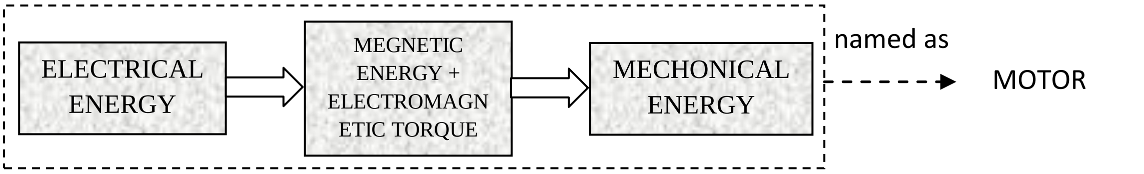
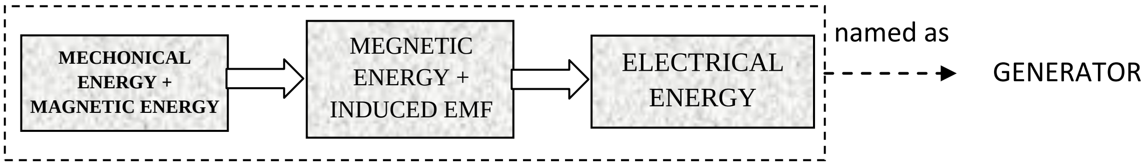
UNIT III ELECTRICAL MACHINES

Principles of operation and characteristics of; DC machines, Transformers (single and three phase), Synchronous machines, three phase and single phase induction motors.

Introduction

D.C. machines are the electro mechanical energy converters which work from a D.C. source and generate mechanical power or convert mechanical power into a D.C. power.





Types of DC machines

1. DC generators
2. DC motors

1. Types of DC generators.

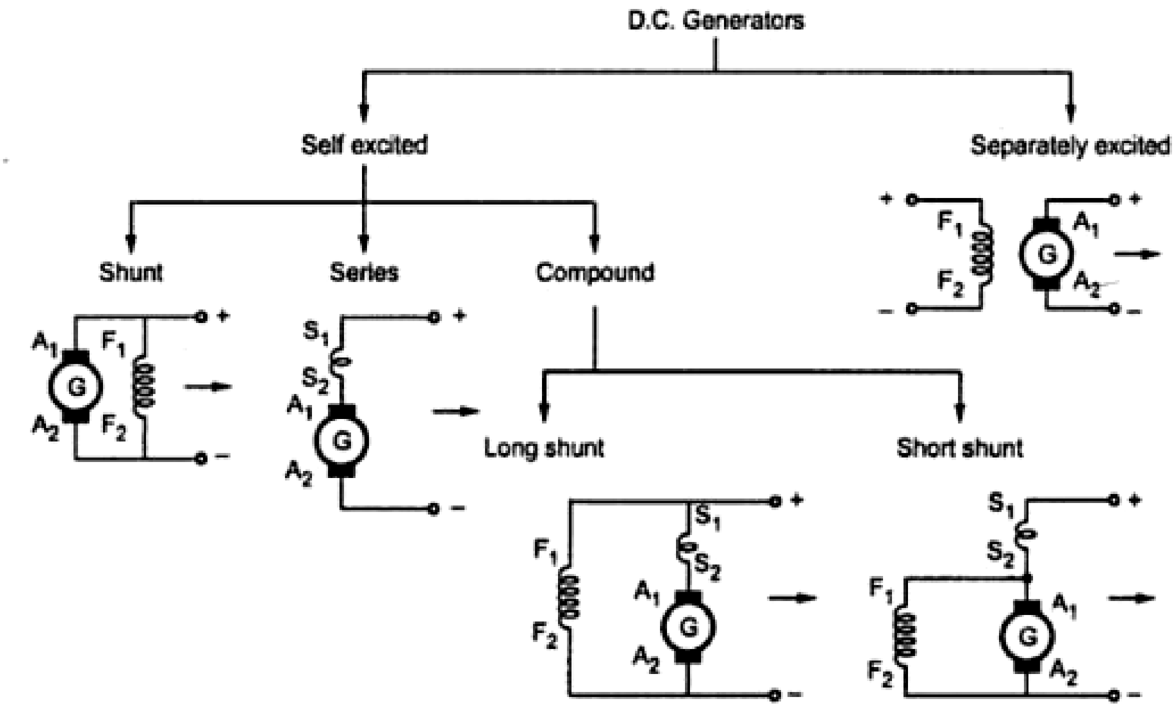


Figure: 1 - Types of DC generators

2. *Types of DC motors.*

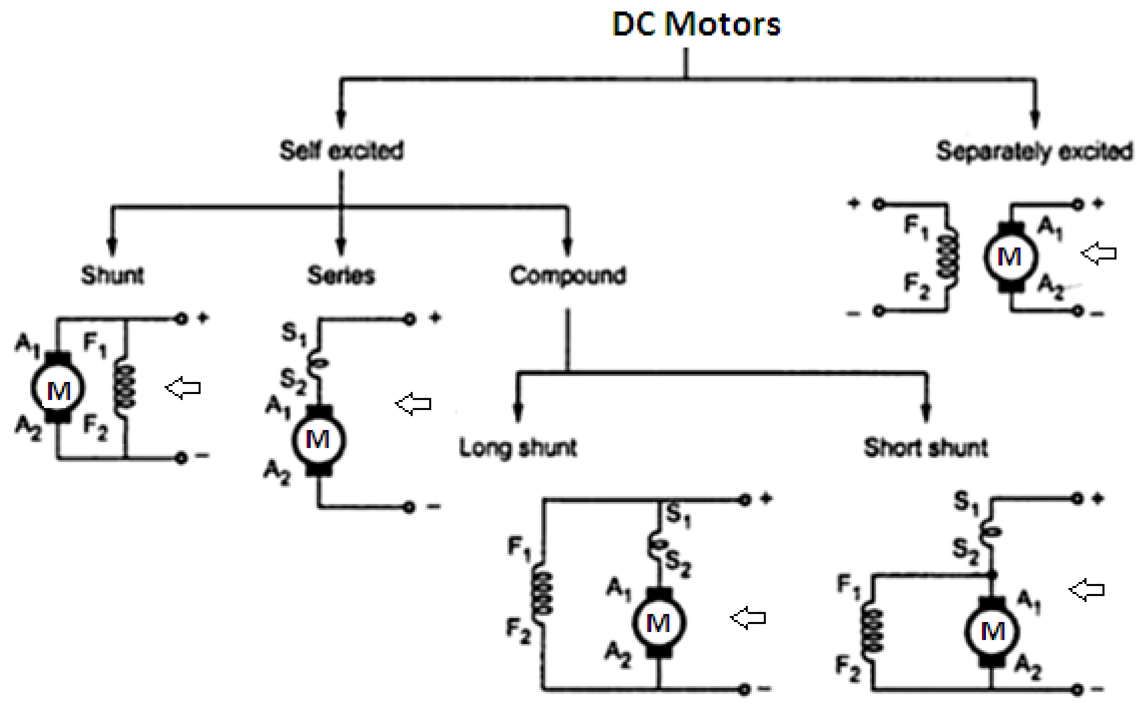


Figure: 2 - Types of DC motors

Construction details of DC Machine

A D.C. machine consists mainly of two part the stationary part called stator and the rotating part called armature (or) rotor.

The major parts are,

1. Yoke
2. Stator core and windings
3. Armature
4. Commutator and brush arrangement
5. Shaft and Other mechanical parts

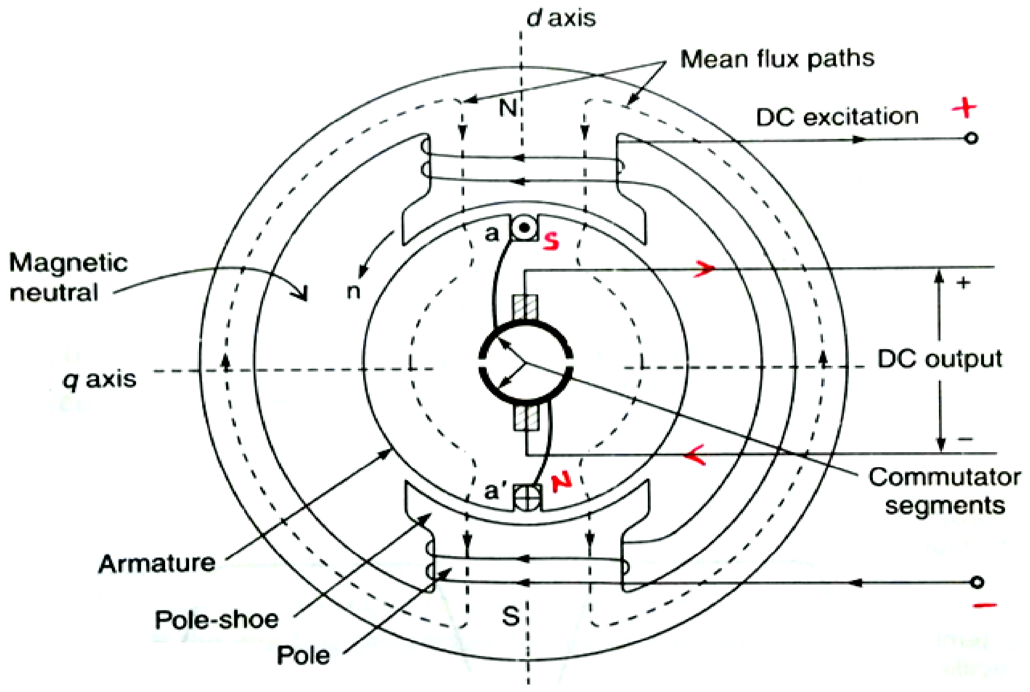


Figure: 3 - Cross sectional view of DC machine

1. **Yoke**.
   * Manufactured by using cast iron material. Cast iron has high mechanical strength and corrosion free characteristics.
   * Used to provide mechanical support to all internal parts and protect from external environment.

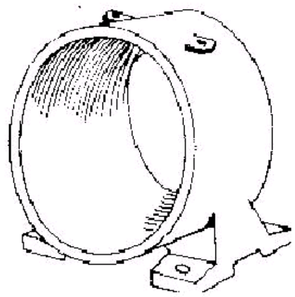
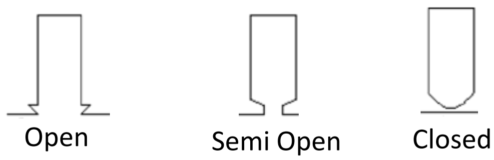


Figure: 4 - Yoke.

2. **Stator core and windings**

❖ ***Stator core***

* Stator core is used to hold field winding and used to provide magnetic flux path.
* This is a laminated stamped core, manufactured by using silicon steel.
* It contains several numbers of slots and inward projected poles.
* Types of slots are open, semi open and closed.

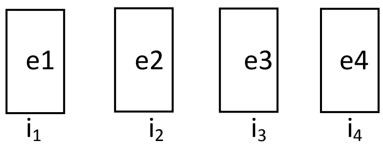


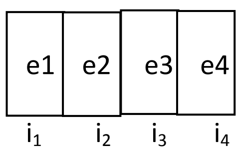
➢ **Hysteresis loss**

* To reduce hysteresis loss (H_{loss}),theflux density (B) has to be reduced. ($H_{loss} \alpha$ B)
* To reduce flux density (B), the flux path area (a) has to be increased. $(B \ \alpha \frac{1}{a})$
* For increasing flux path area large number of stamping are used to form a core instead of solid core.

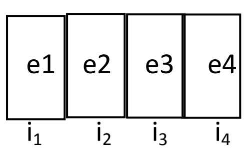
➢ **Eddy current loss**

* Due to flux linkage each stamping induces a minimum voltage (e) and a minimum circulating current (i_e) starts to circulate in each closed stamping.
* To reduce eddy current loss all stampings are insulated by using a thin layer of warmish coating and then stamped.





⟹ Without Insulation $i = i_1 + i_2 + i_3 + i_4$



⟹ With Insulation $i = i_1 = i_2 = i_3 = i_4$

❖ ***Field winding***

* Insulated copper conductors used to form field winding.
* Field winding placed inside the slot and around the pole.

* Field winding excited by DC supply to develop field flux.
* Types of windings: 1. Lap winding   2. Wave winding
* Lap winding can be used for high speed applications and number of parallel paths is equal to number magnetic poles (A= No. of mag. poles)
* Wave winding can be used for medium and low speed supplications and number of parallel paths is equal to number magnetic poles (A= 2)

3. Armature

* Armature core construction is similar to that of stator core.
* Armature is a rotating part which placed around the shaft.
* Armature winding excited by DC supply through commutator and brush arrangement.
* Air gap between field and armature must be constant and minimum as possible.

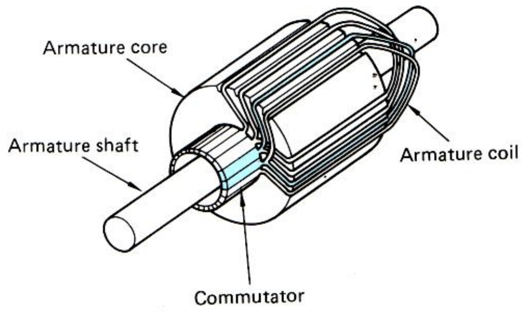
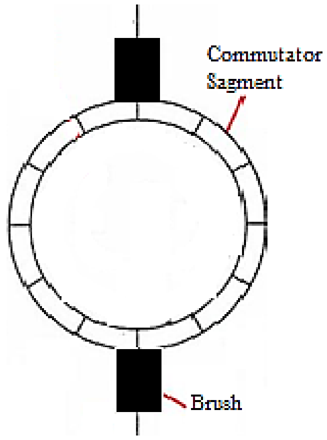


Figure: 5 - Armature

4. Commutatorand brush arrangement

* Commutator has several no. of segments.
* The no. of commutator segments is equal to the number of slots or coils (or) half the number of conductors.
  No. of commutator segments = No. of slots = No. of coils
* It is because each coil has two ends and two coil connections are joined at each Commutator segment.
* Commutator acts as "Rotary converter"
  In Motor : DC to AC
  In Generator : AC to DC
* Commutator needs frequent maintenance.
* Carbon or Copper brushes are used.



5. Shaft and Other mechanical parts

* Solid iron bar used as shaft.
* shaft is used to provide mechanical support to armature and commutator arrangement
* And also used to deliver mechanical output (motor) and used to collect the mechanical input (generator)
* Cooling fans, Bearings and End shields are placed around the shaft at both ends.
  Cooling fan : To provide cooling by circulate fresh air.
  Bearing : To reduce mechanical friction.
  End shields : To protect the internal parts from external environment.

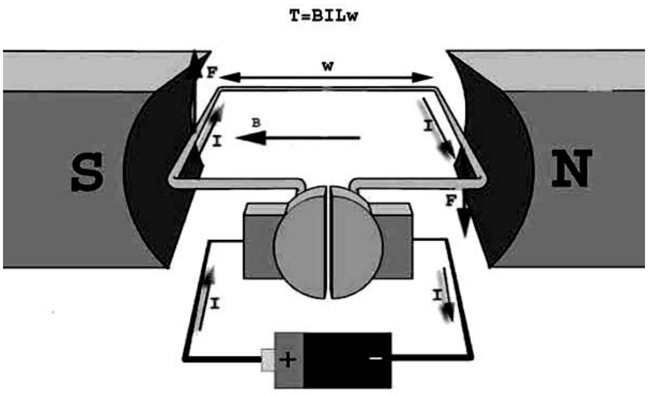
Working principle

* Field winding develops the constant magnetic field by exciting DC supply.
* The developed magnetic flux lines travels towards to armature through air gap.

➢ **DC Motor**

* Armature excited by DC supply through commutator.
* Commutator act as a “Rotary Converter” and converts the DC in to AC. So finally armature receives AC supply and develops an alternating magnetic field.
* This alternating magnetic field interact with constant magnetic field and leads to develop the electromagnetic torque.
* The final mechanical output power delivered through shaft.

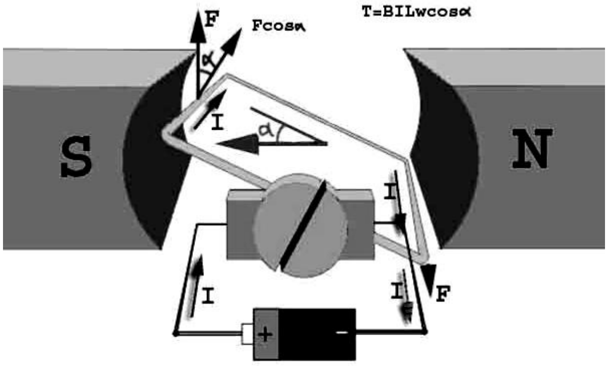
Step 1:



* At starting point or reference position where the angle $\alpha = 0$.
* Since $\alpha = 0$, the termcos $\alpha = 1$, hence torque at this position is maximum.
* This high starting torque helps in overcoming the initial inertia of rest of the armature and sets it into rotation.

$$\mathbf{T = BIL\cos 0^{o} \times \omega = BIL \times \omega}$$

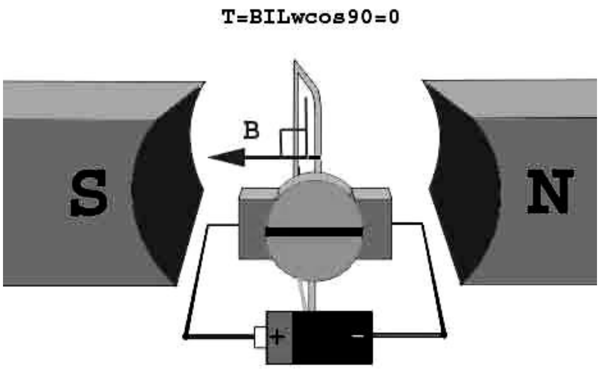
Step 2:



* When the angle $\alpha > 0^{o}$,the term cosα decreases.
* Now the torque is given by

$$\mathbf{T = BIL\cos 0^{o} \times \omega}$$

Step 3:



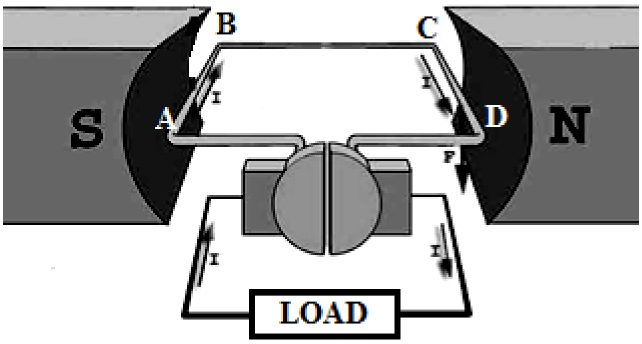
* When angle $\alpha > 90^{o}$,the term $\cos(90^{o}) = 0$.
* Now the torque is given by,

$$\mathbf{T = BIL\cos 90^{o} \times \omega = 0}$$

➢ **DC Generator**

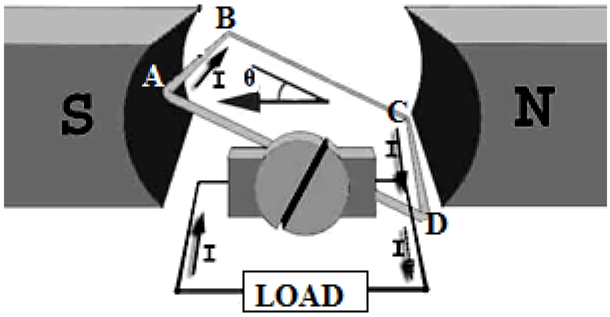
* From figure – 3, mechanical input (angular velocity) is given to the armature through shaft.
* Now the armature winding cuts the constant magnetic field.
* As per “faraday electromagnetic induction law”, an AC emf induced in armature winding.
* Commutator act as a “Rotary Converter” and converts the AC in to DC. So finally it delivers DC supply, can collect across A_1 and A_2.

Step:1



- At starting point or reference position where the angle θ = 0.
- Since θ = 0, the term sin θ = 0, hence induced emf at this position (ABCD) is 0.

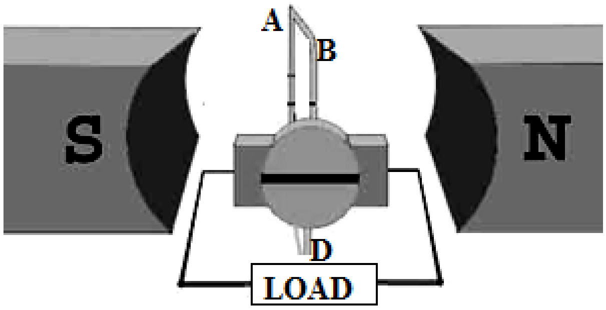
Step: 2



- At this position, where the angle θ # 0.
- Since θ # 0, the term sin θ > 0, hence induced emf at this position (ABCD) is,

$$e = E_m \sin\theta$$

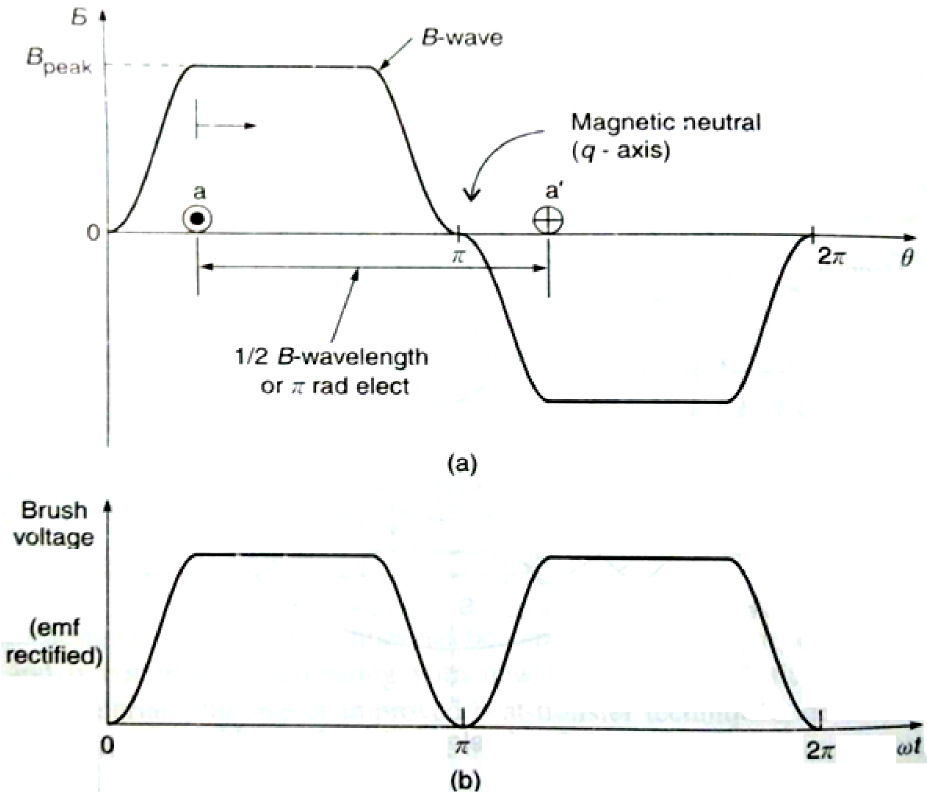
Step: 3



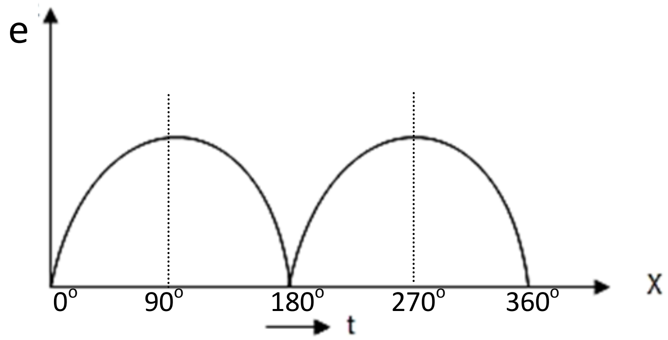
- At this position, where the angle θ =90°.
- Since θ =90°, the term sin 90° =1, hence induced emf at this position (ABCD) is,

$$e = E_m$$

- **Wave forms for induced voltage and brush voltage**



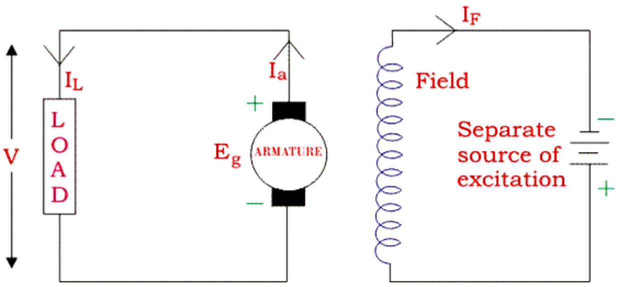
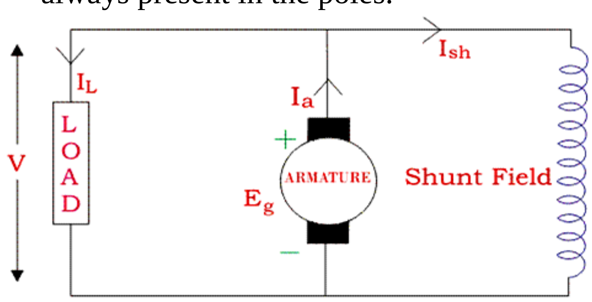
➢ **The DC output voltage at different time periods,**



Types of DC Generators

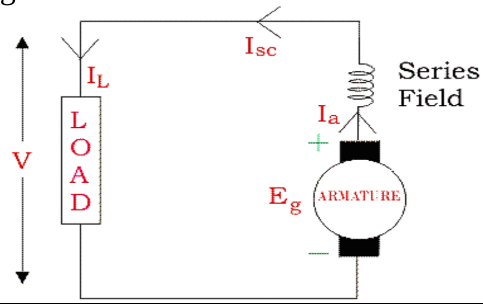
General parameters for DC generators,

I_a	= Armature current	E_g	= Generated emf
I_F	= Field current	R_{sh}	= Shunt field resistance
I_L	= Load current	R_{se}	= Series field resistance
V	= Terminal voltage	R_a	= Armature resistance

Types of DC Generator	Expressions
➢ **Separately Excited DC Generator** ∗ Field and armature windings excited separately.  	∗ Voltage drop in the armature = $I_a \times R_a$ ∗ Let, $I_a = I_L = I$ ∗ Now Voltage drop across the load, $V = I \times R_a$ ∗ Generated emf, $E_g = V$ ∗ Power generated, $P_g = E_g \times I = V \times I$. ∗ Power delivered to the external load, $P_L = V \times I$.
➢ **Self-excited DC Generators**	
1. Shunt wound generator ∗ Shunt field winding is connected with armature in parallel. ∗ Shunt field winding has large no. of turns and less cross sectional area of conductor. ∗ Shunt field and armature windings excited by single electrical source. ∗ Due to residual magnetism some flux is always present in the poles.  	∗ Shunt field current, $I_{sh} = \frac{V}{R_{sh}}$ ∗ Armature current, $I_a = I_{sh} + I_L$ ∗ Voltage across the load, $V = E_g - I_a R_a$ ∗ Generated emf, $E_g = V + I_a R_a$ ∗ Power generated, $P_g = E_g \times I_a$ $P_g = V + I_a^2 \times R_a$ ∗ Power delivered to the load, $P_L = V \times I_L$

2. *Series Wound Generator*

- Series fieldwinding is connected with armature in series.
- Series field winding has less no. of turns and large cross sectional area of conductor.
- Series field and armature windings excited by single electrical source.



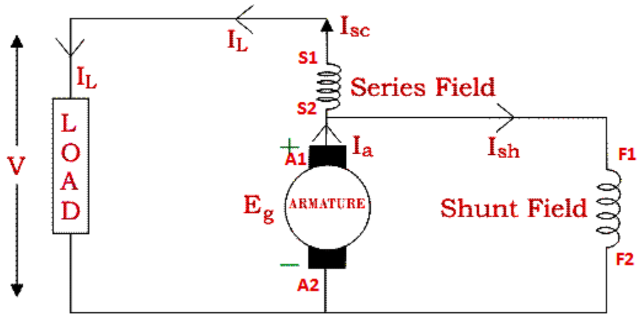
- Series field current,
$I_{sc} = I_a = I_L = I$ (say)
- Voltage across the load,
$V = E_g - (I_a \times R_a + I_{se}R_{se})$
- Generated emf,
$E_g = V + (I_a \times R_a + I_{se}R_{se})$
- Power generated,
$P_g = E_g \times I$
- Power delivered to the load,
$P_L = V \times I$

3. *Compound Wound DC Generator*

This type of DC generator has both series and shunt field windings.

3a. *Short Shunt Compound Wound DC Generator*

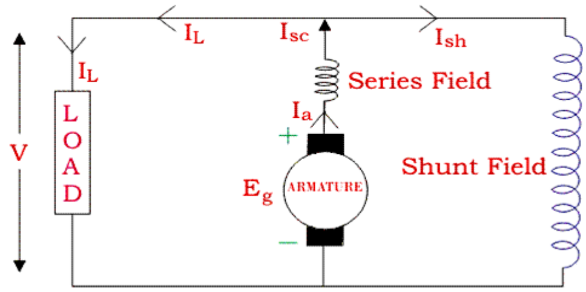
- F_1 terminal of shunt field winding is connected between S_2 and A_1



- Series field current, $I_{sc} = I_L$
- Shunt field current, $I_{sh} = I_a - I_{se}$
- Armature current,
$I_a = I_{sh} + I_{se}$
- Voltage across the load,
$V = E_g - (I_a R_a + I_{sc}R_{sc})$
- Generated emf,
$E_g = V + (I_a \times R_a + I_{se}R_{se})$
- Power generated, $P_g = E_g \times I_a$
- Power delivered to the load, $P_L = V \times I_L$

3b. *Long Shunt Compound Wound DC Generator*

- F_1 terminal of shunt field winding is connected at S_1
- Depends current flow direction in series and shunt field windings, can classify as,
  1. Cumulative compounding – same direction
  2. Differential compounding– opposite direction



- Shunt field current,
$I_{sh} = V/R_{sh}$
- Armature current, I_a= series field current
$I_a = I_{sc} = I_L + I_{sh}$
- Voltage across the load,
$V = E_g - (I_a R_a + I_{sc}R_{sc})$
- Generated emf,
$E_g = V + (I_{se}R_{se})$
- Power generated,
$P_g = E_g \times I_a$
- Power delivered to the load,
$P_L = V \times I_L$

➢ EMF Equation

- Assume full-pitch armature coils.
- Developed flux per pole $= \frac{\text{Flux}}{\text{pole}} = \frac{\varphi}{p}$

* Flux linkage per pole $\lambda_1 = N_C \varphi$

  Where, λ_1 = Flux linkage at time t_1

  N_c = Number of turns per coil

* As the coil moves through one pole pitch, now the flux linkage changes and it links in opposite polarity. Now the new flux linkage per pole at time t_2

$$\lambda_2 = - N_C \varphi$$

* During the movement t_1 to t_2 the change in flux ($\Delta\lambda$)

$$\Delta\lambda = \lambda_2 - \lambda_1$$

$$\Delta\lambda = - 2 N_C \varphi$$

* The time of flux travel through one pitch is, (time interval between t_2 and t_1)

$$\Delta t = \frac{2\pi}{p \times \omega_m}$$

  Where, 2π = Circumference of armature core in metre.

  ω_m = Armature speed in mechanical rad/sec.

  p = Number of magnetic poles.

* As per faraday electromagnetic induction law, the average emf per coil is,

$$E_c = -\frac{\Delta\lambda}{\Delta t} = -\left\{\frac{-2N_c \times \varphi}{\left(\frac{2\pi}{p \times \omega_m}\right)}\right\}$$

$$E_c = \varphi \times \omega_m \times N_c \times p$$

* Now the average emf is $E_a = E_c \times \frac{\text{Coil span}}{\pi}$

* Coil span $(C_p) = \frac{\text{Number of coils}}{\text{parallel path}}$

* Average emf $E_a = \varphi \times \omega_m \times N_c \times p \times \frac{C_p}{\pi}$

* But we know that $N_c \times C_p = \frac{\left(\frac{Z}{2}\right)}{A} = \frac{\text{number of turns}}{\text{parallel path}}$

  Where, Z = Number of conductors

* Average emf $E_a = \frac{\varphi \times Z \times \omega_m}{2\pi} \times \frac{p}{A}$

* Average emf can also written as, $\mathbf{E_a = \frac{\varphi \times \mathit{Z} \times \mathit{n}}{60} \times \frac{p}{\mathit{A}}}$ where, $\omega_m = \frac{2 \times \pi \times n}{60}$

  Where n = armature speed in rps

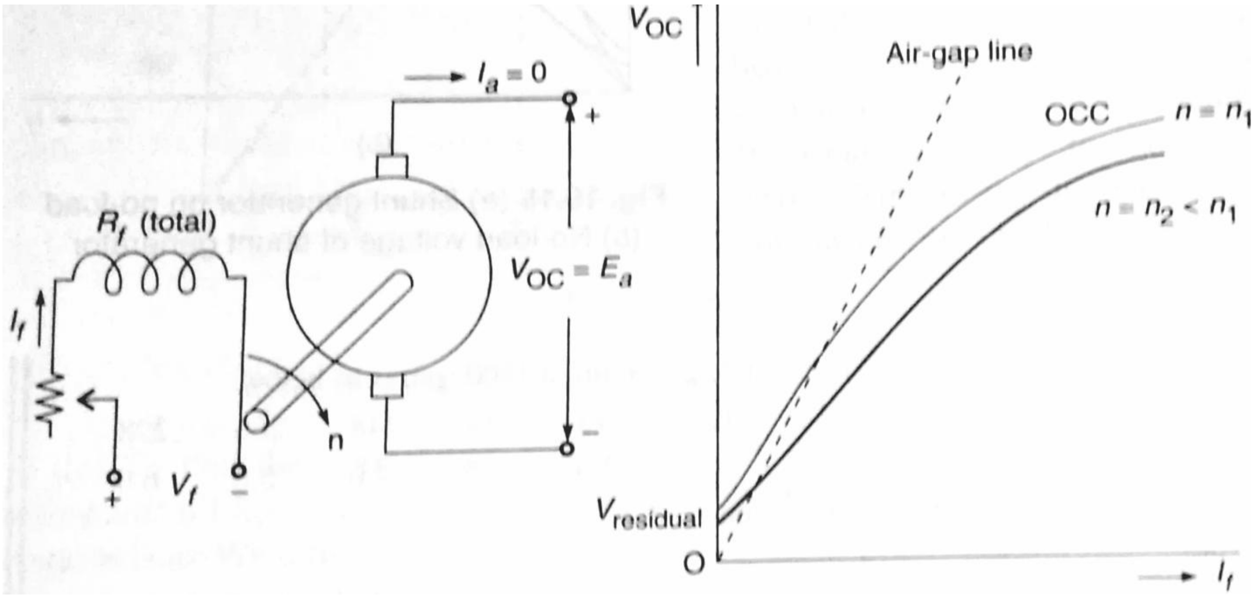
Generator Characteristics

The most important characteristics or curves of a D.C generator are:

1. **Open Circuit Characteristic (OC**C)
2. **Short circuit characteristics (SCC)**

1. **Open Circuit Characteristic (OCC)**
   - OCC is also called as "Magnetization Characteristics" or "Internal Characteristics".

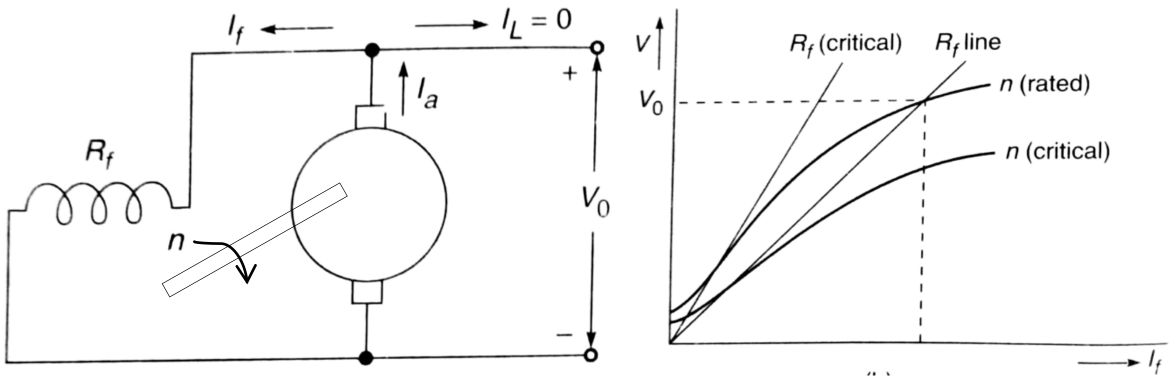
- **Separately Excited DC Generator.**
  - Separately Excited DC Generator runs by prime mover at a constant speed with open circuited armature.
  - Under this condition, the generated armature emf (E_a) = Open circuit voltage (V_{oc}).



- From the diagram,
  - I_f = Field current in amp.
  - I_a = Armature current in amp.
  - R_f = Total field resistance in ohm.
  - n = speed in rps. (mechanical input to the Generator)
- At I_f = 0Amp, very small amount of voltage induced in armature due to "residual magnetic flux"
- At small value of field current (or) $I_f << I_{f\ rated}$, $E_a \alpha I_f$
- At greater value of field current (or) $I_f \cong I_{f\ rated}$ the generated E_a is slightly saturated.
- The generated armature emf is direct proportional to mechanical input (prime mover speed).

$$E_a \alpha\ n$$

- **Self-Excited DC Generator**



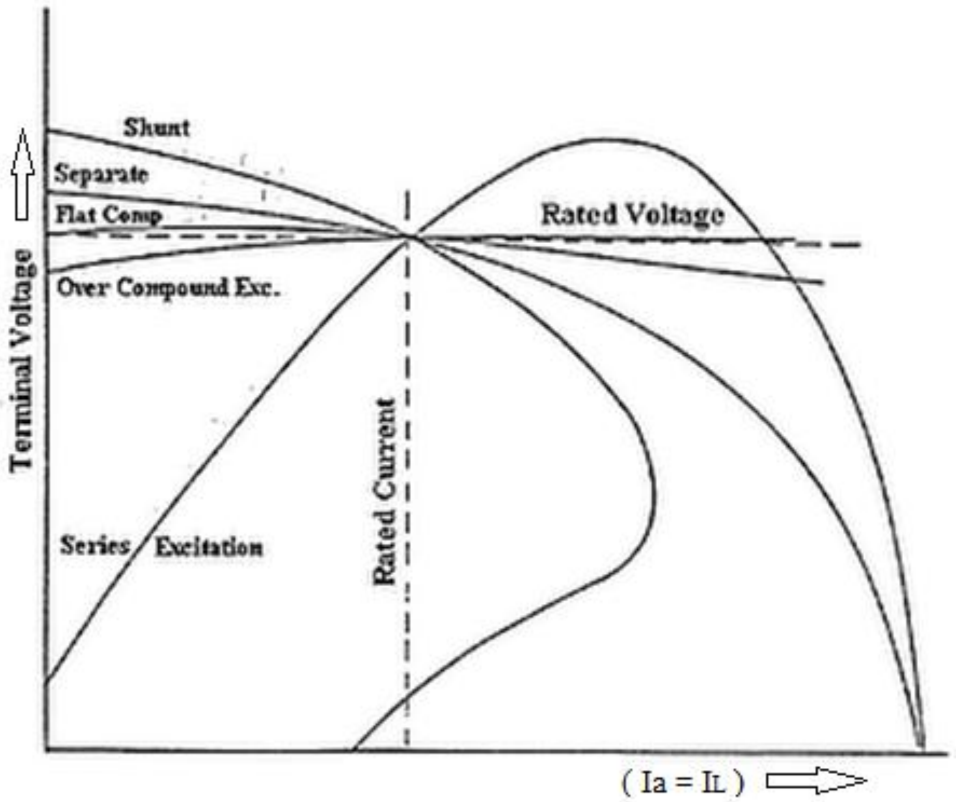
- Self-Excited DC Generator runs by prime mover at a constant speed with open circuited armature.
- Under this condition, the armature current $I_a = I_f$ (very small) and the generated armature emf,

$$E_a = V_{oc} \qquad (I_f<<1;\ I_a<<1;\ I_aR_a<<1)$$

* Critical Field Resistance (R_{fc}) – tangential R_f to the magnetisation characteristics is called R_{fc}.
* When R_f>R_{fc}, generator fails to excite and no load output voltage (V_{OC}) ≅ Residual voltage.
* The speed at critical resistance (R_{fc}) is called "Critical Speed ($n_{critical}$)".
* Regulating Resistance – The out voltage can be adjusted by adding external resistance. The external resistance is called "Regulating Resistance".

2. Short circuit characteristics (SCC)

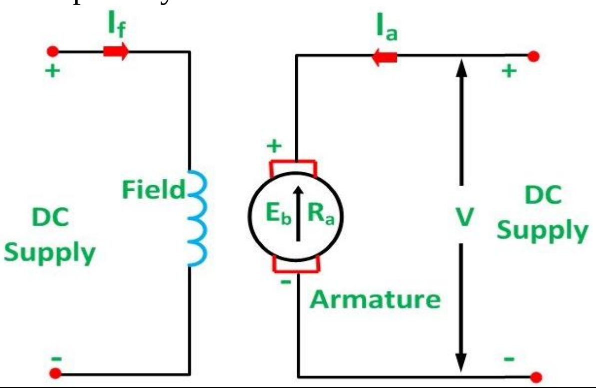
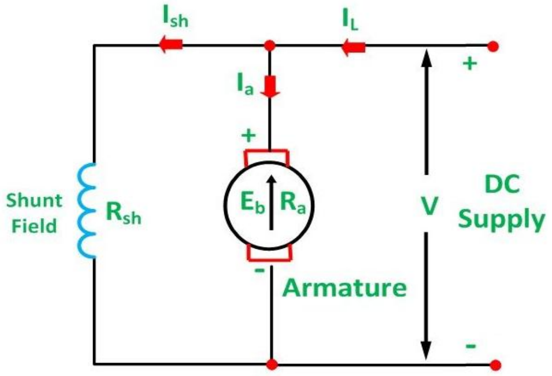
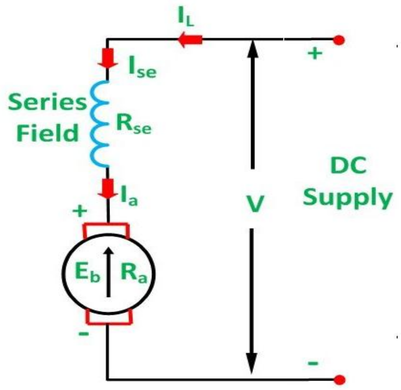
* SCC is also called as "External Characteristics" (or) "Load Characteristics".
* SCC Characteristics curve drawn between terminal voltage (V) and load current (I_L).
* Armature current (I_a) varies with respect to load variation.
* Load is connected across armature terminals.
* I_a>> I_f and can say $I_a = I_L$ for all types of DC generators.
* Load Characteristics curves for all types of DC generators are given below.
* Generated voltage decreases due to armature resistance and armature reaction effect.
* If the field flux remains constant,the generated voltage would tend to remain constantand the output voltage would be equal to the generated voltage



Types of DC Motors

General parameters for DC Motors,

I_a	= Armature current	R_{sh}	= Shunt field resistance
I_F	= Field current	R_{se}	= Series field resistance
I_L	= Load current	R_a	= Armature resistance
V	= Terminal voltage	P_{in}	= Electrical input power
V_a	= Voltage drop in armature	P_{mech}	= Developed mechanical power.
E_b	= Backemf		

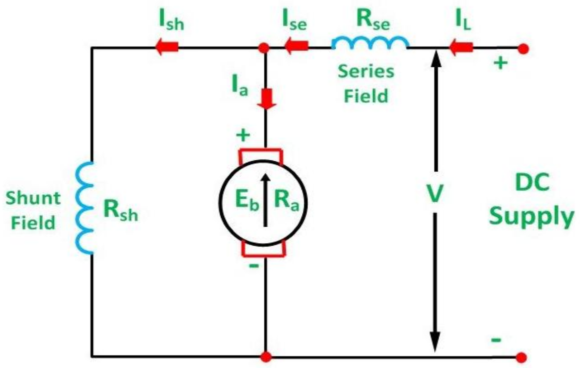
Types of DC Motors	Expressions
➢ **Separately Excited DC Motor** ∗ Field and armature windings excited separately.  	∗ Voltage drop in the armature $V_a = I_a \times R_a$ ∗ Input terminal voltage $V = E_b + I_a \times R_a$ ∗ Electrical power input $P_{in} = V \times I_a$ ∗ Developed Mechanical Power, $P_{mech} = E_b \times I_a$
➢ **Self-excited DC Motor**	
3. Shunt wound generator ∗ Shunt field winding is connected with armature in parallel. ∗ Shunt field winding has large no. of turns and less cross sectional area of conductor. ∗ Shunt field and armature windings excited by single electrical source.  	∗ Shunt field current, $I_{sh} = \frac{V}{R_{sh}}$ ∗ Armature current, $I_a = I_L - I_{sh}$ ∗ Voltage drop in the armature $V_a = I_a \times R_a$ ∗ Input terminal voltage, $V = E_b + (I_a \times R_a)$ ∗ Back emf, $E_b = V - (I_a \times R_a)$ ∗ Electrical power input $P_{in} = V \times I_L$ $P_{in} = V \times (I_a + I_{sh})$ ∗ Developed Mechanical Power, $P_{mech} = E_b \times I_a$
***4. Series Wound* Motor** ∗ Series fieldwinding is connected with armature in series. ∗ Series field winding has less no. of turns and large cross sectional area of conductor. ∗ Series field and armature windings excited by single electrical source.  	∗ Armature current, $I_a = I_{se} = I_L$ ∗ Voltage drop in the armature $V_a = I_a \times R_a$ ∗ Input terminal voltage, $V = E_b + (I_a \times R_a + I_{se} \times R_{se})$ ∗ Back emf, $E_b = V - (I_a \times R_a + I_{se} \times R_{se})$ ∗ Electrical power input $P_{in} = V \times I_L$ ∗ Developed Mechanical Power, $P_{mech} = E_b \times I_a$

5. *Compound Wound DC Generator*

- This type of DC generator has both series and shunt field windings.

3a.Short Shunt Compound Wound DC Generator

- F_1 terminal of shunt field winding is connected between S_2 and A_1



- Armature current,

  $I_a = I_{se} - I_{sh}$
- Voltage drop in the armature $V_a = I_a \times R_a$
- Input terminal voltage,

  $V = E_b + (I_a \times R_a + I_{se} \times R_{se})$
- Back emf,

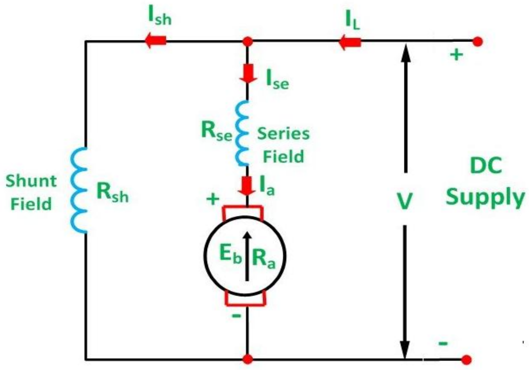
  $E_b = V - (I_a \times R_a + I_{se} \times R_{se})$
- Electrical power input

  $P_{in} = V \times I_L$
- Developed Mechanical Power,

  $P_{mech} = E_b \times I_a$

3b. Long Shunt Compound Wound DC Generator

- F_1 terminal of shunt field winding is connected at S_1



- Armature current,

  $I_a = I_{se} = I_L - I_{sh}$
- Voltage drop in the armature $V_a = I_a \times R_a$
- Input terminal voltage,

  $V = E_b + (I_a \times R_a + I_{se} \times R_{se})$
- Back emf,

  $E_b = V - (I_a \times R_a + I_{se} \times R_{se})$
- Electrical power input

  $P_{in} = V \times I_L$
- Developed Mechanical Power,

  $P_{mech} = E_b \times I_a$

Torque Equation of DC Motor

- The average force on an armature conductor is,

$$f_{av} = B_{av} \times l \times I_c \times r$$

Where, l = Length of active conductor

I_c = Conductor current

r = mean airgap radius

- Average torque on armature by one conductor (Z=1),

$$t_{av} = B_{av} \times l \times I_c \times r$$

- Now the total torque (T) developed by armature conductors (Z),

$$T = B_{av} \times l \times I_c \times r \times Z$$

- The average flux density $B_{av} = \frac{\varphi \times p}{2\pi r l}$
- Now the total torque (T) can be written as,

$$T = \frac{1}{2\pi} \varphi \times I_c \times Z \times p$$

- Substitute for coil current $I_c = \frac{I_a}{A}$ then the total torque will be,

$$\mathbf{T = \frac{1}{2\pi} \varphi \times I_a \times Z \times \frac{p}{A}} \quad \text{in NM.}$$

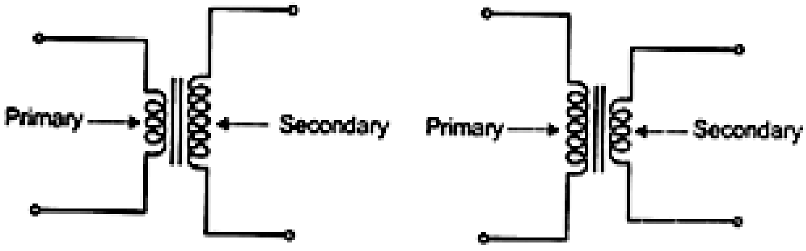
Transformer

Introduction

- ∗ Transformer works on the principle of electromagnetic induction.
- ∗ Transformer is an electrical device, having no moving parts.
- ∗ It consists of two windings insulated from each other and wound on a common core made up of magnetic material.
- ∗ By mutual induction transfers electric energy from primary to secondary at same frequency.
- ∗ Depends the ratio of number of turns in windings the values of voltage and current will be changed..

Working principle of a Transformer

- ∗ The primary winding is connected to an AC source
- ∗ An alternating flux developed and linked both primary and secondary windings by the magnetic path which provide by core.
- ∗ The induced emf in the primary winding (E_1) is almost is equal to the applied voltage V1.
- ∗ The emf induced in the secondary winding (E_2) can be utilized to deliver power to any load.
- ∗ Thus power is transferred from the primary to the secondary by electromagnetic induction.
- ∗ Frequency remains same and the magnitude of the emf induced in the secondary winding will depend upon its number of turns.



Step up Transformer   Step down Transformer

- ∗ Number of turns in the primary winding = N_1
- ∗ Number of turns in the secondary winding = N_2

$N_2 > N_1$ = Step up transformer

$N_2 < N_1$ = Step down transformer

Classification of Transformer

Transformers are classified on the basis of

i) Duty they perform

a) Power transformer – for transmission and distribution purposes
b) Current transformer- instrument transformers
c) Potential transformer- instrument transformers

ii) Construction

a) Core type transformer
b) Shell type transformer
c) Berry type transformer

iii) Voltage Output

a) Step down transformer (Higher to Lower)
b) Step up transformer (Lower to Higher)
c) Auto transformer (Variable from ‘0’ to rated value)

iv) Application
- a) Welding transformer
- b) Furnace transformer

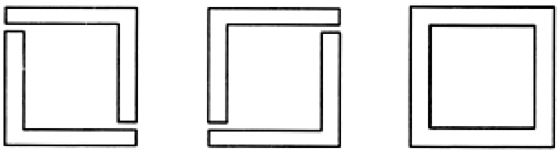
v) Cooling
- a) Air natural (or) Air blast
- b) Oil immersed
- c) Self cooled
- d) Forced air cooled
- e) Water cooled
- f) Forced oil cooled

vi) Input Supply
- a) Single phase transformer
- b) Three phase transformer
  1. Star – Star
  2. Star- Delta
  3. Delta- Delta
  4. Delta – Star
  5. Open – Delta
  6. Scott Connection

Constructional Details

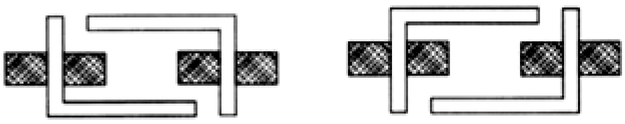
The main components are:
1) The magnetic core
2) Primary and Secondary windings
3) Insulation of windings
4) Expansion tank or conservator
5) Lead and tapings for coils with their supports, terminals and terminal insulators
6) Tank, oil, cooling arrangement, temperature gauge, oil gauge
7) Buchholz relay
8) Silica gel breather

1) Magnetic core
- ∗ It is a laminated stamped core made by silicon steel.
- ∗ The thickness of stampings varies from 0.35 mm to 0.5 mm.
- ∗ Eachstampings are insulated from each other by varnish coating.
- ∗ Joints are tagged to increase mechanical strength and to reduce magnetising current.
- ∗ General types of stampings are given below,



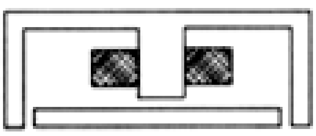
- ∗ The two types of transformer cores are:
  1. Core type 2. Shell type

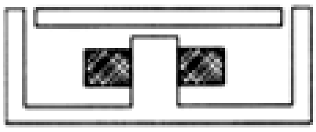
➢ **Core Type Transformer**
- ∗ Coilsplaced surround the core and has only one magnetic path.
- ∗ It has two limbs for the two windings and is made up of two L-type stampings.
- ∗ Generally coils wound as cylindrical type and for high power transformers, stepped cores with circular cylindrical cores type are used.



➢ **Shell type transformer**
- ∗ Coilsplaced insidethe core and have two magnetic paths.

* Two coils are carried by central limb.
* The core is made up of E and I stampings and has three limbs.
* It has two parallel paths for magnetic flux.





Winding

* There are two windings in a transformer.
    - Primary windings
    - Secondary windings.
* Generally the windings are made of copper.

Insulation

* Paper is still used as the basic conductor insulation.
* Enamel insulation is used as the inter-turn insulation for low voltage transformers.
* For power transformers enamelled copper with paper insulation is also used.

Insulating Oil

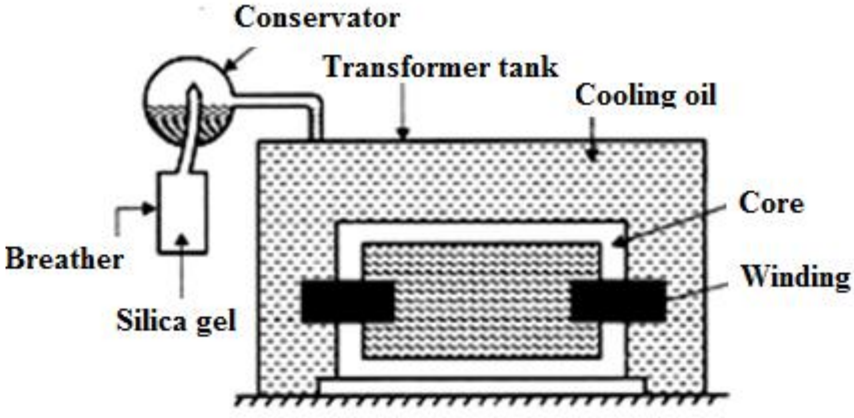
* Insulating oil is used in transformer to protect the paper from dirt and moisture and removes the heat produced in the core and coils.
* It also acts as insulating medium.
* The oil must have the following properties.
    i) High dielectric strength
    ii) Free from inorganic acid, alkali
    iii) Low viscosity to provide good heat transfer

Expansion Tank or Conservator

* A small oil tank mounted above the transformer and connected to the main tank by a pipe.
* Its function is to keep the transformer tank full of oil despite expansion or contraction of the coil with the changes in temperature.

Temperature Gauge and Oil Gauge

* Temperature gauge isused to indicate oil temperature.
* Oil gauge is used to indicate the oil level present in the tank.
* The oil gauge may be provided with an alarm contact which gives an alarm when the oil level has dropped beyond permissible height due to oil leak or due to any other reason.



Buchholz Relay

* Buchholz Relayis usedto give an alarm in case of minor fault and to disconnect the transformer from the supply mains incase of severe faults.

Breather

* The breather is filled with some drying agent, such as calcium chloride or silica gel.
* Calcium chloride or silica gel absorbs moisture and allows dry air to enter the transformer tank.
* The drying agent is replaced periodically as routine maintenance.

Bushings

* Connections from the transformer windings are brought out by means of bushings.
* Ordinary porcelain insulators can be used up to a voltage of 33kv.
* Above 33kv, capacitor and oil filled type of bushings are used. Bushings are fixed on transformer tank.

Methods ofcooling ofTransformers.

Types of cooling method are as follow,

1. Air natural
2. Air blast
3. Oil natural
4. Oil natural – air forced
5. Oil natural water forced
6. Forced circulationofoil
7. Oil forced –air natural
8. Oil forced –air forced
9. Oil forced – waterforced

1. Air natural cooling

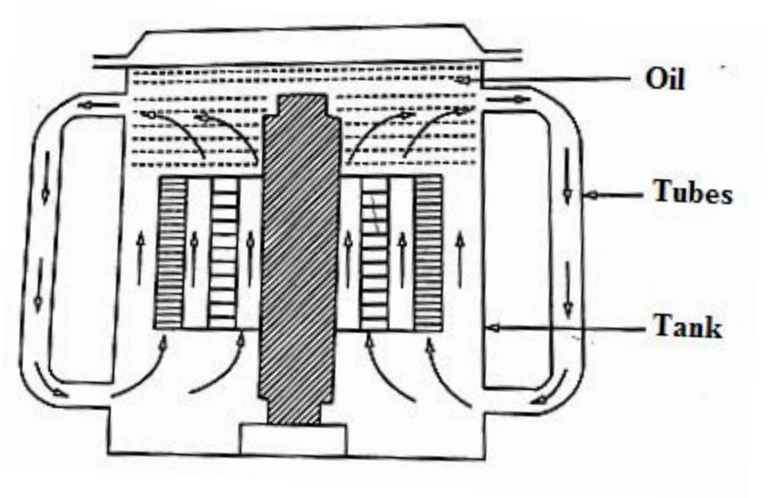
* The atmosphere air surrounding the tank walls is used as a cooling medium to carry away the heat generated, by *natural convection*.
* This method can be used for small voltage transformers.

2. Air blast cooling

* In large transformers, air is forced on core and winding with a help of fans.
* This method improves the *heat dissipation.*
* The air supply must be filtered to prevent accumulation of dust particles.

3. Oil natural cooling

* The power transformer windings immersed in insulating& cooling oil as shown fig.
* This improves the heat dissipation by convection method.
* The cooling oil must be filtered to prevent accumulation of dust particles.

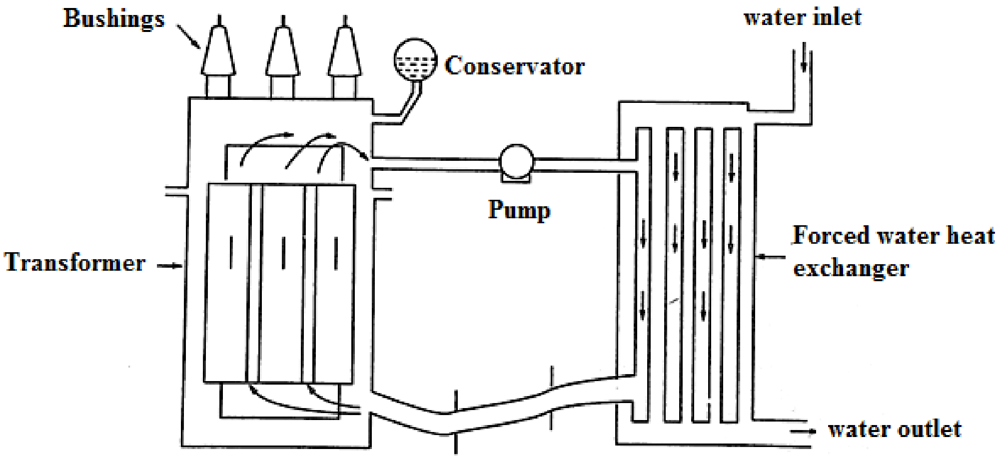


4. **Oil natural air forced cooling**

* In this method both oil cooling and air blast methods used.
* Here the tank made as hollow and air is forced into the hollow space of transformer.

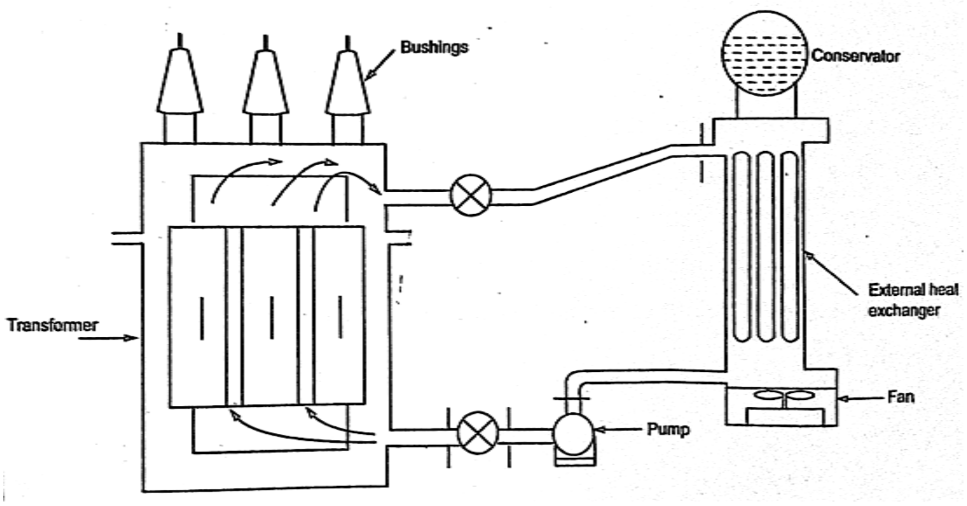
5. **Oil natural water forced**

* In the external heat exchanger the heated oil is blasted with the help of pumps as shown in fig.
* The method is used for the transformers at hydroelectric stations as large water supply with appropriate water head is easily available.

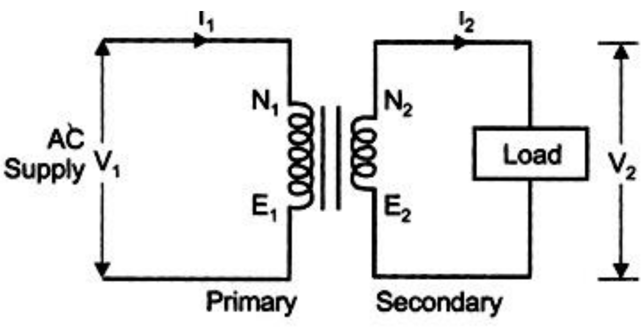


6. **Oil forced –air forced**

* In the external heat exchanger the heated oil is blasted with the help of pumps as shown in fig.
* In this method the external air is forced and circulated into the heat exchanger by using fans as shown in fig.



EMF equation of Transformer



* From the diagram,

A - Area of core in mm^2

F - Frequency of AC supply in Hz

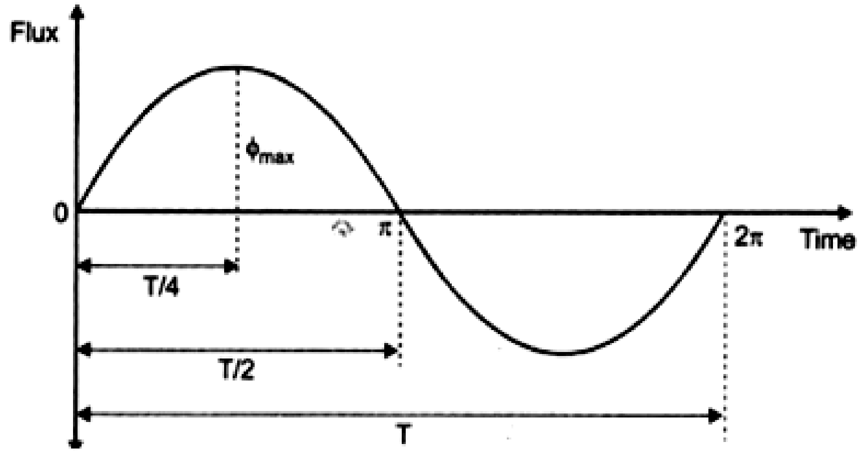
V_1 - Supply voltage across primary

V_2 - Terminal voltage across

I_1 - Full load primary current in amp
I_2 - Full load secondary current in amp
E_1 - ENF induced in primary
E_2 - ENF induced in secondary

* Applied voltage and developed flux are inphase.
* From the fig it is clear that the flux is attaining its maximum value in one quarter of the cycle. i.e., T/4 sec

  where 'T' is the time period in second. $T = \frac{1}{f}$ where f is frequency in Hz.



* Average rate of change of flux $= \frac{\varphi_m}{1/4f}$ in web/sec.
* Assume single turn coil, now the average emf induced in single turn coil,

  $= 4f \times \varphi_m$ in volts
* Form factor $= \frac{\text{RMS value}}{\text{Average Value}} = 1.11$
* RMS value = Form factor × Average value
* Now RMS value of induced emf / turn $= 1.11 \times 4f \times \varphi_m = 4.44f \times \varphi_m$ in volts
* Now RMS value of induced emf in entire primary winding,

  $E_1 = 4.44f \times \varphi_m \times N_1$ in volts
* Now RMS value of induced emf in entire primary winding,

  $E_2 = 4.44f \times \varphi_m \times N_2$ in volts

Voltage Regulation of Transformer

The voltage regulation of a transformer is defined as reduction in magnitude of the terminal voltage due to load, with respect to the no load terminal voltage.

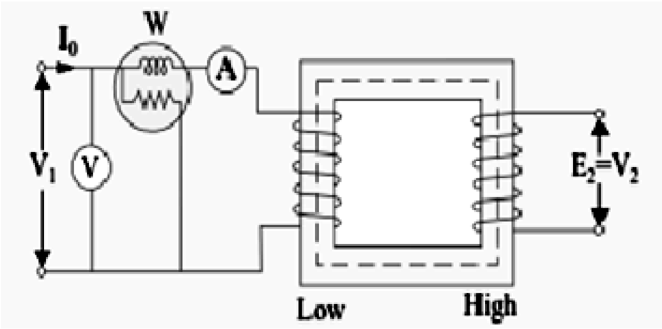
$$\%\,\text{regulation} = \frac{|V_2 \text{ on no load voltage}| - |V_2 \text{ when loaded}|}{|V_2 \text{ on no load voltage}|} \times 100$$

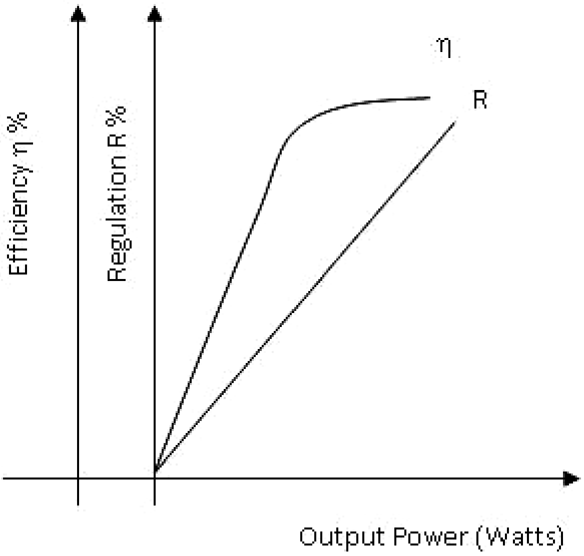
TransformerTests

1. Open-circuitorno-loadtest
2. Shortcircuitorimpedancetest

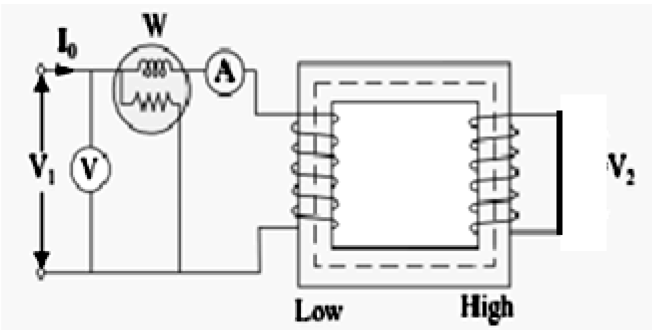
1. **Open-circuit (or) No-loadTest**.
   * Ammeter, voltmeter and wattmeterare connected on primary side
   * Secondary winding is kept at open circuited.

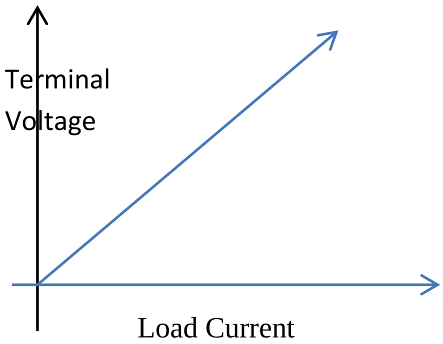
* Normal rated voltage isapplied tothe primary.
* Ironloss =Inputpoweronno-load W_0in watts(wattmeterreading)
* No-load current=0 amperes (ammeter reading)





2. Short-circuitorImpedance Test.





* Ammeter, voltmeter and wattmeterare connected on primary side
* Secondary winding is kept at short circuited.
* Ammeter, voltmeter andwattmeterareconnected onprimary side.
* Usually 5 to10%ofnormalratedprimary voltageatnormalfrequency isappliedtotheprimary.
* The readingofwattmeter givestotalcopperloss(iron loss is negligible dueto verylowappliedvoltageandverysmallfluxlinkingwiththecore)atfullload.

Efficiency

$$\% \text{ Efficiency} = \frac{\text{Output}}{\text{Input}} \times 100$$

* Another better method is to determine the losses and then to calculate the efficiency from the below expression,

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{Total Losses}} = \frac{\text{Output}}{\text{Output} + \text{Cu Losses} + \text{Iron losses}}$$

$$\text{Efficiency} = \frac{\text{Input} - \text{Total losses}}{\text{Input}} = 1 - \frac{\text{Total losses}}{\text{Input}}$$

* Efficiency is maximum at Unity power factor.

Condition for maximum efficiency

$$\text{Efficiency} = \frac{\text{Input - Total losses}}{\text{Input}} = \frac{V_1 I_1 \cos\phi - \left(I_1^2 R_{01} + W_i\right)}{V_1 I_1 \cos\phi}$$

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

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 maximum efficiency $\frac{d\eta}{dI_1} = 0$

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

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

$$W_i = I_1^2 R_{01}$$

Cu Loss = Iron Loss

All-day Efficiency

$$\eta_{allday} = \frac{\text{output in kw}}{\text{Input in kw}} \quad \text{for 24 hours}$$

Regulation of a Transformer

* The change in secondary terminal voltage from full load to no load.
* For laggingpower factor→ Terminal Voltage decreases.
* Forleading power factor→ Terminal Voltage increases.

$$\%\ \text{Regulation} = \frac{E - V}{V} \times 100 \quad \text{for 24 hours}$$

SYNCHRONOUS MOTOR

Introduction

* The synchronous motor is one type of 3-phase A.C motors which operate at a constant speed from no load to full load.
* It is similar in construction to 3-phase A.C generator in that it has a revolving field which must be separately excited from a D.C source.
* By changing the D.C field excitation, the power factor of this type of motor can be varied over a wide range of lagging and leading values.
* This motor is used in many applications because of its fixed speed from no-load to full load, its high efficiency and low initial cost.
* It is also used to improve the power factor of 3-phase AC industrial circuits.

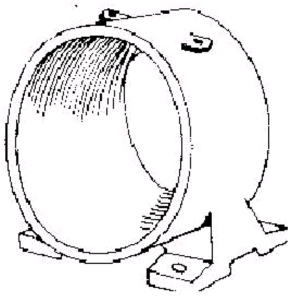
Construction of Synchronous Motor

An alternator has,

- 3-phase AC winding on stator.
- DC field winding on rotor.

Yoke.

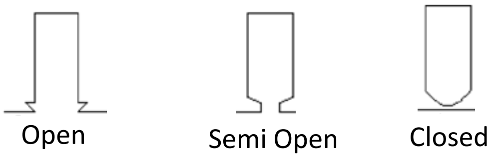
- Manufactured by using cast iron material. Cast iron has high mechanical strength and corrosion free characteristics.
- Used to provide mechanical support to all internal parts and protect from external environment.



Stator core and windings

❖ ***Stator core***

- Stator core is used to hold field winding and used to provide magnetic flux path.
- This is a laminated stamped core, manufactured by using silicon steel.
- It contains several numbers of slots and inward projected poles.
- Types of slots are open, semi open and closed.

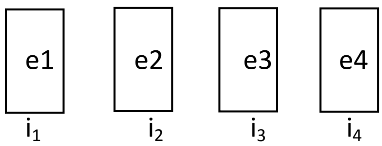


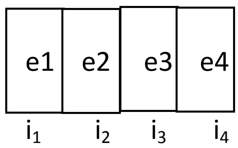
➢ **Hysteresis loss**

- To reduce hysteresis loss (H_{loss}),the flux density (B) has to be reduced. ($H_{loss} \alpha$ B)
- To reduce flux density (B), the flux path area (a) has to be increased. $(B \, \alpha \frac{1}{a})$
- For increasing flux path area large number of stamping are used to form a core instead of solid core.

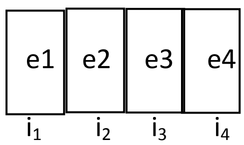
➢ **Eddy current loss**

- Due to flux linkage each stamping induces a minimum voltage (e) and a minimum circulating current (i_e) starts to circulate in each closed stamping.
- To reduce eddy current loss all stampings are insulated by using a thin layer of warmish coating and then stamped.





⇨ Without Insulation $i = i_1 + i_2 + i_3 + i_4$



⇨ With Insulation $i = i_1 = i_2 = i_3 = i_4$

❖ ***3phase AC winding***

- Insulated copper conductors used to form 3phase ACwinding.
- 3phase ACwinding placed inside the slot and around the pole.
- 3phase ACwinding excited by 3 phase AC supply to develop alternative magnetic flux.

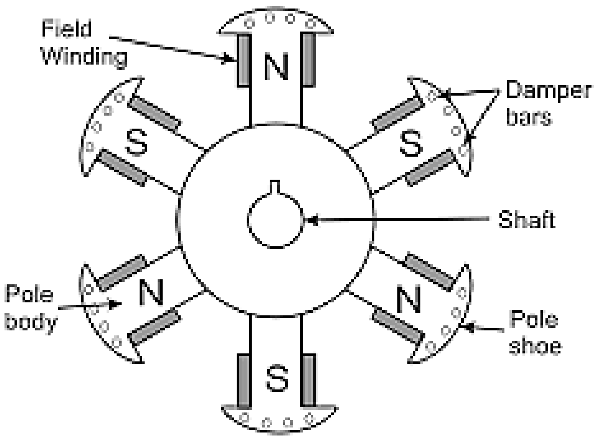
* Types of windings: 1. Lap winding   2. Wave winding
* Lap winding can be used for high speed applications and number of parallel paths is equal to number magnetic poles (A= No. of mag. poles)
* Wave winding can be used for medium and low speed supplications and number of parallel paths is equal to number magnetic poles (A= 2)

1. Rotor

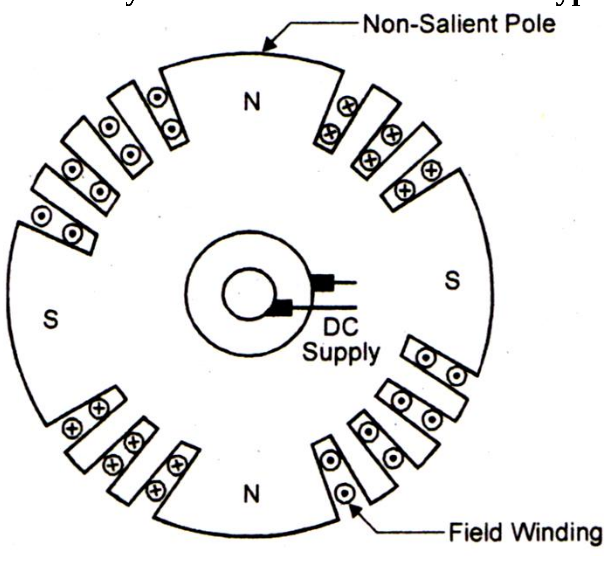
* Rotor core construction is similar to that of stator core.
* Rotor is a rotating part which placed around the shaft.
* Rotor winding excited by DC supply through slip ring arrangement.
* Air gap between stator and rotor must be constant and minimum as possible.
* Types of rotor,
    1 Salient (or) projecting pole type
    2 Non-salient pole (or) cylindrical type.

Salient Pole Rotor

* The salient pole rotoris made by using thick steel laminations and stamped together.
* The salient pole rotorhas large diameter and short axial length.
* This type is used for slow and moderate speed motors.
* This type has very high peripheral, high windage loss speed and low mechanical strength.
* Damper windings are provided at the pole faces.
* Damper windings are used to provide starting torque.
* The field coils are placed around the poles and connected in series.
* The field windingisexcited by a DC source through slip-rings arrangement.

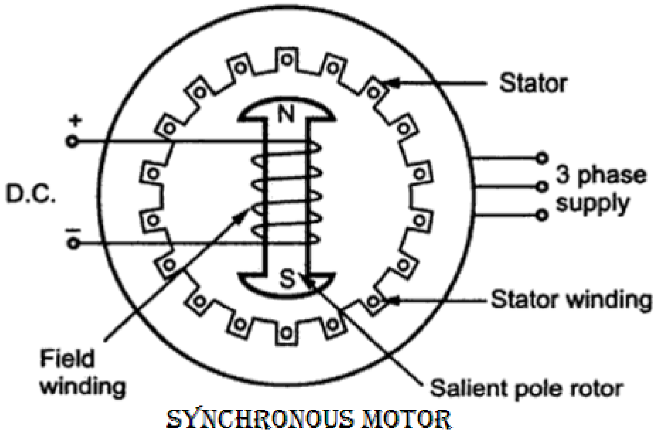


Smooth Cylindrical or Non-salient Pole Type



* This type of rotor is used in very high speed motors.
* This type of rotorhas a small diameter and very long axial length.
* This type is used for high speed motors.
* This type has low peripheral speed and less windage loss
* The tor shape is looks like cylinder.

Working principle



SYNCHRONOUS MOTOR

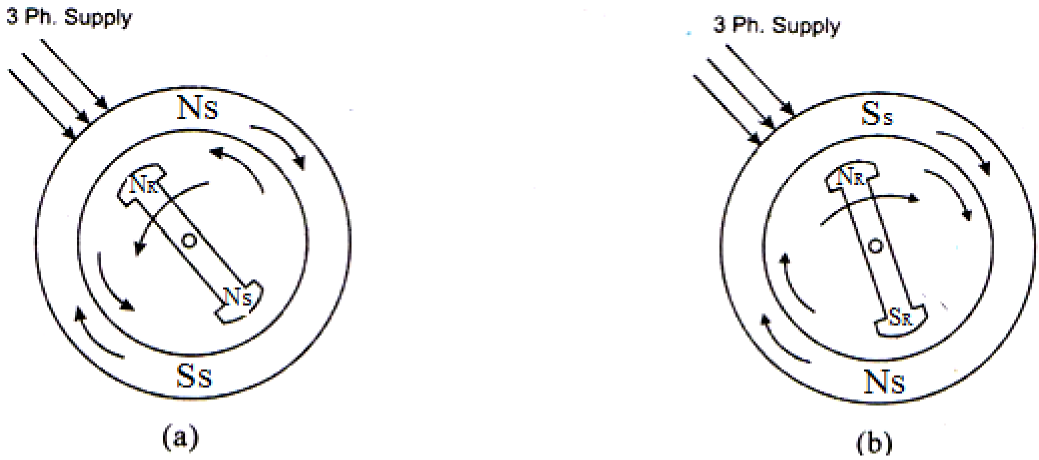
- 3 phase stator windings are displaced by 120^o
- 3 phase stator windings are excited by 3 phase AC supply and then rotating magnetic field (RMF) developed.
- The speed of RMF is called synchronous speed (N_s).

$$N_s = \frac{120\ f}{p}$$

Where, f = Supply frequency in Hz.

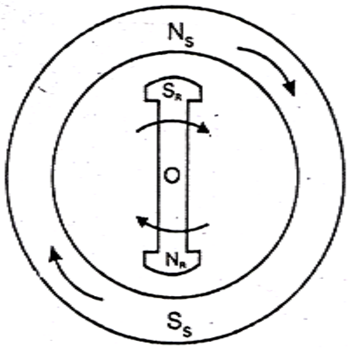
p = Number of magnetic poles.

- The rotor winding excited by DC supply,hence rotor winding developed constant magnetic flux.
- Now the rotor core act as electromagnet and it is placed in the rotating magnetic field (RMF).
- The electromagnet is magnetically locked with this rotating magnetic field and rotates with same direction and speed of RMF.
- This leads to run the motor at constant speed such as Synchronous speed (N_s)

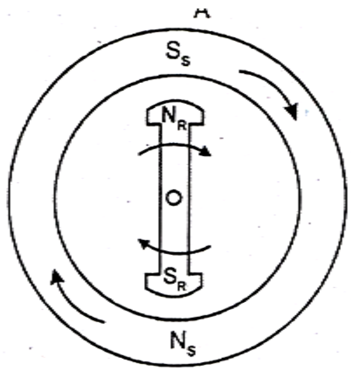


- N_R and S_R are formed by the DC excitation.
- From fig.(a) N_S and $N_R$and S_S and $S_R$are repel each other, and the rotor tries to rotate in the anti-clockwise direction.
- Since Ns and Ss are moving in clockwise direction, half a cycle later, the stator poles shows in figure (b).
- From fig.(b) N_S and $N_R$and S_S and $S_R$are attract each other, and the rotor tries to rotate in the clockwise direction.
- As a result, the rotor is at standstill due to its large inertia.
- This explains why a synchronous motor has no starting torque and cannot start by itself.

* Damper winding is used to provide starting torque or the rotor is rotated separately by a prime mover in the same direction of RMF.
* Because of the interlocking between the stator and rotor poles, the motor runs only at synchronous speed.



(a)



(b)

Torque equation of the synchronous motor

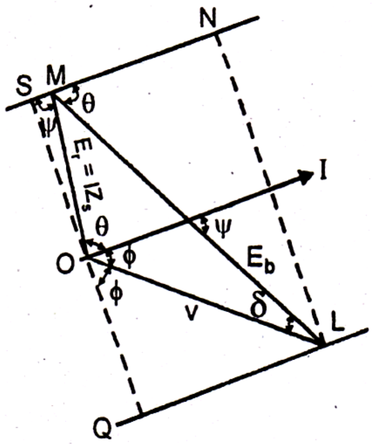
OL = Supply voltage / phase

I = Armature current

LM = Back e.m.f at a load angle of δ

OM = Resultant voltage, E_R

E_r = I Z_s (or I X_s if R_a is negligible)



* I lags / leads V by an angle φ and lags behind E_r by an angle θ.

$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right)$$

* Line NS is drawn at angle δ to LM
* LN and QS are perpendicular to NS

* Mechanical power developed per phase in the rotor,

$$P_{mech} = E_b I \cos\psi$$

ΔOMS, MS = I $Z_s$cos ψ

MS = NS – NM = LQ – NM

$$I Z_s \cos\psi = V\cos(\theta - \delta) - \frac{E_b}{Z_s}\cos\theta$$

Or

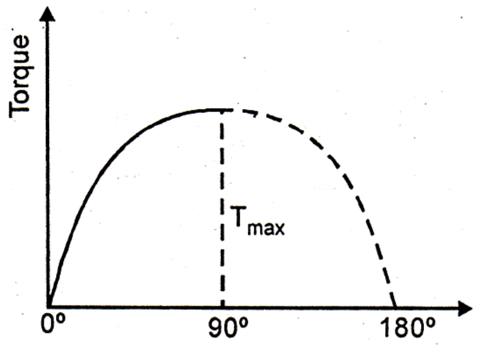
$$I\cos\psi = \frac{V}{Z_s}\cos(\theta - \delta) - \frac{E_b}{Z_s}\cos\theta$$

* $P_{mech/phase} = E_b\left\{\frac{V}{Z_s}\cos(\theta - \delta) - \frac{E_b}{Z_s}\cos\theta\right\}$
* $P_{mech/phase} = \left\{\frac{E_b V}{Z_s}\cos(\theta - \delta) - \frac{E_b^2}{Z_s}\cos\theta\right\}$

* This is the expression for the mechanical power developed in terms of load angle (a) and the internal angle 0 of the motor for a constant voltage V &Eb.

Maximum Power Developed

* Condition for maximum power developed $\theta = \delta$ and R_a is neglected, $\theta = 90°$



* The various torques associated with a synchronous motor are described below.
  1. Starting torque
  2. Running Torque
  3. Pull in torque
  4. Pull out torque

Single phase induction motor

Introduction

* The single-phase motors are used in homes, offices, shops and factories.
* They provide motive power for fans, washing machines, hand tools like, drillers, record player, refrigerators, juice makers etc.
* The single phase motors are simple in construction.
* The main disadvantages of these motors are
  1. Lack of starting torque
  2. Reduced power factor
  3. Low efficiency

Single phase induction motors

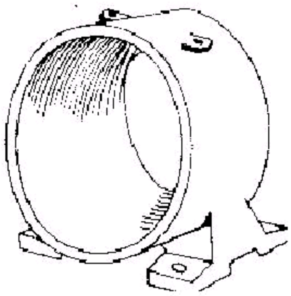
The majority of single phase motors are of induction type. The power rating is in terms of fractional horse power. They are classified according to the starting methods, employed. They are

1. Resistance - start (split-phase)
2. Capacitor— start induction motor
3. Capacitor — run induction motor
4. Shaded pole induction motor

Construction of single-phase induction motor

* The main parts of single phase induction motor,
  1. Yoke
  2. Stator core and windings
  3. Rotor core
  4. Shaft and Other mechanical parts

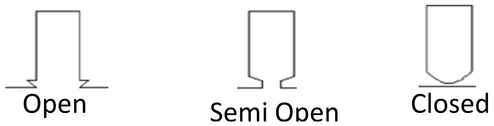
Yoke.

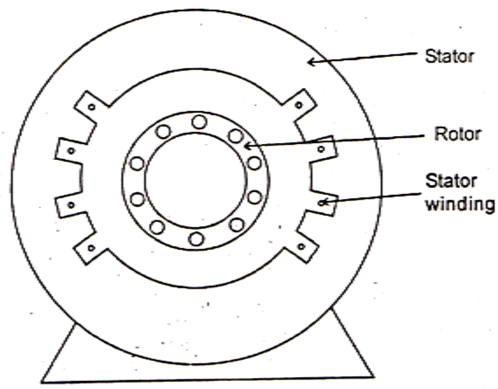


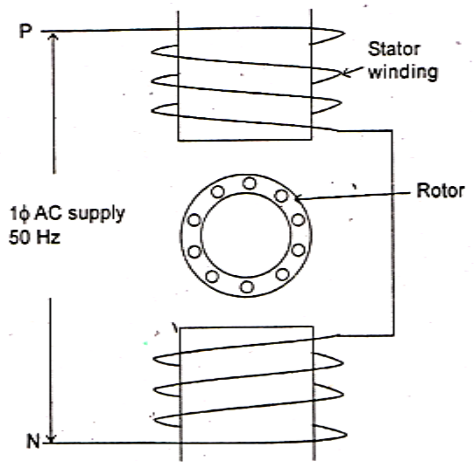
- ∗ Manufactured by using cast iron material. Cast iron has high mechanical strength and corrosion free characteristics.
- ∗ Used to provide mechanical support to all internal parts and protect from external environment.

Stator core and windings

- ❖ ***Stator core***
- ∗ Stator core is used to hold field winding and used to provide magnetic flux path.
- ∗ This is a laminated stamped core, manufactured by using silicon steel.
- ∗ It contains several numbers of slots and inward projected poles.
- ∗ Types of slots are open, semi open and closed.



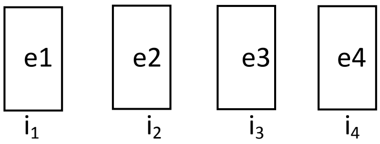


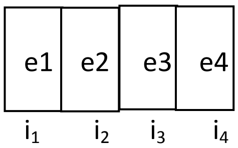


- ➢ **Hysteresis loss**
- ∗ To reduce hysteresis loss (H_{loss}),theflux density (B) has to be reduced. ($H_{loss} \alpha$ B)
- ∗ To reduce flux density (B), the flux path area (a) has to be increased. ($B\ \alpha \frac{1}{a}$)
- ∗ For increasing flux path area large number of stamping are used to form a core instead of solid core

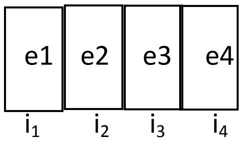
.

- ➢ **Eddy current loss**
- ∗ Due to flux linkage each stamping induces a minimum voltage (e) and a minimum circulating current (i_e) starts to circulate in each closed stamping.
- ∗ To reduce eddy current loss all stampings are insulated by using a thin layer of warmish coating and then stamped.





⟹ Without Insulation $i = i_1 + i_2 + i_3 + i_4$

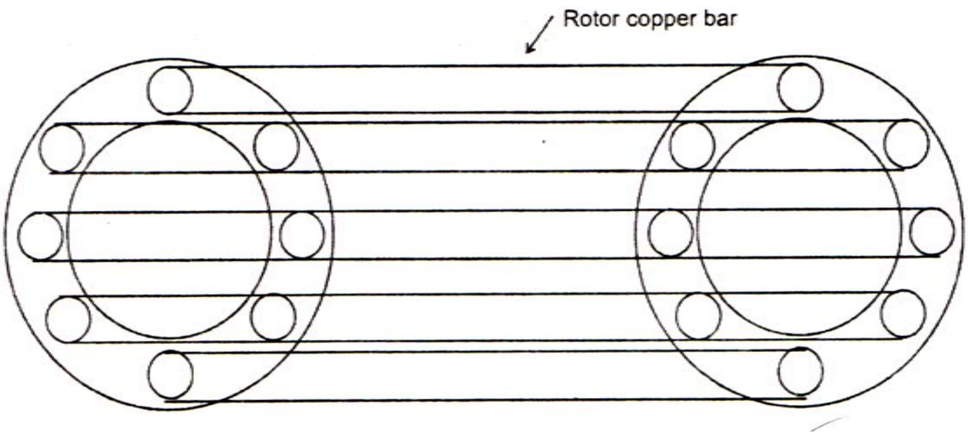


⟹ With Insulation $i = i_1 = i_2 = i_3 = i_4$

❖ ***Stator winding***

- Insulated copper conductors used to form stator winding.
- Stator winding placed inside the slot and around the pole.
- Stator winding excited by AC supply to develop magnetic flux.
- Types of windings: 1. Lap winding 2. Wave winding
- Lap winding can be used for high speed applications and number of parallel paths is equal to number magnetic poles (A= No. of mag. poles)
- Wave winding can be used for medium and low speed supplications and number of parallel paths is equal to number magnetic poles (A= 2)

Rotor



- This is a laminated stamped core, manufactured by using silicon steel.
- It contains several numbers of slots and outward projected poles.
- The rotor conductors are heavy bars of copper, short circuited at both ends by end rings.
- Hence this rotor is also called a short circuited rotor.
- The entire rotor resistance is very small.
- External resistance cannot be connected in the rotor circuit.

Shaft and Other mechanical parts

- Solid iron bar used as shaft.
- shaft is used to provide mechanical support to armature and commutator arrangement

* And also used to deliver mechanical output (motor) and used to collect the mechanical input (generator)
* Cooling fans, Bearings, centrifugal switch and End shields are placed around the shaft at both ends.

  Cooling fan : To provide cooling by circulate fresh air.

  Bearing : To reduce mechanical friction.

  centrifugal switch: To disconnect the auxiliary winding from excitation.

  End shields : To protect the internal parts from external environment.

Working principle of Single phase induction

* The stator winding is excited by single phase AC supply.
* Then a magnetic field is developed in the stator.
* As per faraday electromagnetic induction law,emf induced in rotor conductors.
* The direction of the current is to oppose the stator mmf and the torque angle is zero and no starting torque is developed in the motor.
* From the principle of operation, the single phase induction motor has no self starting torque. This can be explained in two ways.
    1) Double revolving field theory
    2) Cross field theory

Double revolving field theory

* The alternating flux ϕ_m produced in the single phase induction motor.
* ϕ_m can be represented by two equal and opposite revolving fluxes $\frac{\phi_m}{2}$, $\frac{\phi_m}{2}$ and each rotating synchronously $N_S = \frac{120\,f}{p}$ in opposite directions.

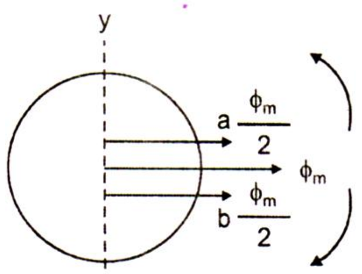


Figure 1

* Fig.1 shows the vectors when they have been rotated by an angle $+\theta$ and$+\theta$

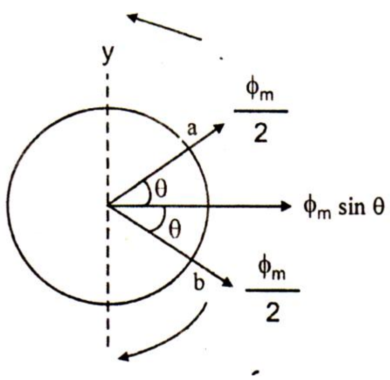


Figure 2

* The resultant flux would be $2 \times \frac{\varphi_m}{2} \frac{\sin 2\theta}{2} = \varphi_m \sin\theta$.
* After a quarter cycle of rotation, fluxes **a** and **b** will be oppositely directed as shown in fig.3

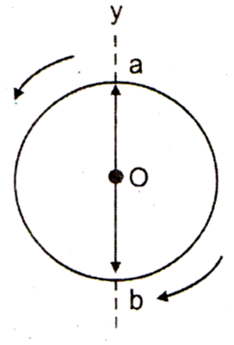


Figure 3

* The resultant flux is now zero.
* After half cycle, fluxes **a** and**b** will have resultant of $-2 \times \frac{\varphi_m}{2} = -\varphi_m$ which is shown in figure 4.

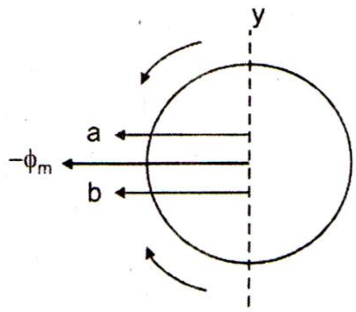


Figure 4

* After three quarters of a cycle, again the resultant is zero as shown in fig 5.

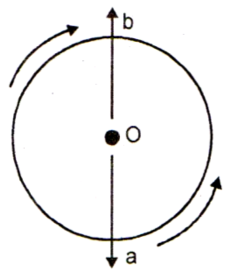


Figure 5.

* So the flux variation is $\varphi_m, 0, -\varphi_m, 0$. this flux variation with respect to θ is plotted which is shown in figure 6.

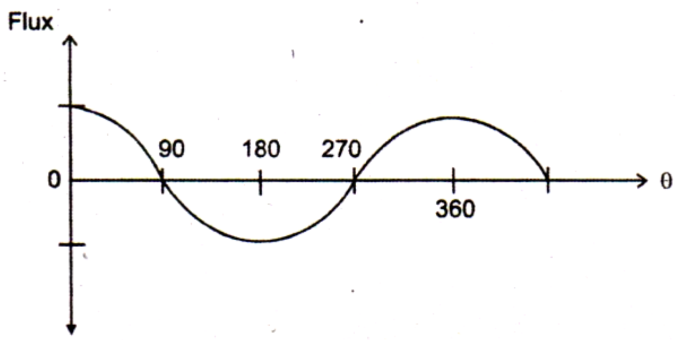
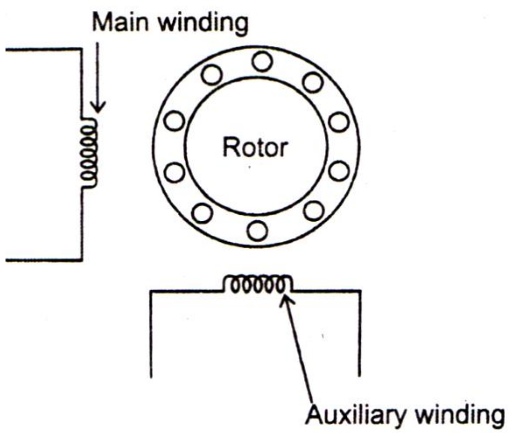


Figure 6

* Thus an alternating flux can be looked upon as composed of two revolving fluxes each of half the values and revolving synchronously in opposite direction.
* The slip of the rotor is given by $s_b = \frac{N_S - N}{N_S}$

Starting of single-phase induction motor

* Auxiliary winding is provided and motor starts as a two phase motor.
* The main winding axis and auxiliary winding axis are displaced by 90 electrical degrees.
* As a result of this, a rotating stator field is produced and the rotor rotates.
* When the motor speed is about 75% of synchronous speed, the auxiliary winding is disconnected from the circuit by centrifugal switch.
* Now single phase induction motor can develop torque by main winding only, called running winding.

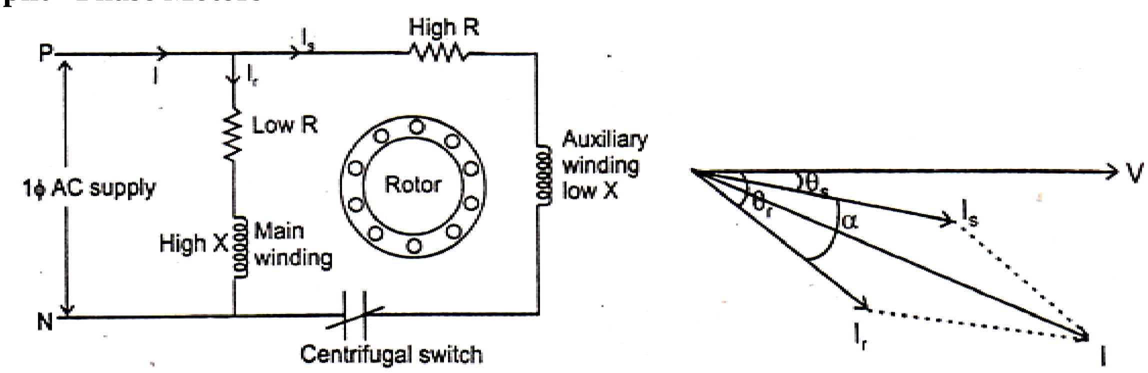


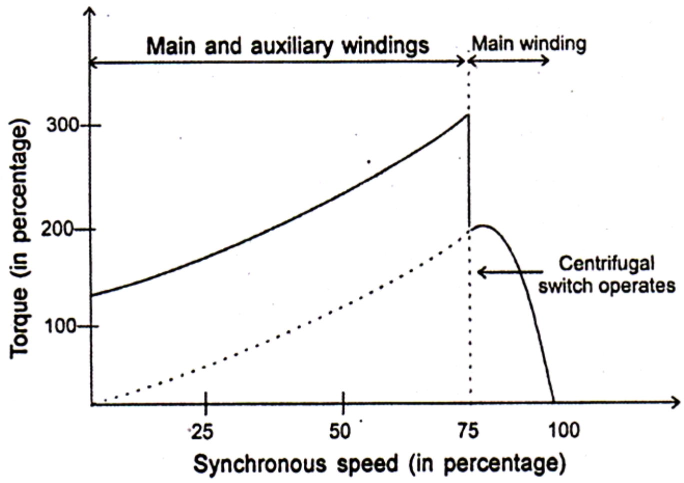
Types of single-phase induction motor

* The auxiliary winding has high resistance and low reactance and main winding has low resistance and high reactance.
* Speed-torque characteristic of split-phase induction motor shows that after 75% of the rated speed only the main winding is present in the circuit.

* The classifications are
  1. Split—phase motors
  2. Capacitor — start motors
  3. Capacitor — run motors
  4. Capacitor - start and — run motors
  5. Shaded — pole motors

1) Split - Phase Motors

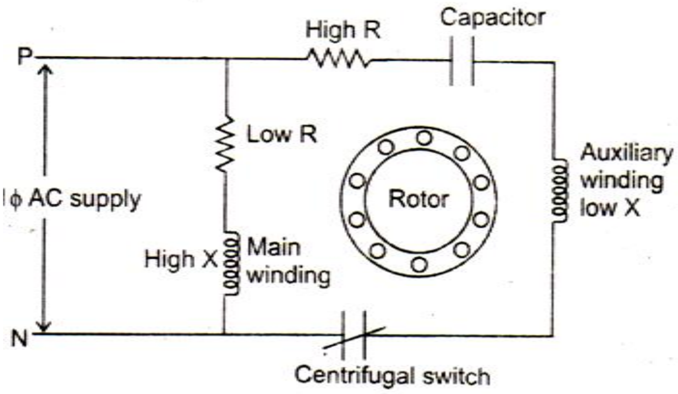


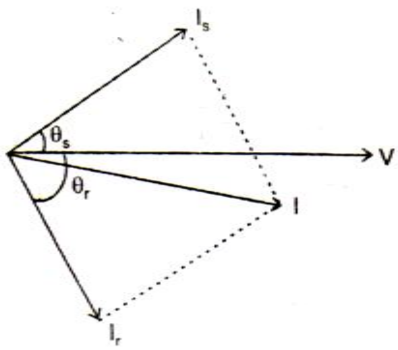


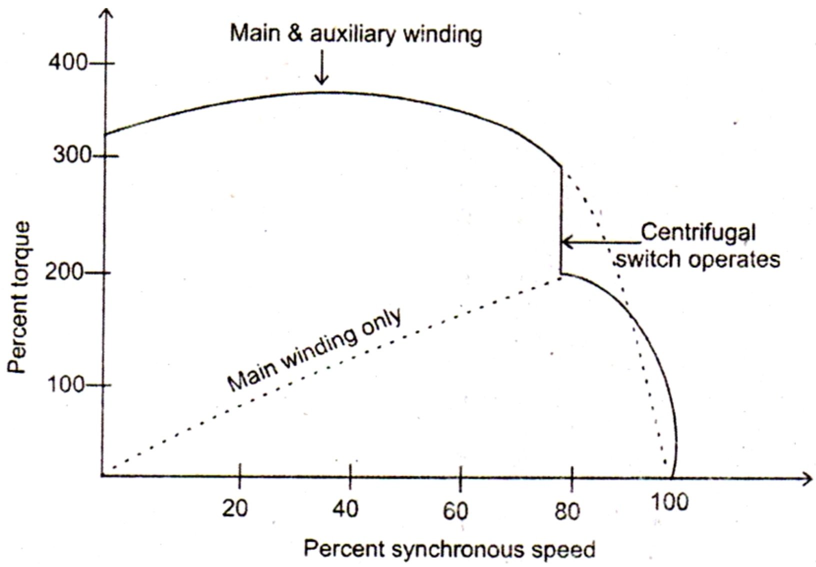
* The characteristics of this motor are,
    1. The starting torque is 100% to 250% of the rated value.
    2. The breakdown torque is upto 300%. of the rated value
    3. The power factor of this motor is 0.5 to 0.65.
    4. The efficiency of the motor is 55% to 65%.
    5. The power rating of this motor is in the range of 0.5 to 1 HP.
* The applications are

1) fans
2) blowers
3) centrifugal pumps
4) Washing machines

2) Capacitor start single phase Induction motor



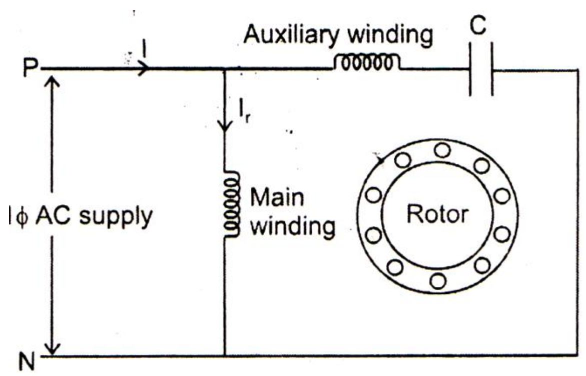


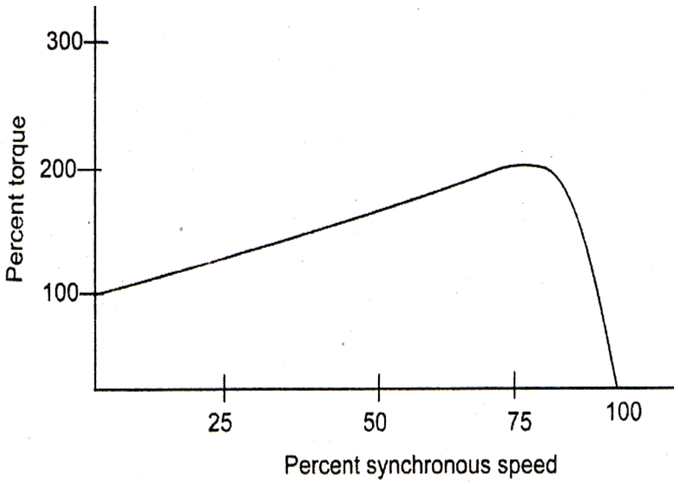


* Characteristics of these motorsare
    1. The starting torque is 250% to 400% of the rated value.
    2. The breakdown torque is upto 350%. of the rated value.
    3. Power factor of the motor is 0.5 to 0.65.
    4. The efficiency of the motor is 55% to 65%.
* The applications are

1. Compressors.
2. Pumps
3. Conveyors
4. Refrigerators
5. Air conditioning equipments
6. Washing machines

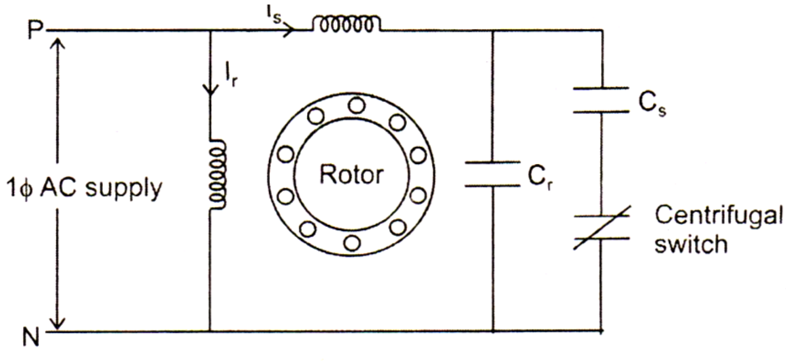
3) Capacitor- Run motor

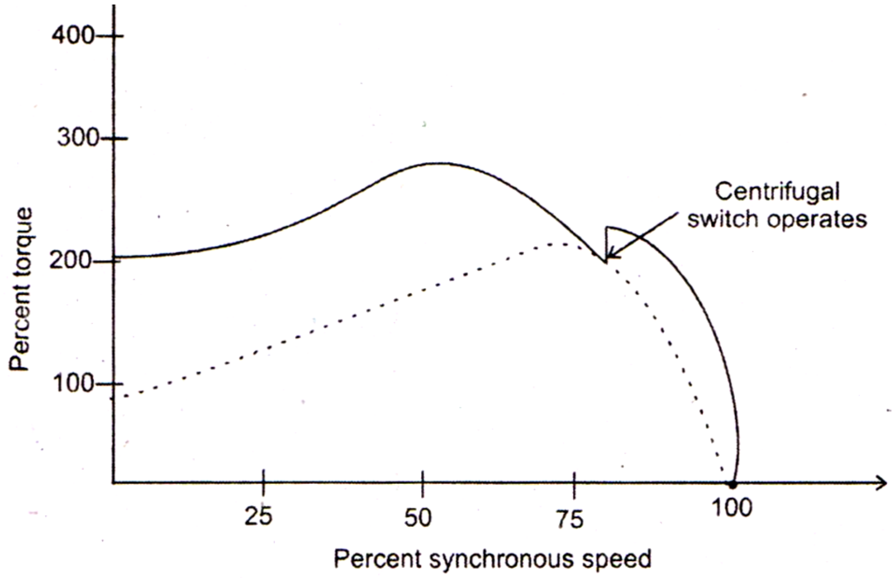




* Characteristics of these motorsare
    1. The starting torque is 100% to 200% of the rated value.
    2. The breakdown torque is upto 250%. of the rated value.
    3. The power factor of the motor is in the range of 0.75 to 0.9.
    4. The efficiency of the motor is 60 to 70%.
* The applications are
    1. Fans
    2. Blowers
    3. Centrifugal pumps

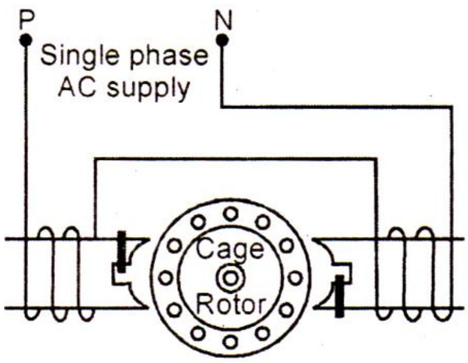
4) Capacitor-start Capacitor-run motor





* The Characteristics are
  1. The percentage of starting torque is 200% to 300% of rated value
  2. The rated breakdown torque is upto 250% of rated value
  3. The power factor of the motor is in the range of 0.75 to 0.9.
  4. The efficiency of the motor is 60 to 70%.
* The applications,
  1. Compressors
  2. Pumps
  3. Conveyors
  4. Refrigerators

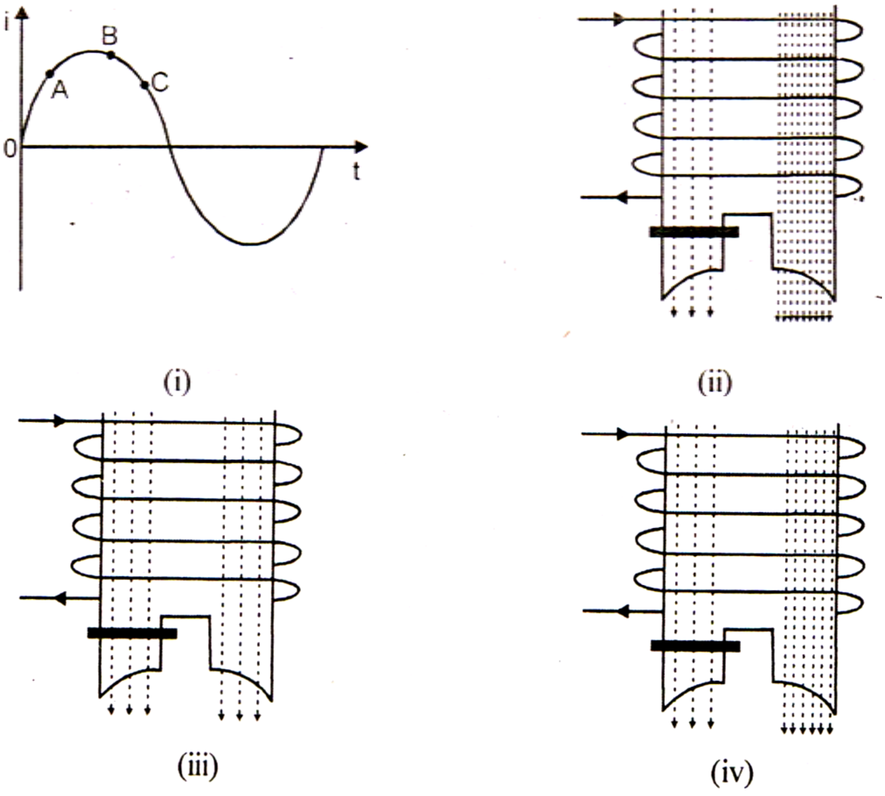
5) Shaded Pole Motor



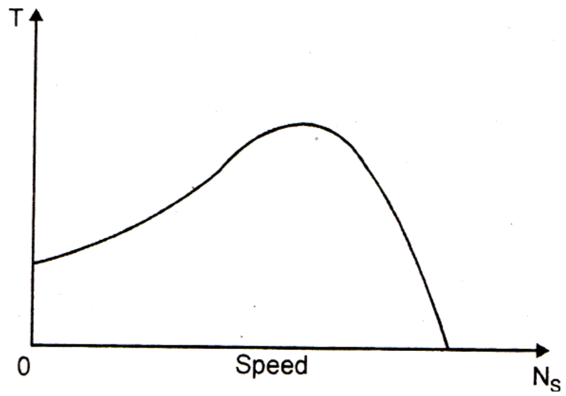
Operation

- During the portion OA of the alternating current cycle the flux begins to increase and an emf is induced in the shading coil.
- The resulting current in the shading coil will be in such a direction as to oppose the change in flux. Thus the flux in the shaded portion of the pole is weakened while that in the un shaded portion is strengthened as shown in figure (ii).
- During the portion A B of the alternating current cycle, the flux has reached almost maximum value and is not changing. Consequently, the flux distribution across the pole is uniform since no current is flowing in the shading coil shown figure (iii).
- As the flux decreases i.e. portion BC of the alternating current cycle, current is induced in the shading coil so as to oppose the decrease in current.

➢ Thus the flux in the shaded portion of the pole is strengthened while that in the un-shaded portion is weakened as shown in figure (iv).



* The shading coil is used to shift the field flux,across the pole face from the un-shaded to the shaded portion.
* The squirrel cage rotor placed in moving magnetic field. So, a small starting torque is developed.
* This torque starts to revolve the rotor; additional torque is produced by single phase induction motor action.
* The characteristics of these motors are
    1. The starting torque is 40% to 60% of rated value
    2. The breakdown torque is upto 140% of rated value
    3. The power factor of the motor is in the range of 0.25 to 0.4.
    4. The efficiency of the motor is 25% to 40%.
    5. The power rating of the motor ranges upto 40 W.



* The main applications of these motors are for loads requiring low starting torque such as
    1. Fans
    2. Blowers
    3. Turntables
    4. Hair driers
    5. Motion picture projectors

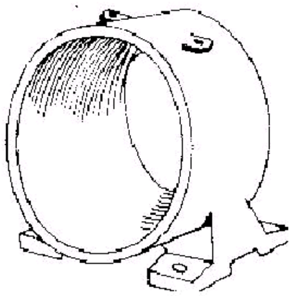
Three phase induction motor

Construction of three phase induction motor

* The main parts of single phase induction motor,
  1. Yoke
  2. Stator core and windings
  3. Rotor core
  4. Shaft and Other mechanical parts

Yoke.

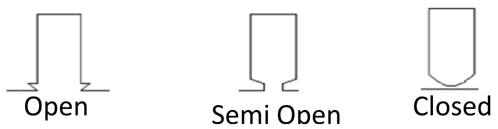
* Manufactured by using cast iron material. Cast iron has high mechanical strength and corrosion free characteristics.
* Used to provide mechanical support to all internal parts and protect from external environment.

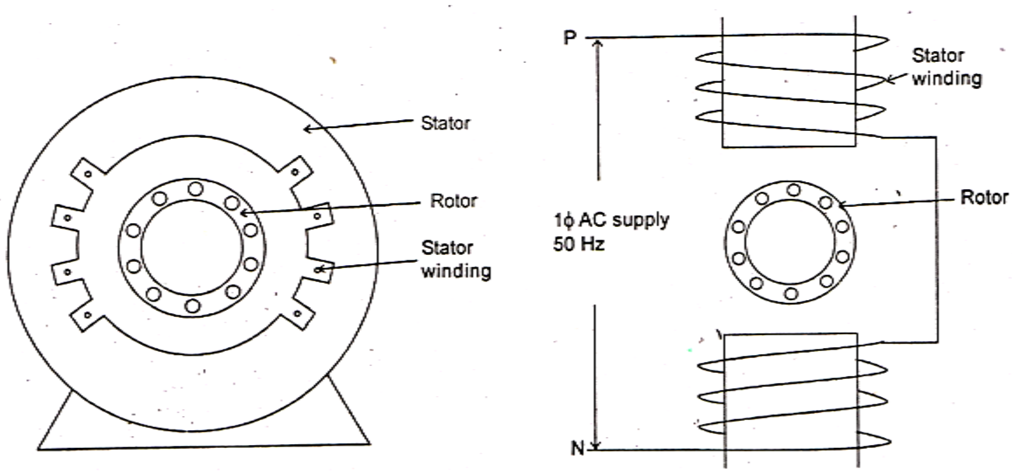


Stator core and windings

❖ ***Stator core***

* Stator core is used to hold field winding and used to provide magnetic flux path.
* This is a laminated stamped core, manufactured by using silicon steel.
* It contains several numbers of slots and inward projected poles.
* Types of slots are open, semi open and closed.



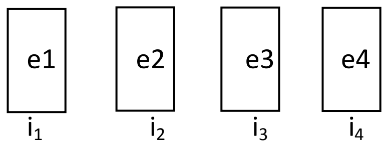


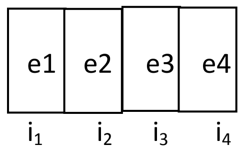
➢ **Hysteresis loss**

* To reduce hysteresis loss (H_{loss}),theflux density (B) has to be reduced. ($H_{loss} \alpha$ B)
* To reduce flux density (B), the flux path area (a) has to be increased. $(B \, \alpha \frac{1}{a})$
* For increasing flux path area large number of stamping are used to form a core instead of solid core.

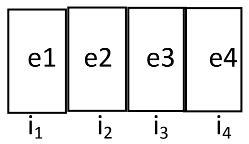
➢ **Eddy current loss**

- Due to flux linkage each stamping induces a minimum voltage (e) and a minimum circulating current (i_e) starts to circulate in each closed stamping.
- To reduce eddy current loss all stampings are insulated by using a thin layer of warmish coating and then stamped.





⟹ Without Insulation $i = i_1 + i_2 + i_3 + i_4$



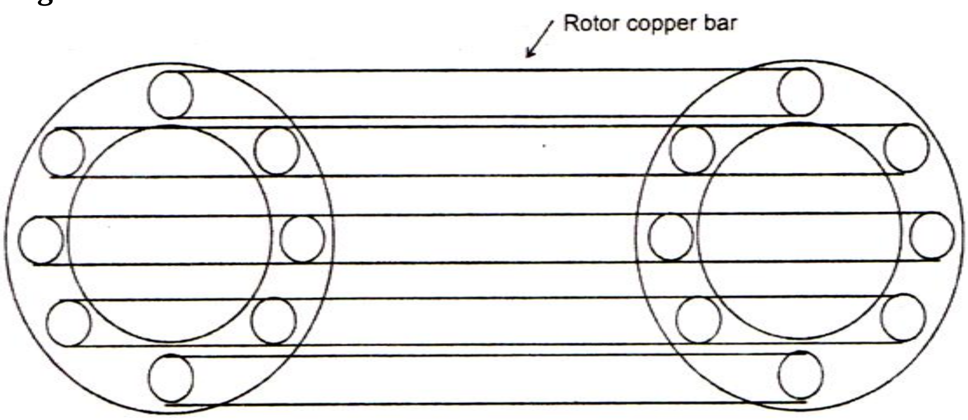
⟹ With Insulation $i = i_1 = i_2 = i_3 = i_4$

❖ ***Stator winding***

- Insulated copper conductors used to form stator winding.
- Stator winding placed inside the slot and around the pole.
- Stator winding excited by AC supply to develop magnetic flux.
- Types of windings: 1. Lap winding 2. Wave winding
- Lap winding can be used for high speed applications and number of parallel paths is equal to number magnetic poles (A= No. of mag. poles)
- Wave winding can be used for medium and low speed supplications and number of parallel paths is equal to number magnetic poles (A= 2)

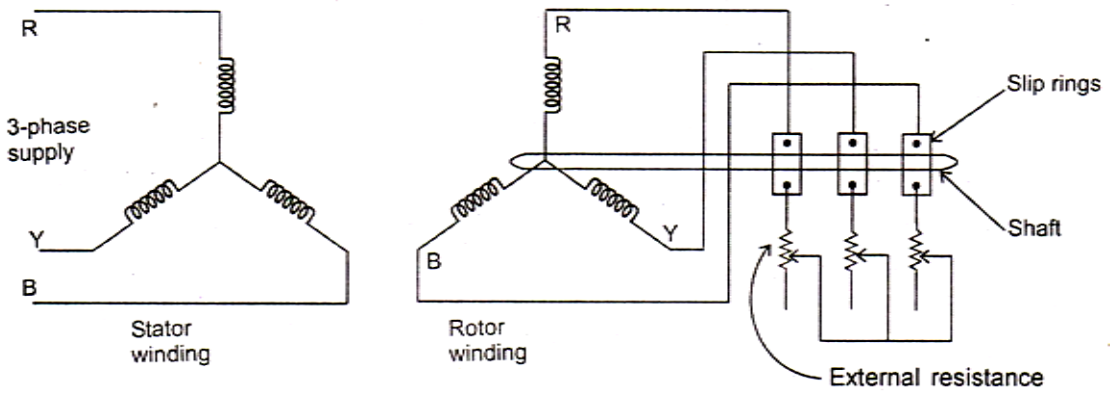
Rotor

1. **Squirrel cage rotor**



- This is a laminated stamped core, manufactured by using silicon steel.
- It contains several numbers of slots and outward projected poles.
- The rotor conductors are heavy bars of copper, short circuited at both ends by end rings.
- Hence this rotor is also called a short circuited rotor.
- The entire rotor resistance is very small.
- External resistance cannot be connected in the rotor circuit.

2. Slip ring or wound rotor



* In this type of rotor, rotor windings are similar to the stator winding.
* The rotor winding may be star or delta connected, distributed winding.
* The three phases are brought out and connected to slip rings mounted on the rotor shaft.
* Variable external resistance can be connected in the rotor circuit, with the help of brushes and slip ring arrangements.
* By varying the external resistance, the motor speed and torque can be controlled.
* This motor is called slip ring induction motor or wound rotor induction motor.

Shaft and Other mechanical parts

* Solid iron bar used as shaft.
* shaft is used to provide mechanical support to armature and commutator arrangement
* And also used to deliver mechanical output (motor) and used to collect the mechanical input (generator)
* Cooling fans, Bearings and End shields are placed around the shaft at both ends.
  Cooling fan : To provide cooling by circulate fresh air.
  Bearing : To reduce mechanical friction.
  End shields : To protect the internal parts from external environment.

Comparison of Squirrel Cage and Slip Ring Induction Motor

Sl.No	Squirrel cage induction motor	Slip ring induction motor
1.	Low starting torque	Much higher starting torque (by inserting resistances in rotor circuit)
2.	No slip rings, brush gears, etc	Extra slip rings, brush gears, etc
3.	Cheaper	Higher cost
4.	Minimum maintenance	Higher degree of maintenance
5.	Comparatively high efficiency	Comparatively lower efficiency.
6.	No speed control.	Speed control (by varying resistance in the rotor circuit).
7.	Carmot be used for loads demanding high starting torque	Capable of starting with load demanding high starting torque.
8.	Higher starting current (5 to 6 times the full load current)	Comparatively lesser starting current (2 to 3 times the full load current
9.	. Needs a starter	Can be started directly on line (resistance in the rotor circuitacts like a starter and reduces the starting current)
10.	Rugged in construction	Construction somewhat different from squirrel cage induction motor

Concept of rotating magnetic field

* A balanced 3 phase voltage is applied to a balanced 3 phase winding; it produces a rotating magnetic field of constant amplitude.
* The expressions for instantaneous values of the three fluxes are given by

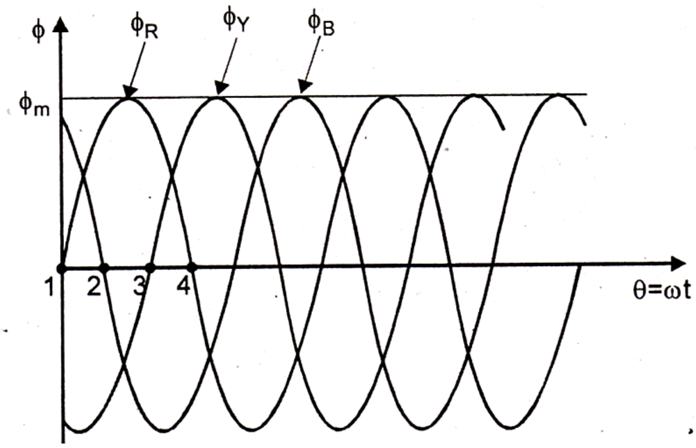
$$\varphi_R = \varphi_m \sin \omega t \qquad \ldots\ldots\ldots\ldots(1)$$

$$\varphi_Y = \varphi_m \sin (\omega - 120^\circ) \qquad \ldots\ldots\ldots\ldots(2)$$

$$\varphi_B = \varphi_m \sin (\omega - 240^\circ) \qquad \ldots\ldots\ldots\ldots(3)$$

* The resultant flux is (φ_{RES})

$$\overline{\varphi_{RES}} = \overline{\varphi_R} + \overline{\varphi_Y} + \overline{\varphi_B}$$



Case 1:

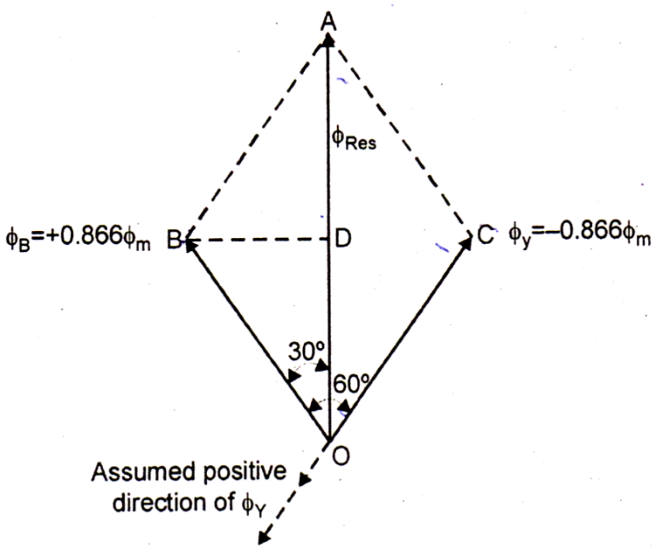
$\omega t = \theta = 0^o$

Substituting $\omega t = \theta = 0^o$ in equations (1), (2) and (3), we get,

$$\varphi_R = \varphi_m \sin \omega t = 0$$

$$\varphi_Y = \varphi_m \sin (-120^\circ) = -0.866\ \varphi_m$$

$$\varphi_B = \varphi_m \sin (-240^\circ) = +0.866\ \varphi_m$$



* Figure shows the phasor addition of the above three fluxes. From the figure, we get

$$OD = DA = \frac{\varphi_{RES}}{2}$$

$$\angle BOD = 30^\circ$$

Therefore, $$\cos 30^\circ = \frac{OD}{OB} = \frac{\frac{\varphi_{RES}}{2}}{0.866\varphi_m}$$

$$\varphi_{RES} = 2 \times 0.866\ \varphi_m \times \cos 30^o = 1.5\,\varphi_m$$

* Therefore, the magnitude of φ_{RES} is $1.5\,\varphi_m$ and its position is vertically upwards.

Case 2:

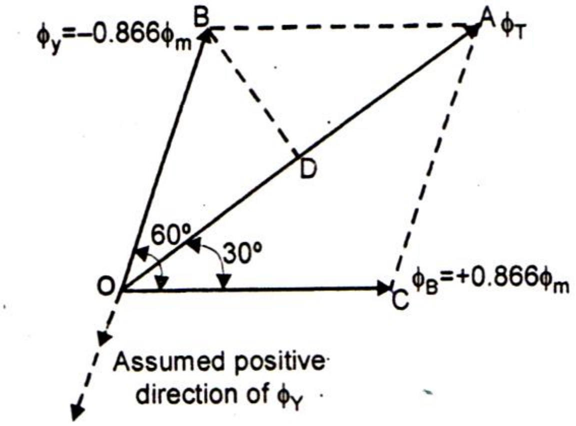
$\omega\, t = \theta = 60^o$

Substituting $\omega\, t = \theta = 60^o$ in equations (1), (2) and (3), we get,

$$\varphi_R = \varphi_m \sin 60^o = 0.866\ \varphi_m$$

$$\varphi_Y = \varphi_m \sin(60^o - 120^o) = -0.866\ \varphi_m$$

$$\varphi_B = \varphi_m \sin(60^o - 240^o) = 0$$



* Figure shows the phasor addition of the above three fluxes. From the figure, we get

$$OD = DA = \frac{\varphi_{RES}}{2}$$

$$\angle BOD = 30°$$

Therefore, $$\cos 30° = \frac{OD}{OB} = \frac{\frac{\varphi_{RES}}{2}}{0.866\varphi_m}$$

$$\varphi_{RES} = 2 \times 0.866\ \varphi_m \times \cos 30^o = 1.5\,\varphi_m$$

* Therefore, the magnitude of φ_{RES} is $1.5\,\varphi_m$ and it is rotated through 60° in space in clockwise direction compared to its previous position in case 1.

Case 3:

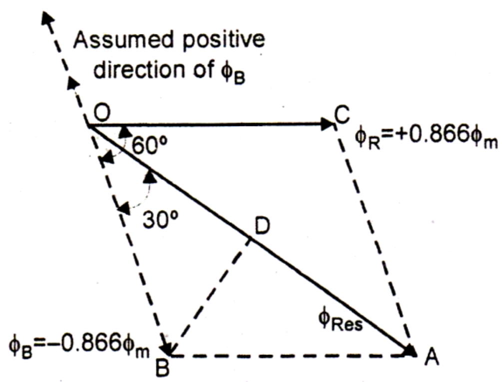
$\omega\, t = \theta = 120^o$

Substituting $\omega\, t = \theta = 120^o$ in equations (1), (2) and (3), we get,

$$\varphi_R = \varphi_m \sin 120^o = 0.866\ \varphi_m$$

$$\varphi_Y = \varphi_m \sin(120^o - 120^o) = 0$$

$$\varphi_B = \varphi_m \sin(120^o - 240^o) = -0.866\ \varphi_m$$



∗ Figure shows the phasor addition of the above three fluxes. From the figure, we get

$$OD = DA = \frac{\varphi_{RES}}{2}$$

$$\angle BOD = 30°$$

Therefore, $$\cos 30° = \frac{OD}{OB} = \frac{\frac{\varphi_{RES}}{2}}{0.866\varphi_m}$$

$$\varphi_{RES} = 2 \times 0.866\ \varphi_m \times \cos 30^o = 1.5\ \varphi_m$$

∗ Therefore, the magnitude of φ_{RES} is $1.5\varphi_m$ and it is rotated through 120° in space in clockwise direction compared to its previous position in case 1.

Case 4

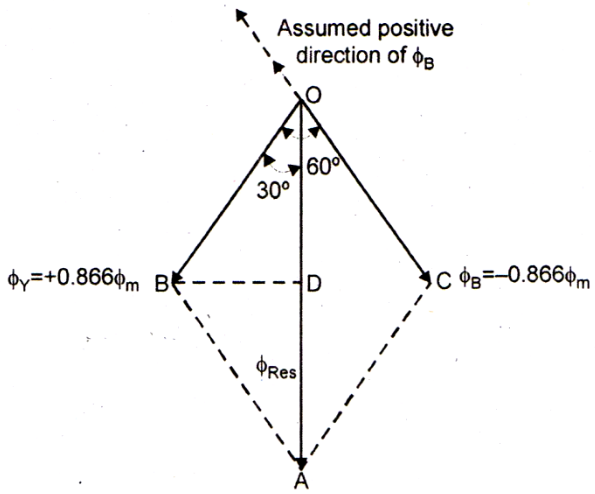
$$\omega t = \theta = 180^o$$

Substituting $\omega t = \theta = 180^o$ in equations (1), (2) and (3), we get,

$$\varphi_R = \varphi_m \sin 180^o = 0$$

$$\varphi_Y = \varphi_m \sin(180^o - 120^o) = 0.866\ \varphi_m$$

$$\varphi_B = \varphi_m \sin(180^o - 240^o) = -0.866\ \varphi_m$$



∗ Figure shows the phasor addition of the above three fluxes. From the figure, we get

$$OD = DA = \frac{\varphi_{RES}}{2}$$

$$\angle BOD = 30°$$

Therefore, $$\cos 30° = \frac{OD}{OB} = \frac{\frac{\varphi_{RES}}{2}}{0.866\varphi_m}$$

$$\varphi_{RES} = 2 \times 0.866\ \varphi_m \times \cos 30^o = 1.5\ \varphi_m$$

∗ Therefore, the magnitude of φ_{RES} is $1.5\varphi_m$ and it is rotated through 180° in space in clockwise direction compared to its previous position in case 1.

Principle of operation of three phase induction motor

∗ Three-phase supply is given to the stator winding.
∗ It produces a rotating magnetic field in the space between stator and rotor.
∗ This magnetic field rotates at synchronous speed given by,

$$N_S = \frac{120\,f}{p}$$

Where,

N_S = synchronous speed

f = supply frequency

p = number of poles for which the stator is wound.

- As a result of the rotating magnetic field cutting the rotor conductors, an emf is induced in the rotor and developed rotor magnetic field.
- The interaction of stator and rotor field develops torque.
- Then the rotor rotates in the same direction as the rotating magnetic field.
- The rotor runs at a speed slightly less than the synchronous speed. Therefore this machine is called an asynchronous machine.
- The difference between synchronous speed and rotor speed is called the slip speed.

$$\text{Slip speed} = N_S - N$$

$$\%\ \text{Slip}\quad s = \frac{N_S - N}{N_S} \times 100$$

$$\text{So}\quad N = N_s\,(1 - s)$$

Advantages of squirrel cage induction motor

- Cheaper.
- Light weight.
- Rugged construction.
- Higher efficiency.
- Requires less maintenance.
- It can be operated in dirty & explosive environment.

Disadvantages of squirrel cage induction motor

- Moderate starting torque.
- External resistance cannot be connected to rotor circuit. So starting torque cannot be controlled.

Applications of squirrel cage induction motor

- Used in lathes
- Drilling machines
- Fans
- Water pumps
- Grinders
- Printing machines etc.,

Advantages of slip ring induction motor

- The starting torque can be controlled by varying the rotor circuit resistance.
- The speed of the motor can also be controlled by varying the rotor circuit resistance

Disadvantages of slip ring induction motor

- Big size
- High cost.
- High speed limitation.
- Frequent maintenance

Frequency of rotor current or emf

$$\mathbf{f_r = s\,f}$$

Where, f_r = Rotor frequency, s = slip, f = Supply frequency

Torque equation

- The torque T is proportional to the product of the flux per pole and armature current

$$T \,\alpha\, \varphi\, I_a$$

- The flux and rotor current, the rotor power factor has also to be taken into account.

$$T \,\alpha\, \varphi\, I_{2r} \cos\phi_{2r}$$

Where,

φ = flux responsible to produce induced emf

I_{2r} = rotor current under running condition

$\cos\phi_{2r}$ = rotor power factor under running condition

- Let E_2 be the rotor induced emf per phase under standstill condition and X_2 be the rotor reactance per phase under standstill condition. Since the rotor frequency at a slip s is f_r = sf, the rotor reactance varies,

$$X_{2r} = sX_2$$

Also, $$E_2 \,\alpha\, \varphi$$

$$E_2 = sE_2$$

and $$I_2 = \frac{sE_2}{Z_{2r}} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\cos\phi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

- Hence the torque under running condition is,

$$T \,\alpha\, E_2 \times \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$T \,\alpha\, \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

$$T = \frac{KsE_2^2 R_2}{R_2^2 + (sX_2)^2} \qquad \text{N - M}$$

Where, K = constant of proportionality

$$K = \frac{3}{2\pi\, n_S}$$

n_S = synchronous speed in rps

At standstill, s = 1 and therefore the starting torque is,

$$T = \frac{K E_2^2 R_2}{R_2^2 + (X_2)^2} \qquad N - M$$

Condition for maximum torque

* Torque T for fixed input voltage will be maximum when $\frac{dT}{dt} = 0$

$$R_2^2 + (sX_2)^2 (KE_2^2 R_2) - (KsE_2^2 R_2) 2sX_2^2 = 0$$

i.e., $R_2 = s X_2$

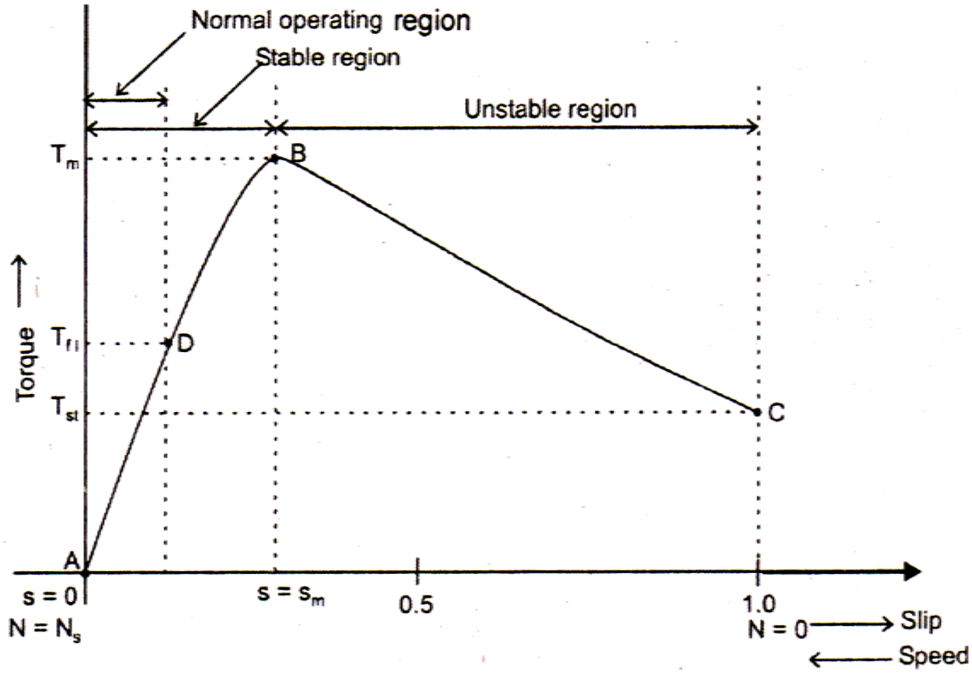
$s_m = \frac{R_2}{X_2}$ is the slip at which torque is maximum.

Then substituting $s = \frac{R_2}{X_2}$ in equation in torque equation, we have

$$T_{max} = \frac{KsE_2^2 sX_2}{2s^2 X_2^2}$$

$$T_{max} = \frac{KE_2^2}{2X_2} \qquad N - M$$

Torque - slip characteristics



* The curve drawn between torque
* Slip s = l => Starting torque
* Torque-slip characteristics of a three-phase induction motor consists three regions.
  1. Stable operating region
  2. Unstable operating region
  3. Normal operating region

Stable region

* In stable region, the slip value‘s’ is very small.
* The term $(sX_2)^2$ is very small as compared to R_2^2. Hence neglecting $(sX_2)^2$

$$T \,\alpha\, \frac{sR_2}{R_2^2} \quad \alpha \quad s \quad \text{as } R_2 \text{ is constand}$$

$$T \;\alpha\; s$$

* In this region, torque is directly proportional to slip

$$\text{Torque} \uparrow \;\Rightarrow\; \text{Speed} \downarrow \;\Rightarrow\; \text{slip} \uparrow$$

* It is indicated in curve AB.

Unstable region

* Here, the slip value is high
* The term $(sX_2)^2$ is very big as compared to R_2^2. Hence neglecting R_2^2

$$T \,\alpha\, \frac{s}{(sX_2)^2} \quad \alpha \quad \frac{1}{s} \quad \text{as } X_2 \text{ is constand}$$

$$T \;\alpha\; \frac{1}{s}$$

* In this region, torque is inversely proportional to slip

$$\text{Torque} \downarrow \;\Rightarrow\; \text{Speed} \downarrow \;\Rightarrow\; \text{slip} \uparrow$$

* It is indicated in curve BC.

Normal operating region

* The region (AD) is also called low slip region and operating region.
* The motor is continuously operated in this region.
* From this curve, we can understand the following terms.
    1. Starting torque (T_{st})
    2. Maximum torque or pull out torque (T_m)
    3. Full load torque (T_{FL})

Starting torque (T_{st})

* In torque-slip characteristics when the slip is 1 the speed is zero.
* At this condition the motor produces a torque called starting torque (T_{st})

Maximum torque (T_m)

* The torque which the motor produces at slip $s = s_m$ is called maximum torque.
* The maximum torque is also called the breakdown torque or pulls out torque.

Full load torque (T_{FL})

* In the slip-torque characteristics, the point D corresponds to full load torque of the motor.
* Normally full load torque is less than the maximum torque.