Single Phase Transformer

A transformer is a static device which consists of two or more stationary electric circuits interlinked by a common magnetic circuit for the purpose of transferring electrical energy between them without a change in frequency, using the principle of electro-magnetic induction.

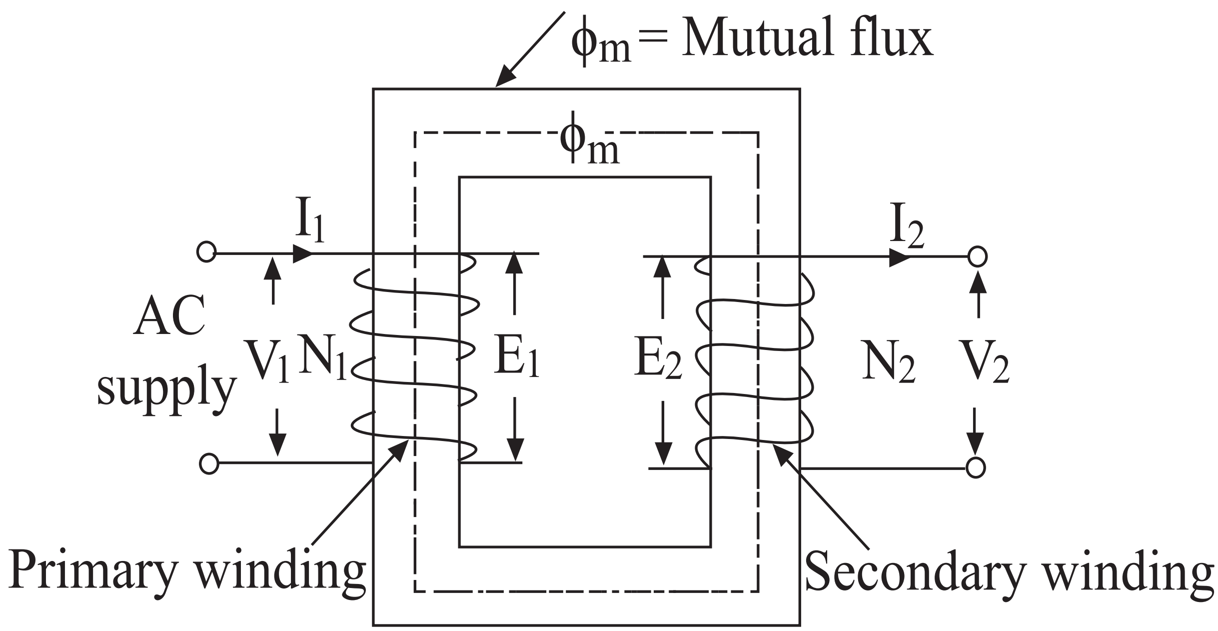


Figure : Two winding transformer

Step up Tranformer : $N_1 < N_2$, $V_1 < V_2$

Step down Transformer : $N_1 > N_2$, $V_1 > V_2$

Where, N_1 = Number of turns in primary side

N_2 = Number of turns in secondary side

V_1 = Voltage across primary side

V_2 = Voltage across secondary side

E_1 = emf developed in primary

E_2 = emf developed in secondary

Ideal Transformer

* Its primary and secondary winding resistances are negligible i.e., no copper losses.
* The core has infinite permeability (μ) so that negligible mmf is required to establish the flux in the core.
* All the flux set up by primary is linked with secondary i.e., no leakage flux.
* There are no losses due to hysteresis and eddy currents i.e., no core losses.

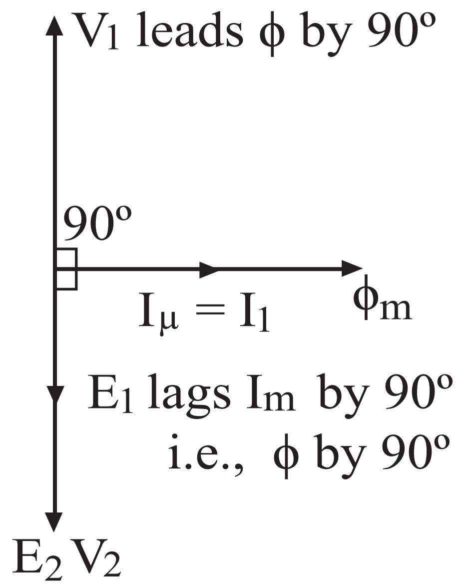


Figure : No-load phasor diagram of an ideal transformer.

For an ideal transformer

$$\frac{N_1}{N_2} = \frac{E_1}{E_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{1}{K} \text{ (Let)}$$

Also,

input kilovolt-Amperes = output kilovolt-Amperes

E.M.F. equation of a transformer

$$\mathbf{E = 4.44\, \phi_m\, f\, N \text{ volt}}$$

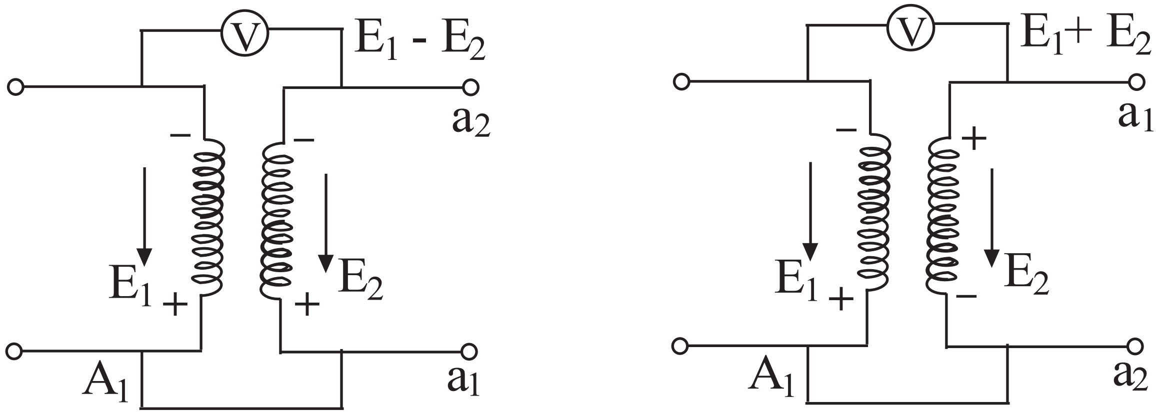
If, B_m = maximum flux density in the magnetic circuit (core) in tesla (T).

A = area of cross-section of the core in square meters (m^2)

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

Transformer Tests

* **Polarity test :** This test is done to check polarity between two winding of a transformer.



(a) Substractive polarity **(b) Additive polarity**

Figure : Polarity test on a two winding transformer.

* **Open-circuit (no-load) test**

This test gives the no-load iron loss or core loss of the transformer. It also gives the no-load current I_0 which is used to calculate the parameters equivalent exciting resistance (R_0) and equivalent exciting reactance (X_m). It is performed on I.v. side with h.v. side open.

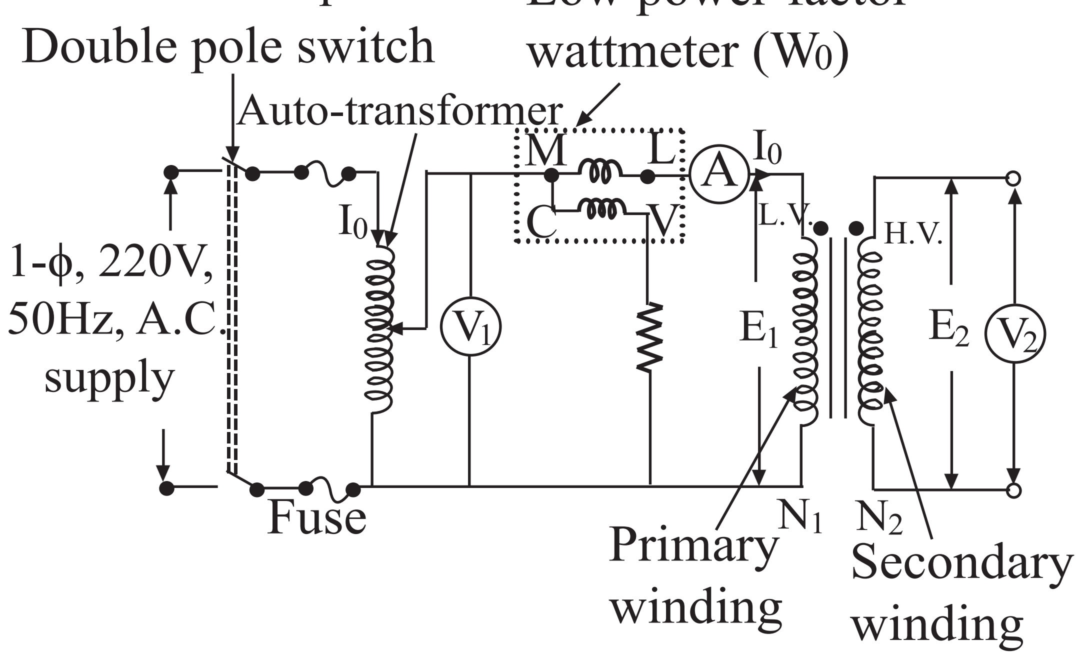


Figure : Open-circuit test on a transformer

ENTRI

Wattmeter reading of iron losses in power factor,

$$W_0 = V_1 I_0 \cos\phi_0 = P_i$$

From phasor diagram,

$$I_c = I_0 \cos\phi_0 \text{ and } I_m = I_0 \sin\phi_0$$

No load power factor,

$$\cos\phi_0 = \frac{W_0}{V_1 I_0} = \frac{I_c}{I_0}$$

$$R_0 = \frac{V_1}{I_c} \text{ and } X_m = \frac{V_1}{I_m}$$

Exciting admittance, $Y_0 = \dfrac{I_0}{V_1}$

Conductance, $G_0 = \dfrac{W_0}{V_1^2}$

Susceptance, $B_0 = \sqrt{Y_0^2 - G_0^2}$

(i) Hysteresis loss $P_h = k_1 B_{max}^{1.6} f$

(ii) Eddy current loss $P_e = k_2 B_{max}^2 f^2$

* **Short-circuit test**

This test is performed on h.v.side with short circuited the I.v. side.

This test is carried out to determine the following.

(i) Copper losses at full load (or at any desired load).

(ii) Equivalent impedance, resistance and leakage reactance of a transformer.

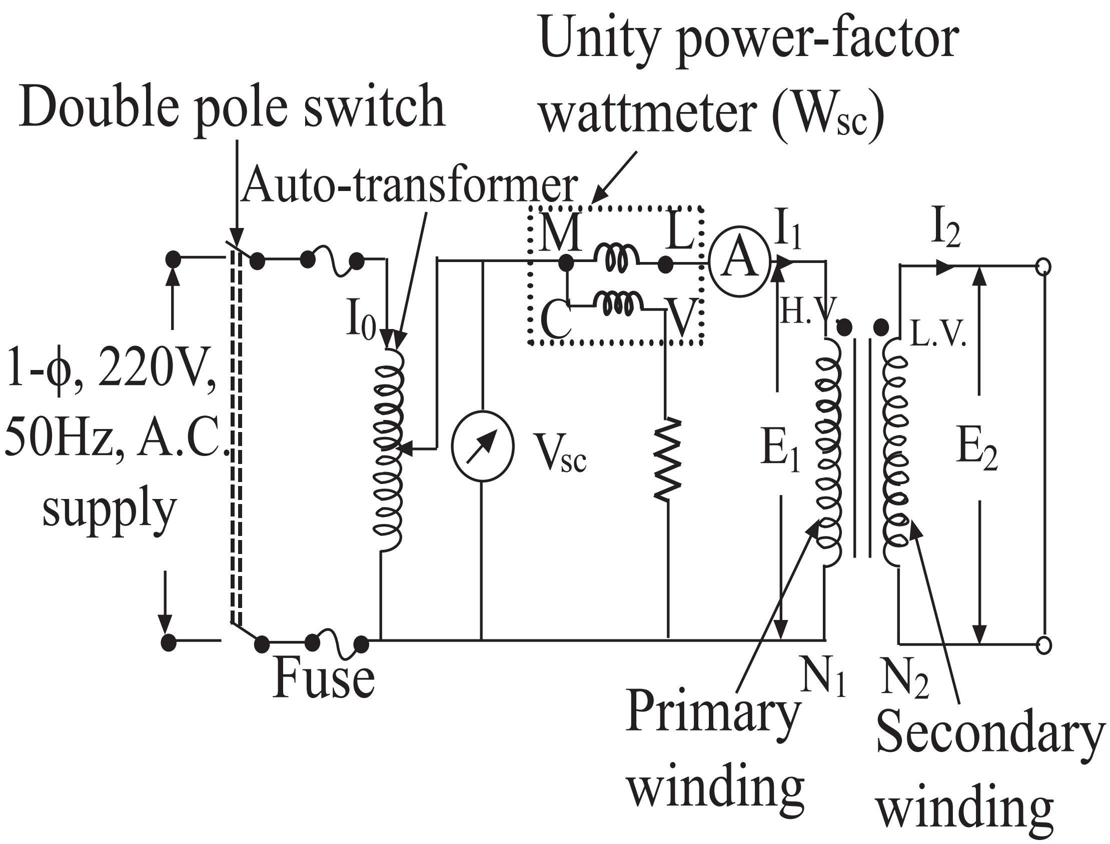


Figure : Short-circuit test on a transformer

Readings of wattmeter (when unity power factor),

$$W_{sc} = I_1^2 R_{01}$$

Equivalent impedance (referred to h.v. or primary side),

$$Z_{01} = \frac{V_{sc}}{I_1} \qquad \text{Equivalent resistance, } R_{01} = \frac{W_{sc}}{I_1^2}$$

Leakage reactance, $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

* **Sumpner's (Back to Back) test or load test**

This test needs two identical transformers and provides data for finding the regulation, efficiency and temperature rise under load conditions.

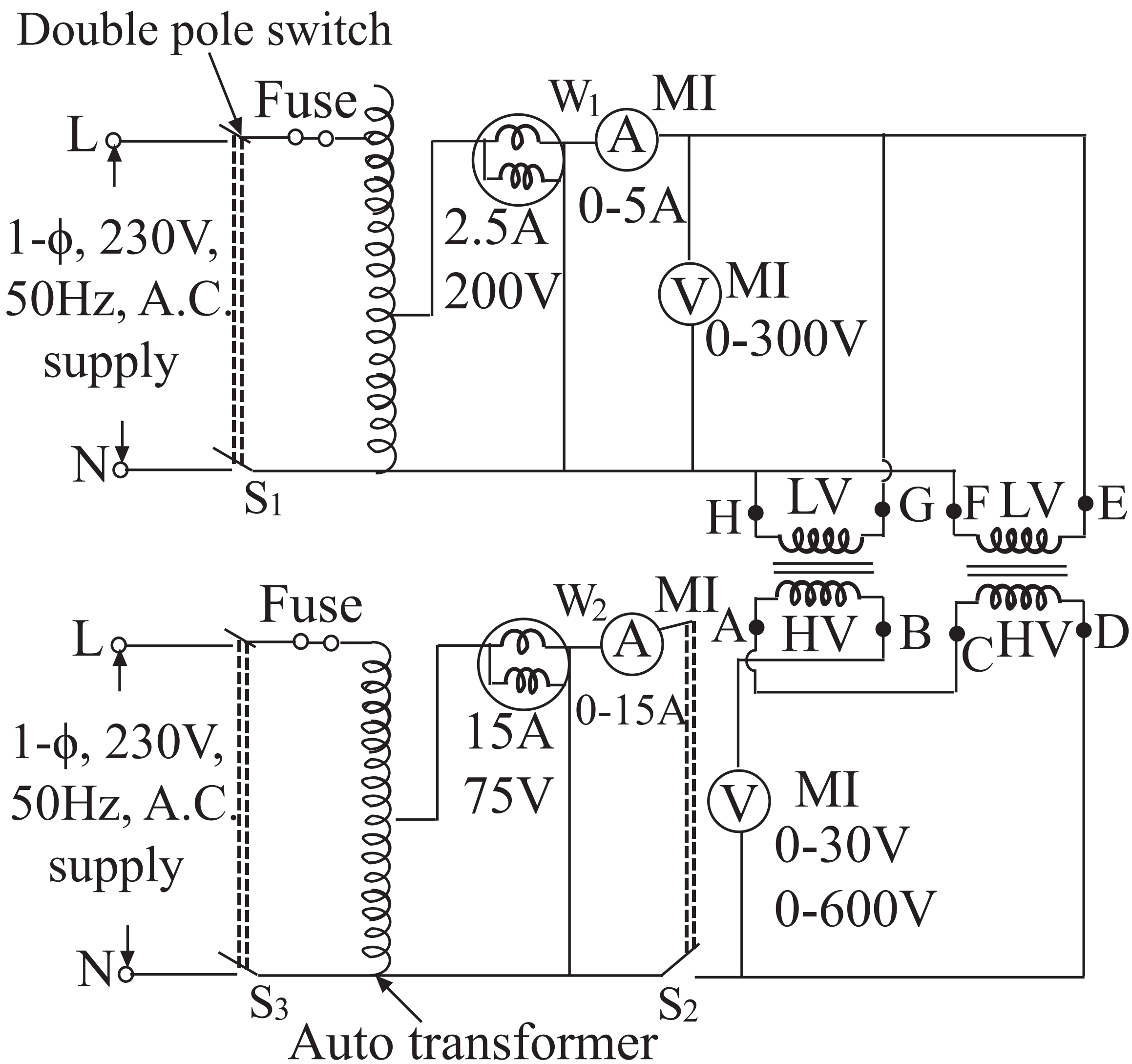


Figure : Sumpner's test on tranformer

Iton losses of each transformer $= \frac{1}{2} W_0$

where, W_0 is the reading of wattmeter W_1,

Full load copper losses of each transformer $= \frac{1}{2} W_c$

where, W_c is the reading of wattmeter W_2

Percentage efficiency at full load,

$$\% \eta_f = \frac{P_0 \times 1000 \times \cos\phi}{P_0 \times 1000 \times \cos\phi + \frac{1}{2} P_i + \frac{1}{2} P_{Cu}} \times 100$$

Efficiency at half-load

$$\% \eta_{\frac{1}{2}f} = \frac{\frac{1}{2} P_0 \times 1000 \times \cos\phi}{\frac{1}{2} P_0 \times 1000 \times \cos\phi + \frac{1}{2} P_i + \frac{1}{8} P_{Cu}} \times 100$$

Regulation and Efficiency

The voltage regulation of a transformer is defined as the arithmetical difference in the secondary terminal voltage between no-load ($I_2 = 0$) and full-rated load ($I_2 = I_{2fl}$) at a given power factor with the same value of primary voltage for both rated load and no-load.

$$\text{Voltage regulation down} = \frac{|V_{2nl}| - V_{2fl}|}{|V_{2nl}|}$$

$$\text{Voltage regulation up} = \frac{|V_{2nl}| - V_{2fl}|}{|V_{2fl}|}$$

Where, V_{2fl} = rated secondary terminal voltage at rated load.
V_{2nl} = no-load secondary terminal voltage with the same value of primary voltage for both rated load and no-load.

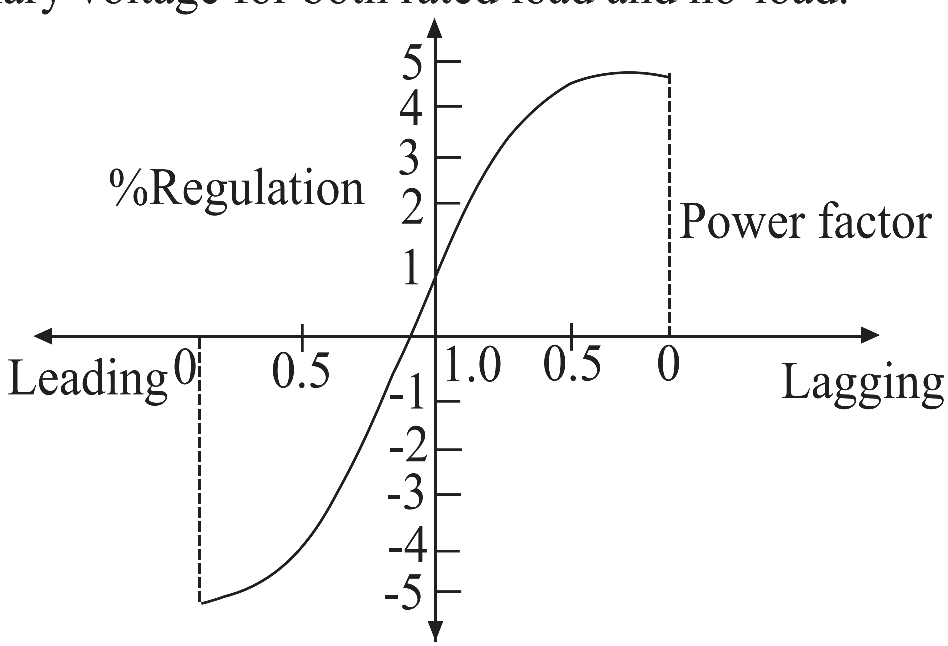


Figure : Variation of full load regulation with power factor.

Regulation at Unit Power Factor

$$\text{Voltage regulation} = \frac{|E_2| - |V_2|}{|V_2|}$$

Calculation of Voltage Regulation

1. Calculate as per unit voltage regulation

$$V_{2nl} = \frac{V_1}{K}$$

$$\frac{V_1}{K} = V_2 \angle 0^o + I_2 Z_{e2}$$

2. Calculate the voltage regulation in terms of primary values

$$= \frac{\left|\frac{V_1}{K}\right| - |V_{2fl}|}{|V_{2fl}|} \text{ pu}$$

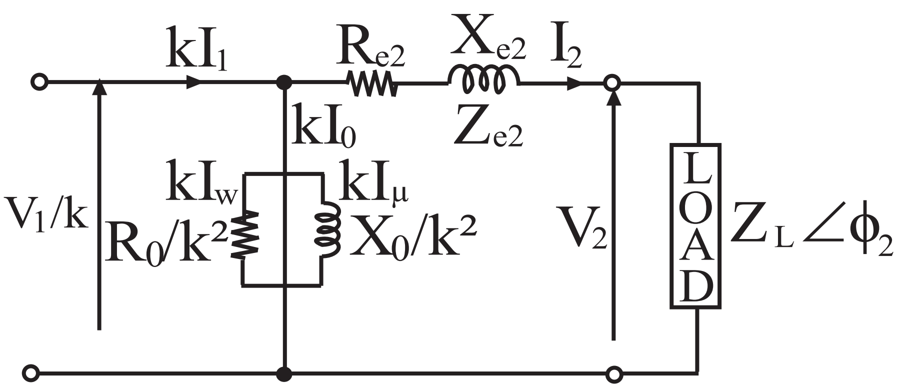


Figure : Equivalent circuit

3. Take V_2 as reference phasor

$$\therefore \quad V_2 = V_2 \angle 0^o = V_2 + j0$$

4. Write I_2 in phasor form

For lagging power-factor $\cos\phi$

$$I_2 = I_2 \angle -\phi_2 = I_2 \cos\phi_2 + jI_2 \sin\phi_2$$

For leading power-factor

$$I_2 = I_2 \angle +\phi_2 = I \cos\phi_2 + jI_2 \sin\phi_2$$

For unit power factor $I_2 = I_2 \angle 0^o = I_2 + j0$

5. Calculate Z_{e2} $Z_{e2} = R_{e2} + jX_{e2}$

Losses in Transformer

In a static transformer, there are no friction or windage losses. Hence, the only losses occuring are

(a) Core losses or iron losses and (b) Copper losses.

The core losses or iron losses consist of hysteresis and eddy current losses. The alternating flux gets set up in the core and it undergoes cycle of magnetisation and demagnetisation. Therefore, loss of energy occurs in this process due to hysteresis.

Hysteresis loss, $P_h = K_h f B_{max}^x$

Where K_h is hysteresis constant depending on the material,

B_m = Maximum flux density

f = Frequency

x = Steinmetz's constant (Varies from 1.5 to 2.5)

$$V \cong E = \sqrt{2}\pi f N B_{max} A$$

where, A = Net core area m².

$$B_{max} = \left(\frac{1}{\sqrt{2}\pi NA}\right) \cdot \left(\frac{V}{f}\right)$$

$$P_h = k_h V^x f^{(1-x)}$$

Eddy current loss, $P_e = K_e f^2 B_{max}^2$

Where, K_e is the eddy current constant.

Total core losses, $P_i = k_h V^x f^{1-x} + k_e V^2$

Core loss per cycle $= \frac{P_i}{f} = k_h B_{max}^x + k_e f \; B_{max}^2$

Total losses take place in transformer

* **Iron loss** occurs in the magnetic core of the transformer. This loss is the sum of P_h and P_e .
* **Total copper loss** in a transformer = primary winding copper loss + secondary winding copper loss

$$P_C = I_1^2 R_1 + I_2^2 R_2$$

* **Stray loss :** Eddy currents produce losses.
* **Dielectric loss** occurs in insulating materials, i.e., in the transformer oil and the solid insulation of transformers. This loss is significant only in high voltage transformer.

Transformer Efficiency

$$\text{Efficiency}(\eta) = \frac{\text{Output power}}{\text{Input power}} = 1 - \text{de-efficiency}$$

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

Energy efficiency of step down transformer all day.

$$= 1 - \frac{\text{Losses in kwh}}{\text{Inputy power in kwh}}$$

All day efficiency $= \dfrac{\text{Output in kWh for 24 hr}}{\text{Input in kWh for 24 hr}}$

Condition for maximum efficiency $\dfrac{d\eta}{dI_2} = 0$

Cu loss = Iron loss

Current at maximum efficiency =

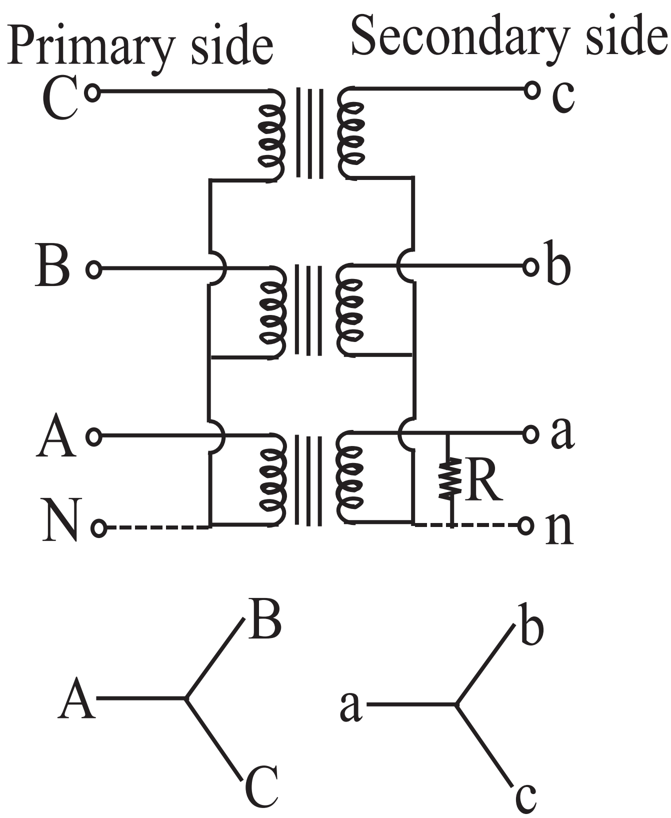
$$(\text{full-load current}) \times \sqrt{\frac{\text{Constant iron loss}}{\text{Full-load copper loss}}}$$

Three Phase Transformers

* Three phase transformers must have three windings connected in the proper sequence in order to match the incoming power and therefore transform the (high-/low) voltage to the useful voltage as per requirement and maintain the proper phasing or polarity.
* These windings are spaced 120 degrees apart. As the windings rotate through the magnetic field they generate power which is then sent out on three lines as in three-phase power.
* The transformers that work on the 3-phase supply have star, mesh or zig-zag connected windings on either primary, secondary or both.

  (i) Star/Star (Y/Y) connection :

  This is the most economical one for small, high-voltage transformers. This connection works satisfactory only for balanced load. This connection produces oscillating neutral.

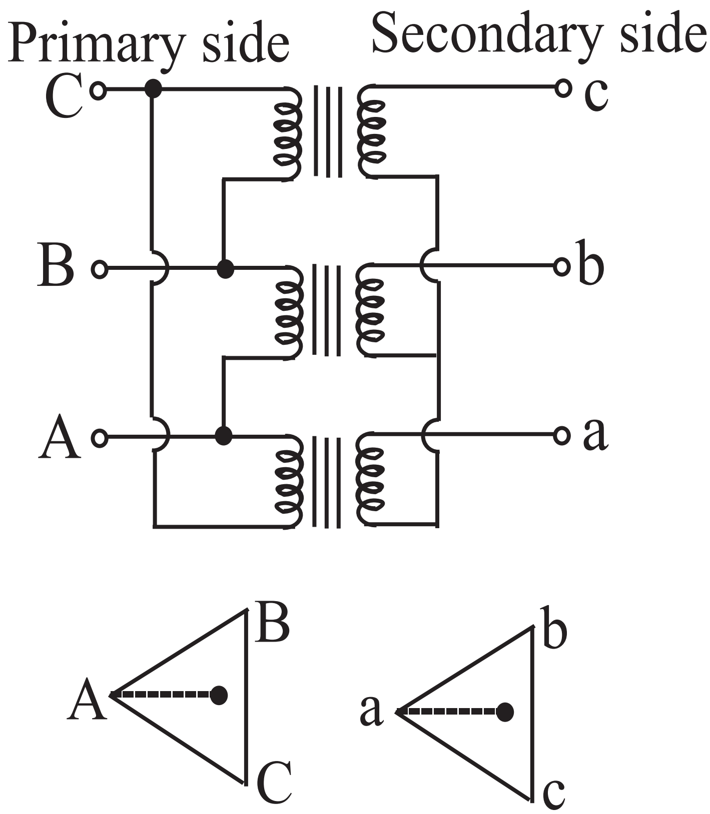


0° Angular Displacement

Figure : A bank of 3 transformers connected in star (Y) on both the primary and the secondary sides

(ii) Mesh/Mesh or Delta-Delta (Δ - Δ) connection :

This connection is economical for large, low-voltage transformers, where insulation problem is not very much important because it increases the number of turns/phase. There is no angular displacement between the primary voltage and secondary voltage and there is no internal phase shift between phase and line voltage on each side.

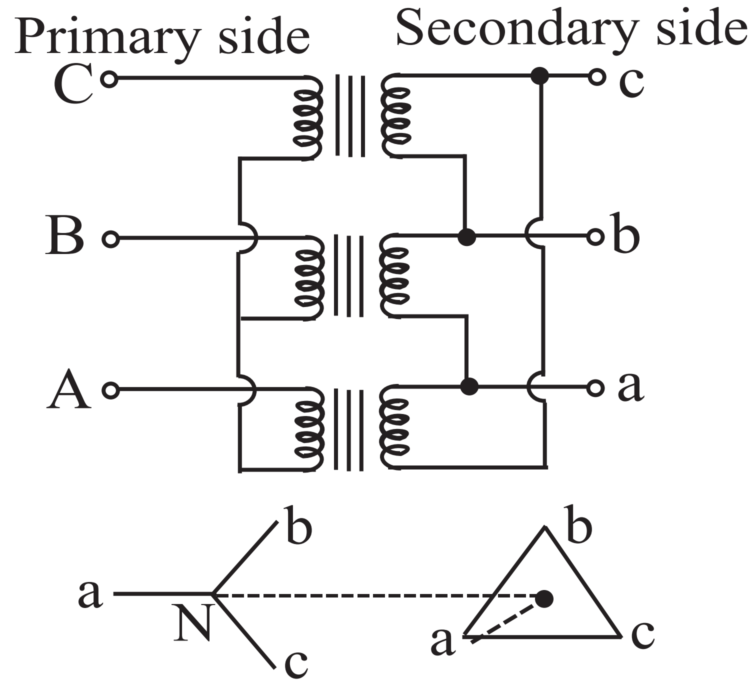


0º Angular Displacement

Figure : A bank of 3 transformers connected in Delta-Delta (Δ - Δ) connection on both the primary and the secondary sides.

(iii) Star/Delta or Wye/Delta (Y/Δ) connection :

At substation end of the transmission line where the voltage is to be stepped down, this type of connection is in use. There is to be stepped down, this type of connection is in use. There is a 30º phase shift between the primary and secondary line voltages.



0º Angular Displacement

Figure : A bank of 3 tranformer connected in Wye/Delta(Y/Δ)

Auto Transformer

It is an electrical transformer with only one winding. The portions of the same winding act as both the primary and secondary.

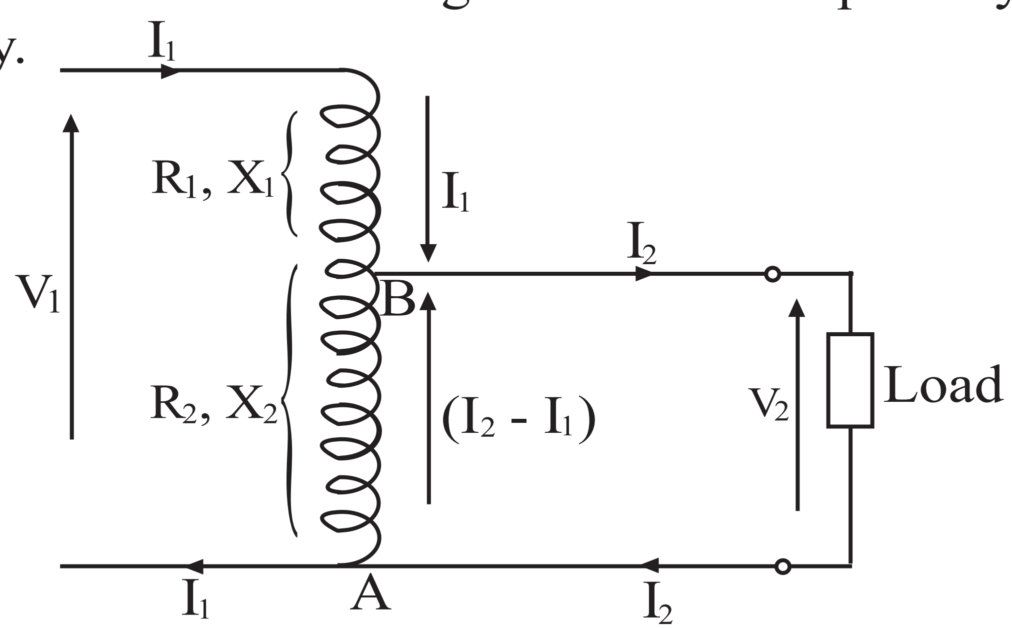


Figure : Equivalent circuit of auto transformer

N_1 = Total number of turns between A & C
N_2 = Total number of turns between A & B
V_1 = Primary applied voltage
V_2 = Secondary voltage across load
I_1 = Primary current
I_2 = Secondary load current
$V_1 : V_2 = N_1 : N_2$
$I_1 N_1 = I_2 N_2$

Conductor material saving in auto transformer

Weight of conductor material in section CB = $\alpha I_1 (N_1 - N_2)$
Weight of conductor material in section AB = $\alpha (I_2 - I_1) N_2$
Total weight of conductor material

$$\alpha[I_2 (N_1 - N_2) + (I_2 - I_1) N_2]$$

Saving of conductor material in using auto-transformer
= Transformation ratio × weight of two winding in conductor material.

DC Machines

* Whether a machine is d.c. generator or a motor the construction basically remains the same.
* The rotating part of the d.c. machine is called the armatue.
* The stator of the machine does not move and normally it is the outer frame of the machine.
* The rotor is free to move and normally it is the inner part of the machine.
* The winding through which a current is passed to produce the main flux is called the field winding.

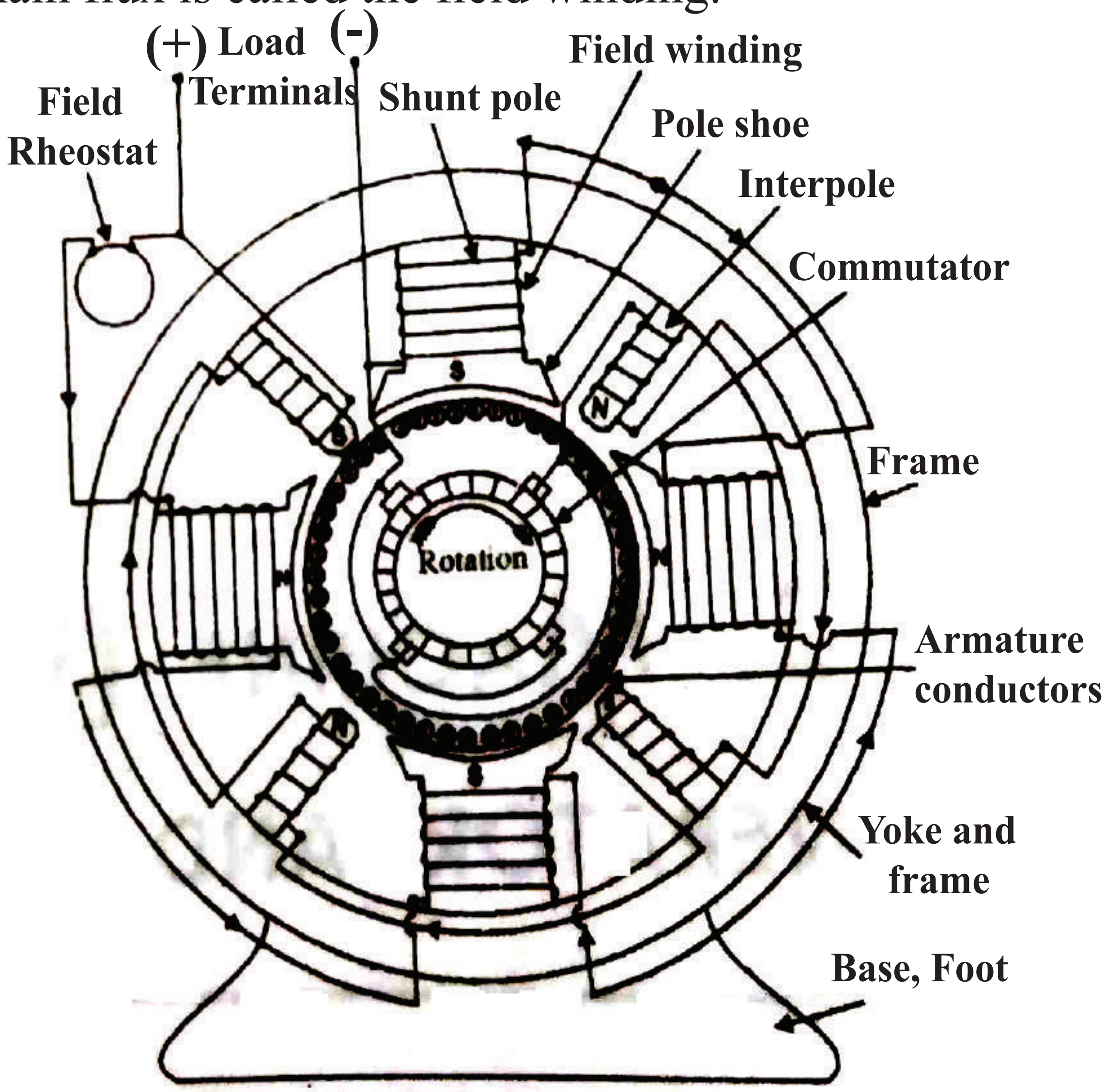


Figure : A cross-section of typical 4 pole d.c. machine.

Any rotating machine in its basic form consists of 2 main parts.

1. Stator
2. Rotor

1. Stator Part

* **Functions of Yoke**

(i) It provides mechanical support for the poles and acts as a protecting cover for the whole machine, so that the insulating materials get protected from harmful atmospheric elements like moisture, dust and various gases like SO_2, acidic fumes etc.

(ii) It carries the magnetic flux produced by the poles. Basically it provides a path of low reluctance for magnetic flux to avoid wastage of power. High reluctance path draw high current and hence high power to produce the same flux.

(iii) It provides path for the poles flux ϕ and carries half of it, i.e., $\phi/2$.

(iv) Yoke is made by fabricated steel for large dc machine.

* **Functions of Pole Core and Pole Shoe**

(i) Pole core basically made from (1.5 mm) thick cast steel and carries a field winding which is necessary to produce the flux.

(ii) It directs the flux produced through air gap to armature core, to the next pole.

(iii) Pole shoe enlarges the area of armature core to come across the flux, which is necessary to produce larger induced e.m.f.

* **Function of Field Winding or Exciting Winding**

(i) To carry current due to which pole core, on which the field winding is placed behaves as an electromagnet, producing necessary flux. It is prepared from copper.

(ii) Field winding is mainly three types which depend on types of machines.

(a) For dc series machines : Small no. of turns of large cross-section are used or thick wire is used.

(b) For dc shunt machines : Large no. of tuns of small cross-section or thin wire is used.

(c) For dc compound machines : Both shunt (thin wire) and series (thick wire) field winding are used.

* **Functions of Interpoles**

(i) These are fixed to the yoke in between the main poles of a d.c. machine.

(ii) Interpoles are used for improving voltage commutation.

* **Functions of Brushes**

(i) To collect current from commutator and make it available to the stationary external circuit.

(ii) Brushes are made of carbon for small dc machine and of electro graphite for all dc. machines.

2. Rotor Part

* **Functions of Armature Core**

(i) Armature core provides house for armature winding i.e., armature conductors.

(ii) To provide a path of low reluctance to the magnetic flux produced by the field winding.

(iii) It is made from laminations of silicon steel to keep down iron losses.

* **Functions of Armature Winding**

(i) Generation of e.m.f. takes place in the armature winding in case of generators.

(ii) To carry the current supplied in case of d.c. motors.

(iii) To do the useful work in the external circuit.

(iv) It is made from copper and consists of large no. of insulation coil.

* **Functions of Commutator**

(i) To facilitate the collection of current from the armature conductos and it is of cylindrical structure.

(ii) To convert internally developed alternating e.m.f. to unidirectional (d.c.) e.m.f.

(iii) To produce unidirectional torque in case of motors.

* **Functions of Shaft**

(i) Hub H of commutator and spinder in big machines.

(ii) End covers are connected to the yoke on one side and to the bearing and shaft.

ENTRI

Types of DC Machines

(i) Separately excited d.c. machine

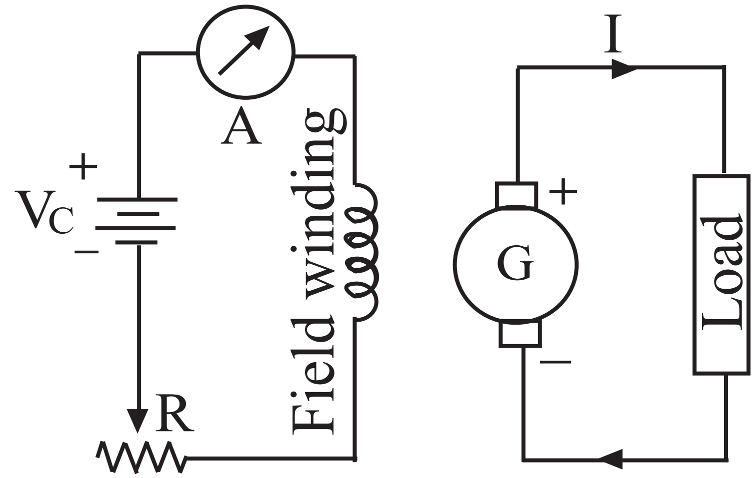


Figure : Separately-excited generators

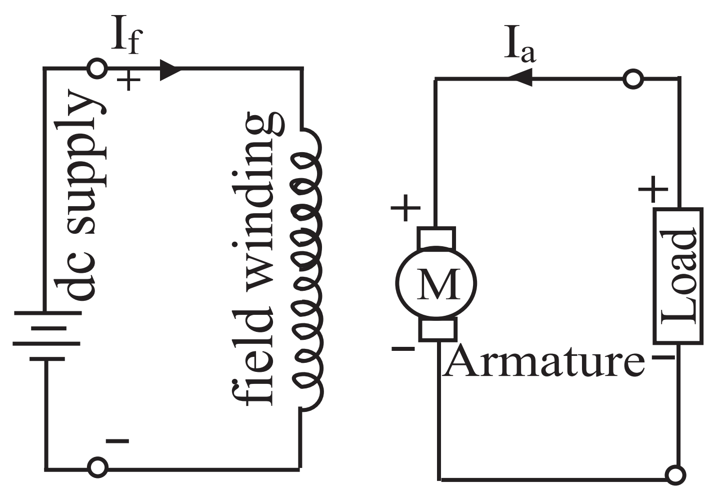


Figure : Separately excited dc motor

(ii) Shunt wound d.c. machine

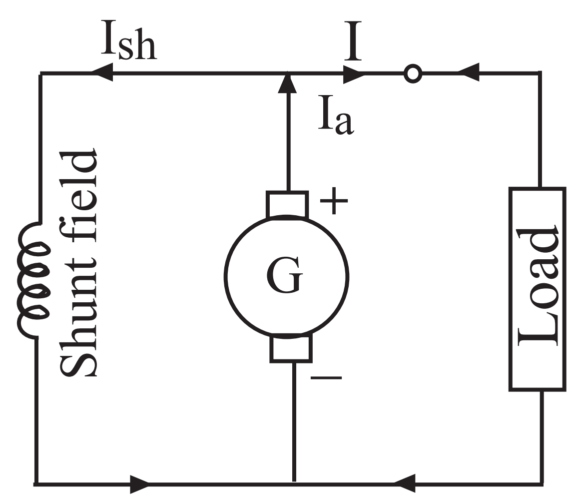


Figure : Shunt wound generator

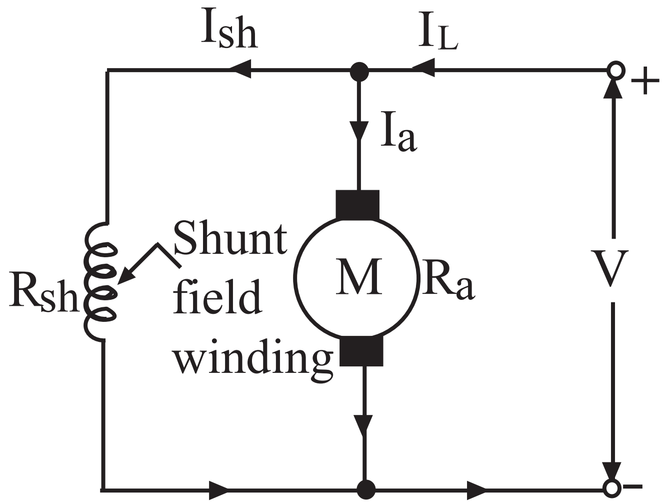


Figure : Shunt wound motor

(iii) Series wound d.c. machine

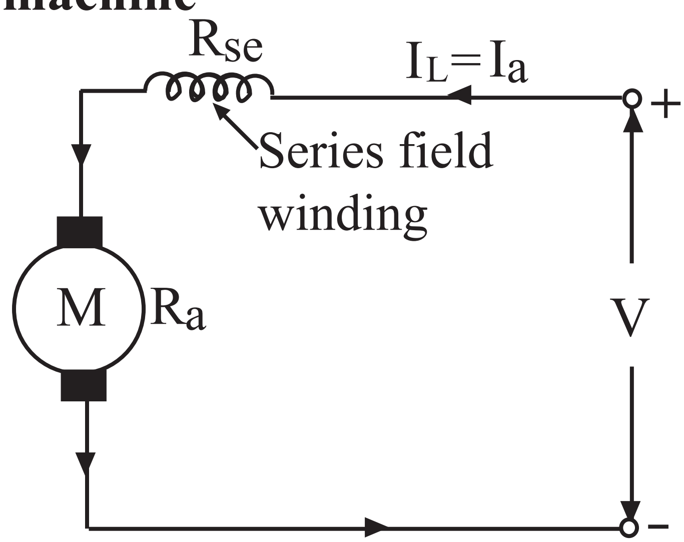


Figure : Series wound motor

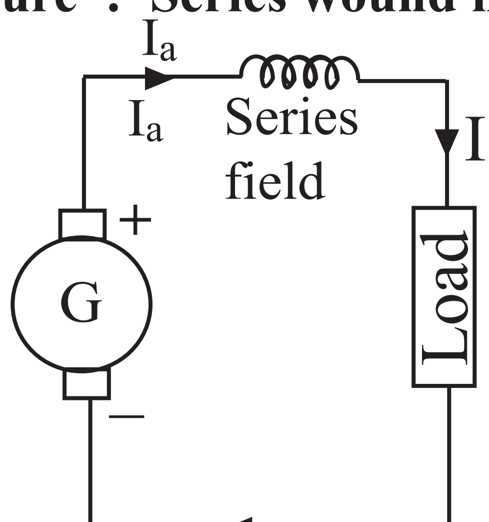
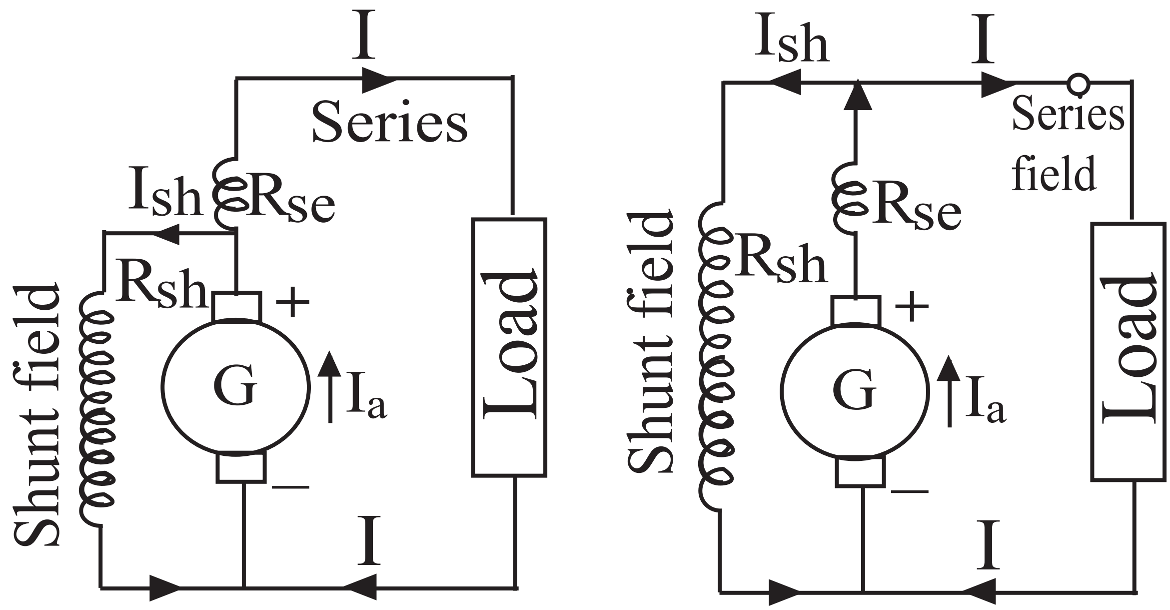


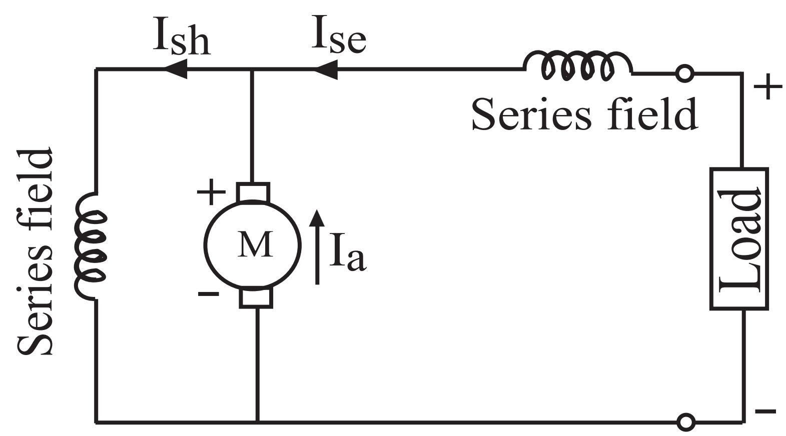
Figure : Series wound generator

(iv) Compound wound d.c. machine

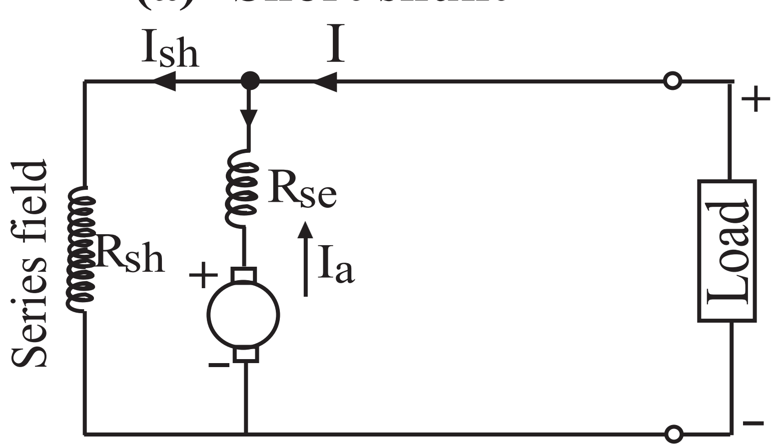


(a) Short-shunt **(b) long-shunt**

Figure : Compound wound generator



(a) Short shunt



(b) Long-shunt

Figure : Compond wound motor

E.M.F. Equation of D.C. Machine

$E = \frac{P\phi NZ}{60A}$ volt [Where, for wave winding : A = 2 & for Lap winding : A = P]

Where,
- ϕ = useful flux per pole in weber (wb).
- P = total number of poles.
- Z = total no. of conductor in the armature.
- N = Speed of rotation of armature in revolutions per second (r.p.s.)
- A = Number of parallel paths through the armature between brushes of opposite polarity.

Methods of improving commutation

(i) Resistance commutation

In this method of improving commutation, the low resistance copper brushes are replaced by high resistance carbon brushes.

(ii) E.M.F. commutation

The method in which reactance voltage produced is neutralized by the reversing e.m.f. in short circuited coil is called e.m.f. commutation. There are two ways of proving e.m.f. commutation.

(a) By giving a forward lead to the brushes

(b) By using interpoles.

For Separately Excited D.C. Generators

* **Open circuit characteristics**

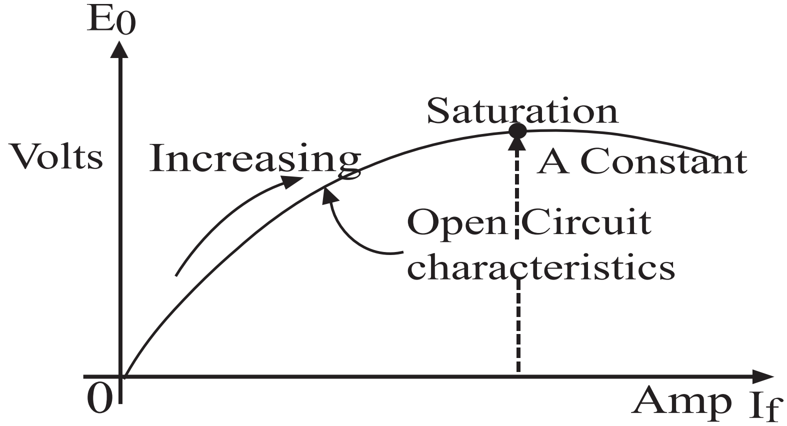


Figure : Open circuit characteristics

* **Load saturation curve**

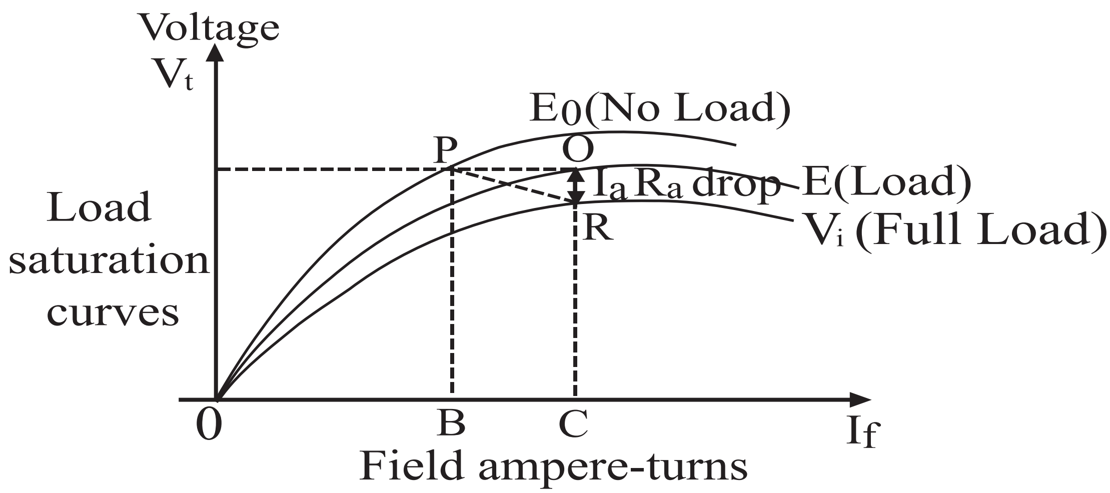


Figure : Load saturation curve

* **Internal and external characteristics**

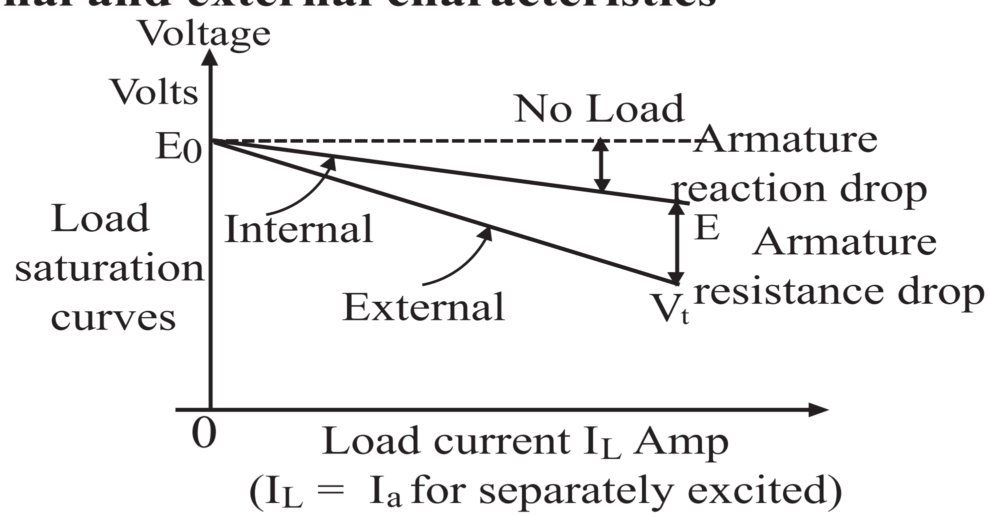


Figure : Internal and external characteristics

For D.C. Shunt Generator

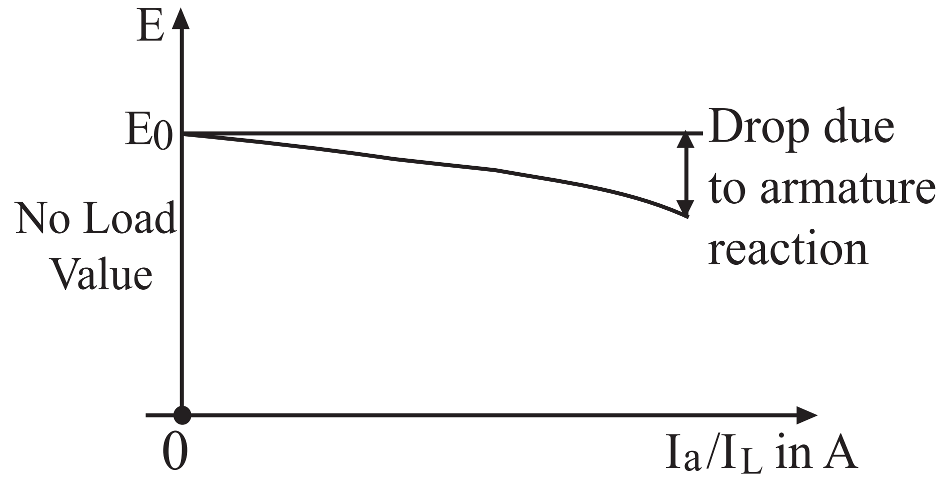


Figure : Internal Characteristics

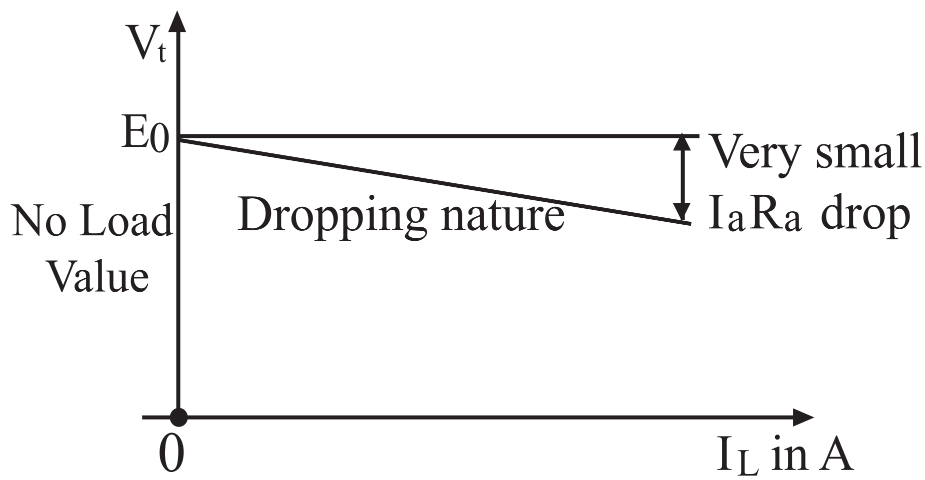


Figure : External Characteristics

For D.C. Series Generator

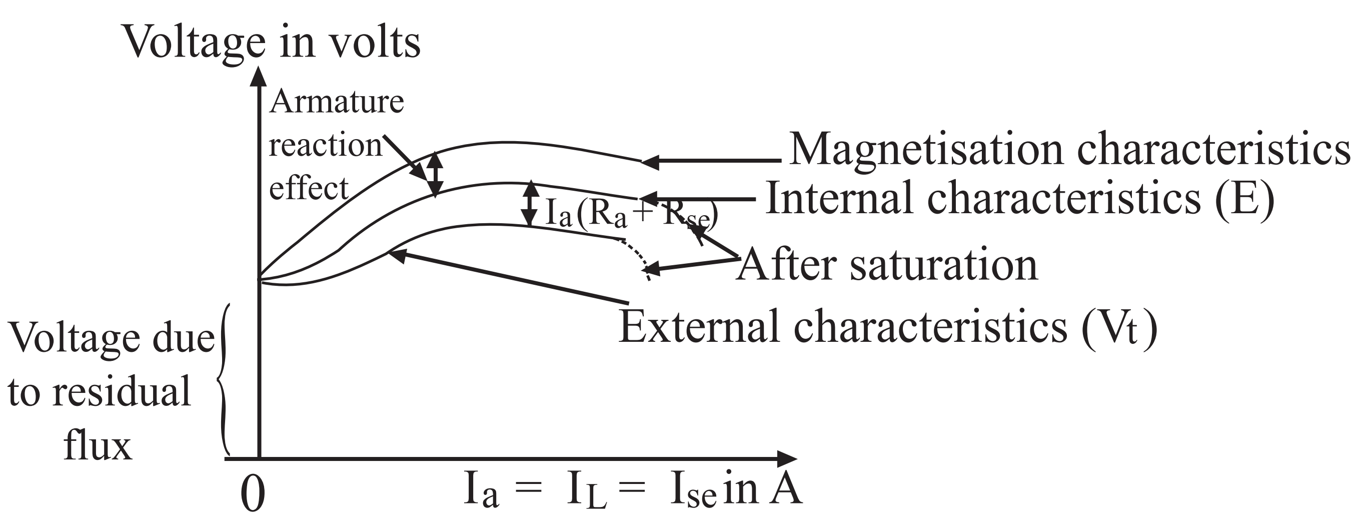


Figure : Characteristics of D.C. series generator

INTRODUCTION

It is an a.c. motor, used for industrial drives since it is cheap, robust, efficient and reliable. It has good speed regulation and high starting torque.

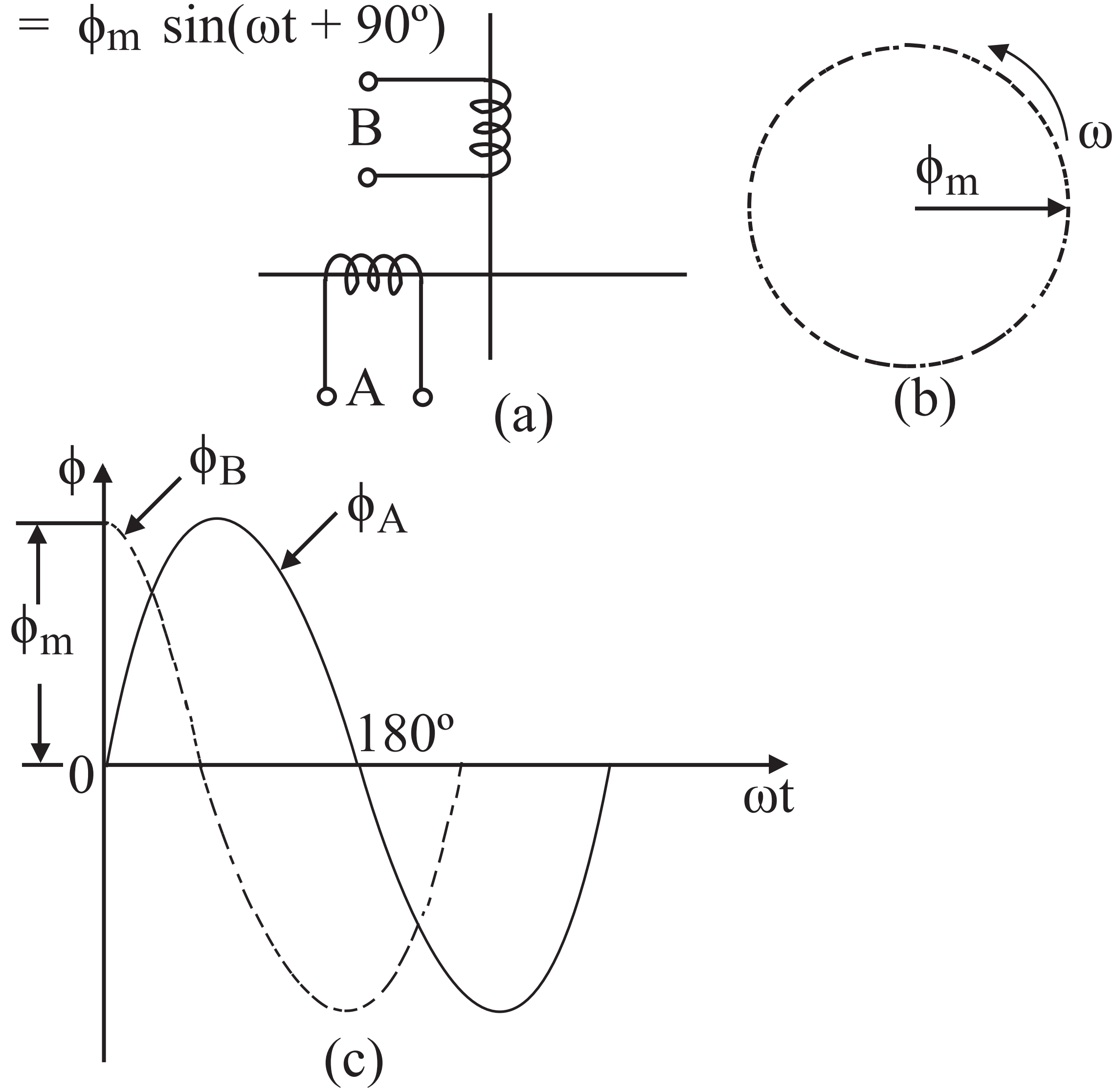
* Power is supplied to the rotor by means of electromagnetic induction, rather than by slip rings and commutators as in slip-ring AC motors.

Single Phase Induction Motor

Production of Rotating Field

$\phi_A = \phi_m \sin\omega t$

$\phi_B = \phi_m \sin(\omega t + 90^o)$



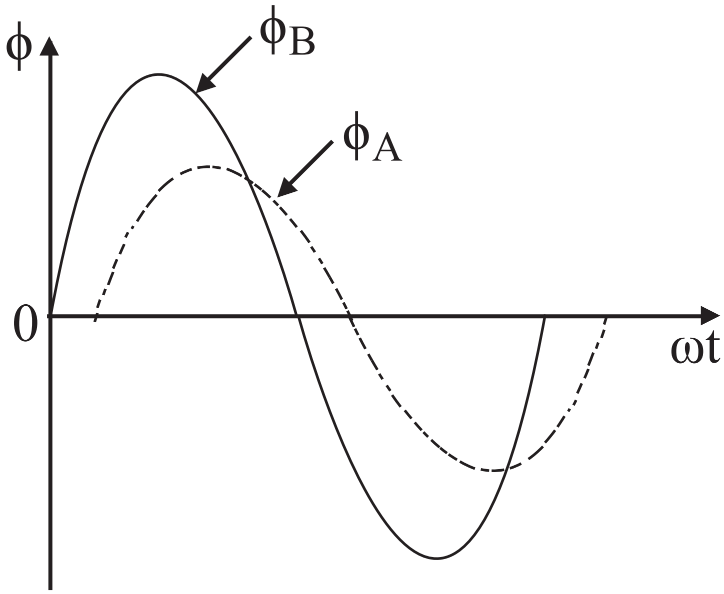


Figure : Displaced 90º in space

* A single phase IM is inherently not self-starting.

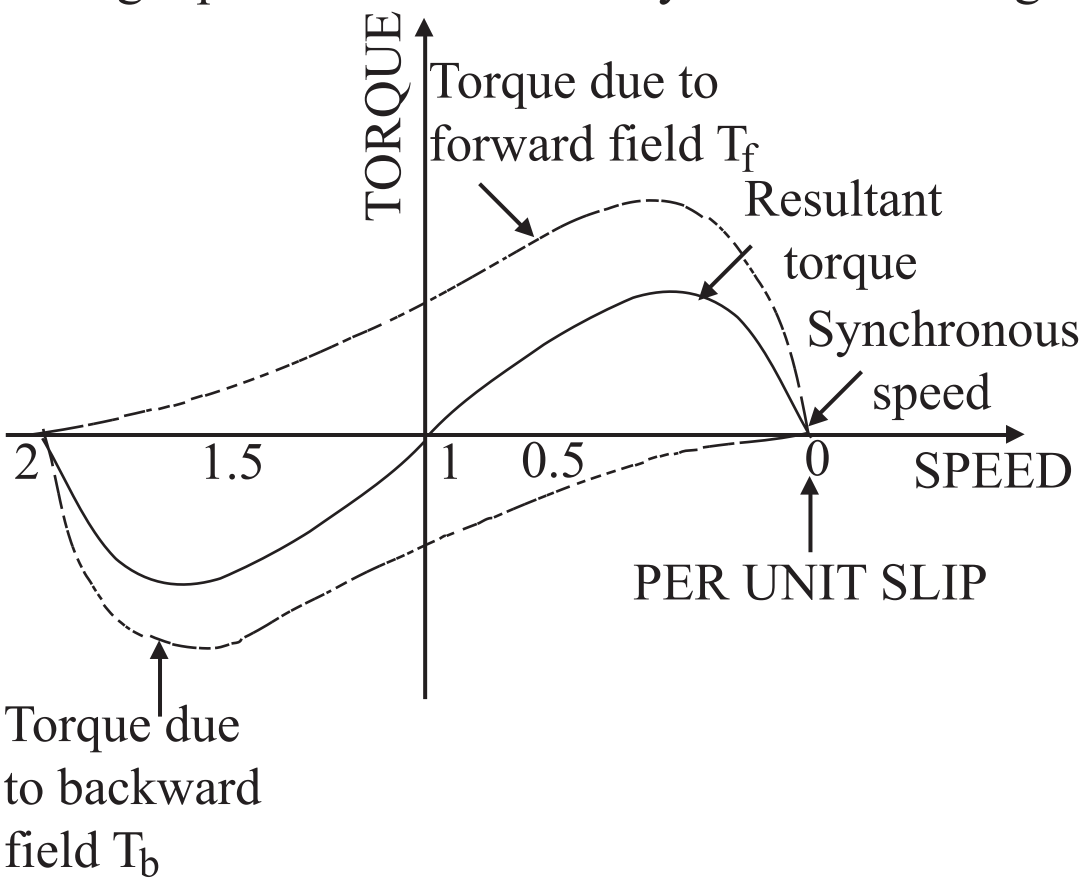


Figure : Torque-speed characteristic of a single-phase induction motor based on constant forward and backward flux waves.

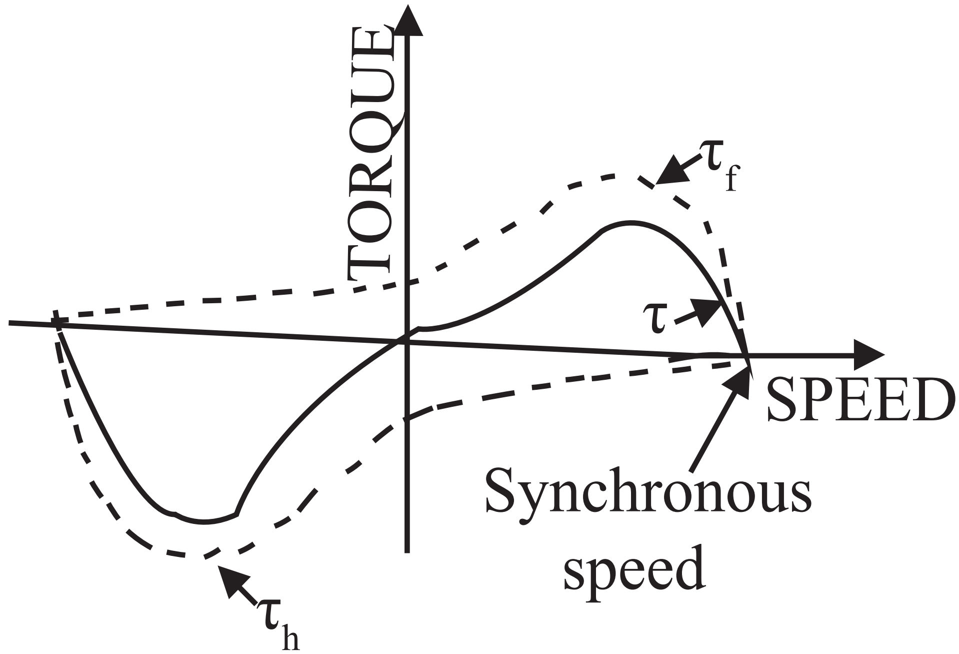


Figure : Actual torque-speed characteristics of a single phase induction motor taking into account changes in forward and backward flux waves

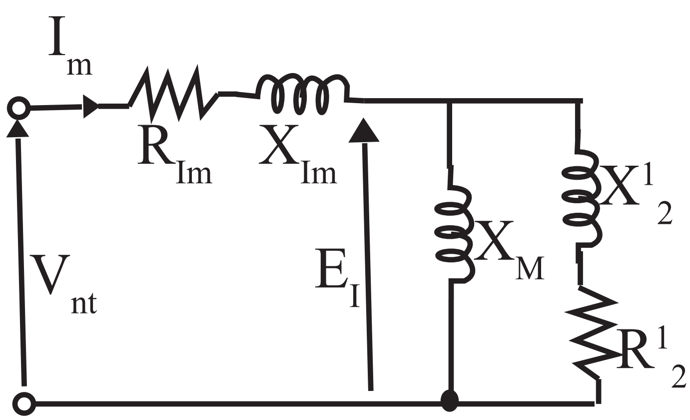


Figure : Equivalent circuit of a single-phase IM at standstill

Three Phase Induction Motor

Principle of three phase induction motor

When a conductor carrying current is put in a magnetic field a force is produced on it. Thus, a force is produced on the rotor conductor. The direction of this force can be found by left hand rule so that the force acting on the conductor is in the same direction as the direction of the rotating magnetic field. The rotor conductor is in a slot on the circumference of the rotor, this force is free to move, It starts rotaing in the same direction as the rotating magnetic field. Thus a three phase induction motor self starting.

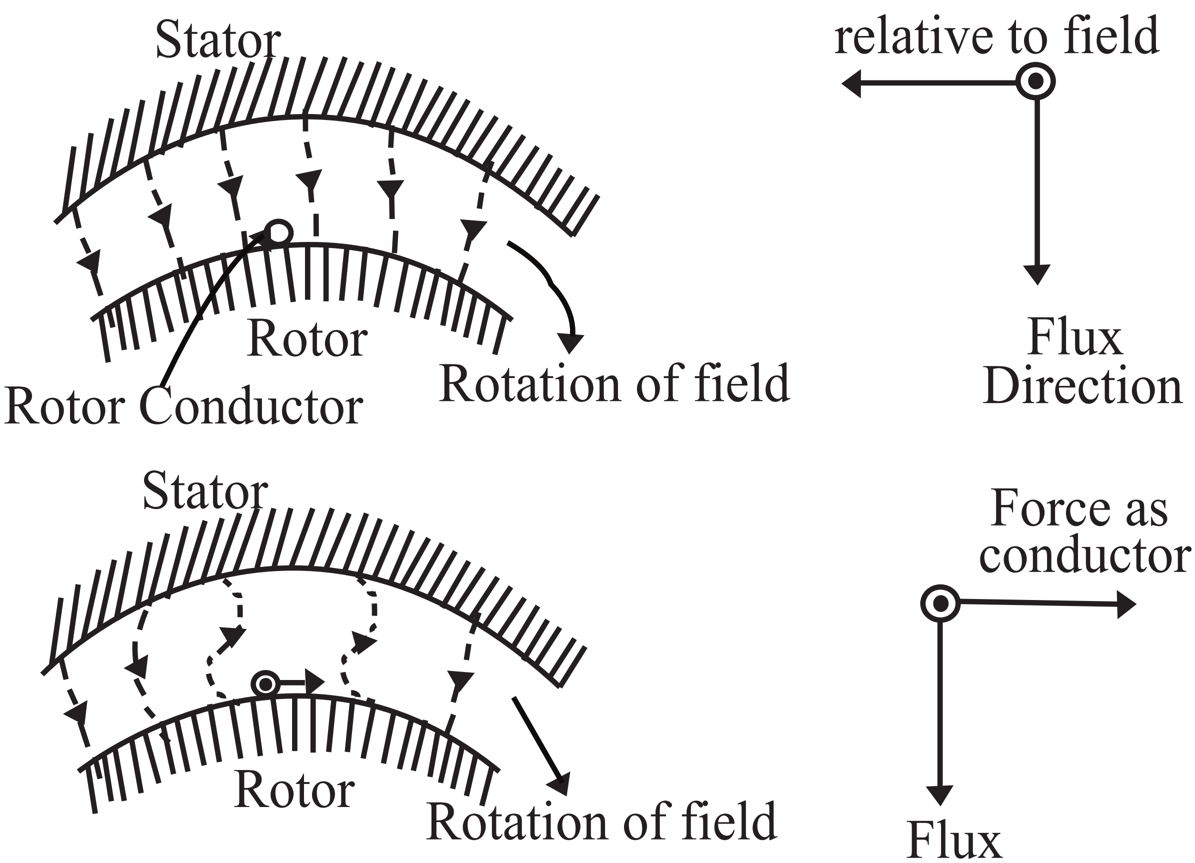


Figure : Production of torque

$$\frac{\text{total } I^2R \text{ loss in rotor}}{\text{input power to rotor}} = \frac{R\pi(n_s - n_r)\tau_d}{2\pi n_s \tau_d} = S$$

where, τ_d = developed torque = torque exerted on the rotor byrotating flux

n_s = synchronous speed (r.p.s)

n_r = rotor speed (r.p.s)

- Rotor copper loss = s × rotor input

$$P_{fc} = sP_{gen} = sP_{ir}$$

- Rotor input = mechanical power developed + rotor copper loss
- $P_{gan}\ P_{te}\ \ P_{md} = 1:s:(1-s)$

- Torque Developed (τ_d)

$$\tau_d = \frac{\text{mechanical power developed}}{\text{Mechanical angular velocity of the rotor}} = \frac{P_{md}}{\omega_r}$$

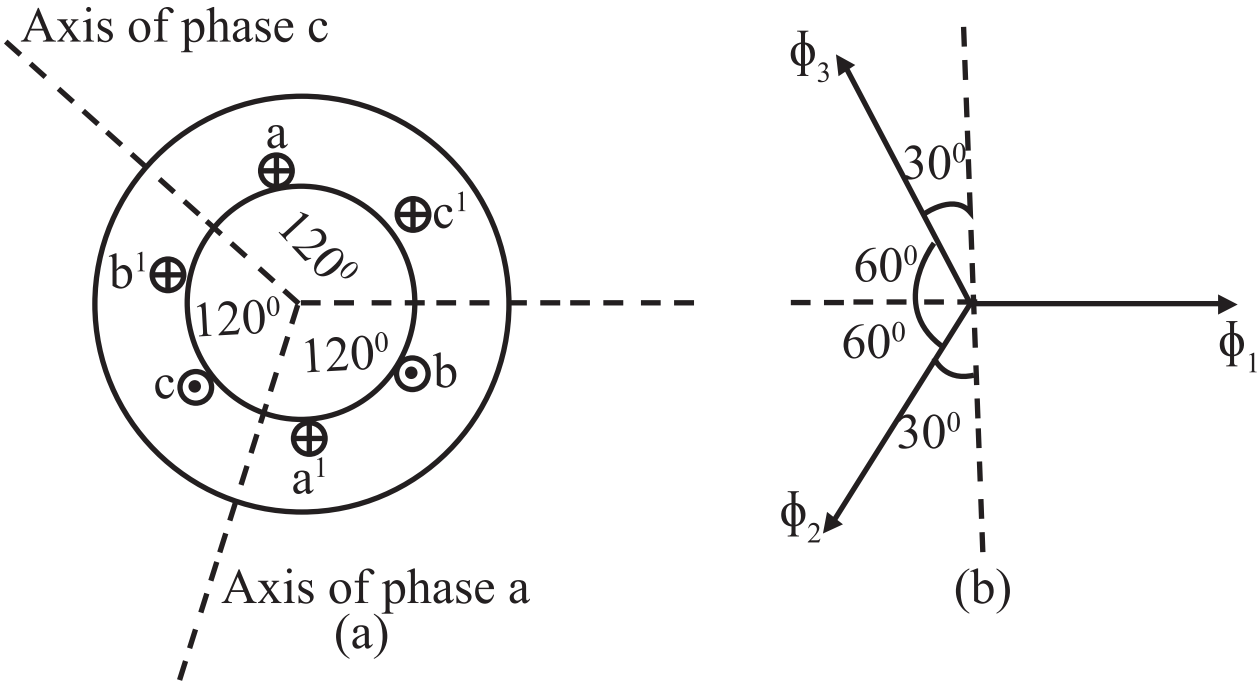
- Output power, $P_0 = \omega_r \tau_{load}$

$$\tau_{load} = \frac{P_0}{\omega_r} = \frac{P_{md} - P_{rot}}{\omega_r}$$

where, P_{md} = machanical power developed

Condition for maximum torque

- Maximum torque is independent of rotor circuit resistance.
- Maximum torque varies inversely as standstill reactance of the rotor.
- The slip at which the maximum torque depends upon the rotor resistance ($s_m = R_2/X_2$).
- The speed of the rotor at maximum torque is



$\phi_1 = \phi_m \sin\omega t$

$\phi_2 = \phi_m \sin(\omega t - 120^o)$

$\phi_3 = \phi_m \sin(\omega t + 120^o)$

The synchronous speed N_S of the rotating magnetic field is given as

$$N_S = \frac{120f}{p} \text{ revolutions per minute.}$$

Speed and Slip

Ship speed expresses the speed of the rotor relative to the field.

If N_S = synchronos speed in r.p.m.

N_r = actual rotor speed in r.p.m.

the slip speed = $N_S - N_r$ r.p.m.

$$s = \frac{N_S - N_r}{N_S} \text{ per unit (p.u.)}$$

* Percentage slip $= \frac{N_S - N_r}{N_S} \times 100$

* The rotor frequency is given by $f_r = \frac{P(N_s - N_r)}{120}$

* Rotor currrent frequency = per unit slip × supply frequency.

$$N_r = 0, s = \frac{N_s - N_r}{N_s} = 1 \text{ and } f_r = f.$$

Functions of Starter

(i) To reduce the heavy starting current.

(ii) To provide overload and under-voltage protection.

Starting of Cage Motors

Let,

I_{st} = Starting current drawn from the supply mains per phase.

I_{f1} = Full-load current drawn from the supply mains per phase.

τ_{est} = Starting torque τ_{ef1} = Full load torque

s_{f1} = Slip at full load

(i) Direct on-line starter : The motor is connected by means of a starter across the full supply voltage.

$$\frac{\tau_{est}}{\tau_{ef1}} = \left(\frac{I_{sc}}{I_{f1}}\right)^2 s_{f1}$$

(ii) Star-delta starter : It is designed to run normally on delta-connected stator winding.

$$\frac{\text{starting torque with star-delta starting}}{\text{full-load torque wih stator winding in delta}} = \left(\frac{I_{st\gamma p}}{I_{fl\Delta p}}\right)^2 s_{f1}$$

$$= \frac{1}{3}\left(\frac{I_{st\gamma p}}{I_{fl\Delta p}}\right)^2 s_{f1}$$

ENTRI

(iii) Auto transformer starter : It is suitable for both star and delta-connected motors. The starting current is limited by using a three-phase auto-transformer to reduce the initial stator applied voltage.

$$\frac{\tau_{est}}{\tau_{efl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_{fl}$$

Speed Control of Induction Motor

(i) By changing the applied frequency :
Synchronous speed of an induction motor is given by $N_s = \frac{120f}{P}$.

(ii) By changing the number of stator poles :
Changing of number of poles is achieved by having two or more independent stator winding's in the same slots.

(iii) Rotor Rheostat control : Addition of external resistance in the rotor circuit. It is applicable to slip ring motor.

(iv) Cascade Connection : The slip power is supplied to an auxiliary induction motor mechanically coupled to the main or primary motor.
If f is supply frequency and P_1 and P_2 are number of poles of the two motors. Then speed,

Main motor : $\frac{f}{P_1}$

Auxiliary motor : $\frac{f}{P_2}$

Differential cascade : $\frac{f}{(P_1 - P_2)}$

Cummulative cascade : $\frac{f}{(P_1 + P_2)}$

$$N_r = (1 - s)N_s \qquad N_s = \frac{120f}{P}$$

* Synchronous speed of the h^{th} space harmonic wave is

$$n_{s(h)} = \frac{n_s}{h} = \frac{120f}{h \times P}$$

where, f = supply frequency

P = Number of poles of the stator.

* **Crawling of motor :** Tendency of the motor to run at stable speed as low as one-seventh of the normal speed N_s and being unable to pick up its normal speed.
* **Cogging :** Magnetic locking between the number of poles and of stator and rotor slots in cage motors. In this condition machine may refuse to start at all.

A.C. Generator/Alternator/Synchronous Generator

* Rotating machines that rotate at a speed fixed by the supply frequency and the number of poles are called synchronous machines.
* In a synchronous machine, the stator carries the armature winding and rotor carries the field winding. The field winding is excited by DC to produce flux in the air gap. It means it is doubly excited machine.
* Alternator is a machine for converting mechanical power from a prime mover to a.c. electric power at a specified voltage and frequency. It rotates at a constant speed called as synchronous speed.
* Synchronous generators are usually of 3-phase type because of the several advantages are used to generate bulk power at thermal, hydro and nuclear power stations.

Speed and Frequency

* One complete cycle of voltage is gererated in an armature coil when a pair of field poles passes over the coil.

$$\frac{N}{60} = n \qquad\qquad \frac{P}{2} = p$$

Where, P = total number of field poles.
p = pair of field poles.
N = speed of field poles in r.p.m.
n = speed of field poles in r.p.s.
f = frequency of the generated voltage in Hz.

If, p = number of cycles per revolution
n = Number of revolutions per second.

$$\text{Frequency} = \frac{\text{number of cycles}}{\text{revolutions}} \times \frac{\text{revolutions}}{\text{seconds}}$$

$$f = p \times n \qquad\qquad f = \frac{PN}{120}$$

Synchronous Speed

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

Number of poles	Synchronous speed N_s in r.p.m.
2	3000
4	1500
6	1000
8	750
10	600
12	500

Stator

* The stator is the stationary part of the machine. It carries the armature winding in which the voltage is generated.
* The rotor produces the main field flux.
* Salient-pole alternators have a large number of poles and operate at lower speed. Salient-pole generator has comparatively a large diameter and a short axial length.
* Non-salient pole rotor machine (cylindrical rotor machine) has its rotor so constructed that it forms smooth cylinder. It has relatively long but small diameter rotor and is used to limit centrifugal forces developed.

*   Smooth rotor of a machine makes less windage losses and the operation is less noisy because of uniform air gap.

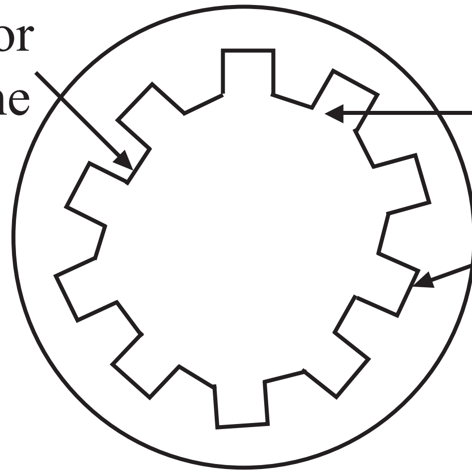


Figure : Alternator stator

E.M.F. Equation of an Alternator

Average value of generated voltage per conductor

$$= \frac{\text{flux cut per revolution in Wb}}{\text{time taken for one revolution in seconds}}$$

E_{av} /conductor $= 2f\phi$

E_{av} /phase $= 2f\phi Z_p$ $E_p = 4.44\ f\phi T_p$

ϕ = useful flux per pole in weber (Wb)

P = total number of poles

Z_p = total number of conductors or coil sides in series per phase.

T_p = Total number of coils or turns per phase.

n = Speed of rotation of rotor in revolution per second (r.p.s.)

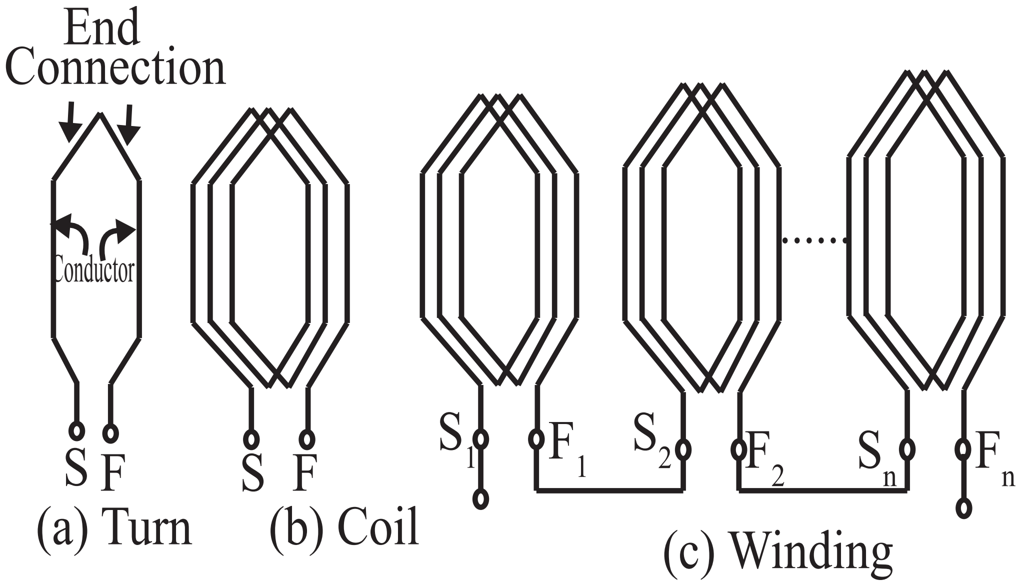
f = frequency of generated voltage (Hz)

Armature Winding

$$\theta_{ed} = \frac{P}{2}\theta_{md}$$

where, θ_{md} = mechanical degrees or angular measure in space.

θ_{ed} = electrical degrees or angular measure in cycles.



$$\text{One pole pitch} = 180^0_{ed} = \frac{360^0_{md}}{P}$$

Chording factor,

$$K_C = \frac{\text{actual voltage generation in the coil}}{\text{voltage generation in the coil of span } 180^0 \text{ electrical}}$$

$$K_C = \cos\frac{\alpha}{2}$$

For full-pitch coil, $\alpha = 0^0$ and $K_C = 1$

For short pitch coil $K_C < 1$.

. Advantages of short pitching (chording)

(i) Shortens the ends of the winding saving in the conductor material.

(ii) Reduces effect of distorting , waveform of the generated voltage is improved sine wave.

Distribution Factor (Breadth factor), k_d

$$k_d = \frac{\text{phasor of coil voltages per phase}}{\text{arithmetic sum of coil voltages per phase}}$$

m = slots per pole per phase, that is slots per phase belt.

$$m = \frac{\text{slots}}{\text{poles} \times \text{phases}}$$

β = angular displacement between ajdacent slots in electrical degrees

$$\beta = \frac{180^o}{\text{slots} \times \text{pole}} = \frac{180^o \times \text{poles}}{\text{slots}}$$

$$k_d = \frac{\sin m\beta/2}{m \sin\beta/2}$$

Actual generated voltage per phase

$$E_p = 4.44\, k_c k_d f\phi T_p$$

Effective turns per phase $T_{ep} = k_c k_d T_p$

Winding factor, $k_w = k_c k_d$

Voltage Regulation

* In case of a synchronous generator, it is the rise in voltage at the terminals when the load is reduced from full-load rated value to zero, speed and field current remaining constant.
* Voltage regulation depends upon the power factor of the load.

Per unit voltage regulation $= \dfrac{|E_a| - |V|}{|V|}$

Percent voltage regulation $= \dfrac{|E_a| - |V|}{|V|} \times 100$

where, $E_a|$ = magnitude of generated voltage per phase

$|V|$ magnitude of rated terminal voltage per phase.

Servomotor (Control Motors)

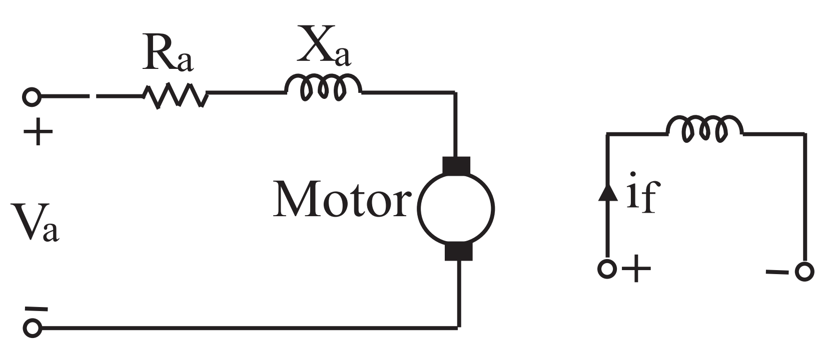
* Used in feedback control systems as output actuators.
* Not used for continuous energy conversion.
* The basic principle is same as that of other electromagnetic motors.
* Have low rotor inertia, high speed of response.
* The rotos of servomotors are designed with relatively long rotor length and smaller diameter.
* Generally operate at very low speed.
* Produces high torque at all speeds including zero speed.
* Accelerate and deaccelerate quickly.
* Withstand higher temperature at lower speeds or zero speed. Dissipation of heat is quick.

Applications :

Radars, computers, robots, machine tools, tracking.

DC Servomotors

* The armature has a large resistance so that the torque-speed characteristic is linear and has a large negative slope.
* A step change in the armature voltage or current produces a quick change in the position or speed of the rotor.
* Most high-power servomotors are dc servomotors.



(a)

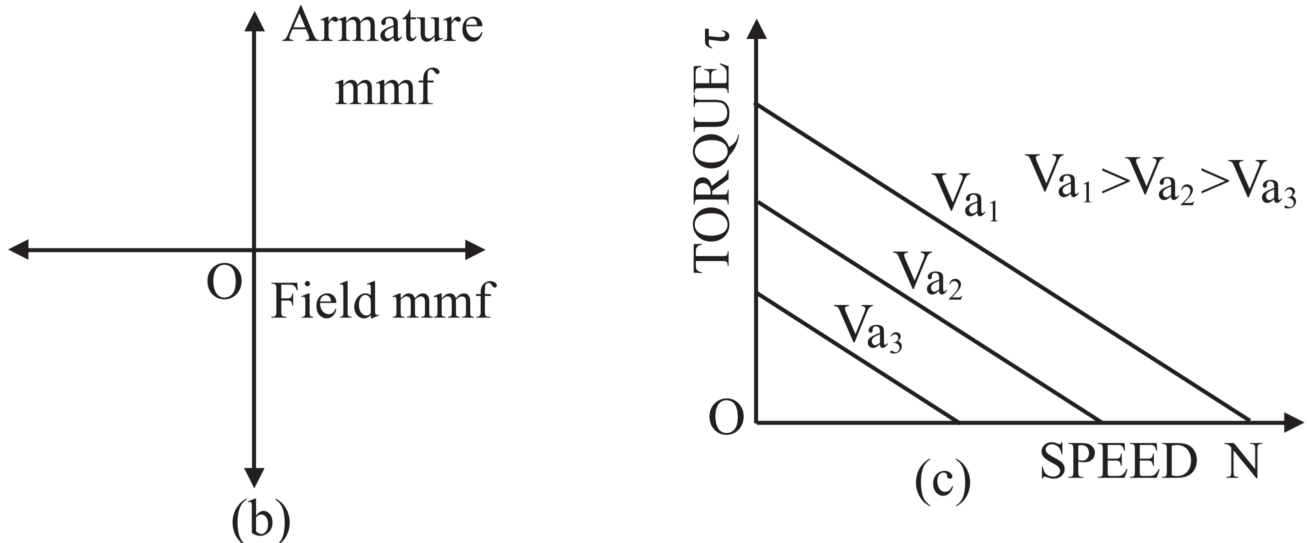


Figure : DC servometer (a) Schematic diagram
(b) Armature mmf and field mmf
(c) Torque-speed characteristics

* **AC Servomotors**

* **Two-phase AC servomotors**

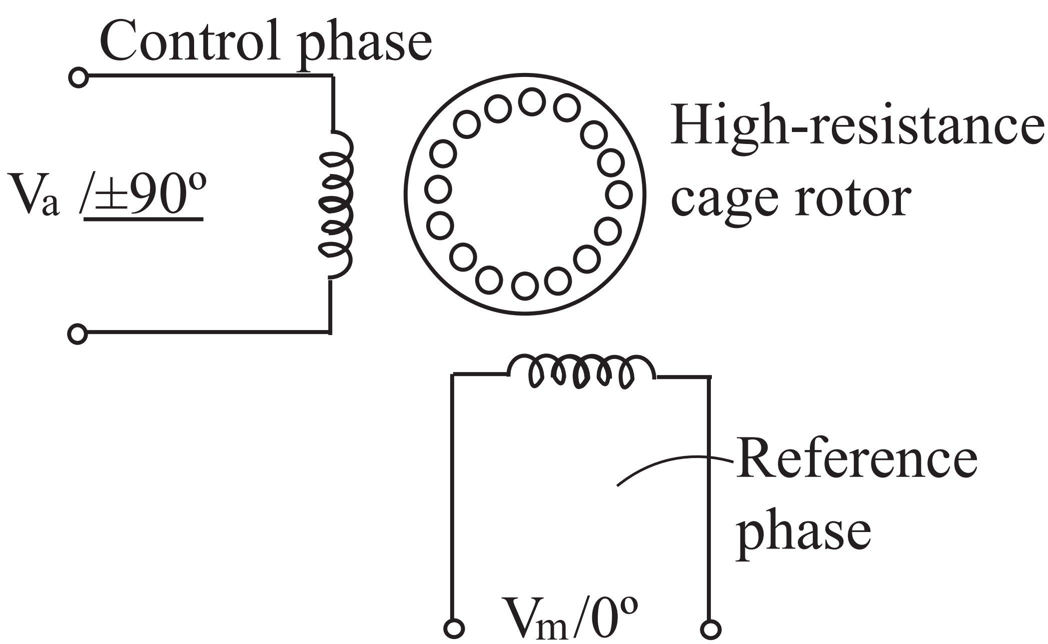


Figure : Schematic diagram of two-phase AC servomotors

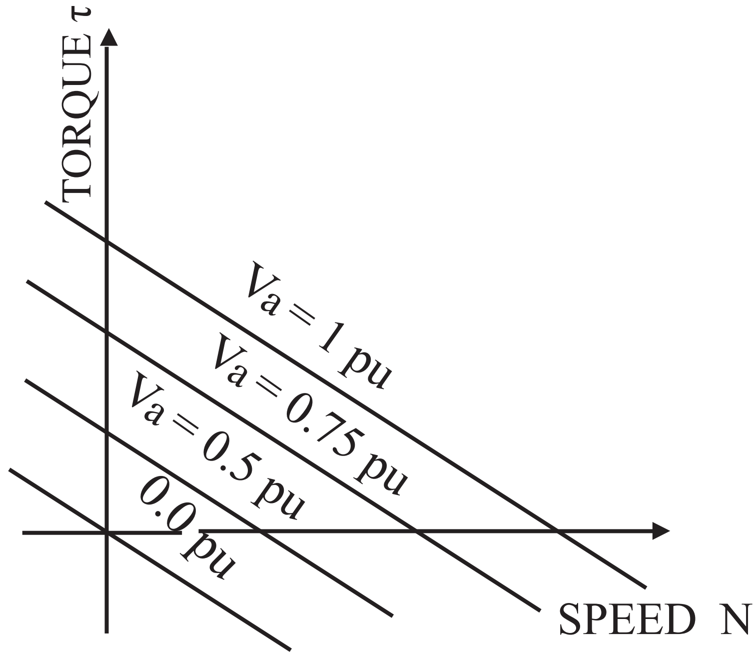


Figure : Torque-speed characteristics

The stator has two distributed windings which are displaced from each other by 90 electrical degrees. A high rotor resistance keeps a negative slope for the torque-speed characteristics over its entire operating range.

* **Three-phase AC servomotors**

It is normally, a highly nonlinear coupled circuit device. Using vector control/field-oriented control, it can be used as a linear decoupled machine.

The current in the machine are controlled in such a way that its torque and flux becomes decoupled as in dc machine

Linear Induction Motor (LIM)

A linear induction motor (LIM) is a motor which gives linear or translational motion instead of rotational motion as in the case of a conventional induction motor.

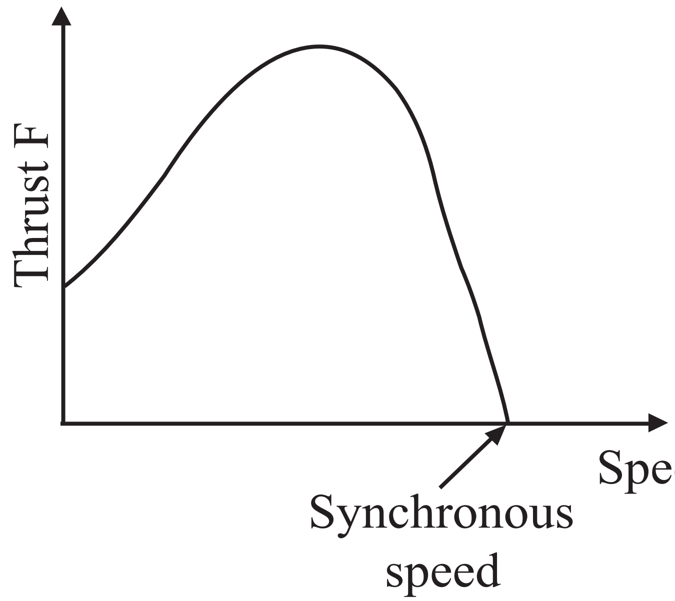


Figure : Thrust-speed curve of a linear induction motor

Linear synchronous speed, $V_s = 2f(\text{pole pitch})\text{m/s}$

Thrust or linear force,

$$F = \frac{\text{air gap power}}{\text{linear synchronous velocity, } v_s}$$

Stepper (or Stepping) Motors

* Stepper motor is a brushless electric motor, having a rotor movement in discrete steps. It divide a full rotation is determined by the number of pulses fed into the control circuit. Each input pulse initiates the drive circuit which produces one step of angular movement.
* Types of rotor arrangements :
  (a) Variable reluctance (VR) type
  (b) Permanent magnet (PM) type
  (c) Hybrid type (combination of VR and PM)

Advantages : Small stp length, greaeter torque per unit volume, less tendency to resonate, high efficiency at lower speeds and lower stepping rates, provides detent torque with winding de-energized.

Disadvantages : Costly, performance is affected by change in magnetic strength, higher inertia and weight due to presence of rotor magnet.

* Resolution of a motor

$$= \frac{\text{number of steps}}{\text{number of revolutions of the rotor}}$$

* The angle by which the rotor of a stepper motor moves when one pulse is applies to the (input) stator is called step angle.
* A standard motor will have a step angle of 1.8° with 200 steps per revolution.

Reluctance Motors

. The rotor of a reluctance motor is basically a squirrel cage with some rotor teeth removed at the appropriate places such as to provide the desired number of salient rotor poles.

. The stator has the main winding and an auxiliary (starting) winding.

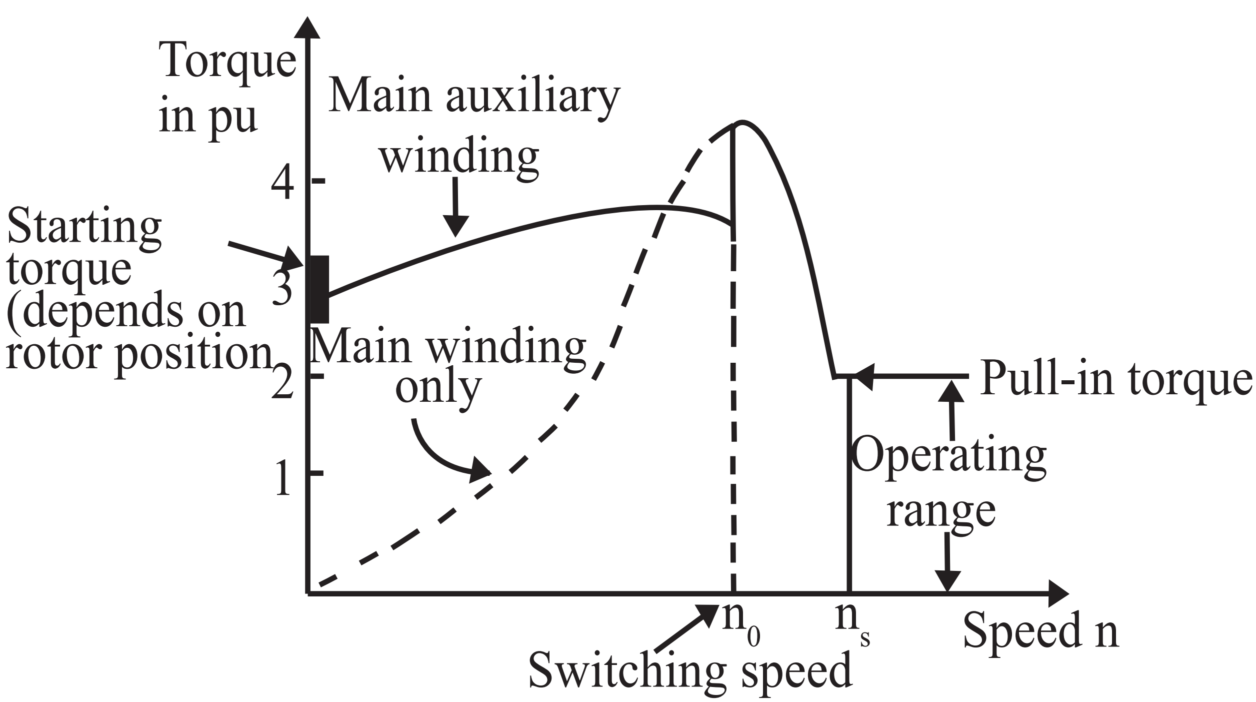


Figure: Torque-speed characteristic of reluctance motor

* Starting torque is dependent upon rotor position because of the salient pole rotor. The value of the starting torque is between 300 to 400 percent of its full-load torque.
* The rotor is unexcited and has sliency, the power factor is lower than that of the equivalent induction motor.
* The main advantages of a reluctance motor are its simple construction (no slip rings, no brushes, no dc field winding), low cost and easy maintenance.
* Used for many constant-speed applications such as electric clocks times, signalling devices, recording instruments and phonographs etc.

Hysteresis Motors

* Basically a synchronous motor with uniform air gap and without d.c. excitation.
* Torque is produced due to hysteresis and eddy current induced in the rotor by the action of the rotating flux of the stator windings.
* Very low noise level, operates at one speed, rotor is smooth (unslotted).
* Applications : Electric clocks and other timing devices.