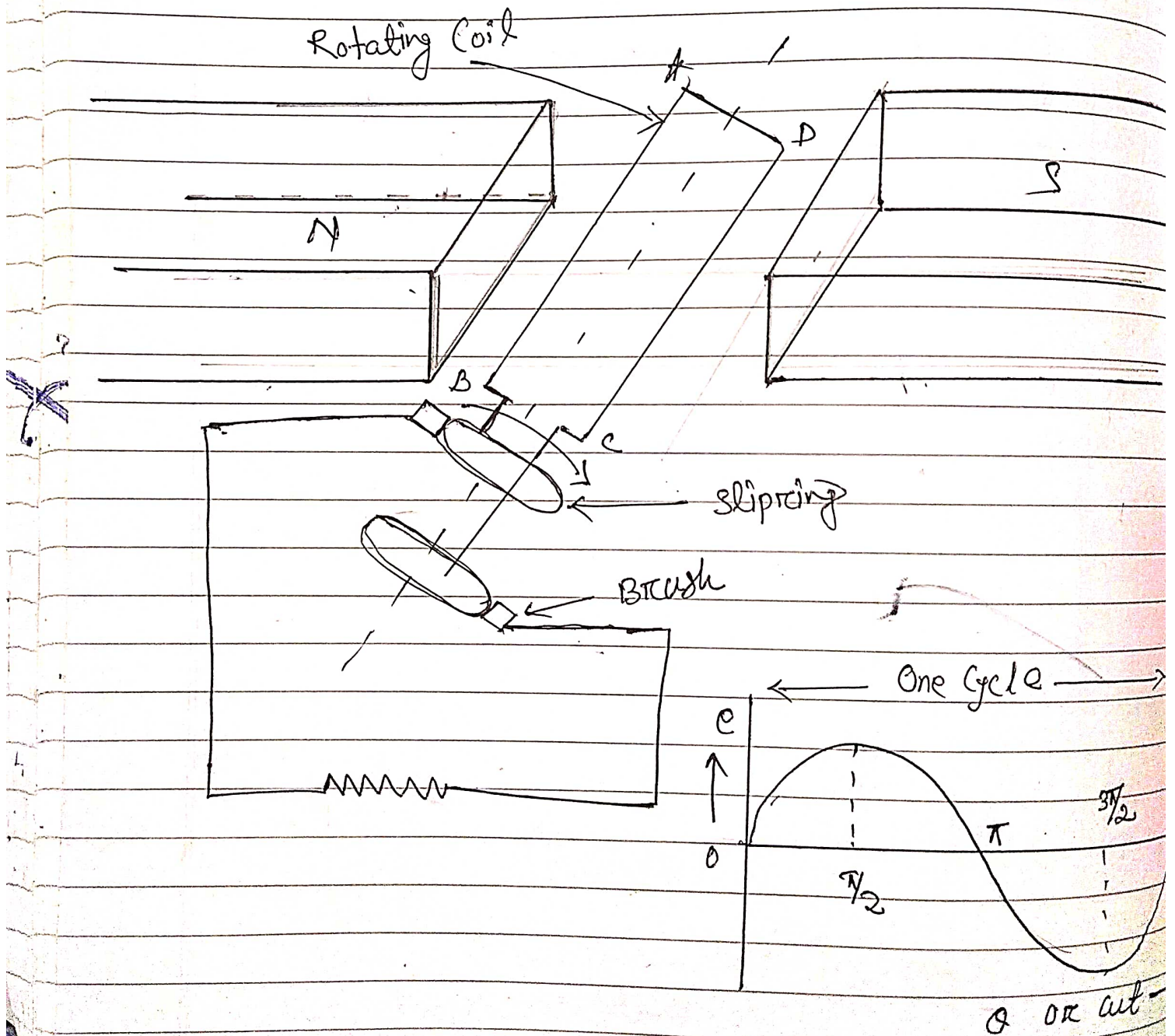


The DC Machine which converts Mechanical energy into electrical energy is called D.C Generator.

Basic Principle:-

When a conductor is rotated inside the magnetic field it cuts the magnetic flux then an emf is induced whose direction is obtained by Fleming's ~~right~~ hand rule. Magnitude is given by

$$E_g = BLV \sin \theta \text{ volt}$$



Working Principle →

The basic principle of DC Generator is based on Faraday's law of electromagnetic induction. This law states that whenever a conductor is placed in a magnetic field the conductor cuts the flux and an emf is induced in it. That causes the flow of current through the conductor if the conductor circuit is closed.

- ① Due to the permanent magnet the magnetic field is produced. Inside the magnetic field a rectangular single turn coil ABCD is placed.
- ② Its terminals are connected to the two slip rings which are insulated from each other. Brushes are pressed against the slip rings.
- ③ R is the external load resistance.
- ④ When the coil is rotated in clockwise in its own axis it cuts the line of magnetic force and hence an emf is induced in it.

⑤ When the coil is perpendicular to the magnetic line of force, the flux linkage is maximum but the induced emf will be zero. Since there is no change in flux linkage.

⑥ When the coil is placed parallel to the magnetic line of force the flux linkage is minimum but the induced emf will be maximum. Since the change in the flux linkage is minimum.

⑦ This process is repeated for a complete cycle. Hence the induced emf is obtained in the form of AC and whose direction is determined by Fleming's right hand rule.

Flux cuts → emf induced

$$\text{Avg } I = \text{average of } I$$

$$\text{Avg } I = \text{average of } I$$

$$\text{Avg } I = \text{average of } I$$

EMF Equation of DC generator:-

Let ϕ = flux per pole webers

Z = Number of armature conductor.

N = Speed in RPM

P = Number of Pole

A = Number of parallel path.

According to Faradays Law of electromagnetic induction the average emf induced in a conductor is the rate of change of flux linkage.

$$\text{Average emf induced/conductor} = d\phi/dt$$

$$= \frac{\text{Flux cut in one revolution}}{\text{Time taken for one revolution}}$$

$$= P\phi / 60/N$$

$$= \frac{P\phi N}{60} \quad \text{--- (1)}$$

$$\text{No of conductor / Parallel path} = Z/A \quad \text{--- (2)}$$

$$\textcircled{1} \times \textcircled{2} \Rightarrow \frac{P\phi N}{60} \times \frac{Z}{A}$$

$$\frac{\text{Average emf induced}}{\text{Parallel path}} = \frac{P\phi N Z}{60 A}$$

$$\Rightarrow E_g = \frac{P\phi Z N}{60 A} \text{ volt}$$

$A = 2$ for wave

$A = P$ for Lap

$$N \text{ Revolution} = 1 \text{ min}$$

$$1 \text{ revolution} = 1/N \text{ min}$$

$$= 60/N \text{ sec}$$

wave winding

If number of parallel path are two then it's called wave winding

$$A = 2$$

Lap winding

If number of parallel path is equal to number of poles then it is called Lap winding

$$A = P$$

Z = no. of conductors

T = no. of turns

$$Z = 2T$$

* In case of low current high voltage wave winding are used.

* High current low voltage Lap winding are used.

Types of Generator

DC Generator

→ Separately excited

→ self excited

→ Shunt

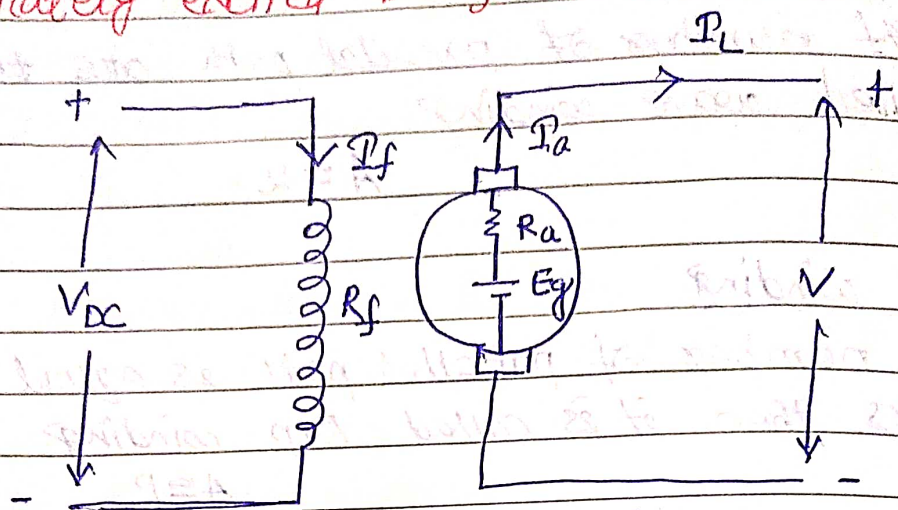
→ Series

→ Compound

→ Long shunt

→ short shunt

① Separately excited D.C Generator.



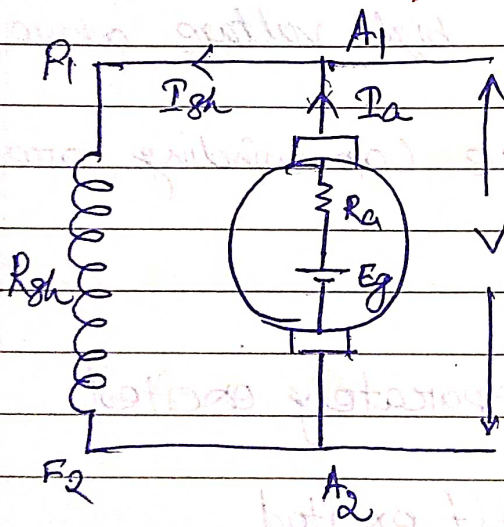
$$E_g - I_a R_a - B.D = V$$

$$I_a = I_L$$

② Self excited D.C Generator.

(a) Shunt type

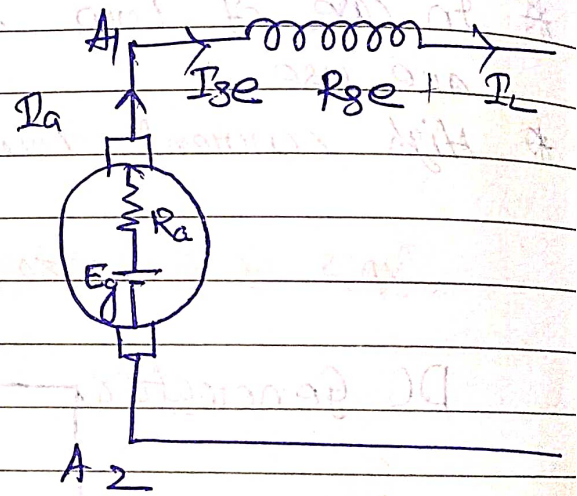
(b) Series type



$$E_g - I_a R_a - B.D = V \quad \text{--- ①}$$

$$I_{sh} R_{sh} = V \quad \text{--- ②}$$

$$I_a = I_L + I_{sh} \quad \text{--- ③}$$

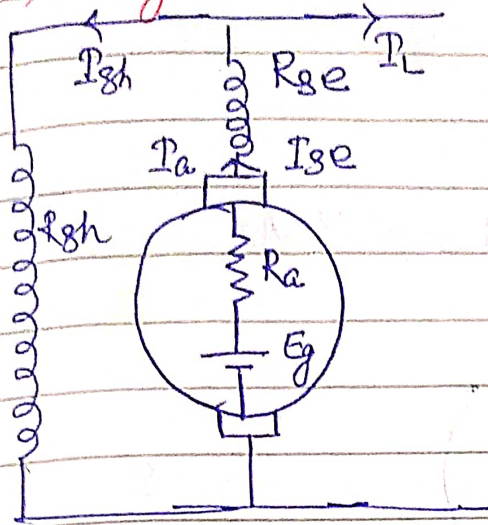


$$E_g - I_a R_a - B.D - I_{se} R_{se} = V$$

$$I_a = I_{se} = I_L$$

(c) Compound

(i) Long shunt

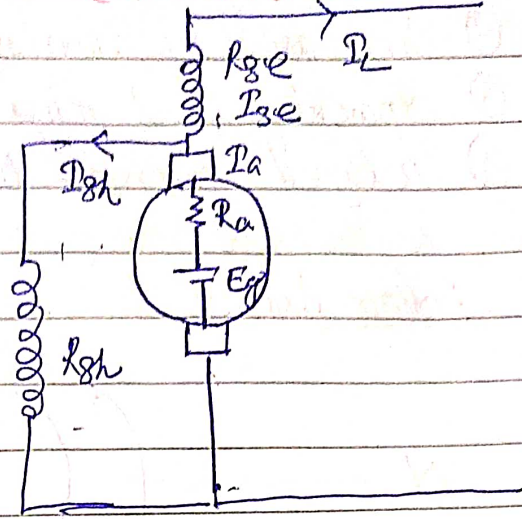


$$E_g - I_a R_a - B.D - I_{se} R_{se} = V$$

$$I_{sh} R_{sh} = V$$

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

(ii) short shunt



$$E_g - I_a R_a - B.D - I_{se} R_{se} = V$$

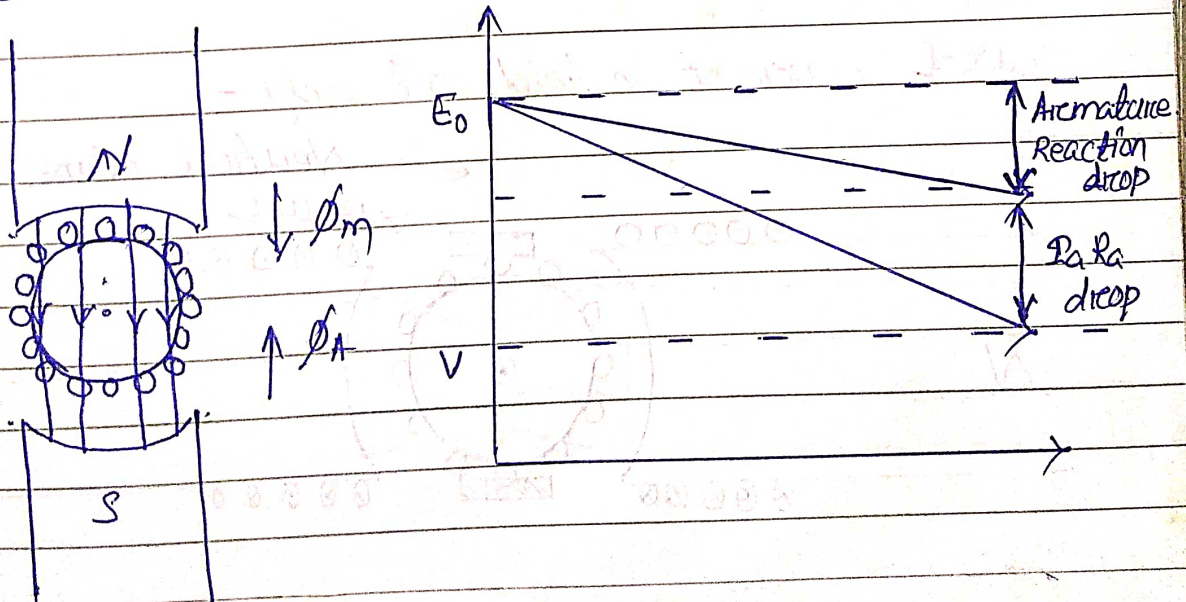
$$I_{sh} R_{sh} - I_{se} R_{se} = V$$

$$I_a = I_{se} + I_{sh}, \quad I_{se} = I_L$$

0 Armature Reaction of DC Machine :-

The flux produced due to current flow through armature conductor opposes the main flux which is known as armature reaction.

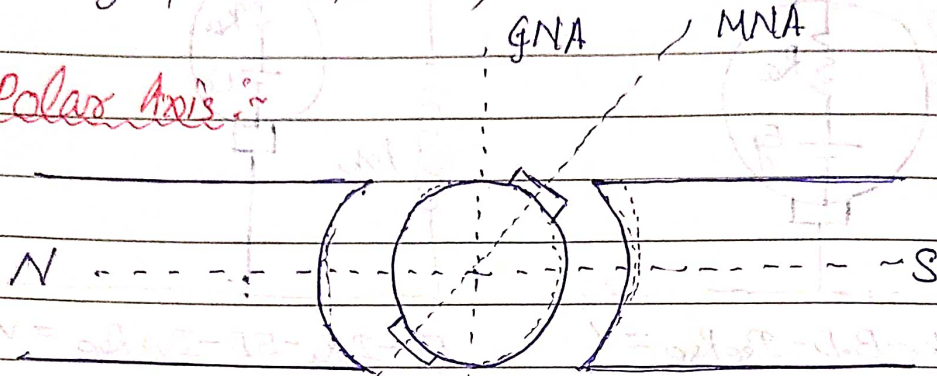
When generator is loaded the resultant flux decreases because of armature reaction. Therefore the induced EMF decreases hence the terminal voltage also decreases.



Effect of Armature Reaction :-

- ① Reduction in induced EMF
- ② Increase in Iron Loss
- ③ Sparking and ring fire
- ④ Delayed commutation

Polar Axis :-



The axis joining the centre of north pole and south pole is called polar axis.

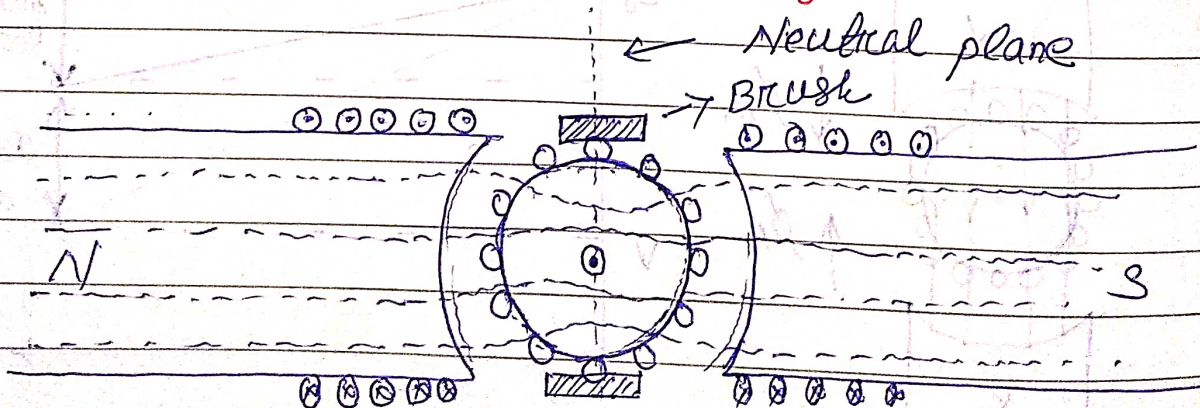
Geometric Neutral Axis (GNA) :-

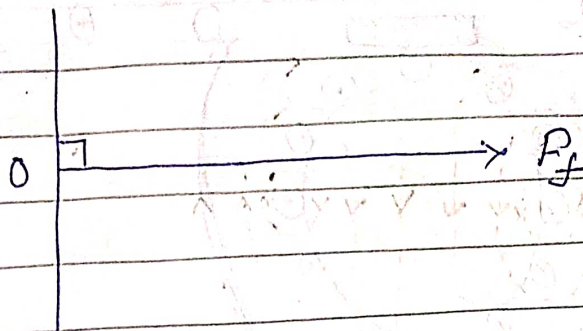
The axis which is perpendicular to polar axis and pass through centre of armature is called GNA.

Magnetic Neutral Axis (MNA) :-

The axis along which there is no induced EMF is known as MNA. Since brushes are provided MNA it is also called brush axis.

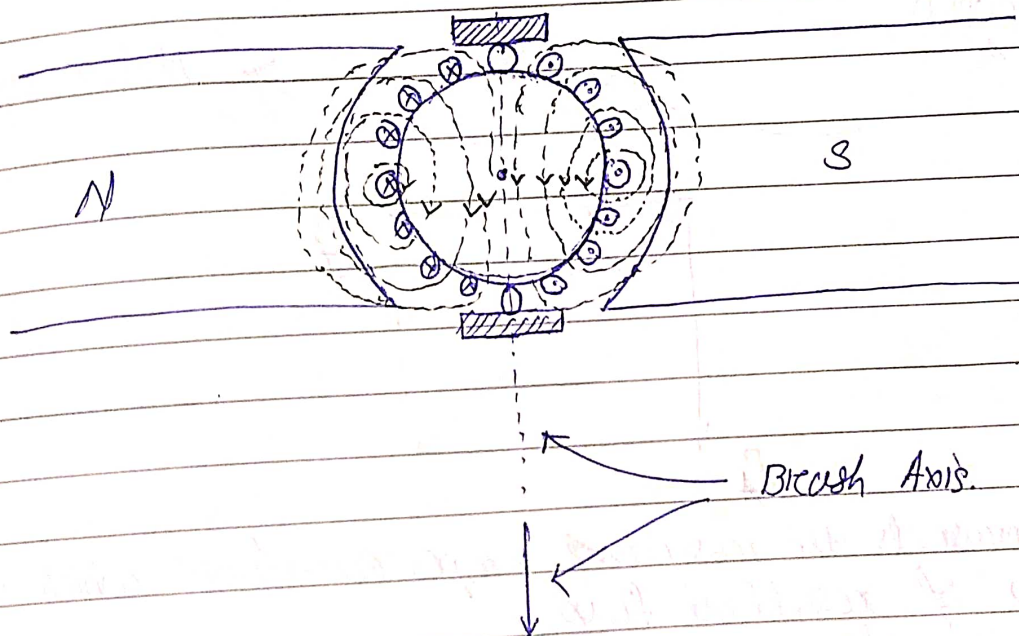
Case-I Current in field coil only -





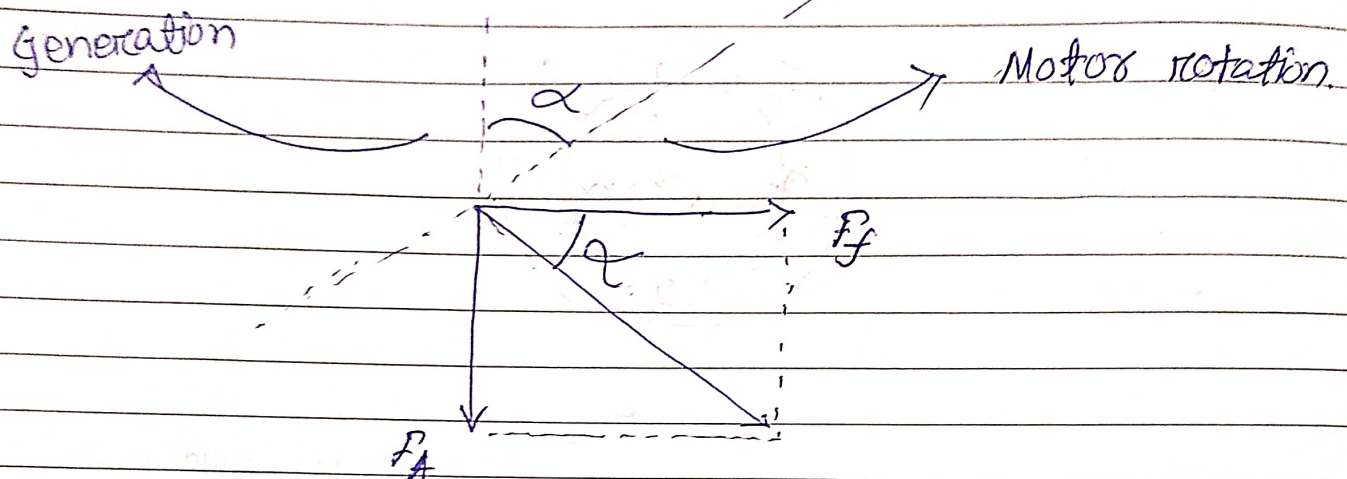
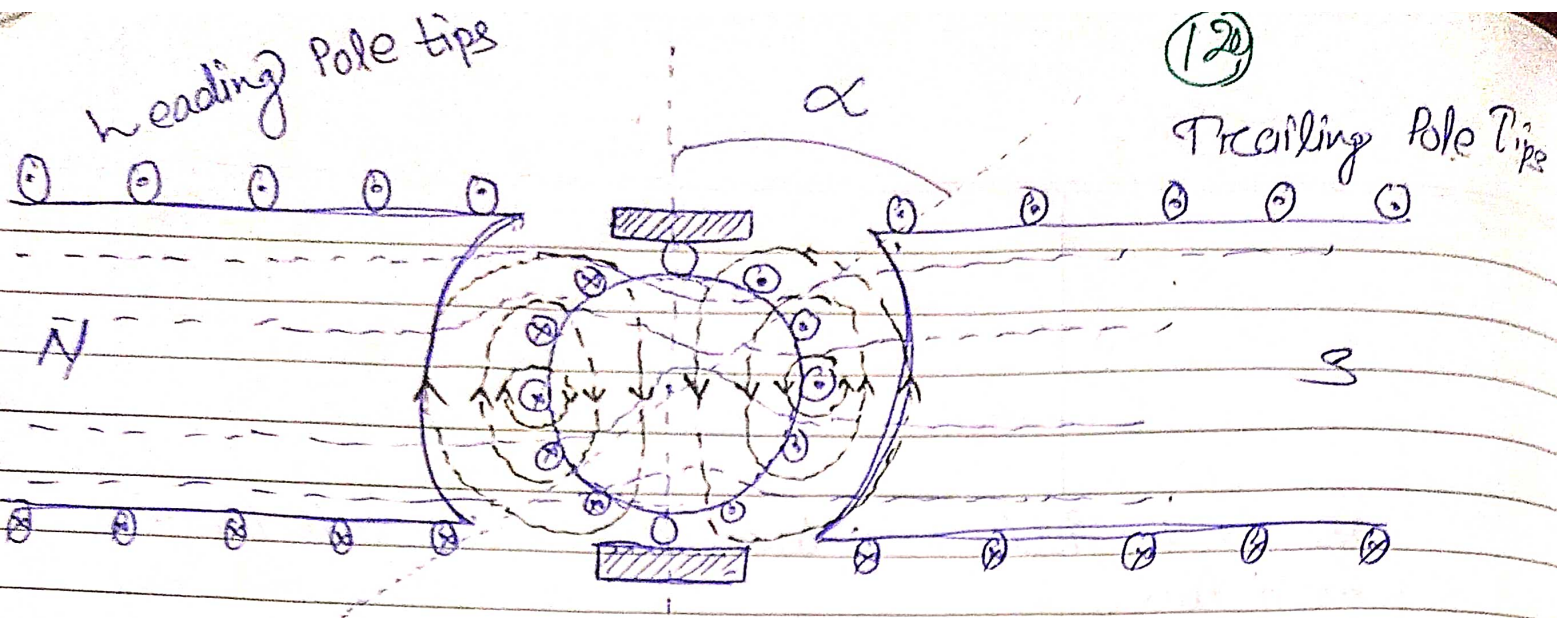
OF_f is the field ampere turn/pole which result flow of main flux.

case-II current in Armature only -



OF_a represents the armature ampere turn/pole which results flow of armature flux.

case-III current in both field and armature Brush axis -



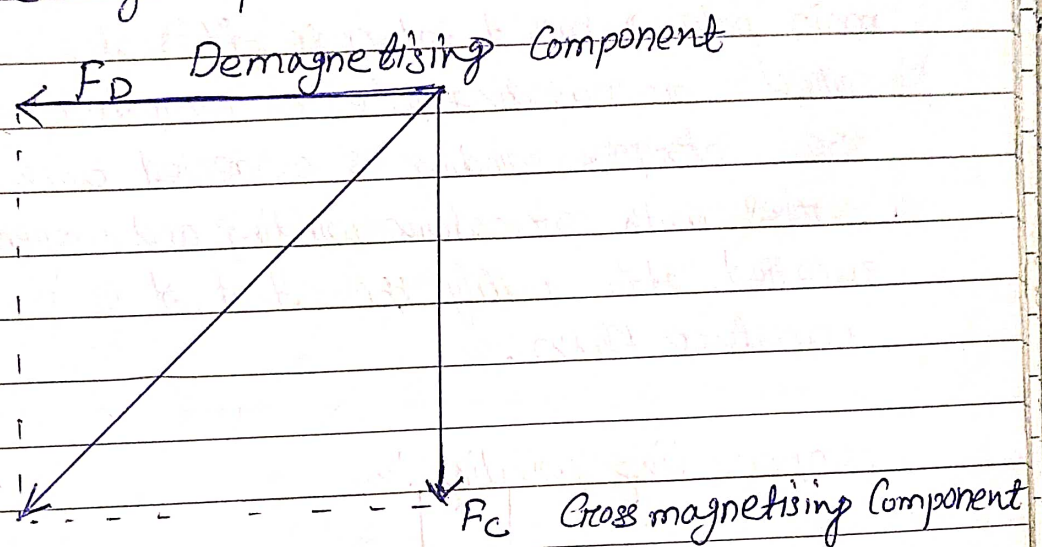
$O F_r$ represents the resultant ampere turn/pole which result in flow of resultant flux.

It can be seen that the field MMF effect and armature MMF F_A combine at right angle to form the resultant field MMF apart.

As the resultant flux is shifted by an angle α in the direction of rotation of armature, the neutral plane is also shifted by the same angle α . As the brushes have to be set in the neutral plane for better commutation, the brush axis is also shifted by an angle α in the direction of rotation of the armature.

The direction of armature field moves with the brushes. Its axis always lies along the brushes axis F_A may be

resolved in to two component. F_D parallel to the polar axis and F_C perpendicular to polar axis. F_D acts in direct opposition to main field therefore it tends to reduce the total flux and so it is called the demagnetising component of the armature reaction. F_C acts right angle the main field producing distortion and is called cross magnetising component of the armature reaction.



$$\begin{aligned} \text{Demagnetising Amp turn/pole} &= \left(\frac{Z}{2P} \cdot \frac{I_a}{180} \right) \times 2P \\ &= \frac{Z}{P} I_a \times \frac{P}{180} \text{ Amp turn} \end{aligned}$$

$$\begin{aligned} \text{Cross magnetising Amp turn/pole} &= \text{Total Amp turn/pole} - \text{Demagnetising Amp turn/pole} \\ &= \frac{Z}{P} I_a \left[\frac{1}{2} - \frac{P}{180} \right] \end{aligned}$$

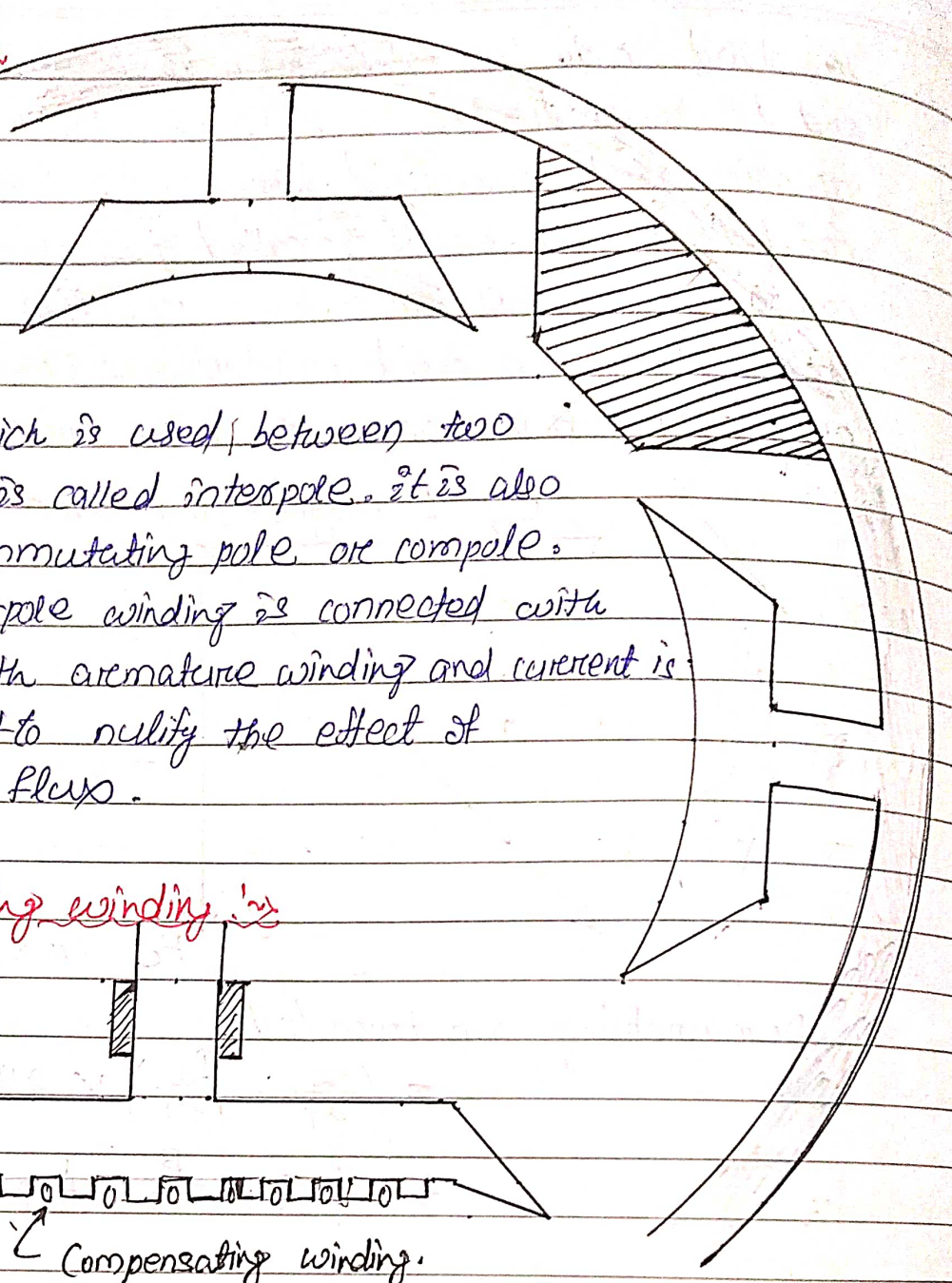
where Z = total no. of armature conductor

P = number of pole

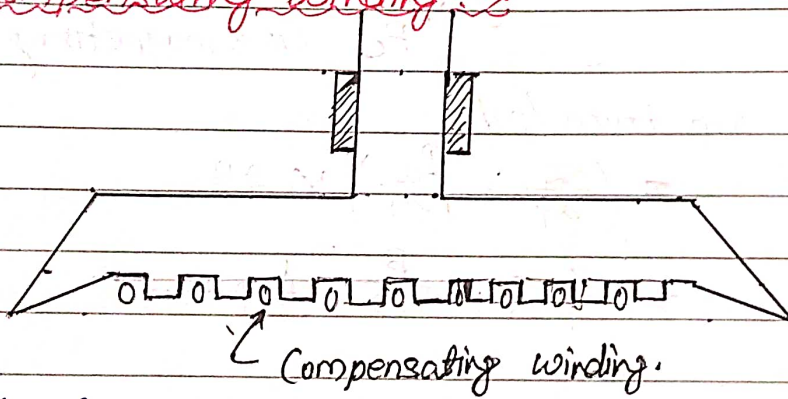
I_a = Armature current

β = Brush Lead in electrical degree

I_z = current flowing through each armature conductor.

Interpole :-


The pole which is used between two main pole is called interpole. It is also called commutating pole or compole. The interpole winding is connected with series with armature winding and current is supplied to it to nullify the effect of armature flux.

Compensating winding :-

In large machines the pole shoe each slotted the winding provided in pole shoe is called compensating winding. This winding is connected in series with armature winding and supply is given in such a way that it reduce the effect of armature reaction partly.

characteristics of DC Generator:-

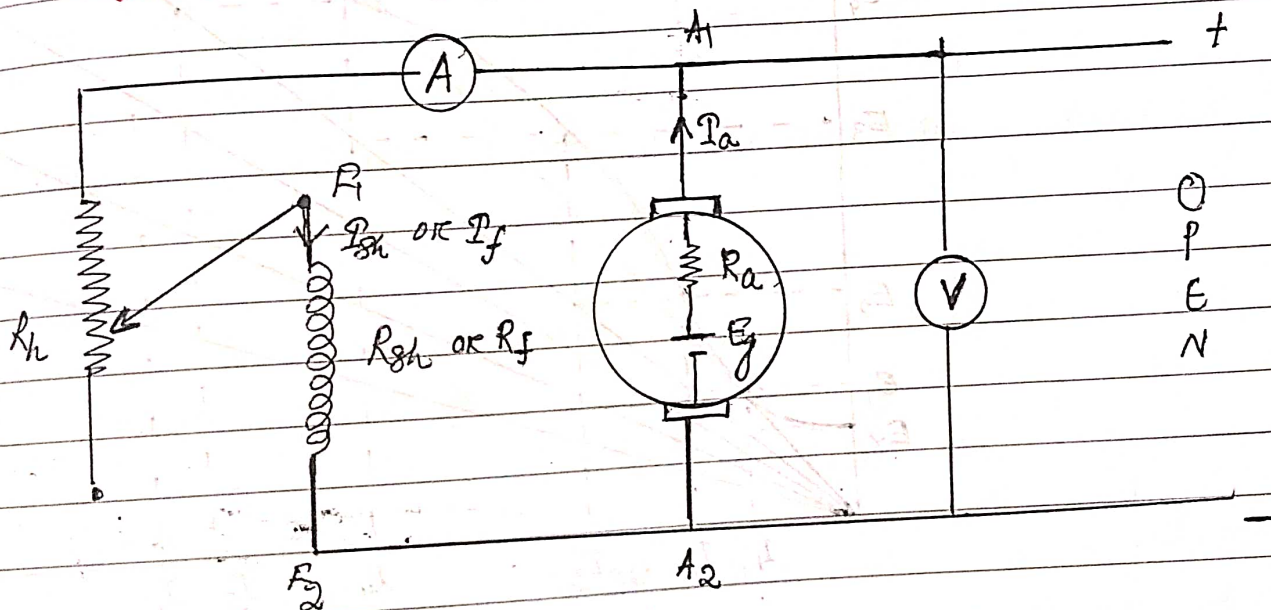
- ① Open Circuit characteristics (O.C.C) } $E_o \text{ Vs } I_f$
 magnetic characteristics
 no load saturation curve
- ② Internal characteristics curve (P.C.C) } $E \text{ Vs } I_a$
 Total characteristics
- ③ Load characteristic curve (L.C.C) } $V_L \text{ Vs } I_f$
 External characteristics

$E_o \rightarrow$ Induced EMF at no load

$E \rightarrow$ Induced EMF at load

$V_L \rightarrow$ Terminal voltage at load

O.C.C. of Shunt Generator:-



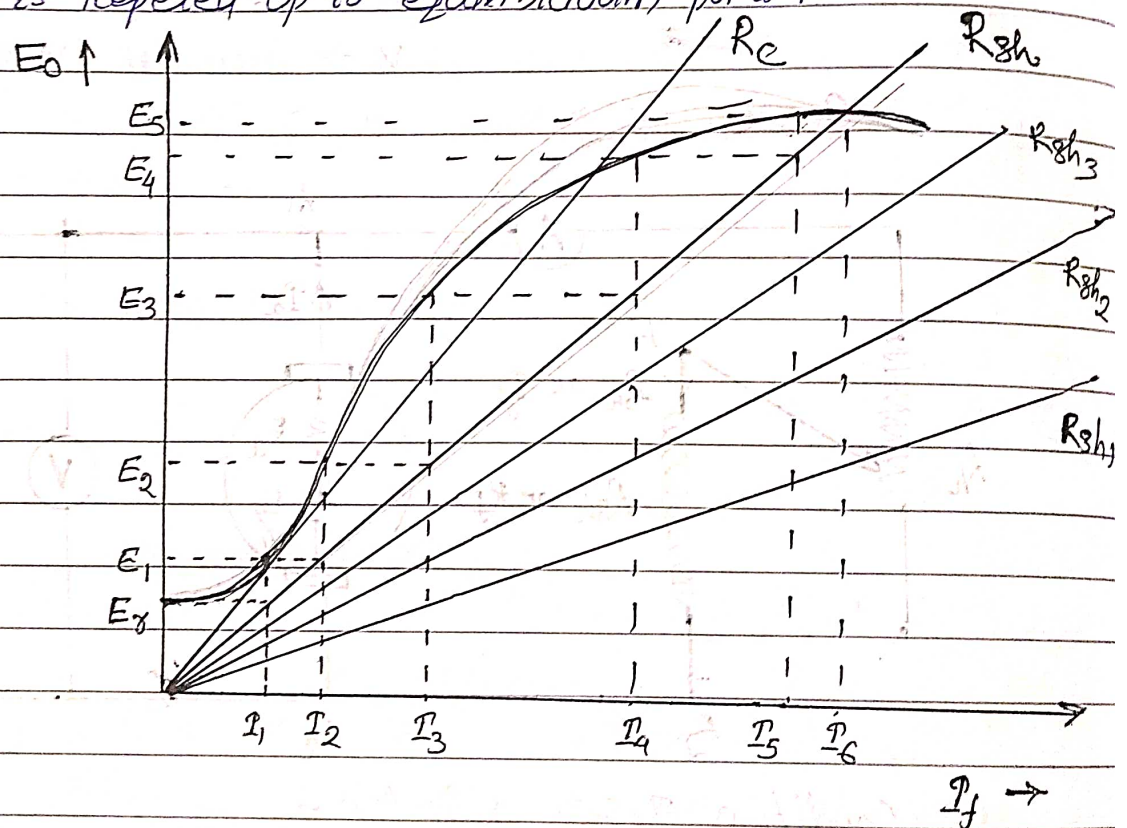
Condition for self excitation -

Self excited generators are those whose field magnets are excited due to current produced by the generator them self. due to residual magnetism there is always present some flux in the poles.

Buildup of emf -

A small amount of flux is produced from the field pole without excitation called residual flux, due to linkage of this flux with armature winding emf is induced known as residual emf (E_r)

This emf drives current I_1 through the field winding and flux is produced. Again due to linkage of this flux emf is induced in the armature, this emf drives current I_2 through the field winding which causes additional flux again. Like this process is repeated up to equilibrium point P.



Critical Resistance -

The shunt field resistance line which is tangent to the O.C.C. in the linear region is called Critical resistance or Critical field resistance.

For any resistance above R_c no emf will be induced in the armature as the resistance line does not intersect O.C.C.

Causes of failure of Build up of emf -

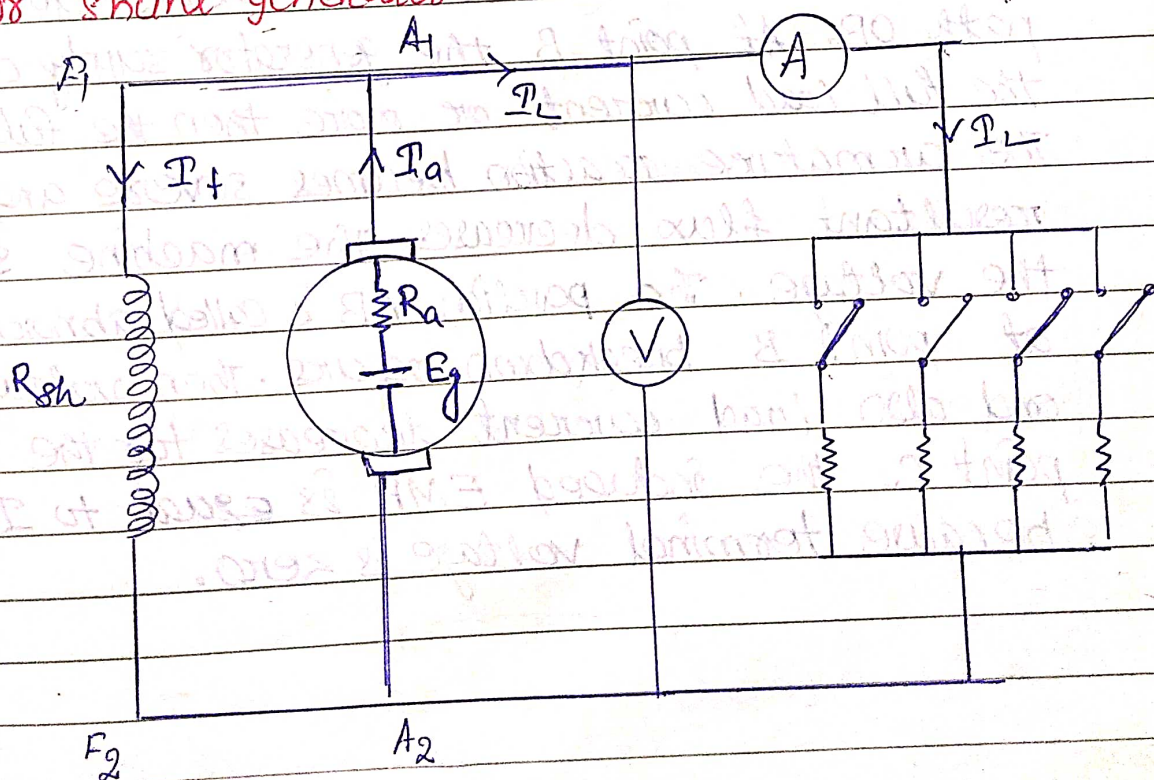
- ① There may not be residual magnetism
- ② The rated speed may be less than critical speed (N_c)
- ③ The total resistance in the field circuit may be more than critical resistance (R_c)
- ④ The field flux due to additional current may not be added to the residual flux.
- ⑤ There may be open ckt in the field winding.

Remedies -

- ① Residual flux should be created
- ② The rated speed should not be less than critical speed.
- ③ The total resistance value should be less than critical speed.
- ④ The additional flux due to field current should be added with residual flux.
- ⑤ The continuity should be maintained in the field circuit.

L.C.C. OR E.C.C. of DC generator :-

① For shunt generator -



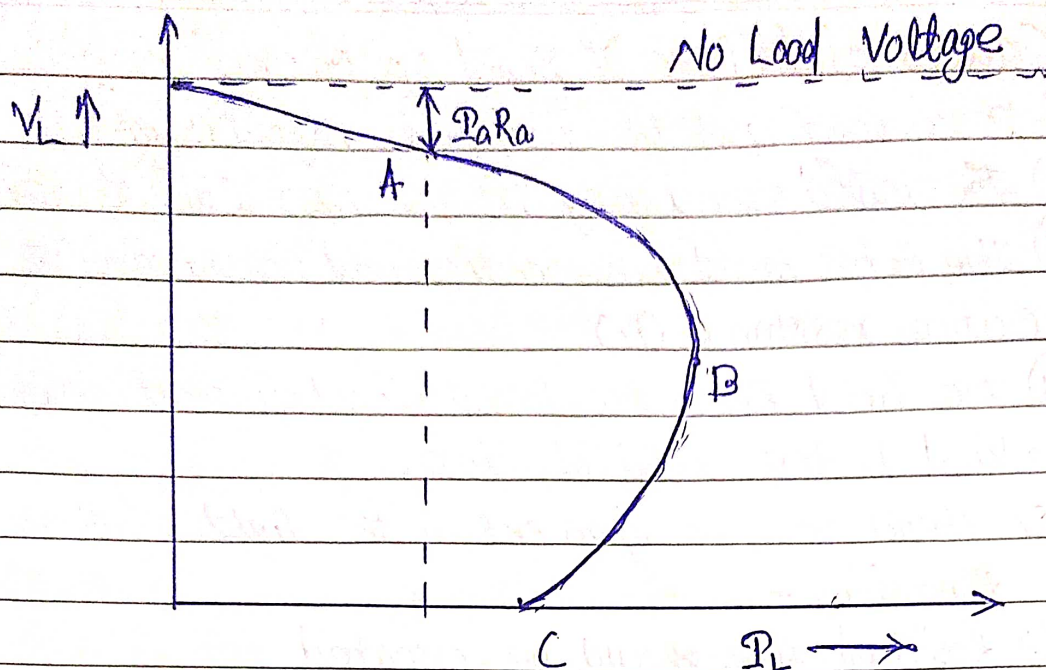
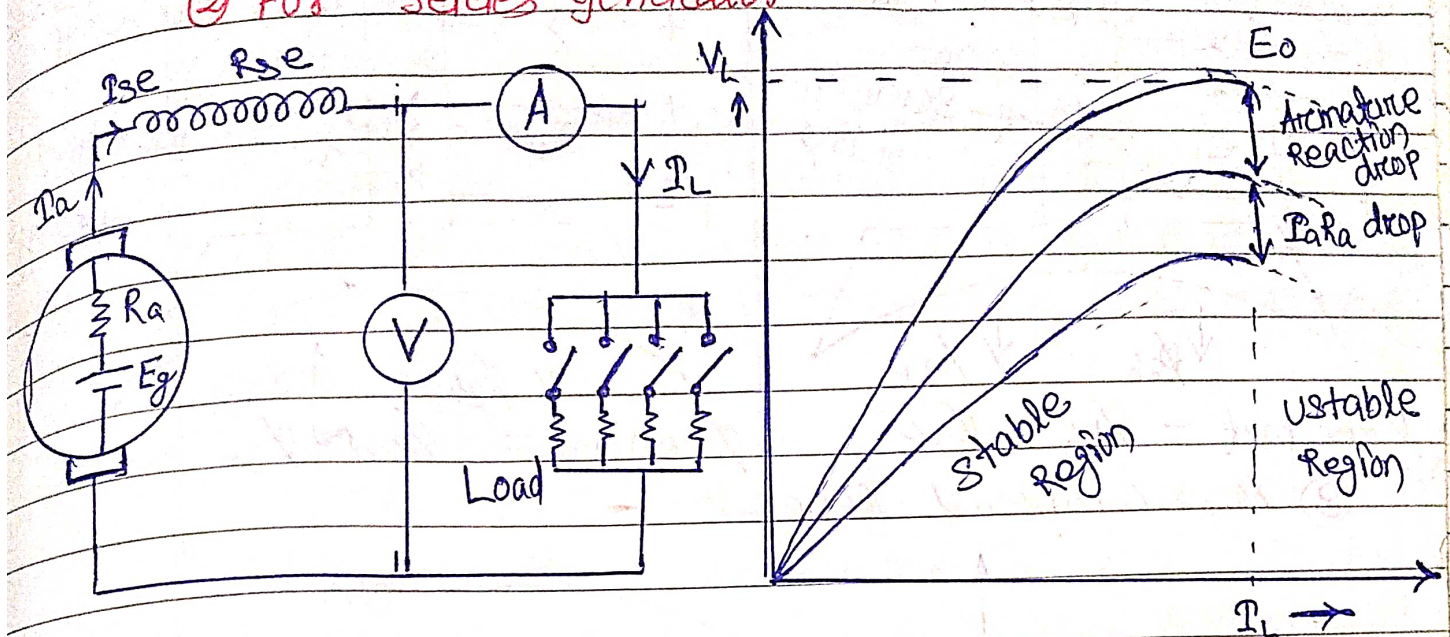


Figure shows LEC drawn with Load current on x -axis and Load voltage on y -axis. The load current in the generator is increased by connecting more resistance in parallel according to the relation $(I_L = \frac{V}{R_{eq}})$.

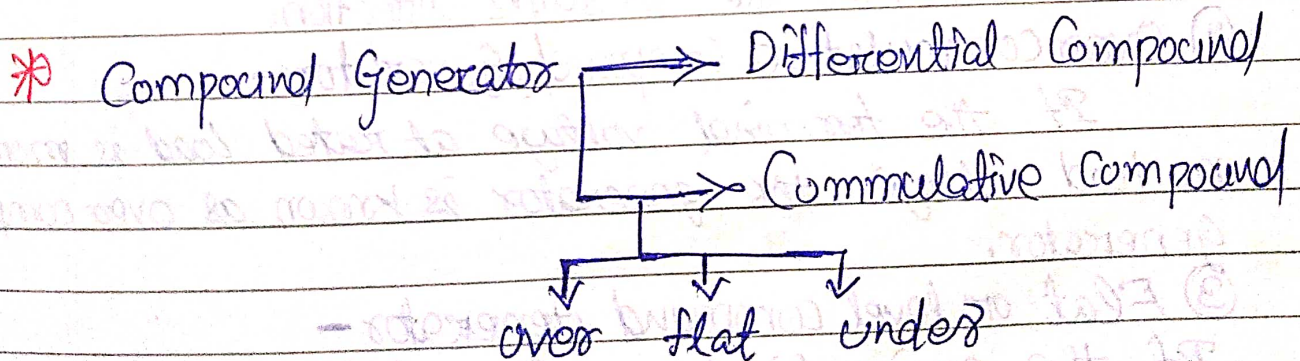
When Load current increases, the terminal voltage decreases because of armature resistance drop and armature reaction drop. The characteristics is divided into three parts like OA, AB & BC. The portion OA is called normal operating region. As the load is increased the terminal voltage decreases along the path OB. At point B the generator supply current 10 times the full load current or more than the full load current. The armature reaction becomes severe and hence the resultant flux decreases. The machine starts on build up the voltage. The portion AB is called abnormal region and at point B breakdown occurs. Then voltage decreases and also load current decreases for the portion BC. At point C the induced EMF is equal to $I_a R_a$ drop because terminal voltage is zero.

② For Series Generator -

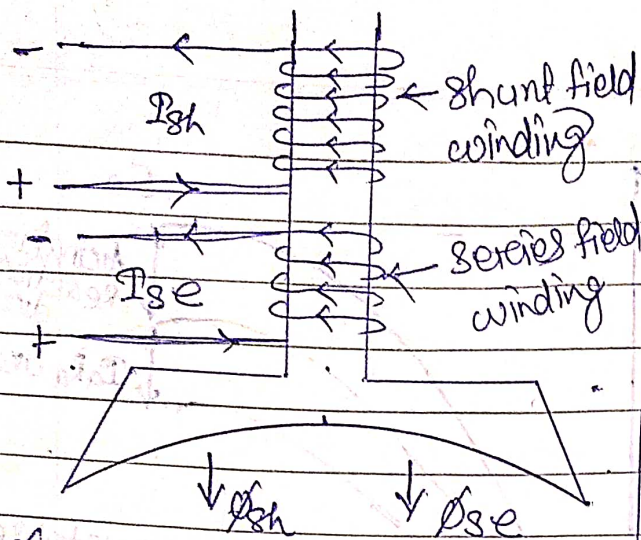


The figure shows LCC with load current on x-axis and load voltage on y-axis. In stable region the voltage of series generator increases with the load current. The series field current and load current are equal as the load current increases field flux increases and hence induced emf increases. Thus series generator has raising characteristics.

In the unstable region the current drawn by the load is very large the armature reaction becomes severe which causes decrease in resultant flux hence gradually induced emf decreases and terminal voltage decreases.

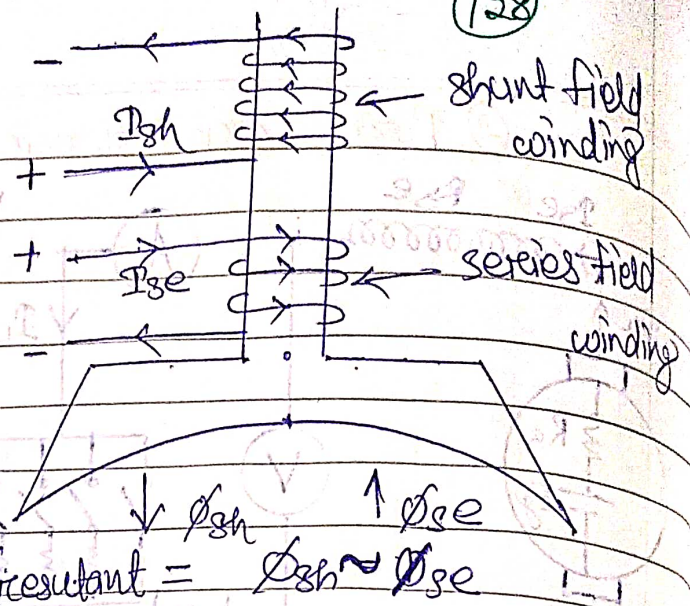


Commulative Compound

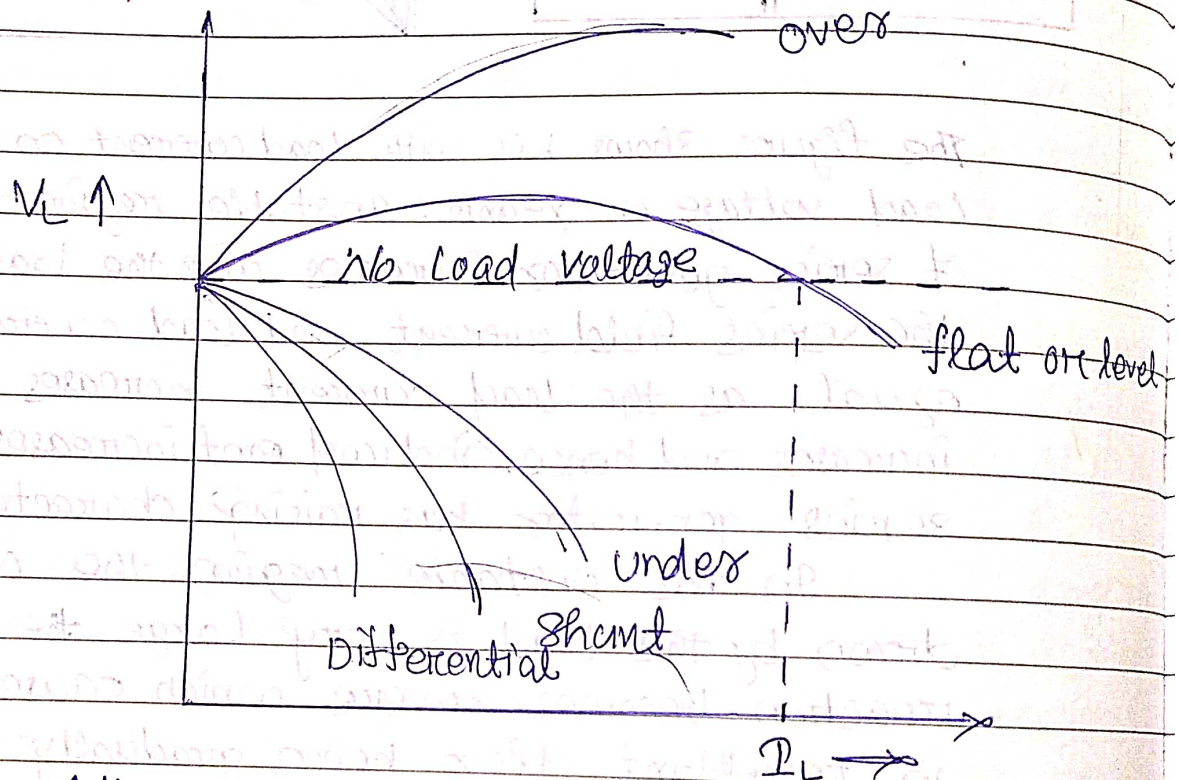


Differential Compound

(128)



③ For compound generator -



① Commulative compound -

In commulative compound generator shunt field MMF and series field MMF are in same direction.

② Over commulative compound generator -

If the terminal voltage at rated load is more than no load voltage, the generator is known as over compound generator.

③ Flat or level compound generator -

If the series field MMF is added with shunt field MMF

such that the load voltage is equal to the no load voltage such generator is known as flat compound or level compound generator.

④ Under commutative Compound Generator -

If the terminal voltage on rated load is less than no load voltage is known as under compound generator.

⑤ Differential Compound Generator -

In differential compound generator the series field MMF and shunt field MMF are in opposite direction. As the load increases the series field MMF increases and the net MMF decreases therefore the terminal voltage on load decreases rapidly.

Parallel Operation of DC Generator :-

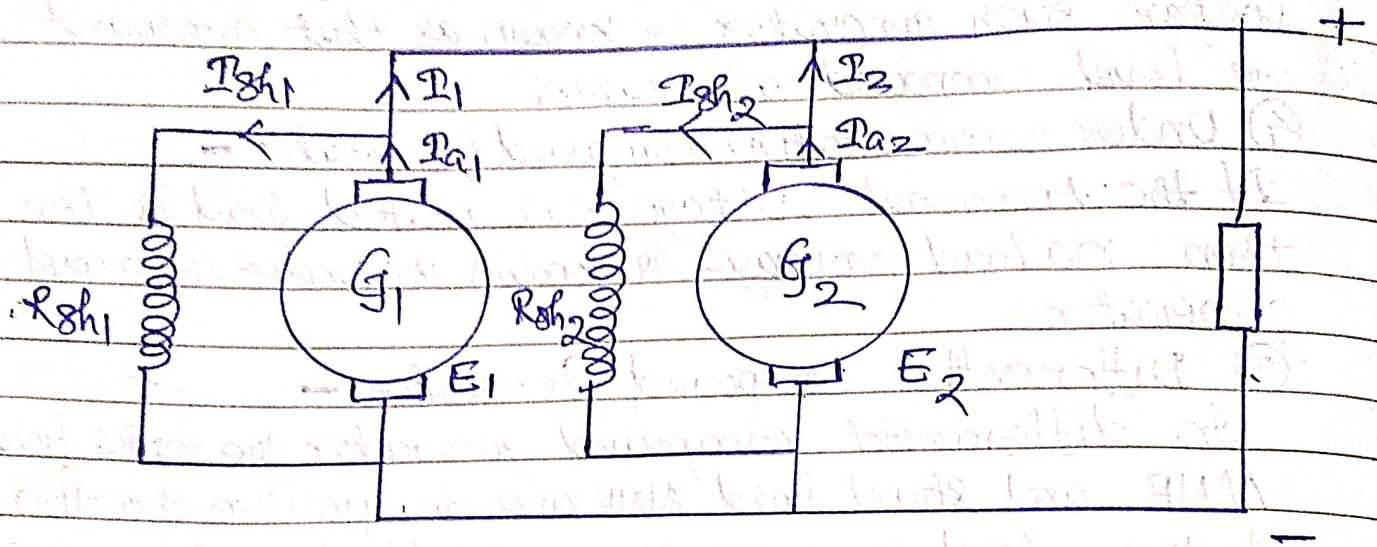
To produce large amount of power with small unit by connecting them in parallel. The reasons

- ① To maintain continuity of supply.
- ② To undertake maintenance work as per schedule.
- ③ To operate generators at their full rated capacity.
- ④ To eliminate stand by units.
- ⑤ To extend station capacity easily.
- ⑥ To increase life of the units by operating them in shift system.

Condition Required for parallel operation -

- ① Polarity must be same.
- ② Voltage magnitude must be same.
- ③ Similar characteristics.

Shunt Generator in Parallel -



$$I = I_1 + I_2 \quad \text{--- (1)}$$

$$I_1 = I_{a1} - I_{sh1}$$

$$= \frac{E_1 - V}{R_{a1}} - \frac{V}{R_{sh1}}$$

$$I_1 = \frac{E_1}{R_{a1}} - \frac{V}{R_{a1}} - \frac{V}{R_{sh1}} \quad \text{--- (2)}$$

Similarly

$$I_2 = \frac{E_2}{R_{a2}} - \frac{V}{R_{a2}} - \frac{V}{R_{sh2}} \quad \text{--- (3)}$$

Putting the value of I_1 and I_2 in eqⁿ (1)

$$I = I_1 + I_2$$

$$= \frac{E_1}{R_{a1}} + \frac{E_2}{R_{a2}} - V \left[\frac{1}{R_{a1}} + \frac{1}{R_{a2}} + \frac{1}{R_{sh1}} + \frac{1}{R_{sh2}} \right]$$

$$V = E_1 - I_{a1} R_{a1} = E_2 - I_{a2} R_{a2}$$

Application of DC Generators :-

Shunt Generator -

- ① Used for battery charging
- ② Electrical power supply
- ③ Due to drooping characteristics it is best suitable for parallel operations.

Series Generator -

As a line booster in dc distribution system to compensate line drop due to raising characteristics.

Differential compound Generator -

used in arc welding.

Commutative compound Generator -

over compound -

It is supply power to distribution line

level compound -

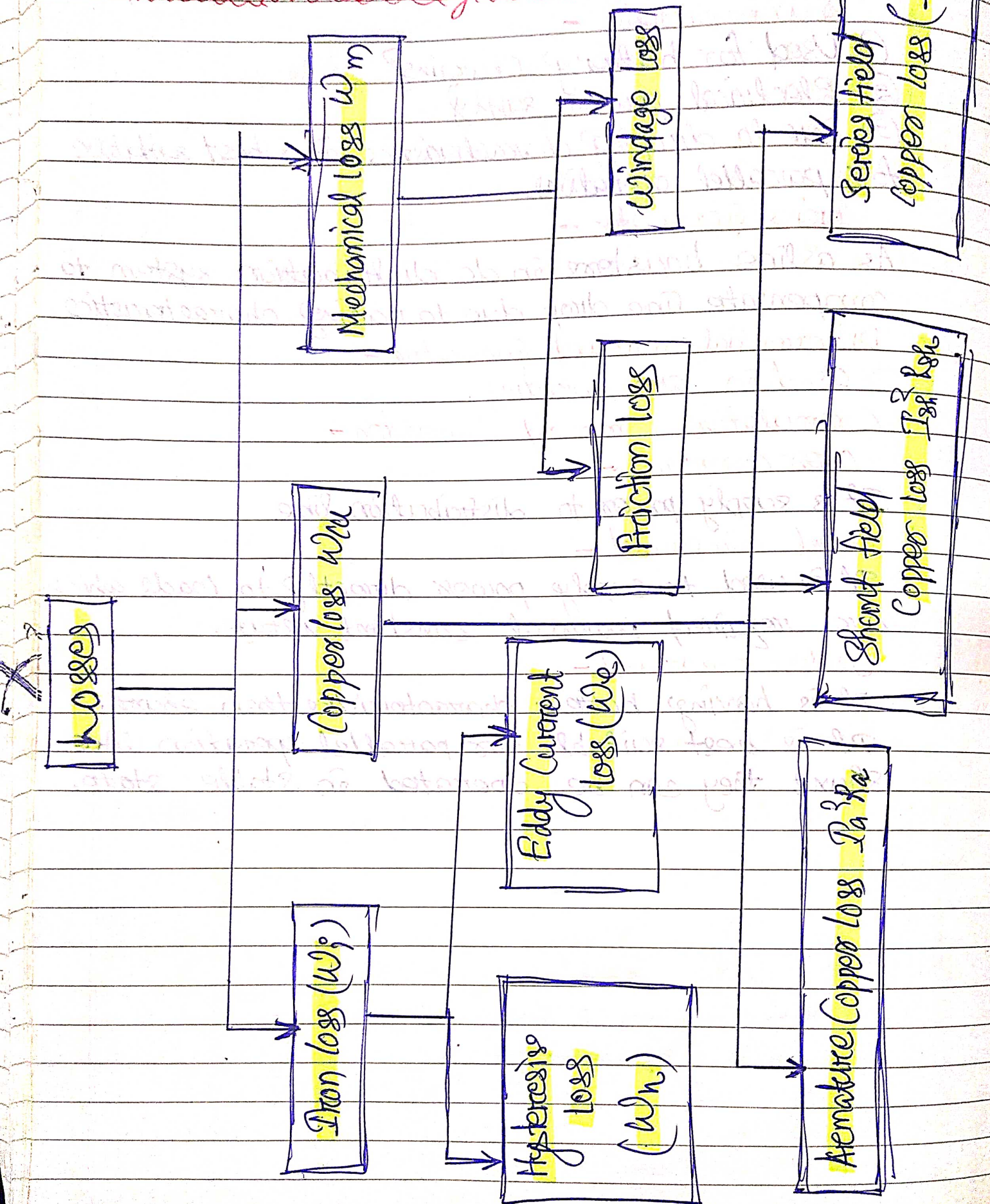
It is used to supply power directly to loads which are required power at constant voltage.

under compound -

It is having better characteristics than shunt.

It is best suitable for parallel operation like shunt they can be operated in stable state.

Losses & Efficiency of DC Machines



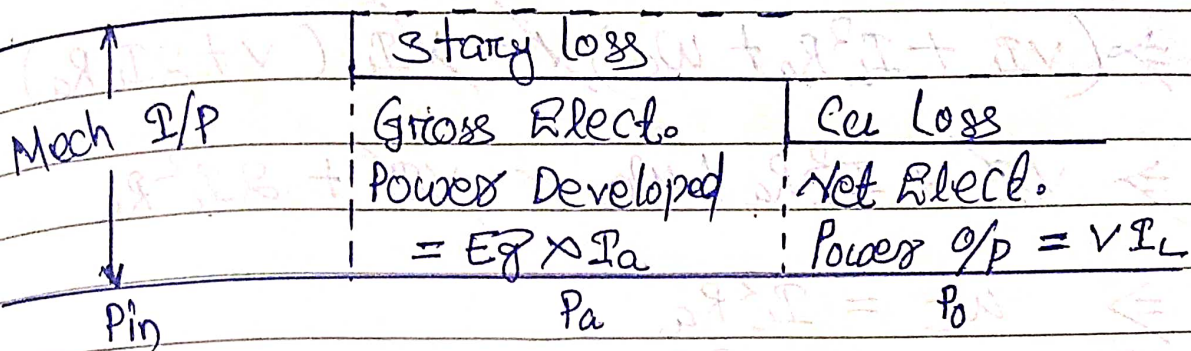
Iron loss + Mechanical loss = Stray loss

Stray loss + Shunt field Cu loss = constant loss

Armature Cu loss, Series field Cu loss = variable loss

constant loss + variable loss = Total loss.

Power flow Diagram of DC Generator:



Efficiency:

$$\eta_{\text{mech}} = \frac{P_a}{P_{\text{in}}} \quad \eta_{\text{elect.}} = \frac{P_o}{P_a}$$

$$\begin{aligned} \eta_{\text{overall}} &= \eta_{\text{elect.}} \times \eta_{\text{mech}} \\ &= \frac{P_o}{P_a} \times \frac{P_a}{P_{\text{in}}} \\ &= \frac{P_o}{P_{\text{in}}} \end{aligned}$$

$$\eta = \frac{P_o}{P_{\text{in}}}$$

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

$$\begin{aligned} \eta &= \frac{\text{o/p}}{\text{i/p}} = \frac{\text{i/p} - \text{Total losses}}{\text{i/p}} \\ &= \frac{\text{o/p}}{\text{o/p} + \text{Total losses}} \end{aligned}$$

Condition for Maximum efficiency =

$$\frac{d\eta}{dI_L} = 0$$

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

$$\Rightarrow (VI_L + I_L^2 R_a + W_c)V = VI_L(V + 2I_L R_a)$$

$$\Rightarrow VI_L + I_L^2 R_a + W_c = VI_L + 2I_L^2 R_a$$

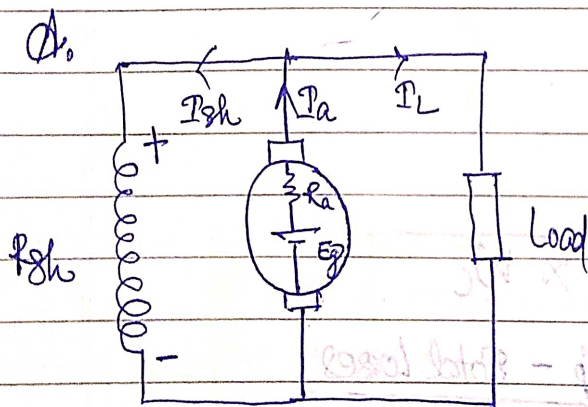
$$\Rightarrow W_c = I_L^2 R_a$$

$$\Rightarrow W_c = I_a^2 R_a$$

$$\Rightarrow \text{constant loss} = \text{variable loss}$$

$$\Rightarrow \text{Iron loss} = \text{Copper loss}$$

Q. The output of a shunt generator 500 A at a terminal voltage of 250 volt. If the armature resistance is 0.04Ω and shunt field resistance is 50Ω . what is the generated EMF.



$$E_g - I_a R_a - B.D = V$$

$$I_{sh} R_{sh} = V$$

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

Given that, $V = 250 \text{ V}$

$$I_L = 500 \text{ A}$$

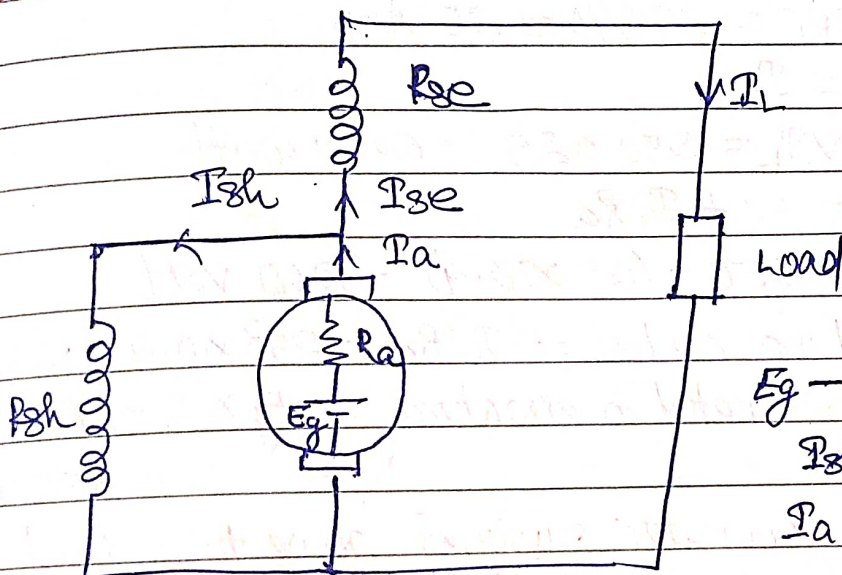
$$R_a = 0.04 \Omega \quad R_{sh} = 50 \Omega$$

$$I_{sh} = \frac{V}{R_{sh}} = \frac{250}{50} = 5 \text{ A}$$

$$I_a = I_L + I_{sh} = 500 + 5 = 505 \text{ A}$$

$$\begin{aligned} E_g &= V + I_a R_a \\ &= 250 + 505 \times 0.04 \\ &= 270.2 \text{ V.} \end{aligned}$$

Q. A 20 kW compound generator works on full load with a terminal voltage of 250 volt. The armature, series, and shunt winding have resistance of 0.05Ω , 0.025Ω and 100Ω respectively. Calculate the total EMF generated in the armature when the machine is connected as short shunt.



$$E_g - I_a R_a - \text{B.D} - I_{se} R_{se} = V$$

$$I_{sh} R_{sh} - I_{se} R_{se} = V$$

$$I_a = I_{sh} + (I_{se} = I_L)$$

Given that, $V = 250 \text{ V}$, $P = 20 \text{ kW}$, $R_a = 0.05 \Omega$, $R_{se} = 0.025 \Omega$, $R_{sh} = 100 \Omega$

$$P = V I_L \Rightarrow I_L = \frac{P}{V} = \frac{20 \times 10^3}{250} = 80 \text{ A}$$

$$I_{se} = I_L = 80 \text{ A}$$

$$I_{sh} = \frac{V + I_{se} R_{se}}{R_{sh}} = \frac{250 + 80 \times 0.025}{100} = 2.52 \text{ A}$$

$$I_a = I_{sh} + I_{se} = 2.52 + 80 = 82.52 \text{ A}$$

$$\begin{aligned} E_g &= 250 + 82.52 \times 0.05 + 80 \times 0.025 \\ &= 256.126 \text{ volt.} \end{aligned}$$

Q. A separately excited generator supplies 250 V to a load of 10Ω . $R_a = 0.4 \Omega$, $R_f = 125 \Omega$.

- Calculate (a) load current
(b) load power
(c) voltage of generator
(d) Armature Copper losses
(e) Power generated in Armature.

Given that $R_a = 0.4 \Omega$
 $V = 250 \text{ V}$
 $R_L = 10 \Omega$

$$(a) I_L = \frac{V}{R_L} = 250/10 = 25 \text{ Amp}$$

$$I_a = I_L$$

$$(b) P_L = VI_L = 250 \times 25 = 6250 \text{ watt}$$

$$(c) E_g = V + I_a R_a$$

$$= 250 + (25 \times 0.4) = 260 \text{ volt}$$

$$(d) \text{armature cu loss} = I_a^2 R_a = 25^2 \times 0.4 = 250 \text{ W}$$

$$(e) \text{Power generated in armature} = E_g \times I_a = 260 \times 25$$

$$= 6500 \text{ W}$$

Q. A series generator supplying 200 V to a load of 10Ω . $R_a = 0.6 \Omega$, $R_{se} = 0.4 \Omega$. Calculate power generated by armature.

Given that, $R_a = 0.6 \Omega$, $R_{se} = 0.4 \Omega$, $V = 200 \text{ V}$
 $R_L = 10 \Omega$

$$I_L = \frac{V}{R_L} = 200/10 = 20 \text{ A}$$

$$I_a = I_{se} = I_L = 20 \text{ A}$$

$$E_g = V + I_a R_a + I_{se} R_{se}$$

$$= 200 + (20 \times 0.6) + (20 \times 0.4)$$

$$= 220 \text{ volt}$$

$$P_a = E_g \times I_a = 220 \times 20 = 4400 \text{ watt}$$

Q. A short shunt compound generator supplying 20 kW power at 200V. $R_a = 0.06 \Omega$, $R_{se} = 0.04 \Omega$, $R_{sh} = 204 \Omega$.

calculate the power generated by armature winding.

Q. Given that, $V = 200V$, $P = 20kW$, $R_a = 0.06 \Omega$, $R_{se} = 0.04 \Omega$, $R_{sh} = 204 \Omega$

$$I = P/V = 20 \times 10^3 / 200 = 100 \text{ Amp}$$

$$I_{se} = I_L = 100 \text{ Amp}$$

$$I_{sh} = \frac{V + I_{se} R_{se}}{R_{sh}}$$

$$= \frac{200 + (100 \times 0.04)}{204}$$

$$= 1 \text{ Amp}$$

$$I_a = I_{se} + I_{sh} = 100 + 1 = 101 \text{ Amp}$$

$$E_g = V + I_a R_a + I_{se} R_{se} = 200 + (101 \times 0.06) + (100 \times 0.04) \\ = 210.06 \text{ volt}$$

$$P_a = E_g \times I_a = 210.06 \times 101 = 21216.06 \text{ watt} = 21.21 \text{ kW}$$

Q. A long shunt compound generator supply 2500 watt power at 250 volt. $R_a = 0.6 \Omega$, $R_{se} = 0.4 \Omega$, $R_{sh} = 250 \Omega$. Calculate power generated by armature.

Q. Given that, $R_a = 0.6 \Omega$, $R_{se} = 0.4 \Omega$, $R_{sh} = 250 \Omega$

$$P = 2500 \text{ watt}, V = 250 \text{ volt}$$

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

$$I_L = \frac{P}{V}$$

$$= \frac{250}{250} = 1 \text{ Amp}$$

$$= \frac{2500}{250} = 10 \text{ Amp}$$

$$I_a = I_{se} = I_L + I_{sh} = 11 \text{ Amp}$$

$$E_g = V + I_a R_a + I_{se} R_{se} \\ = 250 + (11 \times 0.6) + (11 \times 0.4) \\ = 261 \text{ volt}$$

$$P = E_g \times I_a$$

$$= 261 \times 11 = 2871 \text{ watt} = 2.87 \text{ kW}$$

The DC Machine which converts electrical energy to Mechanical energy is known as DC Motor.

Basic Principle

i) D.C. Generator

1. D.C. Generator is a device which converts mechanical energy into electrical energy.

2. Emf generated in a dc generator is

$$E_g = V + I_a R_a$$

$$\text{and } E_g = \frac{\phi Z N P}{60 A}$$

3. When a conductor is rotated inside a magnetic field, it cuts the magnetic flux then an emf is induced.

The magnitude emf is

$$E_g = BLV \sin \theta \text{ volt.}$$

4. The direction of emf is findout by Fleming right hand rule.

D.C. Motor

1. D.C. Motor device which converts electrical energy into mechanical energy.

2. Emf produced in a dc motor is

$$E_b = V - I_a R_a$$

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

3. When a current carrying conductor is placed inside a magnetic field a mechanical force experienced. The magnitude of force $F = BIL \sin \theta$ Newton.

4. The direction of force is findout by Fleming's Left hand rule.

carrying conductor is placed in magnetic field. It experiences certain mechanical force whose direction is given by Fleming's left hand rule and whose magnitude is given by $F = BIL \sin \theta$ N where $B =$ Flux density (wb/m^2)
 $I =$ Current flowing through conductor (A)
 $L =$ Length of conductor (m),
 $\theta =$ Angle between lines of force and conductor (degree)

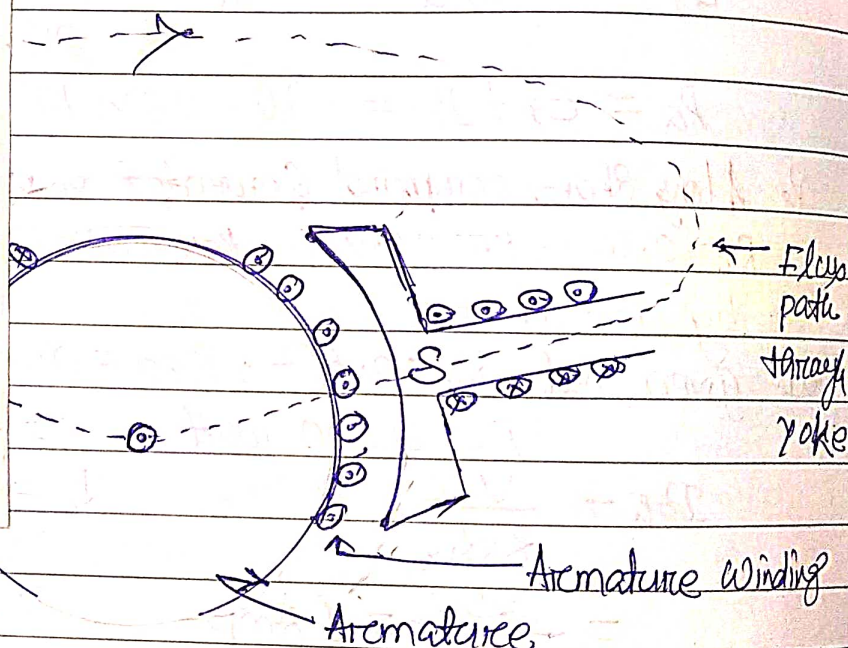
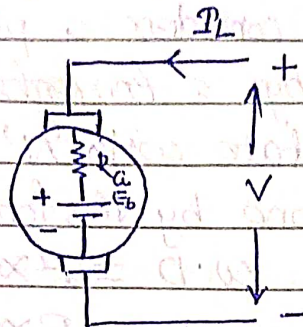


Figure shows a part of multipolar DC motor, when its field magnet are excited and its armature conductors are supplied with current from the supply mains, each armature conductor experiences a force. Armature conductor under north pole are assumed to carry current down ward and those under south pole to carry current up ward due to all the current carrying conductors

a resultant force is developed and hence resultant torque is produced which causes motion of armature in anticlockwise direction. The torque produced is continuous and unidirectional.

Significant of back emf in dc Motor -

Electromagnetic force appearing in an inductive circuit in such a direction as to oppose any change of current in the circuit.



When the armature continues to rotate due to motor action, the armature conductors cut the magnetic flux and therefore emf is induced in them. This induced emf opposes the supply voltage according to Lenz's Law.

Since back emf is induced due to the generator action its magnitude is given by the same expression as that of generated emf

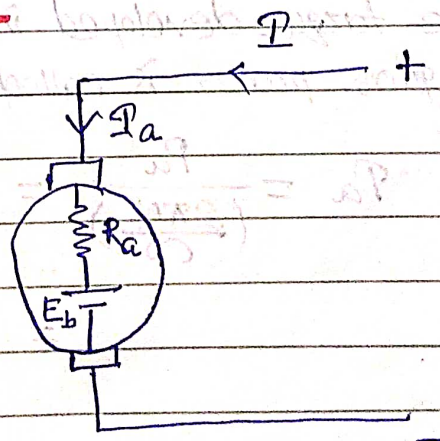
$$E_b = \frac{\phi Z N}{60} \times \frac{P}{A} \text{ volt}$$

$$E_b = K \phi N$$

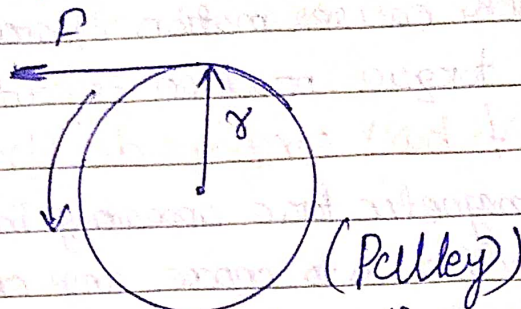
$$E_b \propto \phi N$$

Voltage Equation of Motor -

$$V = E_b + I_a R_a$$



Torque Developed in Motor:



Let us consider a pulley of radius ' r ' meter acted upon by a tangential force ' F ' Newton which causes it to rotate with ' N ' rpm.

Work done by this force in one revolution

$$W.D = F \times \text{Displacement}$$

$$W.D = F \times 2\pi r \quad \text{N-m}$$

work done for N revolution per minute

$$W.D = F \times 2\pi r \times N \quad \frac{\text{N-m}}{\text{min}}$$

$$W.D = F \times 2\pi r \times \frac{N}{60} \quad \frac{\text{N-m}}{\text{sec}} \text{ or } \frac{\text{Joules}}{\text{sec}} \text{ or watt}$$

$$\Rightarrow P = \frac{2\pi N}{60} (F \times r) \text{ watt}$$

$$\Rightarrow P = \frac{2\pi N}{60} T \quad \begin{matrix} (T = \text{torque}) \\ (T = F \times r) \end{matrix}$$

$$\Rightarrow T = \frac{P}{\frac{2\pi N}{60}} \quad \text{N-m}$$

Armature torque (T_a) or Gross torque (T_g) =

The torque developed in armature due to armature power or gross power is called armature torque or gross torque

$$T_a = \frac{P_a}{\left(\frac{2\pi N}{60}\right)} = \frac{E_b \times I_a}{\left(\frac{2\pi N}{60}\right)}$$

$$= \frac{\phi Z N}{60} \times \frac{P}{A} \times I_a \times \frac{60}{2\pi N}$$

$$= \frac{1}{2\pi} \phi Z \frac{P}{A} \times I_a$$

$$\Rightarrow T_a = \frac{1}{2\pi} \phi Z \frac{P}{A} \times I_a$$

$$\Rightarrow T_a = 0.159 \phi Z \frac{P}{A} I_a \quad \text{N-m}$$

$$T_a \propto \phi I_a$$

Shaft torque -

The torque developed in ϕ p that is in shaft due to shaft power or ϕ p power is called shaft torque or ϕ p torque or/

The torque which available for doing useful work is known as shaft torque or useful torque or net torque

$$T_{sh} = \frac{P_{sh}}{\left(\frac{2\pi N}{60}\right)}$$

Lost torque =

The difference between armature torque and shaft torque is called lost torque. It is due to mechanical losses of motor.

$$T_L = \frac{\text{Mechanical loss}}{\left(\frac{2\pi N}{60}\right)} \text{ N-m}$$

Power stage diagram :-

From voltage equation

$$E_b = V - I_a R_a \quad \text{Neglecting B.D}$$

$$\Rightarrow E_b \times I_a = V I_a - I_a^2 R_a$$

$$\Rightarrow P_a \text{ or } P_m = P_{in} - \text{Armature Cu-Loss.}$$

Electrical power $P/p = V \times I_a$	$I_a^2 R_a$	
	Gross Mech.	stator Loss
	Power Developed	Net Mech. Power
	$E_b \times I_a$	ϕ/p

characteristics of DC Shunt Motor:

$$T_a \propto \phi I_a$$

$$E \propto \phi N$$

① T_a Vs I_a

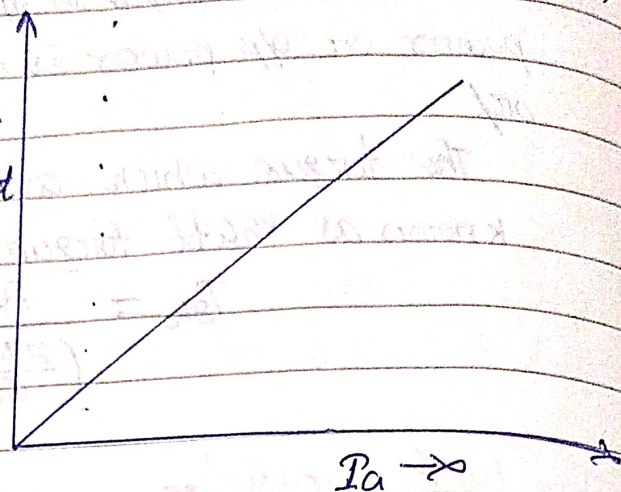
$$T_a \propto \phi I_a$$

$$T_a \uparrow$$

For shunt motor ϕ is constant

$$T_a \propto I_a$$

Hence the characteristics is straight line.



② N Vs I_a

$$\uparrow \text{Load} \Rightarrow N \downarrow \quad \downarrow N \Rightarrow E_b \downarrow$$

$$\downarrow E_b \Rightarrow (V - E_b) \uparrow \Rightarrow I_a \uparrow \quad N \uparrow$$

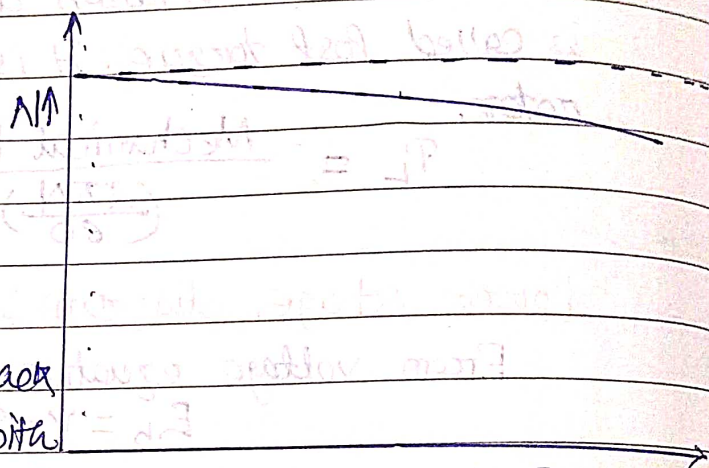
$$V - I_a R_a = E_b$$

$$(V - E_b) = I_a R_a$$

$$\left(\frac{V - E_b}{R_a} \right) \uparrow = I_a \uparrow$$

In actual practice the back emf decreases slightly with

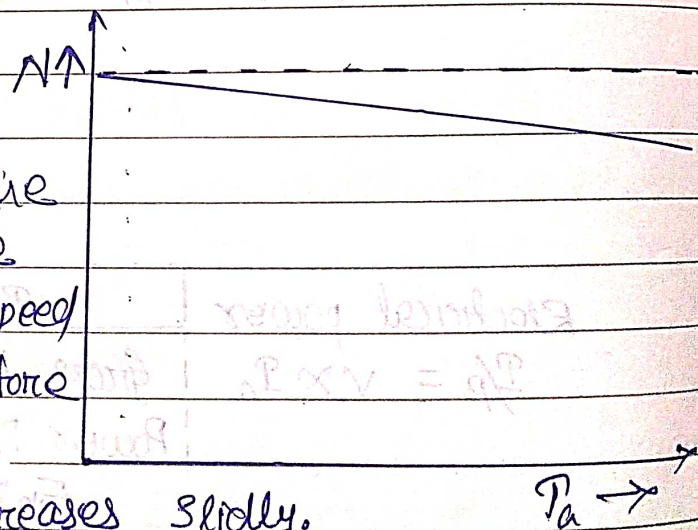
increase in load which results 5 to 15% drop in, $I_a \rightarrow$ speed.



③ N Vs T_a

When armature current increases, Armature torque increases, when Armature current increases the speed decreases slightly. Therefore when Armature torque

increases the speed decreases slightly.

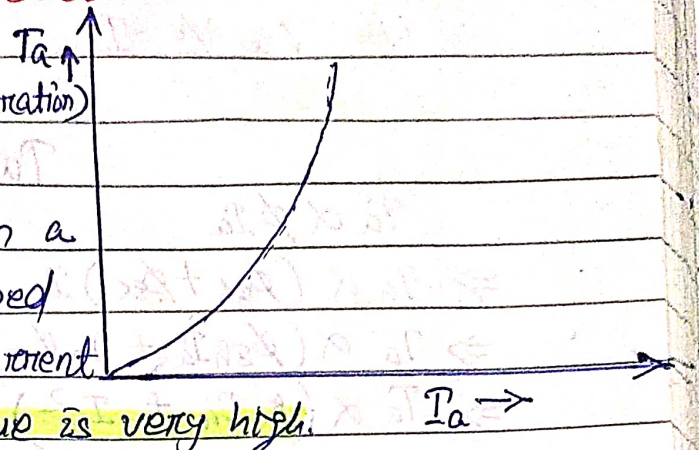


* Shunt Motor is considered as approx. constant speed motor.

characteristics of DC Series Motor :-

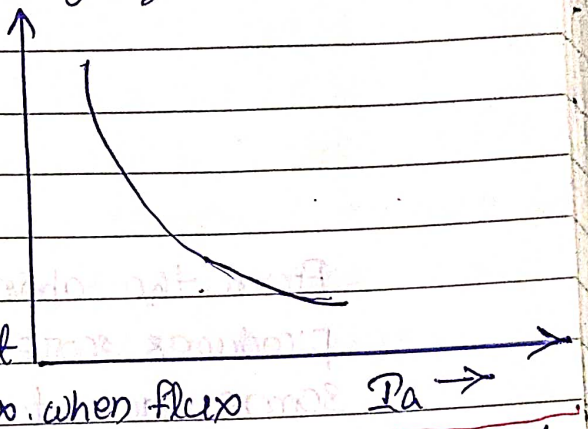
$T_a \propto \phi I_a$ ① $T_a \propto I_a^2$
 For series Motor $\phi \propto I_a$ (up to saturation)
 $T_a \propto I_a^2$

therefore the characteristics in a parabola. Since torque developed is proportional to square of the current for such Motor starting torque is very high.



② $N \propto \frac{1}{\phi}$
 $\uparrow \text{Load} \Rightarrow I_L \uparrow, I_L \Rightarrow \phi \uparrow$
 $\downarrow N \propto \frac{E_b}{\phi} \uparrow$ $N \propto \frac{1}{I_a}$

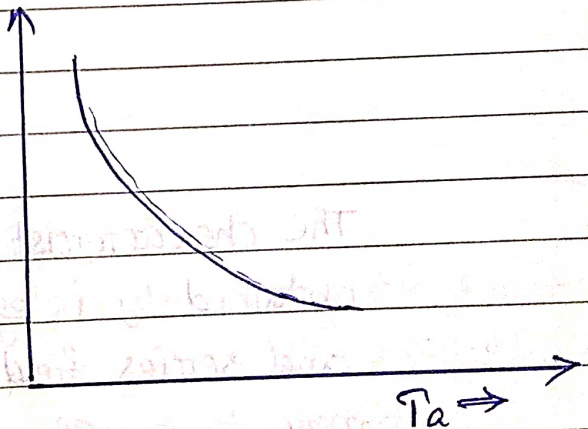
when load increases, load current increases and hence series field current increases which results increase in flux. when flux increases, the speed decreases hence the characteristic is a rectangular parabola.



when load is less, the speed is dangerously high. Hence series motor should not be started without some mechanical load. otherwise due to excessive speed it may be damaged because of heavy centrifugal force.

③ $N \propto \frac{1}{I_a}$

when current increases torque increases also when current increases the speed decreases therefore when torque is high speed is low.



* series Motor is considered as variable speed motor.

Characteristics of DC Cumulative Compound Motor :-

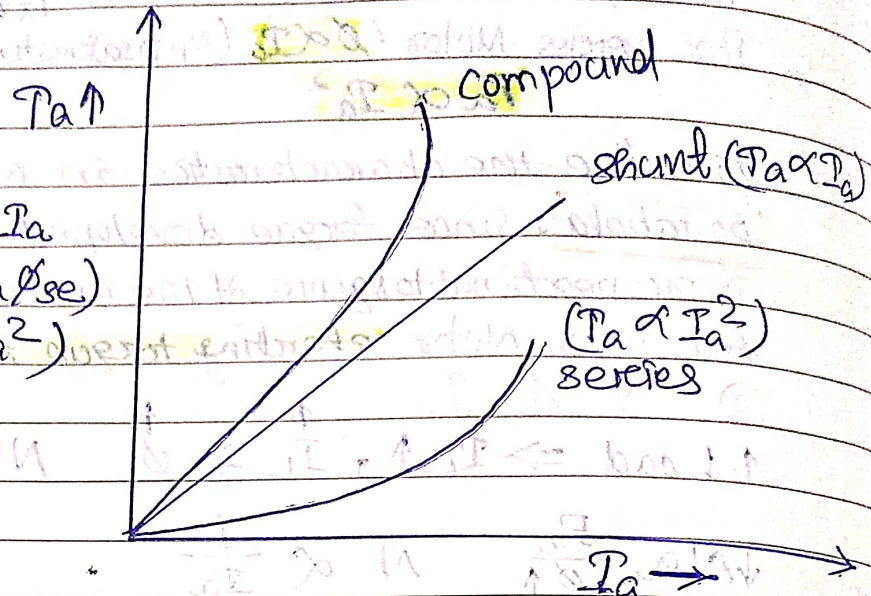
① T_a Vs I_a

$$T_a \propto \phi I_a$$

$$\Rightarrow T_a \propto (\phi_{sh} + \phi_{se}) I_a$$

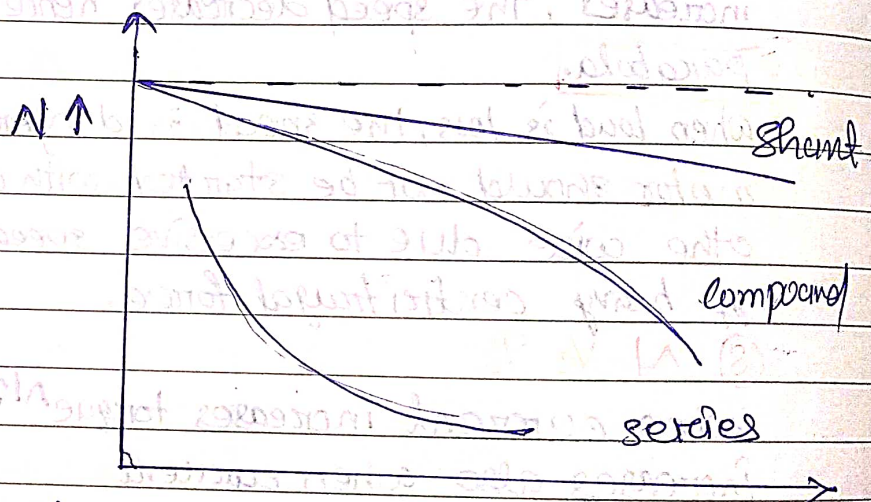
$$\Rightarrow T_a \propto (\phi_{sh} I_a + I_a \phi_{se})$$

$$\Rightarrow T_a \propto (K I_a + I_a^2)$$



From the above characteristics the compound motor produces more torque than shunt motor for the same armature current.

② N Vs I_a



The characteristics of compound motor is obtained by integrating the speed curve of shunt field and series field. The speed of compound motor drops more than shunts for the given armature current.

From the above characteristics it is observed that the torque increasing as speed decreases.

characteristics of DC Differential Compound Motor:

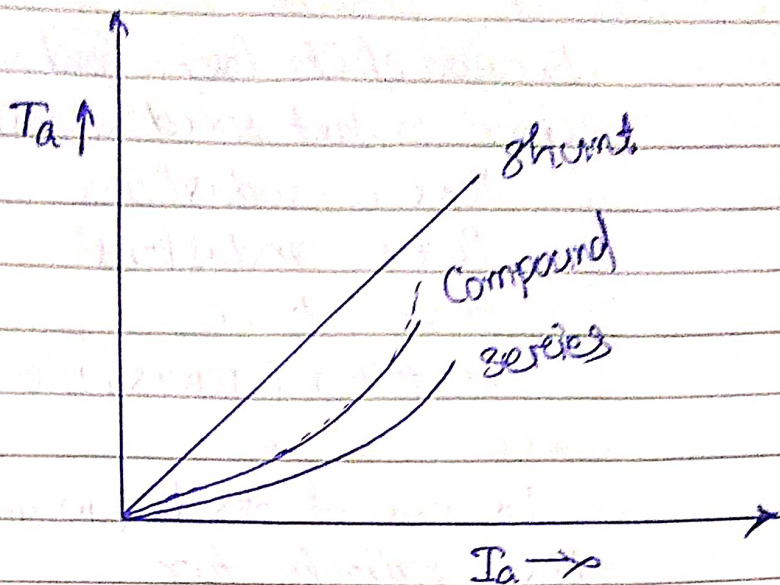
① T_a Vs I_a

$$T_a \propto \phi I_a$$

$$\Rightarrow T_a \propto (\phi_{sh} - \phi_{se}) I_a$$

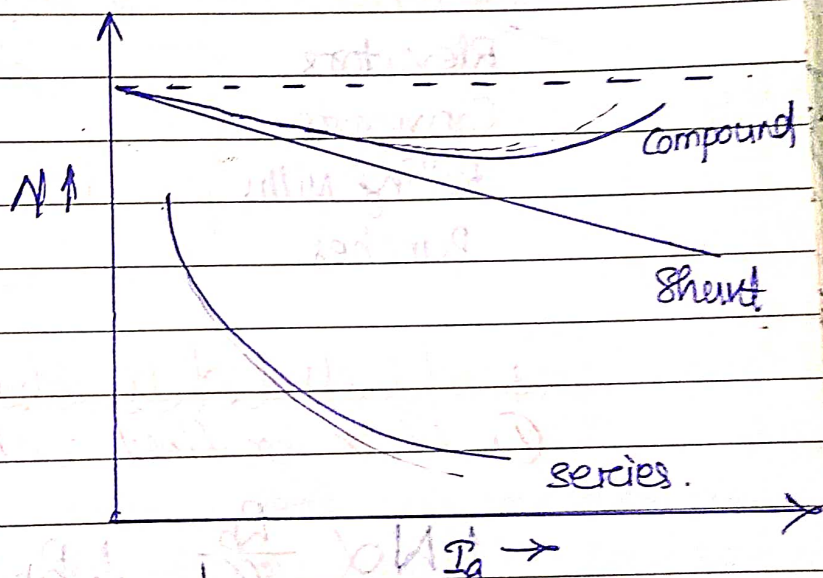
$$\Rightarrow T_a \propto (\phi_{sh} I_a - I_{se} I_a)$$

$$\Rightarrow T_a \propto (K I_a - I_a^2)$$



The series field produce negative torque Hence total torque decreases i.e. Differential compound Motor produces less torque than shunt motor for the same armature current.

② N Vs I_a



The characteristics is obtained by integrating the shunt field and series field effects the speed of differential compound motor drops less than shunt motor for the given armature current.

Application of DC Series Motor:

Shunt Motor -

Because of its torque and speed characteristics it is very useful where constant speed at uniform torque is required

Textile industries

Paper industries

Group drive

Centrifugal pumps, Blowers

Series Motor -

Because of its torque and speed characteristics it is best suitable for

Electric Traction

Cranes

Conveyors

Lift.

Commutative compound Motor -

Elevators

Conveyors

Rolling Mills

Punches

Differential Compound Motor -

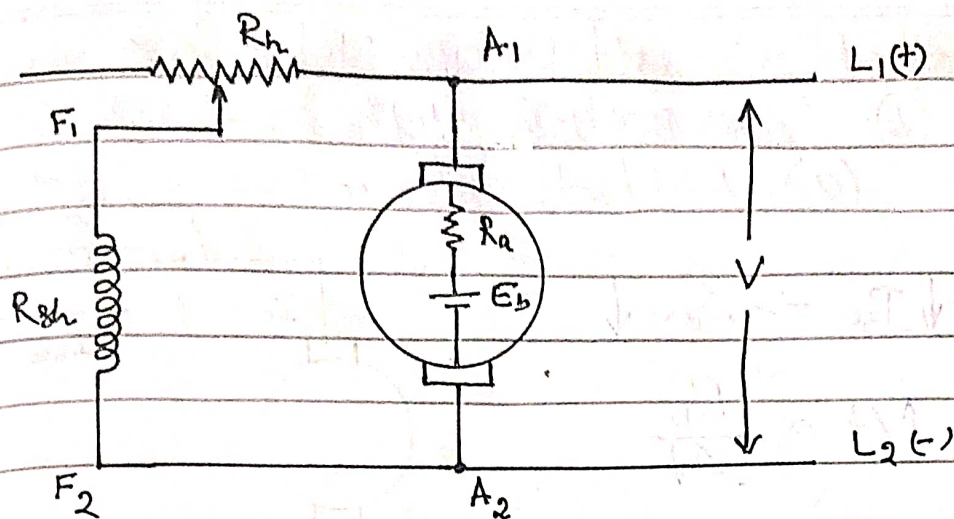
Experimental and Research work.

Speed Control of DC Shunt Motor:

① Flux or field control Method -

$$\uparrow N \propto \frac{E_b}{\phi} \quad \downarrow E_b = \left[V - (I_a(R_a + R)) \right] \uparrow$$

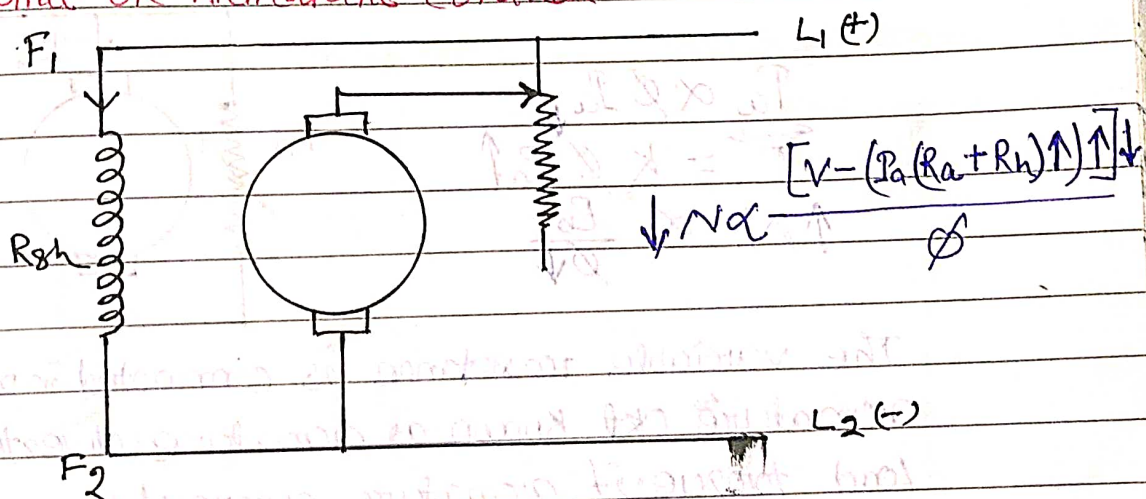
$$\uparrow R_a \Rightarrow N \downarrow$$



A variable resistance is connected in series with field winding which is known as field rheostat or field regulator. By the increasing the resistance of field ckt, the field current can be reduced and hence flux can be reduced. When flux decreases the speed increases.

* The speed control is possible in this method is only above the rated speed.

② Resistance or Armature control -



A variable resistance is connected in series with armature ckt which is known as controller resistance or speed controller. The supply voltage is kept normally constant. By increasing the resistance of armature ckt, armature drop can be increased and hence potential drop across the armature can be decreased. Hence speed can be decreased.

* Speed control is possible below rated speed only.

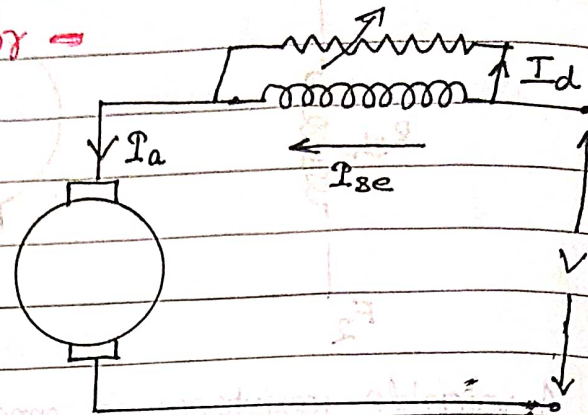
Speed Control of series Motor :-

① Flux control Method :-

(a) Field diverter -

$$\downarrow I_{se} \Rightarrow \phi_{se} \downarrow$$

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



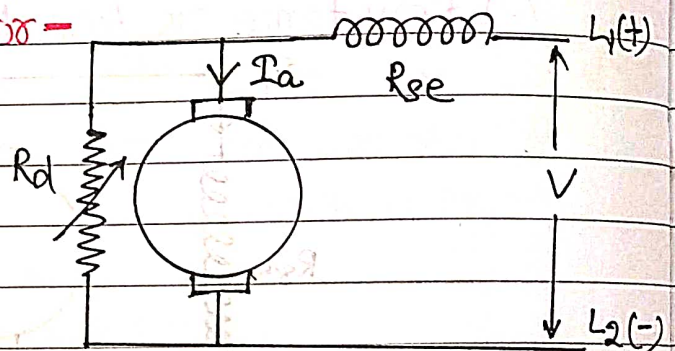
A variable resistance is connected in parallel with series field winding known as field diverter desired amount of current can be passed through the diverter by adjusting its resistance. Since field current decreases field flux decreases and hence the speed increases.

(b) Armature diverter -

$$T \propto \phi I_a$$

$$T = k \phi I_a$$

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



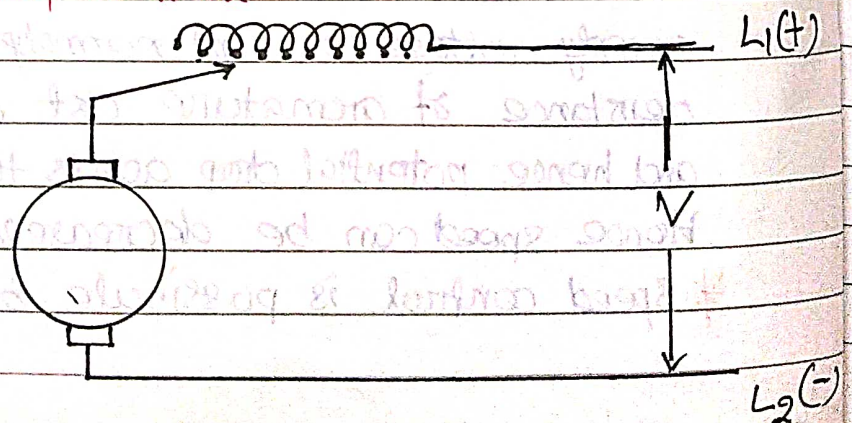
The variable resistance is connected in parallel with armature ckt known as armature diverter for constant load torque if armature current is reduced the flux must be increased. It results falls in speed.

(c) Tapped field control -

$$\uparrow MNP = (AT) \uparrow$$

$$\uparrow MMF \Rightarrow \phi \uparrow$$

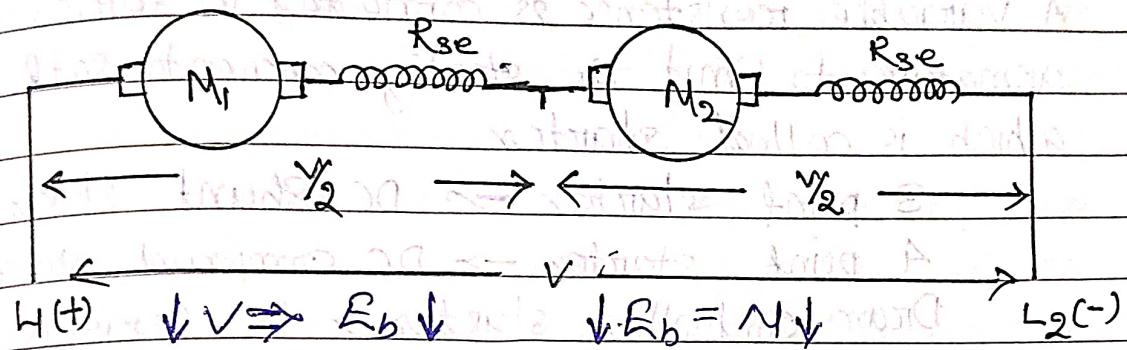
$$\downarrow N \propto \frac{E_b}{\phi \uparrow}$$



By the use of tapping in the field ckt the MMF can be changed and hence flux can be changed when the slider contact taken at the extrem left number of turn increases, when MMF increases Flux increases which results fall in speed.

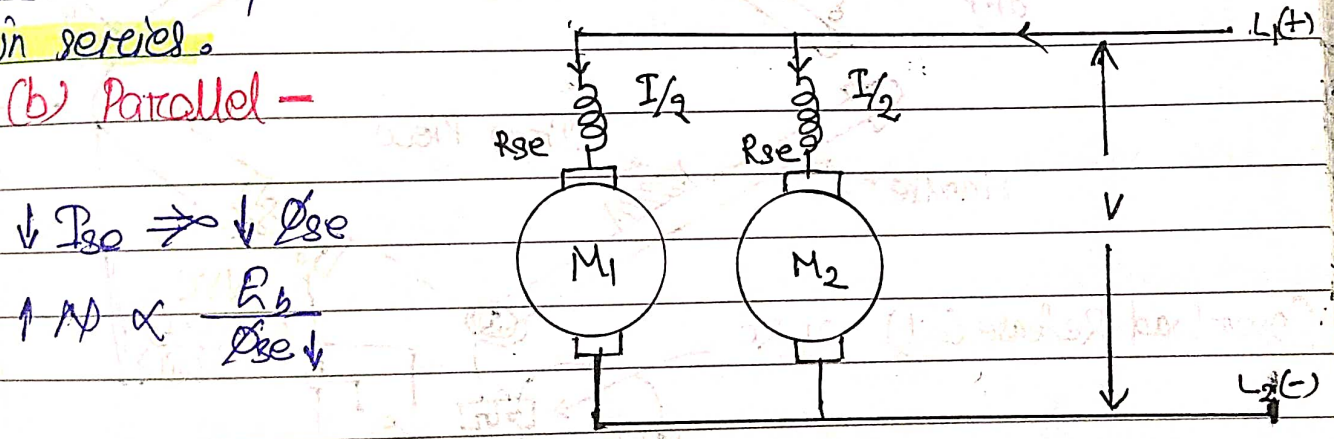
② Series parallel Method ~

(a) Series -



In this method of speed control two similar motor are connected in series. The voltage across each motor becomes half of the supply voltage as the voltage decreases, the speed can be reduced. Hence for low speed the motor are joint in series.

(b) Parallel -



$$\downarrow I_{se} \Rightarrow \downarrow \phi_{se}$$

$$\uparrow N \propto \frac{E_b}{\phi_{se} \downarrow}$$

In this method of speed control, two similar motors are connected in parallel. Current through field coil of each motor becomes half of the supply current as current decreases, Flux decreases and hence speed increases, therefore for high speed motor joint in parallel.

Necessity of starter

We know that $I_a = \frac{V - E_b}{R_a}$

At starting $N=0$, $E_b=0$

$$\therefore I_a = \frac{V}{R_a}$$

Let $V=200V$, $R_a=0.1\Omega$ and rated current $=5A$

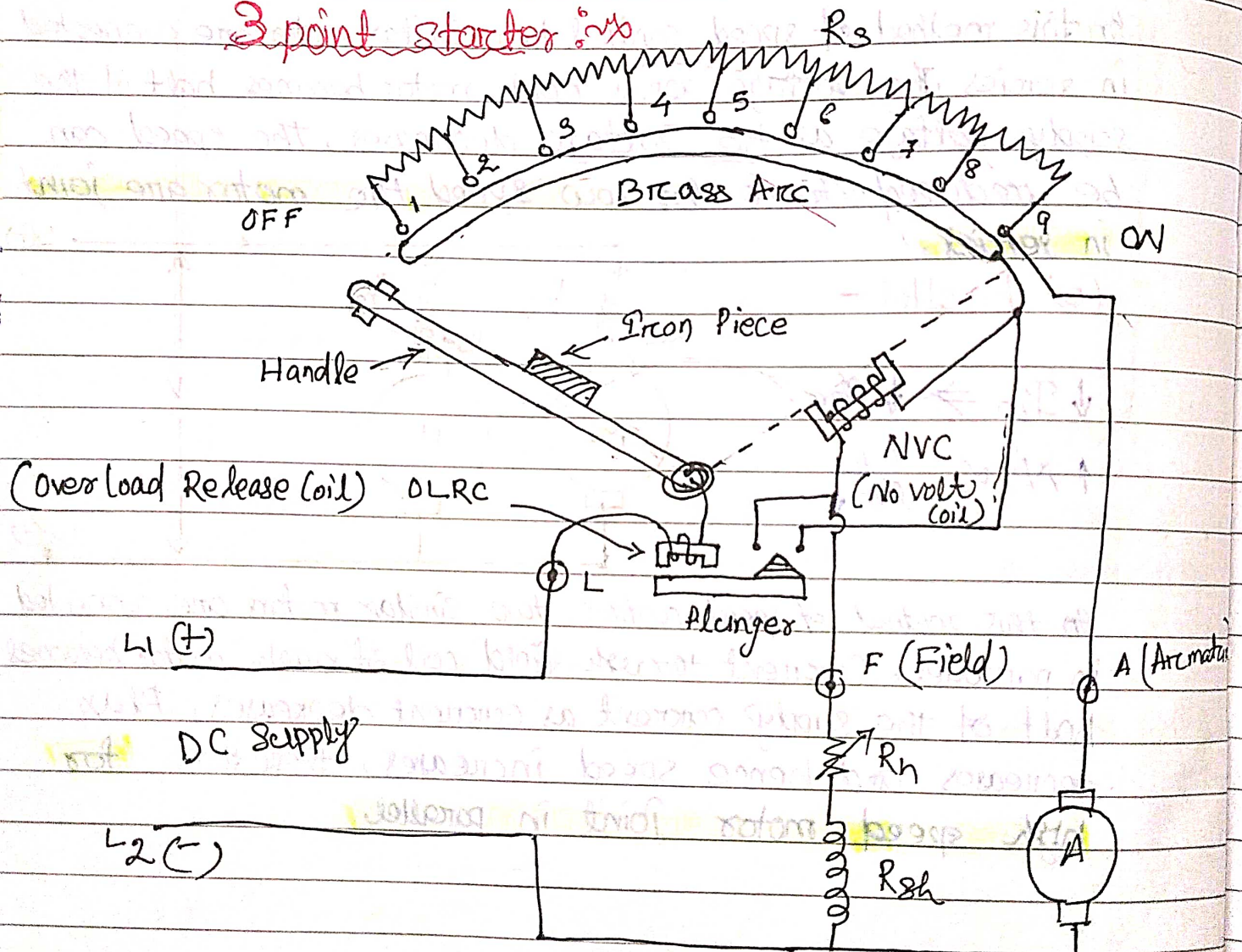
So starting current $I_{st} = \frac{200}{0.1} = 200A$

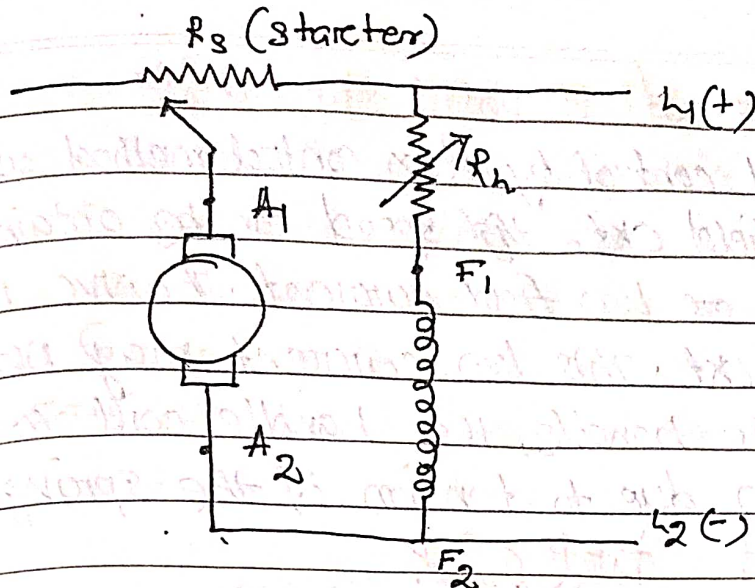
A variable resistance is connected in series with armature to limit the starting current to safe value which is called starter

3 point starter $\rightarrow$ DC Shunt Motor

4 point starter $\rightarrow$ DC Compound Motor

Drum controller starter $\rightarrow$ DC series Motor

3 point starter



(shunt Motor with starter)

→ It consists of handle which moves over the studs. Tappings are taken from various points of starter's resistance and are connected to studs. The armature is connected to the supply through the starter and field coil is directly connected to the supply.

→ when the handle moves to 1st stud, there are two current paths

(i) Through +ve, starter resistance, armature and -ve of DC supply.

(ii) Another path is through +ve, brass arc, field winding and -ve of the DC supply.

→ If the field will be connected through starter's resistance, the current and flux of shunt field winding will be reduced. This is avoided by using brass arc.

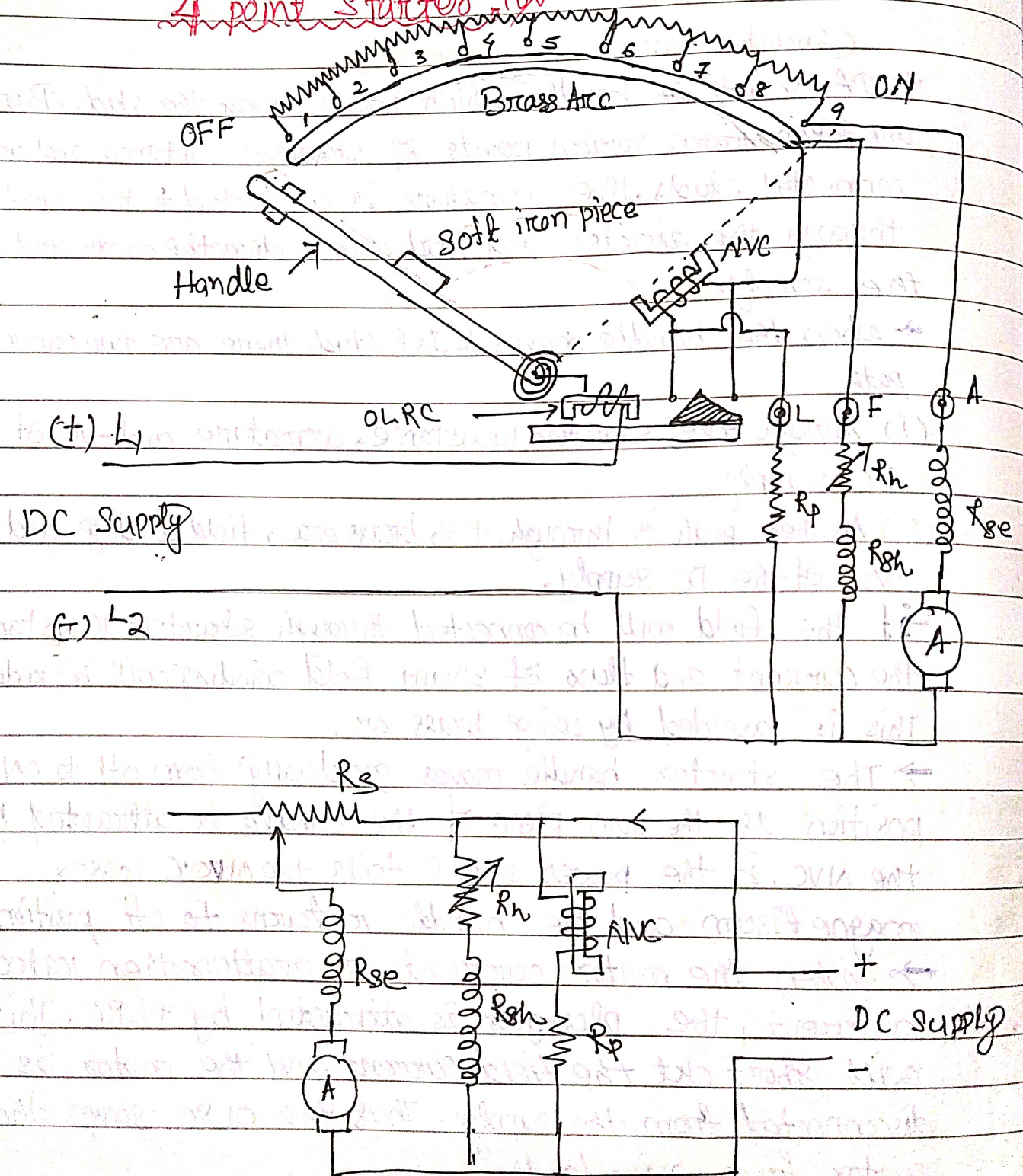
→ The starter handle moves gradually from off to ON position as the iron piece of the handle is attracted by the MNC. If the power supply fails, the MNC loses magnetism and the handle returns to off position.

→ when the motor current is greater than rated current, the plunger is attracted by OLRC. This will short circuit the field current and the motor is disconnected from the supply. Thus the OLRC saves the motor from over loads.

Drawback of 3 point starter

The speed control by flux control method uses a resistance in shunt field ckt. High speed can be obtained with low flux value or low field current. The NVC is connected in the field ckt. This low current may not be sufficient to hold the handle, the handle will come back to off position due to tension of the spring.

4 point Starter

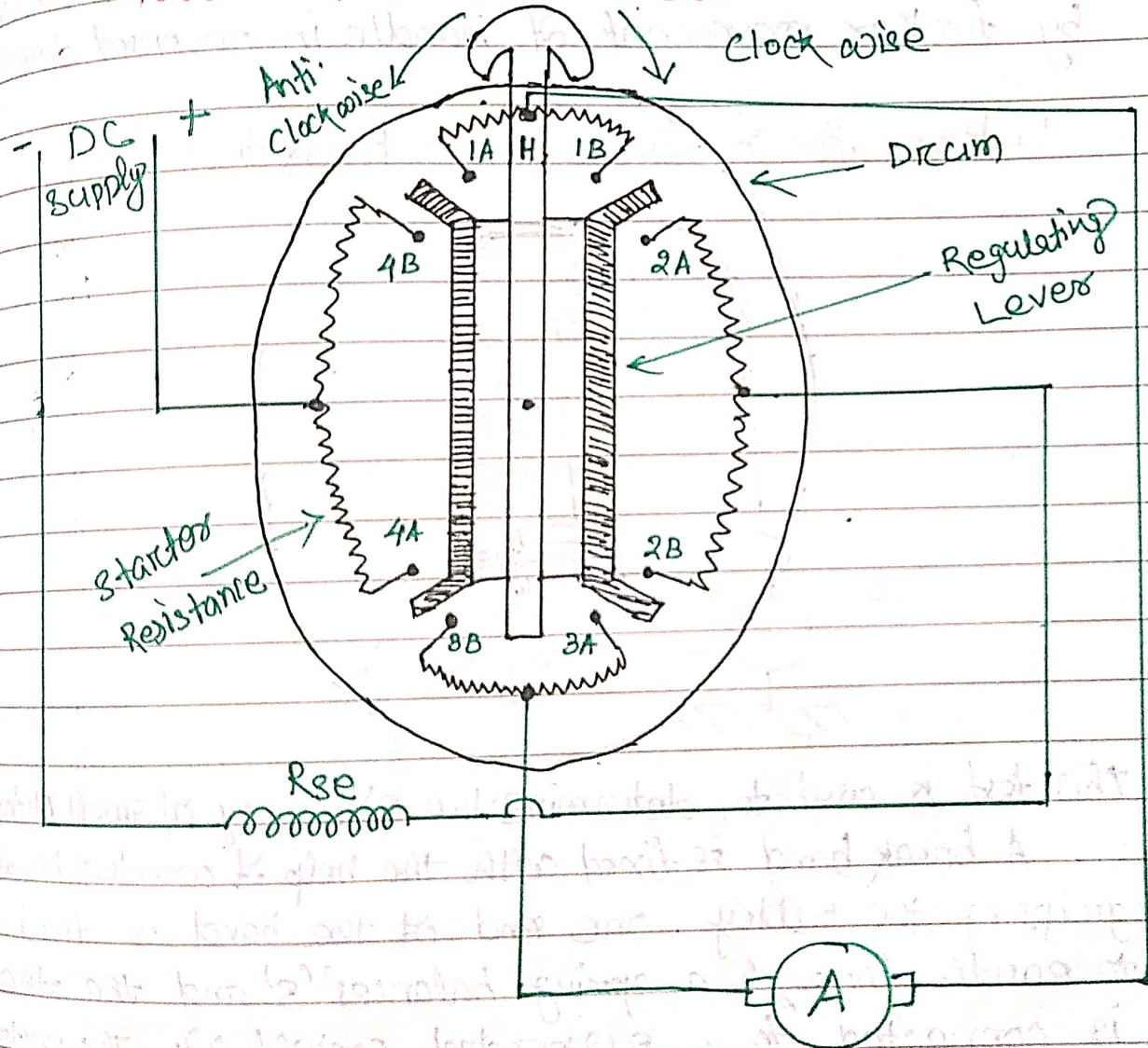


→ The drawback of 3 point starter avoided by using 4 point starter. The NVC is not connected in the field ckt. It is connected to the supply through a protective resistance.

→ When the handle is moved to stud I there are three current path like

- (i) Current through +ve, starter resistance, series field, Armature and -ve of the supply.
- (ii) Current through +ve, brass arc, Shunt field and -ve of the supply.
- (iii) Current through +ve, brass arc, NVC, protective resistance and -ve of the supply.

Dream Controller starter



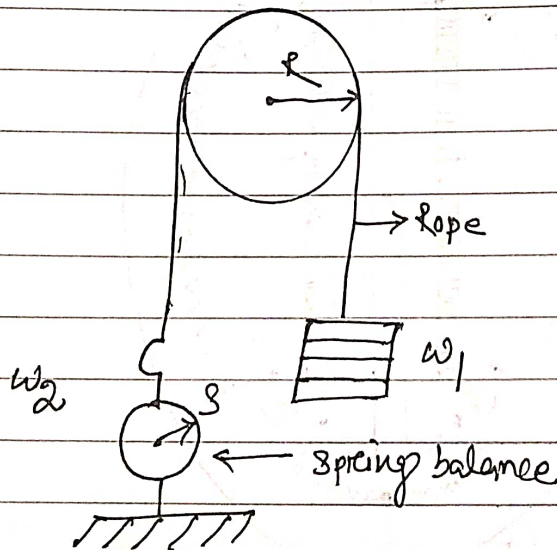
DC series Motor.

This can be used for both starting and speed control of DC series Motor there are 4-resistance section.

When the handle moves in forward direction, the armature and field are connected in series with 4-segments of resistors. The resistors can be gradually varied by moving the handle further clockwise direction. The speed can be varied by varying resistance.

If the handle moves in reversed the direction of armature current can be reversed by the direction of field current remains same. Hence torque is reversed direction therefore the motor rotates in reversed direction. The armature can be reduced by further movement of handle in reversed direction.

Determination of efficiency by break test :-



This test is used to determine the efficiency of small motor.

A break band is fixed with the help of wooden blocks gripping the pulley. One end of the band is fixed to earth through a spring balance 'S' and the other is connected to a suspended weight W_1 . The motor is run and the load on the motor is adjusted till it carries its full load current.

let w_1 = suspended weight in kg
 w_2 = Reading on spring balance in kg. wt.

The net pull on the band due to friction at the pulley is
 $(w_1 - w_2) \text{ kg wt.} = 9.81 (w_1 - w_2) \text{ N}$

if R = radius of the pulley in meters

N = motor / Full speed

The shaft torque T_{sh} developed by the motor

$$T_{sh} = 9.81 (w_1 - w_2) R \text{ N-m}$$

motor o/p power

$$P_{out} = T_{sh} \times 2\pi N$$

$$= 9.81 (w_1 - w_2) R \times 2\pi N \text{ watt}$$

$$P_{out} = 61.638 \text{ N} (w_1 - w_2) R \text{ watt}$$

$$P_{in} = VI \text{ watt}$$

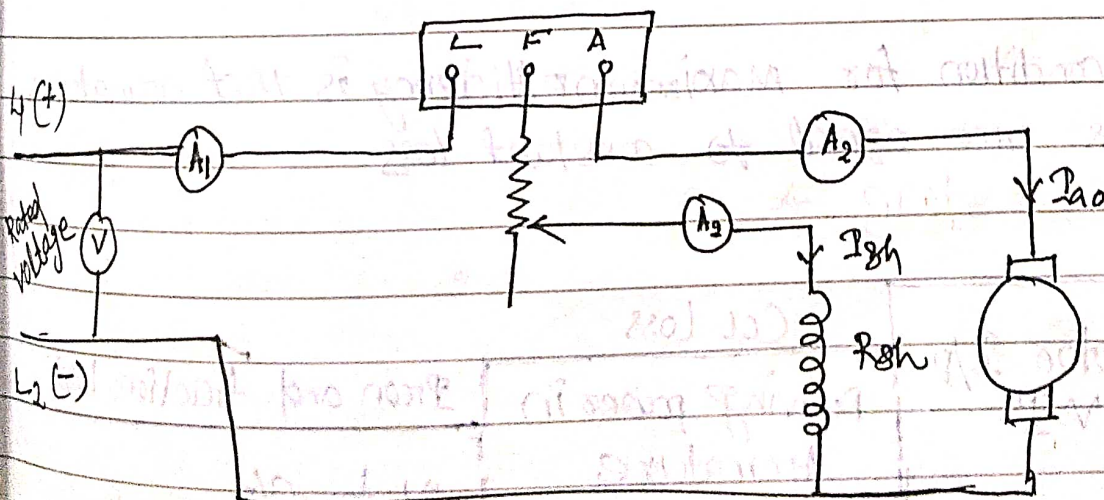
V = supply voltage

I = Full load current taken by the Motor

$$\text{Efficiency} = \eta = \frac{P_{out}}{P_{in}}$$

$$\eta = \frac{61.638 \text{ N} (w_1 - w_2) R}{VI}$$

Determination of efficiency by Swinburn's test :-



This method is only applicable to Level compound and shunt Motors. Run the machine at no load, rated speed and rated full voltage and take the reading. It is the indirect test to predict the efficiency.

$$I/p = O/p + \text{Losses}$$

$$\Rightarrow VI = 0 + (W_c + I_a^2 R_a)$$

$$\text{Losses} = VI$$

$$\Rightarrow \text{constant loss } (W_c) + I_a^2 R_a = VI$$

$$\Rightarrow W_c = VI - I_a^2 R_a$$

$$\eta = \frac{P_o}{P_{in}} = \frac{P_{in} - \text{losses}}{P_{in}} = \frac{VI - (W_c + I_a^2 R_a)}{VI}$$

$$\eta_{\text{motor}} = \frac{VI - W_c - I_a^2 R_a}{VI}$$

$$\eta_{\text{generator}} = \frac{VI}{VI + W_c + I_a^2 R_a}$$

Losses in Motor :-

Losses takes place in the Motor are same as generator

- (i) Copper loss
- (ii) Magnetic loss
- (iii) Mechanical loss

The condition for Maximum efficiency is that armature Cu loss are equal to constant loss

Power stage :-

Motor I/p VI	Cu loss	
	Driving power in Armature $= E_b I_a$	Iron and friction loss Motor O/p

(157)

Condition for Maximum Power :-

The gross Mechanical power developed by a motor is

$$P_m = V I_a - I_a^2 R_a$$

Differentiating both sides w.r.t I_a and equating the result to zero

$$\frac{dP_m}{dI_a} = \frac{d(V I_a)}{dI_a} - \frac{d(I_a^2 R_a)}{dI_a} = 0$$

$$\Rightarrow V - 2 I_a R_a = 0$$

$$\Rightarrow 2 I_a R_a = V$$

$$\Rightarrow I_a R_a = \frac{V}{2}$$

$$\text{As } V = E_b + I_a R_a$$

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

$$\Rightarrow E_b = V - \frac{V}{2}$$

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

Thus gross mechanical power developed by a motor is maximum when back emf is equal to half of applied voltage.

Q. Determine gross torque and shaft torque of a 220V, 4 pole series motor with 800 conductors wave connected supply a load of 2kW by taking 45A from main supply. Flux per pole 0.025wb and armature resistance is 0.6Ω neglect series field resistance.

$$\text{Sol. } V = 220\text{V}, P = 4, Z = 800, P = 2\text{kW}, I = 45\text{A}, \phi = 0.025\text{wb}, R_a = 0.6\Omega$$

$$E_b = 220 - 45 \times 0.6 = 193 \text{ volt}$$

$$E_b = \frac{\phi Z N}{60} \frac{P}{A} \Rightarrow 193 = \frac{0.025 \times 800 \times N}{60} \times \frac{4}{2}$$

$$\Rightarrow N = \frac{193 \times 60}{0.025 \times 800 \times 2} \Rightarrow N = 289.5 \text{ rpm}$$

$$T_g = \frac{E_b \times I_a}{\frac{2\pi N}{60}} = \frac{193 \times 45 \times 60}{2\pi \times 289.5} = 286.47 \text{ N-m}$$

$$T_s = \frac{P_{sh}}{\frac{2\pi N}{60}} = \frac{2000 \times 60}{2\pi \times 289.5} = 65.97 \text{ N-m}$$

Q. A 230 V dc shunt motor takes an armature current of 3.33 A at a rated voltage and at a no load speed of 1000 rpm. The resistance of the armature ckt and field ckt are respectively 0.3 Ω and 160 Ω . The line current at full load and rated voltage is 40 A. Calculate the full load speed if the armature reaction weakens the no load flux by 4%.

Q. $V = 230V$, $I_a = 3.33A$, $N_{no\ load} = 1000\ rpm$, $R_a = 0.3\ \Omega$, $R_{sh} = 160\ \Omega$

$I_{L\ Full\ load} = 40A$

No load. $V - I_a R_a = E_b \Rightarrow E_b = V - I_a R_a \Rightarrow E_b = 230 - 3.33 \times 0.3 = 229V$

Load $I_{sh} = \frac{V}{R_{sh}} = \frac{230}{160} = 1.4375A$

$I_a = I_L - I_{sh} = 40 - 1.4375 = 38.5625A$

$E_b = V - I_a R_a = 230 - 38.5625 \times 0.3 = 218.43V$

$N_1 = 1000\ rpm$ $N_2 = ?$ $\phi_2 = 0.96\phi_1$

$E \propto \phi N$ $E_1 \propto \phi_1 N_1$ — (1) $E_2 \propto \phi_2 N_2$ — (2)

$\frac{E_2}{E_1} = \frac{\phi_2 N_2}{\phi_1 N_1} \Rightarrow \frac{E_2}{E_1} = \frac{0.96\phi_1 N_2}{\phi_1 N_1}$

$\Rightarrow \frac{218.43}{229} = \frac{0.96 N_2}{1000}$

$\Rightarrow N_2 = \frac{218.43}{229} \times \frac{1000}{0.96}$

$\Rightarrow N_2 = 994\ rpm$.

Q. A 250 V shunt motor is running at 1000 rpm and taking 8 A at no load. $R_a = 0.2\ \Omega$, $R_{sh} = 250\ \Omega$. Calculate the speed when motor taking 50 A. Assume constant flux.

No load. $E_b = V - I_a R_a$

$I_{sh} = \frac{V}{R_{sh}} = \frac{250}{250} = 1A$

$I_L = I_a + I_{sh}$

$\Rightarrow I_a = I_L - I_{sh} = 8 - 1 = 7A$

$E_b = V - I_a R_a = 250 - 7 \times 0.2 = 248.6\ volt$

At Load

$E_b = V - I_a R_a$

$I_a = I_L - I_{sh} = 50 - 1 = 49A$

$E_b = 250 - 49 \times 0.2 = 240.2\ volt$

$\frac{E_2}{E_1} = \frac{\phi_2 N_2}{\phi_1 N_1}$

$\Rightarrow N_2 = \frac{E_2}{E_1} \times N_1$

$= \frac{240.2}{248.6} \times 1000$

$\Rightarrow N_2 = 966.21\ rpm$

$\Rightarrow N_2 = 966\ rpm$

Q. A dc shunt machine while running as generator develops a voltage of 250V at 1000 rpm on no load. It has under no load takes 4A at 250V. Calculate the speed of the machine running as motor taking at 250 volt. The armature reaction weakens the field by 4%.

As Generator $V = 250V, I = 4A$
 $R_{sh} = 250V, R_a = 0.5\Omega$
 $I_{sh} = \frac{V}{R_{sh}} = 1, I_a = I_{sh} = 1A$
 $E_g = V + I_a R_a = 250 + 1 \times 0.5 = 250.5V$
 $N_1 = 1000 \text{ rpm}$
 $\frac{E_2}{E_1} = \frac{\phi_2 N_2}{\phi_1 N_1} \Rightarrow N_2 = \frac{E_2}{E_1} \times \frac{\phi_1 N_1}{\phi_2}$
 $\Rightarrow \frac{230.5}{250.5} \times \frac{1000}{0.96}$
 $\Rightarrow N_2 = 958 \text{ rpm.}$

Q. A 460V series motor runs at 500 rpm taking a current of 40A. Calculate (i) % change in torque (ii) speed when the line current is reduced to 30A. Total resistance of motor 0.8Ω assume linear magnetisation.

As $R_a + R_{se} = 0.8\Omega, V = 460V, N_1 = 500 \text{ rpm}, I_{a1} = 40A, I_{a2} = 30A, N_2 = ?$

$$E_{b1} = V - I_{a1}(R_a + R_{se}) = 460 - 40 \times 0.8 = 428 \text{ volt}$$

$$E_{b2} = V - I_{a2}(R_a + R_{se}) = 460 - 30 \times 0.8 = 436 \text{ volt}$$

$$I_{a1} \propto I_{a1}^2 \quad (1) \quad I_{a2} \propto I_{a2}^2 \quad (2)$$

$$\frac{I_{a2}}{I_{a1}} = \frac{I_{a2}^2}{I_{a1}^2} = \left(\frac{30}{40}\right)^2 = 0.5625$$

$$\Rightarrow I_{a2} = 0.5625 I_{a1}$$

$$E \propto \phi N \quad E \propto I_a N \quad (\because \phi \propto I_a)$$

$$\frac{E_2}{E_1} = \frac{I_{a2} N_2}{I_{a1} N_1}$$

$$\Rightarrow N_2 = \frac{E_2}{E_1} \times \frac{I_{a1}}{I_{a2}} \times N_1$$

$$= \frac{436}{428} \times \frac{40}{30} \times 500$$

$$\Rightarrow N_2 = 679 \text{ rpm.}$$

(160)

Q. A DC series Motor running at 350 rpm at 220V taking a current of 25A. The motor resistance is 1Ω . calculate
 (i) Resistance to be added in series to reduce the speed to 250 rpm at constant torque. (ii) The power wasted in the resistor.

Ans. $N_1 = 350 \text{ rpm}$, $V = 220 \text{ V}$, $I_a = 25 \text{ A}$, $R_a = 1\Omega$, $N_2 = 250 \text{ rpm}$

$$E_{b1} = V - I_a R_a - I_{se} R_{se} = 220 - I_a (R_a + R_{se}) = 220 - 25 = 195$$

$$T_{a1} \propto I_{a1}^2 \quad T_{a2} \propto I_{a2}^2 \quad \frac{T_{a2}}{T_{a1}} = \frac{I_{a2}^2}{I_{a1}^2} \Rightarrow I_{a1}^2 = I_{a2}^2 \Rightarrow I_{a1} = I_{a2}$$

$$I_a \propto \phi \quad \phi_1 = \phi_2$$

$$E_1 \propto I_{a1} N_1, \quad E_2 \propto I_{a2} N_2 \quad \frac{E_2}{E_1} = \frac{I_{a2} N_2}{I_{a1} N_1} \Rightarrow E_2 = \frac{N_2}{N_1} \times E_1$$

$$= \frac{250}{350} \times 195$$

$$= 139.28 \text{ V}$$

$$R + R_{se} = \frac{V - E_2}{I_a}$$

$$= \frac{220 - 139.28}{25}$$

$$= 3.22 \Omega$$

$$R = 3.22 - 1 = 2.22 \Omega \quad P = 25^2 \times 2.22 = 1387.5 \text{ watt}$$

Q. A 220V series Motor runs at 800 rpm when taking a current of 15A. The motor has $R_a = 0.3\Omega$, $R_f = 0.2\Omega$. Find the resistance to be connected in series with armature if it has to take the same current at the same voltage at 600 rpm. Assume flux is proportional to current.

Ans. $V = 220 \text{ V}$, $N_1 = 800 \text{ rpm}$, $N_2 = 600 \text{ rpm}$, $I_a = 15 \text{ A}$

$$E_{b1} = V - I_a (R_a + R_{se}) = 220 - 15(0.3 + 0.2) = 212.5 \text{ V}$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} \Rightarrow E_2 = \frac{N_2}{N_1} \times E_1$$

$$= \frac{600}{800} \times 212.5$$

$$= 159.375 \text{ V}$$

$$E_2 = V - I_a (R_a + R_{se}) \Rightarrow V = E_2 + I_a (R_a + R_{se})$$

$$\Rightarrow I_a (R_a + R_{se}) = V - E_2$$

$$\Rightarrow R_a + R_{se} = \frac{V - E_2}{I_a}$$

$$= \frac{220 - 159.375}{15}$$

$$= 4.04 \Omega$$

$$R_{extra} = (R_a + R_{se}) - 0.5 = 4.04 - 0.5 = 3.54 \Omega$$

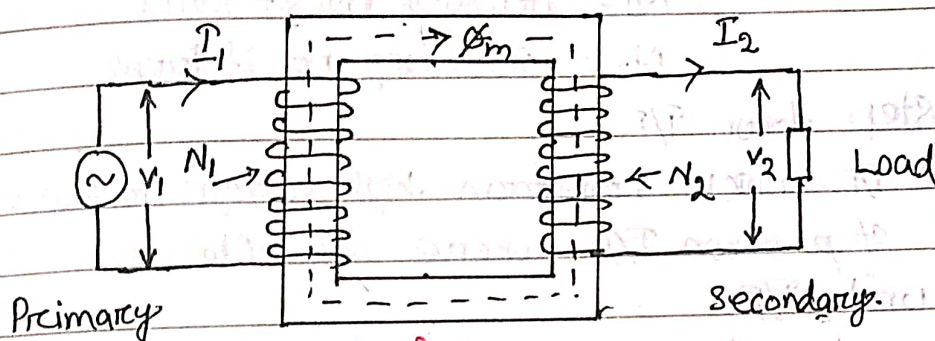
Ch-3 TRANSFORMER (1-0)

(161)

It is defined as a static electrical AC device which transforms power or energy from one circuit to other at constant frequency.

Construction

The transformer consists of two parts like core and windings. The core is made up of silicon steel laminations having thickness of lamination 0.3 to 0.5 mm, in order to reduce eddy current loss. The winding which is connected to supply mains is called primary winding. The winding which is connected to load circuit is known as secondary winding. Both the windings are electrically separated but magnetically coupled. The magnetic coupling takes place by means of transformer core. The core and windings are insulated from each other.



Working Principle

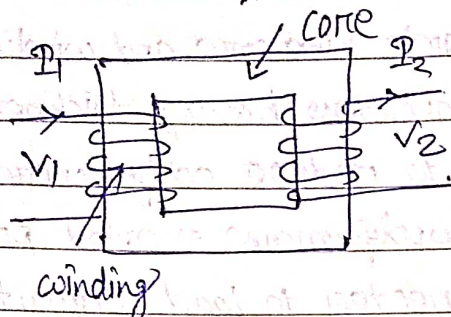
When an AC supply is given to the primary due to alternating current flux is set up. This flux is known as self flux. Due to linkage of this flux with the primary turns, EMF is induced according to Faraday's Law of electromagnetic induction. This EMF is known as primary induced EMF or self induced EMF. The same flux passes through the core and reaches in the secondary side which is called mutual flux due to linkage of this flux with secondary turns, EMF is induced. This EMF is called secondary induced EMF or mutual induced EMF. This EMF drives current towards the load ckt if the terminals are closed. This current is known as secondary or output current.

Hence the working principle of transformer is based on mutual inductance and Faraday's law of electromagnetic induction.

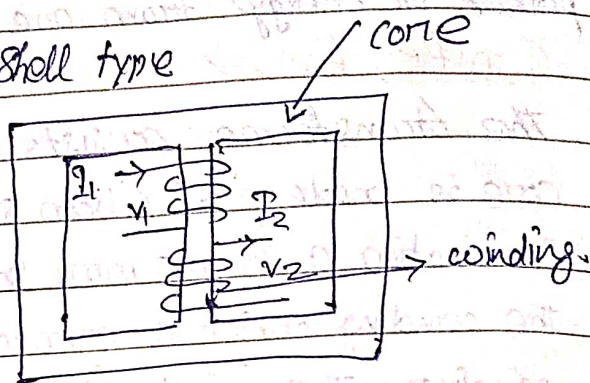
Types of Transformer

(i) Based on connection

(i) Core type



(ii) Shell type



(2) Based on transformation

(a) Step up T/P

The T/P which transform low voltage to high voltage is called step up T/P. when $N_2 > N_1$

N_1 = Primary no. of turns

N_2 = Secondary no. of turns

(b) Step down T/P

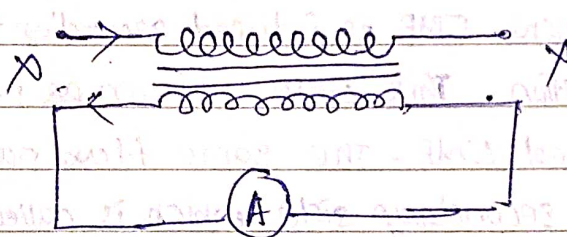
The T/P which transform high voltage to low voltage is called step down T/P. where $N_1 > N_2$

(c) unit T/P

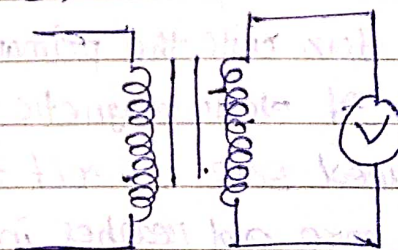
$$N_1 = N_2$$

(3) Based on use

(i) Current T/P



(ii) Potential T/P



EMF Equation of Transformer

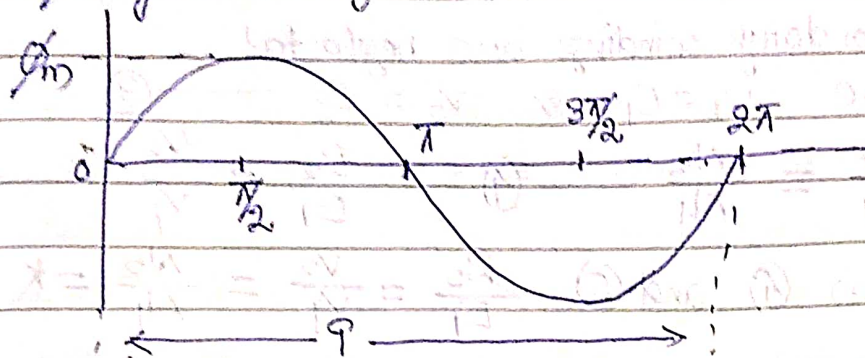
Let N_1 = no. of primary turns

N_2 = no. of secondary turns

ϕ_m = Maximum flux in the core in wb

T = Time taken for complete cycle in sec

f = frequency of supply in Hz



Let us consider the flux of sinusoidal flux for a complete cycle

$$\text{i.e. } \phi = \phi_m \sin \theta$$

The amount of flux becomes max^m after an interval of quarter cycle. According to Faraday's law of electromagnetic induction, the average emf induced in coil is the rate of change of flux linkages.

$$\begin{aligned} \text{Average emf induced/turns} &= \frac{d\phi}{dt} = \frac{(\phi_m - 0)}{(T/4 - 0)} \\ &= \frac{\phi_m}{T/4} = 4\phi_m \frac{1}{T} \\ &= 4\phi f \end{aligned}$$

For sinusoidal wave form

$$\text{form factor} = \frac{\text{RMS value}}{\text{Avg. value}} = 1.11$$

$$\text{RMS value} = 1.11 \times \text{Avg. value}$$

$$\begin{aligned} \text{RMS value of } \phi_{\text{induced/turn}} &= 1.11 \times \text{Avg. value} \\ &= 1.11 \times 4f\phi_m \end{aligned}$$

$$E_t = 4.44 f \phi_m$$

RMS value of induced EMF in primary for N_1 turns

$$E_1 = 4.44 f \phi_m N_1 \text{ volt}$$

RMS value of induced EMF in secondary for N_2 turns

$$E_2 = 4.44 f \phi_m N_2 \text{ volt}$$

Voltage transformation Ratio ~

It is defined as the ratio of secondary voltage to the primary voltage. It is represented by k .

from the EMF Equation

$$E_1 = 4.44 f \phi_m N_1 \quad \text{--- (1)} \quad E_2 = 4.44 f \phi_m N_2 \quad \text{--- (2)}$$

For an ideal transformer the voltage drop in primary and secondary windings are neglected

$$\text{i.e. } V_1 = E_1 \quad \& \quad V_2 = E_2 \quad \text{--- (3)}$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} \quad \text{--- (4)}$$

$$\frac{E_2}{E_1} = \frac{V_2}{V_1} \quad \text{--- (5)}$$

$$\text{from (4) and (5)} \quad \frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = k$$

For step up T/P $V_2 > V_1 \Rightarrow k > 1$

For step down T/P $V_1 > V_2 \Rightarrow k < 1$

Current ratio ~

For an ideal T/P

Primary amperes turn = Secondary Amperes turn

$$\text{i.e. } I_1 N_1 = I_2 N_2$$

$$\frac{N_2}{N_1} = \frac{I_1}{I_2}$$

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

Ideal Transformer

If there is no power loss (Iron and Copper loss) and there is no voltage drop (Primary drop $I_1 Z_1$ and secondary drop $I_2 Z_2$) the transformers.

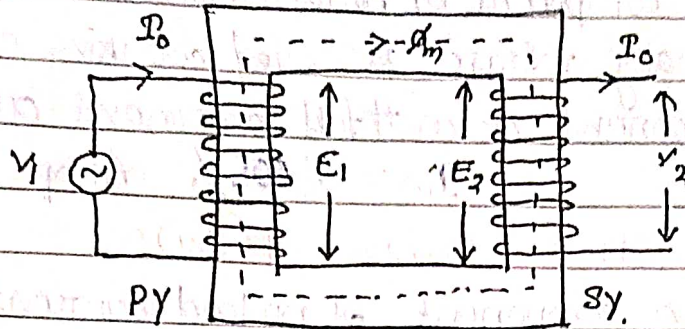
Practically it is impossible to realise such a T/P.

For ideal T/P

$$\text{I/p power} = \text{T/p power}$$

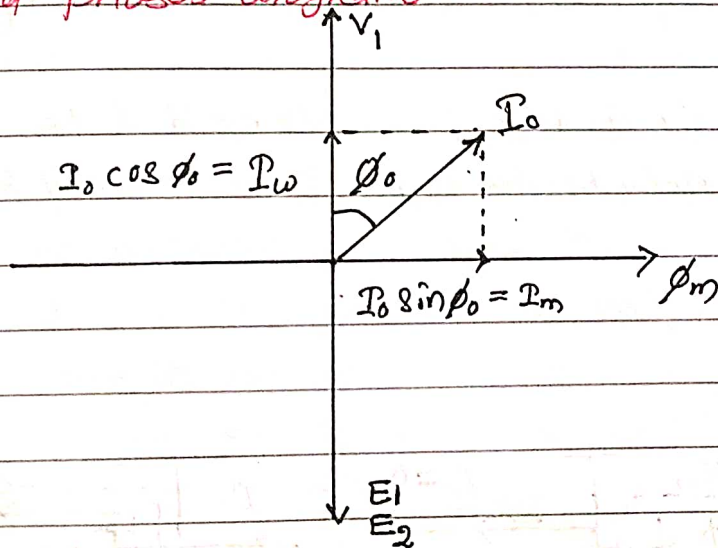
therefore the efficiency is 100%.

T/P with losses but no magnetic leakage in
① No load in



when there is no load in secondary side, the T/P is considered at no load condition. Since the i/p terminal are connected to the supply mains. A small amount of current is drawn from the i/p side known as no load current. If the primary coil is purely inductive, the no load current lags the primary voltage by an angle 90° . But practically the coil is both resistive and inductive in nature. Hence no load current (I_0) lags the primary voltage (V_1) by angle ϕ_0 called no load power factor angle and its value is less than 90° .

No load phasor diagram



The no load current has two components like magnetising component (I_m) and working component (I_w).

Working Component (P_w) ~

The component of no load current which remains in phase with primary voltage is called working component or active component or watt full component or loss component

$$I_w = I_0 \cos \phi_0 \text{ Amp}$$

Magnetising Component (P_m) ~

The component of no load current which remains in quadrature with primary voltage is called magnetising component or inactive component or reactive component or watt less component.

$$I_m = I_0 \sin \phi_0 \text{ Amp}$$

No Load current

$$I_0 = \sqrt{I_w^2 + I_m^2}$$

No Load power factor

$$\cos \phi_0 = I_w / I_0 \text{ (Lag)}$$

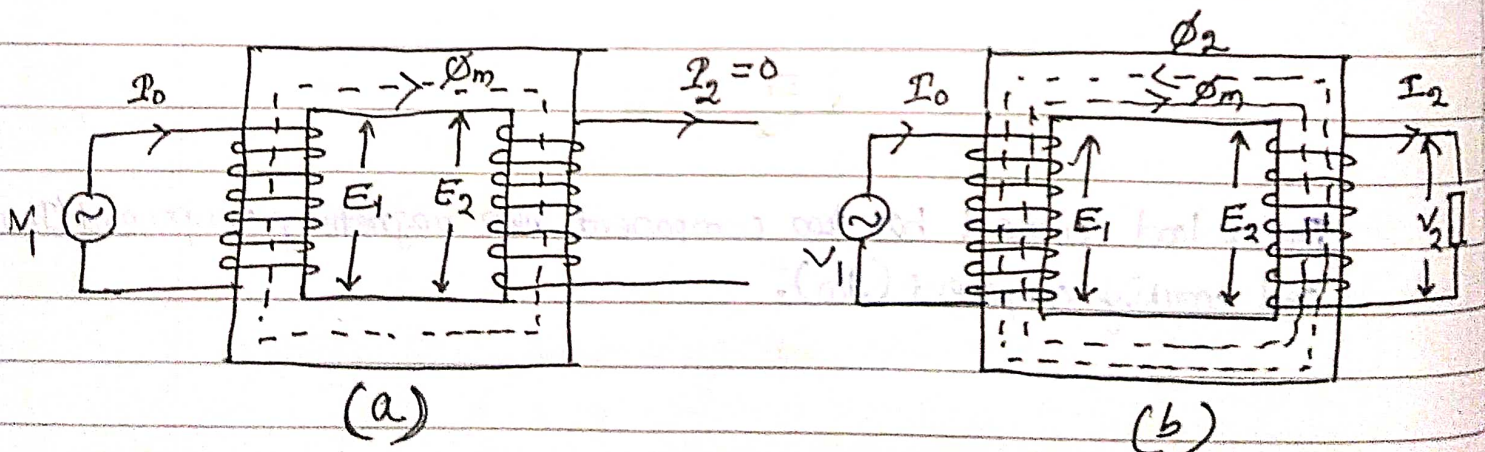
Wp power at no load = No load loss or Iron loss

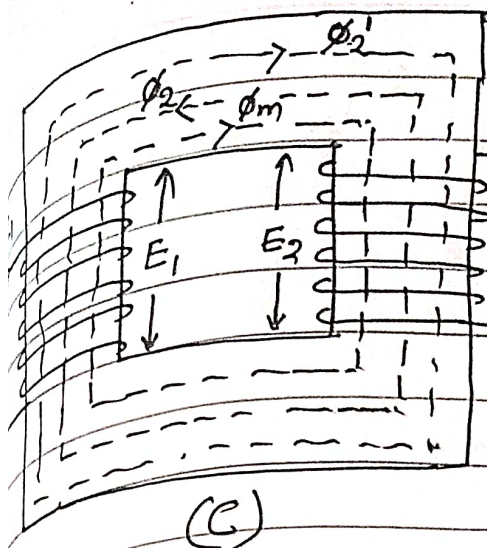
$$W_0 = V_1 I_0 \cos \phi_0 \text{ watt}$$

Important points

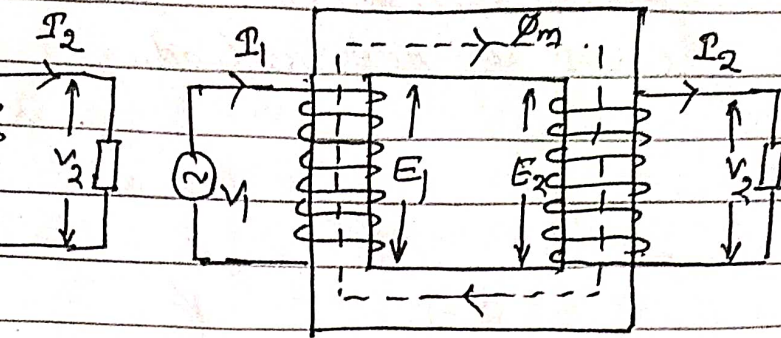
- * No load current I_0 is 1 to 3% of full load primary current.
- * Since I_0 is very less, the loss in the primary winding is neglected.
- * At no load the total i/p power is equal to the iron loss in the core.
- * The no load power factor angle is also called hysteresis angle of advance.

② with load :-





(c)



(d)

Figure (c) shows the no-load condition of the T/P with flux Φ_m in the core. When T/P is loaded either with resistor or inductor or capacitor load certain current I_2 will respond or will flow in the secondary winding which creates flux Φ_2 . Demagnetising Ampere turn $I_2' N_2$ causes flow of flux Φ_2 in opposite direction and hence weakens the primary flux Φ_m . To overcome it a heavy current is drawn from the primary. The additional current drawn from primary is I_2' which is known as mirror current or reflected current. This current creates flux Φ_2' . The new ampere turn $I_2' N_1$ drives this flux in the opposite direction of flux Φ_2 . Since I_2 and I_2' are equal in magnitude and opposite in direction the fluxes Φ_2 and Φ_2' will cancel the effect of each other.

The net flux Φ_m flows through the core hence the T/P core carries some flux Φ_m for all types of loads. Since the flux remains same in the core iron losses which is caused due to alternating flux that remains constant in the T/P core.

Relation between I_2 & $I_2' \rightarrow$

$$\text{As } \Phi_2' = \Phi_2$$

$$\Rightarrow I_2' N_1 = I_2 N_2$$

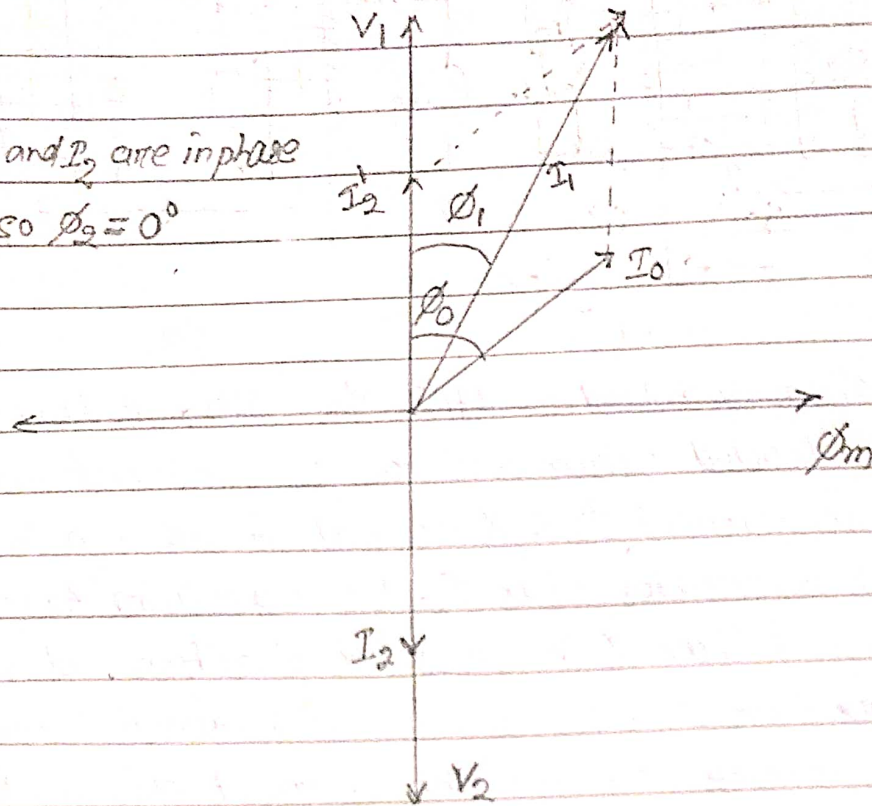
$$\Rightarrow I_2' = I_2 \frac{N_2}{N_1}$$

$$\Rightarrow \boxed{I_2' = K I_2}$$

Phasor Diagram :-

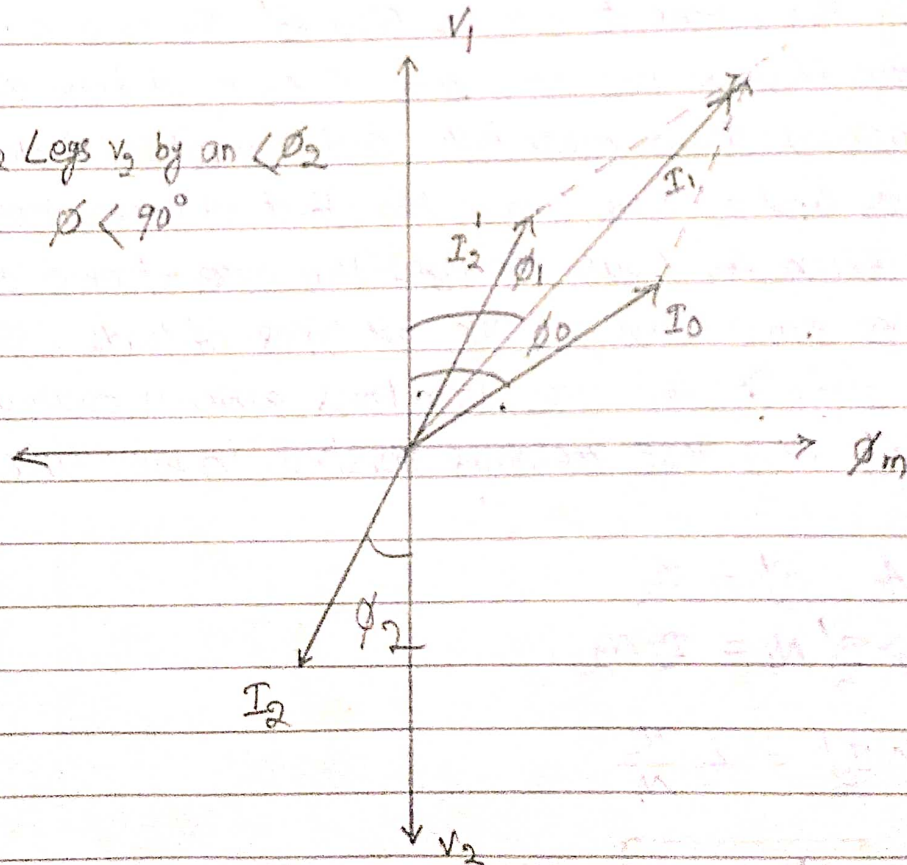
Case-I For resistive load

V_2 and I_2 are in phase
so $\phi_2 = 0^\circ$

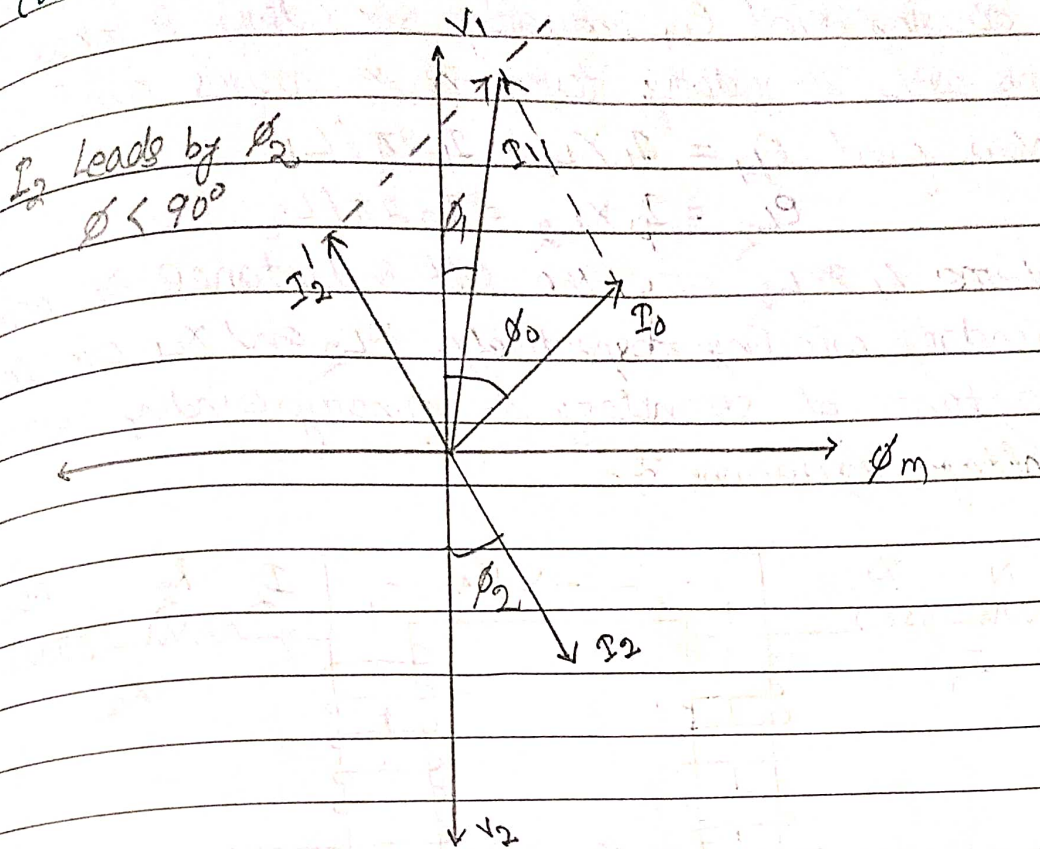


Case-II For inductive load

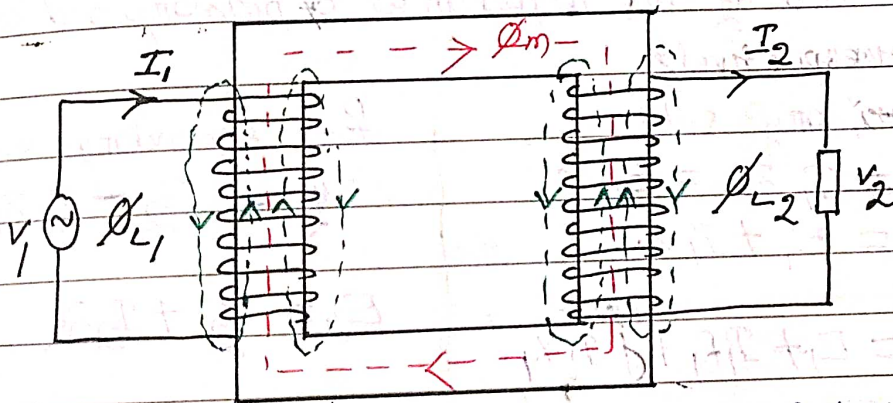
I_2 lags V_2 by an angle ϕ_2
 $\phi < 90^\circ$



Case-III For Capacitive load



T/E with losses and Magnetic Leakage:



In actual practice the total flux created does not link with both the windings and the other hand some amount of flux occurs as leakage flux which is called magnetic leakage. The total flux is divided into 3 parts like main flux (ϕ_m), leakage flux (ϕ_{L1}) through the primary winding & leakage flux (ϕ_{L2}) through secondary winding.

(170)

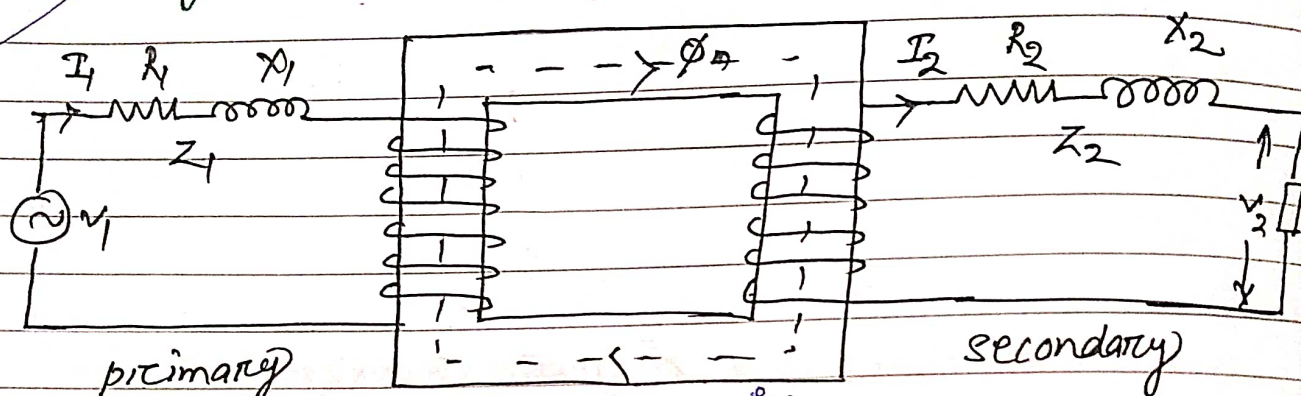
The primary leakage flux (ϕ_1) links with primary turns N_1 causing emf E_1 , similarly secondary leakage flux ϕ_2 links with secondary turns N_2 causes emf E_2 .

$$\text{Now emf } E_1 = I_1 X_{L1} = I_1 2\pi f L_1$$

$$E_2 = I_2 X_{L2} = I_2 2\pi f L_2$$

where L_1 & L_2 are the self inductance of primary & secondary winding respectively. X_{L2} and X_{L1} are leakage reactance of secondary & primary winding respectively.

voltage equations: $\rightarrow$



$$Z_1 = R_1 + jX_1 \quad Z_2 = R_2 + jX_2$$

where Z_1 and Z_2 are impedances of primary and secondary winding respectively

From primary side

$$V_1 - I_1 Z_1 = E_1$$

$$V_1 = E_1 + I_1 Z_1$$

$$\boxed{V_1 = E_1 + I_1 R_1 + j I_1 X_1}$$

from secondary side

$$V_2 = E_2 - I_2 Z_2$$

$$E_2 = V_2 + I_2 Z_2$$

$$E_2 = V_2 + I_2 (R_2 + jX_2)$$

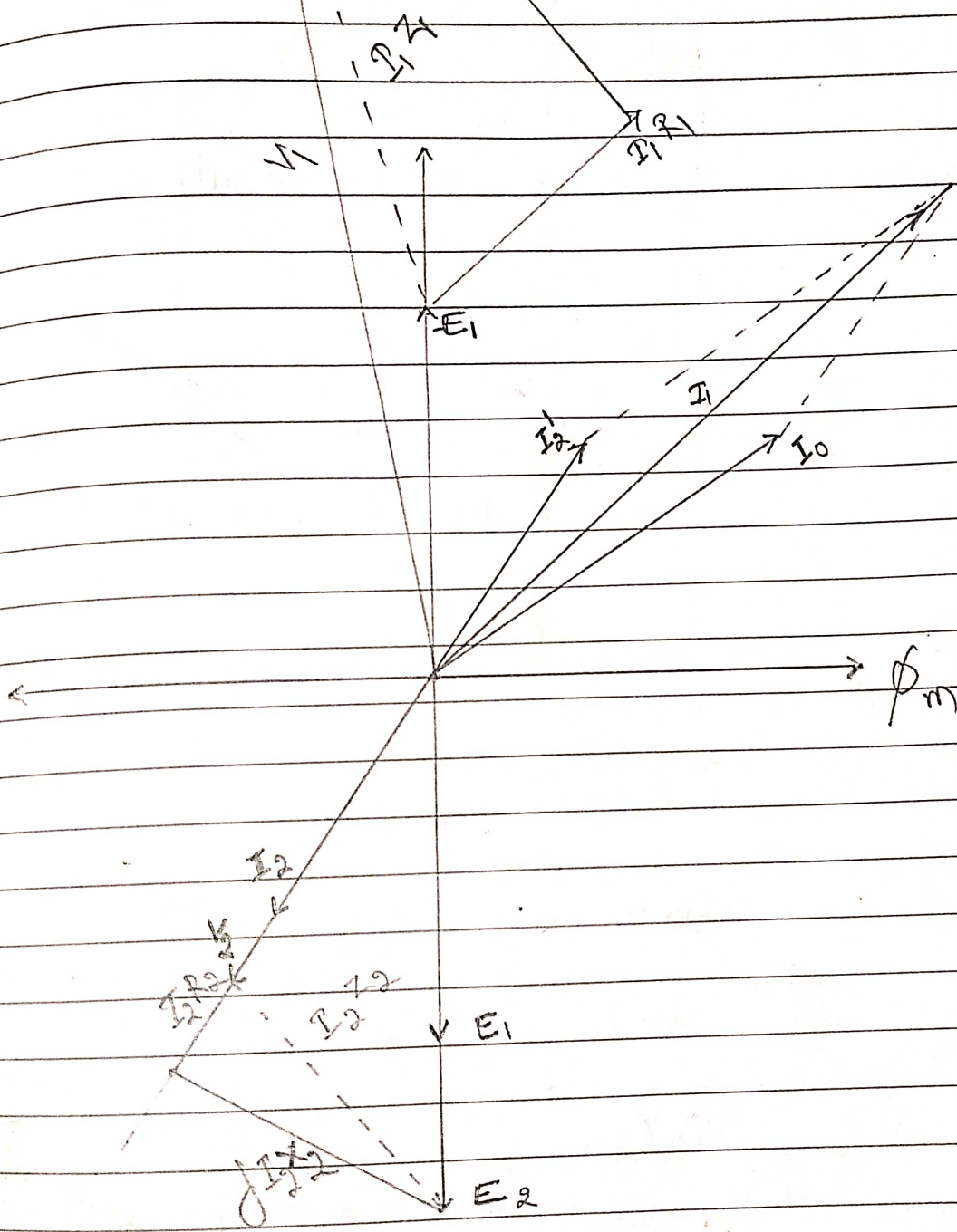
$$\boxed{E_2 = V_2 + I_2 R_2 + j I_2 X_2}$$

(171)

✓ phasor Diagram

case-1 For Resistive load

I_2 in phase with V_2 so $\phi_2 = 0^\circ$

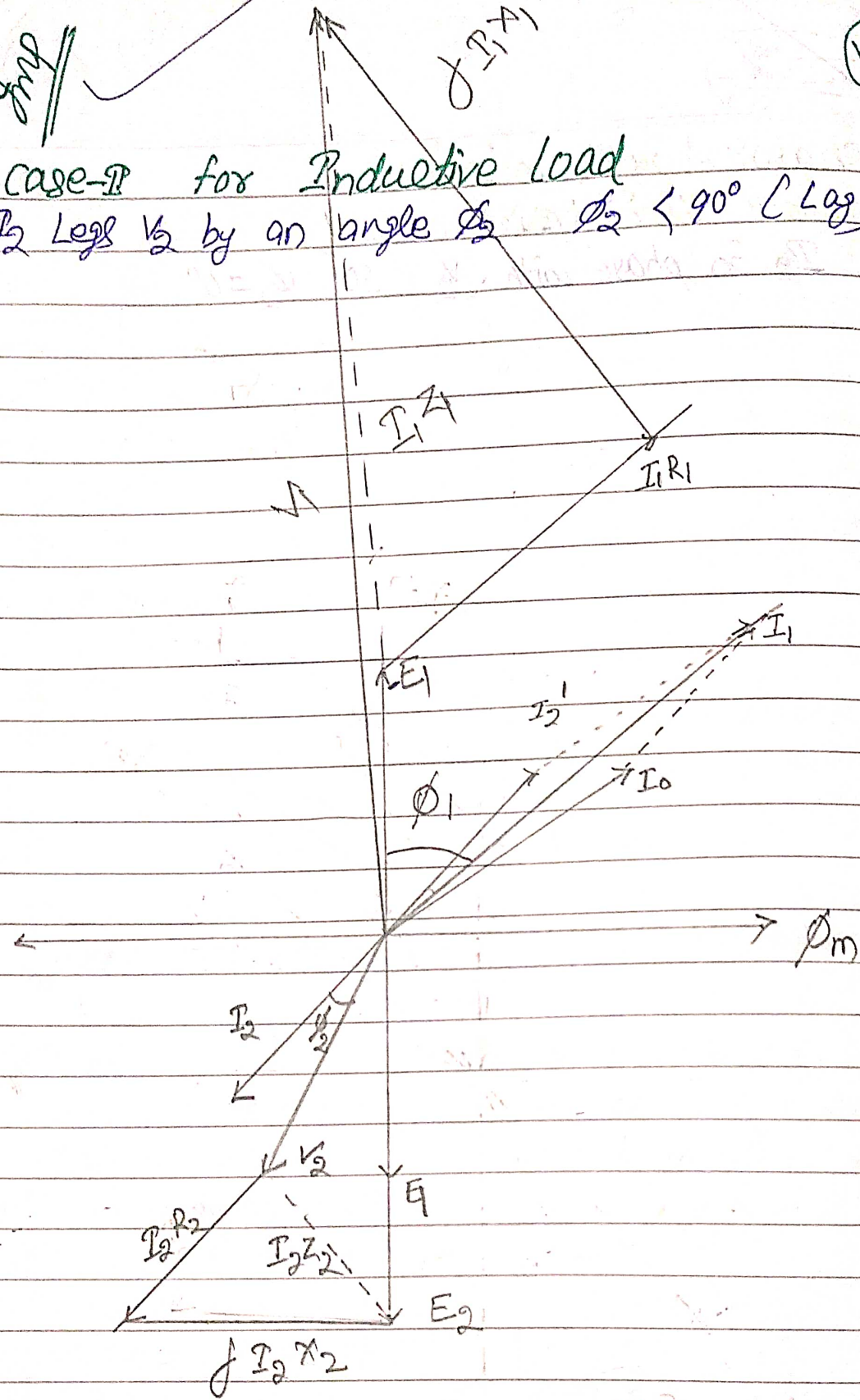


Ans

$\angle I_1 A_1$

(172)

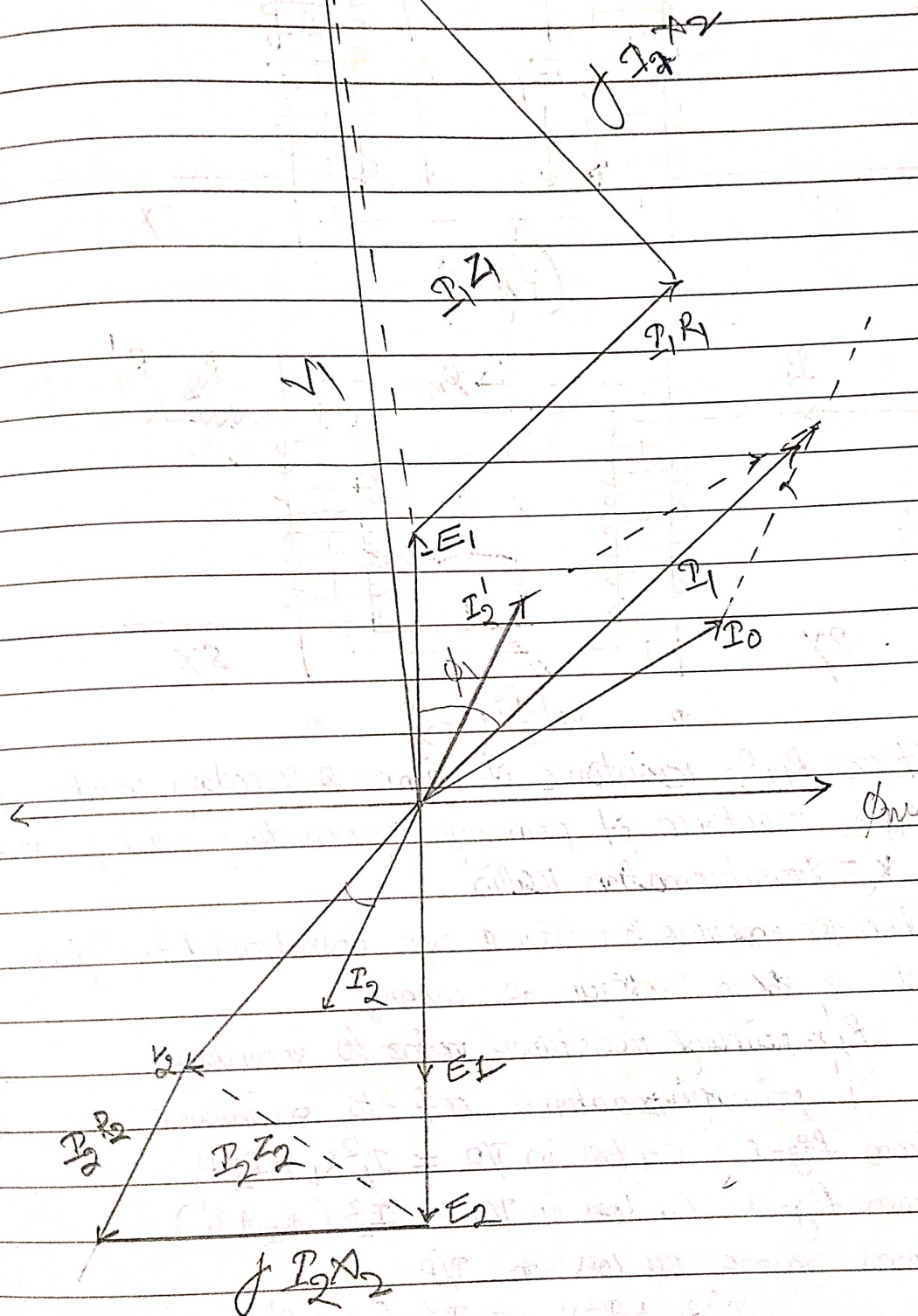
Case-II for Inductive Load
 I_2 lags V_2 by an angle ϕ_2 $\phi_2 < 90^\circ$ (Lag)



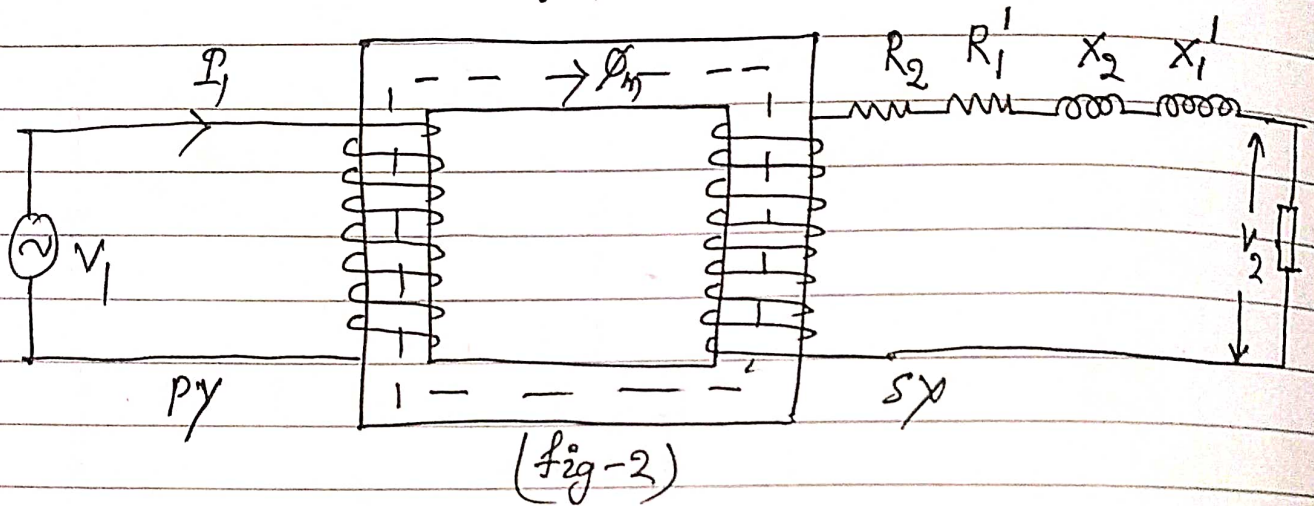
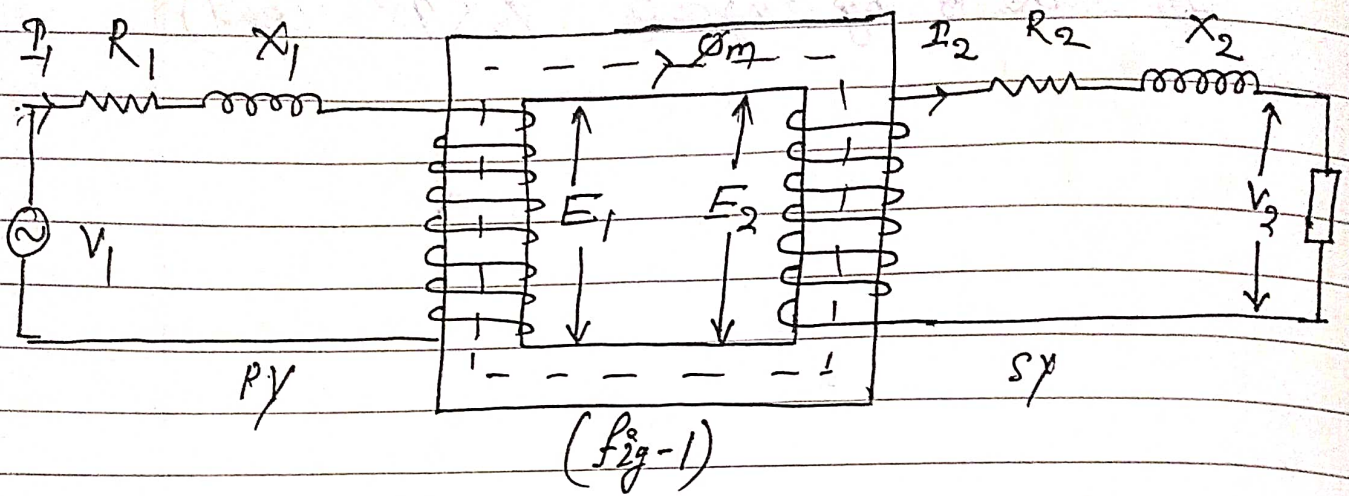
(173)

Case-III for Capacitive Load.

I_2 Leads V_2 by angle ϕ_2 $\phi_2 < 90^\circ$ (Lead)



Equivalent Resistance, Reactance & Impedance



Here R_1, R_2 resistance of primary & secondary winding respectively.
 X_1, X_2 reactance of primary & secondary winding respectively.

k = Transformation ratio

When the resistance & reactance are transformed from primary to secondary side as shown in figure-2 where

R_1' primary resistance refer to secondary

X_1' primary reactance refer to secondary

from fig-1 Cu loss in T/P = $I_1^2 R_1 + I_2^2 R_2$

from fig-2 Cu loss in T/P = $I_2^2 (R_2 + R_1')$

from same Cu loss in T/P

$$I_1^2 R_1 + I_2^2 R_2 = I_2^2 (R_2 + R_1')$$

$$\Rightarrow I_1^2 R_1 + I_2^2 R_2 = I_2^2 R_2 + I_2^2 R_1'$$

$$\Rightarrow I_1^2 R_1 = I_2^2 R_1'$$

$$\Rightarrow R_1' = \left(\frac{I_1}{I_2}\right)^2 R_1$$

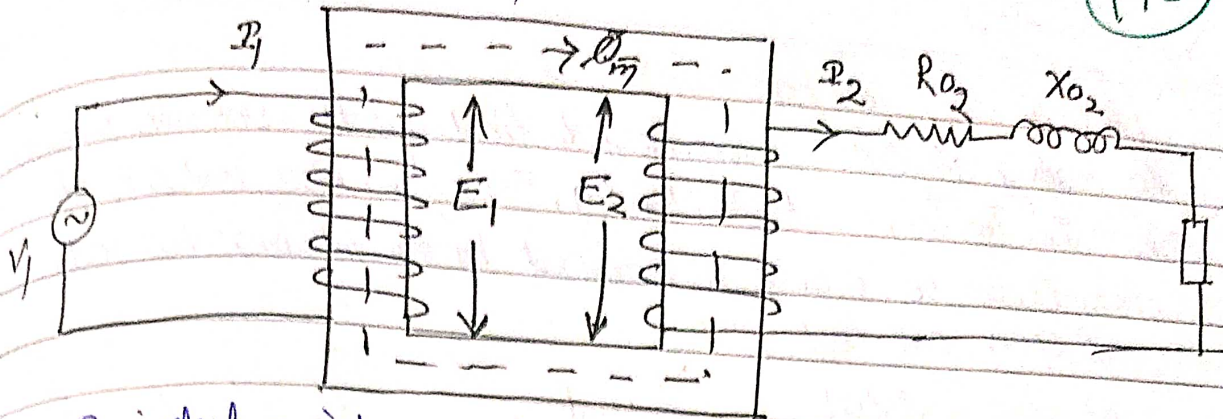
$$R_1' = k^2 R_1$$

similarly $X_1' = k^2 X_1$

$$P_y \xrightarrow{\times k^2} S_y$$

$$S_y \xrightarrow{\times 1/k^2} P_y$$

(175)



Equivalent resistance refer to secondary $R_{02} = R_2 + R_1'$

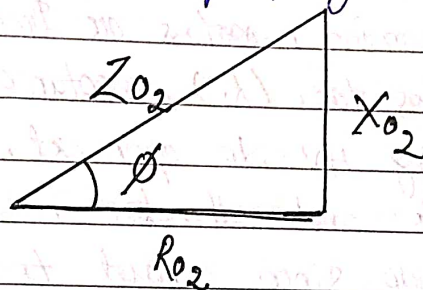
Equivalent reactance refer to secondary $X_{02} = X_2 + X_1'$

Equivalent impedance refer to secondary $Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$

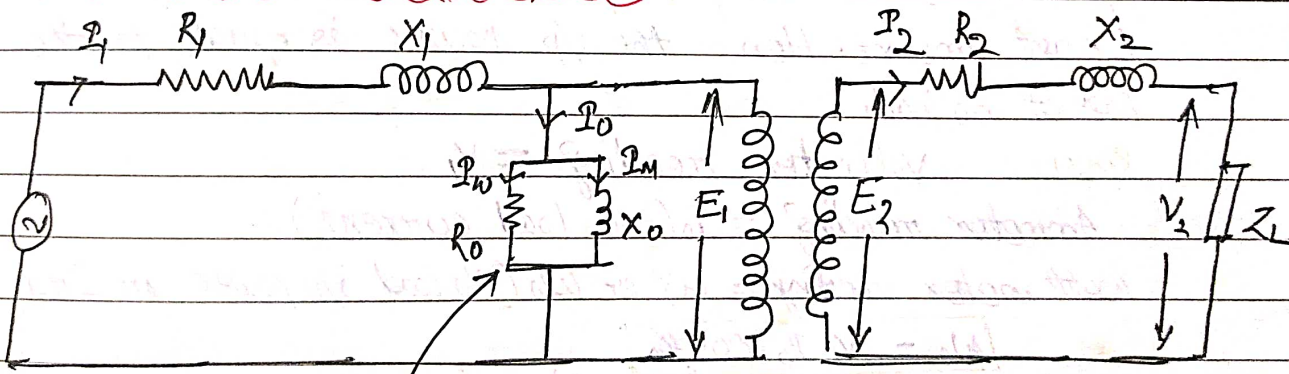
Equivalent resistance refer to primary $R_{01} = R_1 + R_2'$

Equivalent reactance refer to primary $X_{01} = X_1 + X_2'$

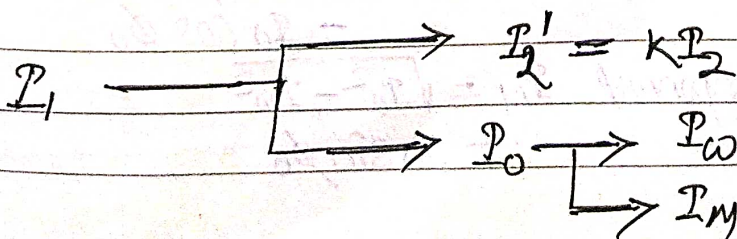
Equivalent impedance refer to primary $Z_{01} = \sqrt{R_{01}^2 + X_{01}^2}$



Actual Equivalent ckt of T/P :->



No Load branch or exciting branch
or shunt branch or magnetising branch



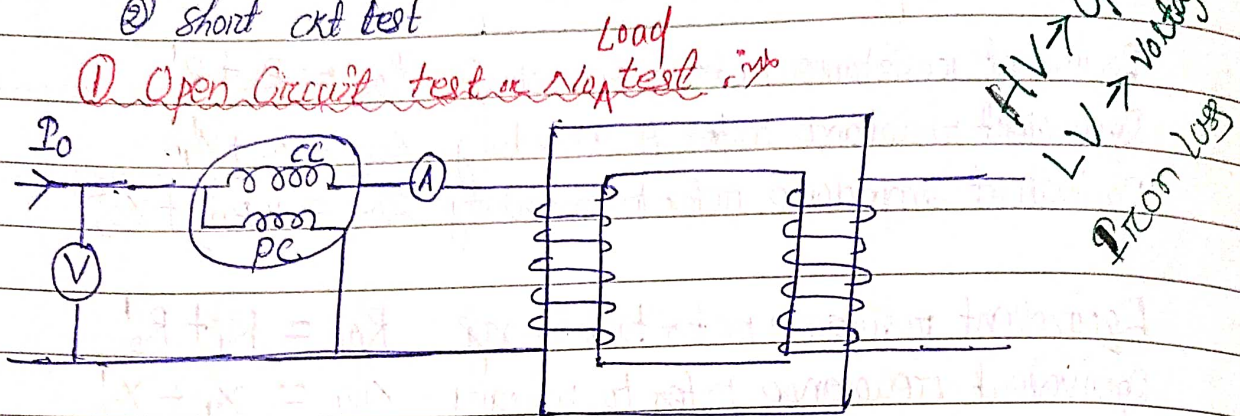
Testing of Transformer

The testing of T/P is required to find out the unknown parameters like I_0 , I_w , I_M , W_0 , R_0 , X_0 , R_0 , X_0 , Z_{01} , P_{30} , W_{30} and %R etc. These constant can be easily determined by the following two tests

① open ckt test

② short ckt test

① Open Circuit test or No load test



AIM ① To determine I_0 , I_M , P_0

② To determine power loss or Iron loss (W_i or W_0)

③ To get resistance (R_0), reactance (X_0) & no load Branch

Procedure Keeping HV side open ckt, connect instrument like, ammeter, voltmeter and wattmeter in LV side rated voltage should be applied at input side. Since output terminals are open circuit, T/P power is zero. Input P₁ side cu loss is neglected due to least amount. Hence the i/p power is equal to the iron loss at no load.

Result voltmeter reading = V_1

Ammeter reading = I_0 (No load current)

Wattmeter reading = W_i or W_0 (No load i/p power or Iron loss)

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

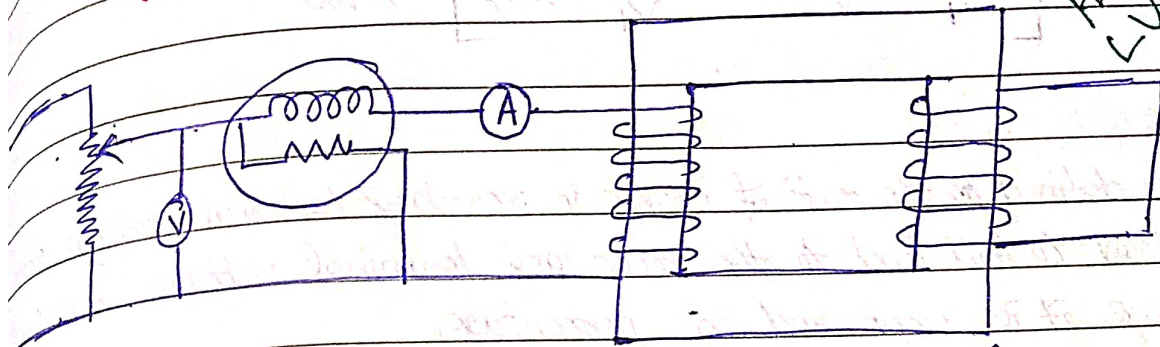
$$\cos \phi_0 = \frac{W_0}{V_1 I_0} \quad \left(\text{No Load cu loss is very small \textcircled{a} compare to iron loss} \right)$$

$$\text{Working component of current } I_w = \frac{W_0}{V_1} = I_0 \cos \phi_0$$

$$\text{magnetising component } I_M = \sqrt{I_0^2 - I_w^2} = I_0 \sin \phi_0$$

Resistance of no load branch $R_0 = \frac{V_1}{I_W}$
 Reactance of no load branch $X_0 = \frac{V_1}{I_M}$

② Short Circuit test or Impedance test



- AIM**
- ① To find out sc current and sc cu loss (FL cu loss of T/F)
 - ② To find out equivalent resistance, reactance & Impedance
 - ③ To get % Regulation

Procedure By keeping LV side short ckt connecting instrument on the HV side, fraction of rated voltage should be applied (5 to 10% supply voltage) till to get full load current on ammeter.

Result V_{sc} = Short Circuit voltage
 = fraction of rated voltage (Reading of voltmeter)

$I_{F.L.}(I_{sc})$ = Short Ckt current
 = Full load current (Reading of ammeter)

$W_{cu}(W_{sc})$ = Short Ckt cu loss
 = Full load cu loss (Reading of wattmeter)
 = $I_{F.L.}^2 R_{01}$ or $I_{sc}^2 R_{01}$

(Because Iron loss for the supply of fraction voltage is neglected)

Equivalent resistance referred to P_1

$$R_{eq} = W_{cu} / I_{F.L.}^2 \Omega$$

$$R_{eq} = W_{cu} / I_{sc}^2 \Omega$$

Equivalent Impedance referred to P_1

$$Z_{eq} = V_{sc} / I_{sc} \Omega$$

$$R = \frac{W_{sc}}{I_{sc}^2}$$

$$Z = \frac{V_{sc}}{I_{sc}}$$

$$X = \sqrt{Z^2 - R^2}$$

Equivalent reactance referred to P_1

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

$$\%R = \left[\frac{I_1 R_{01} \cos \phi \pm \frac{I_1 X_{01} \sin \phi}{V_1}} \right] \times 100$$

Regulation $\rightarrow$

It is defined as the ratio of change in secondary terminal voltage from no load to full load to the secondary terminal voltage at no load. always it is expressed in percentage.

$$\%R = \frac{V_{02} - V_2}{V_{02}} \times 100$$

V_{02} = Secondary terminal voltage at no load

V_2 = Secondary terminal voltage at load

calculation of Regulation $\rightarrow$

Percentage regulation referred to secondary

$$= \frac{\text{Drop referred to sy}}{\text{sy voltage}} \times 100$$

$$= \left(\frac{I_2 R_{02} \cos \phi \pm I_2 X_{02} \sin \phi}{V_2} \right) \times 100$$

$\rightarrow$ for lagging load
 $\rightarrow$ for leading load

$$= \frac{I_2 R_{02}}{V_2} \times 100 \times \cos \phi \pm \frac{I_2 X_{02}}{V_2} \times 100 \times \sin \phi$$

$$= V_R \cos \phi \pm V_X \sin \phi$$

$V_R \rightarrow$ percentage resistive drop

$V_X \rightarrow$ percentage reactive drop

Condition for zero Regulation ~

Regulation referred to secondary

$$r = \frac{I_2 R_2 \cos \phi \pm I_2 X_2 \sin \phi}{V_2}$$

For zero regulation numerator should be zero and considering -ve sign

$$I_2 R_2 \cos \phi - I_2 X_2 \sin \phi = 0$$

$$\Rightarrow I_2 R_2 \cos \phi = I_2 X_2 \sin \phi$$

$$\Rightarrow \frac{R_2}{X_2} = \frac{\sin \phi}{\cos \phi} \Rightarrow \tan \phi = \frac{R_2}{X_2} \Rightarrow \phi = \tan^{-1} \frac{R_2}{X_2}$$

* zero regulation occurs for capacitive load or leading Power factor.

Condition for Maximum Regulation ~

Regulation referred to secondary

$$R = \frac{I_2 R_2 \cos \phi \pm I_2 X_2 \sin \phi}{V_2}$$

For Maximum regulation $\frac{dR}{d\phi} = 0$ and considering +ve sign only

$$\frac{dR}{d\phi} = 0$$

$$\Rightarrow \frac{I_2 R_2}{V_2} \frac{d \cos \phi}{d\phi} + \frac{I_2 X_2}{V_2} \frac{d \sin \phi}{d\phi} = 0$$

$$\Rightarrow \frac{I_2 R_2}{V_2} (-\sin \phi) + \frac{I_2 X_2}{V_2} \cos \phi = 0$$

$$\Rightarrow \frac{I_2 X_2}{V_2} \cos \phi = \frac{I_2 R_2}{V_2} \sin \phi$$

$$\Rightarrow \frac{I_2 X_2}{V_2} \times \frac{V_2}{I_2 R_2} = \frac{\sin \phi}{\cos \phi}$$

$$\Rightarrow \tan \phi = \frac{X_2}{R_2}$$

$$\Rightarrow \phi = \tan^{-1} \frac{X_2}{R_2}$$

* Maximum Regulation occurs for inductive load or lagging Power factor

Losses in Transformer

Since the T/P is a static device there is no mechanical loss or rotational loss. The losses occurring in T/P are iron loss and copper loss.

① Iron loss or core loss or constant loss or Magnetic loss $\rightarrow$

This loss occurs in the iron part and it is caused due to alternating flux. Its magnitude depends upon applied voltage. The iron loss is the sum of hysteresis loss and eddy current loss.

$$W_i = W_h + W_e \text{ watt}$$

(a) Hysteresis loss (W_h) $\rightarrow$

Due to hysteresis property of magnetic material. during magnetisation and demagnetisation certain power loss is occurred called hysteresis loss.

$$\begin{aligned} W_h &= K_h B_m^{1.6} f V \\ W_h &\propto B_m^{1.6} \\ &\propto f \end{aligned}$$

* Silicon steel is preferred for T/P $\propto V$ $V = \text{volume of material}$

(b) Eddy current loss (W_e) $\rightarrow$

Alternating flux is produced due to A.C. The flux not only links with the winding per section but also links with the core and emf is induced in the core internally this emf is ~~induced~~ circulates certain current through the core known as eddy current. The power loss that occurs due to this is called eddy current loss.

$$\begin{aligned} W_e &= K_e B_m^2 f^2 t^2 \\ W_e &\propto B_m^2 \\ &\propto f^2 \\ &\propto t^2 \end{aligned}$$

$t = \text{thickness of the material}$

* The transformer core should be laminated in to strips to reduce eddy current loss.

② Copper loss (W_{cu}) or Variable loss or $I^2 R$ loss :-

The loss that occurs in the copper part is called copper loss. It is caused due to current and ohmic resistance. Its magnitude depends upon the load. When the load varies the cu losses vary proportionally and hence it is called as variable loss.

$$\text{Total cu loss} = I_1^2 R_1 + I_2^2 R_2 \text{ or } I_1^2 R_{01} \text{ or } I_2^2 R_{02}$$

Efficiency of Transformer :-

It is defined as the ratio of o/p power to the i/p power.

$$\eta = \frac{\text{output power}}{\text{input power}}$$

$$= \frac{\text{i/p power} - \text{losses}}{\text{i/p power}}$$

$$= 1 - \frac{\text{losses}}{\text{i/p power}}$$

$$\eta = 1 - \frac{W_i + W_{cu}}{V_1 I_1 \cos \phi_1}$$

$$\eta = 1 - \frac{W_i}{V_1 I_1 \cos \phi_1} - \frac{I_1^2 R_{01}}{V_1 I_1 \cos \phi_1}$$

Condition for Maximum efficiency :-

$$\eta = 1 - \frac{W_i}{V_1 I_1 \cos \phi_1} - \frac{I_1^2 R_{01}}{V_1 I_1 \cos \phi_1}$$

For Maximum condition $\frac{d\eta}{dI_1} = 0$

$$\frac{d\eta}{dI_1} = 0 + \frac{W_i}{V_1 \cos \phi_1} \frac{1}{I_1^2} - \frac{R_{01}}{V_1 \cos \phi_1}$$

$$\Rightarrow \frac{W_i}{V_1 \cos \phi_1} \frac{1}{I_1^2} = \frac{R_{01}}{V_1 \cos \phi_1}$$

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

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

$$\Rightarrow \text{Iron loss} = \text{Copper loss}$$

$$\Rightarrow \text{constant loss} = \text{variable loss}$$

when constant loss equal to variable loss T/P gives Maximum efficiency.

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

$$\Rightarrow I_1 = \sqrt{\frac{W_i}{R_{01}}} \Rightarrow \text{primary Current correspond to Max}^m \text{ efficiency.}$$

$$W_i = I_2^2 R_{02}$$

$$\Rightarrow I_2 = \sqrt{\frac{W_i}{R_{02}}} \Rightarrow \text{secondary Current correspond to Max}^m \text{ efficiency.}$$

$$\left. \begin{aligned} I_1 &= \text{Rated KVA} / V_1 \\ I_2 &= \text{Rated KVA} / V_2 \end{aligned} \right\} \text{on Full load}$$

All day efficiency or Energy Efficiency ^{ratio of}
It is defined as o/p kwh to the i/p in kwh for 24 hours

$$\eta_{\text{all day}} = \frac{\text{o/p in kwh}}{\text{i/p in kwh}} \text{ for 24 hr.}$$

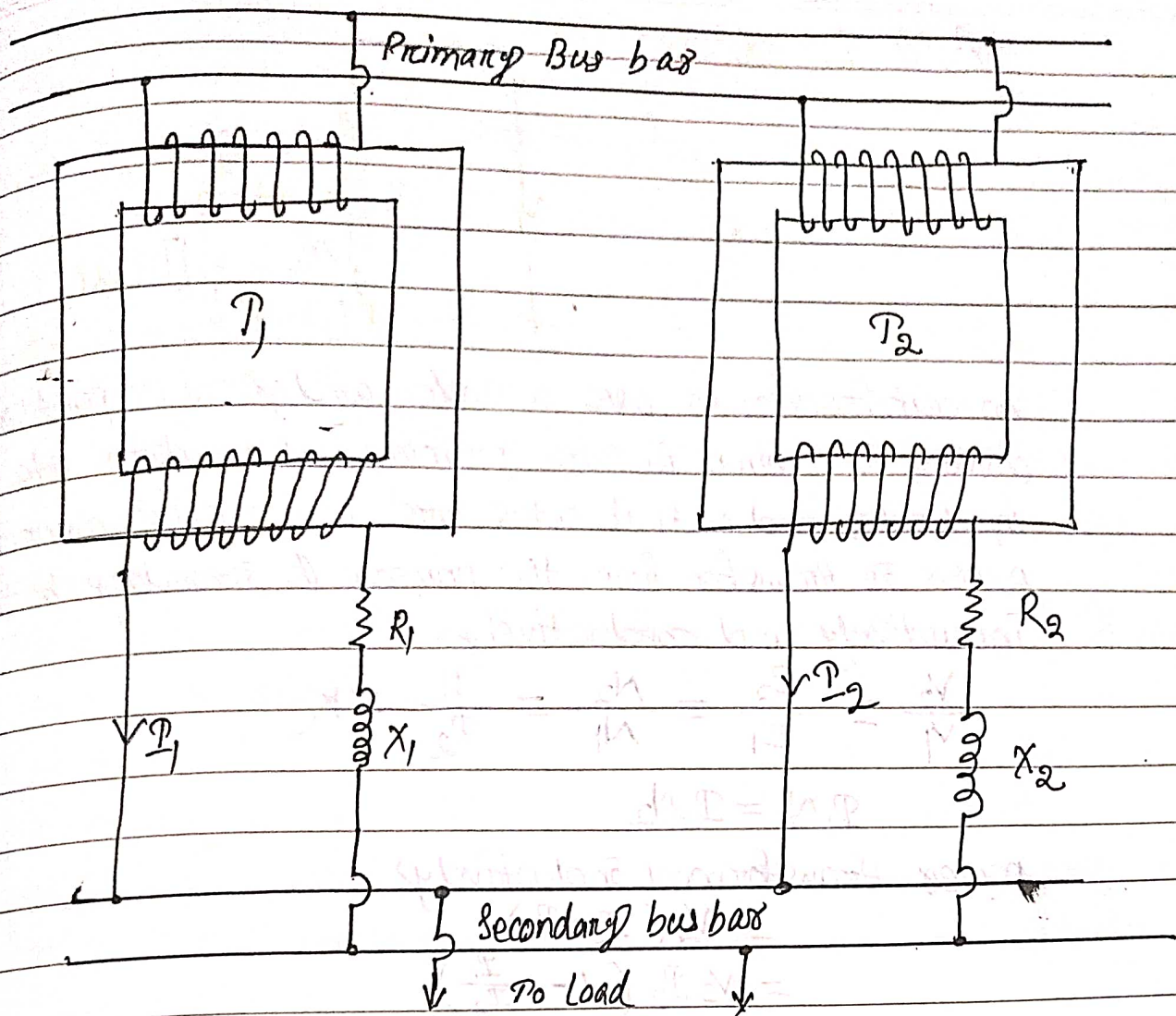
Parallel operation of 1- ϕ Transformers

condition

→ The magnitude of voltage for the both the T/P are same

→ Transformers are properly connected with regard to their polarities

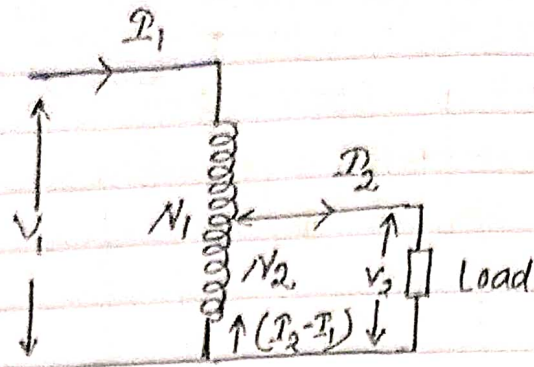
or/ polarities must be maintained.



operation :-

Primary of two T/P are connected to the supply bus and the secondary also are connected together to form a secondary bus. Taking care to observe proper polarities if the transformation ratio are the same, the voltage across the secondary terminals will be the same when this are connected to form a secondary bus, the voltage will not vary with the changing load, if the ratios $\frac{R_1}{X_1}$ and $\frac{R_2}{X_2}$ are equal the current I_1 and I_2 of the transformers will be inphase.

Auto Transformer



An auto transformer uses a single winding only. part of the winding is common to both primary and secondary side. the input side and output sides are electrically connected. power is transfer from the primary to secondary both inductively and conductively.

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

$$I_1 N_1 = I_2 N_2$$

power transferred inductively

$$= V_2 (I_2 - I_1)$$

$$= V_2 I_2 \left(1 - \frac{I_1}{I_2}\right)$$

$$= V_2 I_2 (1 - k)$$

$$= \text{output} (1 - k)$$

power transfer conductively = output $\times k$

Saving of Copper

$$\text{Conductor (Cu) material} = \frac{\text{Conductor used in auto T/P}}{\text{Two winding T/P}}$$

$$= \frac{I_1 (N_1 - N_2) + (I_2 - I_1) N_2}{I_1 N_1 + I_2 N_2}$$

$$= \frac{I_1 N_1 - I_1 N_2 + I_2 N_2 - I_1 N_2}{I_1 N_1 + I_2 N_2}$$

$$= \frac{I_1 N_1 + I_2 N_2 - (I_1 N_2 + I_1 N_2)}{I_1 N_1 + I_2 N_2}$$

$$= 1 - \frac{I_1 N_2 + I_1 N_2}{I_2 N_2 + I_2 N_2} \left(\because I_1 N_1 = I_2 N_2 \right)$$

$$= 1 - \frac{(2N_1)I_1}{(2N_2)I_2}$$

$$= 1 - \frac{I_1}{I_2}$$

$$= 1 - K$$

Advantages $\rightarrow$

- $\rightarrow$ Efficiency is more
- $\rightarrow$ voltage Regulation is better
- $\rightarrow$ Leakage reactance is reduced

Disadvantages $\rightarrow$

Since HV & LV side are electrically interconnected a fault on HV side may subject the LV of transformer to a high value.

Uses $\rightarrow$

- $\rightarrow$ It is use as stator in 3- ϕ induction motor.
- $\Rightarrow$ As interconnecting transformer in 132 kV/330 kV system.
- $\Rightarrow$ In control equipment for single phase and 3- ϕ electrical locomotive.

Q. A 3000/200 V, 50 Hz, 1- ϕ T/F has cross sectional area 150 cm^2 , 80 turns on the low voltage winding calculate

(i) Maximum flux density

(ii) No. of turns in HV winding.

Q. $N_2 = 80$ turns, $A = 150 \times 10^{-4} \text{ m}^2$, $N_1 = ?$, $E_1 = 3000 \text{ V}$, $E_2 = 200 \text{ V}$

$$R_2 = 4.44 f \phi_m N_2$$

$$\Rightarrow \phi_m = \frac{E_2}{4.44 \times 50 \times 80} = 0.011 \text{ wb}$$

$$B_m = \phi_m / A = 0.011 / 150 \times 10^{-4} = 0.733 \text{ wb/m}^2 \text{ or T}$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} \Rightarrow N_1 = \frac{E_1}{E_2} \times N_2 = \frac{3000}{200} \times 80 = 1200$$

Q. A single phase T/F is required to step down from 1900 volt to 240 volt at 50 Hz it has developed 1.5 V per turn. Calculate N_1 and N_2 . Calculate also area of the core when maximum flux density 1.2 wb/m^2

Q. $E_1 = 1900 \text{ V}$, $E_2 = 240 \text{ V}$, $E_t = 1.5 \text{ V}$

$$\text{EMF for 1 turn} = 1.5 \text{ V}$$

$$\begin{aligned}
 E_1/t_{\text{turn}} &= 1.5V \\
 \Rightarrow E_1/N_1 &= 1.5 \\
 \Rightarrow N_1 &= \frac{1900}{1.5} = 1266.667 \approx 1267 \\
 N_2 &= \frac{240}{1.5} = 160 \\
 A &= \phi_m/B_m = 6.75 \times 10^{-3} / 1.2 = 5.625 \times 10^{-3} \text{ m}^2
 \end{aligned}$$

$$\begin{aligned}
 E_1 &= 4.44 f \phi_m N_1 \\
 \Rightarrow \phi_m &= E_1 / 4.44 \times f \times N_1 \\
 \Rightarrow \phi_m &= 1900 / 4.44 \times 50 \times 1267 \\
 &= 6.75 \times 10^{-3} \text{ wb}
 \end{aligned}$$

Q. A 1- ϕ T/P has 500 primary and 1000 secondary turns. The net cross sectional area of the core 80 cm^2 . If the primary winding be connected to 50Hz supply at 400 volt. calculate
 (i) Maximum value of flux density in the core
 (ii) the voltage in the secondary winding.

Q. $E_1 = 400V$, $N_1 = 500$, $N_2 = 1000$, $A = 80 \times 10^{-4} \text{ m}^2$

$$\begin{aligned}
 E_1 &= 4.44 f \phi_m N_1 \\
 \Rightarrow \phi_m &= E_1 / 4.44 f N_1 \Rightarrow \phi_m = 400 / 4.44 \times 50 \times 500 = 3.6 \times 10^{-3} \text{ wb} \\
 B_m &= \phi_m / A = 3.6 \times 10^{-3} / 80 \times 10^{-4} = 0.45 \\
 E_2/E_1 &= N_2/N_1 \Rightarrow E_2 = N_2/N_1 \times E_1 \Rightarrow E_2 = \frac{1000}{500} \times 400 = 800 \text{ V.}
 \end{aligned}$$

Q. The load current of a T/P is 15A. At a power factor 0.2 when supply by 460V, 50Hz frequency. If the primary winding has 550 turns then find

- (i) the magnetising current
- (ii) Iron loss
- (iii) Maximum value of flux.

Q. $I_a = 15A$, $N_1 = 550$, $\cos \phi_0 = 0.2$, $V = 460V$, $f = 50 \text{ Hz}$

$$\begin{aligned}
 I_m &= I_0 \sin \phi_0 = 15 \times \sin(1.36) = 14.66 \text{ A} \\
 \text{Iron loss } W_0 &= V I_0 \cos \phi_0 = 460 \times 15 \times 0.2 = 1380 \text{ watt} \\
 E_1 &= 4.44 f \phi_m N_1 \\
 \Rightarrow \phi_m &= E_1 / 4.44 f N_1 = 460 / 4.44 \times 50 \times 550 = 3.76 \times 10^{-3} \text{ wb}
 \end{aligned}$$

Q. A single phase T/P on no load takes 5A, at a power factor of 0.2 lagging when connected to 220V, 50Hz supply. The number of turns of the primary winding is 250 calculate

- (i) Magnetising current
- (ii) Core losses
- (iii) Max^m value of flux in the core.

(187)

$$I_0 = 5A, \cos \phi_0 = 0.2 (\text{lag}), V = 220V, f = 50 \text{ Hz}, N_1 = 250$$

$$I_M = I_0 \sin \phi_0 = I_0 (\sqrt{1 - \cos^2 \phi_0}) = 5 \sqrt{1 - 0.2^2} = 4.89 A$$

$$W_0 = VI_0 \cos \phi_0 = 220 \times 5 \times 0.2 = 220 \text{ watt}$$

$$\phi_m = E / 4.44 \times f \times N_1 = 220 / 4.44 \times 50 \times 250 = 3.96 \times 10^{-3} \text{ wb.}$$

Q. A single phase transformer has 400 primary and 1000 secondary turns. The net cross sectional area of the core is 60 cm^2 if the primary winding to be connected to a 50 Hz supply at 500 V calculate

(i) the peak value of flux density in the core.

(ii) The voltage induced in secondary winding.

$$N_1 = 400, N_2 = 1000, A = 60 \text{ cm}^2, f = 50 \text{ Hz}, V = 500 \text{ V}$$

$$E_1 = 4.44 \phi_m f N_1$$

$$\Rightarrow \phi_m = E_1 / 4.44 \times f \times N_1 = 500 / 4.44 \times 50 \times 400 = 5.63 \times 10^{-3}$$

$$E_2/E_1 = N_2/N_1 \Rightarrow E_2 = N_2/N_1 \times E_1 = 1000/400 \times 500 = 1250 \text{ V}$$

$$B_m = \phi_m / A = 5.63 \times 10^{-3} / 60 \times 10^{-4} = 0.938 \text{ wb/m}^2$$

Q. Calculate interm of primary the equivalent resistance and the leakage reactance of a $1\text{-}\phi$, 4 kVA , $200/400 \text{ V}$, 50 Hz , T/P which gave the following test results. SC test (HV side): 80 W , 15 V , 10 A .

$$I_{sc} = 10 \text{ A}, V_{sc} = 15 \text{ V}, W_{sc} = 80 \text{ W}$$

$$W_{cu} = I_{sc}^2 R_{02} \Rightarrow R_{02} = W_{cu} / I_{sc}^2 = 80 / 10^2 = 0.8 \Omega$$

$$Z_{02} = V_{sc} / I_{sc} = 15 / 10 = 1.5 \Omega$$

$$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = \sqrt{1.5^2 - 0.8^2} = 1.26 \Omega$$

$$R_{01} = R_{02} / K^2 \quad X_{01} = \frac{X_{02}}{K^2}$$

$$K = V_2/V_1 = 400/200 = 2, R_{01} = 0.8/4 = 0.2 \Omega, X_{01} = \frac{1.26}{4} = 0.315 \Omega$$

Q. A 20 kVA , $2500/250 \text{ V}$, 50 Hz , $1\text{-}\phi$, T/P has the following test results.

OC test (LV side): 250 V , 1.4 A , 105 W

SC test (HV side): 104 V , 8 A , 320 W

compute the parameters of the equivalent ckt referred to LV side and draw the ckt.

Q. OC test

$$I_0 = 1.4 \text{ A}, W_0 = 105 \text{ W}, V = 250 \text{ V.}$$

$$\cos \phi_0 = W_0 / VI_0 = 105 / 250 \times 1.4 = 0.3$$

$$I_w = W_0/V_1 = 105/250 = 0.42 \text{ A}$$

$$I_N = \sqrt{I_0^2 - I_w^2} = \sqrt{1.4^2 - 0.42^2} = 1.33 \text{ A}$$

$$R_0 = V_1/I_w = 250/0.42 = 595.23 \Omega$$

$$X_0 = V_1/I_N = 250/1.33 = 187.96 \Omega$$

SC test

$$I_{sc} = 8 \text{ A}, V_{sc} = 104 \text{ V}, W_{sc} = 320 \text{ W}$$

$$R_{01} = W_{sc}/I_{sc}^2 = 320/8^2 = 5 \Omega$$

$$Z_{01} = V_{sc}/I_{sc} = 104/8 = 13 \Omega$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{13^2 - 5^2} = 12 \Omega$$

$$R_{02} = K^2 R_{01}, X_{02} = K^2 X_{01}, Z_{02} = K^2 Z_{01}$$

$$K = V_2/V_1 = 250/2500 = 0.1$$

$$R_{02} = 0.1^2 \times 5 = 0.05 \Omega$$

$$X_{02} = 0.1^2 \times 12 = 0.12 \Omega$$

$$Z_{02} = 0.1^2 \times 13 = 0.13 \Omega$$

Q. In HV side SC test data for 20 kVA, 2300/250V, T/F one power = 250W, current = 8.7A, voltage = 50V. Calculate equivalent impedance, resistance and reactance referred to HV side

Ans $W_{sc} = 250 \text{ W}, I_{sc} = 8.7 \text{ A}, V_{sc} = 50 \text{ V}$

$$R_{01} = W_{sc}/I_{sc}^2 = 250/8.7^2 = 3.3 \Omega$$

$$Z_{01} = V_{sc}/I_{sc} = 50/8.7 = 5.74 \Omega$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{5.74^2 - 3.3^2} = 4.69 \Omega$$

Q. The instrument reading obtained from OC and SC test on 10kVA 40/120V, 50Hz T/F one

OC test (LV side): 120V, 4.2A, 80W reading on LV

SC test (HV side): 10V, 22A, 120W with LV side short circuited

Calculate ckt parameters also draw the equivalent ckt

Ans OC test $P_0 = 4.2 \text{ A}, W_0 = 80 \text{ W}, V = 120 \text{ V}$

$$I_w = W_0/V = 80/120 = 0.67 \text{ A}$$

$$I_N = \sqrt{I_0^2 - I_w^2} = \sqrt{4.2^2 - 0.67^2} = 4.14 \text{ A}$$

$$R_0 = V/I_w = 120/0.67 = 179.10 \Omega$$

$$X_0 = V/I_N = 120/4.14 = 28.98 \Omega$$

SC test $I_{sc} = 22A$, $V_{sc} = 10V$, $W_{sc} = 120W$

$$R_{01} = W_{sc} / I_{sc}^2 = 120 / 22^2 = 0.24 \Omega$$

$$X_{01} = V_{sc} / I_{sc} = 10 / 22 = 0.45 \Omega$$

$$R_{01} = \sqrt{X_{01}^2 - R_{01}^2} = \sqrt{0.45^2 - 0.24^2} = 0.38 \Omega$$

Q. A transformer has iron loss 350W and cu loss at full load 400W. Find the efficiency at 80% full load. $\cos \phi = 0.8$ and rated KVA is 150 KVA.

Q. $W_i = 350W$, $W_{cu, FL} = 400W$, η at 80% FL, $\cos \phi = 0.8$

$$P = 150 KVA = 150 \times 10^3 VA$$

$$\eta = \frac{P \times \cos \phi}{P \times \cos \phi + W_i + X^2 W_{cu}}$$

$$P = \text{rated KVA}$$

$$X = \text{fraction of load} = \text{Any load KVA} / \text{Full load KVA}$$

$$X = 0.8$$

$$\eta = \frac{150 \times 10^3 \times 0.8 \times 0.8}{150 \times 10^3 \times 0.8 \times 0.8 + 350 + 0.8^2 \times 400} = 0.9937 = 99.37\%$$

Q. Find the efficiency of a Transformer of 100KVA, 6600/240V at

(i) Full load $\cos \phi = 0.8$ (Lag)

(ii) $1/2$ load $\cos \phi = 1$ (Unity)

(iii) 75 FL $\cos \phi = 0.8$ (Lag)

also find the maximum efficiency and at which load it occurs. If $W_i = 1.5KW$, $W_{cu} = 2KW$ at F.L. Find also the corresponding primary current at maximum efficiency.

Q. $P = 100 KVA$, $V_1 = 6600V$, $V_2 = 240V$, $W_i = 1.5KW$, $W_{cu} = 2KW$

(i) $\cos \phi = 0.8$, $X = 1$

$$\eta = \frac{100 \times 1 \times 0.8}{100 \times 1 \times 0.8 + 1.5 + 2} = 0.9580 = 95.8\%$$

(ii) $\cos \phi = 1$, $X = 0.5$

$$\eta = \frac{100 \times 0.5 \times 1}{100 \times 0.5 \times 1 + 1.5 + (0.5)^2 \times 2} = 0.9615 = 96.15\%$$

(iii) $\cos \phi = 0.8$, $X = 0.75$

$$\eta = \frac{100 \times 0.75 \times 0.8}{100 \times 0.75 \times 0.8 + 1.5 + (0.75)^2 \times 2} = 0.9580 = 95.8\%$$

For max^m efficiency

$$W_i = X^2 W_{cu}$$

$$\Rightarrow X = \sqrt{W_i / W_{cu}} = \sqrt{1.5 / 2} = 0.866 = 86.6\%$$

$$\eta_{\max} = \frac{P \times \cos \phi}{P \times \cos \phi + W_i + W_{cu}} = \frac{100 \times 0.866 \times 1}{100 \times 0.866 \times 1 + 2 \times 1.5} = 0.9665 = 96.65\%$$

$$\text{Primary current max^m efficiency } I_1 = \frac{100 \times 10^3 \times 0.866}{6600} = 13.12A$$

Q. A transformer has its maximum efficiency 0.98 at 15 kVA VPF during a day it is loaded as follows

① 12 hr $\rightarrow$ 2 kW at $\cos\phi = 0.5$

② 6 hr $\rightarrow$ 12 kW at $\cos\phi = 0.8$

③ 6 hr $\rightarrow$ 18 kW at $\cos\phi = 0.9$. Find all day efficiency.

$$\eta_{\max} = 0.98 = \frac{P \times \cos\phi}{P \times \cos\phi + W_1 + (W_2 + W_3)}$$

$$\Rightarrow 0.98 = 15 \times 1 / 15 \times 1 + W_1 + W_2$$

$$\Rightarrow 15 + W_1 = 15 / 0.98$$

$$\Rightarrow 2W_1 = 15.3 - 15$$

$$\Rightarrow W_1 = 0.3 / 2 = 0.15 \text{ kW}$$

$$W_1 = 0.15 \text{ kW} = \text{Cu loss at 15 kVA i.e. F.L}$$

$$\text{Iron loss energy} = 0.15 \times 24 = 3.6 \text{ kWh}$$

$$\text{kVA} = \text{kW} / \cos\phi$$

$$= 2 / 0.5 = 4$$

$$(i) \text{ Cu loss} = x^2 W_{cu}$$

$$= (4/15)^2 \times 0.15$$

$$= 0.01 \text{ kW}$$

$$\text{Cu loss energy} = 0.01 \times 12 = 0.12 \text{ kWh}$$

$$(ii) \text{ kVA} = \text{kW} / \cos\phi = 12 / 0.8 = 15$$

$$\text{Cu loss} = (15/15)^2 \times 0.15 = 0.15 \text{ kW}$$

$$\text{Cu loss energy} = 0.15 \times 6 = 0.9 \text{ kWh}$$

$$(iii) \text{ kVA} = \text{kW} / \cos\phi = 18 / 0.9 = 20$$

$$\text{Cu loss} = x^2 W_{cu} = (20/15)^2 \times 0.15 = 0.267 \text{ kW}$$

$$\text{Cu loss energy} = 0.267 \times 6 = 1.6 \text{ kWh}$$

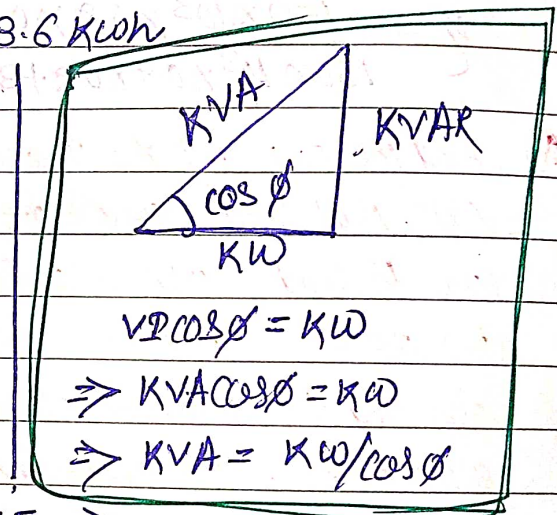
$$\text{Total Cu loss energy} = 0.12 + 0.9 + 1.6 = 2.62 \text{ kWh}$$

$$\text{Iron loss energy} = 3.6 \text{ kWh}$$

$$\eta = \frac{o/p}{g/p} = \frac{g/p}{g/p + \text{losses}}$$

$$o/p \text{ energy} = (2 \times 12 + 12 \times 6 + 18 \times 6) = 204 \text{ kWh}$$

$$\eta = 204 / 204 + (3.6 + 2.62) = 0.9704 = 97.04\%$$



Q. what is the condition of maximum efficiency of a transformer.

A. Iron loss = Full load cu loss

Q. what is the fraction of P.L KVA at which max^m efficiency occur in a T/P?

A. at max^m efficiency $w_i = x^2 w_{cu} \Rightarrow x^2 = w_i / w_{cu} \Rightarrow x = \sqrt{w_i / w_{cu}}$

Q. what is voltage regulation of a 1- ϕ T/P?

A. $\%R = \frac{V_{20} - V_2}{V_2} \times 100$ $V_{20} \Rightarrow$ Secondary terminal voltage at no load
 $V_2 \Rightarrow$ Secondary voltage at no load.

Q. what is an ideal transformer?

There is no power loss and there is no voltage drop in the transformer and efficiency is 100%. is called ideal transformer.

Q. No load loss of a T/P is same to which loss in a 1- ϕ transformer?
 no load loss of T/P is equal to iron loss.

Q. A transformer has iron loss of 200W, and cu loss of 400W at P.L if the load is halved then what will be the value of iron loss and cu loss.

$w_i = 200W$, w_{cu} at P.L = 400W, iron loss remain same

when load reduces halves $x^2 w_{cu} = (1/2)^2 \times 400 = 100W$

Q. what would happen if a power T/P design to operate at 50Hz where connected to a 500Hz source of the same voltage.

What if, $w \propto f^2$

when T/P is connected to 500Hz supply when frequency increases as well as hysteresis and eddy current loss also increases therefore iron loss increases so efficiency will be reduced.

Q. why iron loss constant at all loads in a transformer.

A. In T/P flux remains constant at any load that way iron loss constant at all loads.