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.

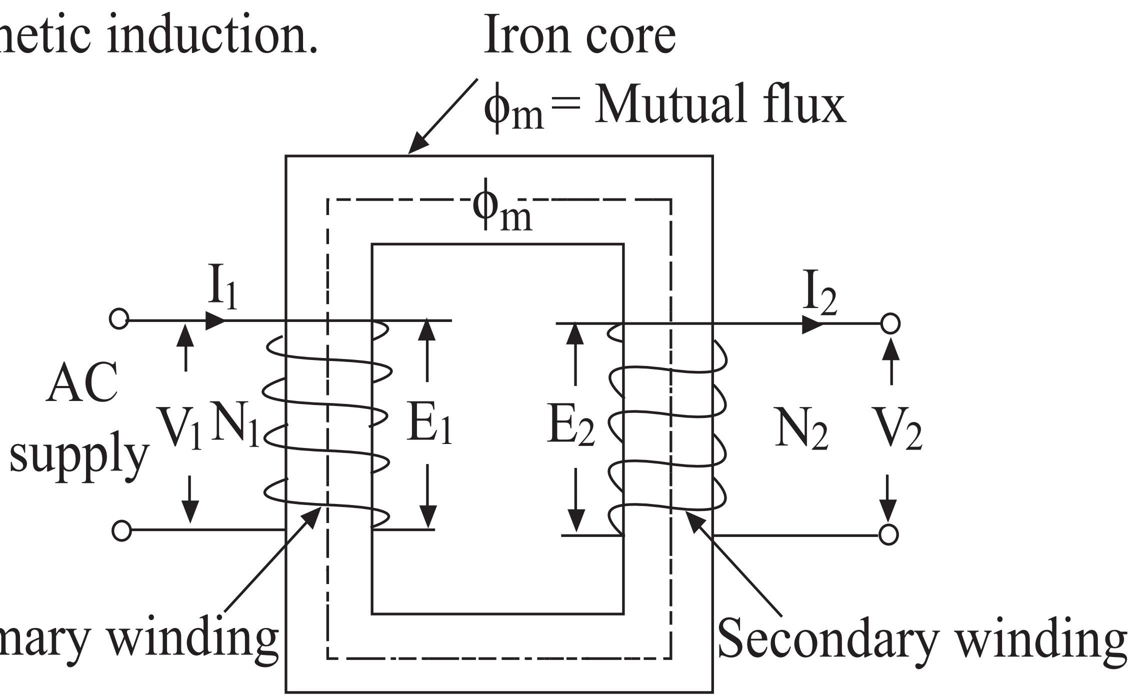


Figure : Two winding transformer

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.

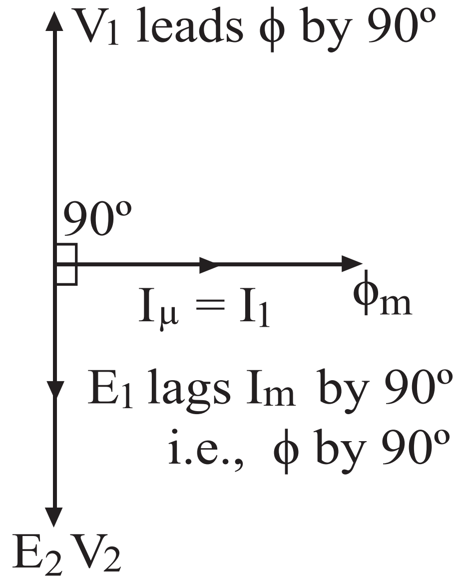


Figure : No-load phasor diagram of an ideal transformer.

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

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

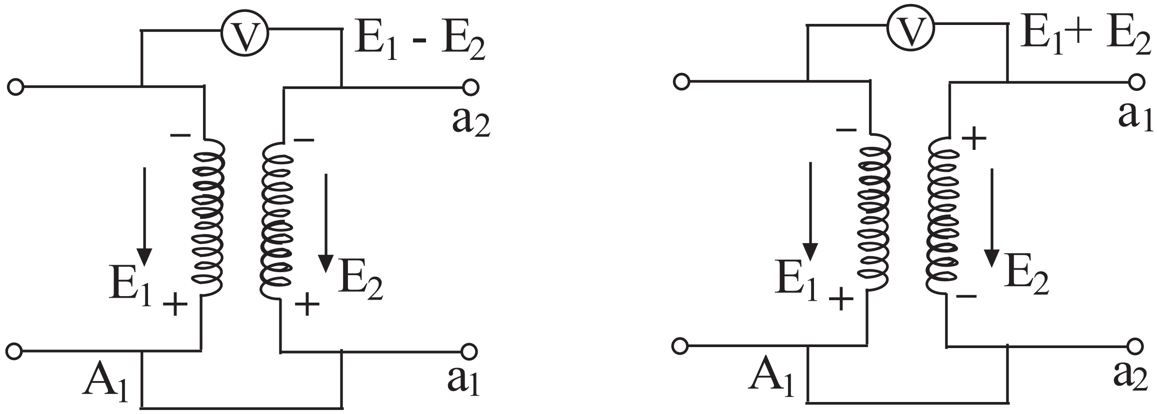
If, B_m = maximum flux density in the magnetic circuit (core) in tesla (T).

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.

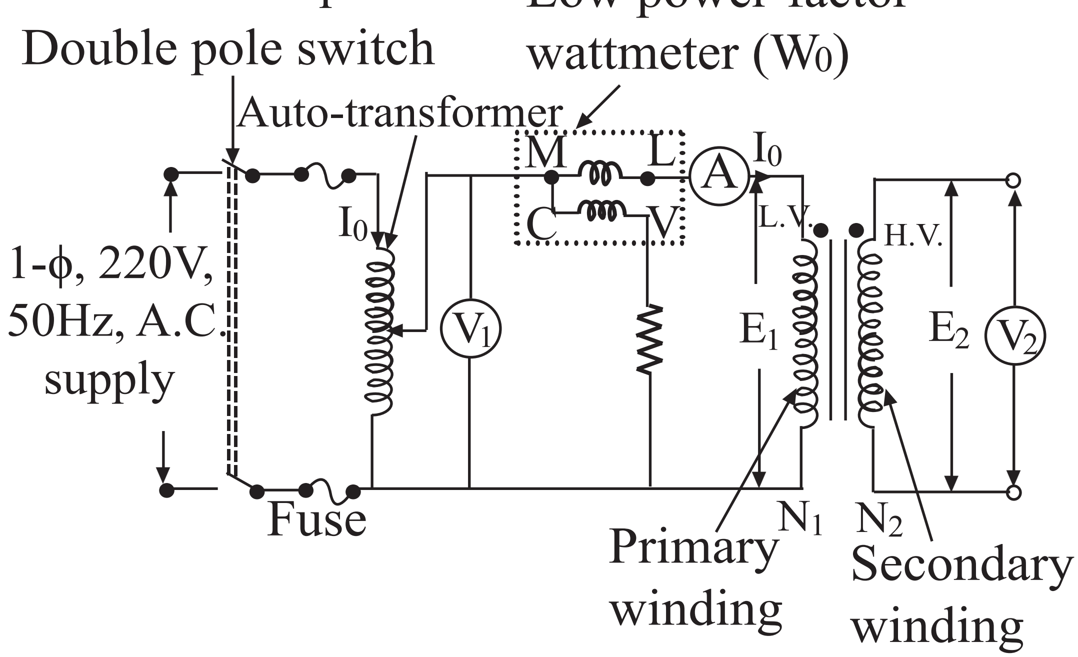


Figure : Open-circuit test on a transformer

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, $Y_0 = \frac{I_0}{V_1}$

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

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.

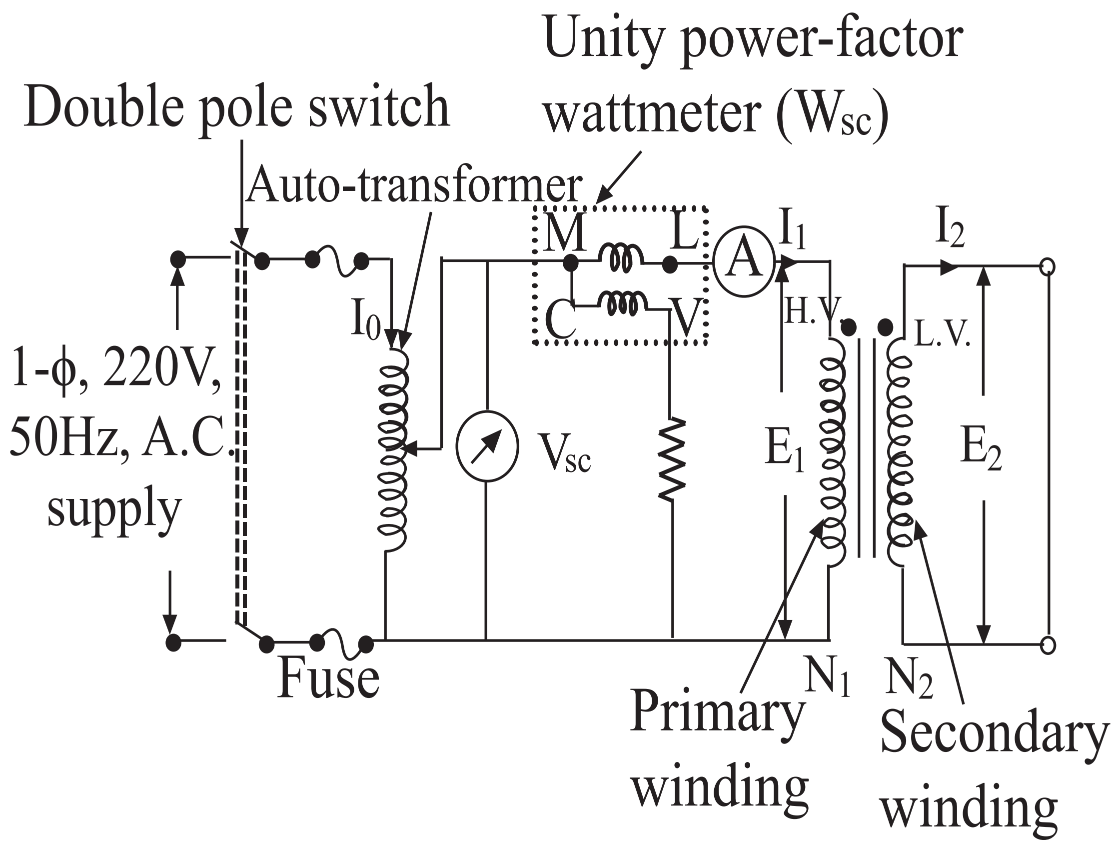


Figure : Short-circuit test on a transformer

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.

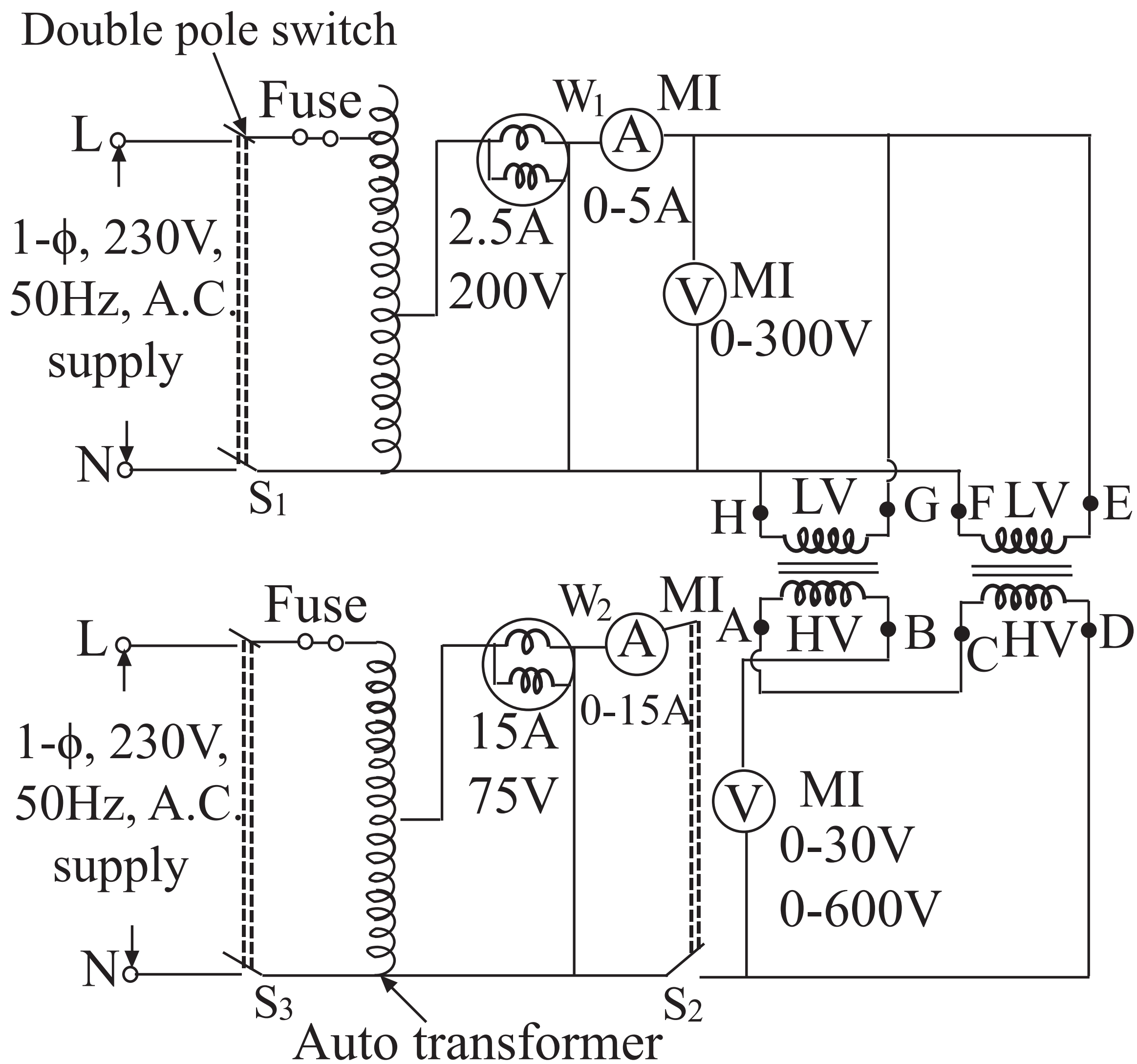


Figure : Sumpner's test on tranformer

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.

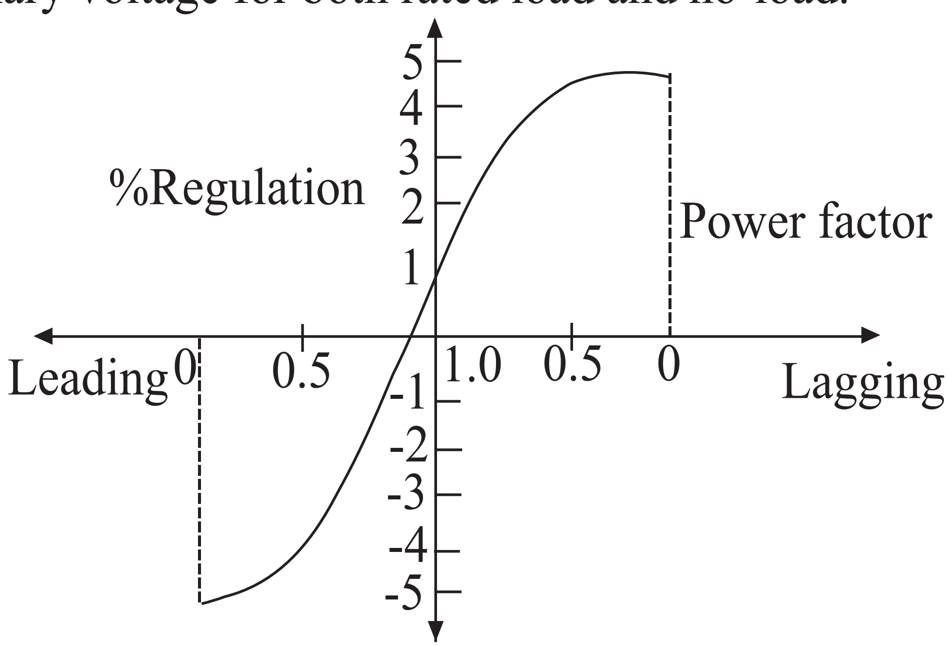


Figure : Variation of full load regulation with power factor.

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

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

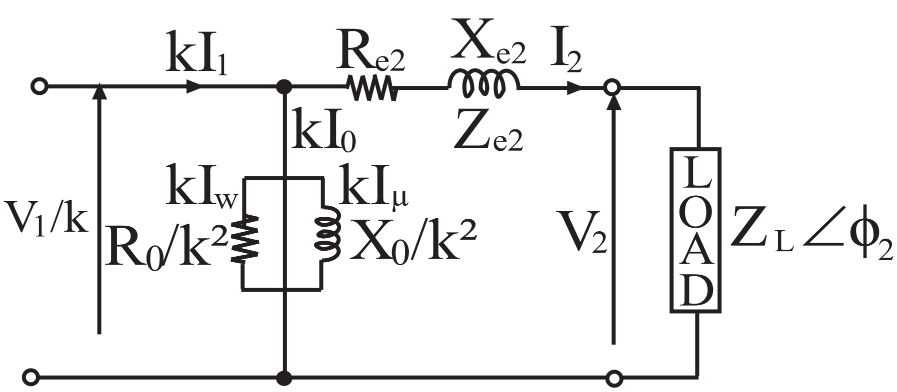


Figure : Equivalent circuit

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 $\quad I_2 = I_2 \angle 0^o = I_2 + j0$

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

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, $\quad P_h = K_h f B_{max}^x$

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, $\quad P_e = K_e f^2 B_{max}^2$

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.

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

ENTRI

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 =

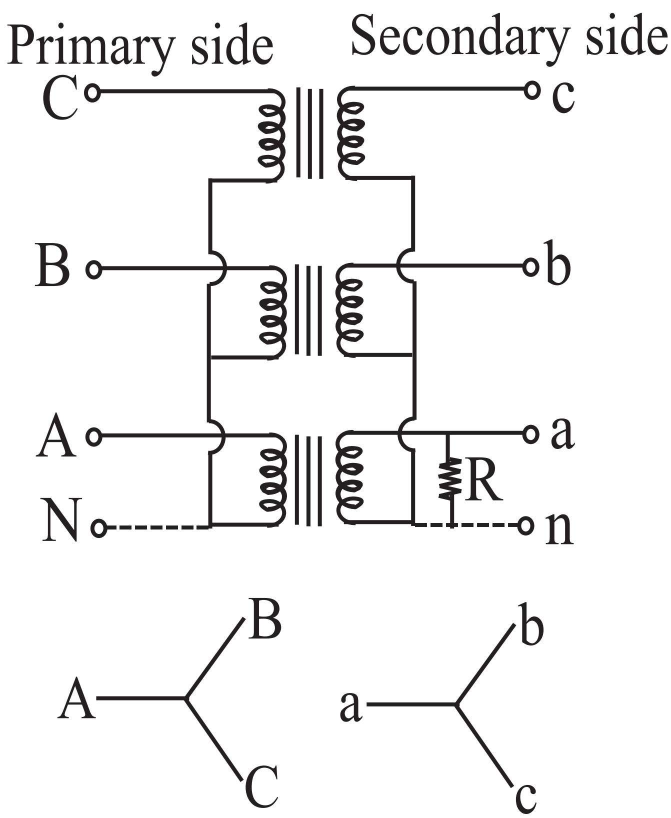
$$(\text{full-load current}) \times \sqrt{\frac{\text{Constant iron loss}}{\text{Full-load copper loss}}}$$

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.

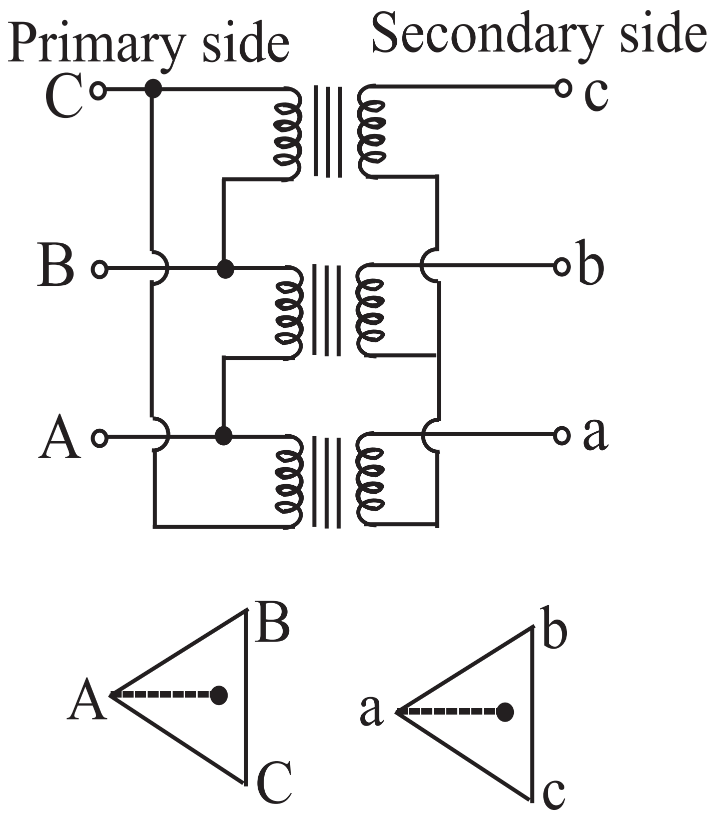


0^{o} Angular Displacement

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.

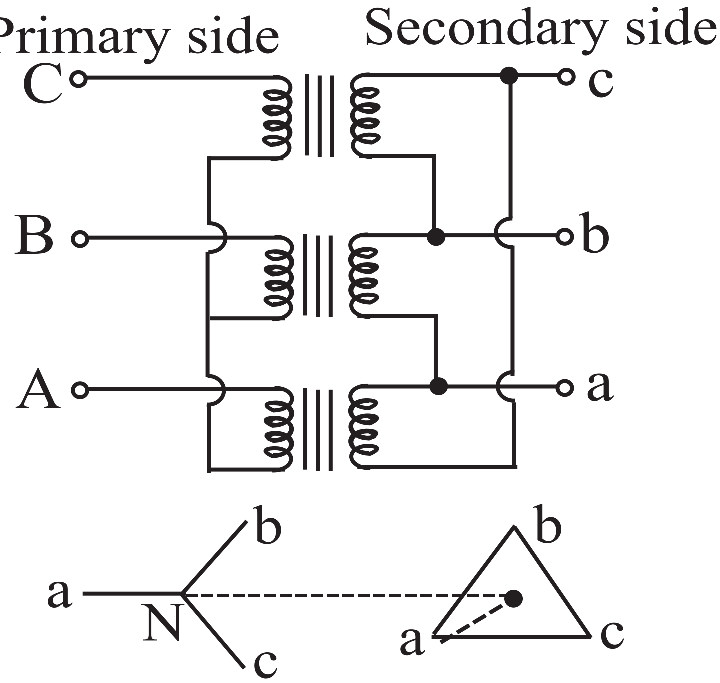


0º Angular Displacement

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.

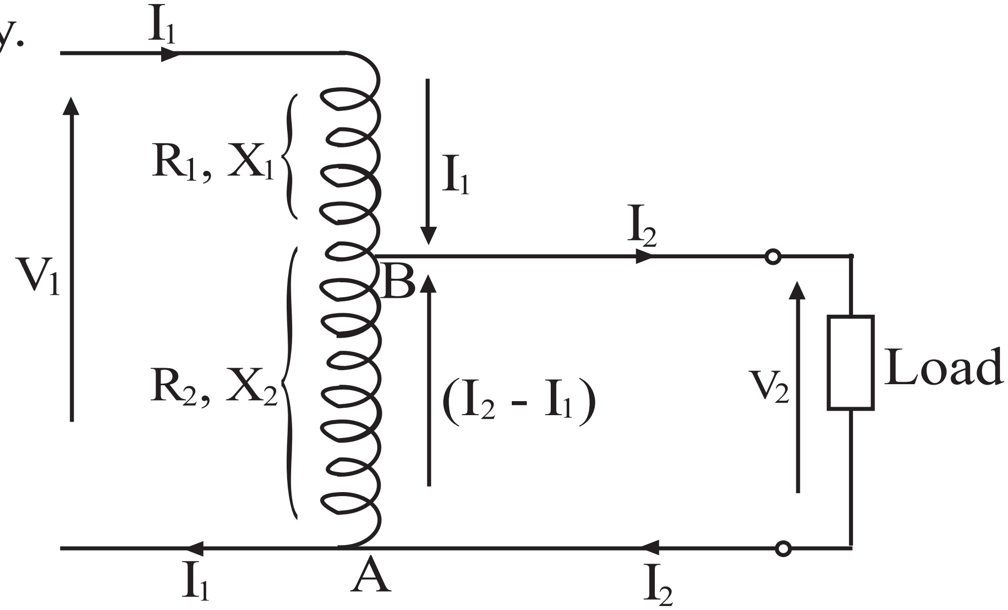


Figure : Equivalent circuit of auto transformer

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.

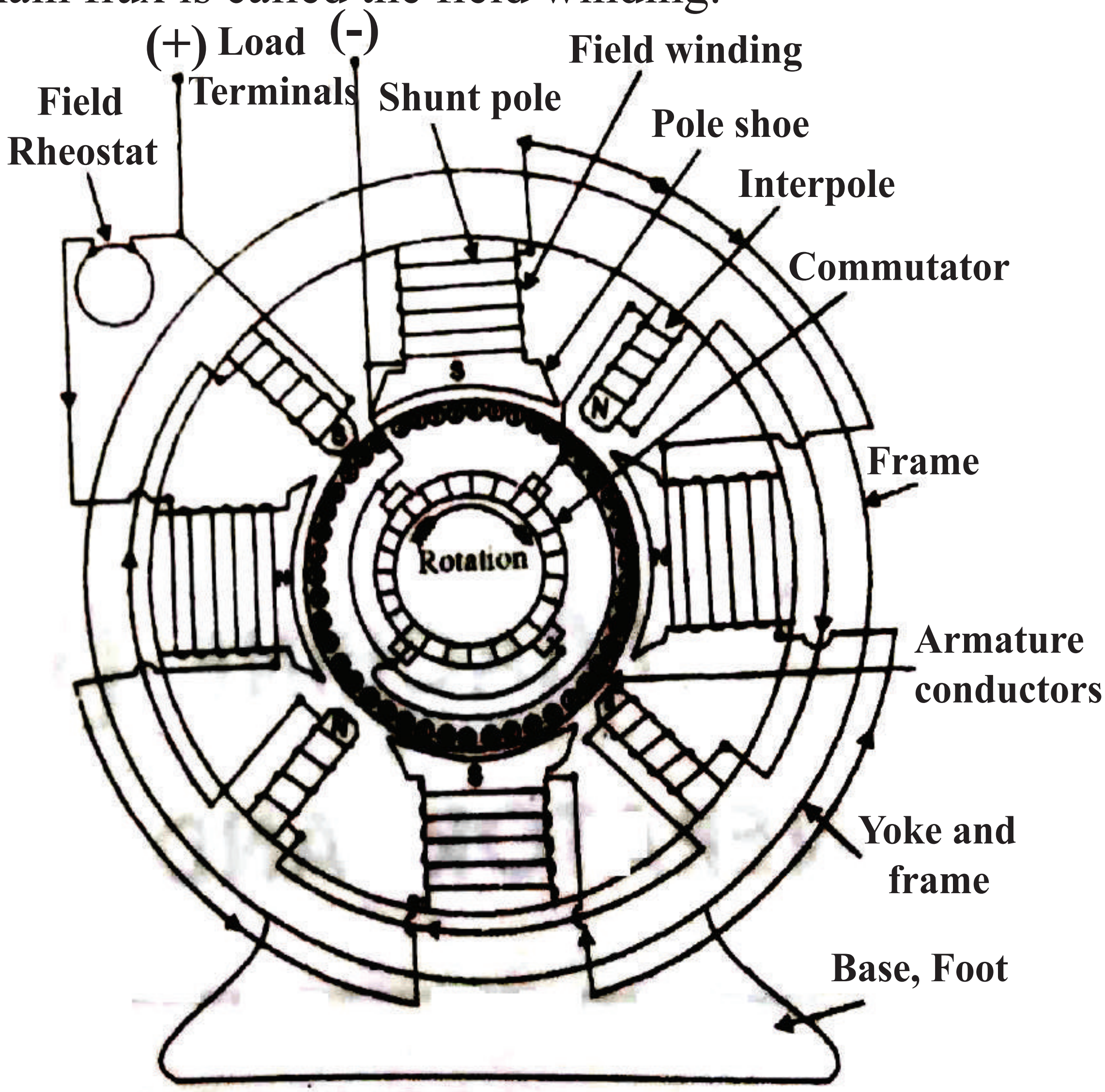


Figure : A cross-section of typical 4 pole d.c. machine.

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.

Types of DC Machines

(i) Separately excited d.c. machine

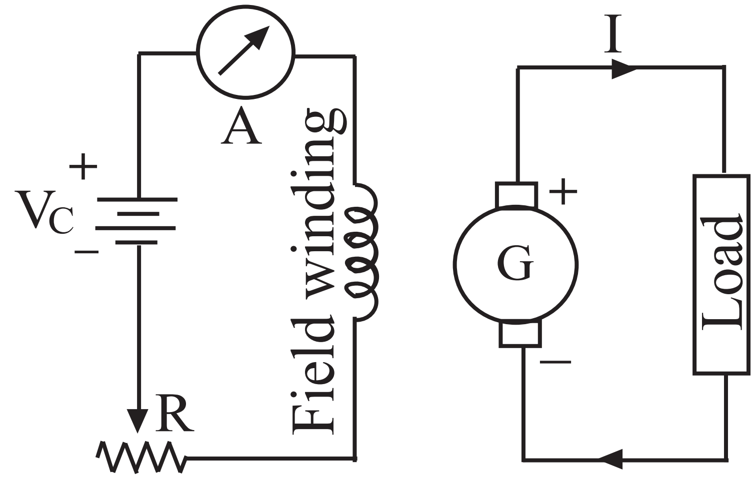


Figure : Separately-excited generators

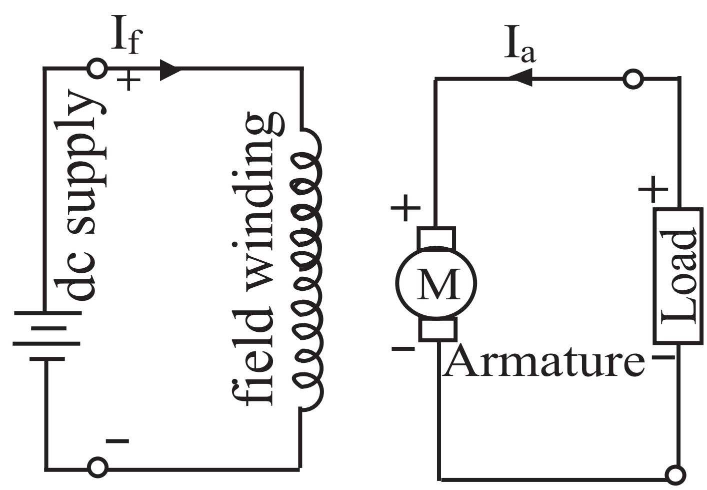


Figure : Separately excited dc motor

(ii) Shunt wound d.c. machine

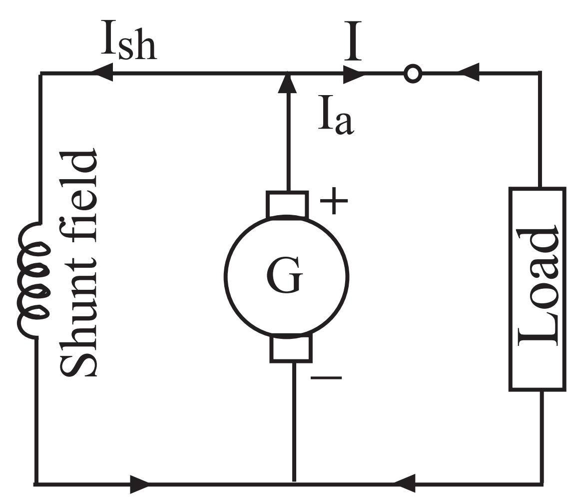


Figure : Shunt wound generator

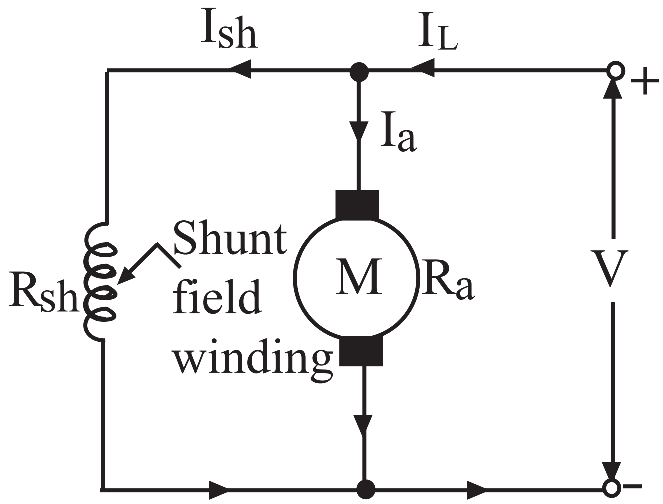


Figure : Shunt wound motor

(iii) Series wound d.c. machine

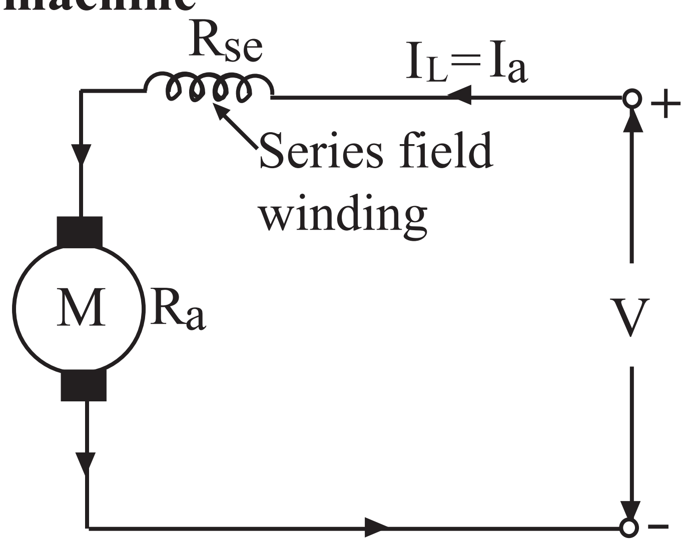


Figure : Series wound motor

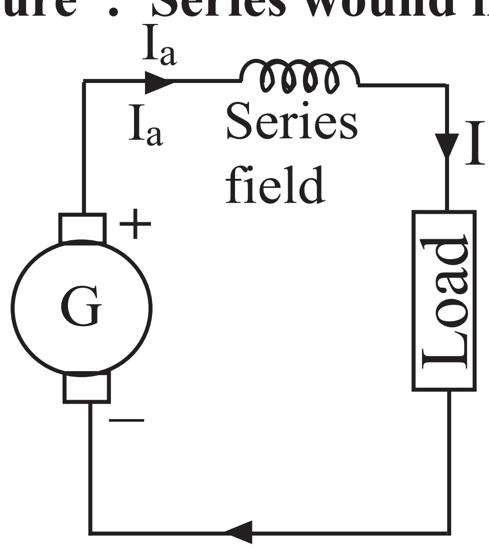
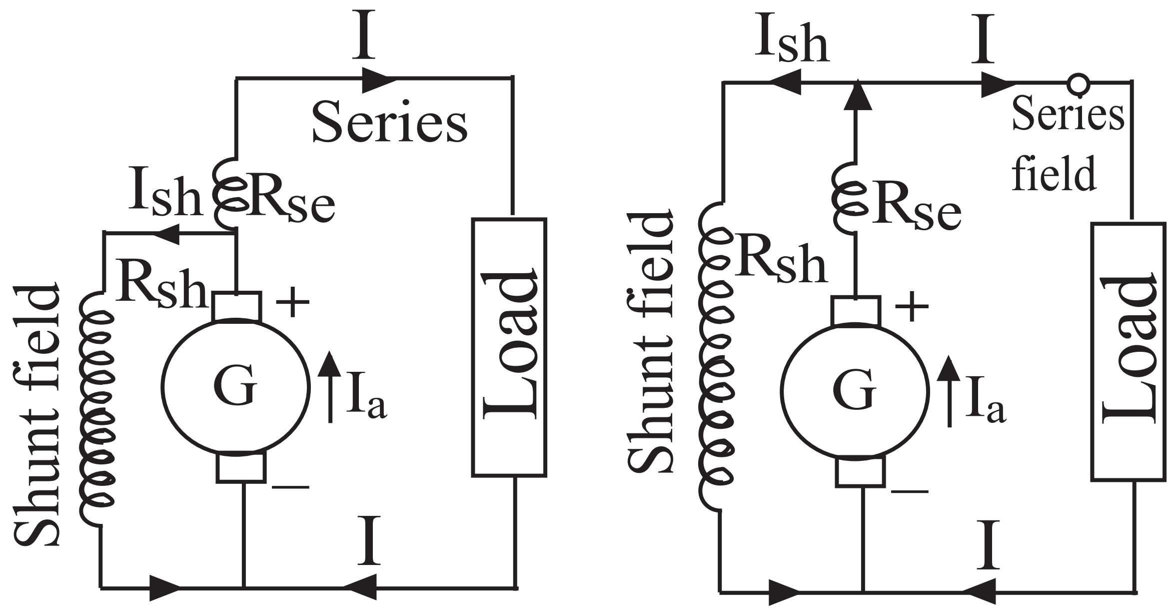


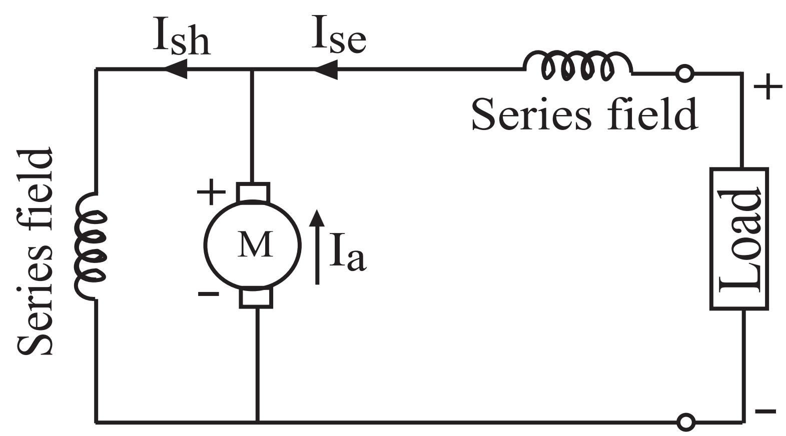
Figure : Series wound generator

(iv) Compound wound d.c. machine

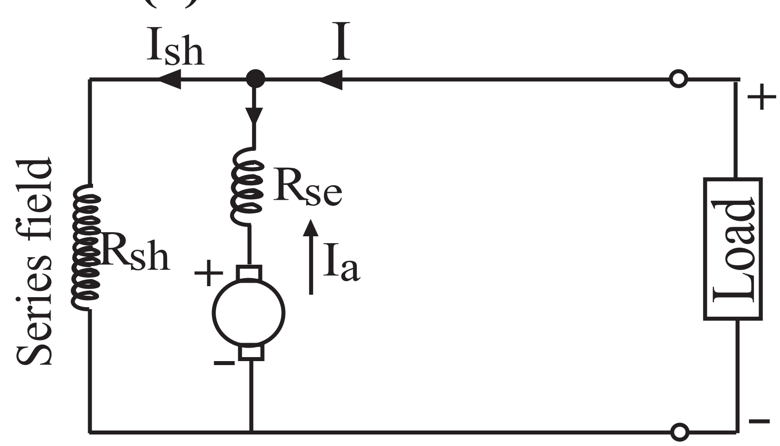


(a) Short-shunt **(b) long-shunt**

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**

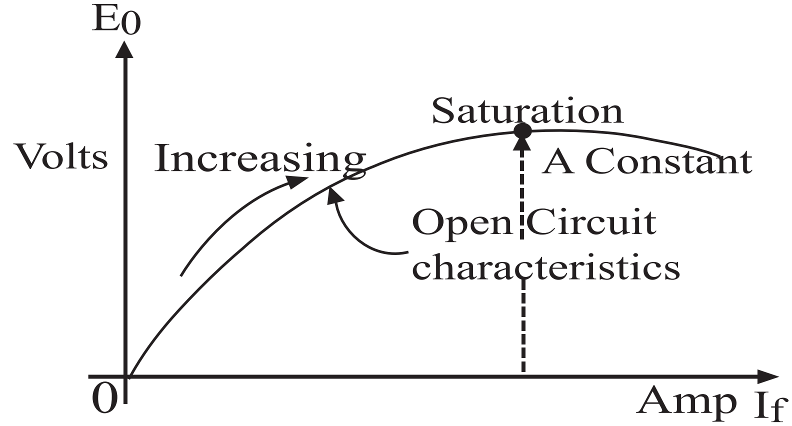


Figure : Open circuit characteristics

* **Load saturation curve**

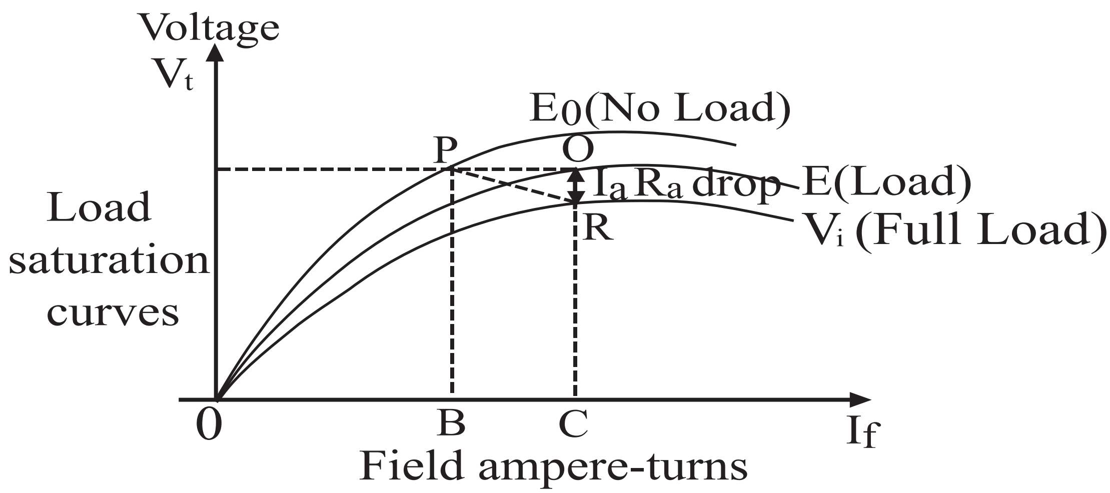


Figure : Load saturation curve

* **Internal and external characteristics**

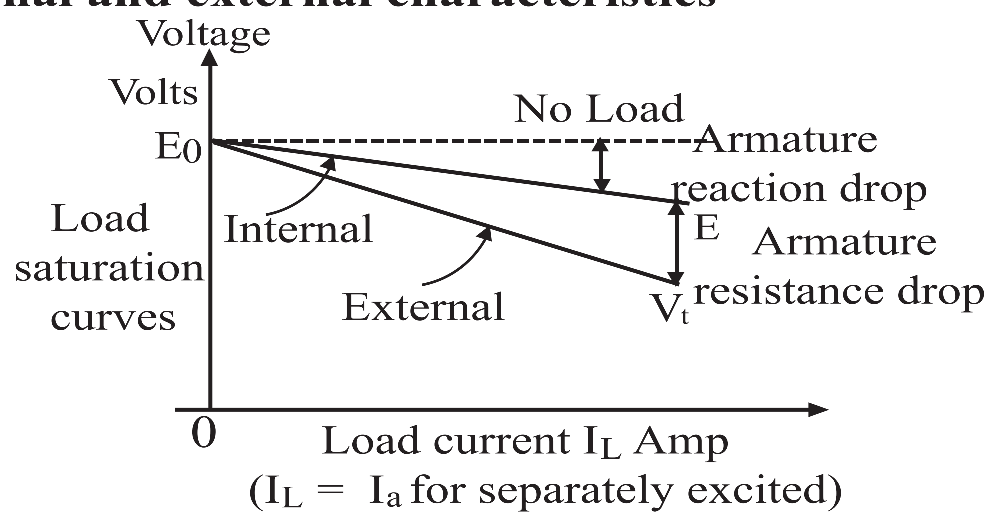


Figure : Internal and external characteristics

For D.C. Shunt Generator

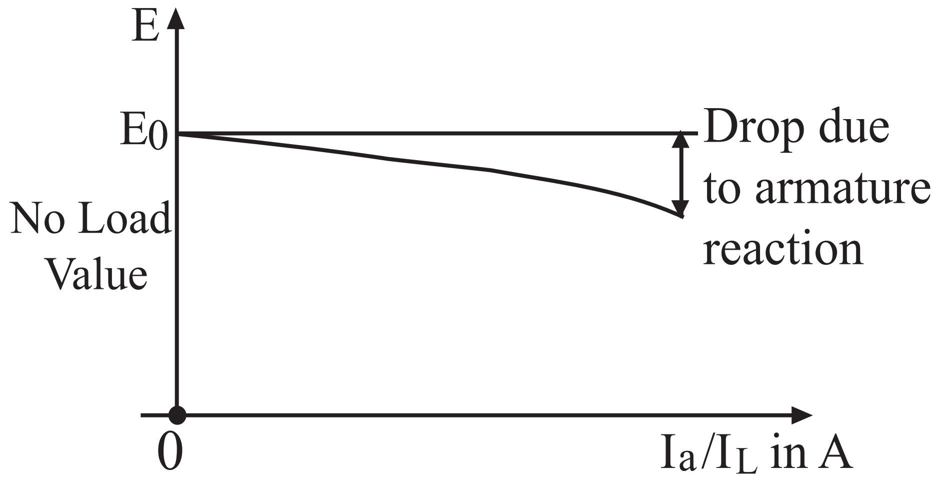


Figure : Internal Characteristics

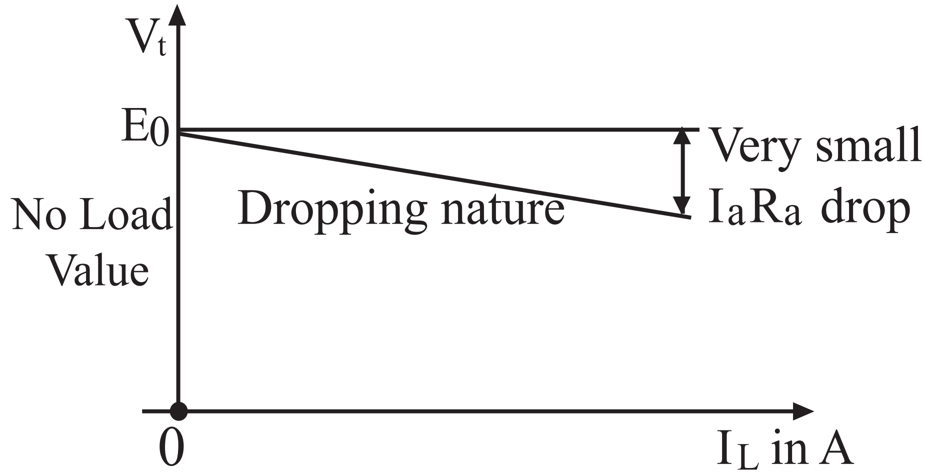


Figure : External Characteristics

For D.C. Series Generator

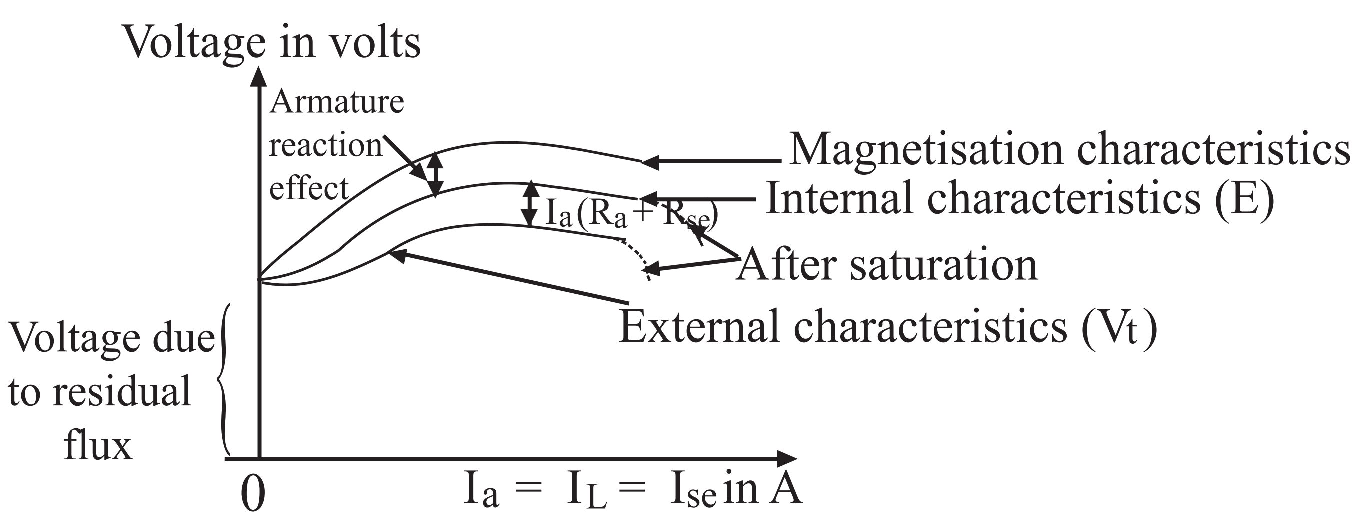


Figure : Characteristics of D.C. series generator