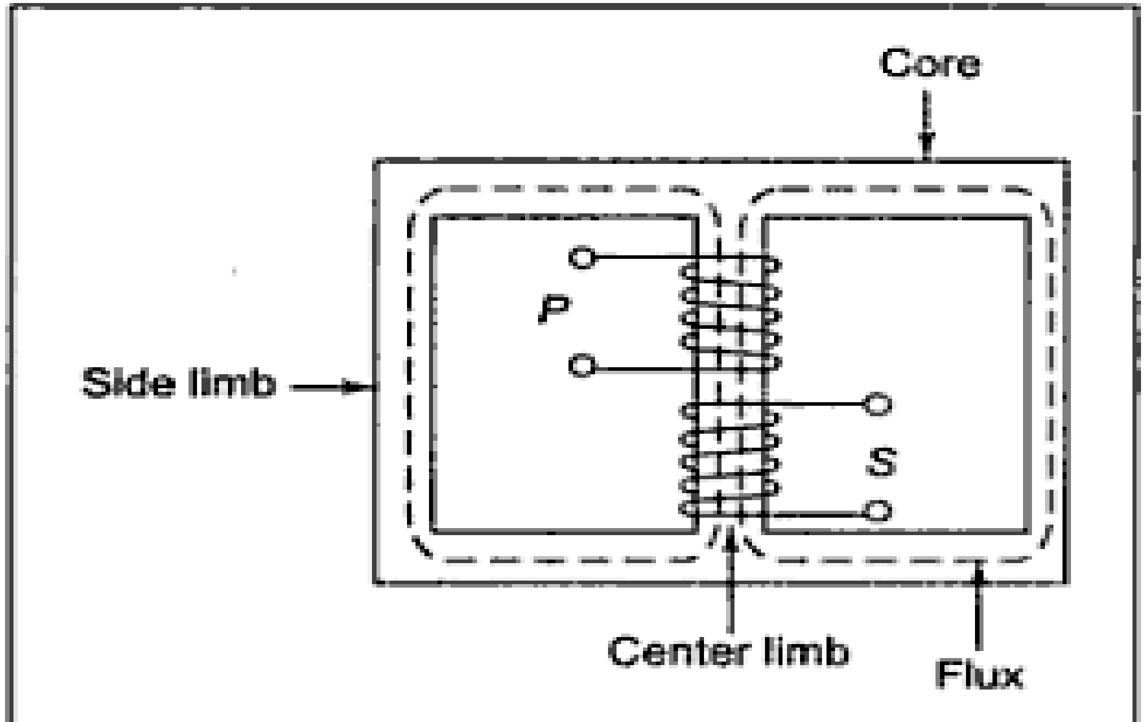
A shell-type transformer has two windows and three limbs. Both the primary and secondary windings are placed on the central limb.



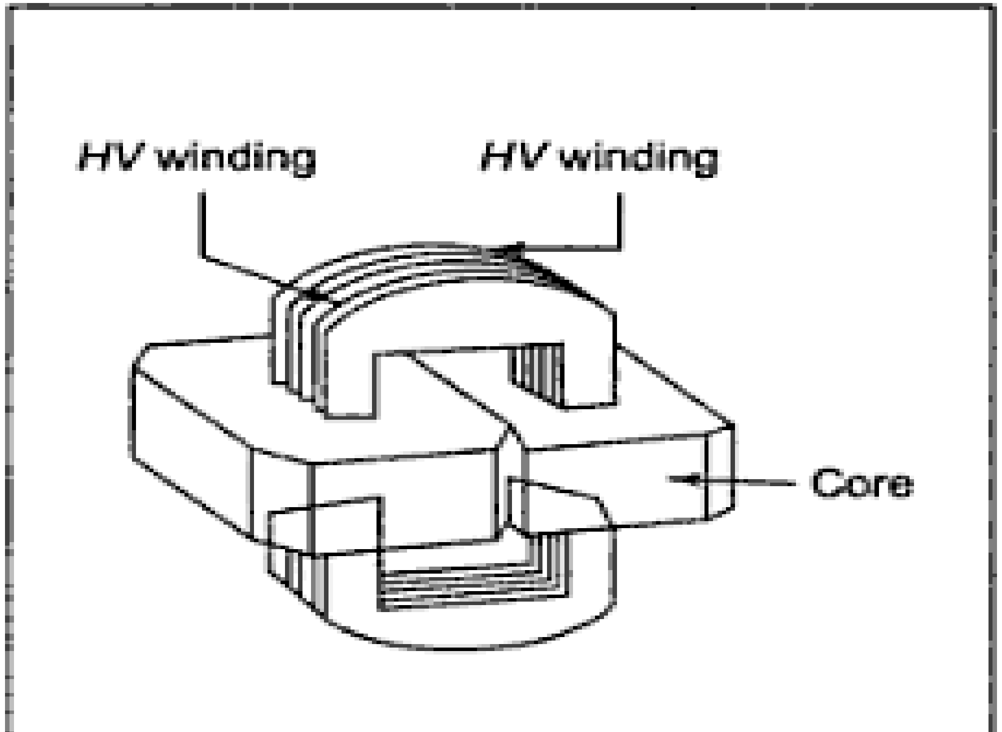



# Constructional details

## Shell Type:



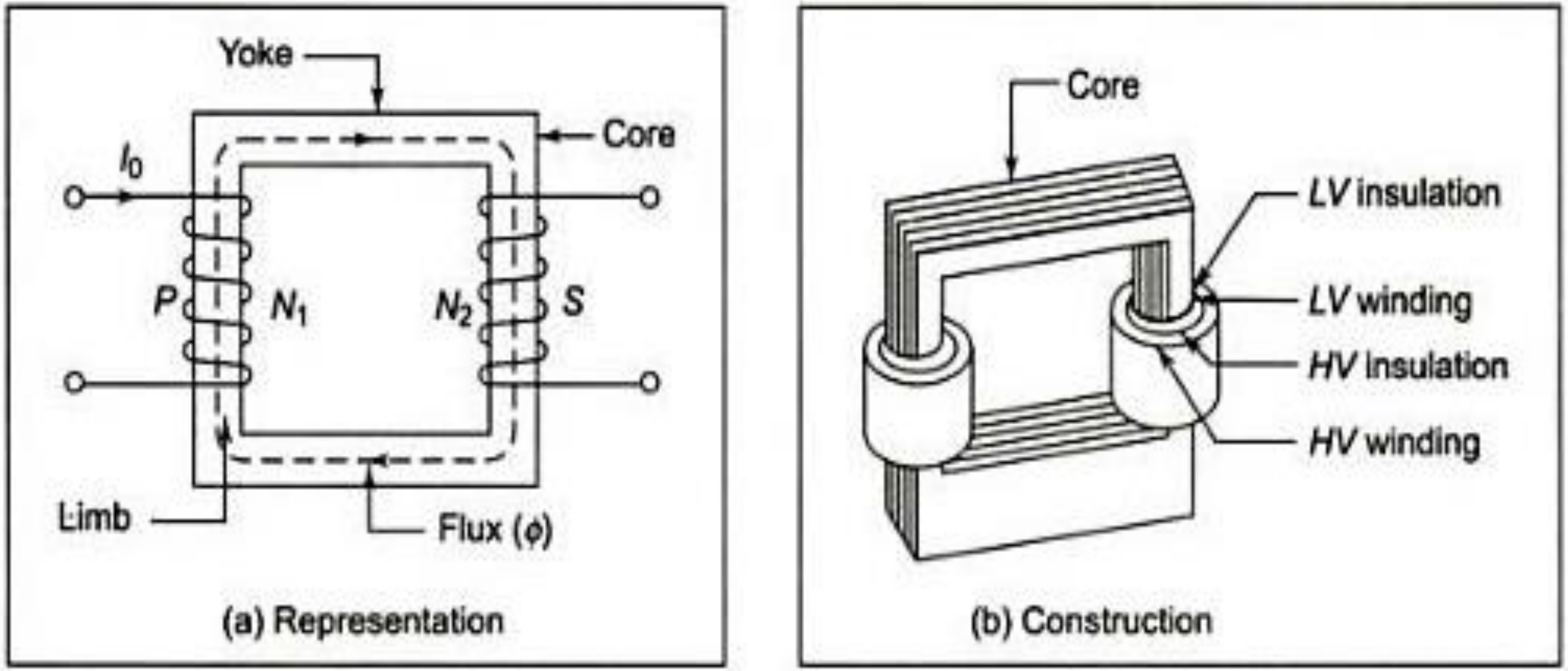

(a) Representation




(b) Construction

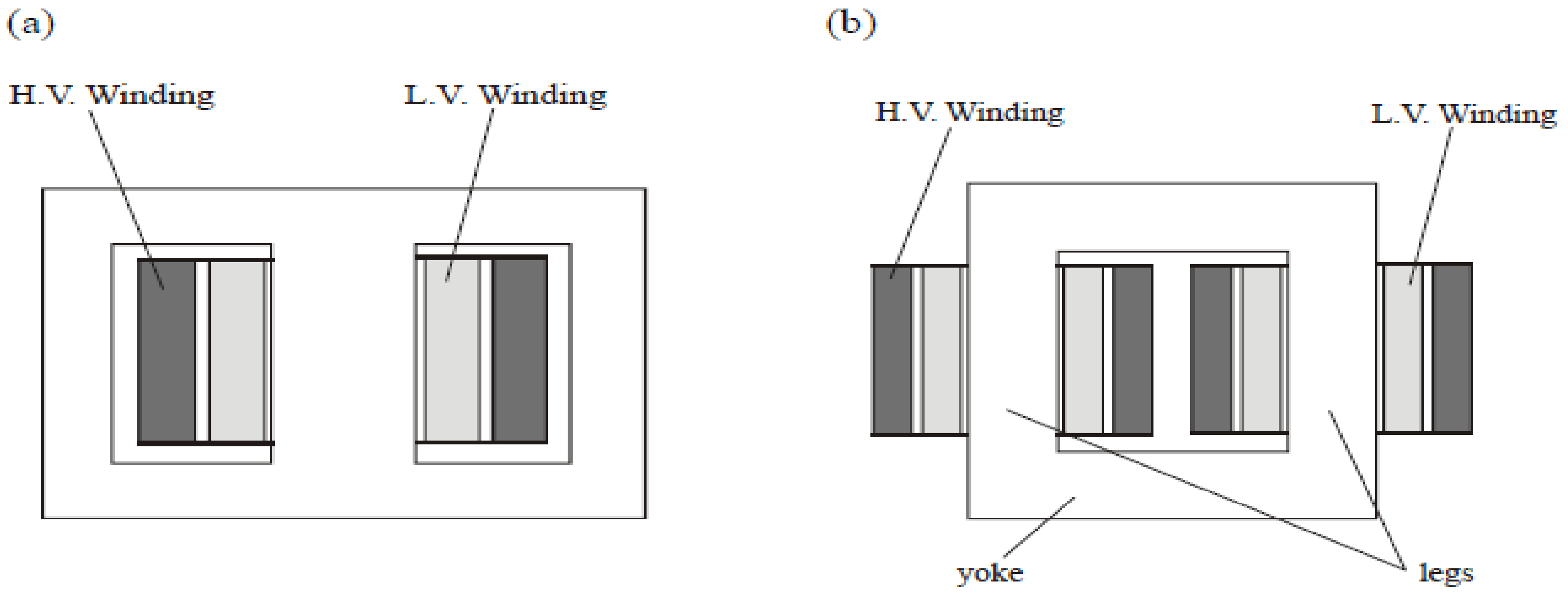
- Windings are wrapped around the center leg of a laminated core.

# Core type:




- Windings are wrapped around two sides of a laminated square core.

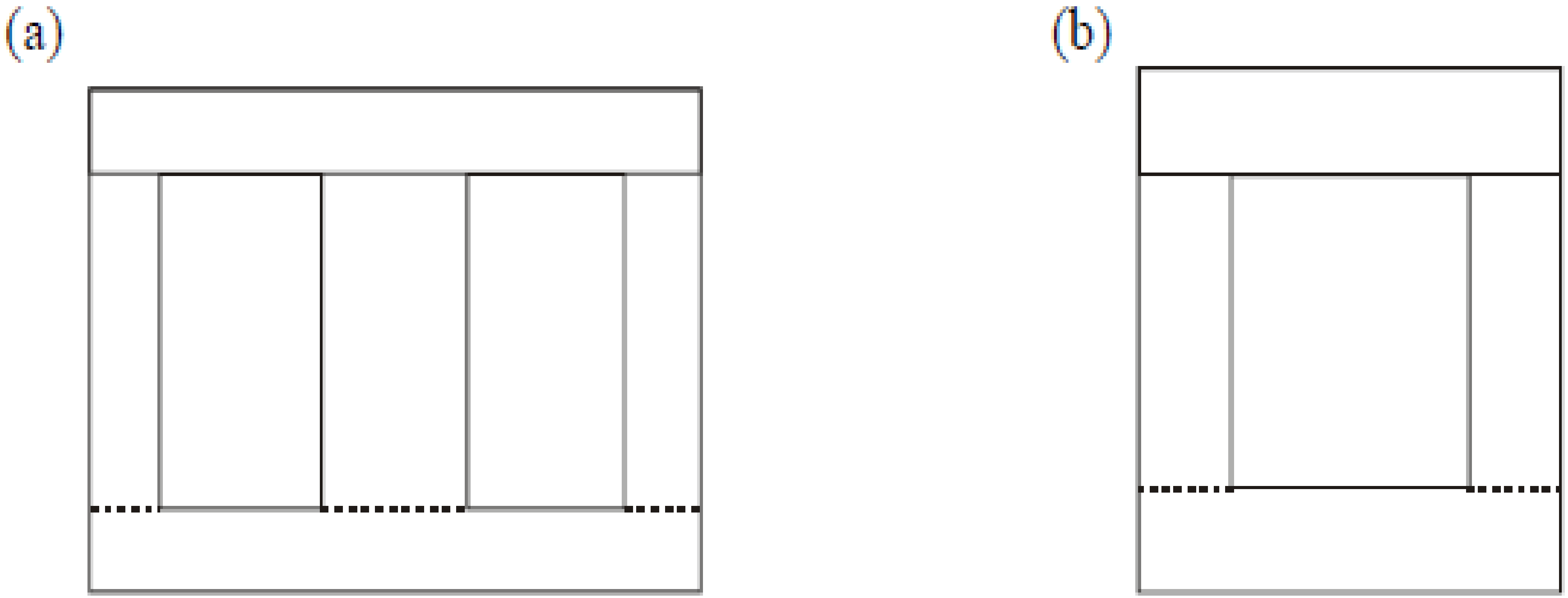
# Sectional view of transformers




(a) Shell-type transformer, (b) core-type transformer

**Note: High voltage conductors are smaller cross section conductors than the low voltage coils.**

# Construction of transformer from stampings:




(a) Shell-type transformer, (b) core-type transformer

## EMF equation of a Transformer :-

Consider that an alternating voltage $V_1$ of frequency $f$ is applied to the primary. The sinusoidal flux $\phi$ produced by the primary can be represented as :

$$\phi = \phi_m \sin \omega t$$

The instantaneous emf $e_1$ induced in the primary is

$$e_1 = -N_1 \frac{d\phi}{dt} = -N_1 \frac{d}{dt}(\phi_m \sin \omega t)$$

$$= -\omega N_1 \phi_m \cos \omega t$$

$$= -2\pi f N_1 \phi_m \cos \omega t$$

$$= 2\pi f N_1 \phi_m \sin(\omega t - 90) \quad \text{--- (1)}$$

It is clear from the above equation that max. value of induced emf in the primary is

$$E_{m1} = 2\pi f N_1 \phi_m \quad \text{--- (2)}$$

The rms value of $E_1$ of primary emf is

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}}$$

(or) $E_1 = 4.44 f N_1 \phi_m$

Similarly $E_2 = 4.44 f N_2 \phi_m$ } —③

∴ In an Ideal Transformer $E_1 = V_1$ and $E_2 = V_2$

**<u>Voltage Transformation ratio (K):-</u>**

From eqn③, we have

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K \quad —④$$

The constant K is called voltage Transformation ratio.

For an ideal Transformer :-

(i) $E_1 = V_1$ and $E_2 = V_2$ as there is no voltage drop in the windings

$$\frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = K \quad \text{—⑤}$$

(ii) There are no losses, Therefore volt-ampere input to the primary are equal to the output volt-amperes i.e.,

$$V_1 I_1 = V_2 I_2$$

$$(\text{or}) \quad \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K} \quad \text{—⑥}$$

Hence currents are in the inverse ratio of voltage Transformation ratio. This simply means that if we raise the voltage there is a corresponding decrease of current.

# Ideal Transformer:

- **Zero leakage flux:**

  -Fluxes produced by the primary and secondary currents are confined within the core
- **The windings have no resistance:**

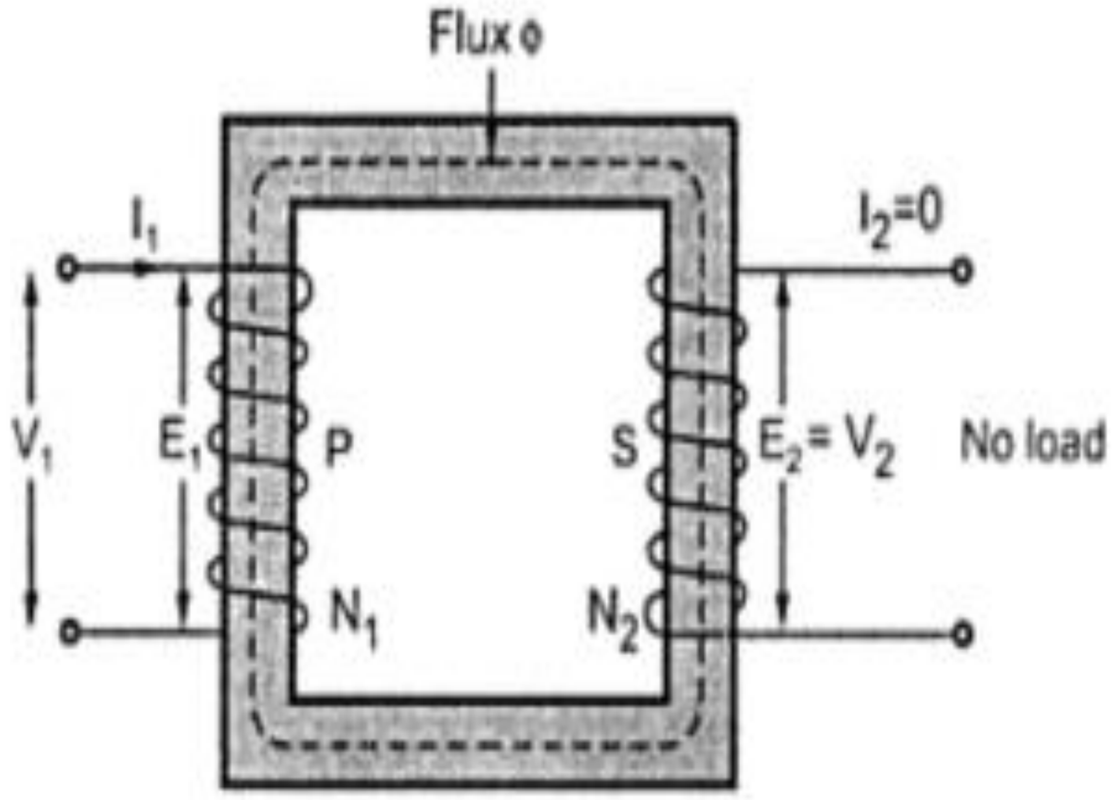
  - Induced voltages have equal applied voltages
- **The core has infinite permeability**

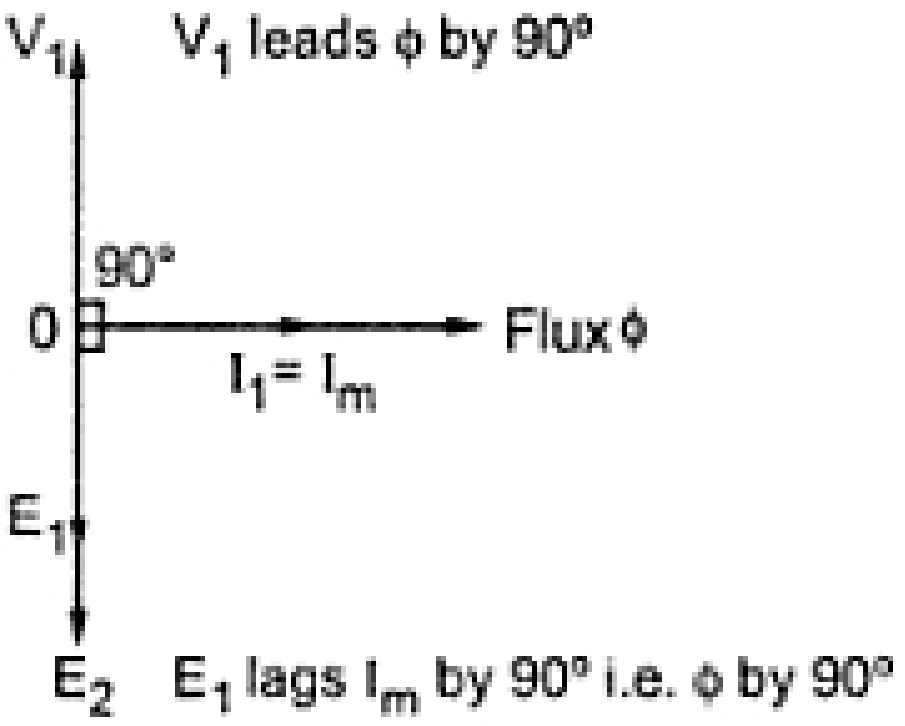
  - Reluctance of the core is zero

  - Negligible current is required to establish magnetic flux
- **Loss-less magnetic core**

  - No hysteresis or eddy currents

(Continued.,)




$V_1$ - supply voltage;

$V_2$ - output voltage;

$I_m$- magnetising current;

$E_1$-self induced emf ;

$I_1$- no load input current ;

$I_2$- output current

$E_2$- mutually induced emf

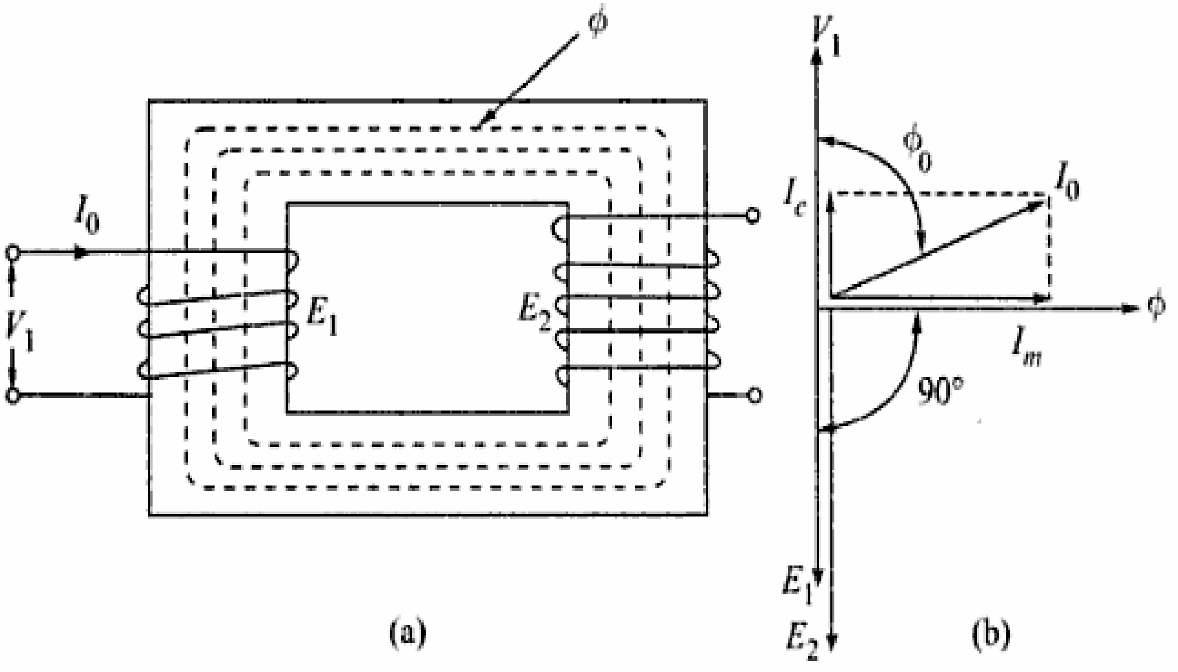
# Practical transformer on load:

Beside figure shows the Phasor diagram of a transformer on load by assuming

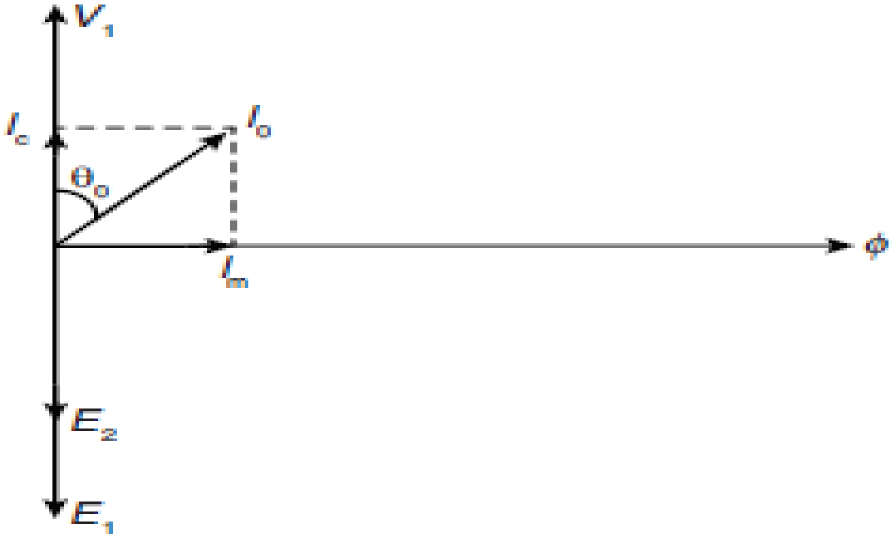
1. No voltage drop in the winding
2. Equal no. of primary and secondary turns

i) The magnetisation component ($I_m$), which is responsible for the production of flux in the core.

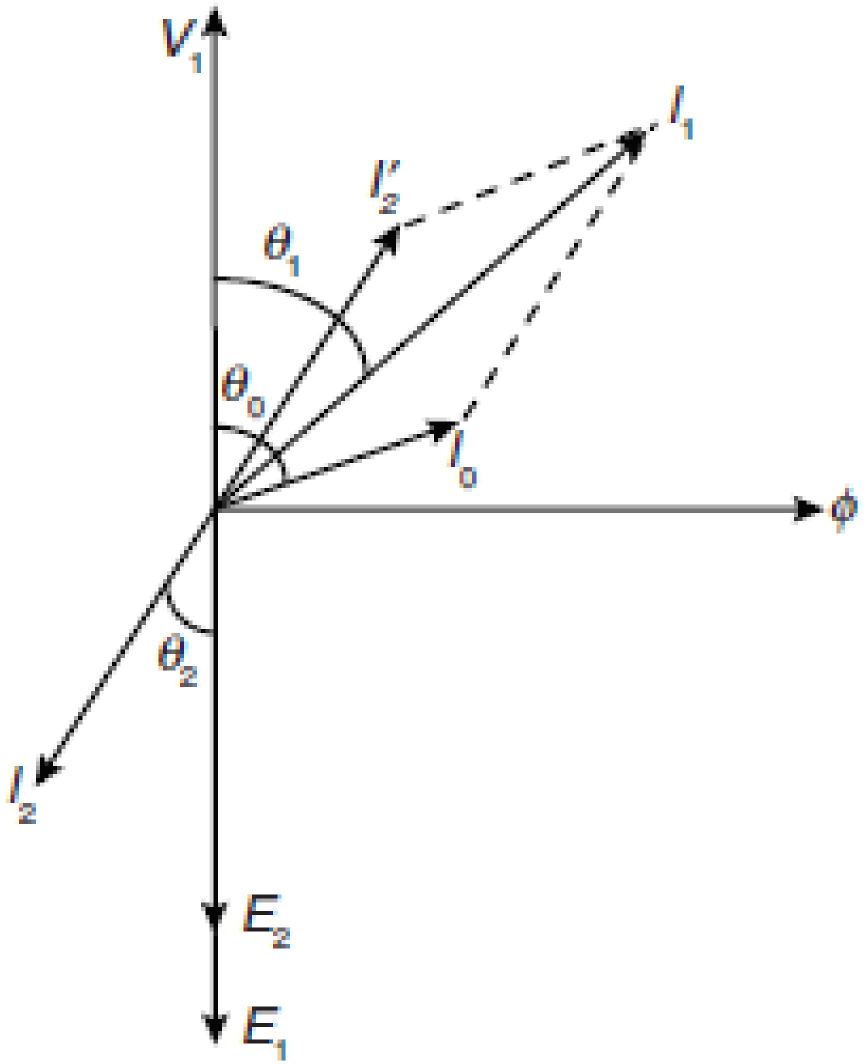
ii) The power component ($I_c$), which will supply the total losses.



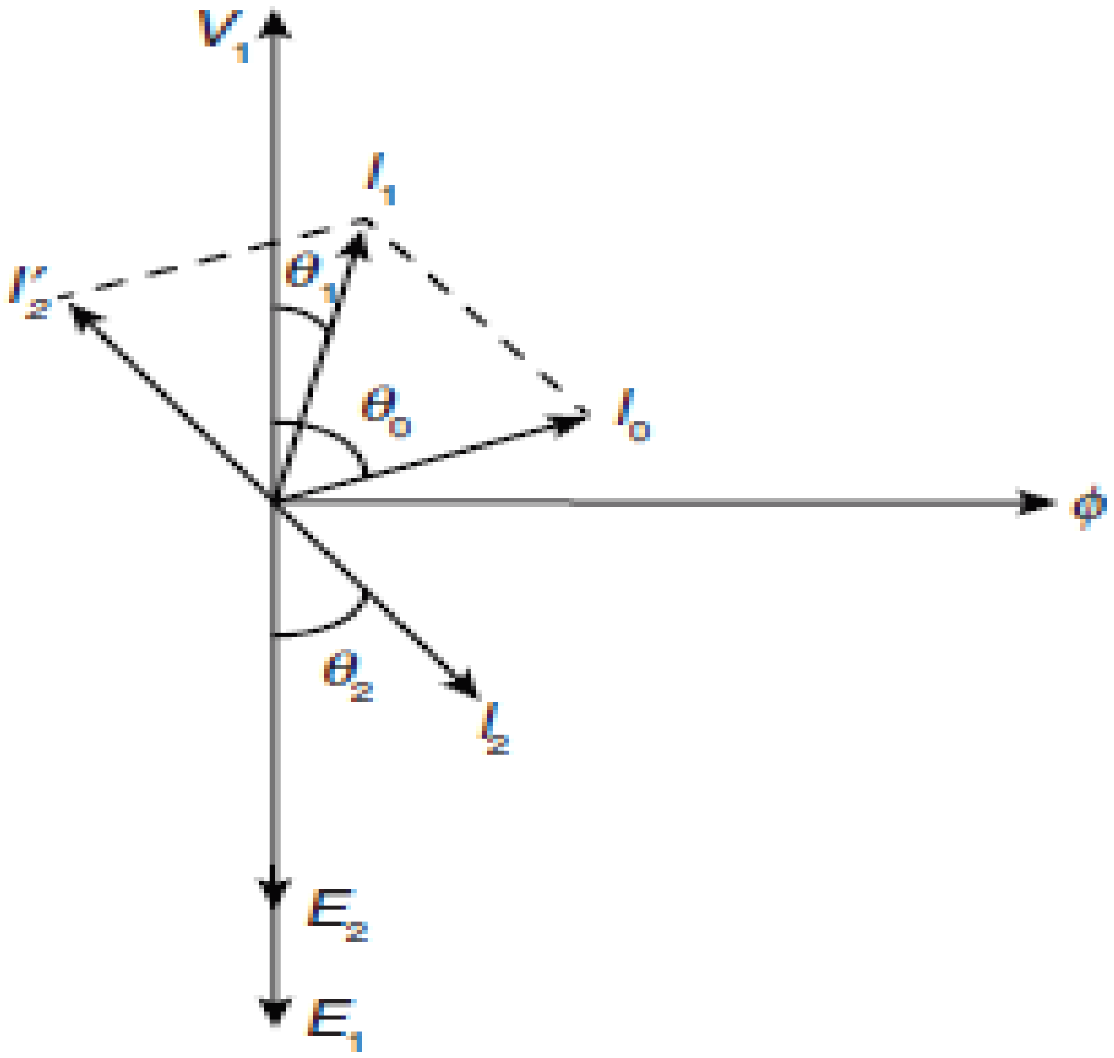

(a) Transformer on no-load (b) Phasor diagram of a transformer on no-load



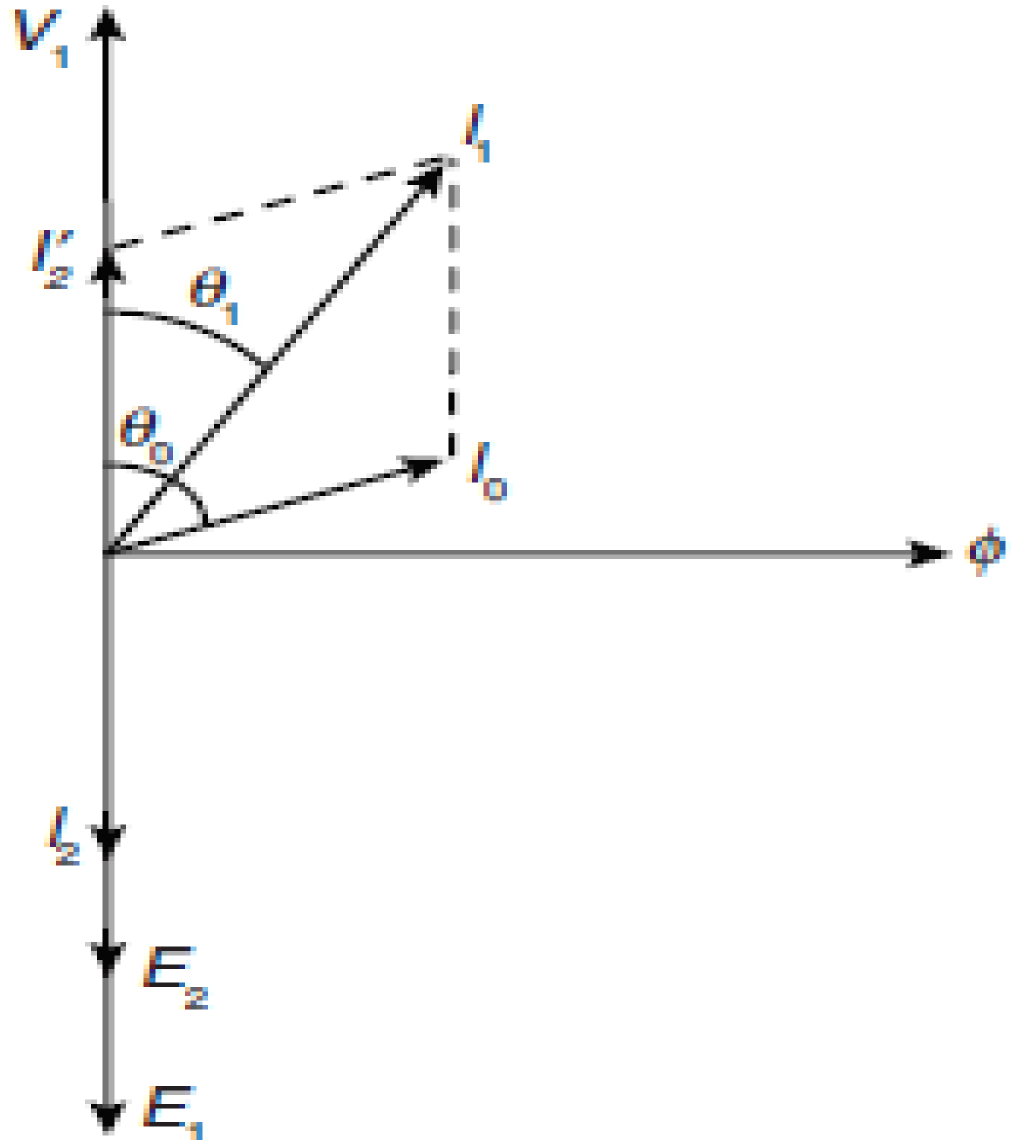
# Phasor diagram of transformer on load: Inductive Load



# Phasor diagram of transformer on load: Capacitive Load

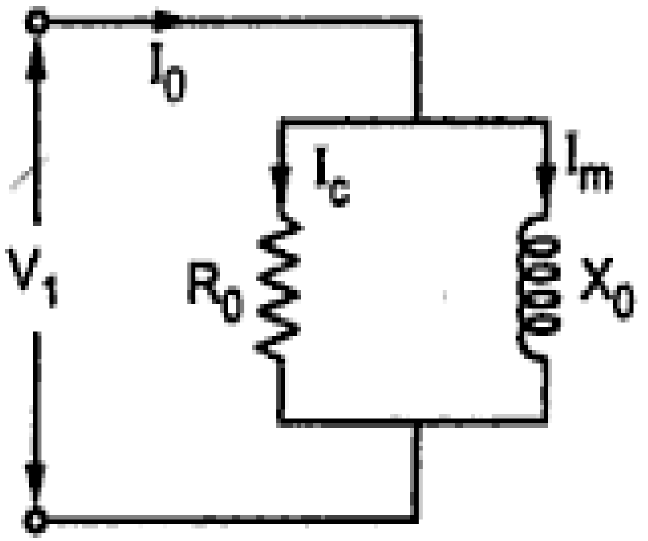


# Phasor diagram of transformer on load: Resistive Load



# Equivalent circuit of a transformer

## No load equivalent circuit:

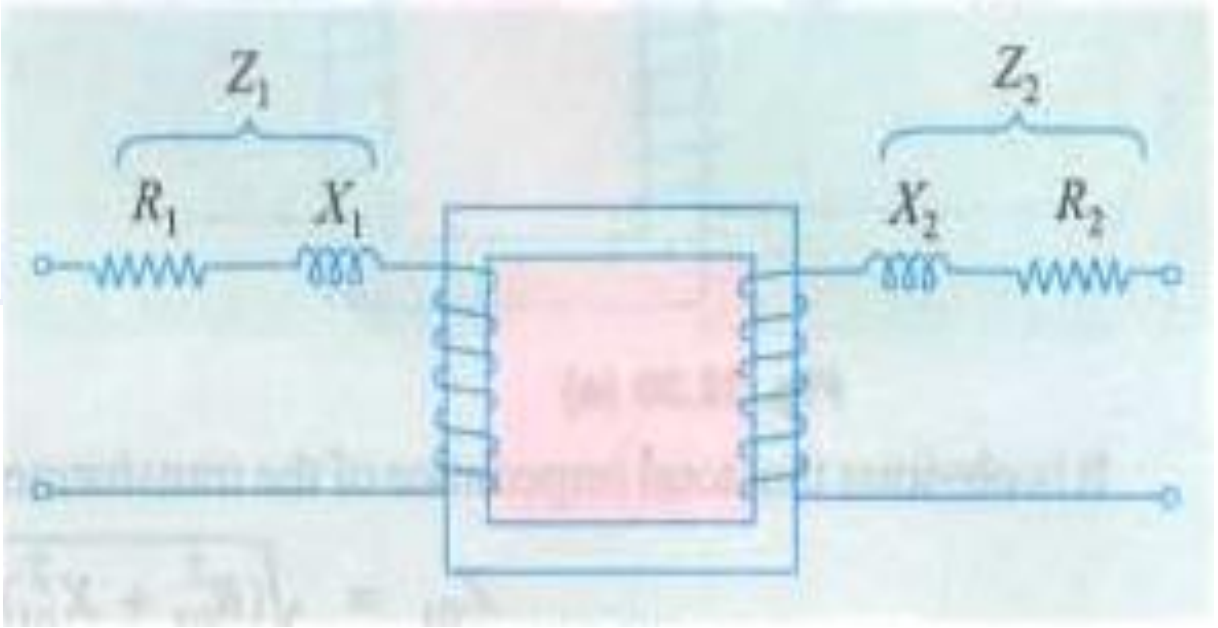



$$R_0 = \frac{V_1}{I_c}$$

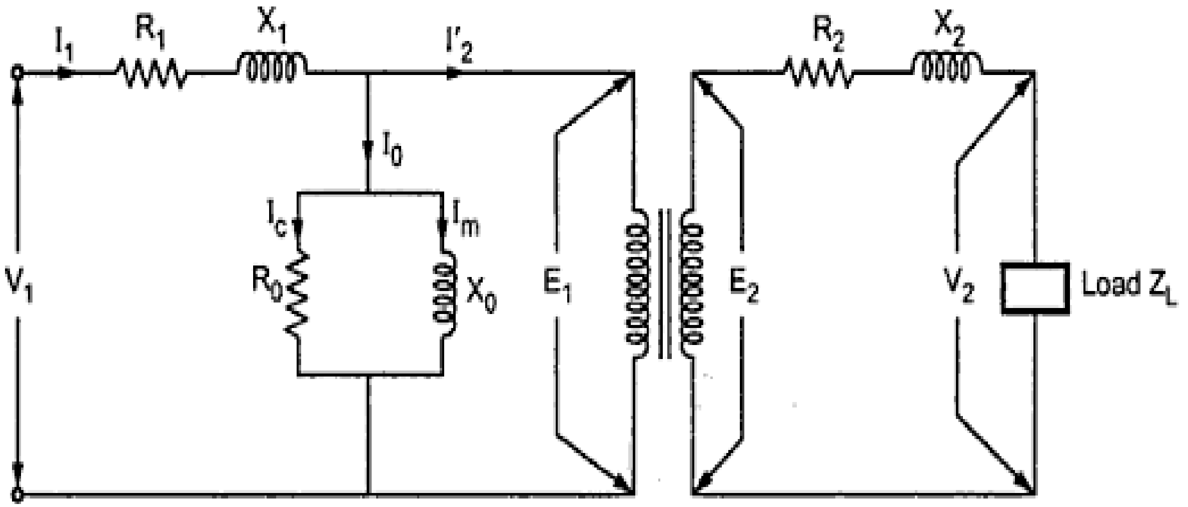
$$X_0 = \frac{V_1}{I_m}$$

$I_m = I_0 \sin \phi_0$ = Magnetising component

$I_c = I_0 \cos \phi_0$ = Active component




## Equivalent circuit of a transformer



## Impedance Ratio:-

Consider a Transformer having Impedance $Z_2$ in the secondary as shown in fig (a)

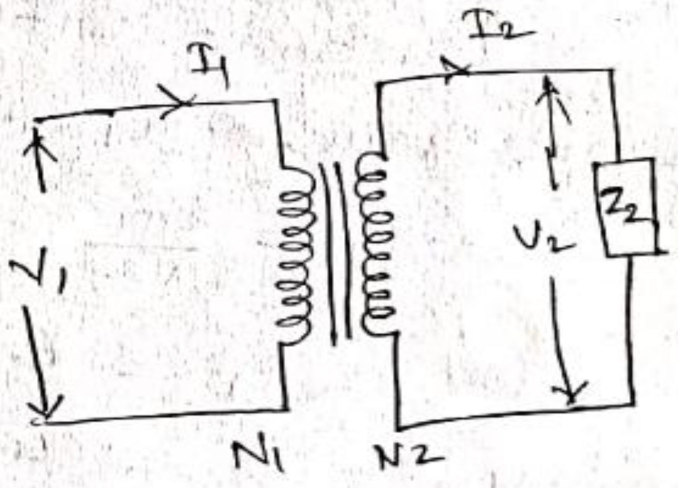



fig (a)

$$Z_2 = \frac{V_2}{I_2}$$

$$Z_1 = \frac{V_1}{I_1}$$

$$\frac{Z_2}{Z_1} = \left(\frac{V_2}{V_1}\right) \times \left(\frac{I_1}{I_2}\right)$$

$$\left[\because \frac{V_2}{V_1} = \frac{I_1}{I_2} = K\right]$$

(or)

$$\left(\frac{Z_2}{Z_1}\right) = K^2$$

Impedance ratio $(Z_2/Z_1)$ is equal to the square of voltage Transformation ratio. In other words, an Impedance $Z_2$ in secondary becomes $Z_2/K^2$ when transfered to primary. Likewise, an impedance $Z_1$ in the primary becomes $K^2 Z_1$ when transferred to the secondary.

Similarly $R_2/R_1 = K^2$ and $\frac{X_2}{X_1} = K^2$.

we can transfer the parameters from one winding to the other.

Thus :

(i) A Resistance $R_1$ in the primary becomes $K^2R_1$ when transferred to the secondary.

(ii) A Resistance $R_2$ in the secondary becomes $\frac{R_2}{K^2}$ when transferred to the primary.

(iii) A reactance $X_1$ in the primary becomes $K^2X_1$ when transferred to the secondary.

(iv) A reactance $X_2$ in the secondary becomes $X_2/K^2$ when transferred to the primary.

Also w.k.t

(i) when transferring resistance or reactance from primary to secondary, multiply it by $K^2$

(ii) when transferring resistance or reactance from secondary to primary divide it by $K^2$

(iii) when transferring voltage or current from one winding to the other, only K is used.

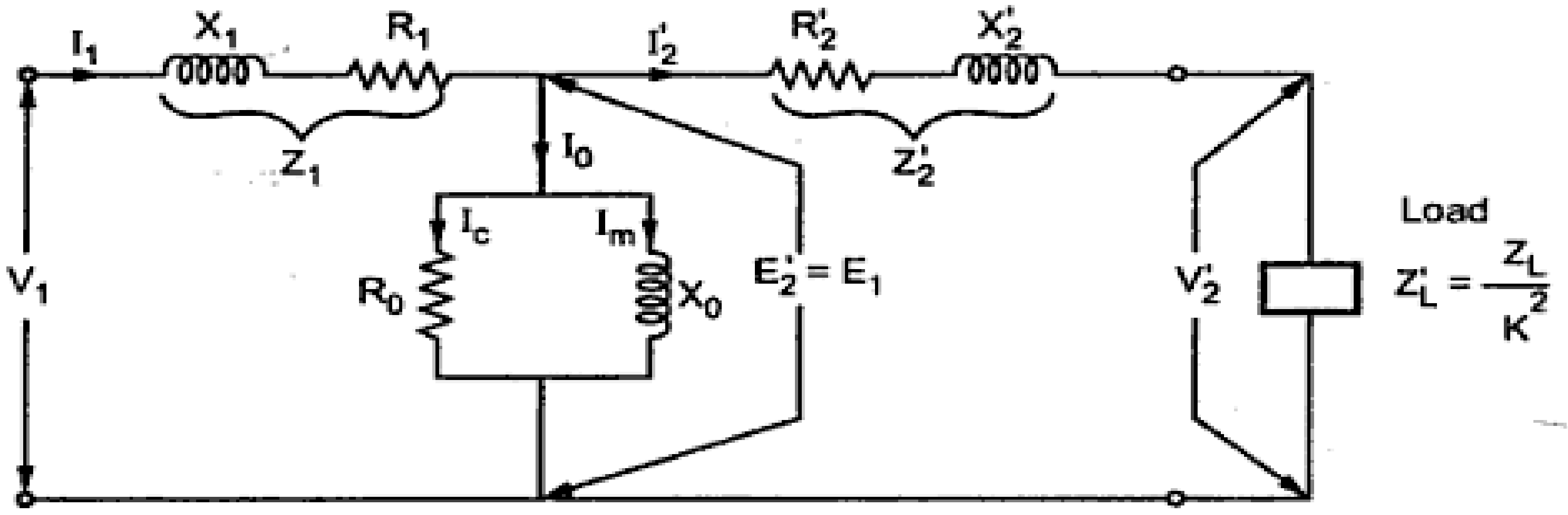
Any voltage $V_1$ in the primary becomes $KV_1$ in the secondary. On the other hand, any voltage $V_2$ in the secondary becomes $V_2/K$ in the primary. Again a current $I_1$ in the primary becomes $I_1/K$ in the secondary. Any current $I_2$ in the secondary becomes $KI_2$ in the primary.

# Transferring secondary parameters to primary side

$$R_2' = \frac{R_2}{K^2}, \quad X_2' = \frac{X_2}{K^2}, \quad Z_2' = \frac{Z_2}{K^2}$$

While $$E_2' = \frac{E_2}{K}, \quad I_2' = KI_2$$

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



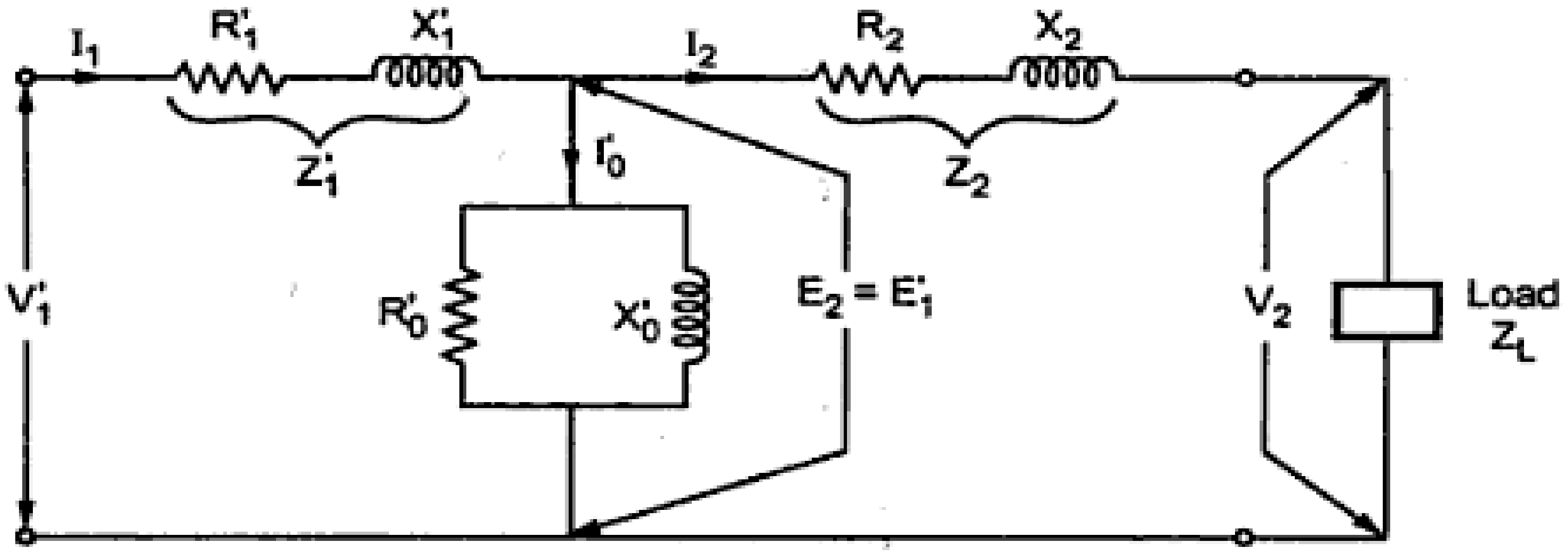

Exact equivalent circuit referred to primary

# Transferring primary parameters to secondary side

$$R_1' = K^2 R_1, \quad X_1' = K^2 X_1, \quad Z_1' = K^2 Z_1$$

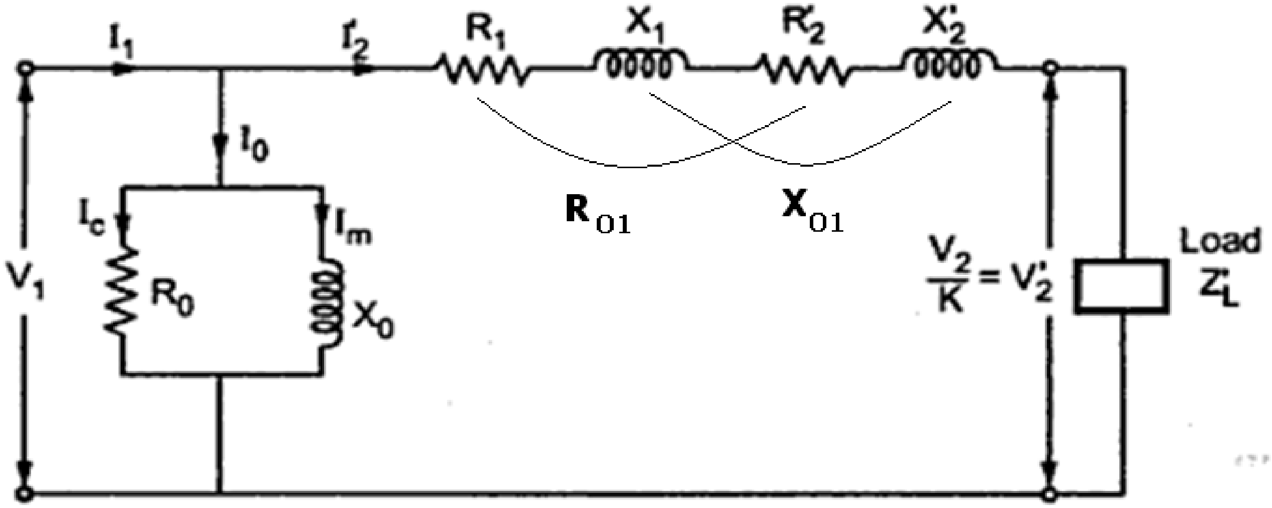
$$E_1' = K E_1, \quad I_1' = \frac{I_1}{K}, \quad I_0' = \frac{I_0}{K}$$

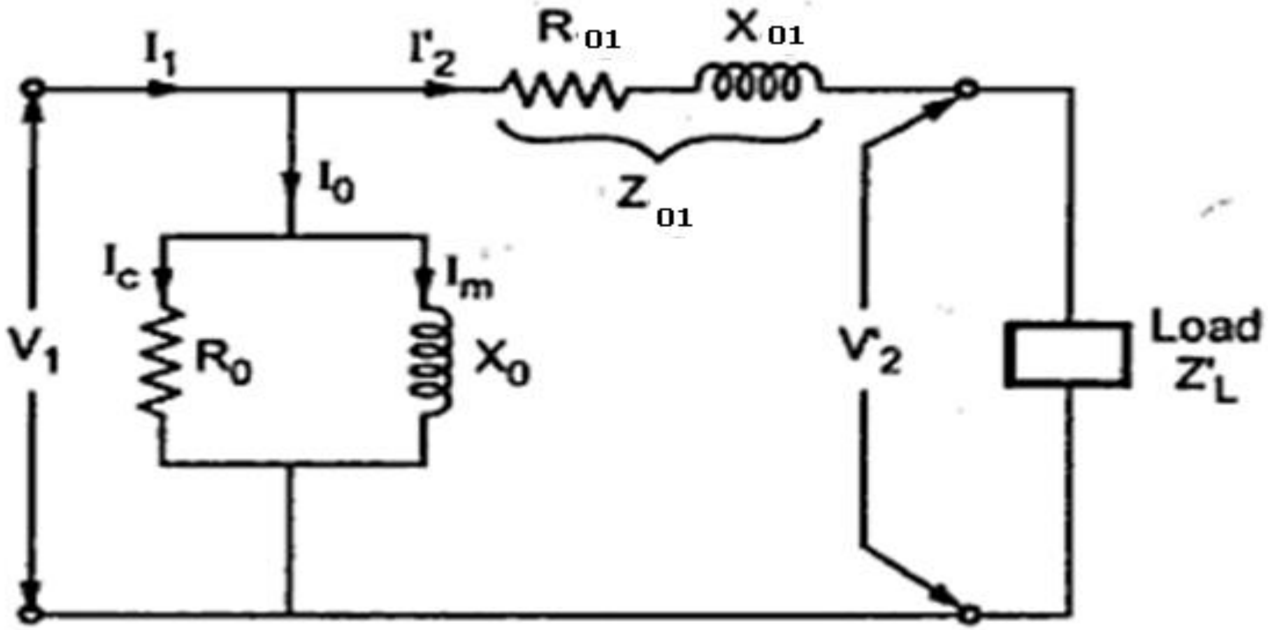
Similarly exciting circuit parameters are also transferred to secondary as $R_o'$ and $X_o'$




Exact equivalent circuit referred to secondary

# Equivalent circuit w.r.t primary




## Where

$$R_{01} = R_1 + R'_2 = R_1 + \frac{R_2}{K^2}$$

$$X_{01} = X_1 + X'_2 = X_1 + \frac{X_2}{K^2}$$

$$Z_{01} = R_{01} + j\,X_{01}$$

# Equivalent circuit w.r.t secondary

(ii) Referred to Secondary :- when primary resistance or reactance is transferred to the secondary, it is multiplied by $K^2$. It is then called resistance or reactance referred to the secondary and equivalent primary resistance or reactance is denoted by $R_1'$ or $X_1'$.

Equivalent resistance of Transformer referred to secondary is

$$R_{02} = R_2 + R_1'$$
$$= R_2 + K^2 R_1$$

Equivalent reactance of Transformer referred to secondary is

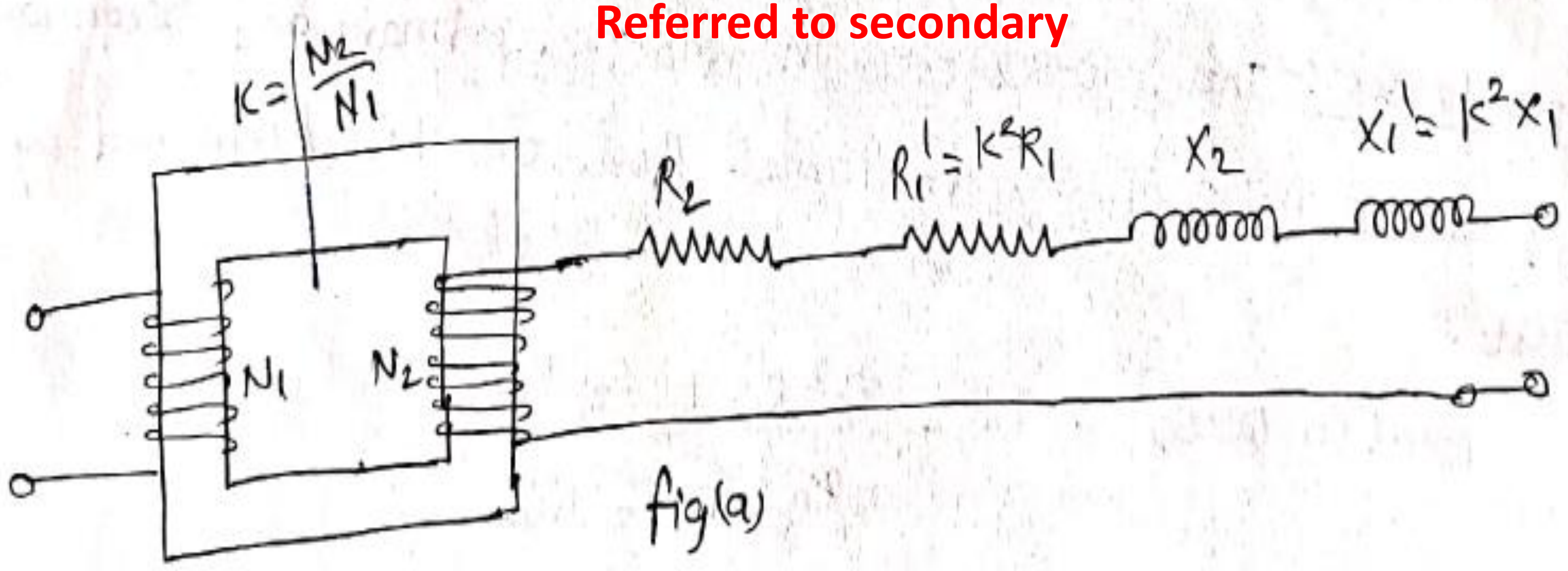
$$X_{02} = X_2 + X_1'$$
$$= X_2 + K^2 X_1$$

Equivalent impedance of Transformer referred to secondary is

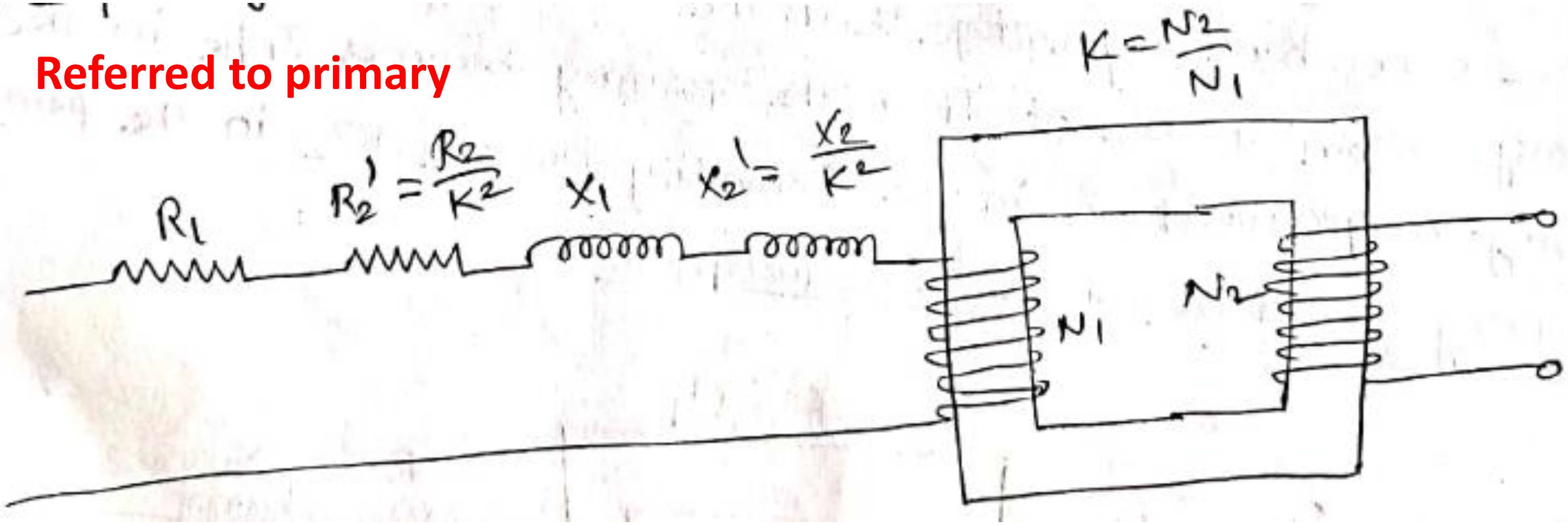
$$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$$

Fig (a) shows the R and X of the primary referred to the secondary. Note that primary now has no resistance or reactance.

## Referred to secondary




## Referred to primary



## Losses in a Transformer:-

The power losses in a Transformer are of two types; namely;

1. core or Iron losses
2. copper losses

these losses appear in the form of heat and produce

(i) an increase in temperature and
(ii) a drop in efficiency.

1. core or Iron losses ($P_i$) :- These consists of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test.

$P_h$ = Hysteresis losses $= K_h f B_m^{1.6}$ watts/m$^3$

$P_e$ = Eddy current losses $= K_e f^2 B_m^2 t^2$ watts/m$^3$.

Both $P_h$ and $P_e$ depends upon (i) maximum flux density $B_m$ in the core and (ii) supply frequency f. Since transformers are connected to constant-frequency, constant voltage supply, both f and $B_m$ are constant. Hence core or Iron losses are practically the same at all loads.

Iron or Core losses $= P_i = P_h + P_e$
= constant losses

The hysteresis loss can be minimised by using steel of high silicon content whereas eddy current loss can be reduced by using core of thin laminations.

2. Copper losses :- These losses occur in both the primary and Secondary windings due to their ohmic resistance. These can be determined by SC Test.

$$\text{Total Cu losses} = P_c = I_1^2 R_1 + I_2^2 R_2$$

$$= I_1^2 R_{01} + I_2^2 R_{02}$$

$$\text{Total losses in a transformer} = P_i + P_c$$

$$= \text{constant losses} + \text{Variable losses}$$

## Efficiency of a Transformer :-

The efficiency of a Transformer is defined as the ratio of output power (in watts or kw) to input power (watts or kw) i.e.,

$$\text{Efficiency} = \frac{\text{output power}}{\text{Input power}}$$

In practice, open-circuit and short-circuit tests are carried out to find the efficiency.

$$\eta = \frac{\text{output}}{\text{Input}} = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{\text{Input}}{\text{Input} - \text{losses}}.$$

The losses can be determined by Transformer tests.

## Efficiency from Transformer Tests:-

Full load Iron loss $= P_i$ – from OC Test

Full load Cu. loss $= P_c$ – from SC Test

Total full load losses $= P_i + P_c$

The full load efficiency of the transformer at any pf without actually loading the transformer.

$$\eta_{FL} = \frac{\text{Full-load VA} \times \text{pf}}{(\text{Full-load VA} \times \text{pf}) + P_i + P_c} \quad \text{—(1)}$$

## Condition for maximum efficiency in T/F:

Also for any load equal to x full load

corresponding total losses = $P_i + x^2 P_c$

corresponding $\eta_x = \dfrac{(x \times \text{full load VA}) \times pf}{(x \times \text{full load VA} \times pf) + P_i + x^2 P_{cu}}$

Note that Iron losses remains the same at all loads

The output current corresponding to maximum efficiency is $I_2 = \sqrt{(W_i/R_{02})}$.

Output KVA corresponding to max efficiency =

$$= \text{Full load} \times \sqrt{\left(\frac{\text{Iron loss}}{\text{F.L. Cu loss}}\right)}$$

$$\text{Cu loss} = I_1^2 R_{01} \text{ or } I_2^2 R_{02} = W_{cu}$$

$$\text{Iron loss} = \text{Hysteresis loss} + \text{Eddy current loss} = W_h + W_e = W_i$$

Considering primary side,

$$\text{Primary input} = V_1 I_1 \cos\phi_1$$

$$\eta = \frac{V_1 I_1 \cos\phi_1 - \text{losses}}{V_1 I_1 \cos\phi_1} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$

$$= 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

Differentiating both sides with respect to $I_1$, we get

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} + \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

For $\eta$ to be maximum, $\dfrac{d\eta}{dI_1} = 0$. Hence, the above equation becomes

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1} \quad \text{or} \quad W_i = I_1^2 R_{01} \text{ or } I_2^2 R_{02}$$

or $\quad$ Cu loss = Iron loss

## All day (or) Energy efficiency :-

The ordinary or commercial efficiency of a Transformer is defined as the ratio of output power to the Input power.

$$\text{commercial efficiency} = \frac{\text{output power}}{\text{Input power}}$$

Now, Similarly if the performance of transformers is Judged on the basis of energy consumption during the whole day (i.e., 24 hours). This is known as all day or energy efficiency.

The ratio of output in kwh to the input in kwh of a Transformer over a 24-hour period is known as all-day efficiency. i.e.,

$$\eta_{all\text{-}day} = \frac{\text{kwh output in 24 hours}}{\text{kwh input in 24 hours}}$$

$$\text{Efficiency}\,(\eta) = \frac{\text{Output Power}}{\text{Input Power}} \times 100 = \frac{\text{Output Power}}{\text{Output Power} + \text{Loss}} \times 100$$

Where,

$$\text{Output Power} = V_2 I_2 \cos\theta_2$$

$$\text{Loss} = \text{Iron loss} + \text{copper loss}$$

$$\text{Iron loss}\,(P_i) = \text{Hysteresis loss} + \text{Eddy current loss}$$

The efficiency of the transformer at a load $x$ times full load will be

$$\eta = \frac{xV_2 I_2 \cos\theta_2}{xV_2 I_2 \cos\theta_2 + P_i + x^2 P_c}$$

# VOLTAGE REGULATION OF TRANSFORMER

Voltage Regulation :- The voltage regulation of a transformer is the arithmetic difference (not phasor difference) between the no-load secondary voltage ($_0V_2$) and the secondary voltage ($V_2$) on load expressed as percentage of no-load voltage i.e.,

In terms of secondary values

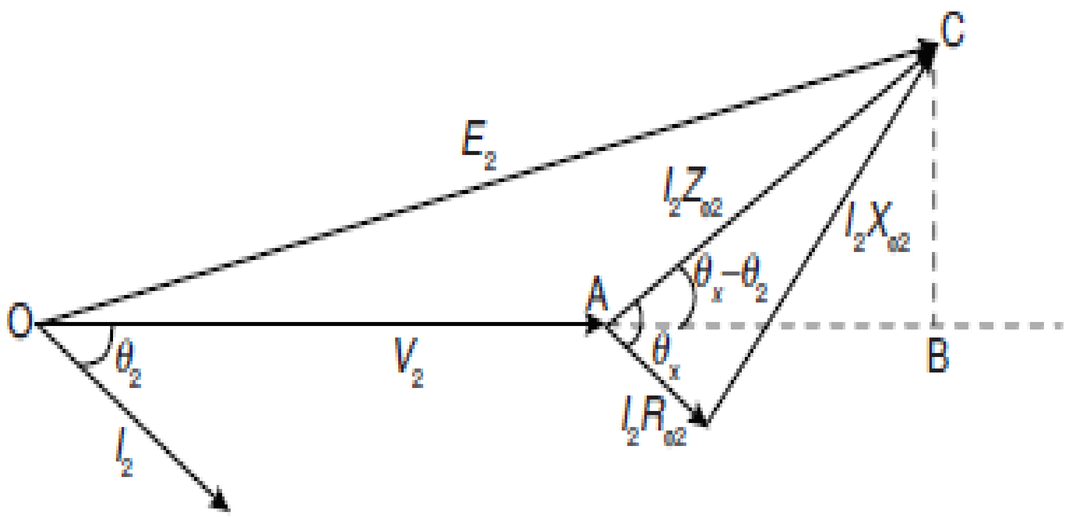
$$\% \text{ regulation} = \frac{{}_0V_2 - V_2}{{}_0V_2} = \frac{I_2 R_{02} \cos\phi_2 \pm I_2 X_{02} \sin\phi_2}{{}_0V_2}$$

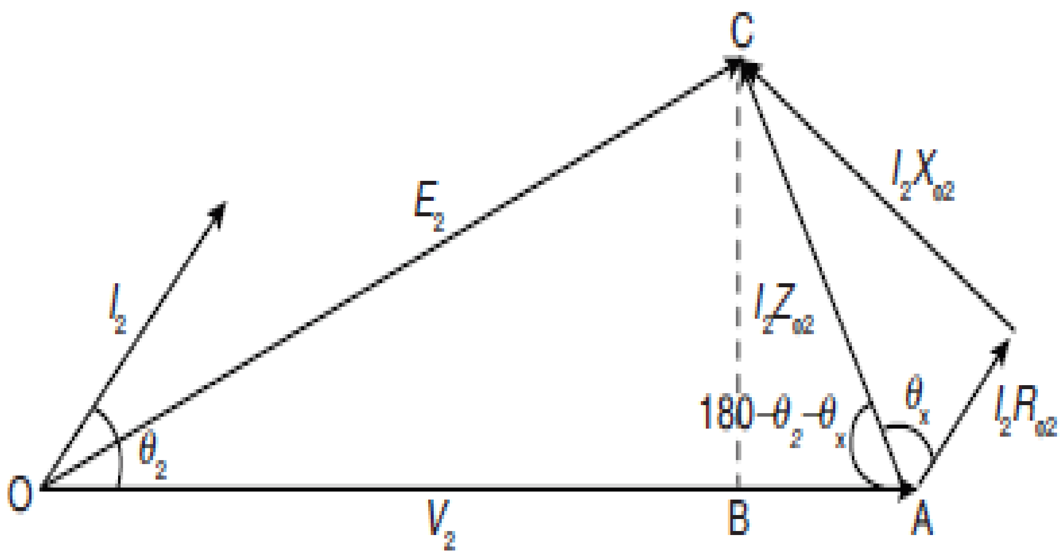
*where* '+' for lagging and '-' for leading

In terms of primary values

$$\% \text{ regulation} = \frac{V_1 - V_2'}{V_1} = \frac{I_1 R_{01} \cos\phi_1 \pm I_1 X_{01} \sin\phi_1}{V_1}$$

*where* '+' for lagging and '-' for leading




**Lagging power factor loads** **Leading power factor loads**

$$\text{Voltage regulation} = \frac{I_2R_{e2}\cos\theta_2 \mp I_2X_{e2}\sin\theta_2}{V_2}\times 100$$

Where,

– ve sign is for leading power factor and +ve sign is for lagging power factor load.

## Transformer Oil:

There are two types of transformer oil used in transformer,

1. Paraffin based transformer oil
2. Naphtha based transformer oil

Transformer oil has following characteristics:

1. It is colourless
2. It has low density
3. It has low viscosity

## Cooling System:

The different transformer cooling methods are as follows:

i) For dry type transformers

a) Air Natural (AN) cooling method

b) Air Blast cooling method

ii) For oil immersed transformers

a) Oil Natural Air Natural (ONAN) cooling

b) Oil Natural Air Forced (ONAF) cooling

c) Oil Forced Air Forced (OFAF) cooling

d) Oil Forced Water Forced (OFWF)

# Transformer Tests :

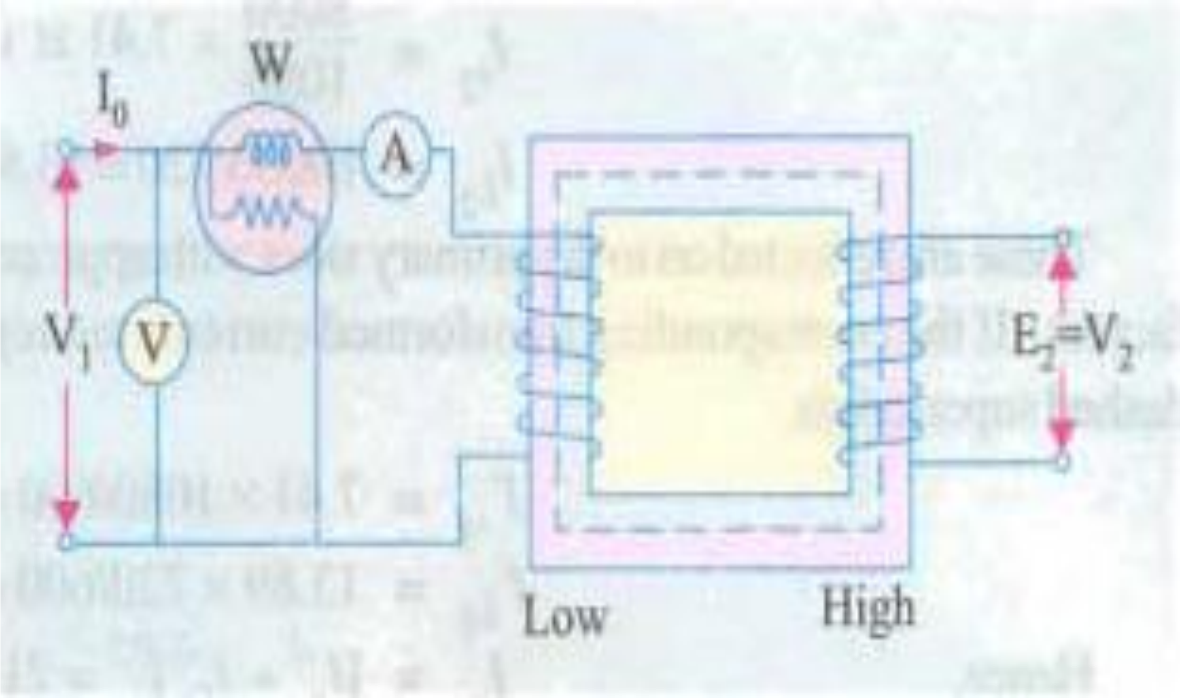
- The performance of a transformer can be calculated on the basis of equivalent circuit
- The four main parameters of equivalent circuit are:
  - $R_{01}$ as referred to primary (or secondary $R_{02}$)
  - the equivalent leakage reactance $X_{01}$ as referred to primary (or) secondary $X_{02}$
  - Magnetising susceptance $B_0$ ( or reactance $X_0$)
  - core loss conductance $G_0$ (or resistance $R_0$)

- The above constants can be easily determined by two tests
  - Open circuit test (O.C test / No load test)
  - Short circuit test (S.C test/Impedance test)

- These tests are economical and convenient
  - these tests furnish the result without actually loading the transformer.

# Open Circuit Test:

In Open Circuit Test the transformer's ***secondary winding is open-circuited***, and its ***primary winding is connected to a full-rated line voltage***.




$$\text{Core loss} = W_{oc} = V_0 I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{W_{oc}}{V_0 I_0}$$

$$\mathrm{I_c} \, or \, \mathrm{I_w} = I_0 \cos\phi_0$$

$$\mathrm{I_m} \, or \, \mathrm{I_\mu} = I_0 \sin\phi_0 = \sqrt{I_0^2 \text{-} I_w^2}$$

$$\mathrm{I_0 = V_0 Y_0}; \quad \therefore \mathrm{Y_o} = \frac{I_0}{V_0}$$

$$\mathrm{W_{oc} = V_0^2 G_0}; \quad \therefore \text{Exciting conductance } \mathrm{G_0} = \frac{\mathrm{W_{oc}}}{\mathrm{V_0^2}}$$

& $\quad \text{Exciting susceptance } \mathrm{B_0} = \sqrt{Y_0^2 - G_0^2}$

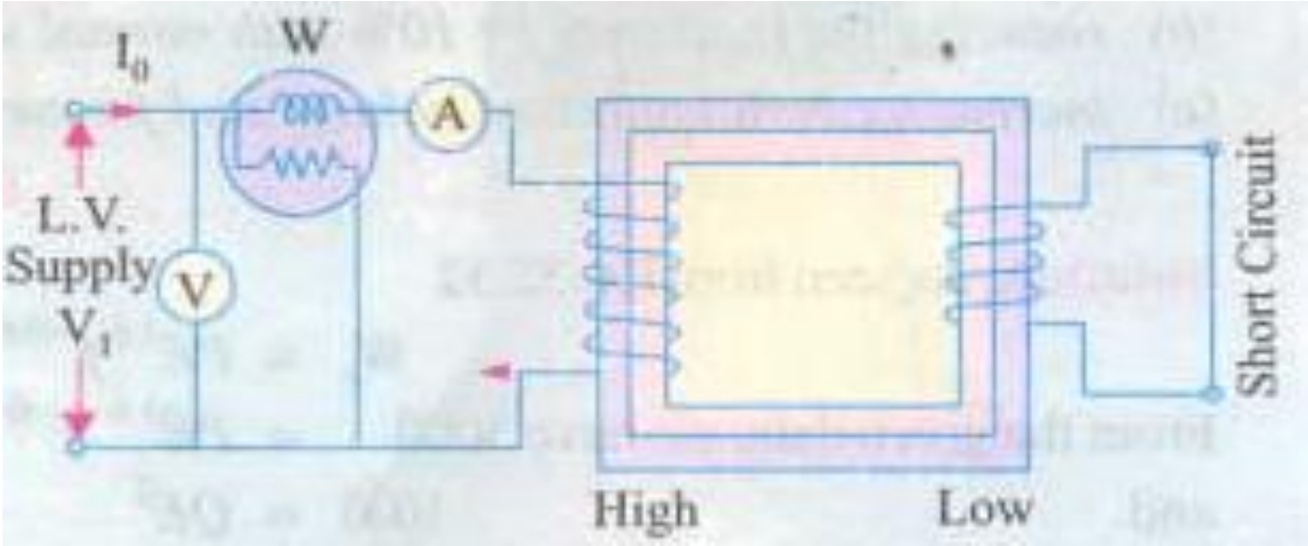
- Usually conducted on L.V side
- To find

  (i) No load loss or core loss

  (ii) No load current $I_o$ which is helpful in finding $G_o$(or $R_o$ ) and $B_o$ (or $X_o$ )

## Short Circuit Test:

In Short Circuit Test the secondary terminals are short circuited, and the primary terminals are connected to a fairly High-voltage source. The input voltage is adjusted until the current in the short circuited windings is equal to its rated value. The input voltage, current and power is measured.




- Usually conducted on H.V side
- To find

  (i) Full load copper loss – to pre determine the efficiency

  (ii) $Z_{01}$ or $Z_{02}$; $X_{01}$ or $X_{02}$; $R_{01}$ or $R_{02}$ – to predetermine the voltage regulation

$$\text{Full load cu loss} = W_{sc} = I_{sc}^2 R_{01}$$

$$R_{01} = \frac{W_{sc}}{I_{sc}^2}$$

$$Z_{01} = \frac{V_{sc}}{I_{sc}}$$

$$\therefore X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

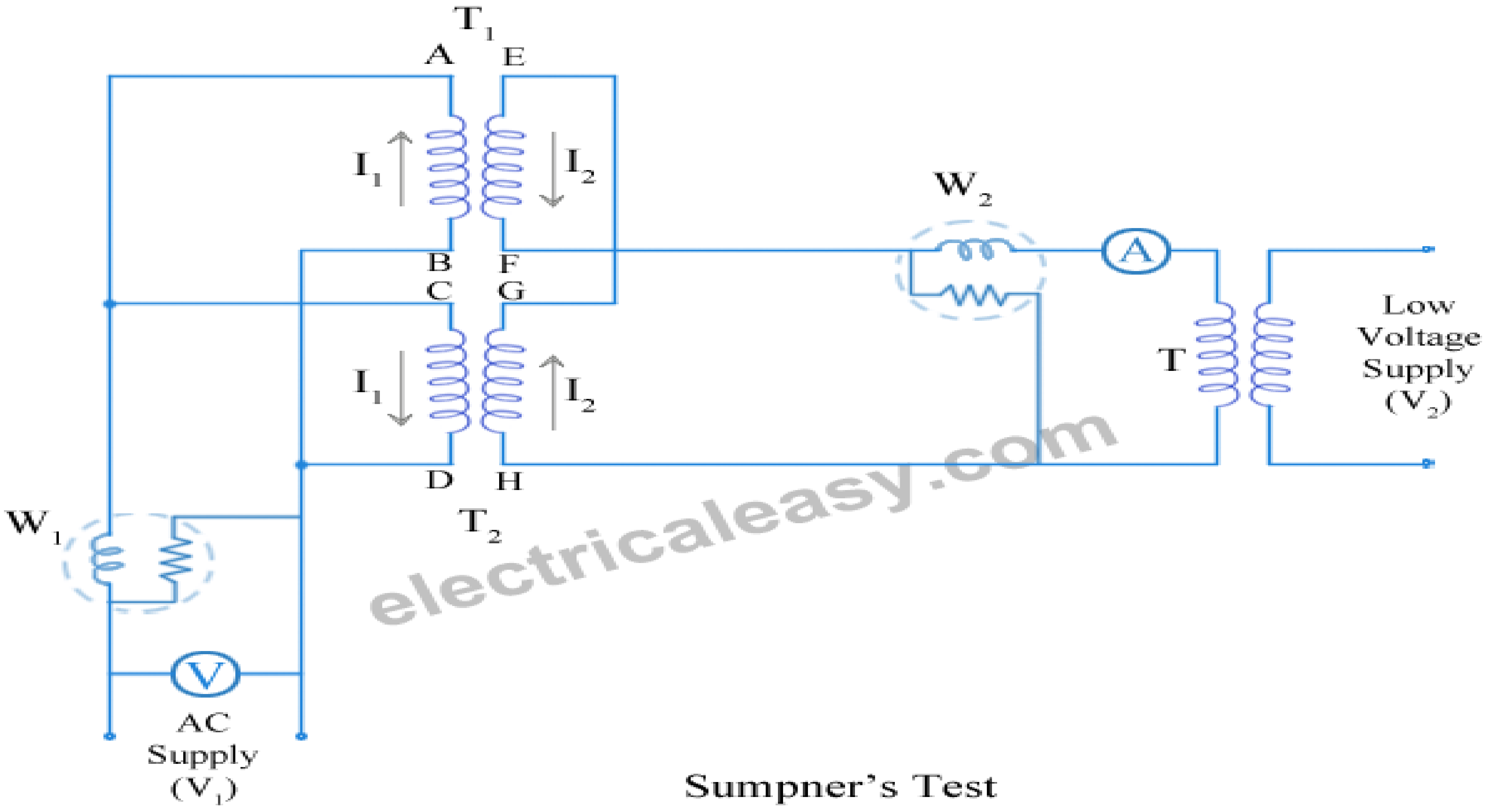
# Sumpner's Test or Back-To-Back Test On Transformer:

The full load test on a small transformer is very convenient, but on the large transformer, it is very difficult. The maximum temperature rise in a large transformer is determined by the full load test. This test is called, back-to-back test, regenerative test or Sumpner’s test.

Sumpner's test or back to back test on transformer is another method for determining transformer efficiency, voltage regulation and heating under loaded conditions. Short circuit and open circuit tests on transformer can give us parameters of equivalent circuit of transformer, but they can not help us in finding the heating information. Unlike O.C. and S.C. tests, actual loading is simulated in Sumpner's test. Thus the Sumpner's test give more accurate results of regulation and efficiency than O.C. and S.C. tests.

Sumpner's test or back to back test can be employed only when two identical transformers are available. Both transformers are connected to supply such that one transformer is loaded on another. Primaries of the two identical transformers are connected in parallel across a supply.

Secondaries are connected in series such that emf's of them are opposite to each other. Another low voltage supply is connected in series with secondaries to get the readings, as shown in the circuit diagram shown below.




Sumpner's Test

In above diagram, $T_1$ and $T_2$ are identical transformers. Secondaries of them are connected in voltage opposition, i.e. $E_{EF}$ and $E_{GH}$. Both the emf's cancel each other, as transformers are identical.

In this case, as per superposition theorem, no current flows through secondary. And thus the no load test is simulated. The current drawn from $V_1$ is $2I_0$, where $I_0$ is equal to no load current of each transformer. Thus input power measured by wattmeter $W_1$ is equal to iron losses of both transformers. i.e. iron loss per transformer $P_i = W_1/2$.

Now, a small voltage $V_2$ is injected into secondary with the help of a low voltage transformer. The voltage $V_2$ is adjusted so that, the rated current $I_2$ flows through the secondary. In this case, both primaries and secondaries carry rated current.

Thus short circuit test is simulated and wattmeter $W_2$ shows total full load copper losses of both transformers. i.e. copper loss per transformer $P_{Cu} = W_2/2$.

From above test results, the full load efficiency of each transformer can be given as -

$$\begin{matrix}\text{\% full load efficiency} \\ \text{of each transformer}\end{matrix} = \frac{\text{output}}{\text{output} + \frac{W_1}{2} + \frac{W_2}{2}} \text{ X } 100$$

## Determination of Temperature Rise:

The temperature rise of the transformer is determined by measuring the temperature of their oil after every particular interval of time. The transformer is operating back to back for the long time which increases their oil temperature. By measuring the temperature of their oil the withstand capacity of the transformer under high temperature is determined.

# Problems

1 A 2000/200V, 20kVA transformer has 66 turns in the secondary. Calculate (i) primary turns (ii) primary and secondary full load currents. Neglect the losses.

2 An ideal 25kVA transformer has 500 turns on the primary winding and 40 turns on the secondary winding. The primary is connected to 3000V, 50Hz supply. Calculate

(i) Primary & secondary currents on full-load (ii) secondary emf and

(iii) maximum core flux

3 A single phase 2200/250V, 50Hz transformer has a net core area of 36cm2 and a maximum flux density of 6Wb/m2. Calculate the number of turns of primary and secondary.

4 A 200/50V, 50Hz single phase transformer is connected to a 200V, 50Hz supply with secondary open. Primary winding has 400 turns.

(i) What is the value of maximum flux through the core if the primary winding has 400 turns

(ii) What is the peak value of flux if the primary voltage is 200V, 25Hz?

5 A single phase 50Hz transformer has square core of 20cm side. The permissible maximum flux density in the core is 1Wb/m2. Calculate the number of turns per limb on the high and low voltage sides for a 3000/220V ratio. To allow for insulation of stampings, assume the net iron length to be 0.9 * gross iron length.

6 A transformer takes a current of 0.6A and absorbs 64W when primary is connected to its normal supply of 200V, 50Hz. The secondary being on open circuit. Find the magnetizing and iron loss currents.

7 A voltage v= 200 sin 314t is applied to the transformer winding in a no-load test. The resulting current is found to be i= 3 sin ($314t-60^o$). Determine the core loss and the parameters of the no-load approximate equivalent circuit.

8 A 10kVA, 2000/400V single phase transformer has $R_1$= 5Ω; $X_1$= 12 Ω; $R_2$= 0.2 Ω and $X_2$= 0.48 Ω. Determine the equivalent impedance of the transformer referred to

(i) Primary side (ii) secondary side

9 A 100kVA, 2200/440V single phase transformer has $R_1$= 0.3Ω; $X_1$= 1.1 Ω; $R_2$= 0.01 Ω and $X_2$= 0.035 Ω. Calculate (i) the equivalent impedance of the transformer referred to the primary and (ii) total copper losses.

10 A 10kVA, 2000/400V single phase transformer has the following data:
$R_1$= 5Ω; $X_1$= 12 Ω; $R_2$= 0.2 Ω and $X_2$= 0.48 Ω. Determine the secondary terminal voltage at full load, 0.8 pf lagging when the primary supply voltage is 2000V.

12 A single phase transformer on full load has an impedance drop of 20V and resistive drop of 10V. Calculate the value of power factor when voltage regulation is zero.

11 The primary and secondary windings of a 40kVA, 6600/250V single phase transformer have resistances of 10 Ω and 0.02 Ω respectively. The leakage reactance of the transformer referred to the primary side is 35 Ω. Calculate the percentage voltage regulation of the transformer when supplying full load current at a pf of 0.8 lag

13 Given below are the results conducted on a 50kVA, 2200/220V transformer.

Open-circuit (L.V side) test : 405W, 5A, 220V

Short-circuit (H.V side) test : 805W, 20.2A, 95V

Calculate the parameters of the equivalent circuit referred to H.V side

14 In a 50kVA transformer, the iron loss is 500W and full-load copper loss is 800W. Find the efficiency at full-load and half full-load at 0.8 pf lagging.

15 A 40kVA transformer has iron loss of 450W and full-load copper loss of 850W. If the power factor of the load is 0.8 lagging. Calculate (i) full-load efficiency (ii) the load at which maximum efficiency occurs and
(iii) the maximum efficiency?

16. The primary & secondary windings of a 50kVA, 6600/220 V transformer has resistances of 7.8Ω and 0.0085 Ω respectively. The transformer draws no-load current of 0.328A at pf of 0.3 lagging. Calculate the efficiency at full-load if the pf of the load is 0.8 lagging.

17 A 440/110V transformer has a primary resistance of 0.03 Ω and secondary resistance of 0.02 Ω. Its iron loss at normal input is 150W. Determine the secondary current at which maximum efficiency will occur and the value of this maximum efficiency at a unity pf load?

18 The following reading were obtained from OC and SC tests on 8kVA, 400/120V, 50Hz transformer.

| | | | |
|---|---|---|---|
| OC test on LV side | : 120V | 4A | 75W |
| SC test on HV side | : 9.5V | 20A | 110W |

Calculate the voltage regulation and efficiency at full load, 0.8 pf lagging.

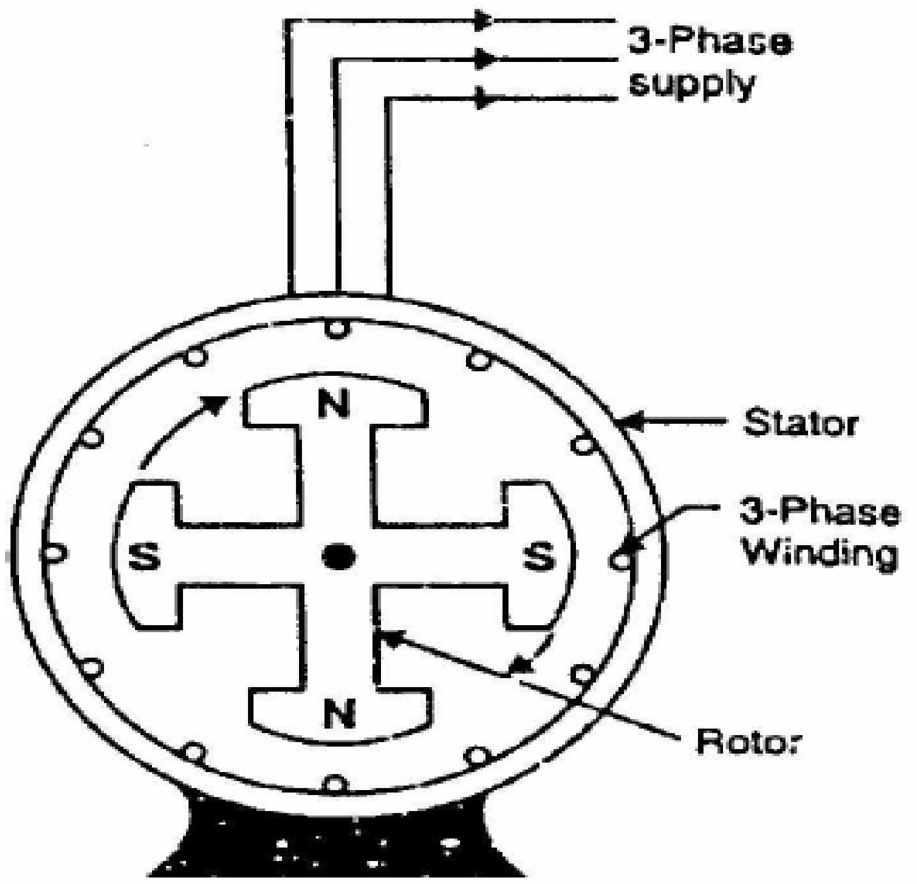
# UNIT-III
# SYNCHRONOUS MACHINES

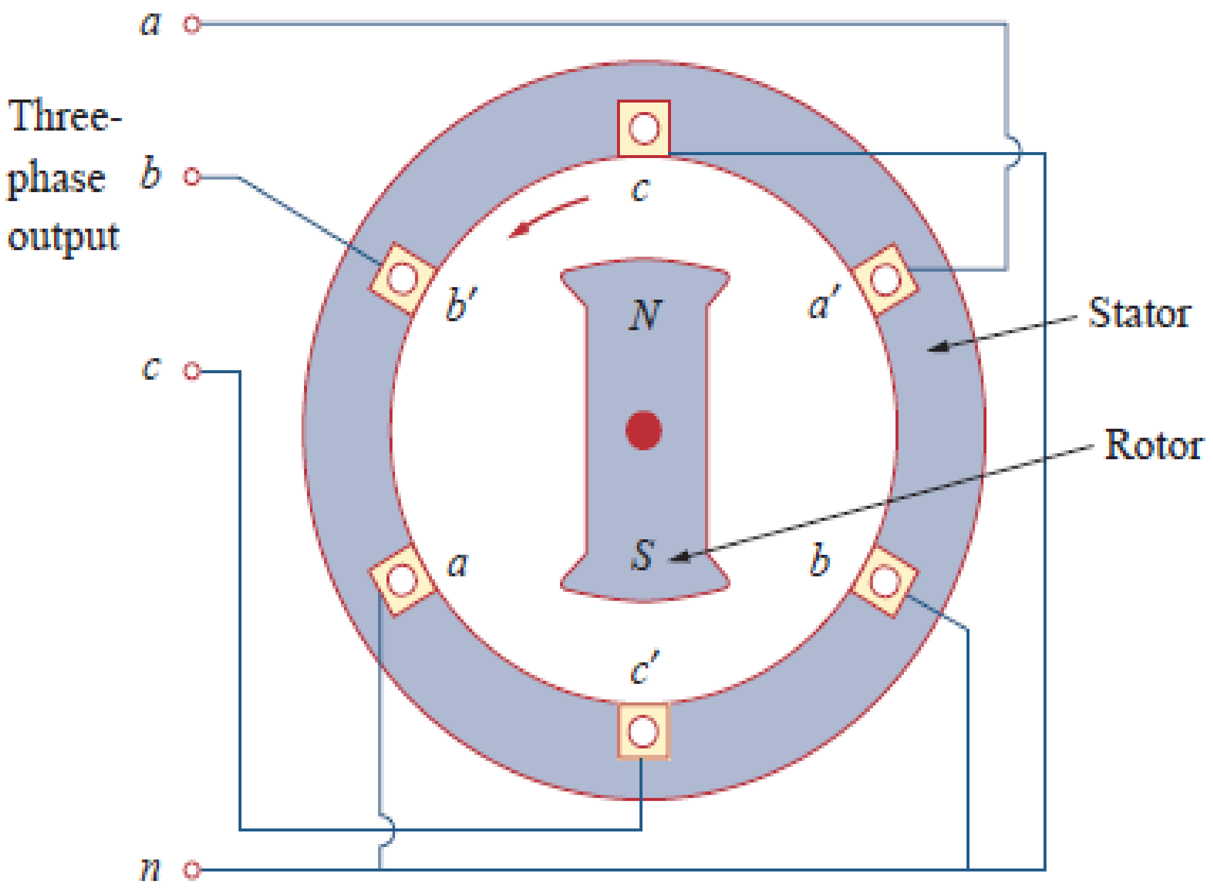
Prepared by

**S Reddy Ramesh**
**Assistant Professor**
**Dept of Electrical and Electronics Engineering**
**Aditya College of Engineering & Technology**
**Surampalem**

# Three-Phase Alternator

The machine which produces 3-phase power from mechanical power is called an alternator or synchronous generator.



# Three-Phase Alternator

- A.C. generators or alternators (as they are usually called) operate on the same fundamental principles of electromagnetic induction as DC generators.

- They also consist of an armature winding and a magnetic field.

- But there is one important difference between the two. Whereas in DC generators, the ***armature rotates*** and the field system is ***stationary***, the arrangement in alternators is just the reverse of it.

# Three-Phase Alternator

## Advantages of stationary armature:

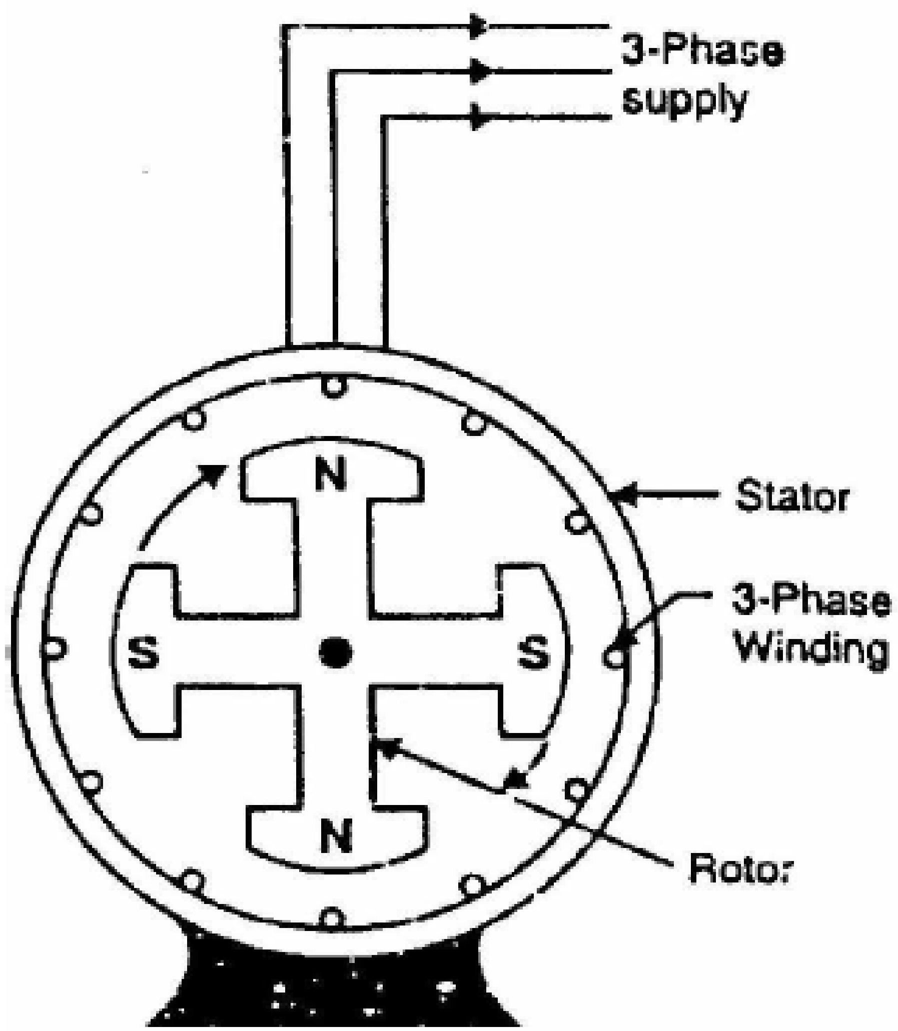
- Less slip rings are used
- High speed operation is possible (less centrifugal force)
- Easy insulation
- Direct connection to load is possible and easy

# Three-Phase Alternator

## Construction details:

An alternator has 3-phase winding on the stator and a DC field winding on the rotor.

- Stator- 3 phase AC winding (armature)
- Rotor- DC field winding (field)

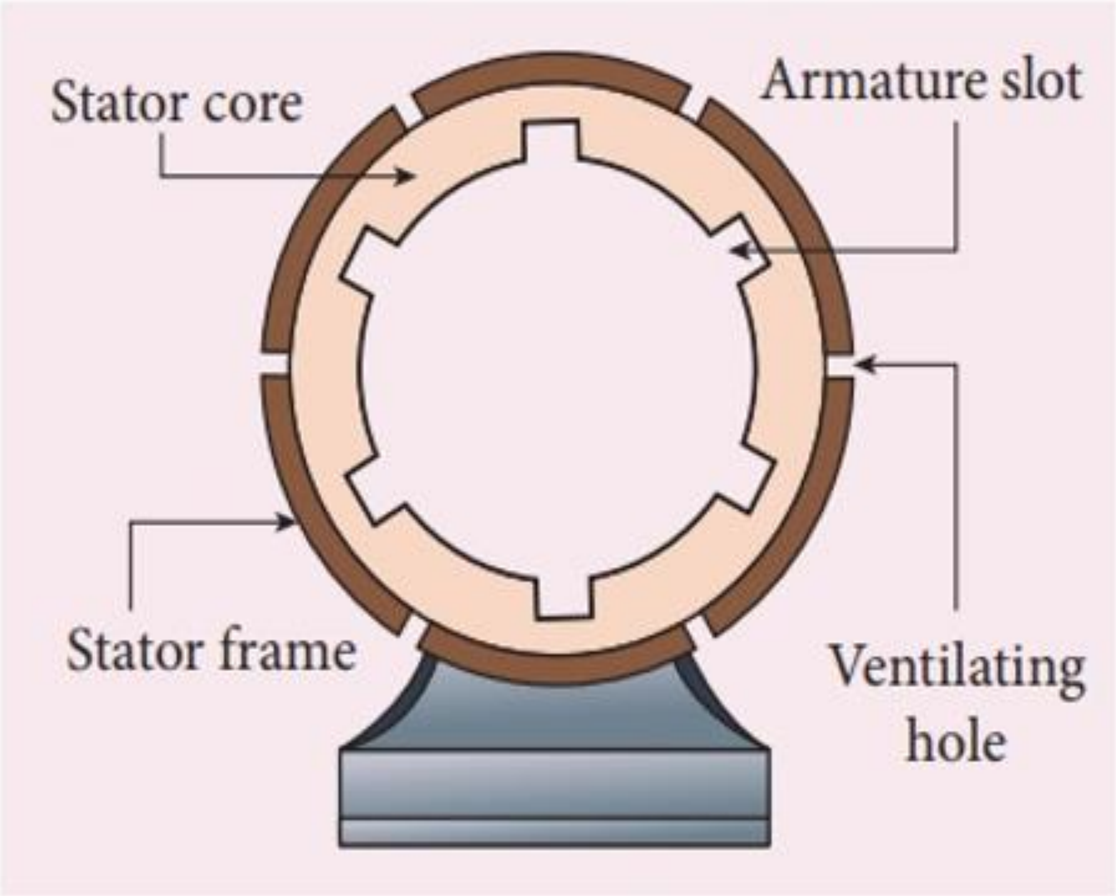


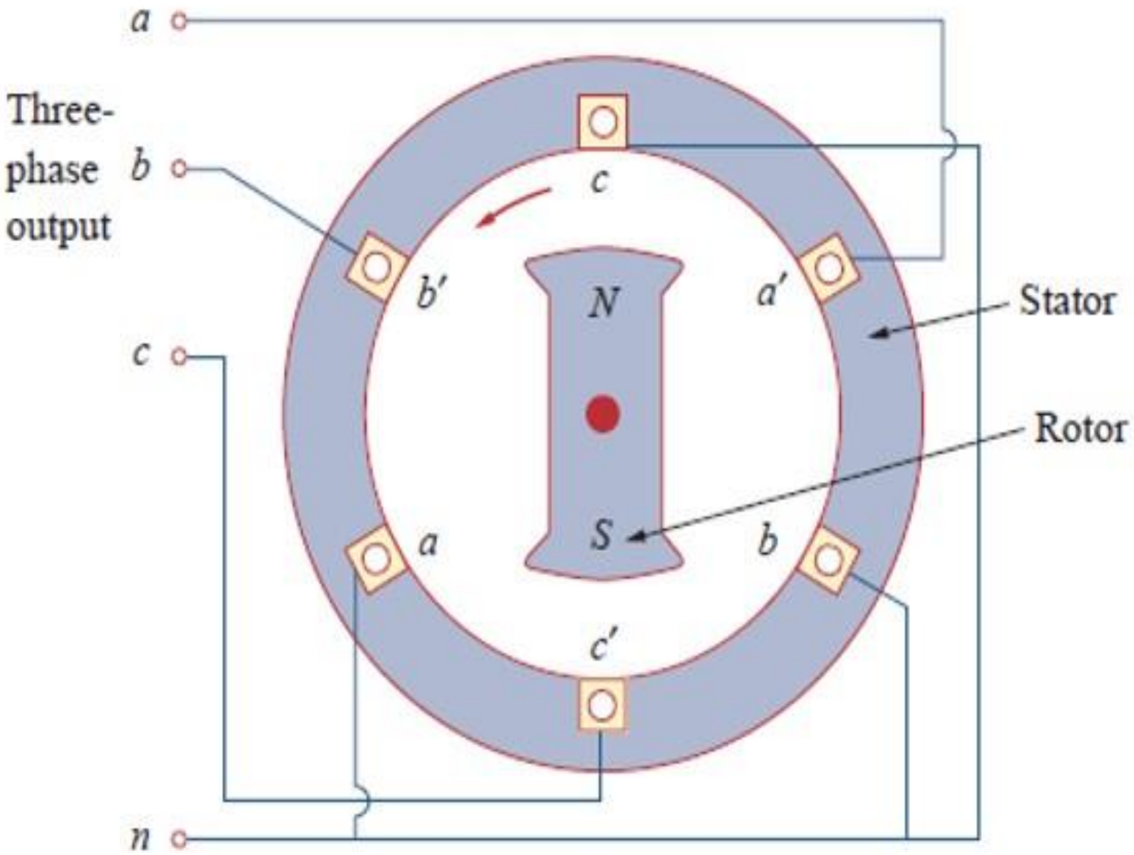
# Three-Phase Alternator

## 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 stator construction is similar to induction motor stator i.e. 3 phase construction
- The armature winding is always connected in star and the neutral is connected to ground.

# Three-Phase Alternator



# Three-Phase Alternator

## Rotor:

- The rotor is rotating part of the alternator.
- It carries a field winding which is supplied with dc current through two slip rings by a separate dc source.

Synchronous generators are classified in two types according to its rotor construction:

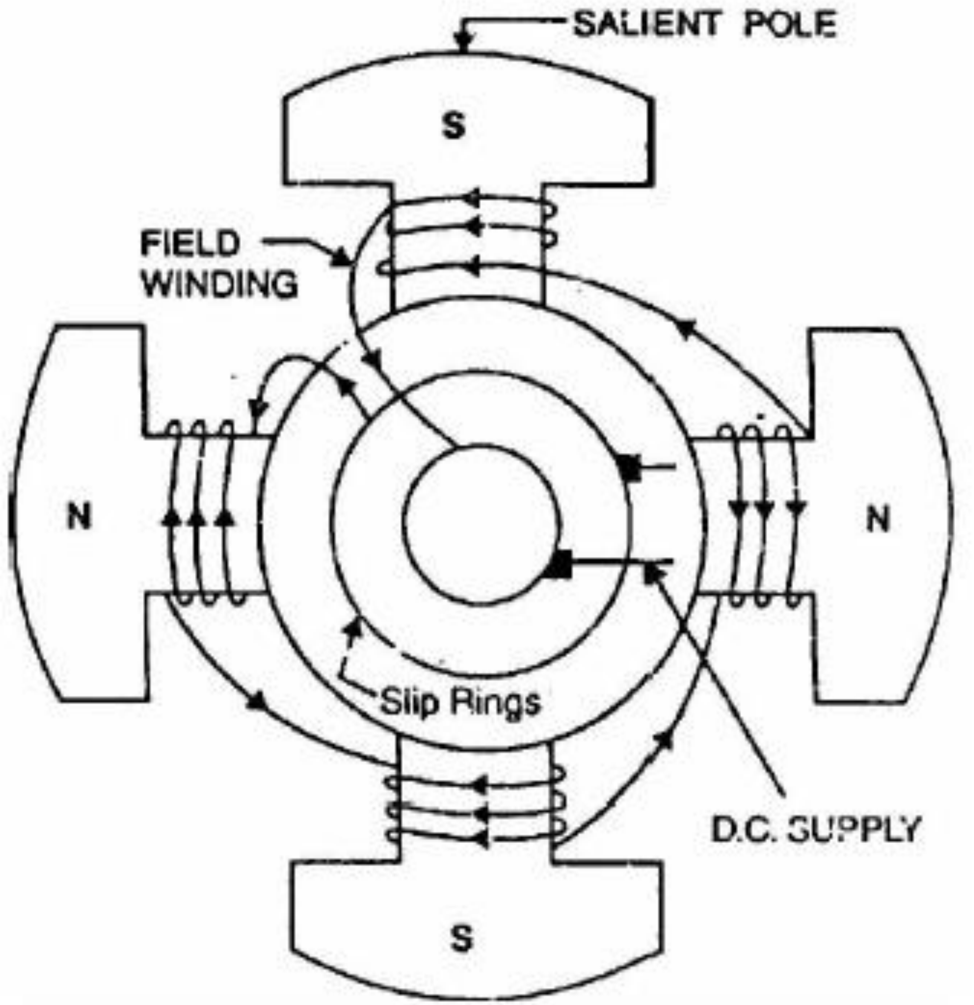
1. Salient Pole Rotor Type
2. Cylindrical Rotor Type

# Three-Phase Alternator

## 1. Salient Pole Rotor Type:

- Salient or projecting poles are mounted on a large circular steel

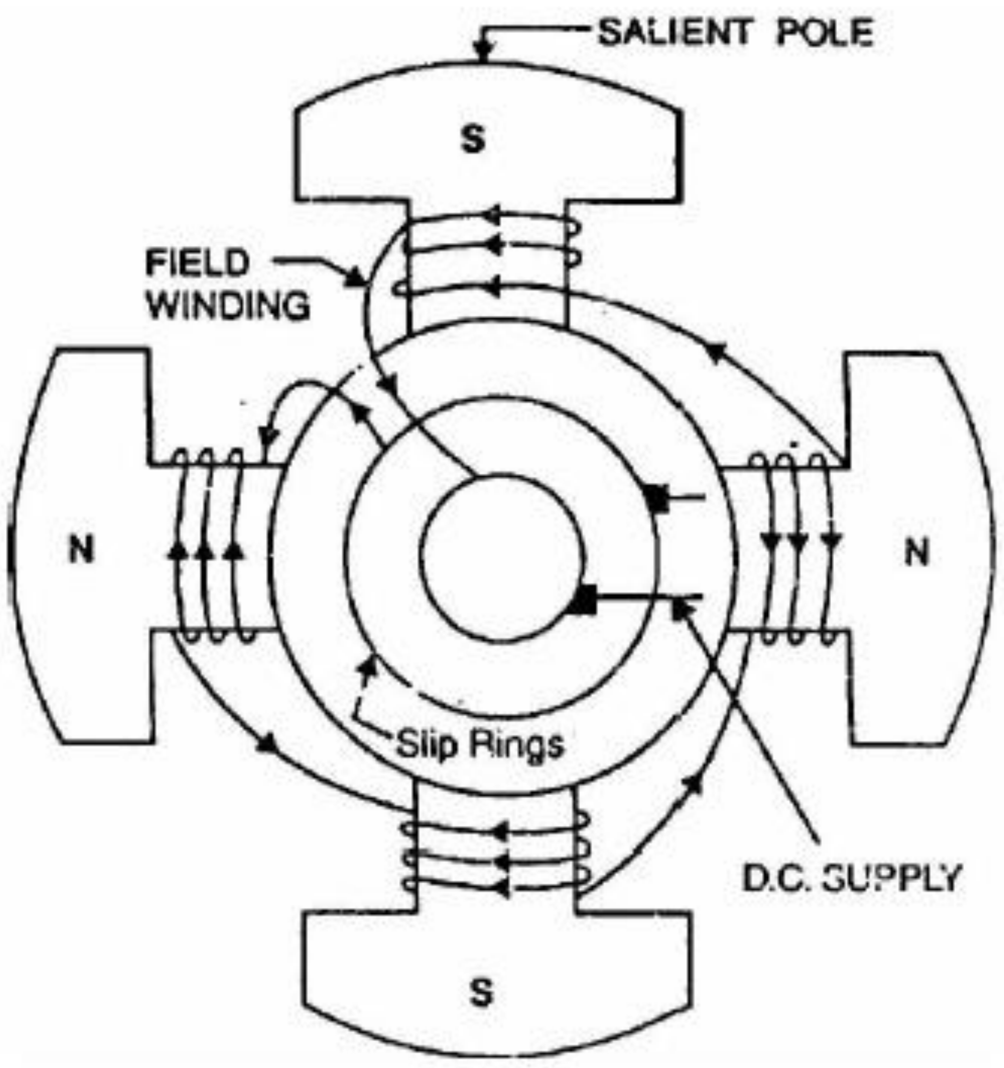
- The individual field pole windings are connected in series in such a way that when the field winding is energized by the d.c exciter, adjacent poles have opposite polarities.



# Three-Phase Alternator

## Salient Pole Rotor Type:

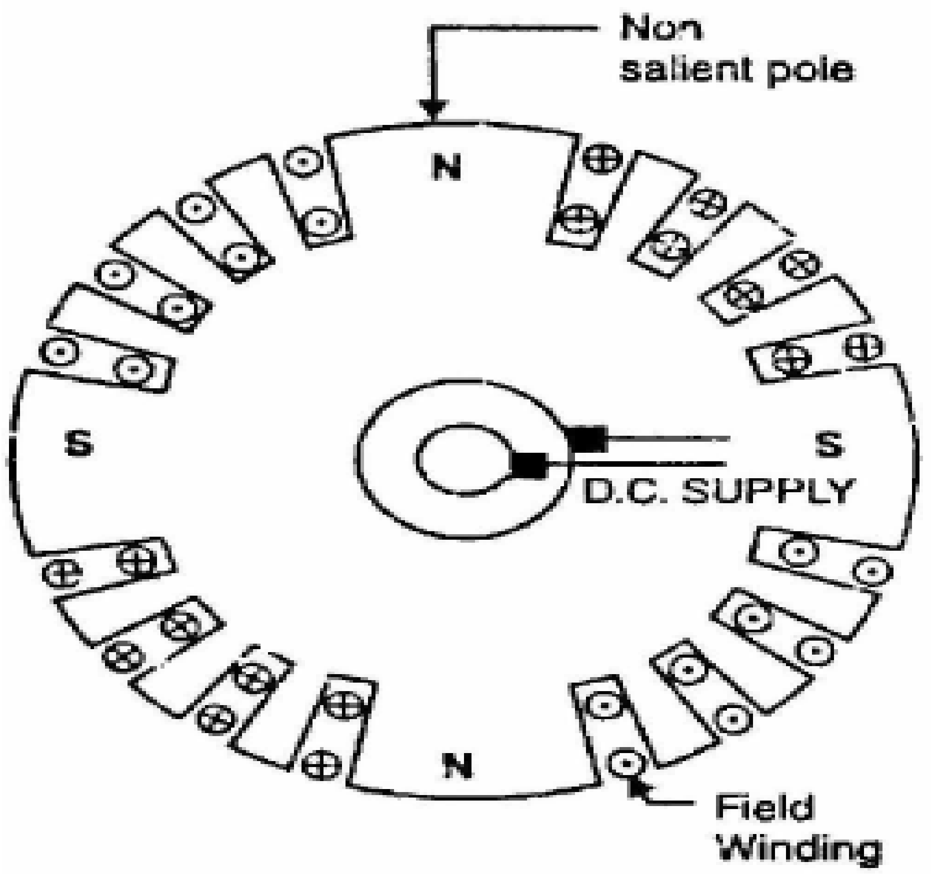
- Non-uniform mass distribution
- High centrifugal force act on the rotor
- Only low speed operation is possible
- Number of poles are higher
- Large diameter and short axial length
- Used with water turbines and diesel engine
- Also called ‘hydro alternator’



# Three-Phase Alternator

## 2. Cylindrical /Non- Salient Pole Rotor Type:

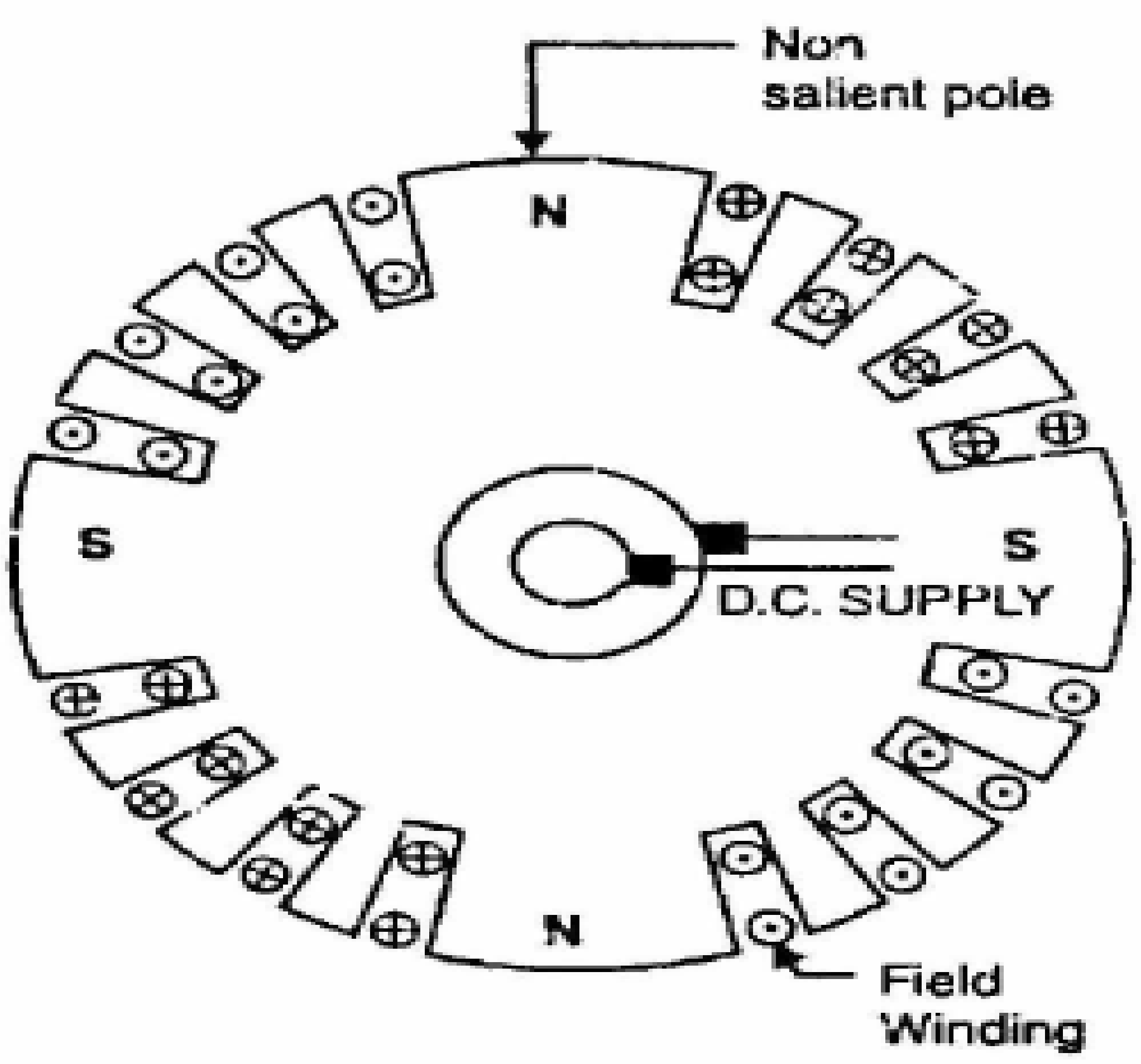
- The rotor is made of smooth solid cylinder having slots along the outer periphery.
- The field windings are embedded in these slots and are connected in series to the slip rings through which they are energized by the d.c exciter.
- The poles formed are non-salient i.e., they do not project out from the rotor surface.



# Three-Phase Alternator

## Cylindrical Rotor Type:

- Uniform mass distribution
- Low centrifugal force act on the rotor
- High speed operation is possible
- Number of poles are lower
- Large axial length and shorter diameter
- Used with steam turbines
- Also called ‘turbo alternator’



# Three-Phase Alternator

## Operation of alternator:

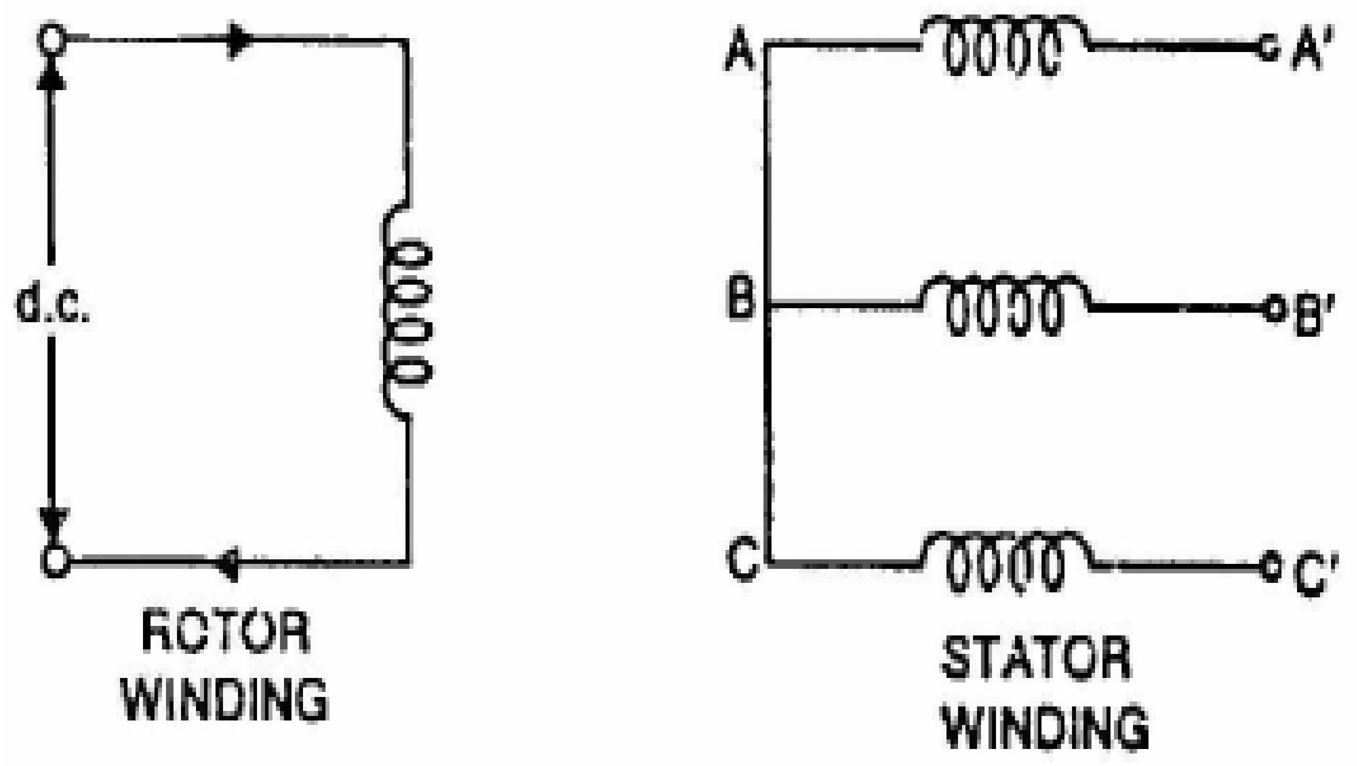
- The rotor winding is energized from the d.c exciter and alternate N and S poles are developed on the rotor.

- When the rotor is rotated by a prime mover, the stator or armature conductors are cut by the magnetic flux of rotor poles.

- Consequently, e.m.f is induced in the armature conductors due to electromagnetic induction.

- The direction of induced e.m.f can be found by Fleming's right hand rule.

# Three-Phase Alternator




$$N = \frac{120 \times f}{P}$$

$N$ = Synchronous speed

$f$ = frequency of supply

$P$ = Number of poles

# Three-Phase Alternator

## E.M.F. Equation of an Alternator:

$$E_{rms/phase} = 4.44 \times K_p \times K_d \times \phi \times f \times T$$

The line voltage will depend upon whether the winding is star or delta connected.

# Three-Phase Alternator

## Alternator on Load:

As the load on an alternator is varied, its terminal voltage is also found to vary as in d.c. generators.

This variation in terminal voltage $V$ is due to the following reasons:

- voltage drop due to armature resistance $R_a$
- voltage drop due to armature leakage reactance $X_L$
- voltage drop due to armature reaction $X_a$

# Three-Phase Alternator

**Armature leakage reactance $X_L$**

# Three-Phase Alternator

**Synchronous reactance $X_S$**

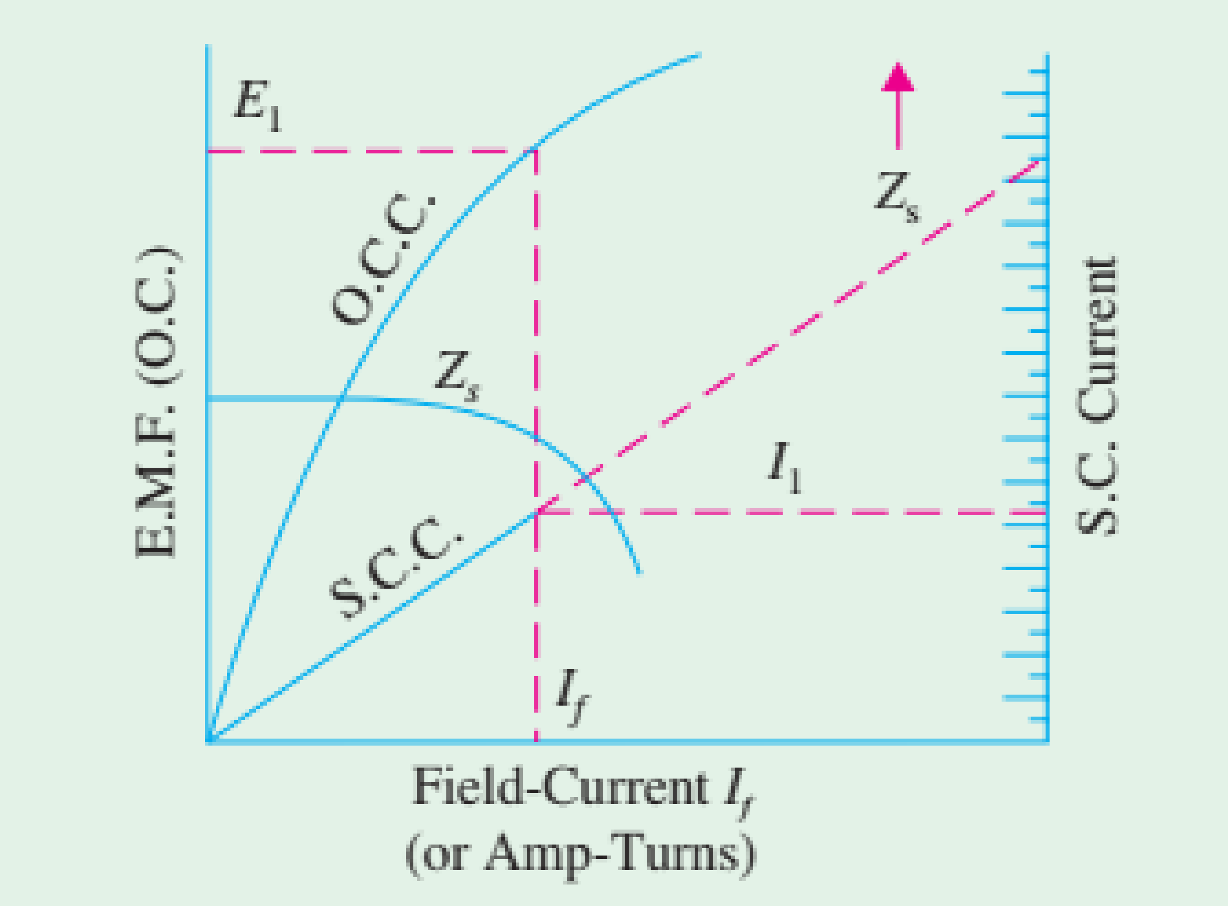
# Three-Phase Alternator

**How to find *Xs***

Open circuit characteristics

Short circuit characteristics

# Three-Phase Alternator



# Three-Phase Alternator

**Example 37.17 (*a*).** *The effective resistance of a 2200V, 50Hz, 440 KVA, 1-phase, alternator is 0.5 ohm. On short circuit, a field current of 40 A gives the full load current of 200 A. The electromotive force on open-circuits with same field excitation is 1160 V. Calculate the synchronous impedance and reactance.* **(Madras University, 1997)**

# Three-Phase Alternator

**Solution.** For the 1-ph alternator, since the field current is same for O.C. and S.C. conditions

$$Z_S = \frac{1160}{200} = 5.8 \text{ ohms}$$

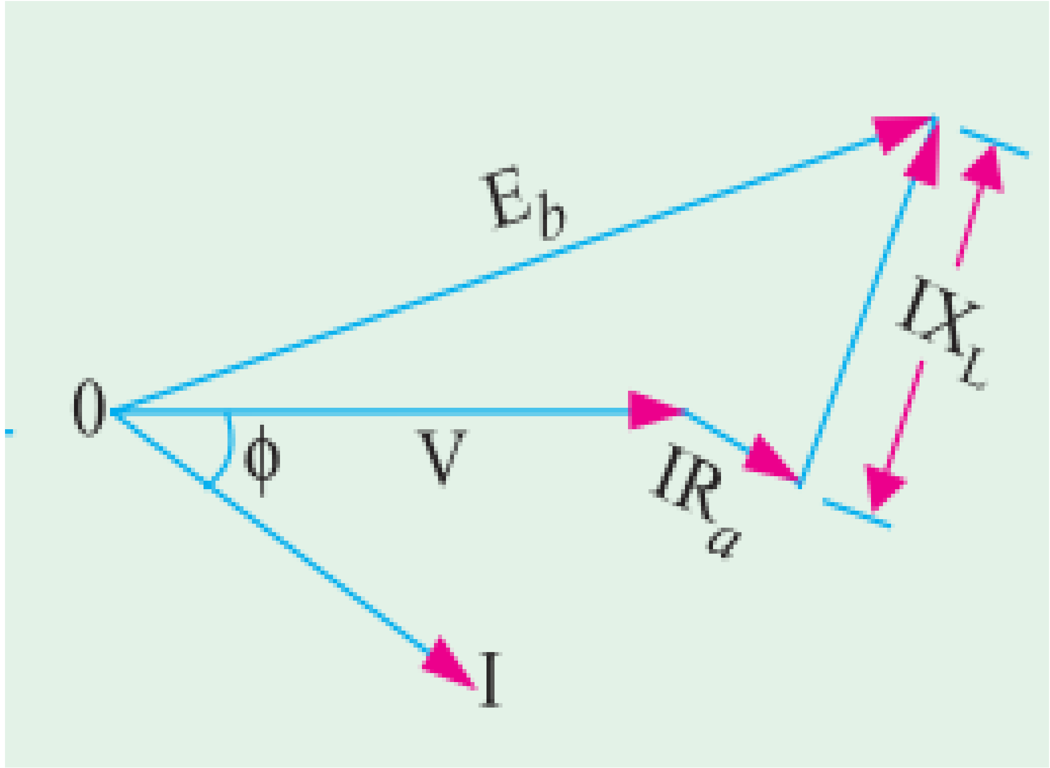
$$X_S = \sqrt{5.8^2 - 0.5^2} = 5.7784 \text{ ohms}$$

# Three-Phase Alternator

## EMF:

$$E = V + I(R_a + jX_s)$$

$$E = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$$



# Three-Phase Alternator

**Example 37.16.** *A 3-phase, star-connected alternator supplies a load of 10 MW at p.f. 0.85 lagging and at 11 kV (terminal voltage). Its resistance is 0.1 ohm per phase and synchronous reactance 0.66 ohm per phase. Calculate the line value of e.m.f. generated.*

# Three-Phase Alternator

**Solution.** F.L. output current $= \dfrac{10\times10^6}{\sqrt{3}\times11{,}000\times0.85} = 618\ A$

$IR_a$ drop $= 618\times0.1 = 61.8$ V

$IX_S$ drop $= 618\times0.66 = 408$ V

Terminal voltage/phase $= 11{,}000/\sqrt{3} = 6{,}350$ V

$\phi = \cos^{-1}(0.85) = 31.8°;\ \sin\phi = 0.527$

As seen from the vector diagram of Fig. 37.28 where $I$ instead of $V$ has been taken along reference vector,

$$E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$$

$$= \sqrt{(6350\times0.85+61.8)^2 + (6350\times0.527+408)^2}$$

$$= 6{,}625\text{ V}$$

Line e.m.f. $= \sqrt{3}\times6{,}625 =$ **11,486 volt**

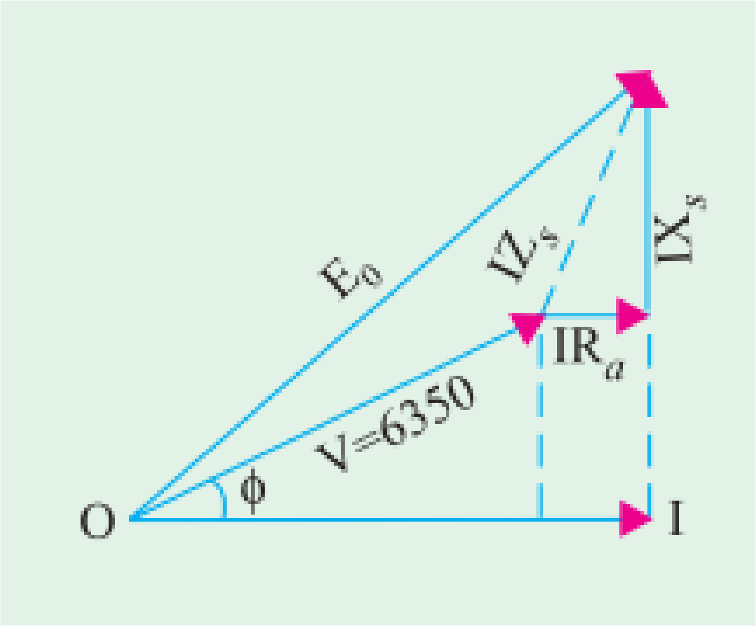


Fig. 37.28

# Three-Phase Alternator

## Voltage Regulation

$$\%V_R = \frac{|E_0| - |V|}{|V|} \times 100$$

Unlike DC machine, the voltage regulation in synchronous machine depends upon

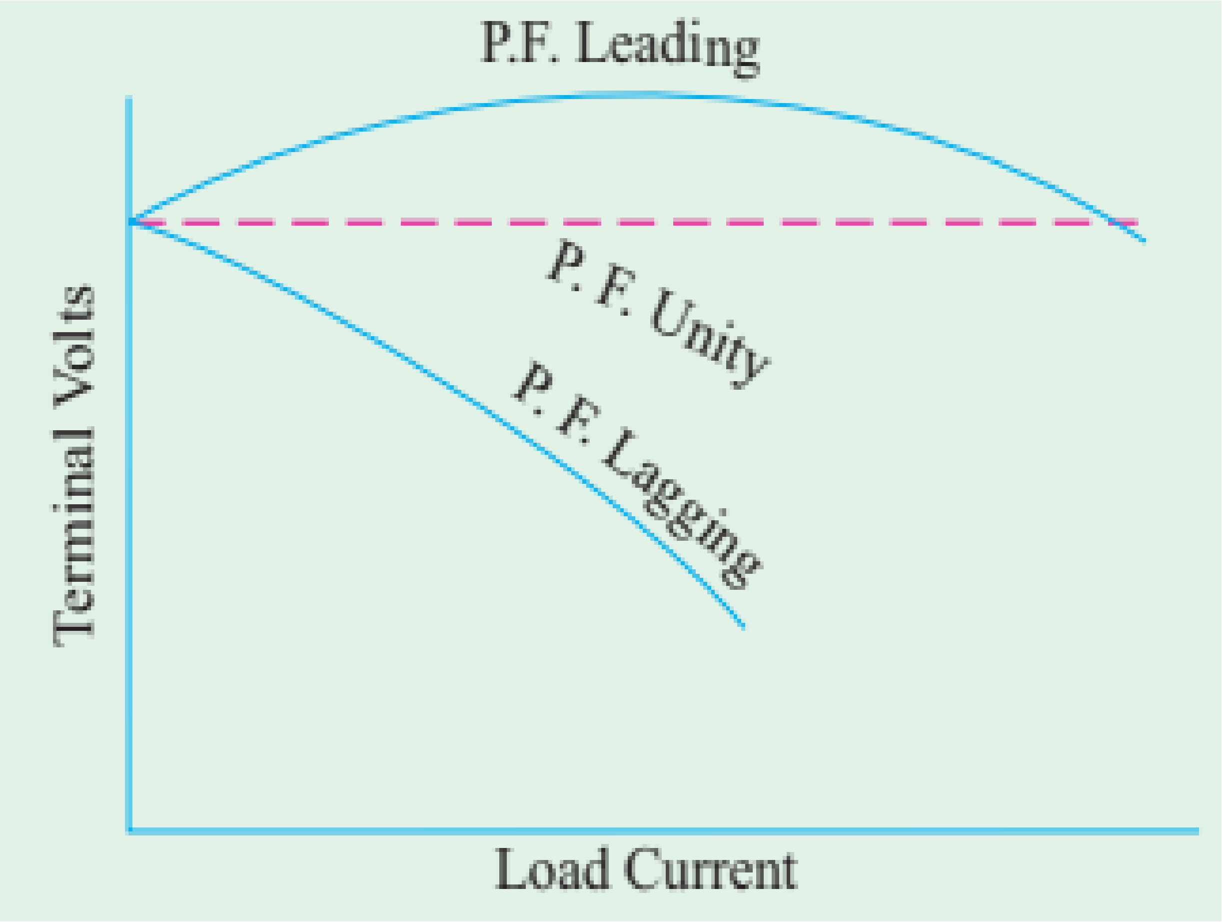
- Magnitude of load
- Type of load

# Three-Phase Alternator

## Voltage Regulation:

Thus for leading load the voltage regulation will be positive.

For lagging load the voltage regulation will be negative.



# Three-Phase Alternator

## Determination of Voltage Regulation:

- Synchronous Impedance or E.M.F Method
- The Ampere-turn or M.M.F. Method
- Zero Power Factor or Potier Method

# Three-Phase Alternator

## Determination of Voltage Regulation by Synchronous Impedance Method:

Step 1. Plot the OCC at different values of $I_f$

Step 2. Plot the SCC at different values of $I_f$

Step 3. Determine $Z_s$ at a particular $I_f$ as

$$Z_S = \frac{V_{OCC}}{I_{SCC}}$$

Step 4. Determine $X_s$ as

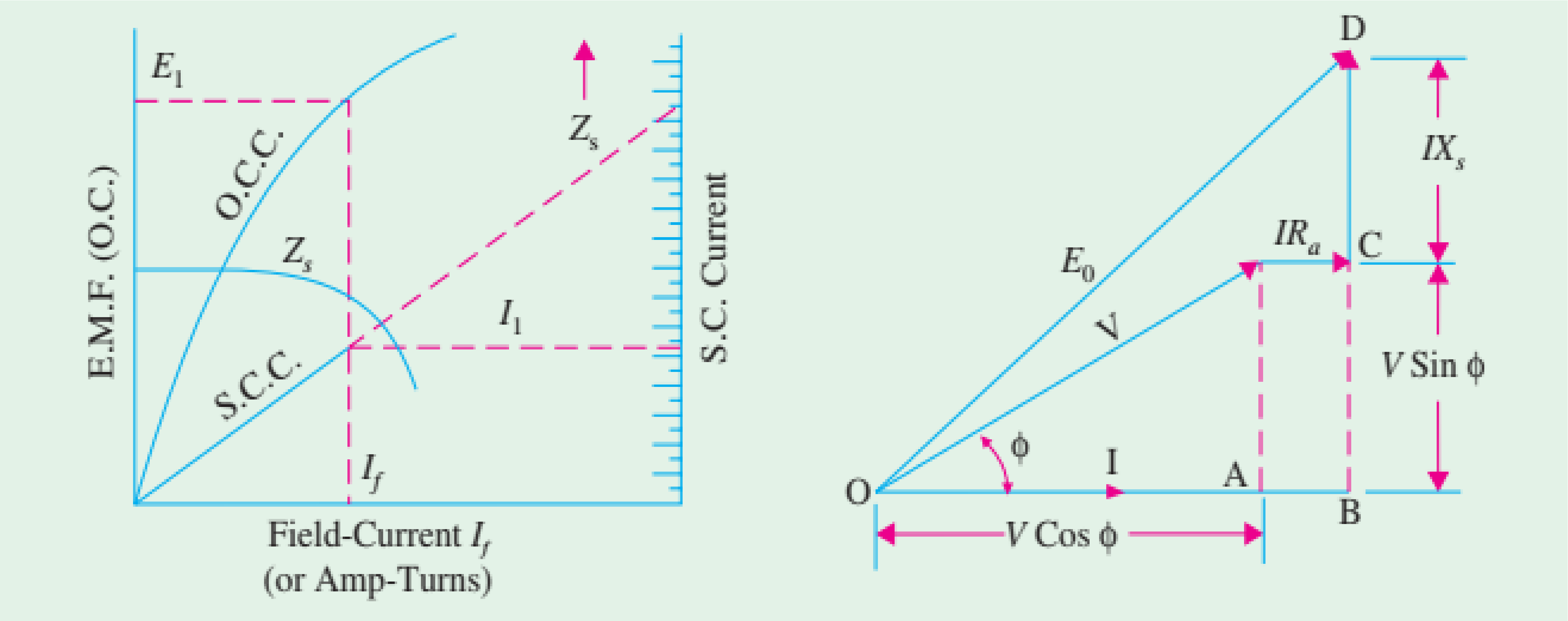
$$X_s = \sqrt{Z_s^{2} - R_a^{2}}$$

Don't copy the text as it is in the exam
…….
Write in your own language

# Three-Phase Alternator

## Determination of Voltage Regulation by Synchronous Impedance Method:

Step 5. Knowing $R_a$ and $X_S$, vector diagram can be drawn for any load at any power factor.



# Three-Phase Alternator

## Determination of Voltage Regulation by Synchronous Impedance Method:

Thus from the above vector diagram

and $$E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$$

Voltage regulation $$\%V_R = \frac{|E_0| - |V|}{|V|} \times 100$$

# Three-Phase Alternator

**Example 37.17 (*b*).** *A 60-KVA, 220 V, 50-Hz, 1-ϕ alternator has effective armature resistance of 0.016 ohm and an armature leakage reactance of 0.07 ohm. Compute the voltage induced in the armature when the alternator is delivering rated current at a load power factor of* **(a)** *unity* **(b)** *0.7 lagging and* **(c)** *0.7 leading.* **(Elect. Machines-I, Indore Univ. 1981)**

# Three-Phase Alternator

**Solution.** Full load rated current $I = 60{,}000/220 = 272.2$ A

$$IR_a = 272.2 \times 0.016 = 4.3 \text{ V};$$
$$IX_L = 272.2 \times 0.07 = 19 \text{ V}$$

**(*a*) Unity p.f.** — Fig. 37.30 (*a*)

$$E = \sqrt{(V + IR_a)^2 + (I X_L)^2} = \sqrt{(220 + 4.3)^2 + 19^2} = \mathbf{225\ V}$$

**(*b*) p.f. 0.7 (lag)** —Fig. 37.30 (*b*)

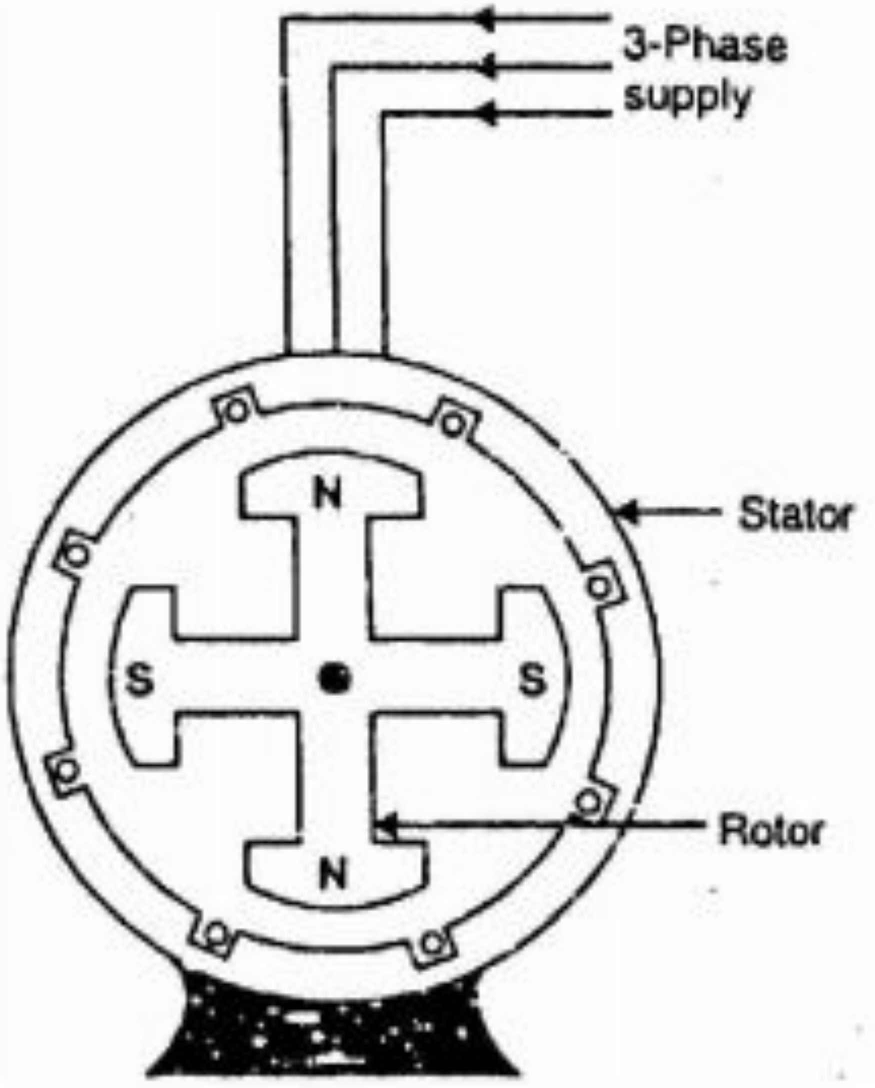
$$E = [V\cos\phi + IR_a)^2 + (V\sin\phi + IX_L)^2]^{1/2}$$
$$= [(220 \times 0.7 + 4.3)^2 + (220 \times 0.7 + 19)^2]^{1/2} = \mathbf{234\ V}$$

**(*c*) p.f. = 0.7 (lead)** —Fig. 37.30 (*c*)

$$E = [(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_L)^2]^{1/2}$$
$$= [(220 \times 0.7 + 4.3)^2 + (220 \times 0.7 - 19)^2]^{1/2} = \mathbf{208\ V}$$

# Synchronous Motor

- A synchronous motor is electrically identical with an alternator
- A synchronous motor is a machine that operates at synchronous speed and converts electrical energy into mechanicalenergy.




## Construction:

Synchronous motors also has two parts

1. Stator (where 3 phase power is received)
2. Rotor (which produces the required magnetic field)

# Synchronous Motor

## Salient features of a synchronous motor are:

- A synchronous motor runs at synchronous speed or not at all. Its speed is constant (synchronous speed) at all loads. The only way to change its speed is to alter the supply frequency ($N_s = 120 f/P$)

- It can be made to operate over a wide range of power factors (lagging, unity or leading). Therefore, a synchronous motor can be made to carry the mechanical load at constant speed and at the same time improve the power factor of the system.

- A synchronous motor is not self-starting and an auxiliary means has to be used for starting it.

# Three-Phase Alternator

**Example 37.19.** *Find the synchronous impedance and reactance of an alternator in which a given field current produces an armature current of 200 A on short-circuit and a generated e.m.f. of 50 V on open-circuit. The armature resistance is 0.1 ohm. To what induced voltage must the alternator be excited if it is to deliver a load of 100 A at a p.f. of 0.8 lagging, with a terminal voltage of 200V.* **(Elect. Machinery, Banglore Univ. 1991)**

# Three-Phase Alternator

**Solution.** It will be assumed that alternator is a single phase one. Now, for same field current,

$$Z_S = \frac{\text{O.C. volts}}{\text{S.C. current}} = \frac{50}{200} = \mathbf{0.25\ \Omega.}$$

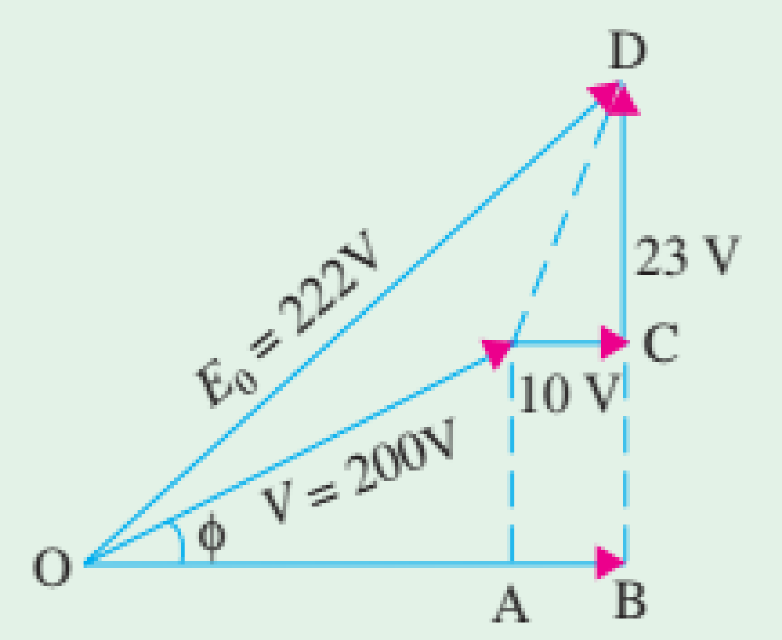
$$X_S = \sqrt{Z_S^2 - R_a^2} = \sqrt{0.25^2 - 0.1^2} = \mathbf{0.23\ \Omega.}$$

Now, $IR_a = 100 \times 0.1 = 10\text{ V}, IX_S = 100 \times 0.23 = 23\text{ V};$

$\cos\phi = 0.8, \sin\phi = 0.6.$ As seen from Fig. 37.34.

$$E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2}$$

$$= [(200 \times 0.8 + 10)^2 + (200 \times 0.6 + 23)^2]^{1/2} = \mathbf{222\ V}$$



# Three-Phase Alternator

**Example 37.20.** *From the following test results, determine the voltage regulation of a 2000-V, 1-phase alternator delivering a current of 100 A at (i) unity p.f. (ii) 0.8 leading p.f. and (iii) 0.71 lagging p.f.*

*Test results : Full-load current of 100 A is produced on short-circuit by a field excitation of 2.5A. An e.m.f. of 500 V is produced on open-circuit by the same excitation. The armature resistance is 0.8Ω.* **(Elect. Engg.-II, M.S. Univ. 1987)**

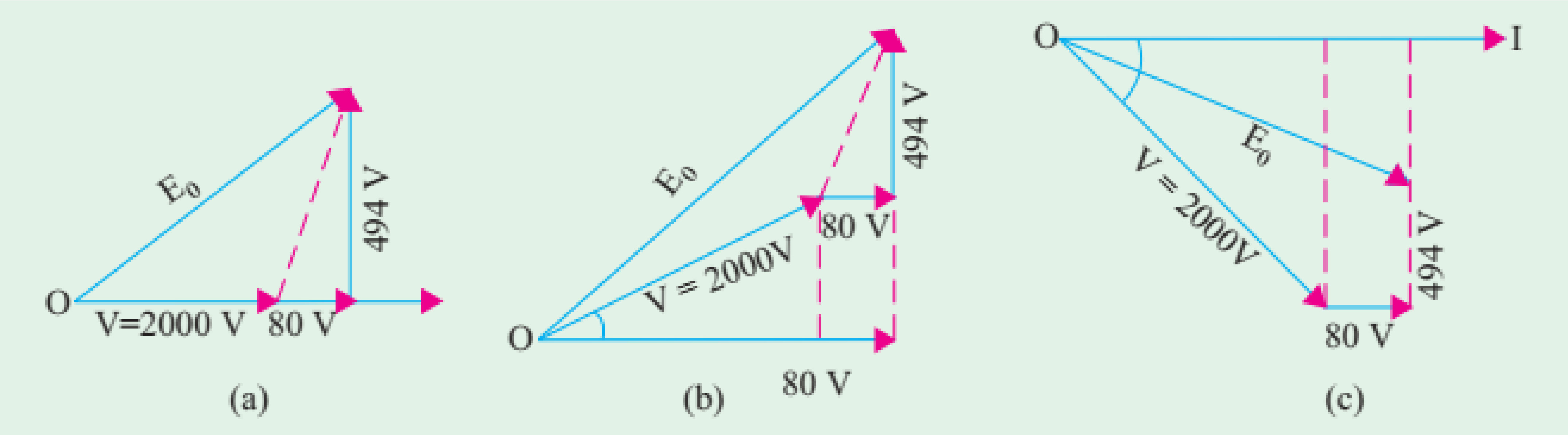
# Three-Phase Alternator

**Solution.** $Z_S = \frac{\text{O.C. volts}}{\text{S.C. current}}$ —for same excitation

for same excitation

$$= 500/100 = 5\ \Omega$$

$$X_S = \sqrt{Z_S^2 - R_a^2} = \sqrt{5^2 - 0.8^2} = 4.936\ \Omega$$



# Three-Phase Alternator

**(*i*) Unity p.f.** (Fig. 37.35 (*a*)]

$$IR_a = 100 \times 0.8 = 80\text{ V}; \quad IX_S = 100 \times 4.936 = 494\text{ V}$$

$$\therefore \quad E_0 = \sqrt{(2000 + 80)^2 + 494^2} = 2140\ V$$

$$\%\text{ regn} = \frac{2140 - 2000}{2000} \times 100 = \mathbf{7\%}$$

**(*ii*) p.f. = 0.8 (lead)** [Fig. 37.35 (*c*)]

$$E_0 = [(2000 \times 0.8 + 80)^2 + (2000 \times 0.6 - 494)^2]^{1/2} = 1820\text{ V}$$

$$\%\text{ regn} = \frac{1820 - 2000}{2000} \times 100 = \mathbf{-9\%}$$

**(*iii*) p.f. = 0.71(lag)** [Fig.37.35 (*b*)]

$$E_0 = [(2000 \times 0.71 + 80)^2 + (2000 \times 0.71 + 494)^2]^{1/2} = 2432\text{ V}$$

$$\%\text{ regn} = \frac{2432 - 2000}{2000} \times 100 = \mathbf{21.6\%}$$

**Example 37.22.** *A 3-phase, star-connected alternator is rated at 1600 kVA, 13,500 V. The armature resistance and synchronous reactance are 1.5 Ω and 30 Ω respectively per phase. Calculate the percentage regulation for a load of 1280 kW at 0.8 leading power factor.*

**(Advanced Elect. Machines AMIE Sec. B, 1991)**

# Three-Phase Alternator

Fig. 37.37

$$1280{,}000 = \sqrt{3} \times 13{,}500 \times I \times 0.8;$$

$$\therefore \quad I = 68.4 \text{ A}$$

$$IR_a = 68.4 \times 1.5 = 103 \text{ V} ; IX_S = 68.4 \times 30 = 2052$$

$$\text{Voltage/phase} = 13{,}500 / \sqrt{3} = 7795 \text{ V}$$

As seen from Fig. 37.37.

$$E_0 = [(7795 \times 0.8 + 103)^2 + (7795 \times 0.6 - 2052)]^{1/2} = 6663 \text{ V}$$

$$\%\text{ regn.} = (6663 - 7795)/7795$$

$$= -0.1411 \text{ or } -14.11\%$$

# Three-Phase Alternator

**Example 37.21.** *A 100-kVA, 3000-V, 50-Hz 3-phase star-connected alternator has effective armature resistance of 0.2 ohm. The field current of 40 A produces short-circuit current of 200 A and an open-circuit emf of 1040 V (line value). Calculate the full-load voltage regulation at 0.8 p.f. lagging and 0.8 p.f. leading. Draw phasor diagrams.*

**(Basic Elect. Machines, Nagpur Univ. 1993)**

# Three-Phase Alternator

**Solution.** $Z_S = \dfrac{\text{O.C. voltage/phase}}{\text{S.C. current/phase}}$ — for same excitation

$$= \frac{1040/\sqrt{3}}{200} = 3\ \Omega$$

$$X_S = \sqrt{Z_S^2 - R_a^2} = \sqrt{3^2 - 0.2^2}$$

$$= 2.99\ \Omega$$

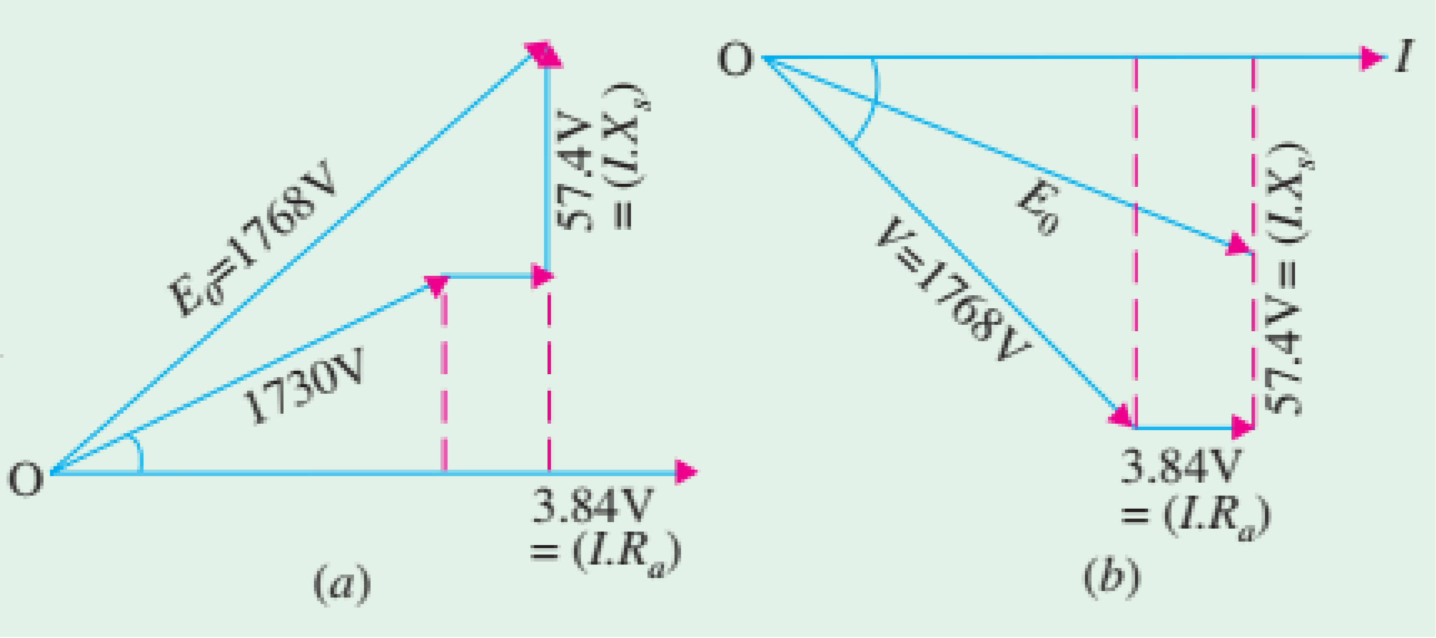
F.L. current,

$$I = 100{,}000/\sqrt{3} \times 3000$$
$$= 19.2\ \text{A}$$
$$IR_a = 19.2 \times 0.2 = 3.84\ \text{V}$$
$$IX_S = 19.2 \times 2.99 = 57.4\ \text{V}$$

Voltage/phase

$$= 3000/\sqrt{3} = 1730\text{V}$$

$$\cos\phi = 0.8\ ;\ \sin\phi = 0.6$$



# Three-Phase Alternator

Fig. 37.36

**(i) p.f. = 0.8 lagging**

—Fig. 37.36 (a)

$$E_0 = [(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2]^{1/2}$$

$$= (1730 \times 0.8 + 3.84)^2 + (1730 \times 0.6 + 57.4)^2]^{1/2} = 1768 \text{ V}$$

$$\%\text{ regn. 'up'} = \frac{(1768 - 1730)}{1730} \times 100 = \mathbf{2.2\%}$$

**(ii) 0.8 p.f. leading**—Fig. 37.36 (b)

$$E_0 = [(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_S)^2]^{1/2}$$

$$= [(1730 \times 0.8 + 3.84)^2 + (1730 \times 0.6 - 57.4)^2]^{1/2}$$

$$= 1699 \text{ V}$$

$$\%\text{ regn.} = \frac{1699 - 1730}{1730} \times 100 = \mathbf{-1.8\%}$$

# Three-Phase Alternator

**Example 37.24.** *The following test results are obtained from a 3-phase, 6,000-kVA, 6,600 V, star-connected, 2-pole, 50-Hz turbo-alternator:*

*With a field current of 125 A, the open-circuit voltage is 8,000 V at the rated speed; with the same field current and rated speed, the short-circuit current is 800 A. At the rated full-load, the resistance drop is 3 per cent. Find the regulation of the alternator on full-load and at a power factor of 0.8 lagging.* **(Electrical Technology, Utkal Univ. 1987)**

# Three-Phase Alternator

**Solution.**

$$Z_S = \frac{\text{O.C. voltage/phase}}{\text{S.C. current/phase}} = \frac{8000/\sqrt{3}}{800} = 5.77\ \Omega$$

Voltage/phase $= 6,600\sqrt{3} = 3,810$ V

Resistive drop $=$ 3% of 3,810 V $= 0.03 \times 3,810 = 114.3$ V

Full-load current $= 6,000 \times 10^3/\sqrt{3} \times 6,600 = 525$ A

Now $IR_a = 114.3$V

$\therefore$ $R_a = 114.3/525 = 0.218\ \Omega$

$$X_S = \sqrt{Z_S^2 - R_a^2} = \sqrt{5.77^2 - 0.218^2} = 5.74\ \Omega \text{ (approx.)}$$

As seen from the vector diagram of Fig. 37.33, (*b*)

$$E_0 = \sqrt{[3,810 \times 0.8 + 114.3)^2 + (3,810 \times 0.6 + 525 \times 5.74)^2]} = 6,180 \text{ V}$$

$\therefore$ regulation $= (6,180 - 3,810) \times 100/3,810 =$ **62.2%**

# BASIC ELECTRICAL ENGINEERING

by

**S Reddy Ramesh**
**Assistant Professor**
Dept of Electrical & Electronics Engineering
Aditya College of Engineering & Technology
Surampalem.

# Unit-IV INDUCTION MACHINES

- Principle of operation
- construction of three-phase induction motors
- slip ring and squirrel cage motors
- slip-torque characteristics
- efficiency calculation
- starting methods
- Brake test on 3-Phase Induction Motor

# THREE PHASE INDUCTION MOTORS

## INTRODUCTION:

The 3-ϕ induction motors are most widely used electric motors in industry. They run at essentially constant speed from no-load to full load. However, the speed is frequency dependent and consequently these motors are not easily adopted to speed control.

We usually prefer dc motors when large speed variations are required. Nevertheless, the 3-ϕ induction motors are simple, rugged, low-priced, easy to maintain and can be manufactured with characteristics to suit most industrial requirements.

Like any electric motor, a 3-ϕ induction motor has a stator and a rotor. The stator carries a 3-ϕ winding(called stator winding) while the rotor carries a short circuited winding(called rotor winding). Only the stator winding is fed from 3-phase supply. The rotor winding gets its voltage and power from the externally energized stator winding through electromagnetic induction and hence the name.

The induction motor may be considered to be a transformer with a rotating secondary and it can, therefore be described as a transformer type AC machine in which electrical energy is converted into mechanical energy.

- Three-phase induction motors are the most common and frequently encountered machines in industry
  - simple design, rugged, low-price, easy maintenance
  - run essentially as constant speed from no-load to full load
  - called as *asynchronous motors*
  - described as —transformer type a.c machine in which electrical energy is converted into mechanical energy.
  - 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

## Advantages

- It has simple and rugged construction.
- It is relatively cheap.
- It requires little maintenance.
- It has high efficiency, good speed regulation 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 motors.

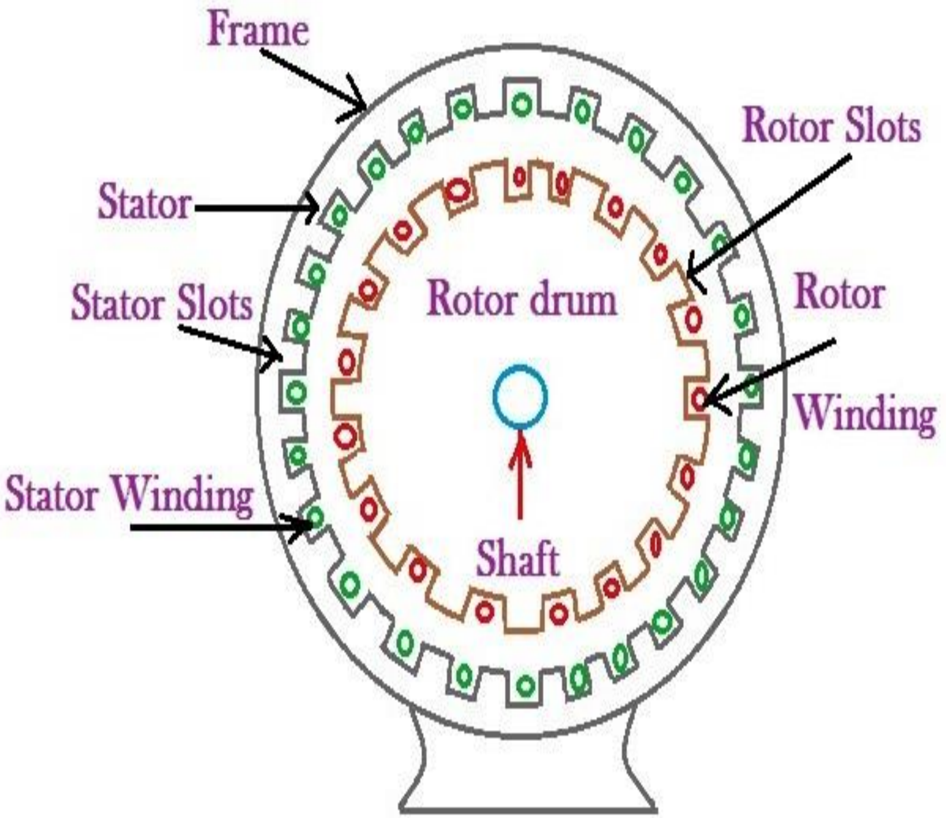
# Construction of 3-phase Induction motor:

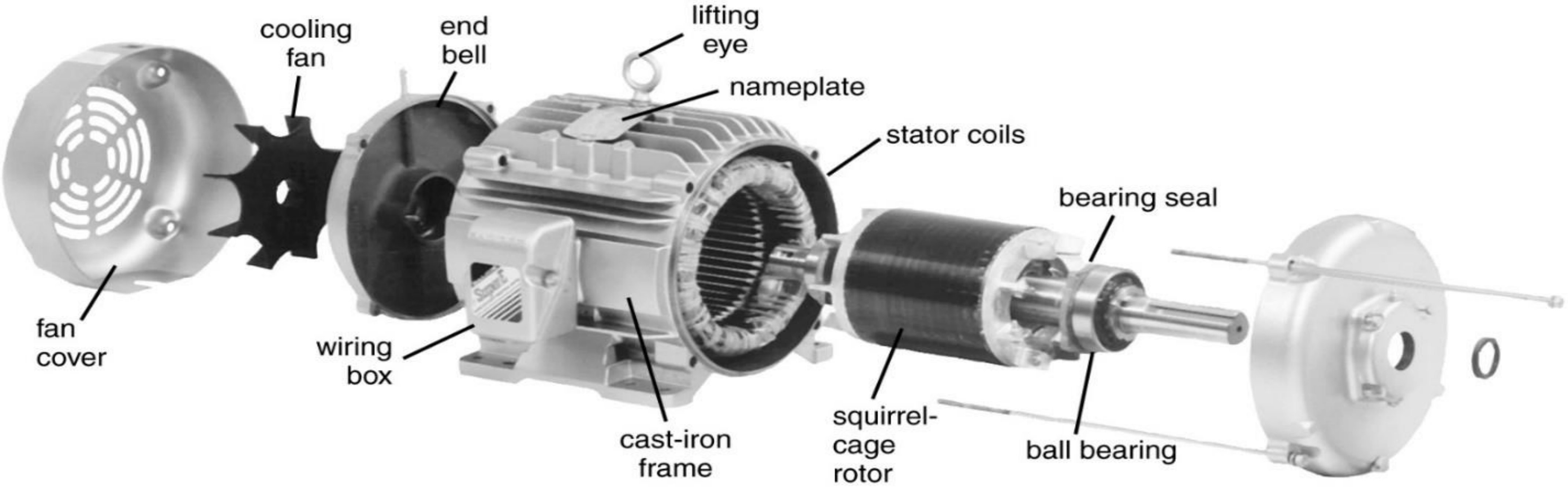
An induction motor consists essentially of two main parts :

(*a*) a stator and (*b*) a rotor.

(*a*) **Stator**

The stator of an induction motor is, in principle, the same as that of a synchronous motor or generator. It is made up of a number of stampings, which are slotted to receive the windings [Fig.34.2 (*a*)]. The stator carries a 3-phase winding [Fig.34.2 (*b*)] and is fed from a 3-phase supply. It is wound for a definite number of poles*, the exact number of poles being determined by the requirements of speed. Greater the number of poles, lesser the speed and *vice versa*. It will be shown in Art. 34.6 that the stator windings, when supplied with 3-phase currents, produce a magnetic flux, which is of constant magnitude but which revolves (or rotates) at synchronous speed (given by $N_s = 120 f/P$). This revolving magnetic flux induces an e.m.f. in the rotor by mutual induction.






- **Frame:**

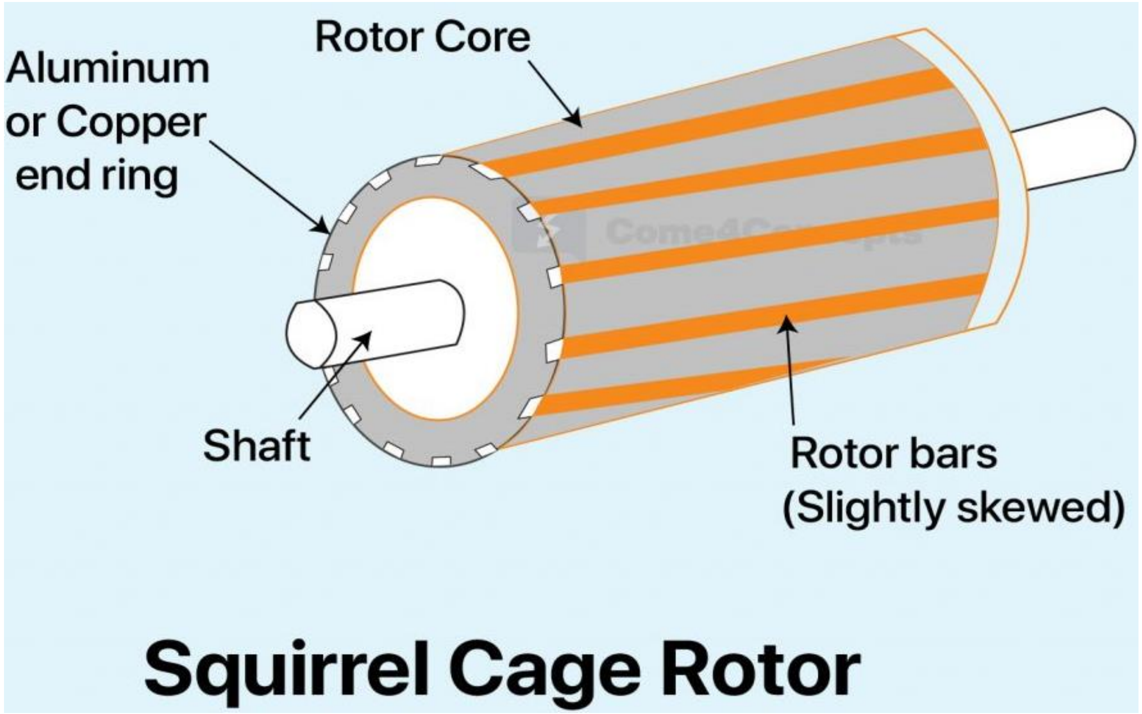
  It is the outer body of the motor. Its function are to support the stator core and winding, to protect the inner parts of the machine and serve as a ventilating housing or means of guiding the coolant into effective channels.

- **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.

## Rotor:

The rotor consists of a laminated core, with slots cut on its outer periphery where windings are placed. The windings may be either of squirrel cage type or wound rotor type. The core is mounted on a steel shaft, provided with bearings on both sides and is supported on end covers attached to the main frame of the motor

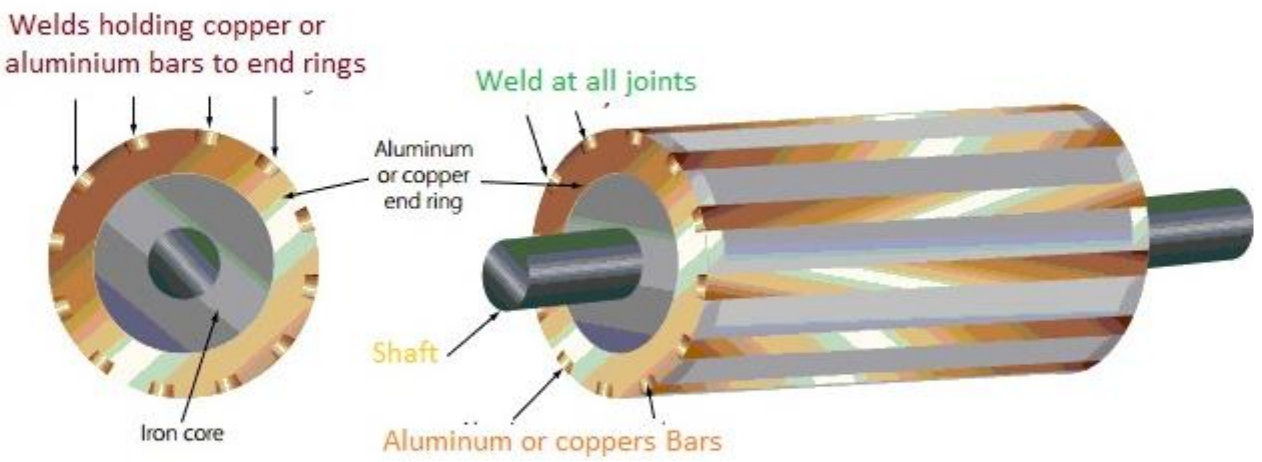



There are two types of the rotor which are used in an induction motor. The first one is the Wound rotor and the other is a squirrel cage rotor.

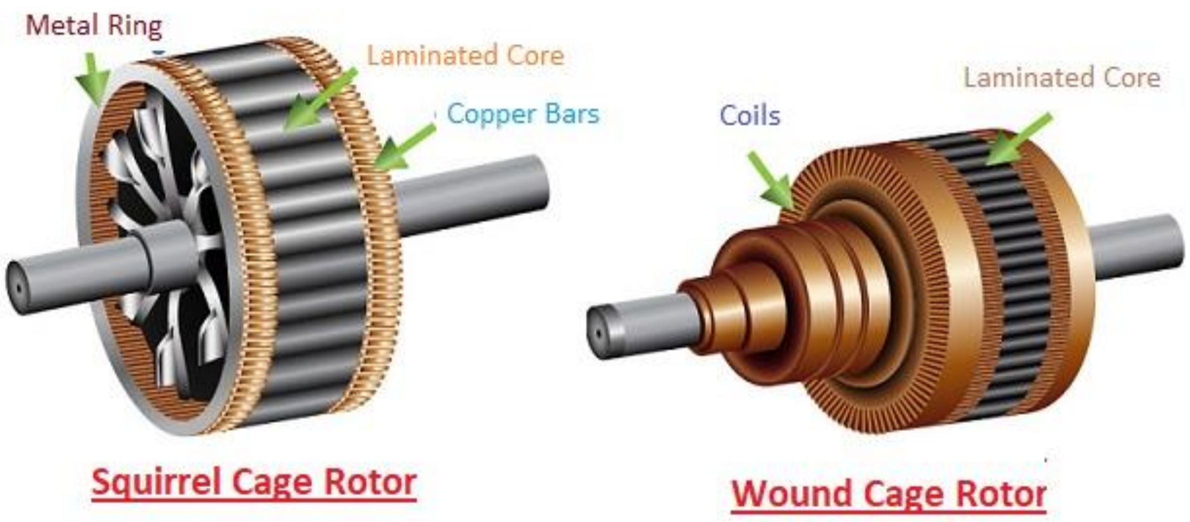
## Squirrel Cage Rotor

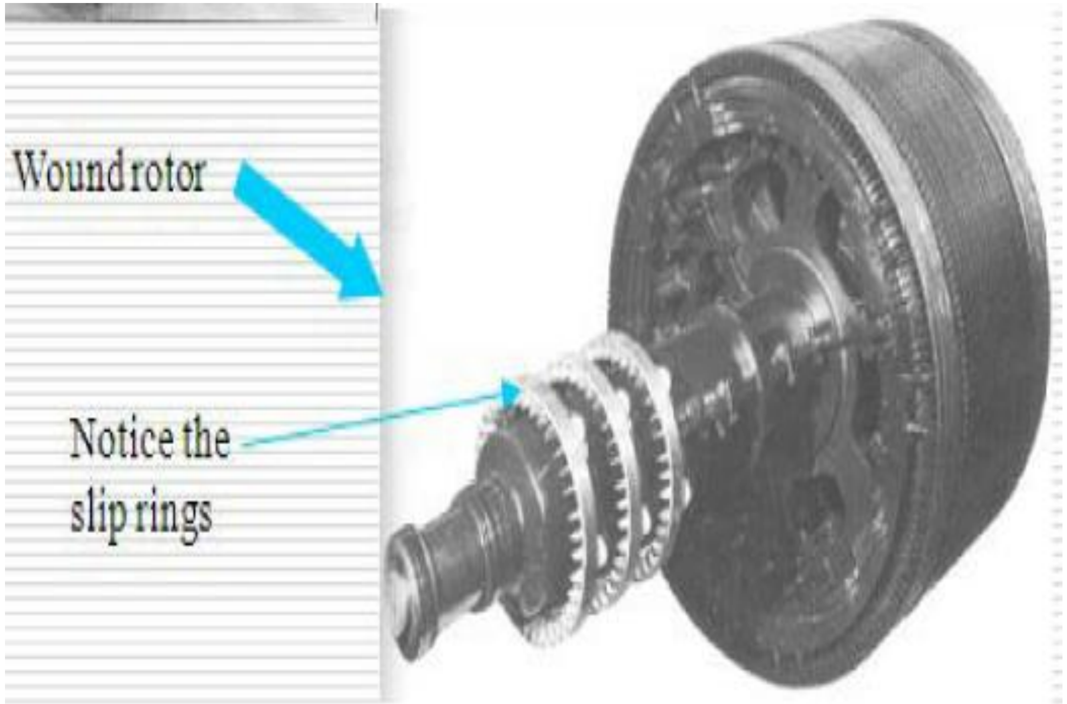
•This rotor is known as squirrel cage because its construction is like a squirrel. Its shape is similar to the cylinder which has laminated slots as a conductor. Every slot consists of copper (Cu), Aluminum (Al), or other conductive material, but it mostly consists of aluminum.

Squirrel Cage Rotor of Induction Motor

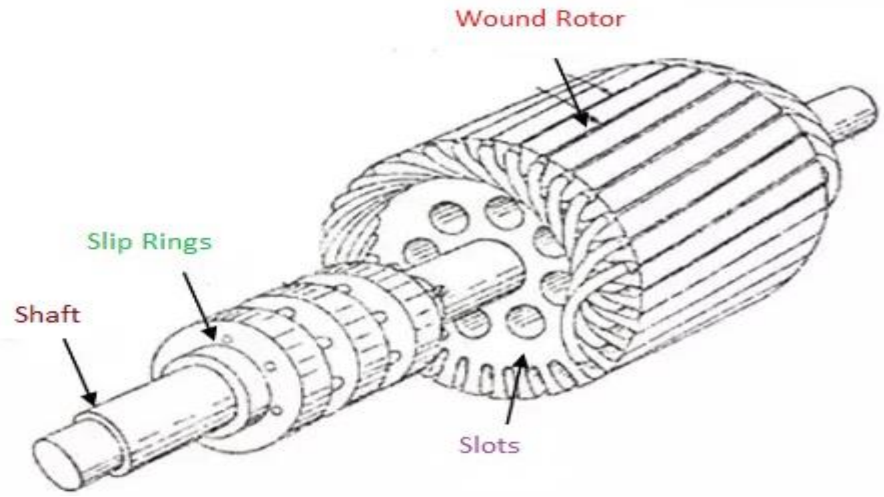


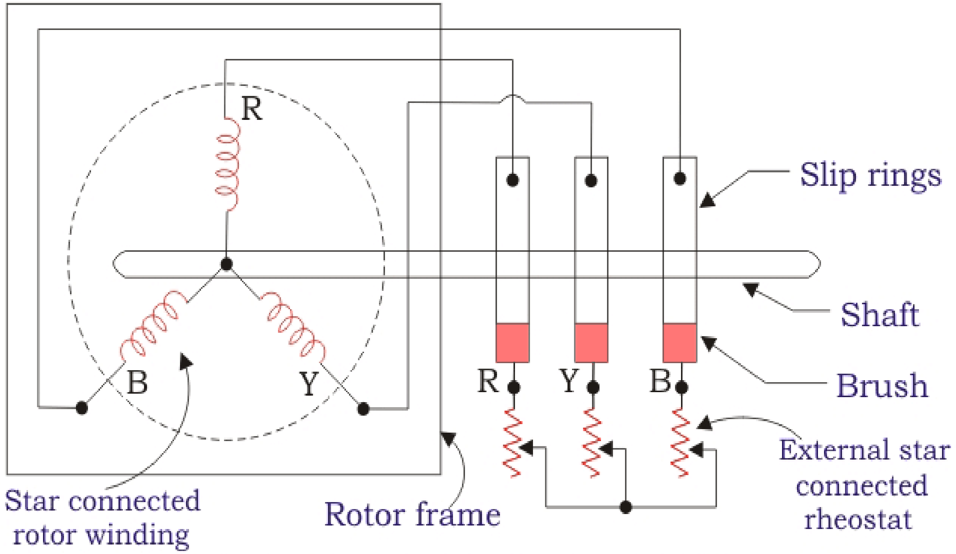
## Rotor of Induction Motor




## Wound Rotor of Induction Motor



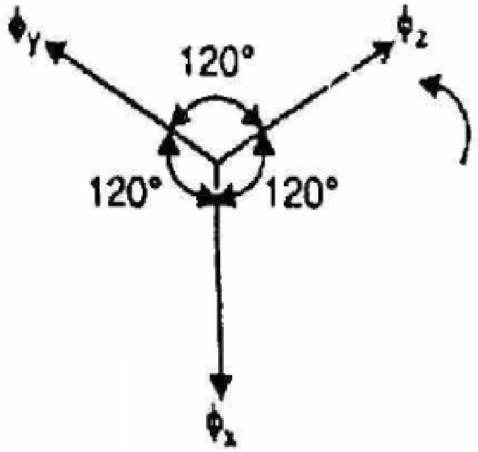

Slip Ring Three Phase Induction Motor

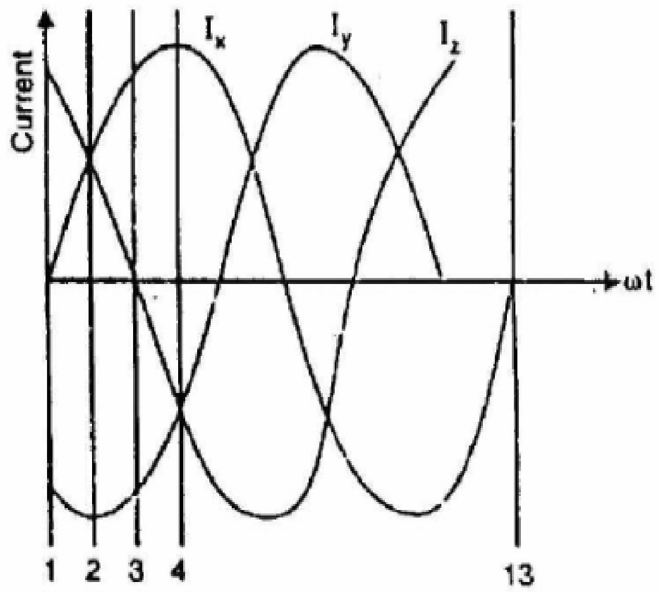
# Wound Rotor of Induction Motor:

- In this kind of rotor, windings are linked with the exterior resistors by the slip ring.
- By varying the value of resistance, we can vary the torque of the motor.
- Wound rotor induction motor can start its operation by the less starting current, by introducing higher resistance (R) in the rotor circuitry, when the motor rushes, the resistance (R) can be reduced.

## Rotating Magnetic Field Due to 3-Phase Currents

$$\phi_x = \phi_m \sin \omega t$$
$$\phi_y = \phi_m \sin (\omega t - 120°)$$
$$\phi_z = \phi_m \sin (\omega t - 240°)$$




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

Where,

$Ns$ = Synchronous speed of stator field

$f$ = *frequency of the supply*

$P$ = *Number of poles*

9

## 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, an 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

## WORKING PRINCIPLE

- When three phase supply is given to the stator of three phase induction motor, a rotating magnetic field is produced which rotates with synchronous speed.
- The flux passes through the air gap and cuts the rotor conductors which are stationary.
- Due to relative speed between rotating flux and stationary conductors. An emf is induced according to faradays laws of electromagnetic induction.
- Since the rotor bars or conductors forms a closed circuit , rotor current is produced whose direction is given by lenz law.
- Hence current in rotor will produce its own flux and to reduce relative speed , the rotor starts to running in same direction as that of rotating flux and tries to catch up with rotating flux.

Consider a portion of 3-phase induction motor as shown in Fig. 19.7. The operation of the motor can be explained as under :

*(i)* When 3-phase stator winding is energised from a 3-phase supply, a rotating magnetic field is set up which rotates around the stator at synchronous speed $N_s$ (= $120\ f/P$).

*(ii)* The rotating field passes through the air-gap and cuts the rotor conductors, which as yet, are stationary. Due to the relative speed between the rotating flux and the stationary rotor, e.m.f.s are induced in the rotor conductors. Since the rotor circuit is short-circuited, currents start flowing in the rotor conductors.

*(iii)* The current-carrying rotor conductors are placed in the magnetic field produced by the stator. Consequently, mechanical force acts on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a torque which tends to move the rotor in the *same direction* as the rotating field.

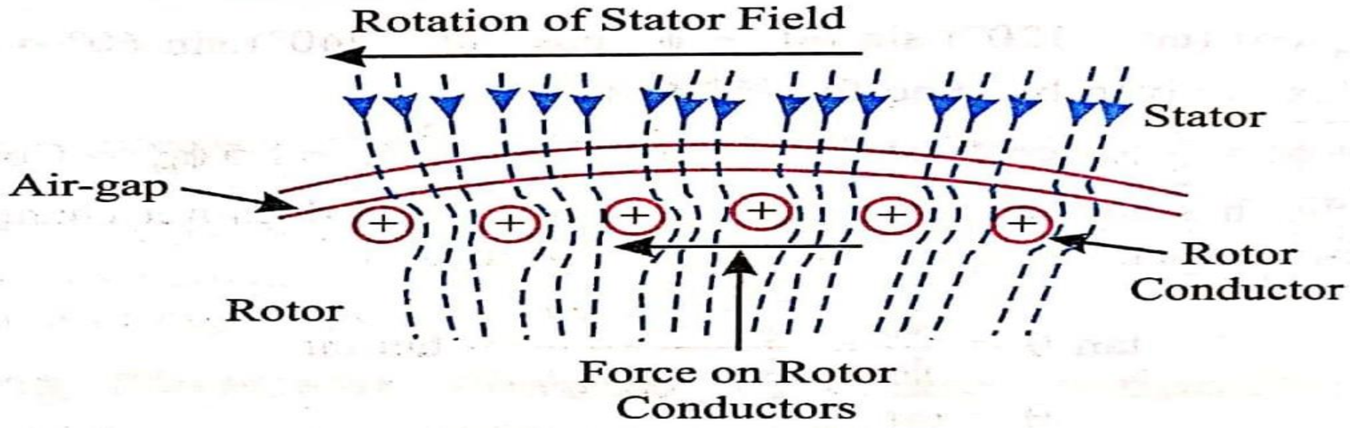



**Fig. 19.7**

*(iv)* The fact that rotor is urged to follow the stator field (*i.e.*, rotor moves in the direction of stator field) can be explained by Lenz's law. According to this law, the direction of rotor currents will be such that they tend to oppose the cause producing them. Now, the cause producing the rotor currents is the relative speed between the rotating field and the stationary rotor conductors. Hence to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it.

# INDUCTION MOTOR SPEED

- 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

# SLIP

The difference between the synchronous speed $N_s$ of the rotating stator field and the actual rotor speed N is called slip. It is usually expressed as a fraction or percentage of synchronous speed i.e.

$$\text{Fractional slip, s} = \frac{\text{Synchronous Speed} - \text{Rotor Speed}}{\text{Synchronous Speed}}$$

$$= \frac{(Ns - N)}{Ns}$$

$$\%\text{ age slip, } s = \frac{N_s - N}{N_s} \times 100$$

(i) The quantity $N_s$ - N is sometimes called slip speed.

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

(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.

# ROTOR CURRENT FREQUENCY

$$\text{Frequency} = \frac{N_{relative} P}{120}$$

where $N_{relative}$ = Relative speed between magnetic field and the winding

P = Number of poles

For a rotor speed N, the relative speed between the rotating flux and the rotor is $N_s$ - N. Consequently, the rotor current frequency f ' is given by;

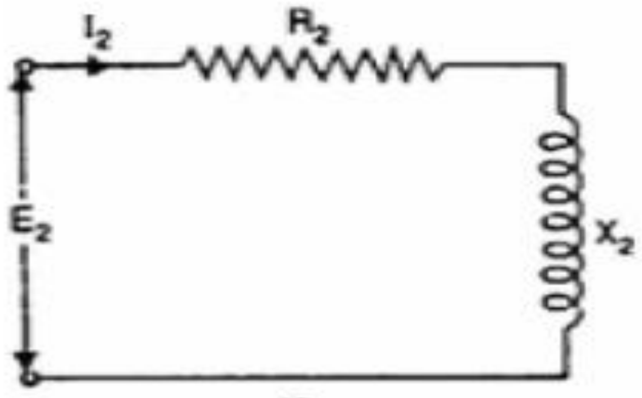
$$f' = \frac{(N_s - N)P}{120}$$

$$= \frac{sN_sP}{120} \qquad \left(\because s = \frac{N_s - N}{N_s}\right)$$

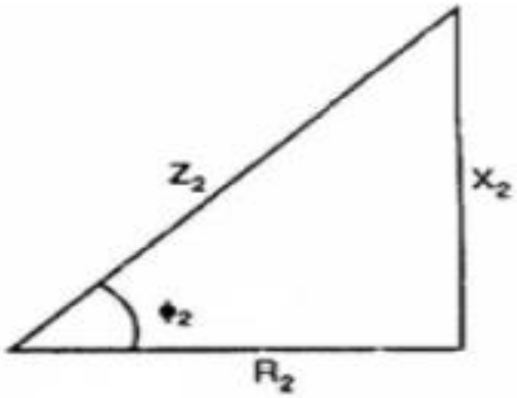
$$= sf \qquad \left(\because f = \frac{N_sP}{120}\right)$$

i.e., *Rotor current frequency = Fractional slip x Supply frequency*. Therefore it is called slip frequency.

**At standstill:** Fig. (i) shows one phase of the rotor circuit at standstill.



(i)




At standstill, s=1

Induced emf per phase in rotor at standstill = $E_2$

Rotor winding resistance per phase = $R_2$

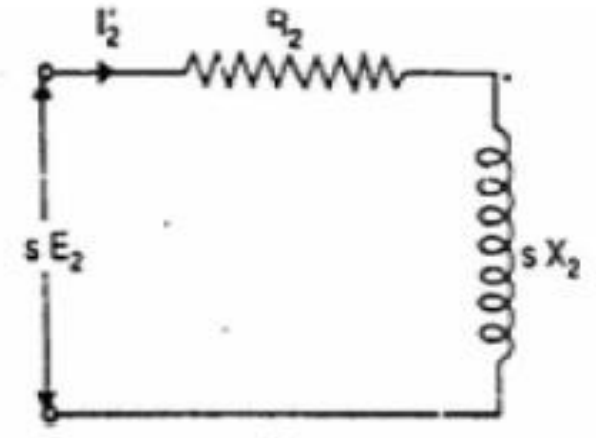
Rotor winding reactance per phase, $X_2 = 2\pi fL_2$, where f is the supply frequency.

Rotor winding impedance per phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$

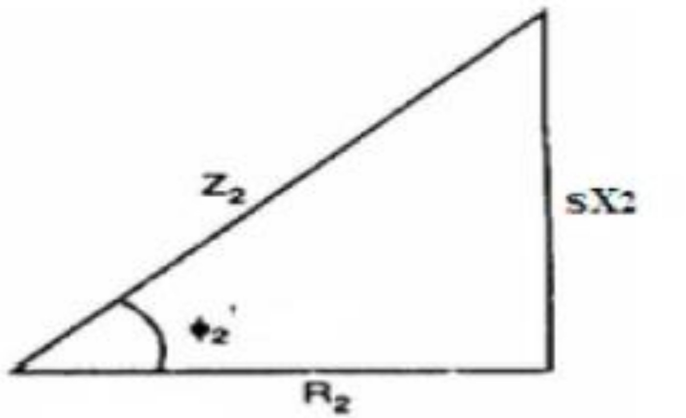
$$\text{Rotor current/phase, } I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

$$\text{Rotor p.f., } \cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

**When running at slip s**: Fig (ii) shows one phase of the rotor circuit when the motor is running at slip s.




(ii)




Induced emf per phase in rotor winding = $sE_2$

Rotor winding resistance per phase = $R_2$

Rotor winding reactance per phase = $2\pi f' L_2 = 2\pi sf L_2 = s2\pi f L_2 = sX_2$

Rotor winding impedance per phase, $Z_2' = \sqrt{R_2^2 + (sX_2)^2}$

$$\text{Rotor current, } I'_2 = \frac{sE_2}{Z'_2} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\text{Rotor p.f., } \cos\phi'_2 = \frac{R_2}{Z'_2} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

# ROTOR TORQUE

The torque T developed by the rotor is directly proportional to:

(i) rotor current

(ii) stator flux per pole, $\Phi$

(iii) power factor of the rotor circuit

i.e. $T \alpha \Phi I_2 \cos \Phi_2$

$\Phi \alpha E_1$

where $E_1$ is the stator induced emf

At standstill, $E_1 \alpha E_2$

$$\therefore \quad T \propto E_2 I_2 \cos\phi_2$$

or $$T = K E_2 I_2 \cos\phi_2$$

where $I_2$ = rotor current at standstill
$E_2$ = rotor e.m.f. at standstill
$\cos\phi_2$ = rotor p.f. at standstill

# TORQUE UNDER RUNNING CONDITION

Let the rotor at standstill have per phase induced e.m.f. $E_2$, reactance $X_2$ and resistance $R_2$. Then under running conditions at slip s,

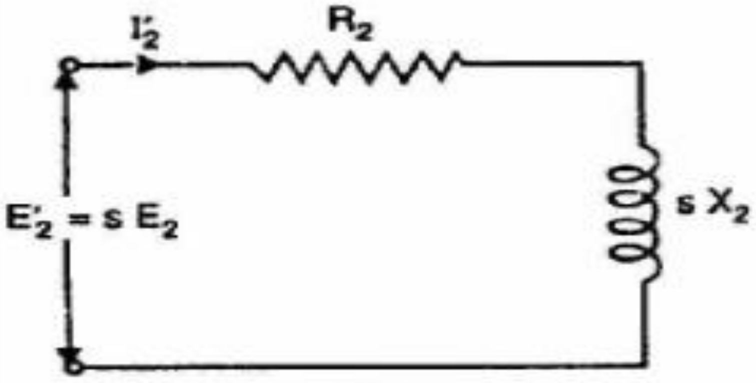
$$\text{Rotor e.m.f./phase, } E'_2 = sE_2$$

$$\text{Rotor reactance/phase, } X'_2 = sX_2$$

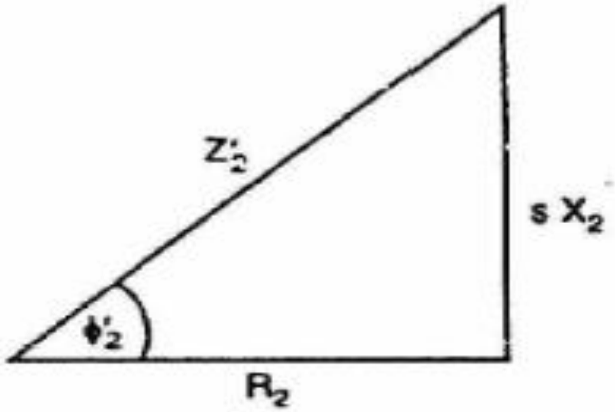
$$\text{Rotor impedance/phase, } Z'_2 = \sqrt{R_2^2 + (sX_2)^2}$$

$$\text{Rotor current/phase, } I'_2 = \frac{E'_2}{Z'_2} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\text{Rotor p.f., } \cos\phi'_m = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$




(i).




(ii)

Running Torque, $T_r \propto E'_2 I'_2 \cos\phi'_2$

$$\propto \phi I'_2 \cos\phi'_2 \qquad (\because E'_2 \propto \phi)$$

$$\propto \phi \times \frac{s E_2}{\sqrt{R_2^2 + (s X_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (s X_2)^2}}$$

$$\propto \frac{\phi s E_2 R_2}{R_2^2 + (s X_2)^2}$$

$$= \frac{K \phi s E_2 R_2}{R_2^2 + (s X_2)^2}$$

$$= \frac{K_1 s E_2^2 R_2}{R_2^2 + (s X_2)^2} \qquad (\because E_2 \propto \phi)$$

If the stator supply voltage V is constant, then stator flux and hence $E_2$ will be constant.

$$\therefore \quad T_r = \frac{K_2 s R_2}{R_2^2 + (s X_2)^2}$$

where $K_2$ is another constant.

It may be seen that running torque is:

(i) directly proportional to slip i.e., if slip increases (i.e., motor speed decreases), the torque will increase and vice-versa.

(ii) directly proportional to square of supply voltage ($E_2 \propto V$) .

It can be shown that value of $K_1 = 3/2\pi N_s$ where $N_s$ is in r.p.s.

$$\therefore \quad T_r = \frac{3}{2\pi N_s} \cdot \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2} = \frac{3}{2\pi N_s} \cdot \frac{s E_2^2 R_2}{(Z'_2)^2}$$

At starting, s = 1 so that starting torque is

$$T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

# STARTING TORQUE

Let $E_2$ = rotor e.m.f. per phase at standstill

$X_2$ = rotor reactance per phase at standstill

$R_2$ = rotor resistance per phase

Rotor impedance/phase, $Z_2 = \sqrt{R_2^2 + X_2^2}$ ...at standstill

Rotor current/phase, $I_2 = \dfrac{E_2}{Z_2} = \dfrac{E_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

Rotor p.f., $\cos\phi_2 = \dfrac{R_2}{Z_2} = \dfrac{R_2}{\sqrt{R_2^2 + X_2^2}}$ ...at standstill

$\therefore$ Starting torque, $T_s = K E_2 I_2 \cos\phi_2$

$$= K E_2 \times \frac{E_2}{\sqrt{R_2^2 + X_2^2}} \times \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$= \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Generally, the stator supply voltage V is constant so that flux per pole f set up by the stator is also fixed. This in turn means that e.m.f. $E_2$ induced in the rotor will be constant.

$$\therefore \quad T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} = \frac{K_1 R_2}{Z_2^2}$$

where $K_1$ is another constant.

It can be shown that $K = 3/2 \pi N_s$.

$$\therefore \quad T_s = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

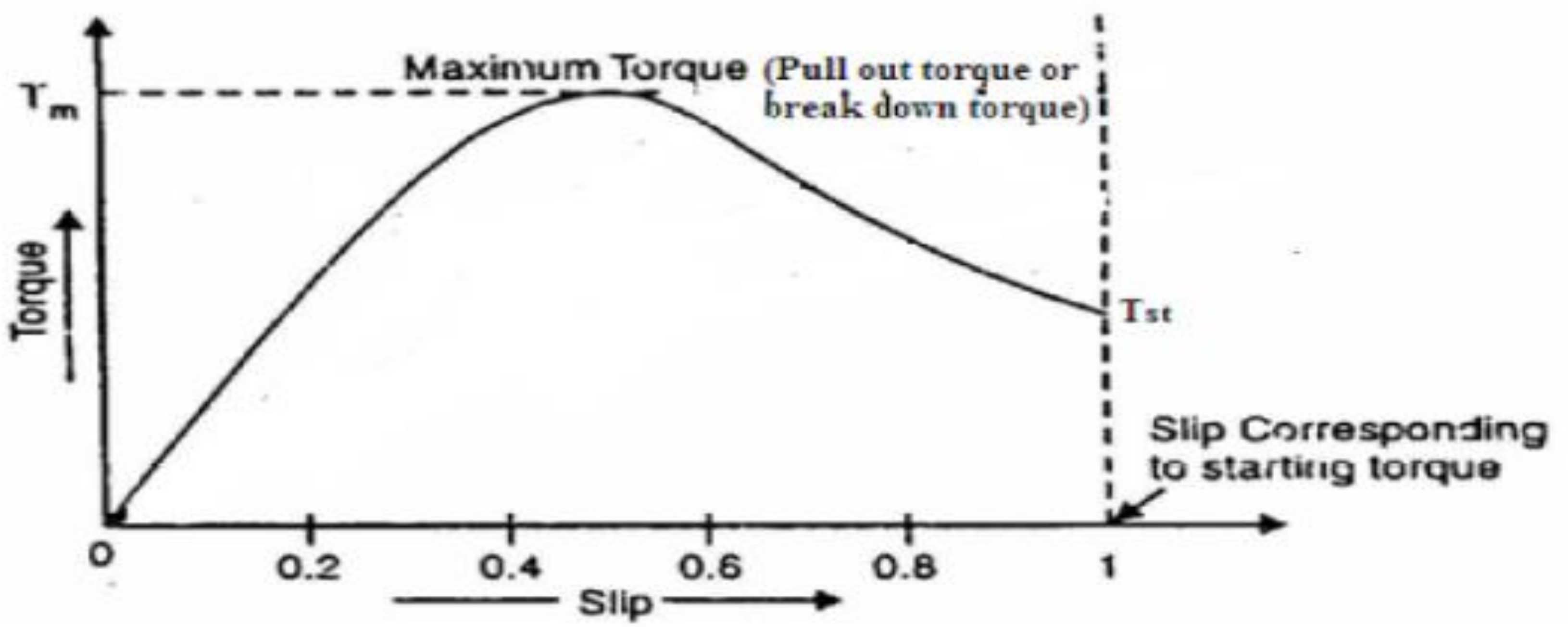
Note that here $N_s$ is in r.p.s.

# TORQUE- SLIP CHARACTERISTICS

The motor torque under running conditions is given by:

$$T = \frac{K_2 \; s \; R_2}{R_2^2 + s^2 \; X_2^2}$$

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.



The following points may be noted carefully:

(i) At $s = 0$, $T = 0$ so that torque-slip curve starts from the origin.

(ii) At normal speed, slip is small so that $s X_2$ is negligible as compared to $R_2$.

$$\therefore \quad T \propto s/R_2$$

$$\propto s \qquad \text{... as } R_2 \text{ is constant}$$

Hence torque slip curve is a straight line from zero slip to a slip that corresponds to full-load.

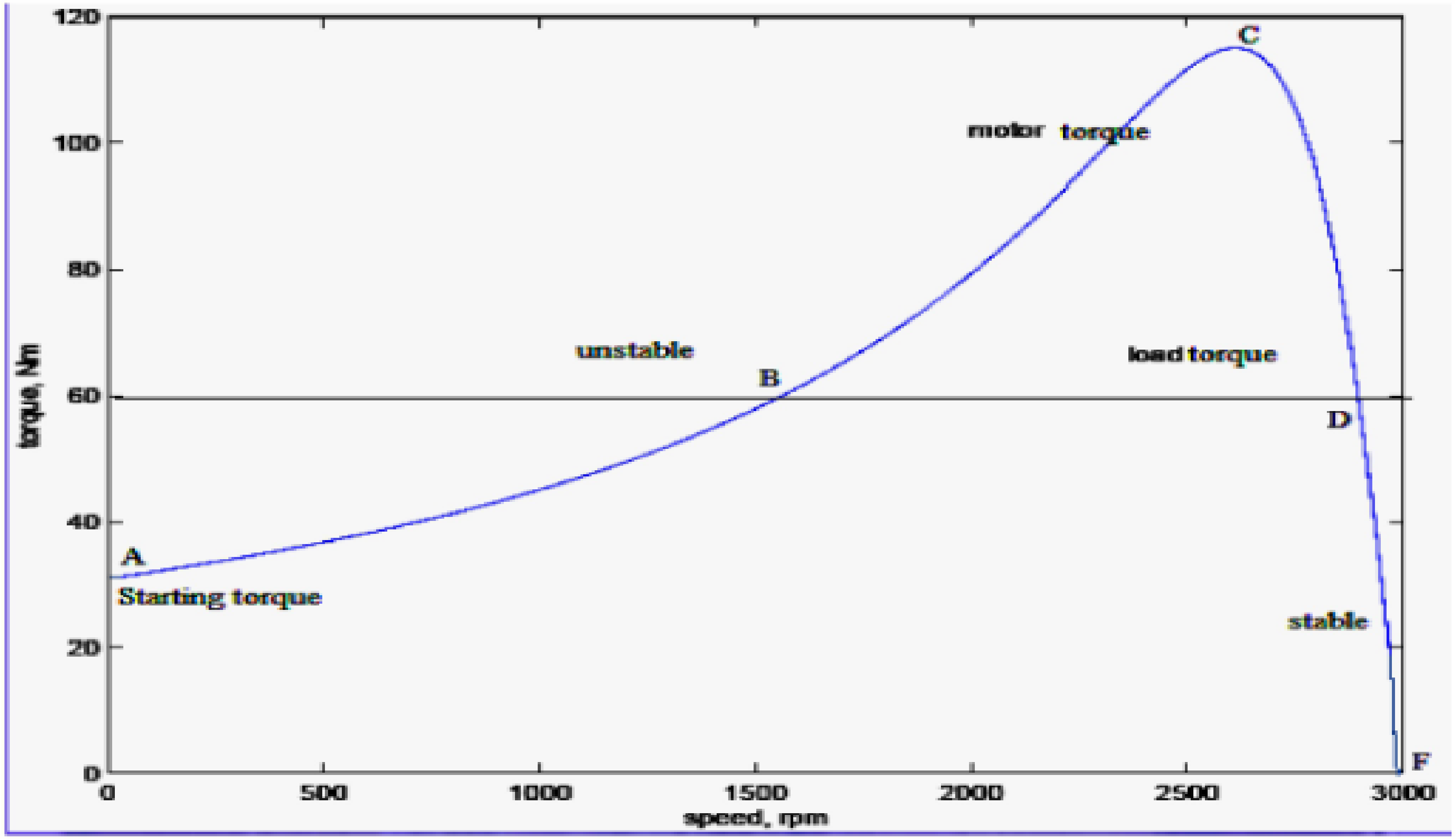
(iii) As slip increases beyond full-load slip, the torque increases and becomes maximum at $s = R_2/X_2$. This maximum torque in an induction motor is called pull-out torque or break-down torque. Its value is atleast twice the full-load value when the motor is operated at rated voltage and frequency.

(iv) When slip increases beyond that corresponding to maximum torque, the term $s^2X_2^2$ increases very rapidly so that $R_2^2$ may be neglected as compared to $s^2X_2^2$.

$$\therefore \quad T \propto s/s^2 X_2^2$$

$$\propto 1/s \qquad \text{... as } X_2 \text{ is constant}$$

# TORQUE – SPEED CHARACTERISTICS



# EFFECT OF CHANGE IN SUPPLY VOLTAGE ON TORQUE – SPEED CHARACTERISTIC

$$T_s = \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

Since $E_2 \propto$ Supply voltage V

$$\therefore \quad T_s = \frac{K_2 V^2 R_2}{R_2^2 + X_2^2}$$

where $K_2$ is another constant.

$$\therefore \quad T_s \propto V^2$$

Similarly

$$T_m \propto V^2$$

A 220-V, three-phase, two-pole, 50-Hz induction motor is running at a slip of 5 percent. Find:

(*a*) The speed of the magnetic fields in revolutions per minute

(*b*) The speed of the rotor in revolutions per minute

(*c*) The slip speed of the rotor

(*d*) The rotor frequency in hertz

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

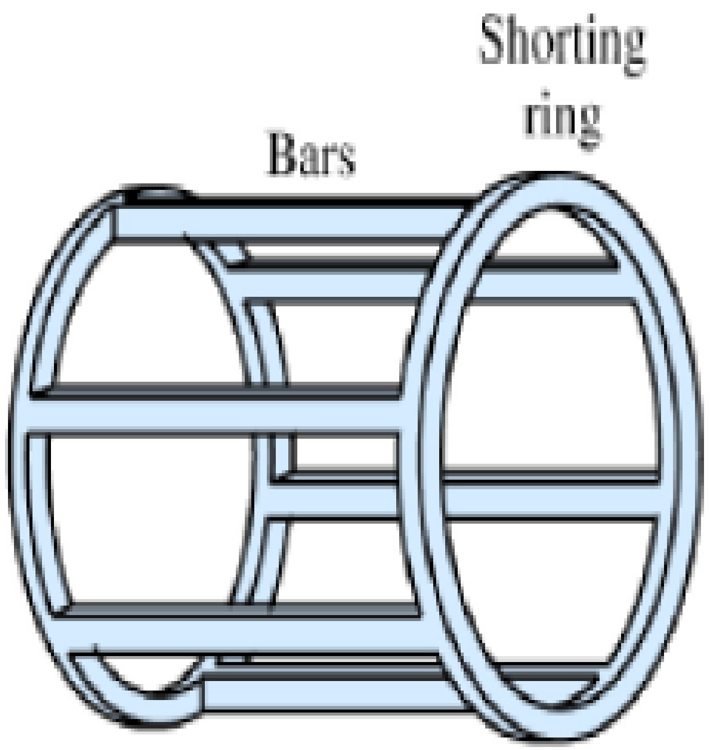
1. What is the synchronous speed of this motor?
2. What is the rotor speed of this motor at rated load?
3. What is the rotor frequency of this motor at rated load?
4. What is the shaft torque of this motor at rated load?

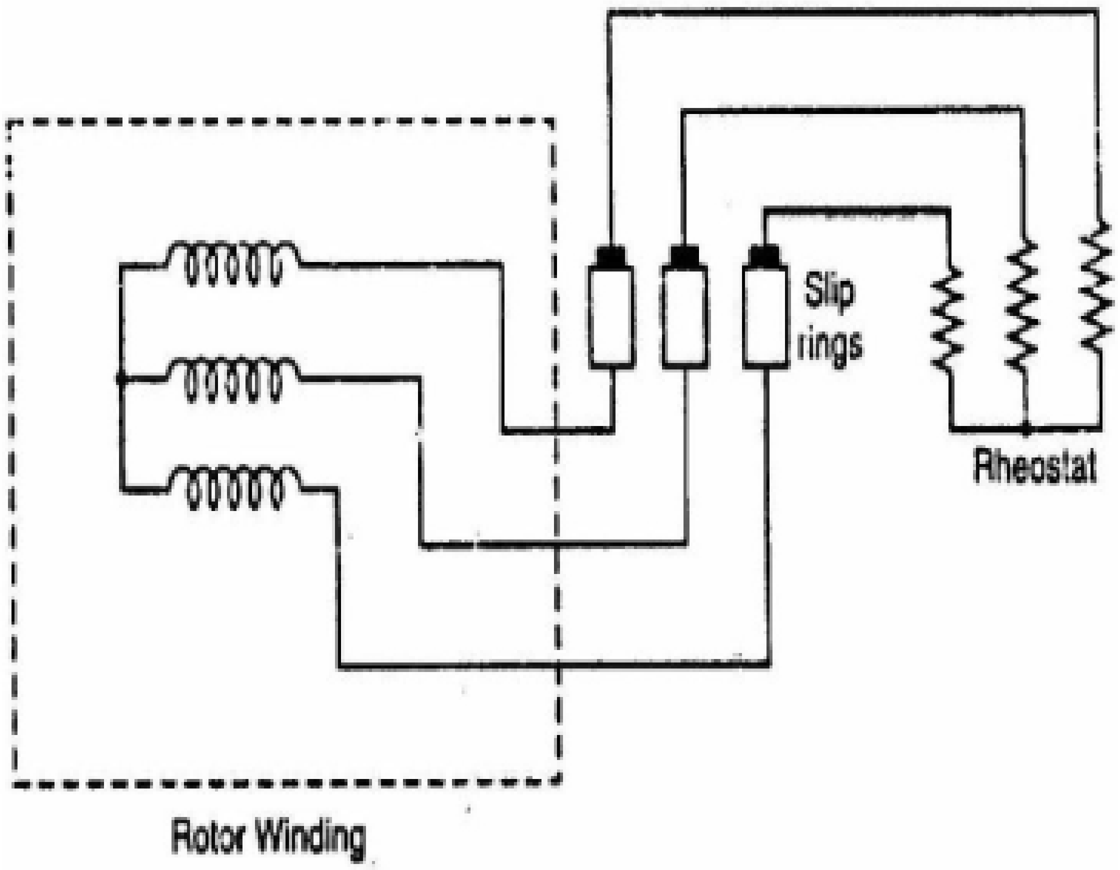
# Necessity of Starter

- If we start the Motor directly then…..
- HIGH current will flow through the rotor which will damage the rotor bars.
- To prevent that we can add some resistance in the rotor similar to DC motor starter.
- WRIM has the facility to add the resistance but what will happens to the SCIM ???

## Squirrel cage rotor

## Wound rotor



# SOLUTION

- INDUCTION MOTOR STARTER
- By Adjusting voltage during starting, the current drawn by the motor and the torque produced by the motor can be reduced and controlled.
- There are 3 types of starter used for SCIM
  - □ D.O.L starter (Direct on line)
  - □ Star delta starter
  - □ Auto transformer starter

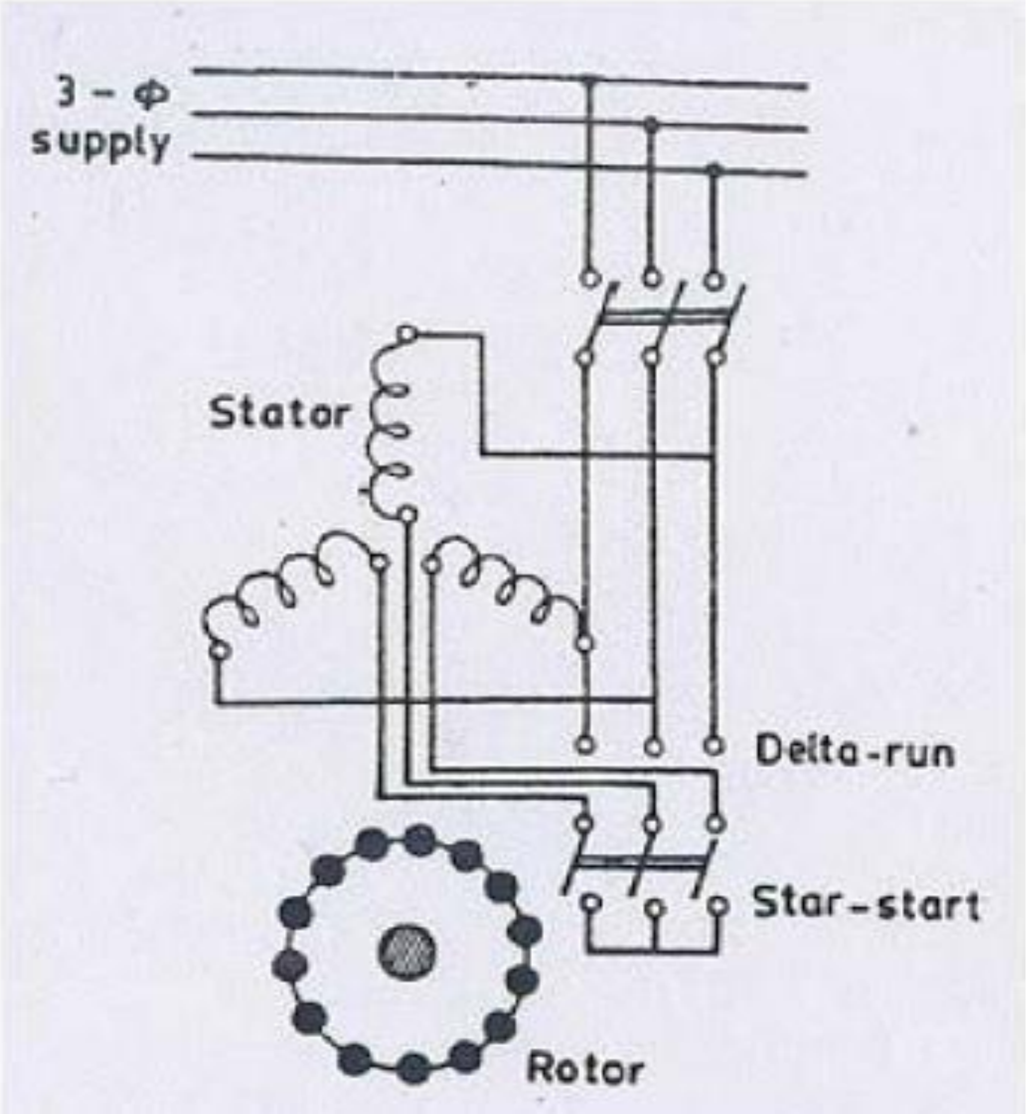
# DOL STARTER

- A starter which connects a motor directly across the line is called D.O.L. Starter.
- In this method, the motor is connected by means of a starter across the full supply voltage.
- Switching by this starter is directly from line without any provision to control the starting current i.e.
- There is no device to reduce the starting current in this starter.
- This method is used for low rating induction motors.

# DOL STARTER

# STAR-DELTA STARTER



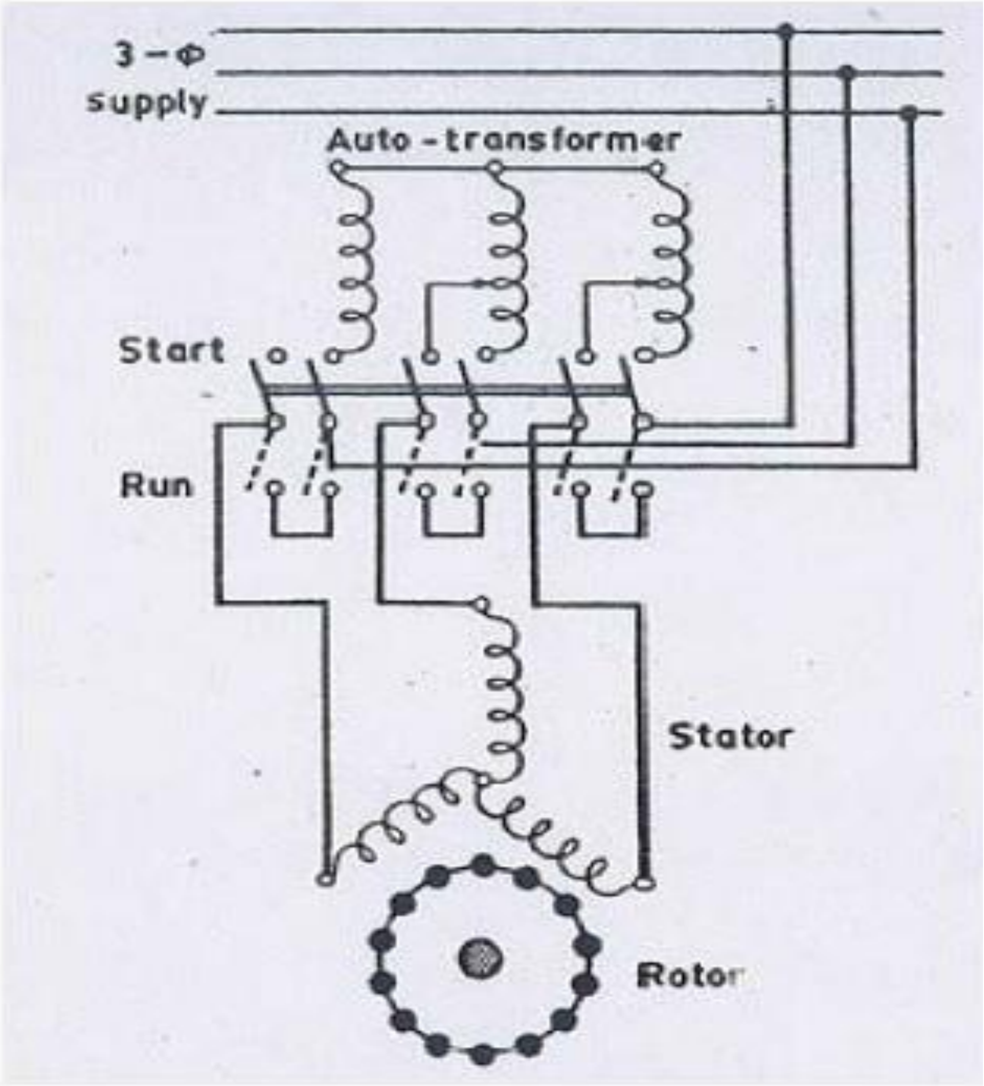



# STAR-DELTA STARTER

- At starting, the stator winding is connected in star, therefore the applied voltage to each phase of winding is $1/\sqrt{3}$ of the rated voltage of the motor.
- When the motor has picked-up the speed(say 70 to 80% of its normal speed ) the phases of the stator winding are connected in delta so that full supply voltage is applied across the stator windings.
- This is very commonly used starter, compared to the other types of the starters.

# AUTOTRANSFORMER STARTER

- An auto-transformer starter makes it possible to start squirrel cage induction motors with reduced starting current, as the voltage across the motor is reduced during starting.
- On starting, the motor is connected to the tapping of the auto-transformer.
- The method is suitable for long starting periods.

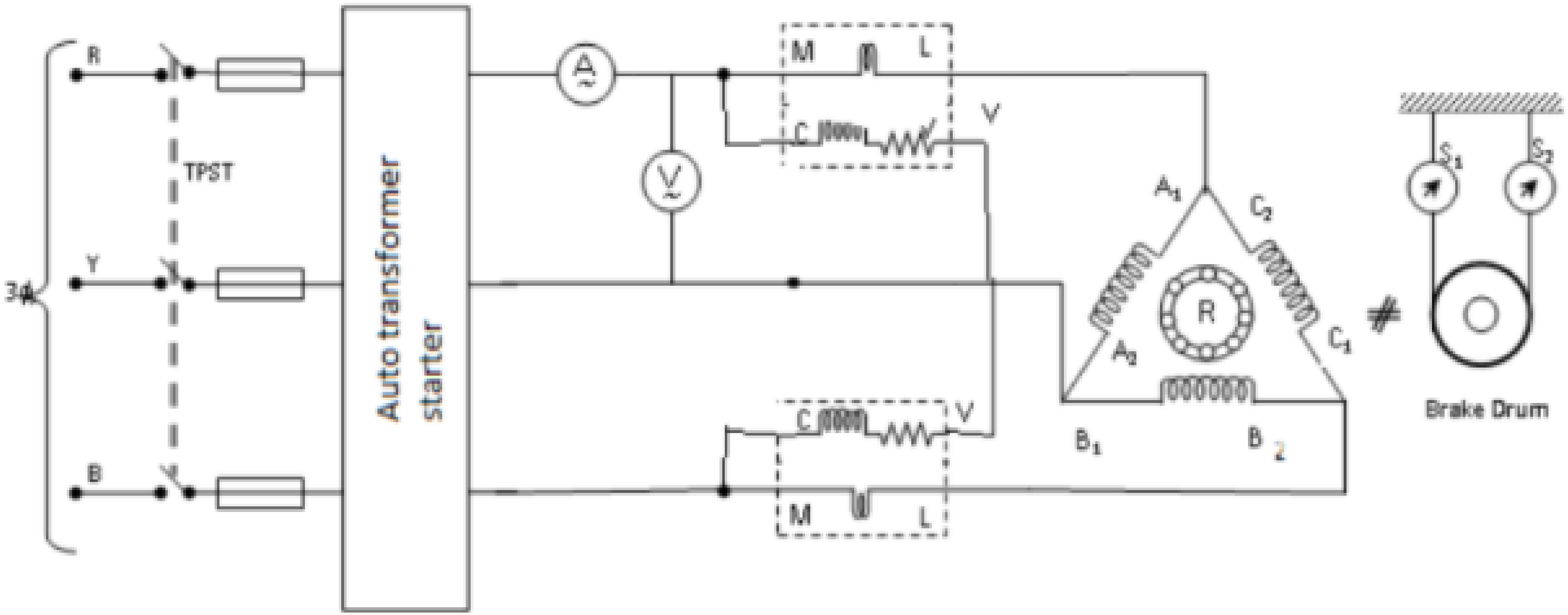



Starting Motor With
Auto-transformer

# BRAKE TEST ON THREE PHASE INDUCTION MOTOR:

To determine the performance characteristics of 3-phase squirrel cage induction motor by direct loading.

## CIRCUIT DIAGRAM:



The load test on 3-phase induction motor is performed to obtain its various characteristics including efficiency. A belt and brake drum arrangement as shown in the circuit diagram can load the motor.

If $S_1$ and $S_2$ are the tensions provided at the two sides of the belt, then the load torque is given by:

$T = (S_1 \sim S_2) * 9.81 * R$ N-m.

Where R is the radius of the brake drum in meter.

The mechanical output of the motor is given by:

$P_m = 2 * \pi * N * T / 60$ Watts

Where N is the speed of the motor in, RPM.

The power input to the motor is given by:

$P_i = V_L I_L$ watt

The efficiency of the motor is given by:

$Efficiency = P_m / P_i$

# PROCEDURE:

1 The connections are made as per the circuit diagram.

2 Power supply is obtained from the control panel.

3 The TPST switch is closed.

4 Rated voltage of 3-phase induction motor, is applied by adjusting autotransformer

5 The initial readings of ammeter, voltmeter and wattmeter are noted.

6 By increasing the load step by step, the reading of ammeter, voltmeter and wattmeter are noted.

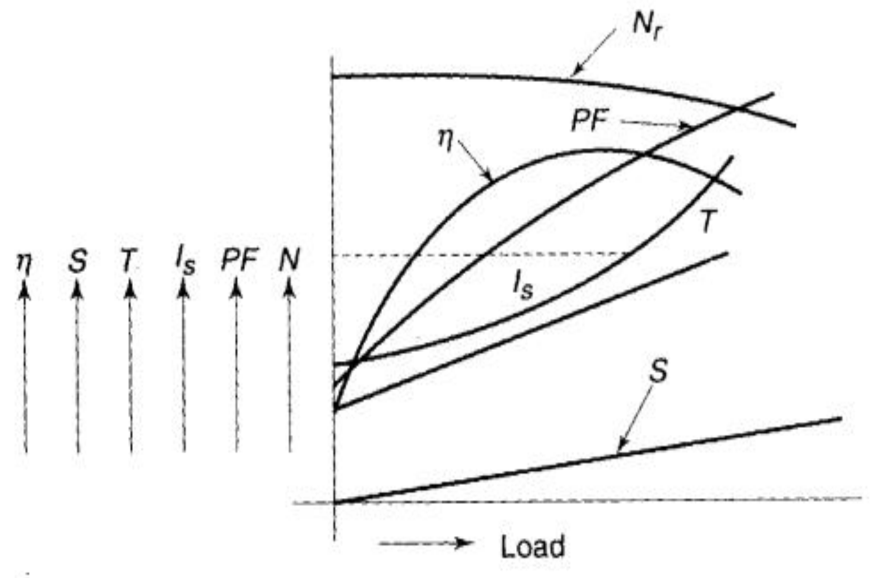
7 Step 6 is repeated till the ammeter shows the rated current of 3-phase induction motor.

8 Decrease the load, bring auto-transformer to its minimum voltage position.

9 Switch off the supply.

# MODELGRAPH:

The graph drawn for
Output Power vs Speed
Output Power vs Line current
Output Power vs Torque
Output Power vs Power factor
Output Power vs Efficiency
Output Power vs %Slip.




*Graphical representation of the effect of load on rotor speed, efficiency power factor, output torque, stator current and slip of an induction motor.*

# FORMULAE USED:

1 Torque = $(S_1 \sim S_2) * R * 9.81$ N-m
$S_1$, $S_2$ – spring balance readings in Kg.
R – Radius of the brake drum in meter

2 Output power = $2\pi NT/60$ Watts
N – Rotor speed in rpm.
T – Torque in N-m.

3 Input power = $(W_1+W_2)$ Watts
$W_1$, $W_2$ – Wattmeter readings in watts.

4 Percentage efficiency =
(Output power/Input power) x 100%

5 Percentage Slip = $(N_s – N_r)/N_s \times 100\%$
$N_s$ – Synchronous speed in rpm.
$N_r$ – Speed of the motor in rpm.

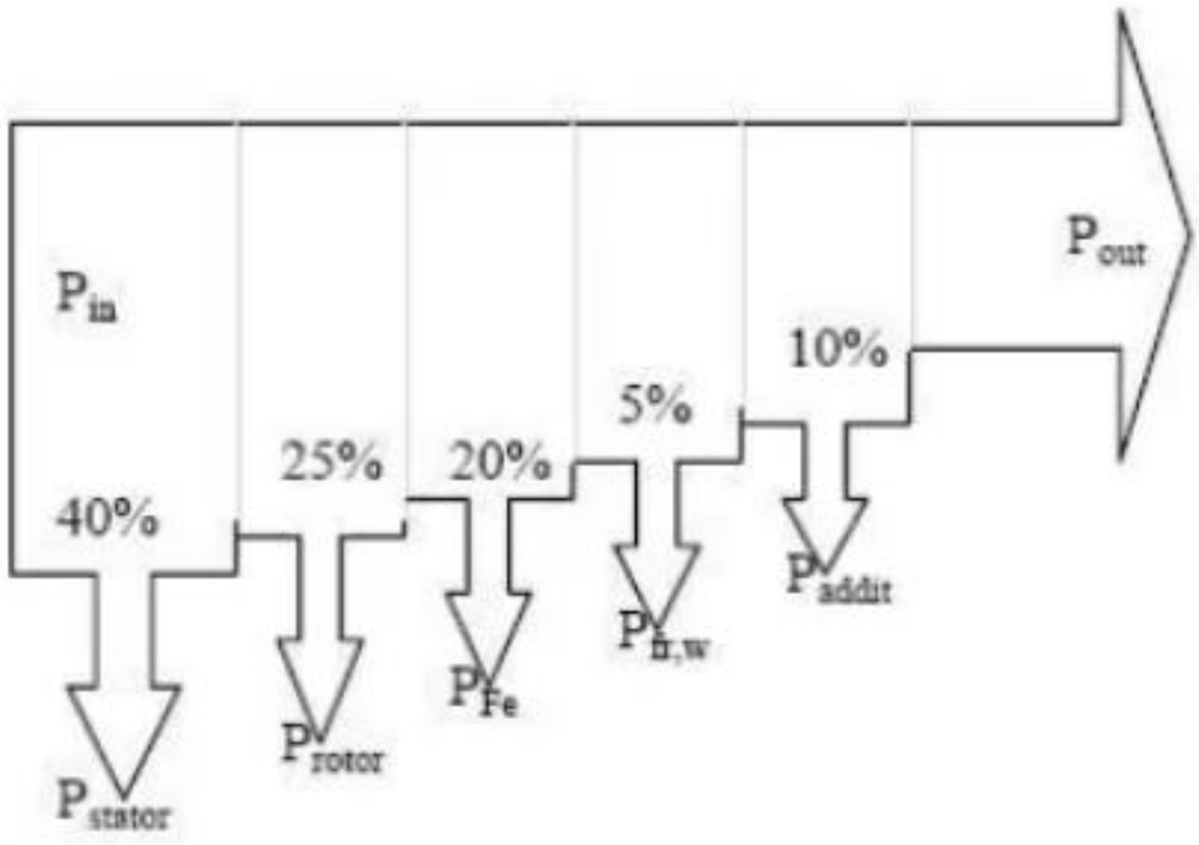
6 Power factor $(\cos \phi) = (W_1+W_2)/\sqrt{3} V_L*I_L$

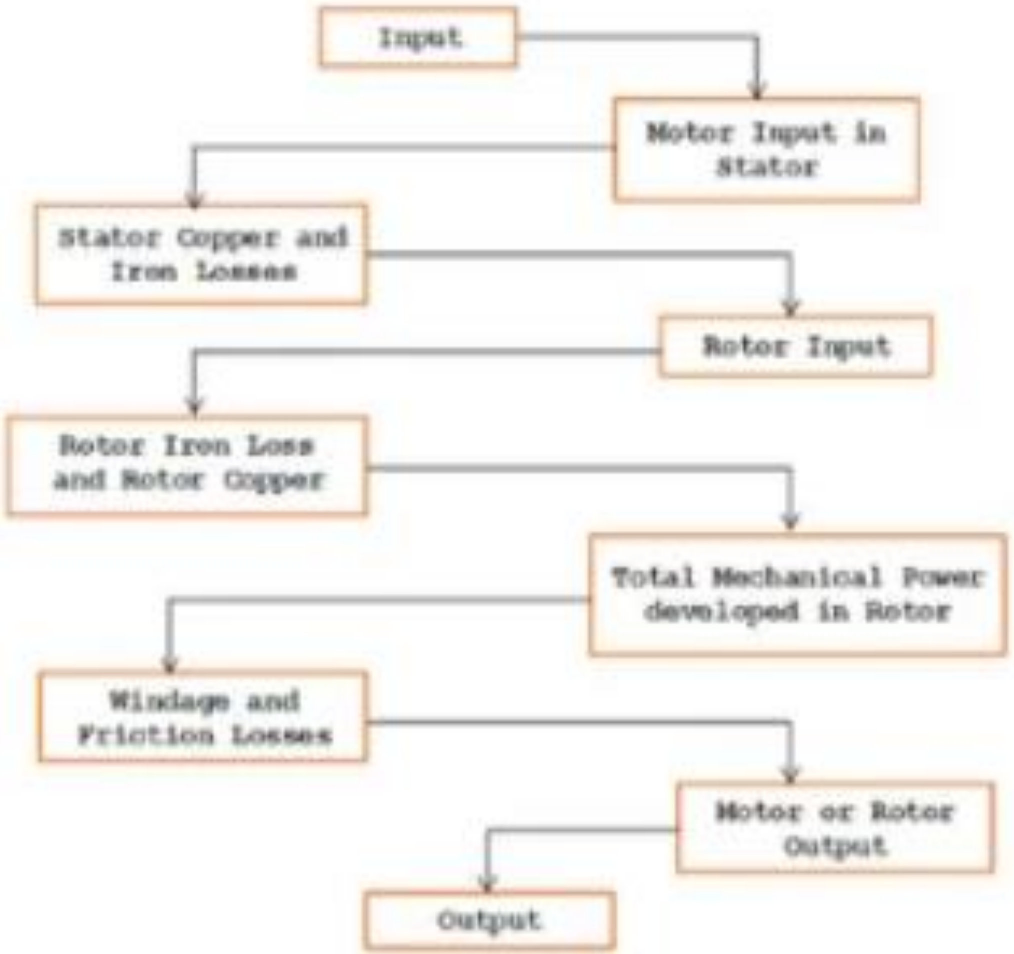
# PRECAUTIONS:

While loading the induction motor by brakes, check whether cooling water is circulated in the drum.

Before starting the motor, loosen the strap and then tighten it gradually when the motor has picked up speed.

# Efficiency & Losses in three phase induction motor:



There are two types of losses occur in three phase induction motor. These losses are,
Constant or fixed losses,
Variable losses.

**Constant or Fixed Losses:**

Constant losses are those losses which are considered to remain constant over normal working range of induction motor. The fixed losses can be easily obtained by performing no-load test on the three phase induction motor.

These losses are further classified as:

Iron or core losses,
Mechanical losses,
Brush friction losses.

**Iron or Core Losses:**

Iron or core losses are further divided into hysteresis and eddy current losses. Eddy current losses are minimized by using lamination on core. Since by laminating the core, area decreases and hence resistance increases, which results in decrease in eddy currents. Hysteresis losses are minimized by using high grade silicon steel.

The core losses depend upon frequency of the supply voltage. The frequency of stator is always supply frequency, f and the frequency of rotor is slip times the supply frequency, (sf) which is always less than the stator frequency. For stator frequency of 50 Hz, rotor frequency is about 1.5 Hz because under normal running condition slip is of the order of 3 %. Hence the rotor core loss is very small as compared to stator core loss and is usually neglected in running conditions.

## Mechanical and Brush Friction Losses:

Mechanical losses occur at the bearing and brush friction loss occurs in wound rotor induction motor. These losses are zero at start and with increase in speed these losses increase. In three phase induction motor the speed usually remains constant. Hence these losses almost remains constant.

## Variable Losses:

These losses are also called copper losses. These losses occur due to current flowing in stator and rotor windings. As the load changes, the current flowing in rotor and stator winding also changes and hence these losses also changes. Therefore these losses are called variable losses.

The copper losses are obtained by performing blocked rotor test on three phase induction motor. The main function of induction motor is to convert an electrical power into mechanical power. During this conversion of electrical energy into mechanical energy the power flows through different stages.

This power flowing through different stages is shown by power flow diagram. As we all know that the input to the three phase induction motor is three phase supply.

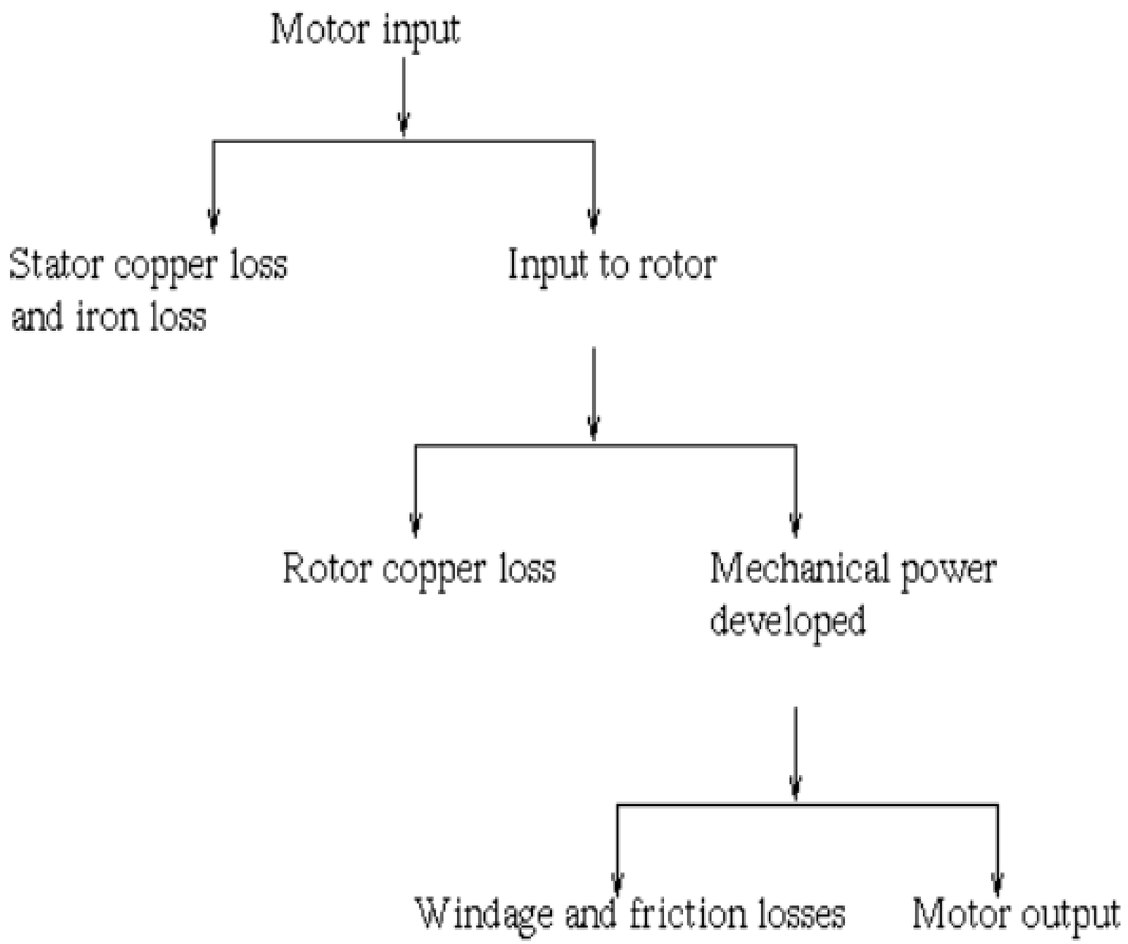
So, the three phase supply is given to the stator of three phase induction motor.

Let, $P_{in}$ = electrical power supplied to the stator of three phase induction motor,

$V_L$ = line voltage supplied to the stator of three phase induction motor,

$I_L$ = line current,

$\cos\phi$ = power factor of the three phase induction motor.



Electrical power input to the stator, $P_{in} = \sqrt{3}V_L I_L \cos\phi$

A part of this power input is used to supply stator losses which are stator iron loss and stator copper loss. The remaining power i.e., (input electrical power – stator losses) are supplied to rotor as rotor input.

So, rotor input $P_2 = P_{in}$ – stator losses (stator copper loss and stator iron loss).

Now, the rotor has to convert this rotor input into mechanical energy but this complete input cannot be converted into mechanical output as it has to supply rotor losses.

As explained earlier the rotor losses are of two types rotor iron loss and rotor copper loss. Since the iron loss depends upon the rotor frequency, which is very small when the rotor rotates, so it is usually neglected. So, the rotor has only rotor copper loss. Therefore the rotor input has to supply these rotor copper losses.

After supplying the rotor copper losses, the remaining part of Rotor input, $P_2$ is converted into mechanical power, $P_m$.

Let $P_c$ be the rotor copper loss,
$I_2$ be the rotor current under running condition,
$R_2$ is the rotor resistance,
$P_m$ is the gross mechanical power developed.

$P_c = 3I_2^2R_2$

$P_m = P_2 - P_c$

Now this mechanical power developed is given to the load by the shaft but there occurs some mechanical losses like friction and windage losses. So, the gross mechanical power developed has to be supplied to these losses also. Therefore, the net output power developed at the shaft, which is finally given to the load is $P_{out}$.

$P_{out} = P_m$ – Mechanical losses (friction and windage losses).

$P_{out}$ is called the shaft power or useful power.

## Efficiency of Three Phase Induction Motor:

Efficiency is defined as the ratio of the output to that of input,

$$Efficiency,\ \eta = \frac{output}{input}$$

Efficiency is defined as the ratio of the output to that of input,

$$Efficiency,\ \eta = \frac{output}{input}$$

Rotor efficiency of the three phase induction motor ,

$$= \frac{rotor\ output}{rotor\ input}$$

= Gross mechanical power developed / rotor input

$$= \frac{P_m}{P_2}$$

Three phase induction motor efficiency,

$$= \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$$

Three phase induction motor efficiency

$$\eta = \frac{P_{out}}{P_{in}}$$

# BASIC ELECTRICAL ENGINEERING

by

**S Reddy Ramesh**
**Assistant Professor**
Dept of Electrical & Electronics Engineering
Aditya College of Engineering & Technology
Surampalem.

# Unit-V SPECIAL MACHINES

- Principle of operation and construction of
- Single Phase Induction Motor
- Shaded Pole Motor
- Capacitor Motors and
- AC Servo Motor

# 1-ϕ Induction Motor

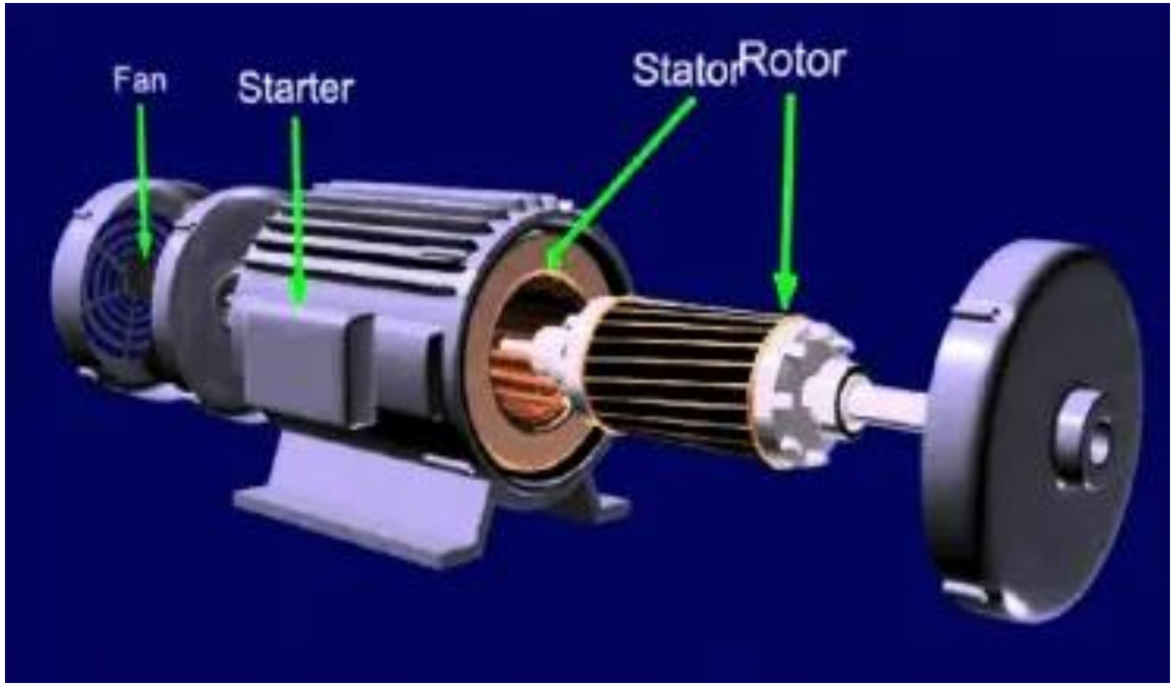
- This is an induction motor which works on 1 phase supply.
- When fed from a single-phase supply, its stator winding produces a flux (or field) which is only alternating i.e. one which alternates along one space axis only.
- Now, an alternating or pulsating flux acting on a stationary squirrel-cage rotor cannot produce rotation (only a revolving flux can). That is why a single-phase motor is not self starting.

## Construction:

- The construction of single phase induction motor is almost similar to the squirrel cage three-phase induction motor. But in case of a single phase induction motor, the stator has two windings instead of one three-phase winding in three phase induction motor.

# Working Principle:

# Double field revolving theory:



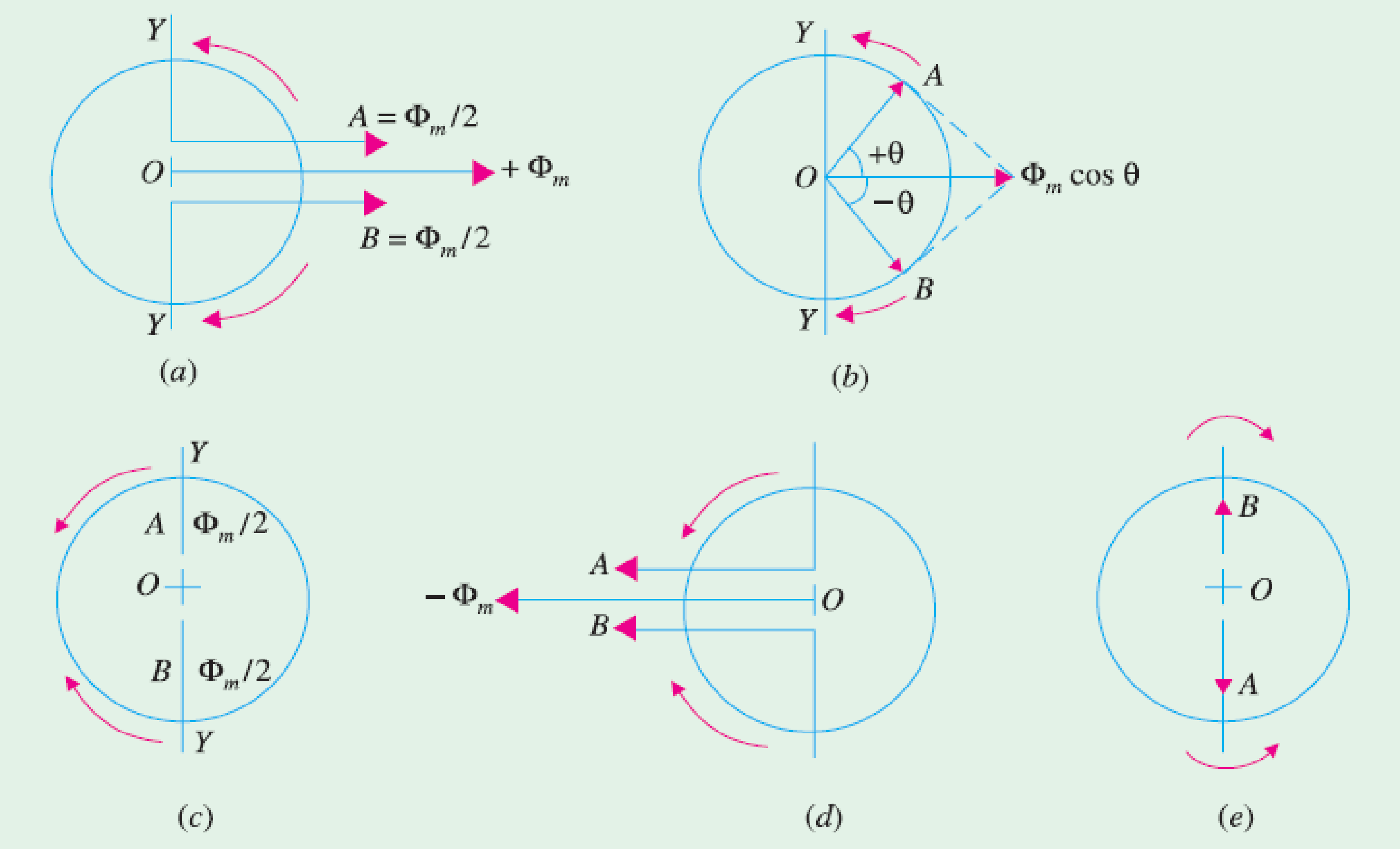

Accordingly, an alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously ($N_s$ = 120f/P) in opposite direction.

When we apply a single phase AC supply to the stator winding of single phase induction motor, it produces its flux of magnitude, $\phi_m$.

According to the double field revolving theory, this alternating flux, $\phi_m$ is divided into two components of magnitude $\phi_m/2$. Each of these components will rotate in the opposite direction, with the synchronous speed, $N_s$.

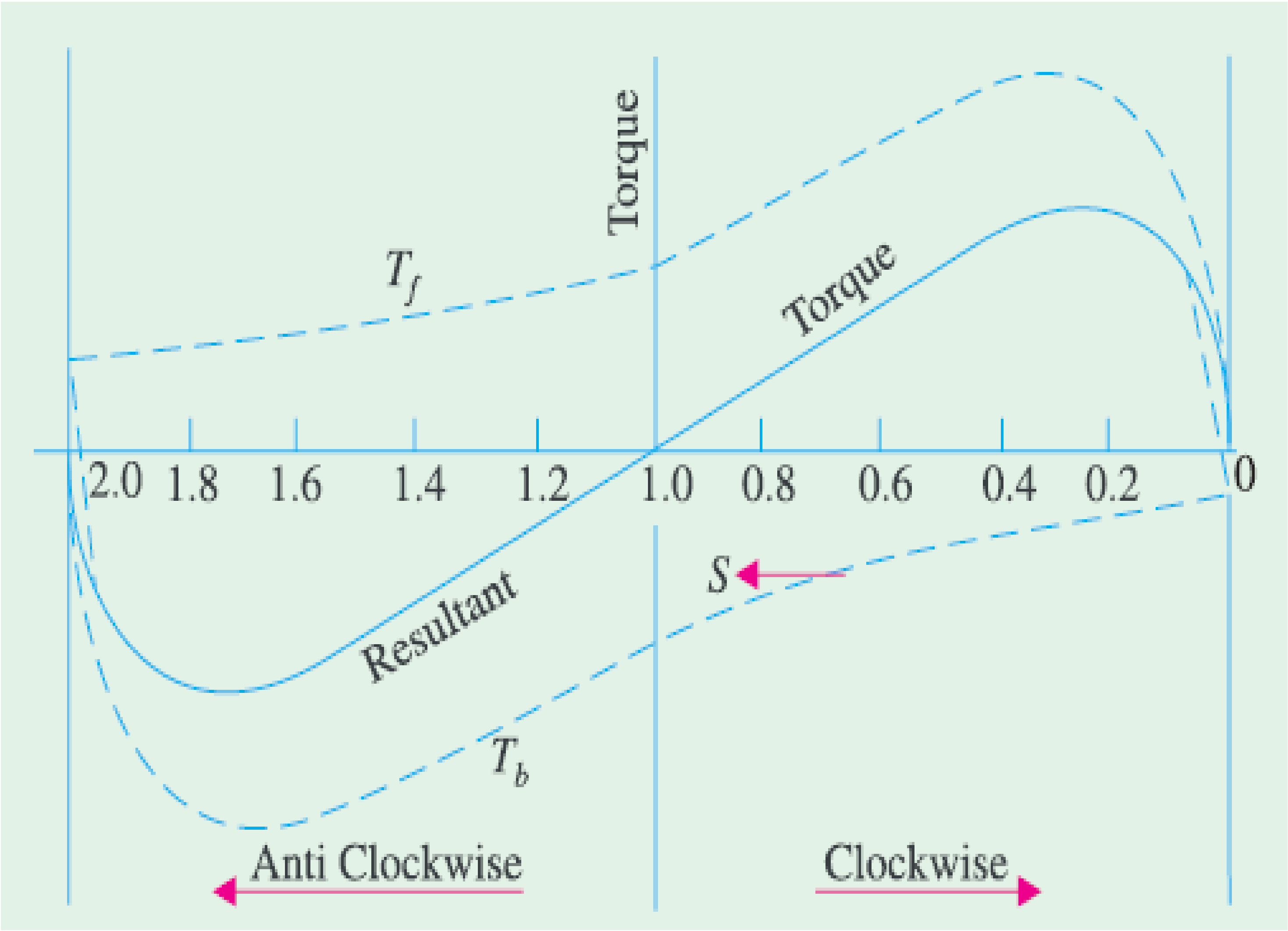
Let us call these two components of flux as forwarding component of flux, $\phi_f$ and the backward component of flux, $\phi_b$.

The resultant of these two components of flux at any instant of time gives the value of instantaneous stator flux at that particular instant.


Y
$A = \Phi_m/2$
O
$+\Phi_m$
$B = \Phi_m/2$
Y
(a)
Y
A
O
$+\theta$
$-\theta$
$\Phi_m \cos\theta$
B
Y
(b)
Y
A
$\Phi_m/2$
O
B
$\Phi_m/2$
Y
(c)
A
$-\Phi_m$
O
B
(d)
B
O
A
(e)

Now at starting condition, both the forward and backward components of flux are exactly opposite to each other. Also, both of these components of flux are equal in magnitude.

So, they cancel each other and hence the net torque experienced by the rotor at the starting condition is zero. So, the single phase induction motors are not self-starting motors.



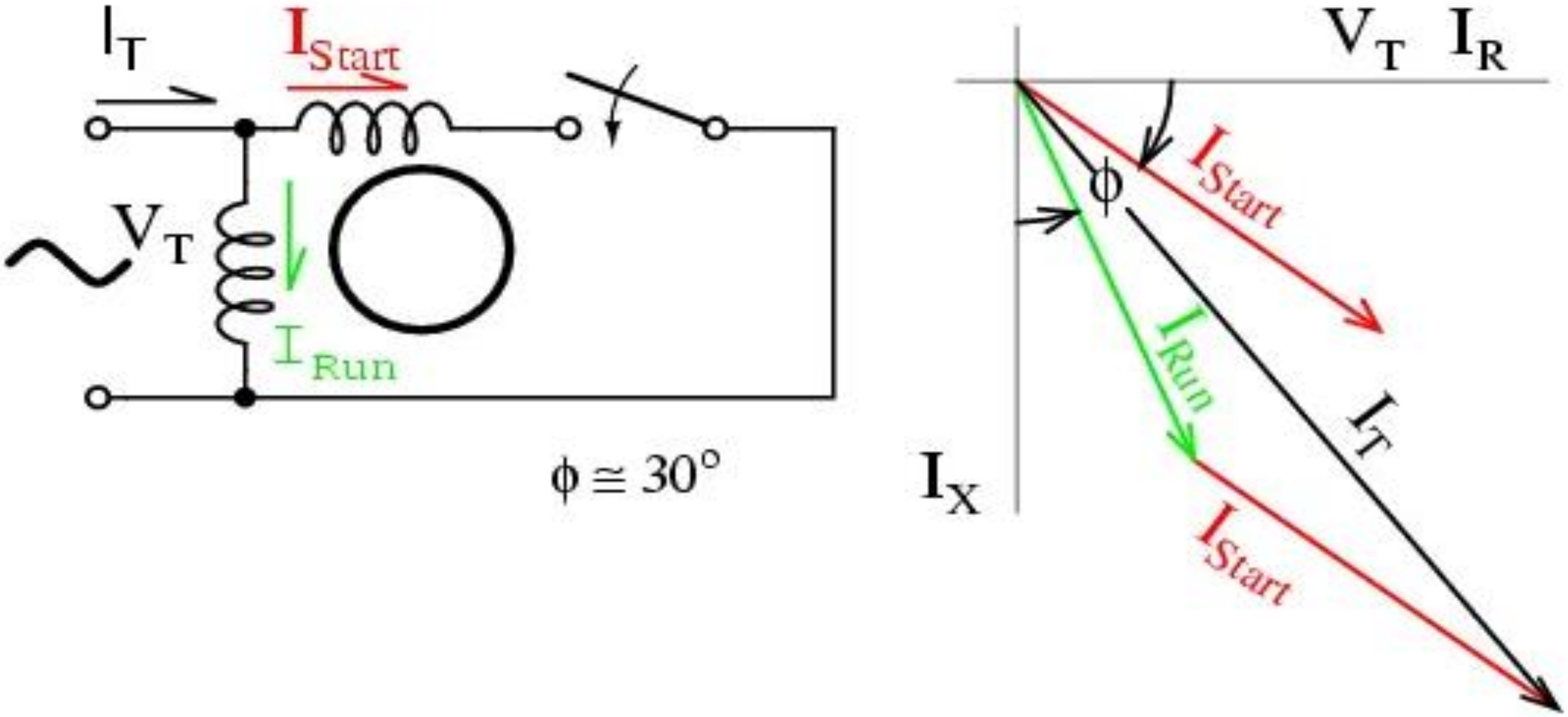
# Self starting:

- If we make the stator flux rotating type, rather than alternating type, which rotates in one particular direction only, then the induction motor will become self-starting.
- Now for producing this rotating magnetic field, we require two alternating flux, having some phase angle difference between them. When these two fluxes interact with each other, they will produce a resultant flux. This resultant flux is rotating in nature and rotates in space in one particular direction only.
- Once the motor starts running, we can remove the additional flux. The motor will continue to run under the influence of the main flux only.
- Depending upon the methods for making asynchronous motor as Self Starting Motor, there are mainly four types of single phase induction motor namely:

1. Split phase induction motor,
2. Capacitor start inductor motor,
3. Capacitor start capacitor run induction motor,
4. Shaded pole induction motor.

# Split Phase Induction Motor:

- In addition to the main winding or running winding, a single-phase induction motor’s stator carries another winding called auxiliary winding or starting winding.
- A centrifugal switch is connected in series with auxiliary winding. This switch aims to disconnect the auxiliary winding from the main circuit when the motor attains a speed up to 75 to 80% of the synchronous speed.
- The starting winding is highly resistive so, the current flowing in the starting winding lags behind the applied voltage by a very small angle and the running winding is highly inductive in nature so, the current flowing in running winding lags behind applied voltage by a large angle.

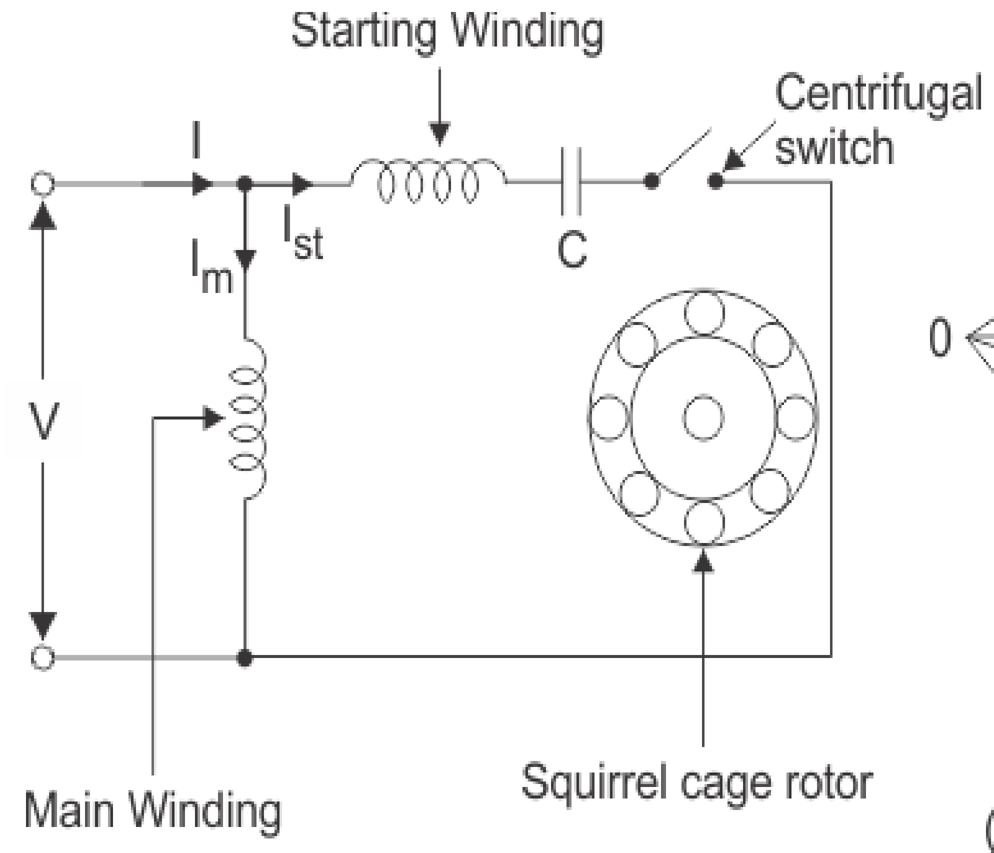



## Applications:

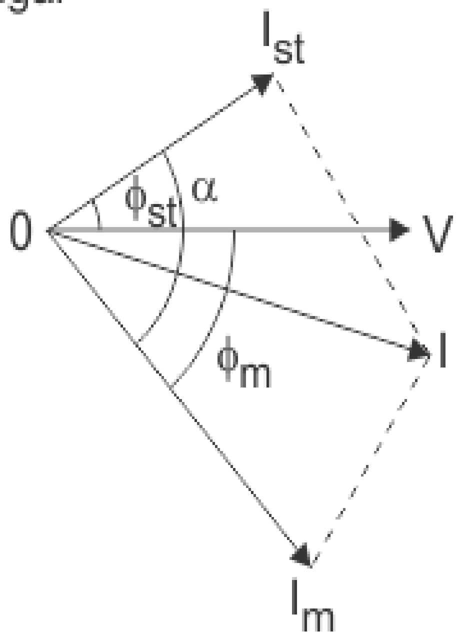
- Split phase induction motors have low starting current and moderate starting torque.
- These motors are used in fans, blowers, centrifugal pumps, washing machines, grinders, lathes, air conditioning fans, etc.

# Capacitor Start & Capacitor Start-Capacitor Run Induction Motor

- The working principle of capacitor-start inductor motors is almost the same as capacitor-start capacitor-run induction motors.
- In the case of a split-phase induction motor, we use resistance for creating phase difference, but here we use a capacitor for this purpose. We are familiar with the fact that the current flowing through the capacitor leads to the voltage.
- So, in capacitor start inductor motor and capacitor start capacitor run induction motor, we are using two winding, the main winding, and the starting winding. With starting winding, we connect a capacitor, so the current flowing in the capacitor, i.e., $I_{st}$ leads the applied voltage by some angle.
- Now there occur large phase angle differences between these two currents, which produce a resultant current. This will produce a rotating magnetic field since the torque produced by these motors depends upon the phase angle difference, which is almost $90^o$.




(a) Schematic representaion




(b) Phasor diagram

So, these motors produce very high starting torque. In the case of capacitor start induction motor, the centrifugal switch is provided to disconnect the starting winding when the motor attains a speed up to 75 to 80% of the synchronous speed.

But in the case of capacitor start capacitors run induction motor. There is no centrifugal switch so, the capacitor remains in the circuit and improves the power factor and the running conditions of the single-phase induction motor.

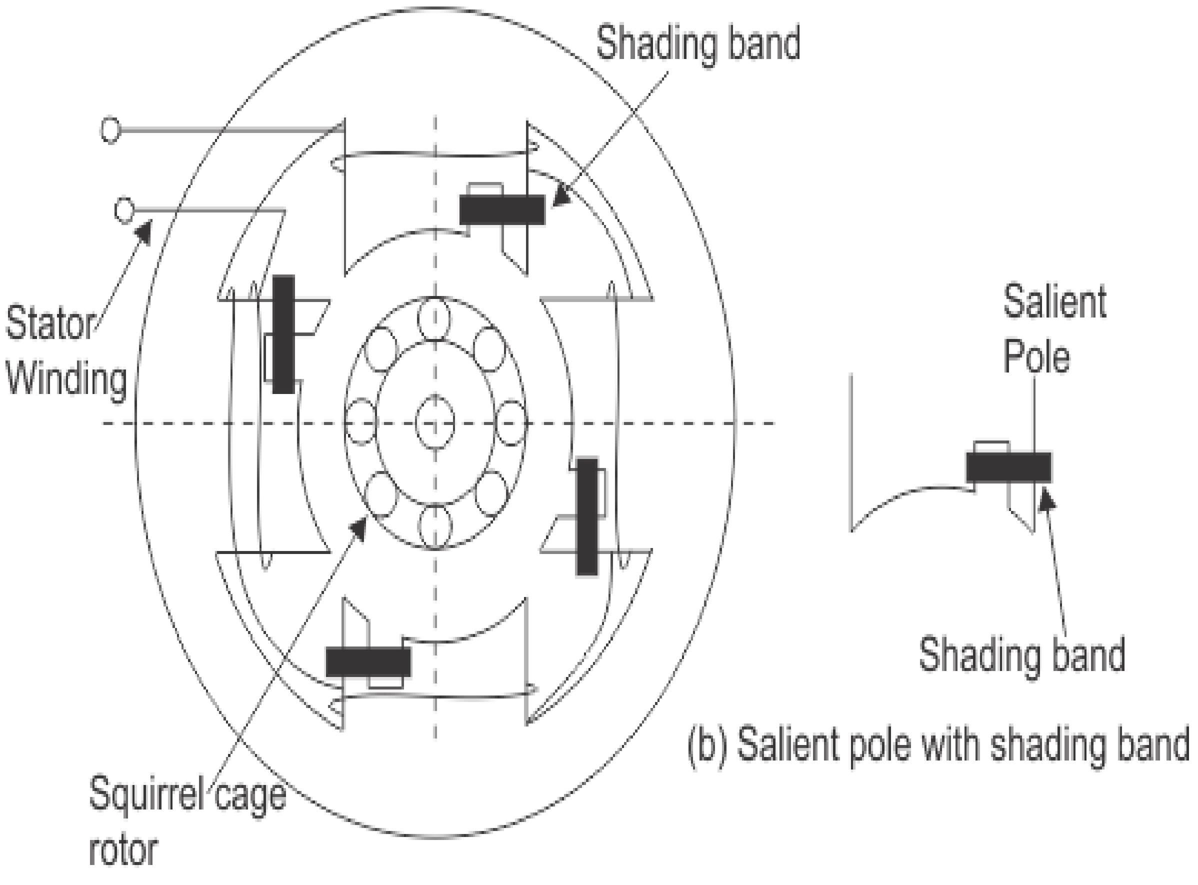
## Applications:

These motors have high starting torque; hence they are used in conveyors, grinders, air conditioners, compressors, etc.

# Shaded Pole Induction Motor

In such motors, the necessary **phase splitting** is produced by **induction.** These motors have salient poles on the stator and a squirrel cage type rotor shown in beside figure.

One pole of such a motor is shown separately in next figure. The laminated pole has a slot cut across the laminations approximately one-third distance from one edge. Around the small part of the pole is placed a short circuited copper coil known as **shading coil.** This part of the pole is known as shaded part and the other as unshaded part.



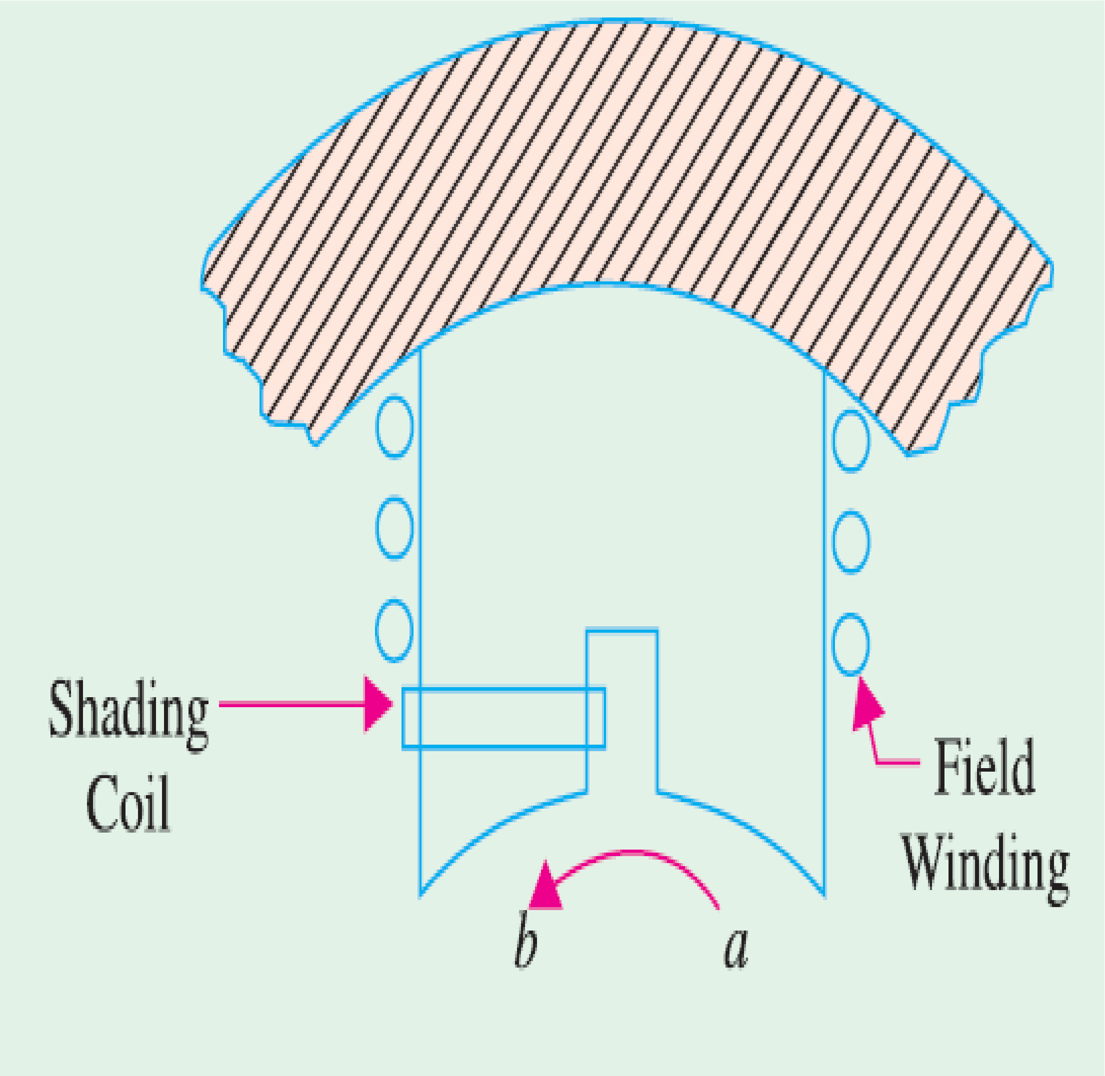
(b) Salient pole with shading band

(a) 4-pole shaded pole construction

When an alternating current is passed through the exciting or field winding surrounding the whole pole, the axis of the **pole shifts from the unshaded part a to the shaded part b.** This shifting of the magnetic axis is, in effect, equivalent to the actual physical movement of the pole. Hence the rotor starts rotating in the direction of this shift.

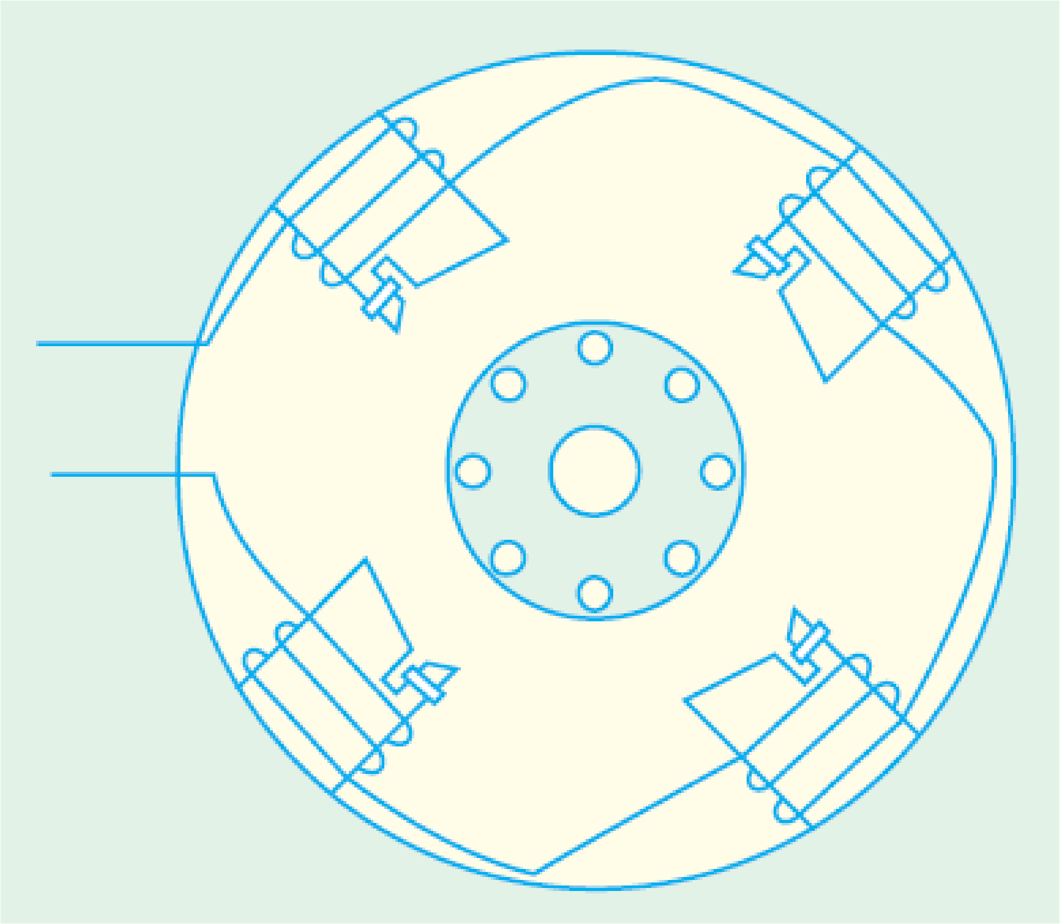
# Construction:

- Stator – The stator of the shaded pole motor has a salient pole.
- Each pole of the motor is excited by its exciting coil.
- The slot is constructed at some distance apart from the edge of the poles. The short-circuited copper coil is placed in this slot.
- The part which is covered with the copper ring is called the shaded part and which are not covered by the rings are called unshaded part.

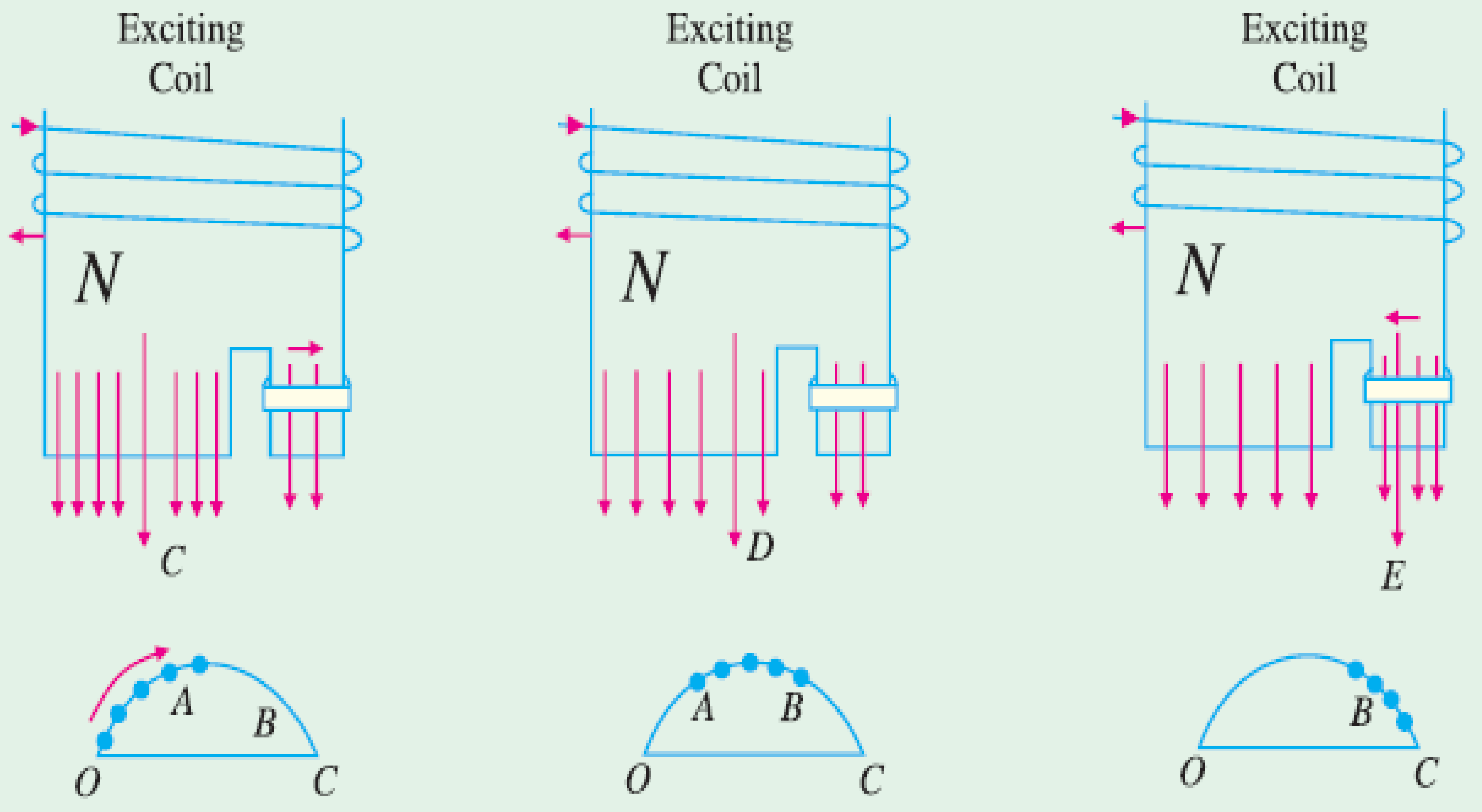


# Working:

- When the supply is connected to the windings of the stator, the alternating flux induces in the core of the rotor.
- The variation in the flux induces the voltage inside the ring because of which the circulating current induces in it.
- The circulating current develops the flux in the ring which opposes the main flux of the motor.
- The flux induces in the shaded portion of the motor, and the unshaded portion of the motor have a phase difference.
- Due to this a rotating magnetic field is created which runs the motor.



Rotor – The shaded pole motor uses the squirrel cage rotor.


Exciting
Coil
N
C
A
B
O
C
Exciting
Coil
N
D
A
B
O
C
Exciting
Coil
N
E
B
O
C

(a) (b) (c)

# Applications:

The various applications of the Shaded Poles Motor are as follows:-

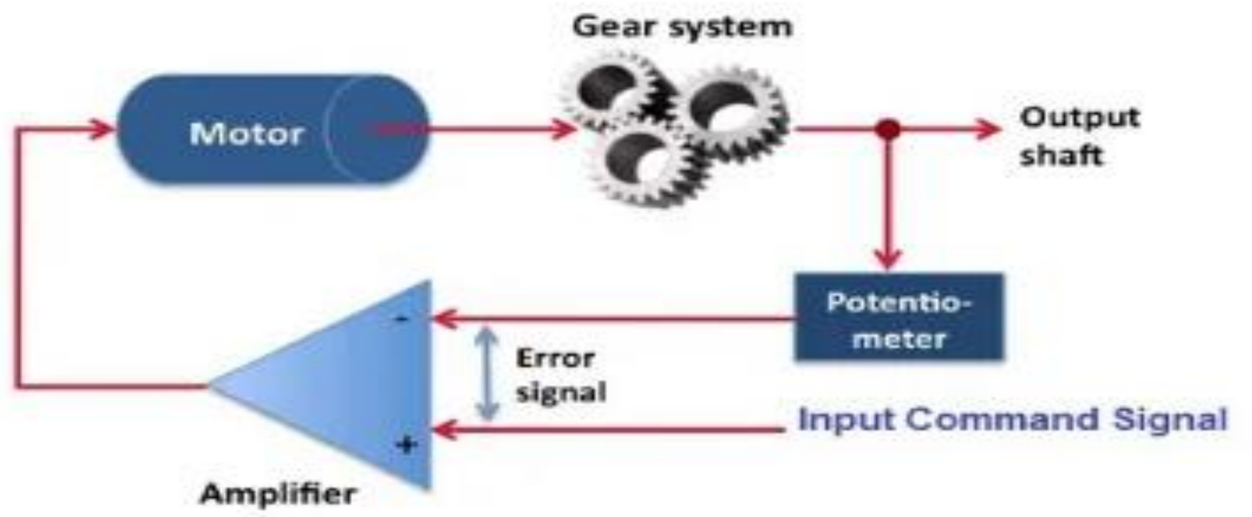
- They are suitable for small devices like relays and fans because of its low cost and easy starting.
- Used in exhaust fans, hair dryers and also in table fans.
- Used in air conditioning and refrigeration equipment and cooling fans.
- Record players, tape recorders, projectors, photocopying machines.
- Used for starting electronic clocks and single-phase synchronous timing motors.

# Servomotors:

A servomotor (or servo motor) is a simple electric motor, controlled with the help of servomechanism.

If the motor as a controlled device, associated with servomechanism is DC motor, then it is commonly known as a DC Servo Motor.

If AC operates the controlled motor, it is known as a AC Servo Motor.




A servo system primarily consists of three basic components – a controlled device, a output sensor, a feedback system.

This is an automatic closed loop control system. Here instead of controlling a device by applying the variable input signal, the device is controlled by a feedback signal generated by comparing output signal and reference input signal.

When reference input signal or command signal is applied to the system, it is compared with output reference signal of the system produced by output sensor, and a third signal produced by a feedback system.

This third signal acts as an input signal of controlled device.

This input signal to the device presents as long as there is a logical difference between reference input signal and the output signal of the system.

After the device achieves its desired output, there will be no longer the logical difference between reference input signal and reference output signal of the system.

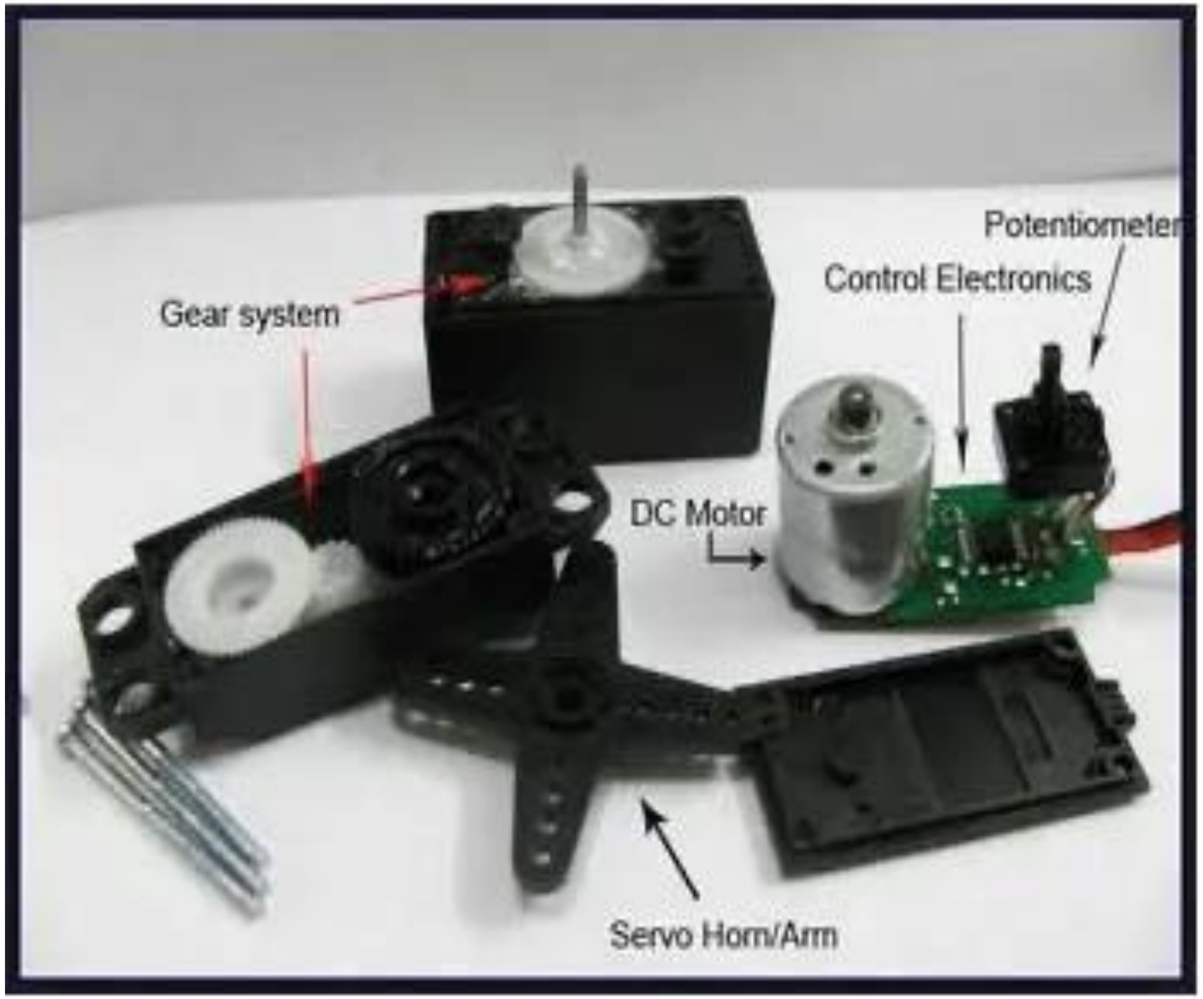
Then, the third signal produced by comparing theses above said signals will not remain enough to operate the device further and to produce a further output of the system until the next reference input signal or command signal is applied to the system.

Hence, the primary task of a servomechanism is to maintain the output of a system at the desired value in the presence of disturbances.

# Working:

In a servo unit, you will find a small DC motor, a potentiometer, gear arrangement and an intelligent circuitry. The intelligent circuitry along with the potentiometer makes the servo to rotate according to our wishes.

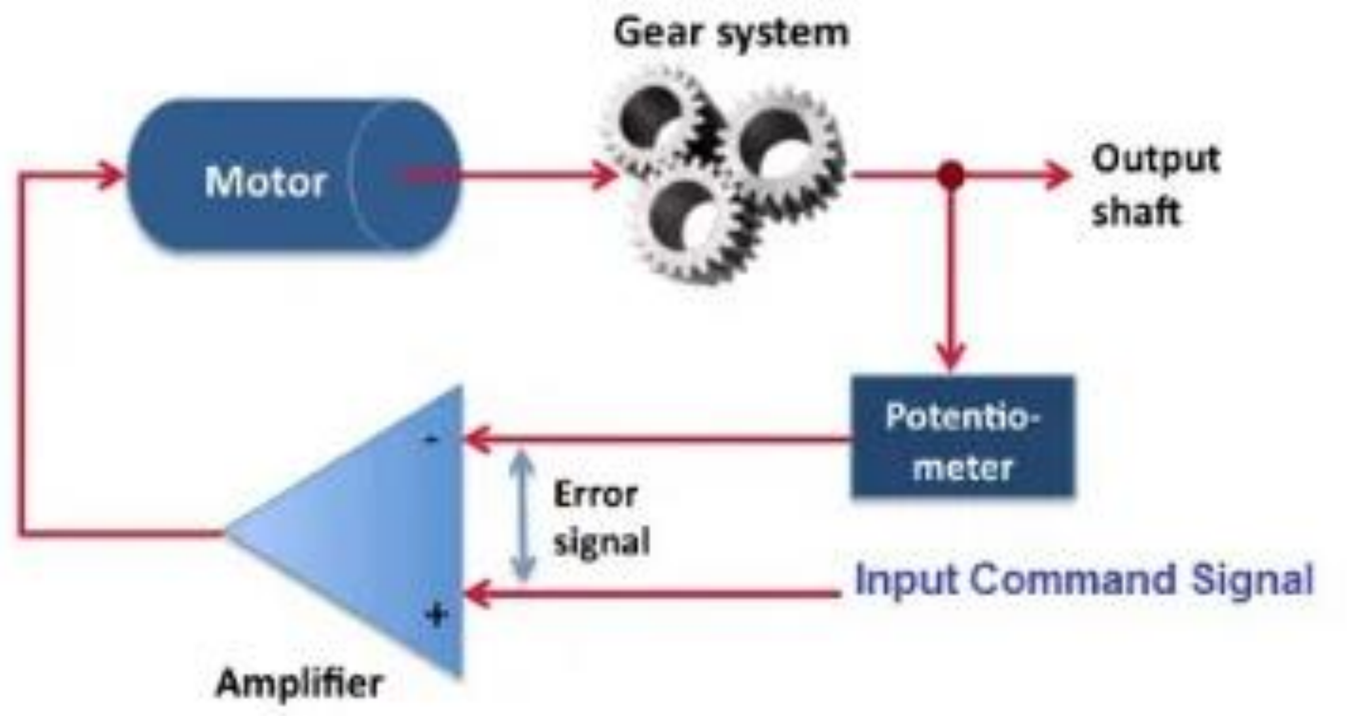
As we know, a small DC motor will rotate with high speed but the torque generated by its rotation will not be enough to move even a light load.



This is where the gear system inside a servomechanism comes into the picture. The gear mechanism will take high input speed of the motor (fast) and at the output, we will get an output speed which is slower than original input speed but more practical and widely applicable.

Say at the initial position of servo motor shaft, the position of the potentiometer knob is such that there is no electrical signal generated at the output port of the potentiometer. This output port of the potentiometer is connected with one of the input terminals of the error detector amplifier. Now an electrical signal is given to another input terminal of the error detector amplifier. Now difference between these two signals, one comes from potentiometer and another comes from external source, will be amplified in the error detector amplifier and feeds the DC motor.

This amplified error signal acts as the input power of the DC motor and the motor starts rotating in desired direction. As the motor shaft progresses the potentiometer knob also rotates as it is coupled with motor shaft with help of gear arrangement.




As the position of the potentiometer knob changes there will be an electrical signal produced at the potentiometer port. As the angular position of the potentiometer knob progresses the output or feedback signal increases. After desired angular position of motor shaft the potentiometer knob is reaches at such position the electrical signal generated in the potentiometer becomes same as of external electrical signal given to amplifier.

At this condition, there will be no output signal from the amplifier to the motor input as there is no difference between external applied signal and the signal generated at potentiometer. As the input signal to the motor is nil at that position, the motor stops rotating. This is how a simple conceptual servo motor works.

## Applications:

Servo motors are used in
Robotics
Conveyors
Vehicles
Solar Tracking Systems