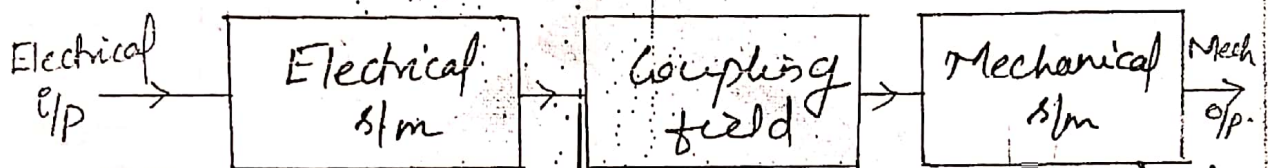


MODULE - I

ELECTROMAGNETIC PRINCIPLES FOR MACHINES

→ The conversion of electrical energy into mechanical energy or vice versa is known as electromechanical energy conversion.



→ Electromechanical energy conversion involves the interchange of energy between an electrical system and a mechanical system through the medium of a coupling electric field or a magnetic field. An electromechanical conversion system has three essential parts.

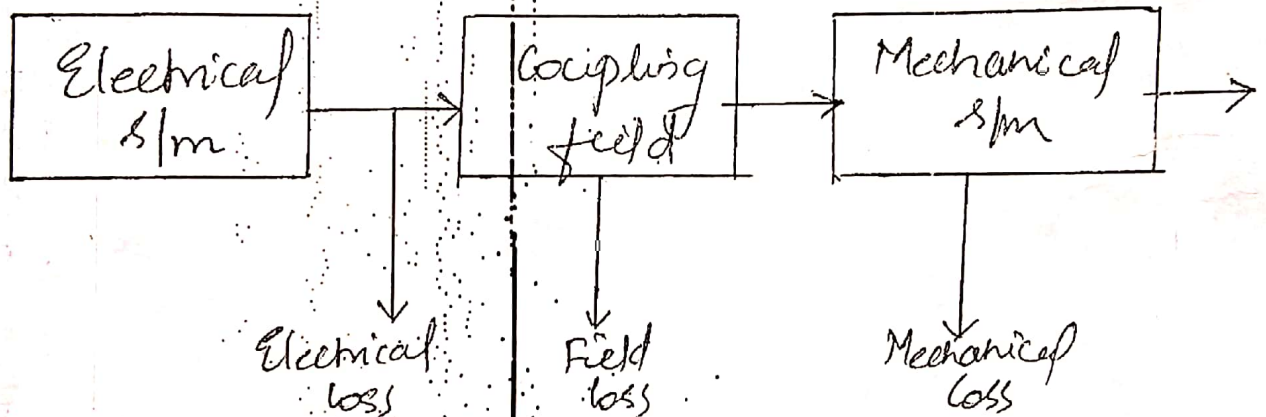
1. Electrical system.
2. Mechanical system.
3. Coupling Field.

The conversion devices are mainly divided into three :-

1. Transducers.
2. Force producing devices.
3. Continuous energy conversion devices.

Features of Electromechanical Energy Conversion

- 1). The principle of conservation of energy holds good: i.e. energy can be neither created nor be destroyed. It can only be changed from one form to another.
- 2). Various losses occur during energy conversion.



- 3). It is reversible process except for the losses in the system.
- 4). Electromechanical conversion devices are built with airgaps in the magnetic circuit to separate the fixed and moving parts.
- 5). The rotating electrical machines continuously convert electrical energy into mechanical energy or vice versa.

Energy Balance Equation

$$\left(\begin{array}{c} \text{Electrical energy} \\ \text{input from source} \end{array} \right) \Rightarrow \left(\begin{array}{c} \text{Mechanical} \\ \text{energy o/p} \end{array} \right) + \left(\begin{array}{c} \text{Increase in} \\ \text{energy stored} \\ \text{in coupling field} \end{array} \right) + \left(\begin{array}{c} \text{Energy} \\ \text{losses} \end{array} \right) \quad \text{--- (i)}$$

→ Equation ① is applicable to all conversion devices.

→ During energy conversion losses occur due to three causes:

- (i) I^2R losses in the winding
- (ii) Core or field losses due to changing magnetic field.
- (iii) Friction and windage losses due to the motion of moving parts.

→ All these losses are converted into heat. Hence Equation ①, the energy balance equation can be written as:-

$$\left\{ \begin{array}{c} \text{Electrical energy} \\ \text{i/p - resistance} \\ \text{losses} \end{array} \right\} \Rightarrow \left\{ \begin{array}{c} \text{Mechanical} \\ \text{o/p + Friction} \\ \text{and windage} \\ \text{losses} \end{array} \right\} + \left\{ \begin{array}{c} \text{Increase in} \\ \text{Stored field} \\ \text{energy +} \\ \text{core losses} \end{array} \right\} \quad \text{--- (ii)}$$

→ Let us consider a differential time dt during which an increment of electrical energy dW_{elect} (excluding i^2R losses) flows to the s/m. During this time dW_{fld} be the energy supplied to the field. and dW_{mech} the energy converted to mechanical form. the equation (ii) can be written as.

$$dW_{\text{elect}} \Rightarrow dW_{\text{mech}} + dW_{\text{fld}}$$

If no mechanical work is done

$$\text{i.e. } dW_{\text{mech}} \Rightarrow 0$$

$$dW_{\text{elect}} \Rightarrow dW_{\text{fld}}$$

i.e. In this case, the electrical energy input is stored as the magnetic field.

ELECTRO DYNAMICAL EQUATIONS

→ The electromechanical energy conversion devices operate with electrical system on one side and mechanical system on the other side. It is the behaviour of the entire electromechanical system, i.e. because a particular system may operate satisfactorily under steady state conditions but may fail miserably under the electromechanical transients.

→ Simple model of singly excited electro-mechanical systems are represented as the figures below.

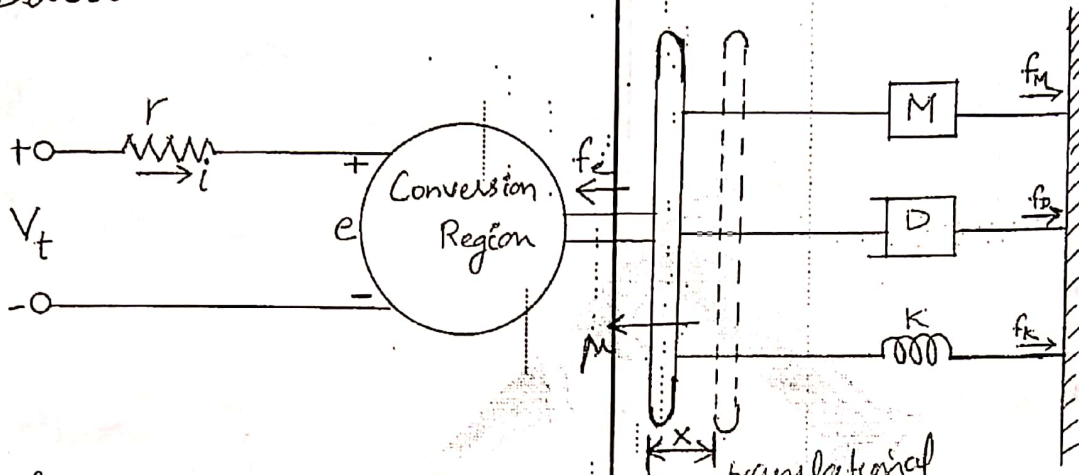


Fig (a). Model of a singly excited electromechanical s/m involving restricted linear movement.

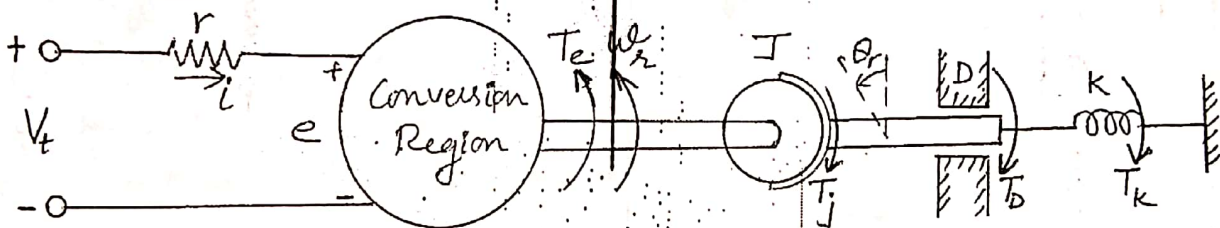


Fig (b). Model of singly excited rotational electromechanical s/m involving restricted rotary motion.

→ The fig (a) is applicable only to restricted linear movement because of the presence of a spring.

→ The fig (b) is for the restricted rotary motion only. If the spring K is replaced by a mechanical load torque, it becomes model of a rotating electrical machine with energy conversion from electrical to mechanical.

∴ The voltage equation for the electrical s/m for both cases in fig ④ & fig ⑤

$$\begin{aligned}
 V_t &\Rightarrow ir + \frac{d\psi}{dt} \Rightarrow ir + \frac{d(Li)}{dt} \\
 &\Rightarrow ir + L \frac{di}{dt} + i \left(\frac{dL}{d\theta_r} \right) \frac{d\theta_r}{dt} \\
 &\Rightarrow ir + L \frac{di}{dt} + i \frac{dL}{d\theta_r} \omega_r \quad \text{--- ①}
 \end{aligned}$$

Where

$L \frac{di}{dt} \Rightarrow$ It is known as transformer voltage.
(i because it involves the time derivative of current).

$i \left(\frac{dL}{d\theta_r} \right) \omega_r \Rightarrow$ The speed or rotational voltage.
(i because the presence of ω_r)
& this term determines the flow of energy b/w electrical & Mechanical systems.

In fig ④ the magnetic force f_e is opposed by the inertia force f_m , damping force f_D and restraining spring force f_k .

∴ The force balance equation is

$$\begin{aligned}
 f_e &\Rightarrow f_m + f_D + f_k \\
 &\Rightarrow M \frac{du}{dt} + D u + K \int u dt
 \end{aligned}$$

$$\text{i.e. } f_e \Rightarrow M \frac{d^2 x}{dt^2} + D \frac{dx}{dt} + K x \quad \text{--- ②}$$

In the ~~fig~~ (a)

Where

$M \Rightarrow$ Mass is Kgs.

$D \Rightarrow$ Coefficient of friction or damping constant is N/m/sec.

$K \Rightarrow$ Linear spring constant is newton/metre displacement.

$u = \frac{dx}{dt}$, linear velocity is metre/sec.

In the ~~fig~~ (b)

The magnetic torque T_e is opposed by torque T_f , damping torque T_D and restraining spring torque T_k . Therefore the torque balance equation is

$$T_e \Rightarrow T_f + T_D + T_k$$

$$\Rightarrow J \frac{d\omega_r}{dt} + D\omega_r + K \int \omega_r dt$$

$$T_e \Rightarrow J \frac{d^2\theta_r}{dt^2} + D \frac{d\theta_r}{dt} + K\theta_r \quad \text{--- (iii)}$$

In the equation (3)

Where

$J \Rightarrow$ Moment of inertia is kg m^2 .

$D \Rightarrow$ damping constant is N-m per rad/sec.

$K \Rightarrow$ rotary spring constant is N-m/radian.

$\omega_r \Rightarrow \frac{d\theta_r}{dt}$, angular velocity is rad/sec.

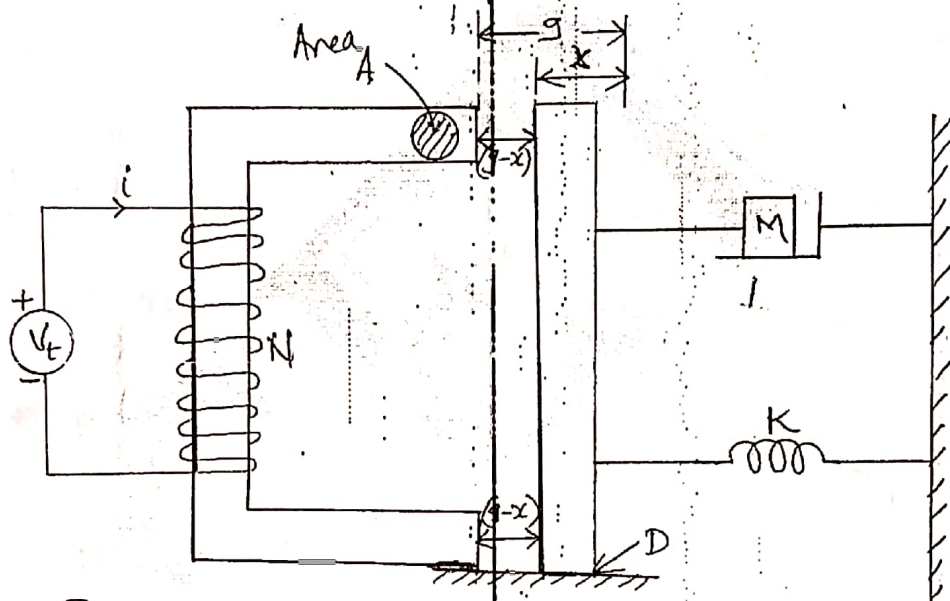
dynamic eq $\Rightarrow T_e \Rightarrow J \frac{d^2\theta_r}{dt^2} + D \frac{d\theta_r}{dt} + T_L$ --- (iii)

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$T_L \Rightarrow$ load torque opposing the mag. torque T_e .

→ The magnetic force f_c or torque T_c can be calculated from the partial derivative of W_{fld} as played before.

→ Thus both the equations describe the total behaviour of a linear electromechanical s/m and both equations ② & ③ that of a rotary electromechanical system.



By considering the above figure we can formulate the dynamic equation for the s/m

Reluctance of the airgap is series

$$R_l \Rightarrow \frac{2(g-x)}{\mu_0 A}$$

Let us assume the iron to have infinite permeability, self inductance of the

$$\text{s/m} \quad L(x) \Rightarrow \frac{N^2}{R_l} = \frac{N^2 \cdot \mu_0 A}{2(g-x)}$$

Hence f_c is given as

$$f_c \Rightarrow \frac{1}{2} i^2 \frac{dL(x)}{dx}$$

(Sub is $L(x)$ is the equation from above)

$$\Rightarrow \frac{1}{2} i^2 \frac{N^2 \mu_0 A}{2(g-x)^2}$$

$$f_c \Rightarrow \frac{i^2 N^2 \mu_0 A}{4(g-x)^2}$$

$\therefore$ the equation (1) & (2) can be the two differential equations governing the s/m dynamic performance are as :-

$$\text{eq. (1)} \Rightarrow U_t \Rightarrow i \ddot{x} + \frac{N^2 \mu_0 A}{2(g-x)} \times \frac{di}{dt} + i \frac{N^2 \mu_0 A}{2(g-x)^2} \times \frac{dx}{dt} \rightarrow (3)$$

$$\text{eq. (2)} \Rightarrow f_c = \frac{i^2 N^2 \mu_0 A}{4(g-x)^2}$$

$$\Rightarrow M \frac{d^2 x}{dt^2} + D \frac{dx}{dt} + K \cdot x \rightarrow (4)$$

Hence equations (3) & (4) the non-linear differential equations which can be solved numerically on a digital computer & can be linearised for small movements about the equilibrium or operating point & then can be solved for dynamic or steady-state condition.

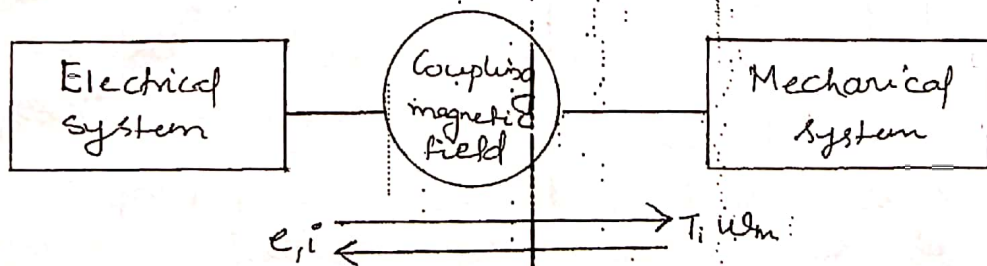
ROTATION MOTION SYSTEM

→ Rotating motion s/m or rotating electrical machines continuously convert electrical energy into mechanical energy or vice versa.

→ This interchange of energy between an electrical s/m and a mechanical system takes place through the medium of coupling magnetic field.

→ When the conversion takes place from electrical to mechanical, the m/c is called motor.

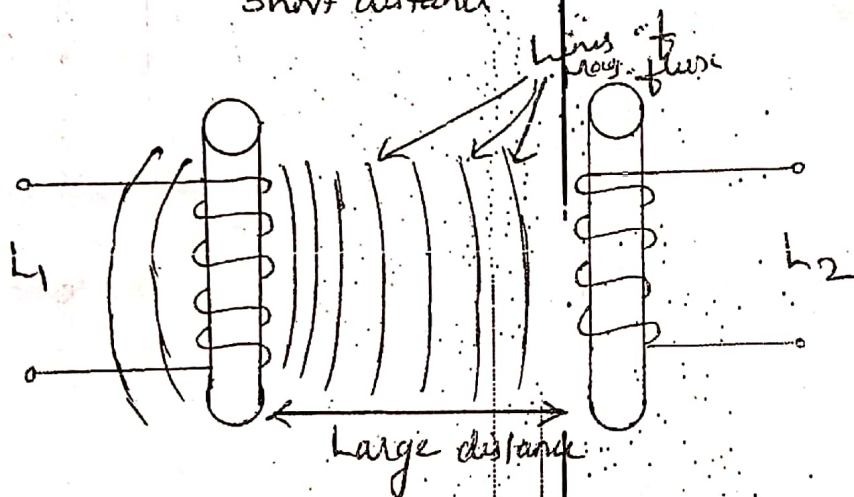
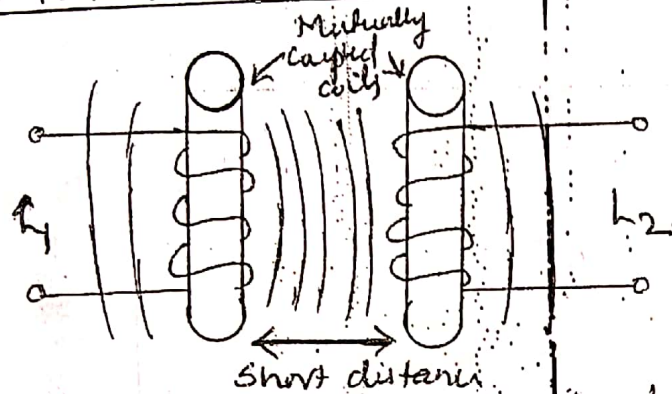
→ When the conversion takes place from mechanical to electrical, the m/c is called generator.



The figure above shows the block diagram of electromechanical energy conversion is a rotating electrical machine. The primary quantities involved in the mechanical system are torque (T) and

angular speed (ω_m) while the analogous quantities in the electrical sm are voltage (e) and current (i) respectively.

MUTUALLY COUPLED COILS



- When the emf is induced in the same circuit in which the current is changing this effect is called self inductance (L). i.e. if emf induced in the adjacent coil is called Mutual inductance (M).
- Then when two or more coils are magnetically linked together by a common magnetic flux they are said to have the property of the Mutual inductance.

→ The amount of mutual inductance that links one coil to another depends very much on the relative positioning of two coils.

→ If the physical distance b/w two coils is less relatively large emf. & therefore producing a large mutual inductance value.

→ If the physical distance b/w two coils are large. the mutual inductance value is small.

→ The mutual inductance that exists b/w the two coils can be greatly increased by positioning them on a common soft iron core using coupling or by increasing the number of turns of either coil as would be found in a transformer.

$$M = \frac{\mu_0 \mu_r N_1 N_2 A}{l}$$

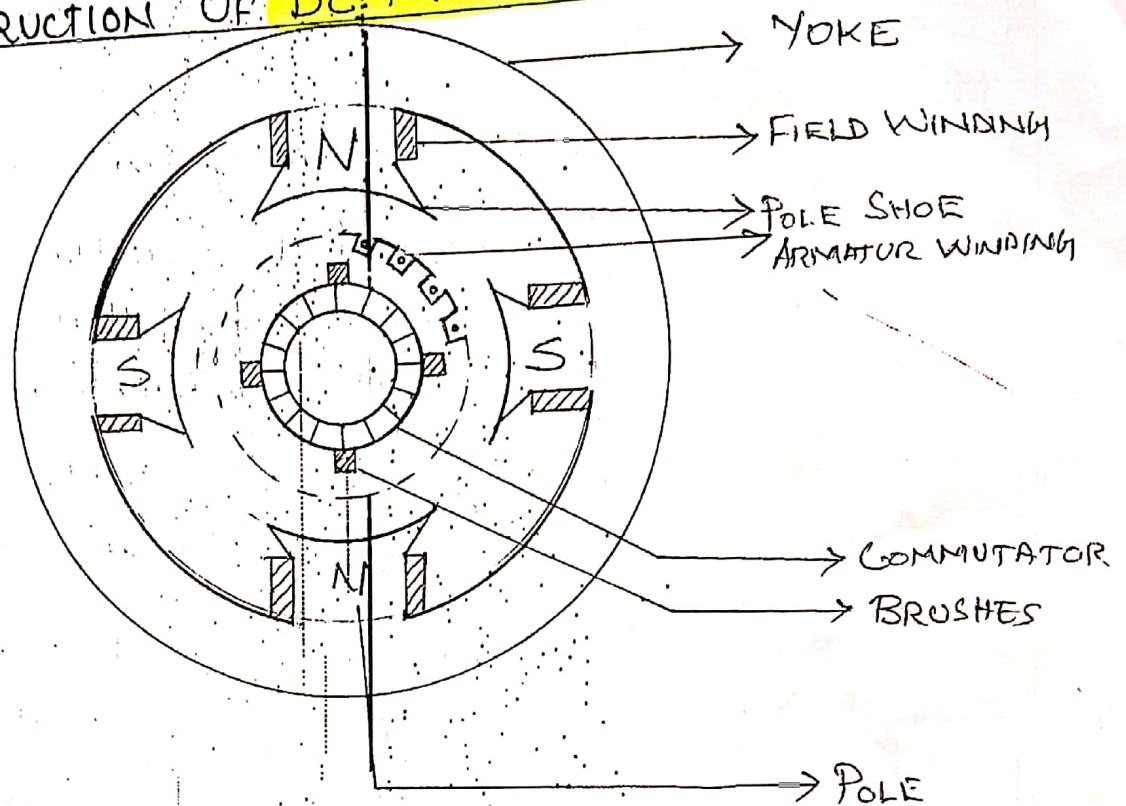
Where μ_0 = Permeability

N = Number of coil turns.

A = Cores sectional area.

l = length in metre.

CONSTRUCTION OF DC MACHINES



The dc machines mainly consist of two parts.

- Rotor** (Rotating part) (**Armature**)
- Stator** (Stationary part). (**Field S/m**)

1) **ARMATURE**

→ **Rotating part** of a DC Machine.

→ **Cylindrical** or **Drum shape**.

It mainly consist of

- armature core**.
- armature winding**.

Armature Core :-

- Keyed to machine shaft.
- Rotates b/w field poles.
- cylindrical core with slots on its outer surface.
- core is laminated to reduce eddy current loss.
- laminations are insulated from each other so that there is no electrical contact with each other.
- * Permits rotation for generator action.
- * houses conductors.
- * Provide low reluctance path for mag. flux.

Armature Winding

- Insulated conductors are placed on the slots of armature core.
- Emf are induced in these conductors.
- Conductors are connected in series parallel known as armature winding.
- armature winding is closed circuit winding.

2) Field System :-

⇒ Create a uniform magnetic field within which the armature rotates.

⇒ Electromagnets are preferred than P.Magnets.

→ Because of greater mag. effect.

→ Field strength regulation by controlling Mag. current.

Field system consists of

- (i) Yoke or Frame
- (ii) Pole Core
- (iii) Pole shoes
- (iv) Magnetizing coils

(i) Yoke / Frame :-

- * Cylindrical yoke is used.
- * Made up of solid cast steel or rolled steel.
- * Carries magnetic flux produced by pole.
- * Supports pole cores & protecting cover to m/c.

(ii) Pole Cores :-

- * Even no. of pole cores are bolted to yoke.
- * Made of cast steel laminations.
- * It has one or more field coils to carry exciting or field current to produce magnetic field.
- * Laminated pole shoes are attached.

(iii) Pole shoe / Pole Faces :-

- * Each pole core has pole shoe.
- * It supports field coils.
- * Spreads out the flux over the armature periphery more uniformly.
- * Because of large cross section reduce the reluctance of mag. path.

(iv) Magnetising Coil :-

- * Placed over pole core.
- * produces magnetic field.
- * Field coils are in series with one another.
 - So when current flows through it, alternating N & S poles are produced in the direction of rotation.
- * Magnetic flux passes through pole pieces, air gap armature and frames.

3. COMMUTATOR

- Mechanical rectifier which converts AC in armature winding to DC across brushes.
- Made of copper segments insulated from each other by mica sheets.
- It is pressed on armature shaft.
- Care should be taken in building the commutator because any eccentricity will cause the brushes or them to bang, causing sparking.

4. BRUSHES

- Brushes ensure electrical connections between rotating commutator and stationary external load circuit.

- Made of carbon (to improve conductivity we add a small amt. of copper).
- Multipole m/c have many brushes ($p=4$, brushes=4).
- Successive brushes have +ve & -ve polarity.
- Brushes having same polarity are connected together. So 2 terminals +ve & -ve are obtained.
- Pressure exerted by brushes on commutator are adjusted by spring.

5. BEARING.

- In small machines, ball bearings are used at both ends.
- In large machines, roller bearings are used at driving end and ball bearings are used at commutator end.

6. SHAFT.

- Made of mild steel with maximum breaking strength.
- Used to transfer mechanical power from or to the machine.
- Rotating parts such as armature, commutator, cooling fans etc. are keyed to shaft.

EDDY CURRENTS AND EDDY CURRENT LOSSES.

→ When there is a change in magnetic flux or field voltage induced in armature conductors and armature core. This voltage produces a circulating current in the armature core. These are called eddy currents.

→ The power loss occurs due to these circulating current is called eddy current loss. The eddy current loss appears as heat which raises the temperature of the machine and lowers its efficiency.

→ If a continuous solid iron core is used then resistance to eddy current path will be small due to large cross-sectional area of the core. Hence eddy current & eddy current losses will be large.

→ The magnitude of eddy current can be reduced by making core resistance as high. The core resistance can be greatly increased by constructing the core of thin round iron sheets called laminations. The laminations are insulated

from each other with a coating of varnish. The insulating coating has high resistance, so very little current flows from one lamination to the other. Hence reduces the eddy current losses.

$$P_e = k_e B_{\max}^2 f^2 t^2 V \text{ Watts.}$$

where

$k_e \Rightarrow$ Constant

$B_{\max} \Rightarrow$ Maximum flux density. wb/m^2 .

$f \Rightarrow$ frequency of Magnetic reversal in Hz .

$t \Rightarrow$ Thickness of lamination is m .

$V \Rightarrow$ Volume of core is m^3 .

Here all other parameters are constants and only thickness is variable.

$$P_e \propto t^2$$

$\rightarrow$ Hence eddy current depends on the lamination thickness. So kept the lamination thickness as small as possible.

ARMATURE WINDINGS

→ Armature winding is an arrangement of the conductors to develop desired emf by relative motion in a heteropolar magnetic field. The slots of the armature core hold insulated conductors that are connected in suitable manner.

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

→ Induced emf's in the winding is given by

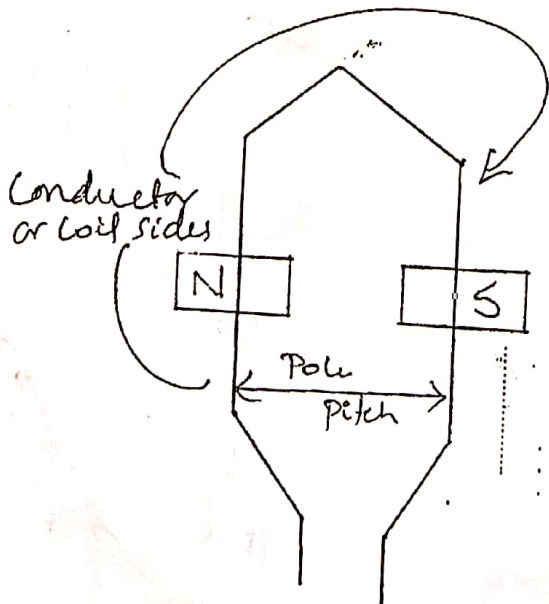
$$e \Rightarrow Blv \text{ Volts}$$

Where

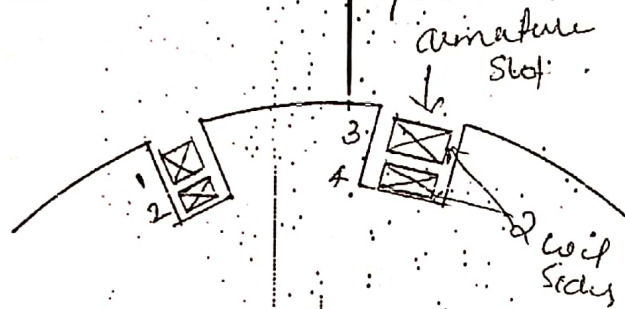
$B \Rightarrow$ Magnetic flux density in Wb/m^2 .

$l \Rightarrow$ Length of the conductor in metres.

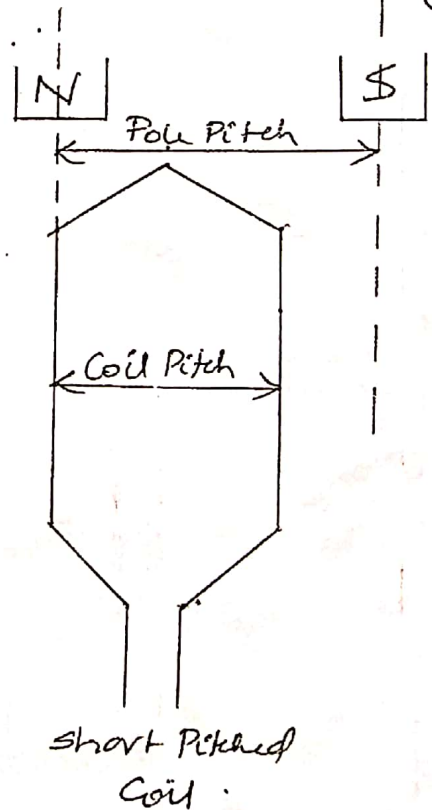
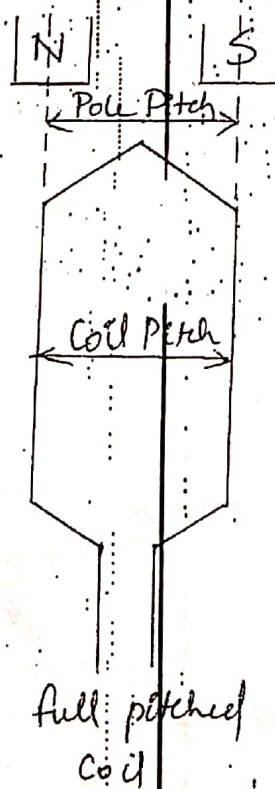
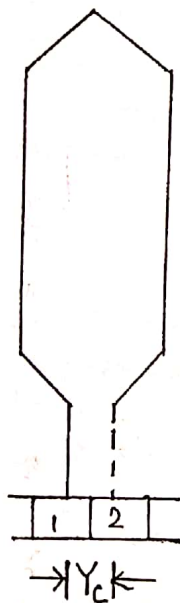
$v \Rightarrow$ Velocity (in m/s) of the conductor.



- Armature conductors are connected to form coils. There are single-turn coils & multi-turn coils.
- The coil sides of a coil are placed a pole span apart.
 - i.e. One coil side is under North pole and the other coil side under south-pole.
- DC armature windings are double layer windings.
 - i.e. 2 conductors/slot.



COMMUTATOR PITCH (Y_c), POLE PITCH, COIL SPAN or COIL PITCH (Y_s)



COMMUTATOR PITCH (Y_c)

→ It is the number of commutator segments spanned by each coil of the winding. It is denoted by (Y_c).

POLE PITCH

→ It is the distance measured in terms of number of armature slots per pole.

eg:- If a 4-pole generator has 16 coils, the number of slots is 16.

$$\text{Pole Pitch} = \frac{16}{4} = 4 \text{ slots.}$$

COIL SPAN or COIL PITCH (Y_s)

→ It is the distance measured in terms of the number of armature slots spanned by a coil.

FULL PITCHED COIL

If the coil span = Pole Pitch
It is called full pitched coil.

SHORT PITCHED COIL

If the coil span or coil pitch is less than the pole pitch, it is called short-pitched coil.

BACK PITCH (Y_B)

It is the distance measured in terms of armature conductors between the two sides of a coil at the back of the armature.

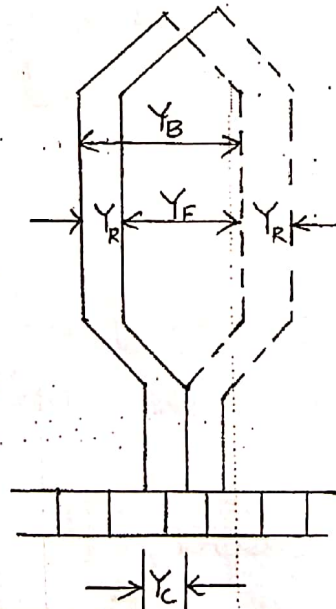
It is denoted by (Y_B).

FRONT PITCH (Y_F)

It is the distance measured in terms of armature conductors between the coil sides attached to any one commutator segment.

RESULTANT PITCH (Y_R)

It is the distance between the beginning of one coil and the beginning of the next coil.



GENERAL RULES FOR DC ARMATURE WINDINGS

- (i) The back pitch (Y_B) as well as front pitch (Y_F) should be nearly equal to pole pitch.
- (ii) Y_B & Y_F should be odd.
- (iii) The number of commutator segments is equal to the number of slots or coils.
- (iv) The windings must close upon itself.
i) should be closed circuit winding.

TYPES OF ARMATURE WINDINGS

→ Mainly two types

- a) Open coil winding
- b) Closed coil winding.

→ Open coil winding is that which does not close on itself. It is used in ac machines.

→ Closed coil winding is that winding which closes on itself. It is used for DC machines.

→ Two Types:

- a) Lap winding
- b) Drum winding.

DRUM WINDING

Two Types

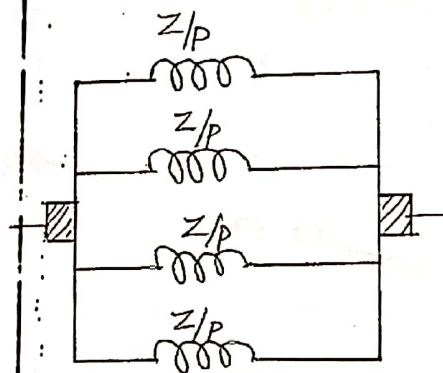
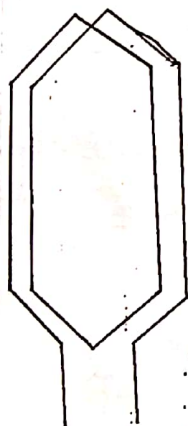
↓
Lap Winding ↓
Wave Winding.

LAP WINDING

→ First hand end of one coil is connected to a commutator segment and to the start end of the adjacent coil situated under the same pole and similarly all coils are connected. This winding is known as lap winding.

→ The sides of the successive coils overlap each other.

→ Lap winding may be classified as simplex and multiplex.



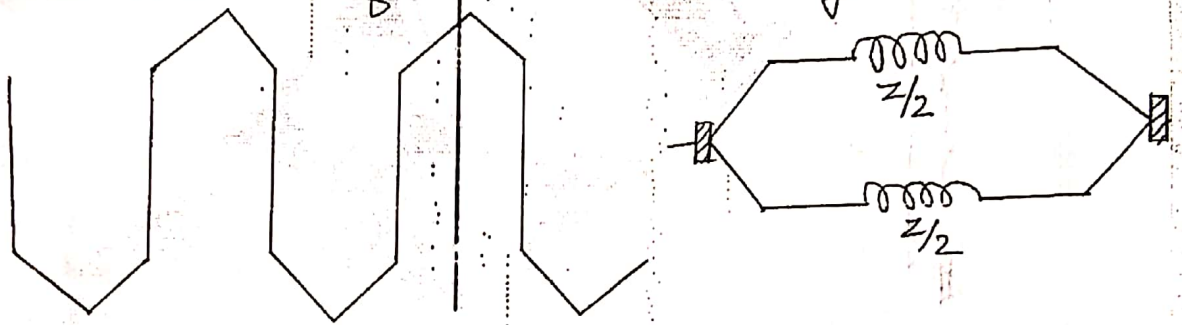
→ A winding in which the number of parallel paths b/w the brushes is equal to the number of poles is called simplex lap winding.

→ A winding in which the number of parallel path b/w the brushes is twice the number of poles is called duplex (multiplex) lap winding.

WAVE WINDING

→ Sometimes known as series windings.

→ End of one coil is connected to the starting of another coil of the same polarity.



→ Number of parallel path equal to 2.

Q₁. Design a 4-pole, duplex lap winding suitable for an armature containing 20 slots. Assume single-turn coil with 2 conductors per slot.

Number of commutator segments $\Rightarrow$ No. of slots $\Rightarrow 20$

Number of armature coil $\Rightarrow$ No. of slots $\Rightarrow 20$

No. of armature conductors $\Rightarrow 2 \times 20 = 40$

$$\text{Pole pitch} = \frac{Z}{P} = \frac{40}{4} = 10 \text{ conductors.}$$

For progressive lap winding

Back Pitch $Y_B \Rightarrow \frac{Z}{p} + 1 = 10 + 1 \Rightarrow 11$ conductors.

Front Pitch $Y_F \Rightarrow \frac{Z}{p} - 1 = 10 - 1 \Rightarrow 9$ conductors.

Winding Table.

Back Connection

1 to $(1+11) \Rightarrow 12$

3 to $(3+11) \Rightarrow 14$

5 to $(5+11) \Rightarrow 16$

7 to $(7+11) \Rightarrow 18$

Front Connection

$\rightarrow 12$ to $(12-9) \Rightarrow 3$

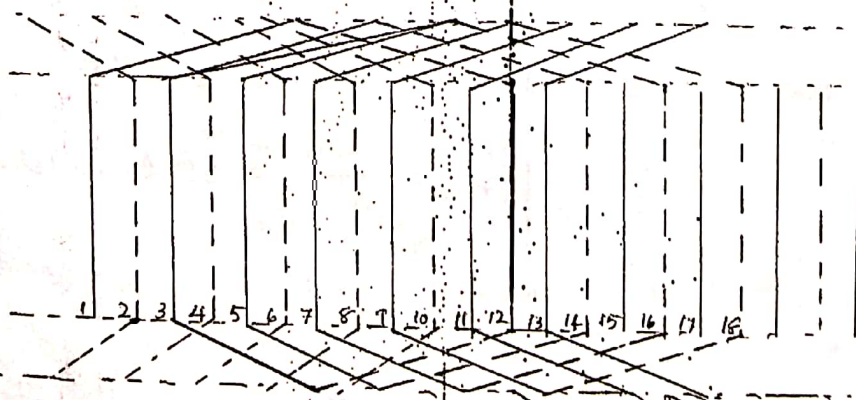
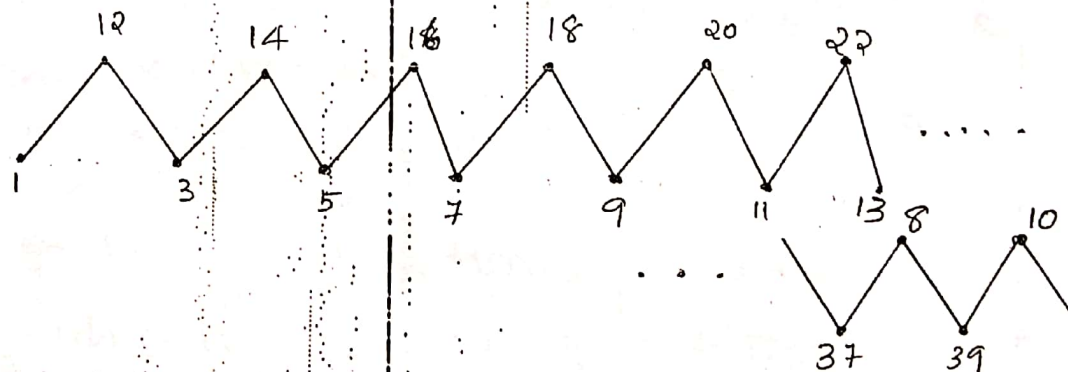
$\rightarrow 14$ to $(14-9) \Rightarrow 5$

$\rightarrow 16$ to $(16-9) \Rightarrow 7$

$\rightarrow 18$ to $(18-9) \Rightarrow 9$

39 to $(39+11) = 50$

upto 40 $(50-40) \Rightarrow 10 \rightarrow 10$ to $(10-9) = 1$



Developed winding

COMPARISON BETWEEN SIMPLEX LAP AND WAVE WINDING

Sr. No.		Simplex Lap Winding	Simplex-Wave Winding
1)	EMF	ϕ, Z, n does not depend on the number of poles.	$\frac{\phi Z n P}{2}$, depends up on the number of poles.
2)	Average coil span	$\frac{2C}{P}$ coil sides. where C = Number of coils	$\frac{2C}{P}$ coil-sides.
3)	Back Pitch (Y_B)	$\frac{2C}{P} + 1$, odd	$(Y_w - Y_F)$ odd
4)	Front Pitch (Y_F)	$Y_B \pm 2$, odd (+ for retrogressive windg & - for progressive windg.)	$(Y_w - Y_B)$ is odd
5)	Commutator Pitch (Y_c)	± 1	$\frac{C \pm 1}{P/2}$
6)	Winding Pitch (Y_w)	± 2	$\frac{2C \pm 2}{P/2} = Y_B + Y_F$
7)	Number of Parallel path (a)	P	2
8)	Number of brushes	P	2
9)	Dummy coils	Not needed	May be required
10)	Equalizer rings	May be required	Not required.
11)	Conductor current	$I_c = \frac{I_a}{A}$	$I_c = \frac{I_a}{2}$
12)	Applications	Low Voltage high current machines	High Voltage low power m/c.

EQUALIZER RINGS

→ For a lap winding, the circulating currents will exist if the emfs are generated in the various parallel paths (equal to the number of poles) are not equal.

→ The existence of circulating currents in lap-connected machines may be due to any one or all of the following reasons:-

(i) ⇒ The air gap under different poles may not be the same, due to wear of the bearings or faulty assembly. As a result, some poles carry more flux than that of other pole and different emfs are generated in the various parallel paths.

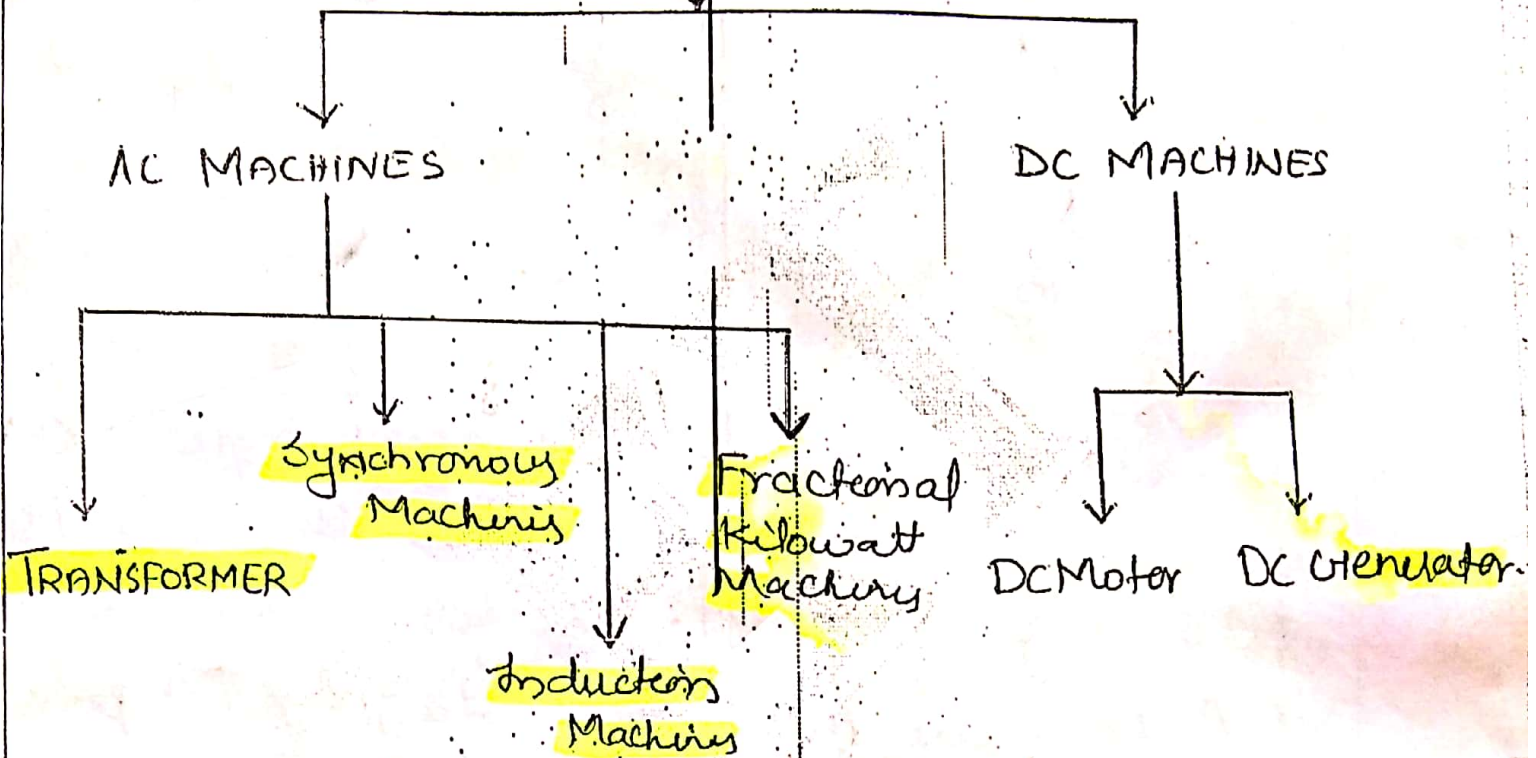
(ii) ⇒ The joints b/w poles cores and yokes or b/w pole cores and pole faces may not be identical for all the poles. This results in different reluctances for the various magnetic circuits.

(iii) ⇒ The different reluctances for each magnetic path may also be due to the irregularities or imperfections in the materials constituting the magnetic circuit.

⇒ All these above reasons will produce sparking at brushes. To relieve the brushes of same potential are connected together by means of copper bars are called equalizer rings.

MODULE-II

ELECTRICAL MACHINES



DC GENERATOR

→ DC machine is actually an alternating current machine, but furnished with a special device called commutator, which under certain condition convert ac into dc and vice versa.

→ Electric generators are machine that converts mechanical energy into electrical energy

→ They are worked on the principle of electromagnetic induction

GENERATOR PRINCIPLE

→ Whenever flux is cut by a conductor, an emf is induced which will cause a current to flow if the conductor circuit is closed. The direction of induced emf and hence current is given by Fleming's Right Hand Rule.

** Fleming's Right Hand Rule :- Stretch the thumb, fore-finger and middle finger of your right hand so that they are at right angle to each other. If the fore finger points the direction of field, thumb is the direction of motion of the conductor, then the middle finger will point in the direction of induced emf.

The essential components of a generator are :-

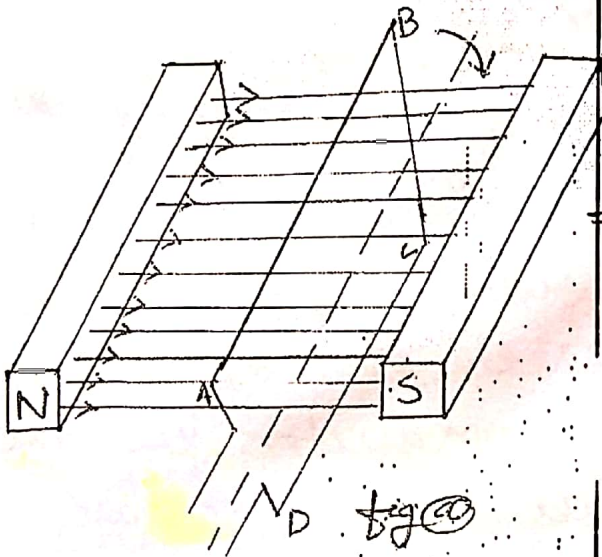
- * Magnetic Field.
- * Conductor or group of conductors.
- * Motion of conductor w.r. to field.

SIMPLE LOOP GENERATOR

→ Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed.

→ As the loop rotates, the flux linking the coil sides AB and CD changes continuously. Hence an emf is induced in it.

→ The magnitude of emf induced at any instant is proportional to the rate of change of flux linking at that instant and its direction is given by Fleming's right hand rule.



→ While rotating the loop ABCD assumes the position as in fig @ is parallel to field ~~current~~ magnets.

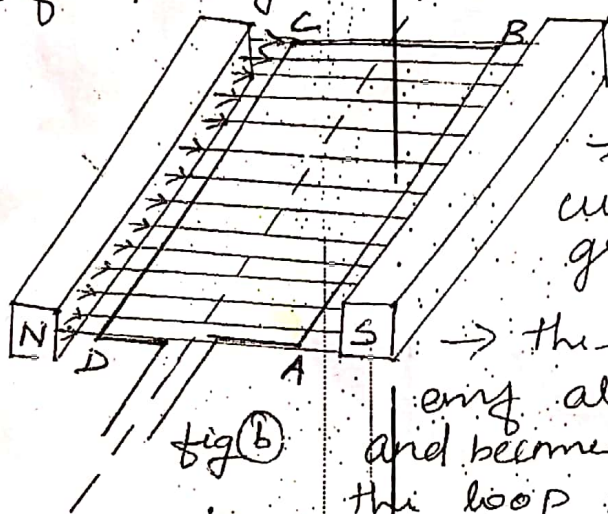
⇒ The flux linking with the loop is maximum, but rate of change of flux linking is zero, as no flux is cut by conductors

AB and CD which are just moving parallel to them.

Hence the induced emf is zero.

→ This position of the loop is called neutral position and is considered as the starting position.

→ As the coil is turned in the clockwise direction at a constant speed, the conductors begin to cut across the field at gradually increasing rate. Thus the magnitude of induced emf also increases gradually and becomes the maximum when the conductors are at right angle to the field magnets.

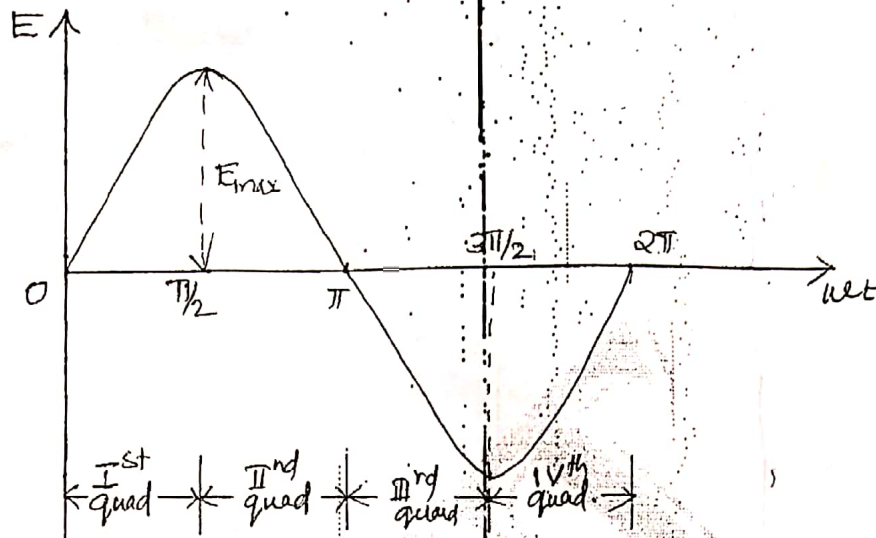


In the next quarter of revolution
→ the rate at which conductors cut across the field gradually decreases.

→ the magnitude of induced emf also decreases gradually and becomes zero at the instant the loop becomes again parallel to field magnets.

→ In the third quarter of revolution, the rate at which the conductors cut the field and hence the induced emf increases gradually and becomes maximum when the loop is at right angles to the field magnets. But the direction of induced emf is opposite.

→ In the fourth quarter of revolution, the induced emf decreases and becomes zero when it completes 360° from the starting instant.



→ The emf thus generated is the ~~single~~ loop is as in the figure above. The emf induced is of pulsating in nature. Such emf is known as the alternating emf.

If the loop the load is connected at the ends of the loop, then alternating current will flow through the load.

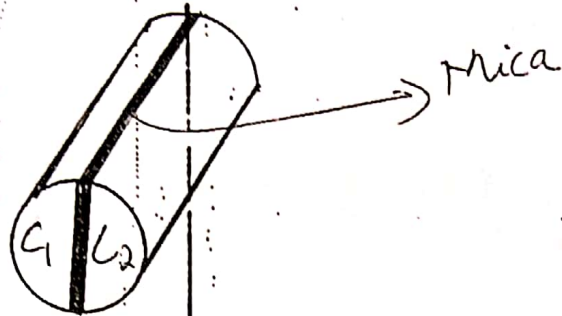
To obtain unidirectional current or DC in the external circuit, we use commutator.

COMMUTATOR

→ It has 2 segments C_1 and C_2

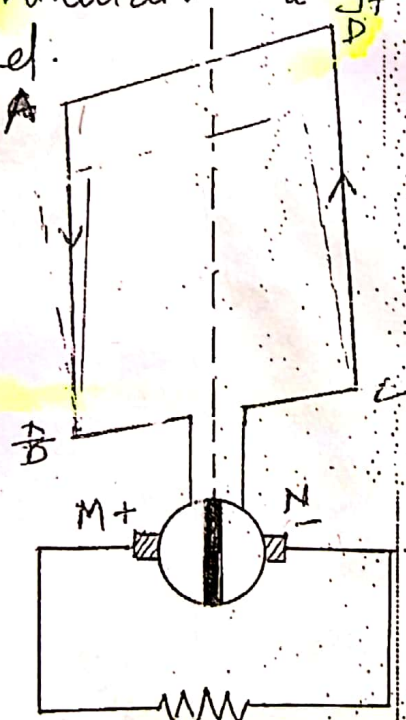
→ It has a cylindrical metal ring cut into two halves or segments C_1 and C_2 separated by a thin sheet of mica.

→ Commutator is mounted on but insulated from rotor shaft.



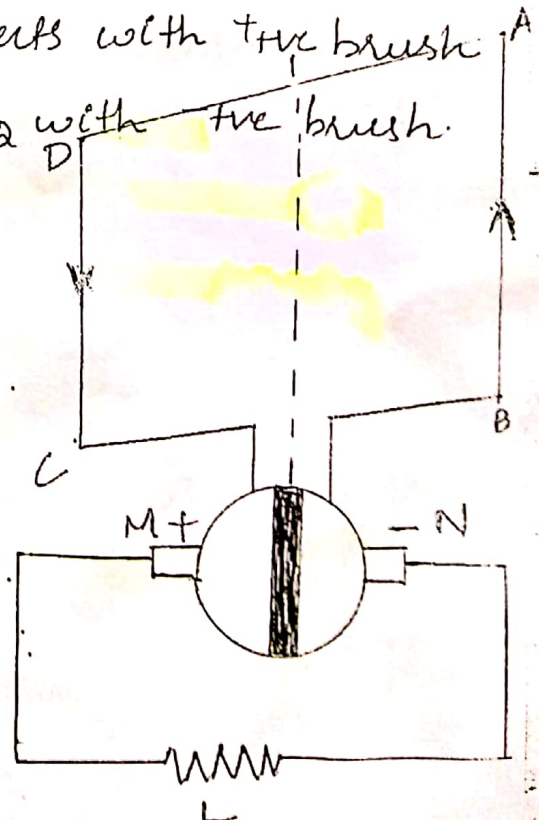
→ Cold sides AB and CD are connected to the segments C_1 and C_2 respectively.

→ Two stationary carbon brushes rest on the commutator. A leads current to the external load.



In the first half revolution current flows through the ABMLNCDA.

C_1 connects with the brush and C_2 with the brush.



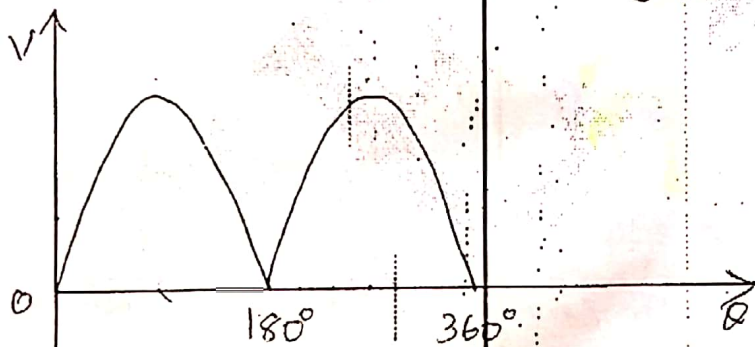
In the next half revolution the direction of induced currents of the coil is reversed.

The commutator segments C_1 and C_2 also moved through 180° .

if C_1 connects with -ve brush & C_2 with +ve brush.
Thus the direction of current in the external load circuit is in same direction.

→ The emf or current induced in the armature of dc generator is alternating and is rectified by split rings or commutator.

→ Brushes is to lead current from rotating loop to the external stationary load.



→ The voltage appearing across the brushes varies from zero to maximum value and back to zero twice for each revolution of the loop. So o/p is not steady it has pulsating characteristics.

→ Pulsating current is not suitable for most of the commercial application. So by employing a large number of coils and commutator segments with the coils evenly distributed around the surface of the armature, the brush voltage may be made practically constant.

EMF EQUATION OF DC GENERATOR

Let

$\phi \Rightarrow$ Flux/pole in wb.

$Z \Rightarrow$ Total no. of armature conductors.

$P \Rightarrow$ Number of poles.

$N \Rightarrow$ Speed of armature in rpm.

$A \Rightarrow$ Number of parallel paths.

$A \Rightarrow 2$ for wave winding

$A \Rightarrow P$ for Lap winding

Let Flux cut by one conductor in one revolution of the armature.

$$d\phi = P\phi$$

Time taken to complete one revolution

$$dt \Rightarrow \frac{60}{N} \text{ sec.}$$

EMF generated per conductor

$$E_g \Rightarrow \frac{d\phi}{dt} \Rightarrow \frac{P\phi N}{60} \text{ Volts.}$$

Total EMF generated $\Rightarrow$ EMF per parallel path

$\Rightarrow (\text{EMF/conductor}) \times \text{No. of conductors in series per parallel path.}$

$$E_g \Rightarrow \frac{P\phi N}{60} \times \frac{Z}{A}$$
$$\Rightarrow \frac{P\phi N Z}{60 A} \text{ Volts}$$

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

Notes :-

(i) When the DC machine operates as motor, the induced emf in armature is called counter emf or back emf (E_b)

$$E_b \Rightarrow \frac{\phi Z N P}{60 A} \text{ Volts}$$

(ii) In DC machine, P, Z, ϕ, A are constant.

$$\text{So } \underline{E_g/E_b \propto \phi N}$$

Q1. A 4 pole wave wound armature has 720 conductors and is rotated at 1000 rev/min. If the useful flux is 20 mwb. Calculate the generated emf.

$$P=4, A=2, Z=720, N=1000 \text{ rpm}$$

$$\phi = 20 \times 10^{-3} \text{ wb}$$

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

$$\Rightarrow \frac{20 \times 10^{-3} \times 720 \times 1000}{60} \times \frac{4}{2}$$

$$\Rightarrow \underline{\underline{480 \text{ V}}}$$

Q₂. A dc generator has an armature emf of 100 V when the useful flux per pole is 20 mWb and the speed is 800 rpm. Calculate the generated emf.

(a) with same flux and a speed of 1000 rpm.

(b) with a flux per pole of 24 mWb & N of 900 rpm.

$$E_1 = 100 \text{ V}, \phi = 20 \times 10^{-3} \text{ Wb}, N = 800 \text{ rpm}$$

$$E_1 \Rightarrow \frac{\phi Z N}{60} \times \frac{P}{A} = \left(\frac{PZ}{60A} \right) \times \phi N = K \phi N$$

$$100 \Rightarrow \frac{P \times 20 \times 10^{-3} \times Z \times 800}{60A} \Rightarrow K \phi_1 N_1$$

$$E_2 \Rightarrow \frac{P \times 20 \times 10^{-3} \times Z \times 100}{60A} \Rightarrow K \phi_2 N_2$$

$$(i) \frac{E_1}{E_2} = \frac{100}{E_2} = \frac{\phi_1 N_1}{\phi_2 N_2} = \frac{800}{1000}$$

$$\therefore \frac{100}{E_2} = \frac{800}{1000}$$

$$E_2 \Rightarrow \frac{100 \times 1000}{800}$$

$$\Rightarrow 125 \text{ V}$$

$$(ii) \frac{E_1}{E_2} = \frac{100}{E_3} = \frac{20 \times 10^{-3} \times 800}{24 \times 10^{-3} \times 900}$$

$$\Rightarrow \frac{100}{E_3} = \frac{20 \times 8}{24 \times 9}$$

$$E_3 = \frac{24 \times 9 \times 100}{20 \times 8} \Rightarrow 135 \text{ V}$$

Q₃. An 8 pole generator has 500 armature conductors and has a useful flux per pole of 0.065 Wb. What will be the emf generated if it is lap connected and runs at 1000 rpm. What must be the speed at which it is to be driven to produce the same emf if it is wave wound.

$$P = 8, Z = 500, \phi = 0.065 \text{ Wb}$$

$$A = P = 8 \quad N = 1000 \text{ rpm}$$

$$E = \frac{\phi Z N P}{60 A} \Rightarrow \frac{8 \times 0.065 \times 500 \times 1000}{60 \times 8}$$

$$\Rightarrow \underline{\underline{541.67 \text{ V}}}$$

$$E = 541.67 \Rightarrow \frac{8 \times 0.065 \times 500 \times N}{60 \times 2}$$

$$N = \frac{541.67 \times 120}{8 \times 0.065 \times 500}$$

$$\Rightarrow \underline{\underline{250 \text{ rpm}}}$$

Q₄. The armature of a 6 pole, 600 rpm. lap wound generator has 90 slots. If each coil has 4 turns. Calculate ϕ /pole req to generate an emf of 288 V?

Let $P = 6$, $N = 600 \text{ rpm}$, $A = 6$, $E = 288$

1 turn = 2 conductor

$Z = 90 \times 4 \times 2 \Rightarrow 720$

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

$288 \Rightarrow \frac{6 \times \phi \times 720 \times 600}{60 \times 6}$

$\phi = \frac{288 \times 60 \times 6}{6 \times 720 \times 600} \Rightarrow \underline{\underline{0.04 \text{ Wb}}}$

Q5. A 4 pole dc generator has 1200 arm. conductors and generates 250V on OC. when running at a speed of 500 rpm. The diameter of the pole shoe circle is 0.35m. & ratio of pole arc to pole pitch is 0.7. While the length of the shoe is 0.2m. Find the mean flux density in the air gap. Assume lap connected armature winding.

$P = 4$, $E_g = 250 \text{ V}$, $Z = 1200$, $N = 500$, $D = 0.35$

$\frac{\text{Pole arc}}{\text{Pole Pitch}} \Rightarrow 0.7$ ($\phi = B \times A$)

Pole Pitch $\Rightarrow$ distance b/w 2 adj poles.

$\Rightarrow$ armature periphery

no. of poles.

$\Rightarrow \frac{\pi \times 0.35}{4} \text{ m} \Rightarrow \underline{\underline{0.2748}}$

$$\text{Pole arc} \Rightarrow 0.7 \times \text{Pole pitch}$$

$$\Rightarrow 0.19242$$

$$\text{Area of pole face} \Rightarrow \text{Pole arc} \times \text{length}$$

$$\Rightarrow 0.19242 \times 0.2$$

$$\Rightarrow 0.03848 \text{ m}^2$$

$$E = \frac{\phi ZNP}{60A}$$

$$\Rightarrow \frac{4 \times \phi \times 1200 \times 500}{60 \times 4}$$

$$\phi \Rightarrow \frac{250 \times 60}{1200 \times 5.00}$$

$$\Rightarrow 0.025 \text{ wb}$$

$$B = \frac{\phi}{A} = \frac{\text{flux/pole}}{\text{area of pole shoe}}$$

$$\Rightarrow \frac{0.025}{0.03848}$$

$$\Rightarrow 0.65 \text{ T}$$

TYPES OF DC GENERATOR

→ Generators are classified accordingly to their methods of field excitation.
production of magnetic flux or m.f. by circulating current in the field windg is called excitation.

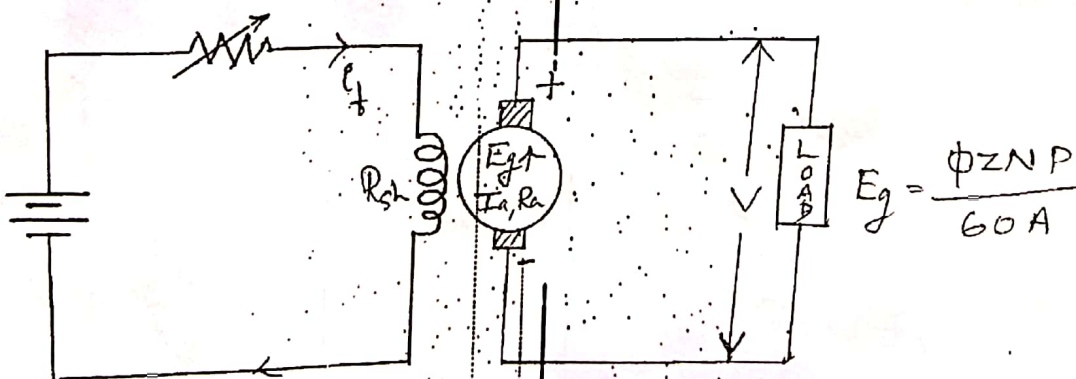
→ The magnetic field in a dc generator is normally produced by electromagnets rather than permanent magnets.

DC generator are mainly classified into two types on the modes of excitation.

1. Separately excited DC generator.
2. Self excited DC generator.

1. SEPARATELY EXCITED DC GENERATOR

→ Field winding is supplied from an independent external DC source.



Armature current $I_a = I_L$

Terminal Voltage $V = E_g - I_a R_a$

Electrical power developed $\Rightarrow E_g I_a$

Power delivered to load $\Rightarrow E_g I_a - I_a^2 R_a$

$\Rightarrow I_a (E_g - I_a R_a)$

$\Rightarrow V I_a$

SELF EXCITED DC GENERATOR

→ **Field winding** is supplied from the **output of the generator itself**.

→ Depending upon the **manner in which the field winding is connected to armature**, there are **3 types of self excited generators**.

- ① **Series Generator**
- ② **Shunt Generator**
- ③ **Compound Generator**

(i) **Short Shunt**

(ii) **Long Shunt**

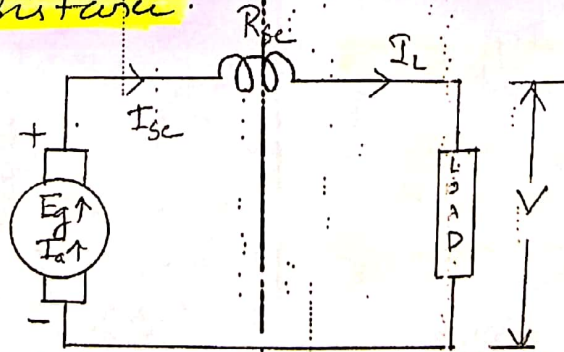
→ When the arm. is rotated, small voltage is induced in arm. due to residual flux in the pole. This volt. produces a small field current in field windg. and causes flux pole to increase. This takes place repeatedly & generator builds up to rated generated voltage.

① SERIES GENERATOR

→ The **field winding** is in **series** with the **armature winding**.

→ The whole armature current I_a flows through the field windg.

→ It has **few turns of thick wire** having **low resistance**.



Here

$$I_a = I_{sc} = I_L = I$$

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

$$\text{Power developed} = E_g I$$

$$\text{Power delivered to the load} \Rightarrow E_g I - I^2(R_a + R_{se})$$
$$\Rightarrow I(E_g - I(R_a + R_{se}))$$
$$\Rightarrow VI$$

$\Rightarrow$ Used for special purposes.

Eg :- Boosters

② SHUNT GENERATOR

$\rightarrow$ Field winding is parallel with armature winding.

$\rightarrow$ Terminal voltage of generator is applied across it.

$\rightarrow$ Have many turns of fine wire having high resistance.

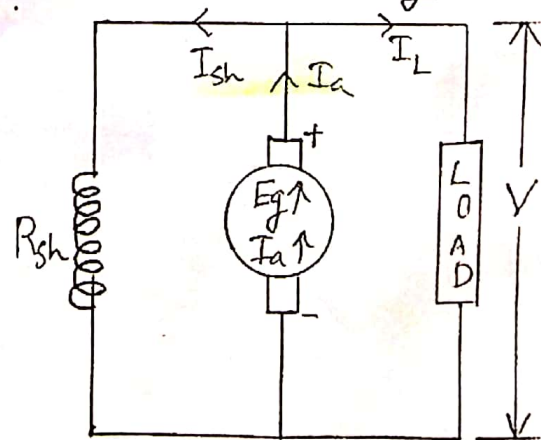
$$\text{but } I_a = I_L + I_{sh}$$

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

$$V = E_g - I_a R_a$$

$$\text{Power developed} \Rightarrow E_g I_a$$

$$\text{Power delivered to load} \Rightarrow VI_L$$



③ COMPOUND GENERATOR

→ Have both shunt and series field.
Compound machine can be connected to 2 ways.

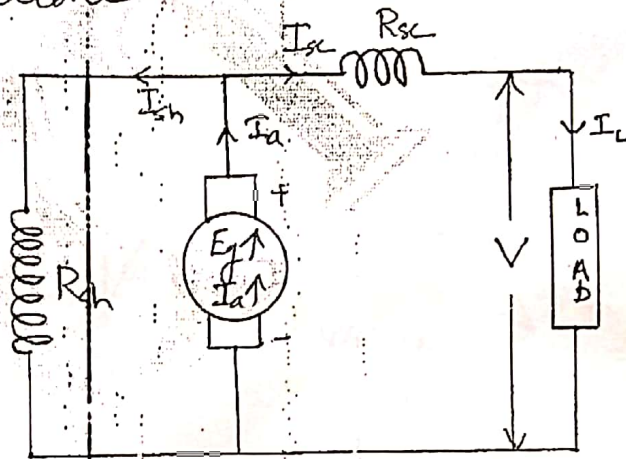
① SHORT SHUNT COMPOUND GENERATOR

→ Shunt field connected parallel to the armature wire alone.

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

$$I_{se} = I_L$$

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



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

Power developed $\Rightarrow E_g I_a$

Power delivered $\Rightarrow V I_L$

② LONG SHUNT COMPOUND GENERATOR

→ Shunt field is parallel to both armature & series field.

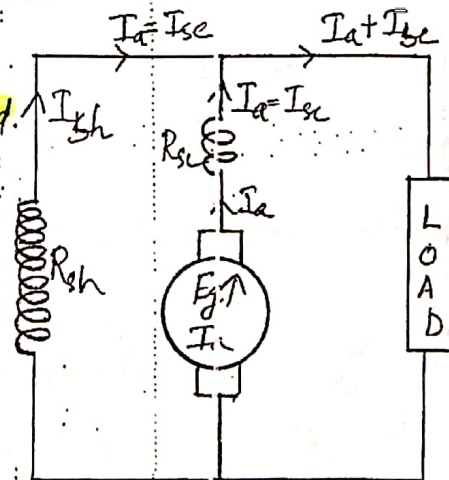
$$I_a = I_{se} = I_L + I_{sh}$$

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

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

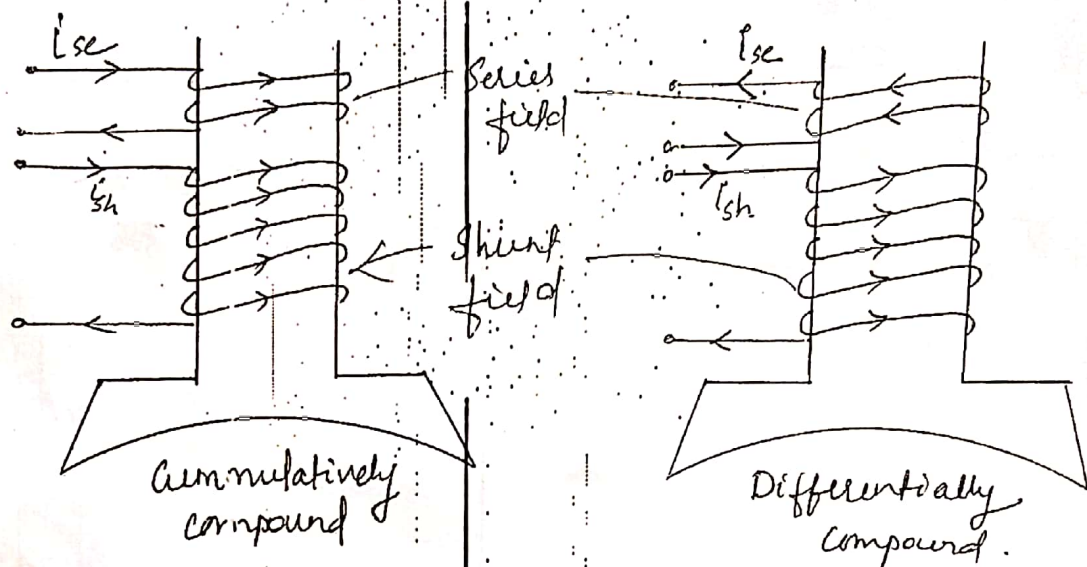
Power developed $\Rightarrow E_g I_a$

Power delivered $\Rightarrow V I_L$



Compound generators are also of 2 types.

- ① Cumulatively compound wound generator
→ series field assists shunt field.
- ② Differentially compound wound generator.
→ series field opposes shunt field.



Armature Resistance (R_a)

includes :- armature winding resistance
brush contact resistance.

→ depends on type of machine.

→ Except for small m/c, it is usually of order of 1Ω .

Brush contact drop :- Voltage drop due to brush contact resistance.

Voltage drop allowed for all brushes of each polarity shall be $1V$ for carbon and graphite brushes. $0.3V$ for metal carbon brushes. Total brush contact drop is double.

Q6. A 4-pole shunt generator with lap connected armature having field and armature resistance of 50Ω and 0.1Ω respectively. Supplies a $2400W$ load at a terminal voltage of $100V$. Calculate total I_a , current/arm. path and the generated emf.

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

$$I_{sh} = \frac{V}{R_{sh}} = \frac{100}{50} = 2A$$

$$P = VI_L$$

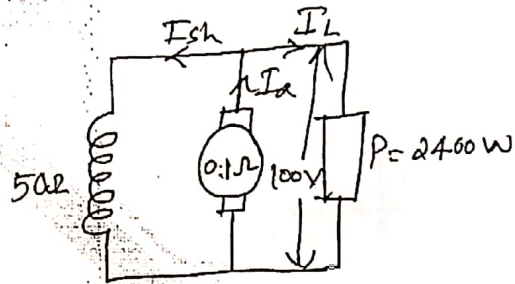
$$2400 = 100 \times I_L \Rightarrow I_L = \frac{2400}{100} = 24A$$

$$\text{Total armature current } I_a = 2 + 24 = 26A$$

In lap winding $A = P = 4$

$$\text{current/parallel path} \Rightarrow \frac{26}{4} = 6.5A$$

$$\begin{aligned} \text{Generated Emf, } E_g &= V + I_a R_a \\ &= 100 + 26 \times 0.1 \\ &= 102.6V \end{aligned}$$



Q7. A long shunt compound generator delivers a load current of $50A$ at $500V$ and has armature, series field and shunt field resistance of 0.05Ω , 0.3Ω and 250Ω respectively. Calculate the generated voltage and I_a . Allow $1V$ brush drop.

$$I_{sh} = \frac{500}{250} = 2 \text{ A}$$

$$I_a = I_{sc} = 50 + 2 = 52 \text{ A}$$

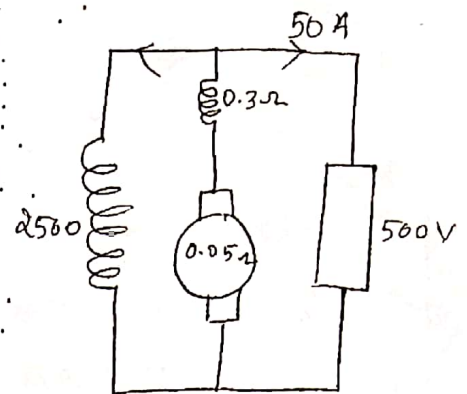
$$E_g = V + I_a R_a + I_{sc} R_{sc} + \text{Brush drop}$$

$$I_{sc} R_{sc} = 52 \times 0.03 = 1.56 \text{ V}$$

$$I_a R_a = 52 \times 0.05 = 2.6 \text{ V}$$

$$\text{drop at brushes} = 2 \times 1 = 2 \text{ V}$$

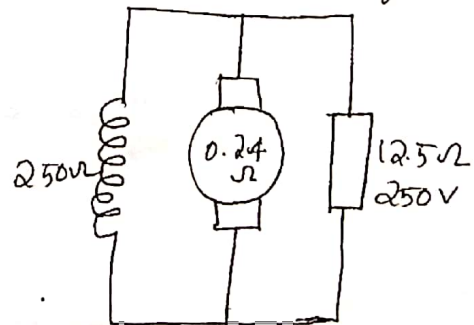
$$\therefore E_g \Rightarrow 500 + 2.6 + 1.56 + 2 \\ \Rightarrow \underline{\underline{506.16 \text{ V}}}$$



Q8. A 8-pole de shunt generator has 778 wave connected arm. conductors running at 500 rpm, supplies a load of 12.5Ω resistance at a terminal voltage of 250V. R_a is 0.24Ω and $R_{sh} = 250 \Omega$. Find I_a , induced emf and flux per pole.

$$I_L = \frac{V}{R_L} = \frac{250}{12.5} = 20 \text{ A}$$

$$I_{sh} = \frac{250}{250} = 1 \text{ A}$$



$$(i) I_a = 20 + 1 = 21 \text{ A}$$

$$(ii) E_g = V + I_a R_a = 250 + 21 \times 0.24 = \underline{\underline{255.04 \text{ V}}}$$

$$(iii) \text{ Flux/pole } \phi = \frac{E_g \times 60 \times A}{P Z N}$$

$$\Rightarrow \frac{255.04 \times 60 \times 2}{8 \times 778 \times 500} = 9.834 \times 10^{-3} \text{ wb} \\ \Rightarrow \underline{\underline{9.834 \text{ mwb}}}$$

Q9. In a 120V compound generator. The resistance of armature shunt and series wdg are 0.06Ω , 25Ω and 0.04Ω resp. I_L is 100A at 120V. Find induced emf and I_a if m/c is connected as.

(i) Long shunt (ii) Short shunt. How will the ampere turns of series field be changed or if a diverter of 0.1Ω is connected in parallel with the series field wdg? Neglect brush contact drop & ignore armature reaction.

Short Shunt.

$$I_L R_{se} = 100 \times 0.04 = 4V.$$

Voltage across shunt wdg $\Rightarrow 124V$

$$I_{sh} = \frac{124}{25} = 5A$$

$$I_a = 100 + 5 = 105A$$

$$I_a R_a = 105 \times 0.06 = \underline{6.3V}$$

$$E_g \Rightarrow V + I_a R_a + I_{se} R_{se}$$

$$\Rightarrow 120 + 6.3 + 4 = \underline{130.3V}$$

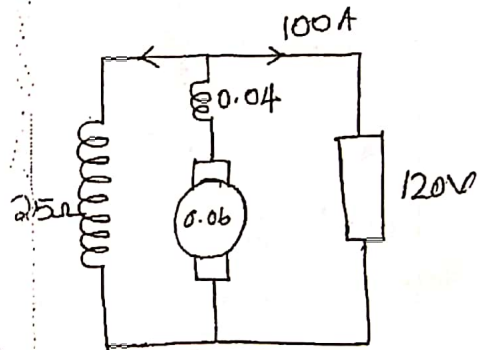
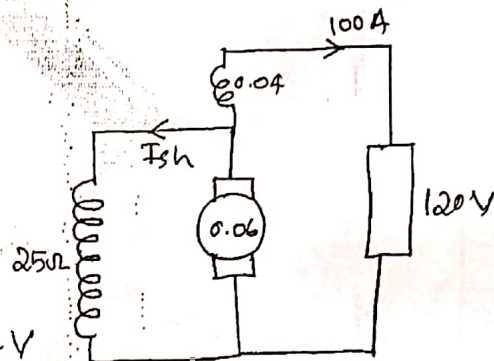
Long Shunt

$$I_{sh} = \frac{120}{25} = 4.8A$$

$$I_a = 100 + 4.8 = 104.8A$$

$$I_{se} R_{se} \Rightarrow I_a R_{se} = 104.8 \times 0.04 = 4.19V$$

$$I_a R_a = 104.8 \times 0.06 = 6.29V$$



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

$$\Rightarrow 120 + 4.19 + 6.29$$

$$\Rightarrow \underline{\underline{130.5V}}$$

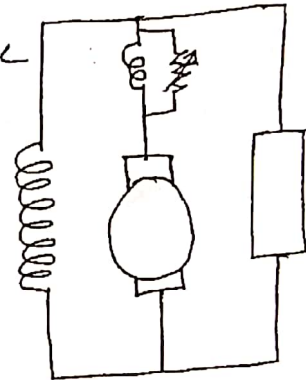
When an 0.1Ω diverter is connected across series field of long shunt generator.

$\therefore$ current through series windg

$$\Rightarrow I_a \times \frac{R_{div}}{R_{div} + R_{se}}$$

$$I_{se} = 104.8 \times \frac{0.1}{0.1 + 0.04}$$

$$\Rightarrow \underline{\underline{74.86A}}$$



Since the number of turns are same, change in series field ampere turns is same as change in current in series winding.

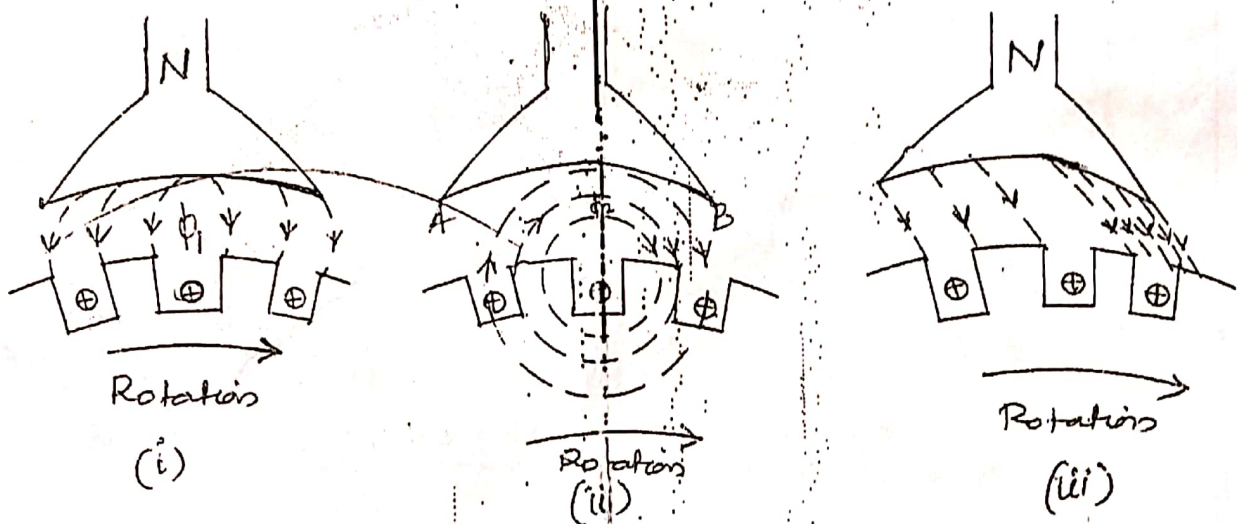
$$\text{Decrease in series field AT} \Rightarrow \frac{104.8 - 74.86}{104.8} \times 100$$

$$\Rightarrow \underline{\underline{28.6\%}}$$

ARMATURE REACTION

→ The effect of magnetic field set up by the armature current on the distribution of flux under the main pole of a dc machine (a generator or a motor) is known as armature reaction.

→ The ^{OR} action of armature flux on the main flux is known as armature reaction.



→ The phenomenon of armature reaction in dc generator is shown in the figure above. Only one pole is shown for clarity.

→ When the generator is on no-load, a small current flowing in the armature does not affect the main flux Φ from the pole as in fig (i).

→ When the generator is loaded, the current flowing through armature conductors set up flux ϕ_2 .

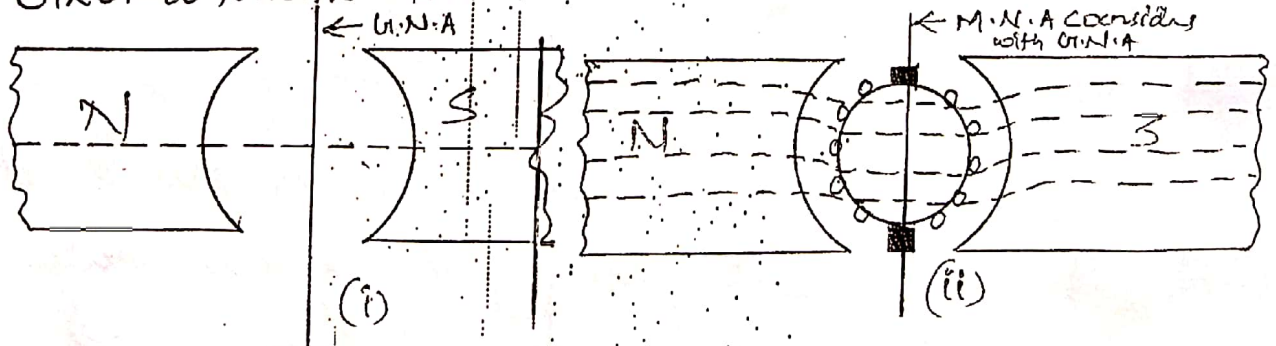
→ Fig(ii) shows flux due to armature current alone. By superimposing ϕ_1 & ϕ_2 the resulting flux ϕ_3 is obtained.

→ Referring to fig(ii) it is clear that flux density at the trailing pole tip (pt B) is increased while at the leading pole tip (pt A) it is decreased. This unequal flux distribution produces the following two effects.

(i) The main flux is distorted.

(ii) Weakening of flux due to armature reaction depends upon the position of brushes.

GEOMETRICAL AND MAGNETIC NEUTRAL AXIS



(i) The geometrical neutral axis (G.N.A.) is the axis that bisects the angle b/w the centre line of adjacent poles. It is the axis of symmetry b/w two adjacent poles.

- (ii) → The magnetic neutral axis (MNA) is the axis drawn perpendicular to the mean direction of the flux passing through the centre of the armature. (With no current in armature conductors).
- No emf is produced along this axis because they cut no flux.
 - In order to achieve sparkless commutation, the brushes must lie along M.N.A.

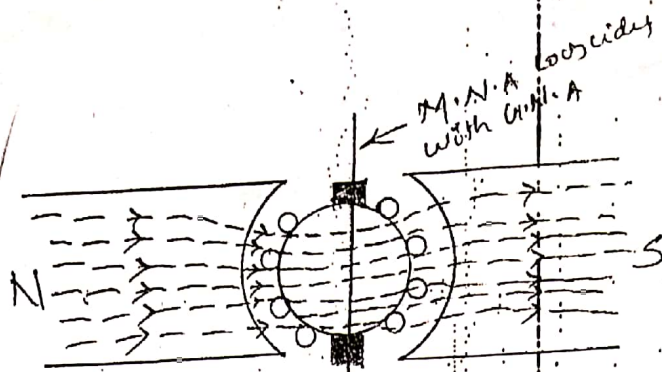
EFFECT OF ARMATURE REACTION.

→ When current flows in armature conductors, the combined action of main flux and armature flux shifts the M.N.A. from G.N.A. Thus the armature reaction has mainly two effects.

- 1). It demagnetises or weakens the main flux.
- 2). It cross-magnetises or distorts the main flux.

→ The effects of armature reaction by considering a 2-pole generator.

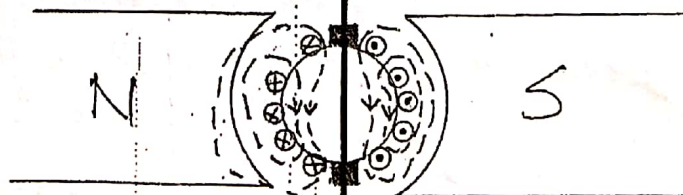
- (i) ⇒ The flux due to main poles (main flux) when the armature carries no current. The flux across the air gap is uniform. The m.m.f. producing the main flux is represented by the vector OF_m . OF_m is perpendicular to G.N.A.



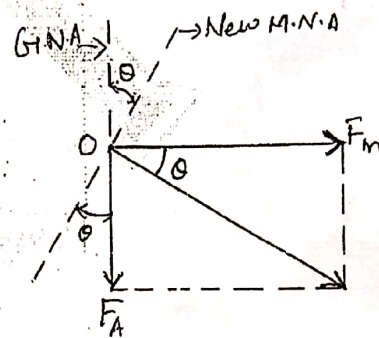
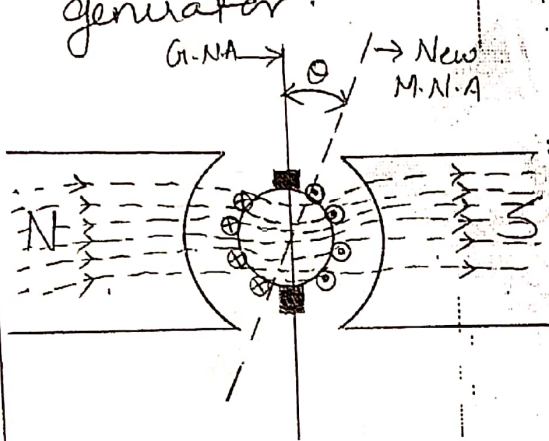
(ii) → The flux due to current flowing armature conductors alone (main poles unexcited).

The armature conductors to the left of G.N.A carry current "in" (X) and those to the right carry current "out" (O). The direction of magnetic lines of force can be found by cork screw rule
 → It is clear that armature flux is directed downward parallel to the brush axis.

→ The m.m.f producing this armature flux is represented in magnitude and direction by the vector F_A .



(iii) The flux due to the main poles and that due to current in armature conductors acting together. The resultant m.m.f. OF is the vector sum of OF_m and OF_A . Since M.N.A is always perpendicular to the resultant m.m.f. the M.N.A is shifted through an angle θ . M.N.A is shifted in the direction of rotation of the generator.

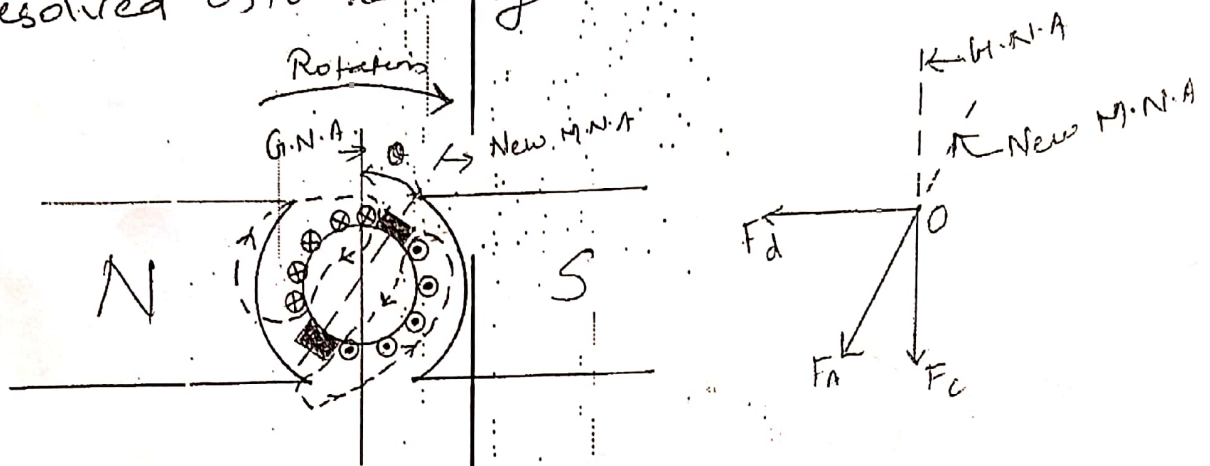


(iv) → In order to achieve sparkless commutation the brushes must lie along the M.N.A.

The brushes are shifted through an angle θ so as to lie along the new M.N.A.

→ Due to the brush shift, the m.m.f. F_A of the armature is also rotated through the same angle θ . It is because some of the conductors which were earlier under N-pole now come under S-pole and vice versa.

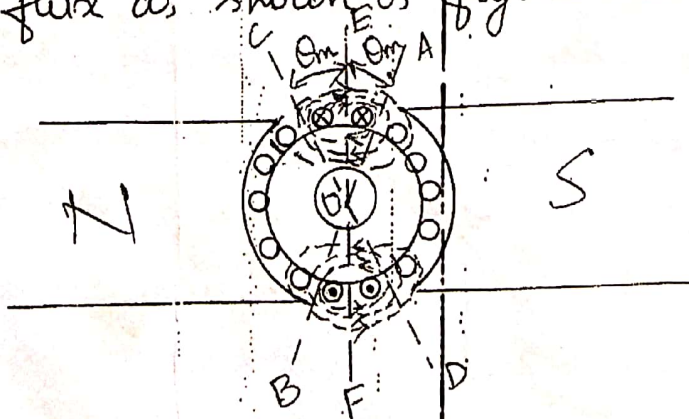
→ The resultant is that armature m.m.f F_A will no longer be vertically downward but will be rotated in the direction of the rotation through an angle θ . Now F_A can be resolved into rectangular components F_c & F_d .



⇒ Note :- It may be noted that with the increase of armature current both demagnetizing and distortion effects will increase.

DEMAGNETISING AND CROSS-MAGNETISING AMPERE TURNS

→ The armature conductors ϕ_m on either side of the G.N.A produce flux in direct opposition to main flux as shown in figure below.



⇒ Thus the conductors lying within angles $AOC = BOD = \alpha$ at the top and bottom of the armature produce demagnetizing effect.

$\Rightarrow$ These are called demagnetizing armature conductors and ampere-turns is demagnetizing ampere-turns.

CALCULATION

Let $Z \Rightarrow$ Total number of armature conductors.

$I \Rightarrow$ current in each armature conductor.

$\Rightarrow I_a/2$ for wave winding.

$\Rightarrow I_a/p$ for lap winding.

$\theta_m \Rightarrow$ forward lead in mechanical degrees.

In the figure

Total demagnetizing armature conductors

$\Rightarrow$ conductors in angles AOC & BOD

$$\Rightarrow \frac{A \theta_m}{360} \times Z$$

Since two conductors constitute one turn,

$\therefore$ Total demagnetizing ampere-turns.

$$\Rightarrow \frac{1}{2} \left[\frac{A \theta_m}{360} \times Z \right] \times I$$

$$\Rightarrow \frac{2 \theta_m}{360} \times Z I$$

These demagnetizing ampere-turns are due to pair of poles.

∴ Demagnetising ampere-turns/pole

$$\Rightarrow \frac{O_m}{360} \times ZI$$

ii $AT_d/\text{pole} \Rightarrow \frac{O_m}{360} \times ZI$

→ The demagnetising ampere-turns of armature reaction can be neutralised by putting extra turns on each pole of the generator.

∴ No. of extra turns/pole $\Rightarrow \frac{AT_d}{I_{sh}}$ -- for shunt generator.

$\Rightarrow \frac{AT_d}{I_a}$... for a series generator.

⇒ When a conductor passes a pair of poles, one cycle of voltage is generated. One cycle contains 360 electrical degree. Suppose there are P poles in a generator. In one revolution, there are 360 mechanical degrees and $360 \times P/2$ electrical degrees.

$$360^\circ \text{ Mechanical} = 360 \times \frac{P}{2} \text{ electrical degrees.}$$

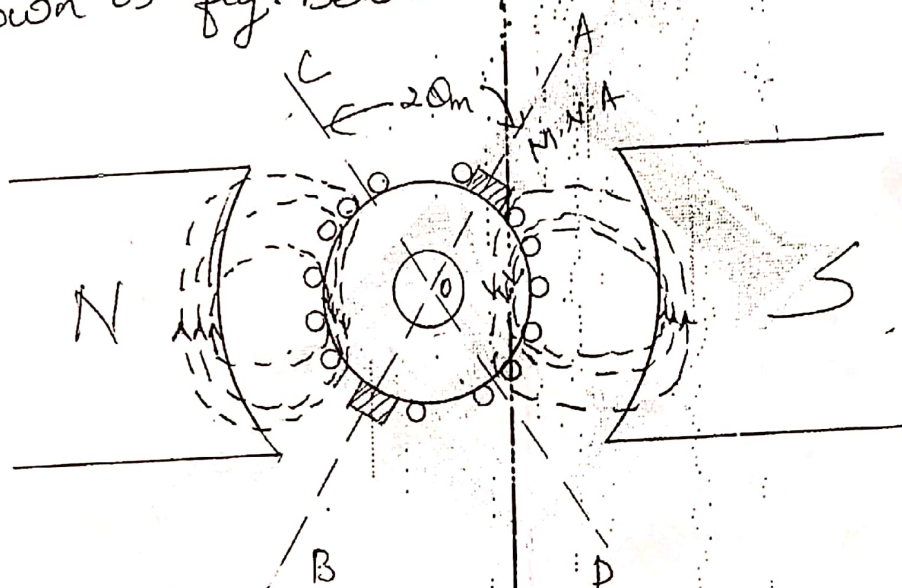
$$1^\circ \text{ mechanical} = \frac{P}{2} \text{ electrical degrees.}$$

$$\theta(\text{mechanical}) = \frac{\theta(\text{electrical})}{\text{Pair of Poles.}}$$

$$O_m = \frac{O_e}{P/2} \quad \therefore O_m = \frac{2O_e}{P}$$

CROSS-MAGNETISING

⇒ The axis of magnetisation of the remaining armature conductors lying between angle AOD and COB is at right angles to main flux as shown in fig. below.



⇒ These conductors produce cross-magnetising (or distortion) effect. They produce uneven flux distribution on each pole. They are called cross magnetising conductors or cross-magnetising ampere turns.

CALCULATION

Cross-magnetising ampere turn/pole ⇒ AT_c/p

Total armature reaction ampere-turn/pole

$$\Rightarrow \frac{Z/p}{P} \times I \Rightarrow \frac{Z}{2P} \times I$$

Demagnetising ampere-turns/pole

$$A_{Td/p} = \frac{O_m}{360} \times ZI$$

$\therefore$ Cross-magnetising ampere-turns/pole

$$A_{Tc/pole} \Rightarrow \frac{Z}{2p} \times I - \frac{O_m}{360} \times ZI$$

$$\Rightarrow ZI \left[\frac{1}{2p} - \frac{O_m}{360} \right]$$

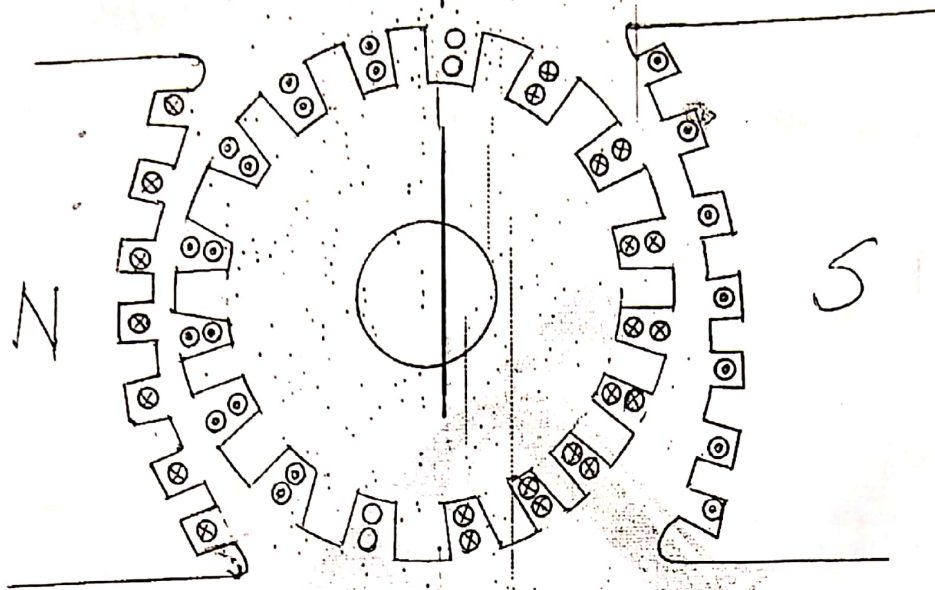
$$A_{Tc/pole} \Rightarrow ZI \left[\frac{1}{2p} - \frac{O_m}{360} \right]$$

COMPENSATING WINDING

$\Rightarrow$ The cross-magnetising effect of armature reaction may cause trouble in d.c. machines subjected to large fluctuations in load.

$\Rightarrow$ In order to neutralize these effect compensating winding are used.

$\Rightarrow$ A compensating winding is an auxiliary winding embedded in slots in the pole faces as shown in figure below.



⇒ It is connected in series with armature in a manner so that the direction of current through the compensating conductor in any one pole face will be opposite to the direction of the current through the adjacent armature conductors.

Let $Z_c \Rightarrow$ No. of compensating conductors/pole face.

$Z_a \Rightarrow$ No. of active armature conductors.

$I_a \Rightarrow$ Total armature current.

$I_a/A \Rightarrow$ Current in each armature conductor.

$$Z_c I_a \Rightarrow Z_a \times \frac{I_a}{A}$$

$$Z_c = \frac{Z_a}{A}$$

COMPEXISATING AT/POLE

Let no: of armature conductors/pole $\Rightarrow \frac{Z}{P}$

No: of armature turns/pole $\Rightarrow \frac{Z}{2P}$

No: of armature turns under pole face $\Rightarrow \frac{Z}{2P} \times \frac{\text{Pole arc}}{\text{Pole Pitch}}$

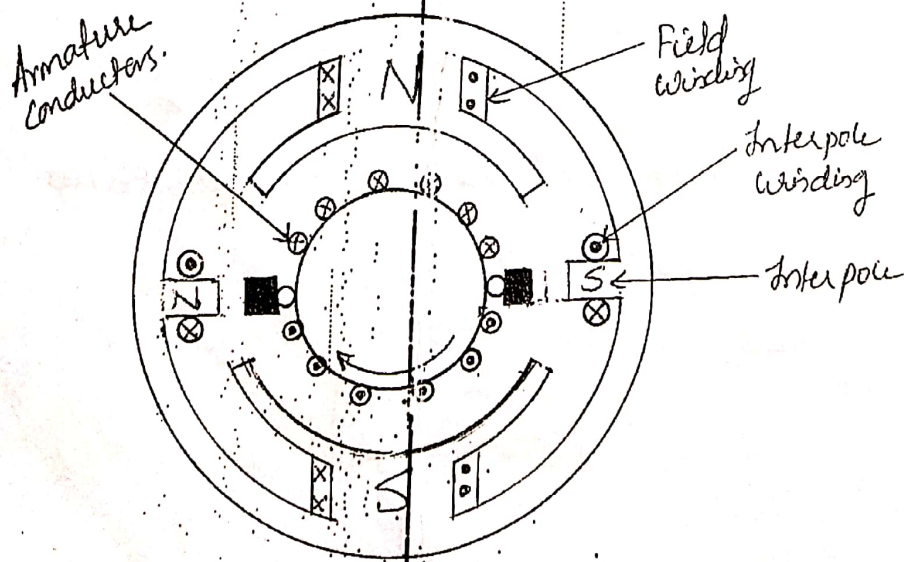
If I is the current through each armature conductor.

then AT/pole required for compensating winding

$$\Rightarrow \frac{ZI}{2P} \times \frac{\text{Pole arc}}{\text{Pole Pitch}}$$

$$\Rightarrow \text{Armature AT/pole} \times \frac{\text{Pole arc}}{\text{Pole Pitch}}$$

COMMUTATING POLES OR INTERPOLES



- ⇒ The commutating poles or interpoles are narrow poles that are located in the interpolar region centred along the mechanical neutral axis of the generator shown in the figure.
- ⇒ The commutating pole windings are connected in series with the armature so that they carry armature current (I_a).
- ⇒ The compole winding must provide enough m.m.f to oppose armature m.m.f and set up magnetic flux for compole air gap and its magnetic circuit.
- ⇒ The interpoles perform the following two functions
- (i) → As their polarity is the same as the main pole ahead, they induce an emf in the coil which opposes the reactance voltage. This leads to sparkless commutation.
 The emf induced by compoles is known as the commutating or reversing emf. → compensating poles
 The neutralization of reactance voltage is automatic. flux
 - (ii) → The m.m.f of the compoles neutralises the cross-magnetising effect of armature reaction.

COMMUTATION

$\Rightarrow$ The current in the coil connected to brush either towards the (positive brush) or negative brush or all directed away from the brush. Therefore, current in a coil will reverse as the coil passes a brush. This reversal of current as the coil passes a brush is called commutation.

$\Rightarrow$ The schematic diagram of 2-pole lap-wound generator is shown in the figure below.

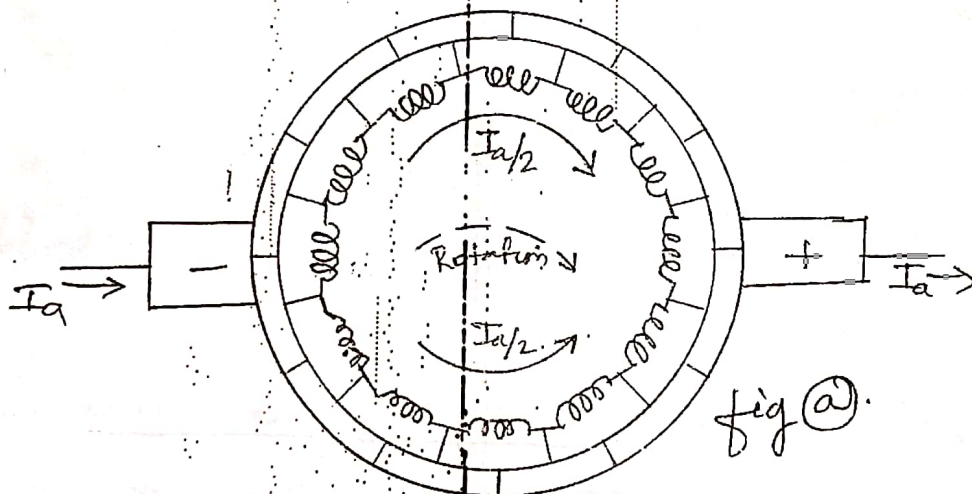


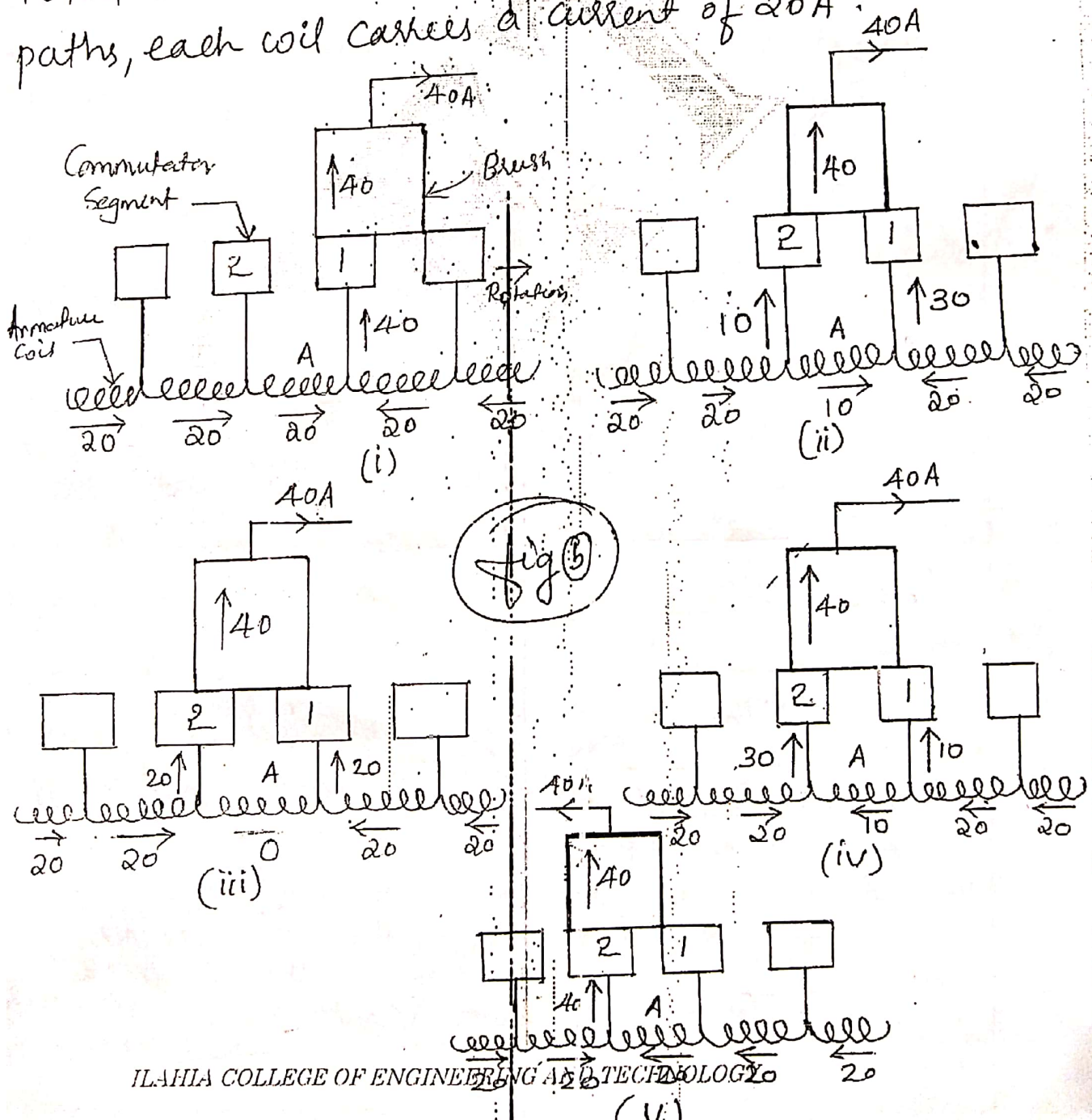
fig (a).

$\Rightarrow$ The reversal of current in the coil as the coil passes the brush axis called commutation.

$\Rightarrow$ When commutation takes place, the coil undergoing commutation is short-circuited by the brush. The brief period during which the coil remains short-circuited is known as commutation period.

Ideal commutation :-

The phenomenon of ideal commutation (i.e. coil has no inductance) in one coil in the armature winding shown in figure (a). In this brush width is equal to the width of one commutator segment and one mica insulation. Suppose the total current is 40A. Since there are two parallel paths, each coil carries a current of 20A.



In figure (b)

(i) $\Rightarrow$ The brush is in contact with segment 1 of the commutator. The commutator segment 1 conducts a current of $40A$ to the brush. $20A$ from coil A & $20A$ from the adjacent coil. The coil A has yet to undergo commutation.

(ii) $\Rightarrow$ As the armature rotates, the brush will make contact with segment 2 and thus short-circuits coil A.

$\rightarrow$ There are two parallel paths into the brush as long as the short-circuited coil A exists.

$\rightarrow$ Here the resistance path through segment 2 is three times the resistance path through segment 1. ($\because$ contact resistance varies inversely as the area of contact of brush with segment).

$\rightarrow$ The brush again conducts a current of $40A$; $30A$ through segment 1 and $10A$ through segment 2.

$\rightarrow$ Current in coil A (the coil undergoing commutation) is reduced from $20A$ to $10A$.

METHODS OF IMPROVING COMMUTATION

⇒ Commutation can be improved ^{mainly} ~~made~~ by two methods.

(i) Resistance commutation

(ii) E.M.F commutation

(i) Resistance Commutation

⇒ The reversal of current in a coil takes place while the coil is short-circuited by the brush. There are two parallel paths for the current as long as the short circuit exists. There will be sparkless commutation by use of high resistance brushes.

⇒ If the contact resistance b/w the brush and the commutator is made large, then the current would divide in the inverse ratio of contact resistances. (as for any two resistances in parallel). This will improve commutation.

⇒ This can be achieved by using carbon brushes (instead of Cu brushes) which have high contact resistance. This method of improving commutation is called resistance commutation.

(iii) $\Rightarrow$ It shows the instant when the brush is one-half on segment 2 and one-half on segment 1. The brush again conducts 40A, 20A through segment 1 and 20A through segment 2.

$\therefore$ The resistance of the two parallel paths are equal. i.e. that now current in coil A is zero.

(iv) $\Rightarrow$ It shows the instant when the brush is ~~one~~ three-fourth on segment 2 and one-fourth on the segment 1. The brush conducts a current of 40A. 30A through segment 2 and 10A through seg. 1. i.e. current in coil A is 10A but is the reverse direction to that before the start of commutation.

(v) $\Rightarrow$ It shows the instant when the brush is in contact only with segment 2. The brush again conducts 40A, 20A from coil A and 20A from the adjacent coil to coil A. Now the current in coil A is 20A but is the reverse direction. Thus the coil A has undergone commutation. coil undergoes commutation in this way as it passes the brush axis.

⇒ This minor drawbacks of carbon brushes are high voltage drop at brushes due to their high contact resistance and their lower current density.

E.M.F COMMUTATION

⇒ This arrangement is made to neutralize the reactance voltage by producing a reversing voltage as the coil undergoes commutation. The reversing voltage is obtained by the following two methods.

(i) By Brush Shifting

(ii) By using interpoles or Compols.

(i) By Brush Shifting

⇒ This method is employed for the improving commutation in non-commutating pole machines. The brushes are shifted so that the sides of coil as it passes through its commutation period will cut the sufficient flux from the main poles to develop the necessary commutating emf.

$\Rightarrow$ The direction of brush shift must be such that this cutting of a portion of the main flux will induce a commutating emf in the coil which will be in the same direction as that of the current through the coil after it has passed through the commutation period.

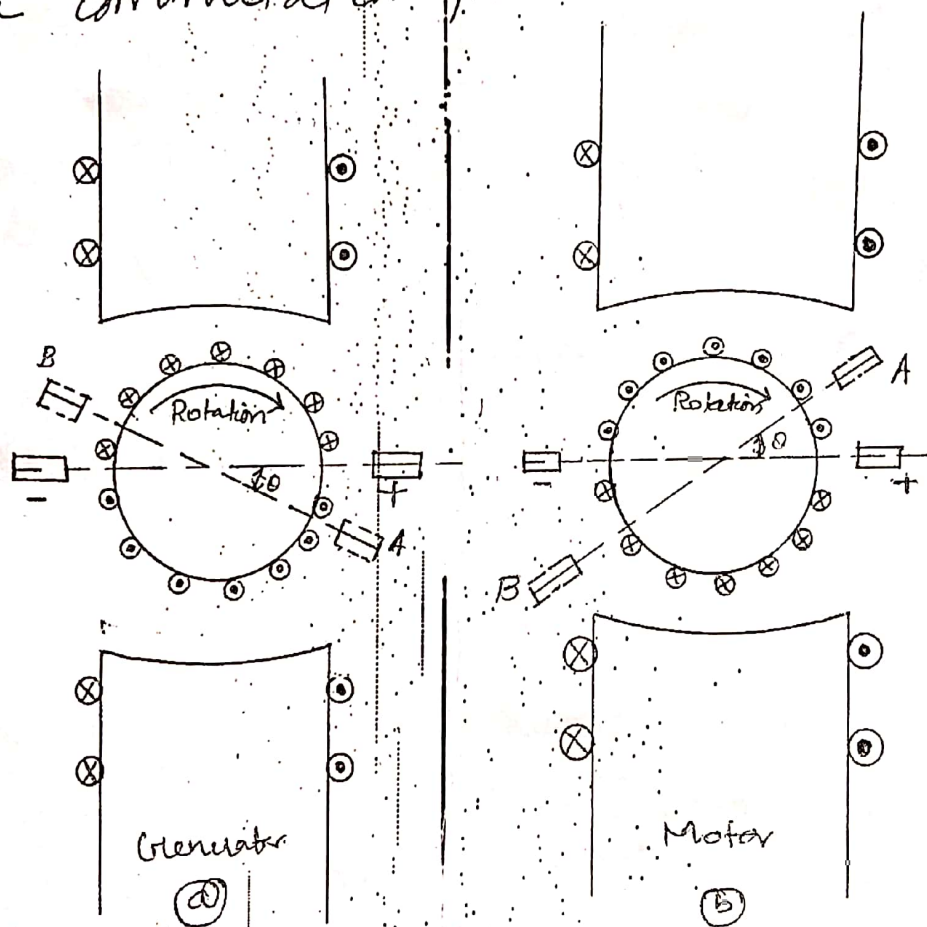


Fig (A) $\Rightarrow$ Brushes must be shifted in the direction of rotation of m/c (Generator)

Fig (B) $\Rightarrow$ Brushes must be shifted in backward of rotation of m/c (Motor).

(ii) By Using Interpoles or Compoles

Already explained in arm. Reaction.

DC GENERATOR CHARACTERISTICS

⇒ Speed of DC generator is practically constant. So the generator performance deals with relation between excitation, terminal voltage, and load.

1) No load characteristics.
or Open circuit characteristics (O.C.C)

⇒ The curve shows the relation between generated emf at no-load E_0 and field current (I_f) at constant speed.

⇒ Also called magnetization characteristics.
(No load saturation curve).

⇒ Shape is practically same for all generators.

2) Internal/Total Characteristics

⇒ Curve shows the relation b/w generated emf on load (E) and the armature current (I_a).

⇒ E is less than E_0 due to demagnetizing effect of armature reaction.

- ⇒ this curve lie below OCC.
- ⇒ cannot be obtained directly by experiment.
- ⇒ Internal characteristics is obtained from the external characteristics if windg resistances are known because armature reaction effect is included in both characteristics.

3) External characteristics (V/I_a)

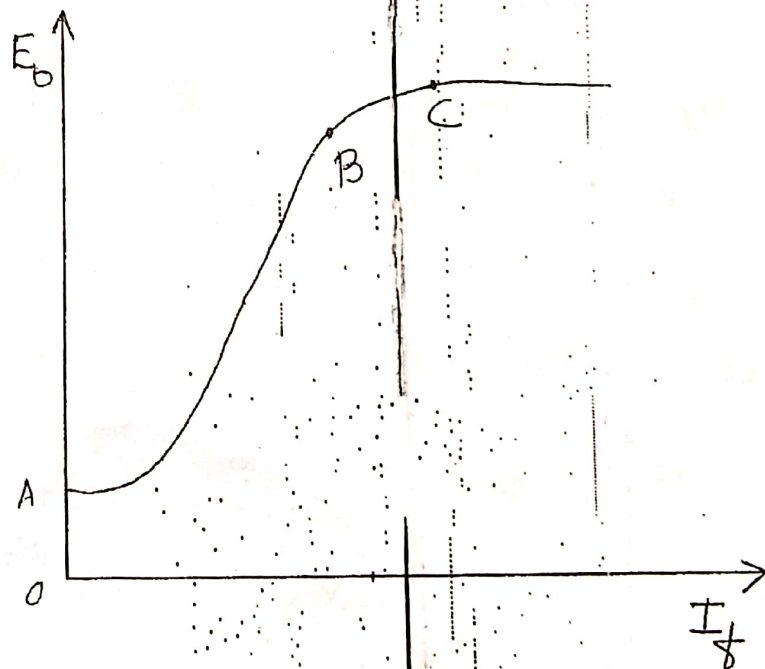
- ⇒ Curve shows the relation b/w the terminal voltage (V) and load current (I_L).
- ⇒ V is less than E due to voltage drop in armature circuit.
- ⇒ Curve lie below the internal characteristics.
- ⇒ Determines the suitability of a generator for a given purpose.

1) Open Circuit characteristics or
No Load characteristics.

② Shunt Generator $\Rightarrow$ The characteristics is same for
shunt, series, & compound generators &
also for separately excited generators.

$\Rightarrow$ In separately excited generator the
excitation is given separately by means of
dc source.

$\Rightarrow$ Self excited generators excitation is
obtained due to residual magnetism.



① $\Rightarrow$ When $I_f = 0$, there is some generated emf (E_b)
i.e. OA is due to residual magnetism.

② Upto B the curve is linear
 $\Rightarrow$ airgap reluctance is constant and the reluctance of iron is negligible.

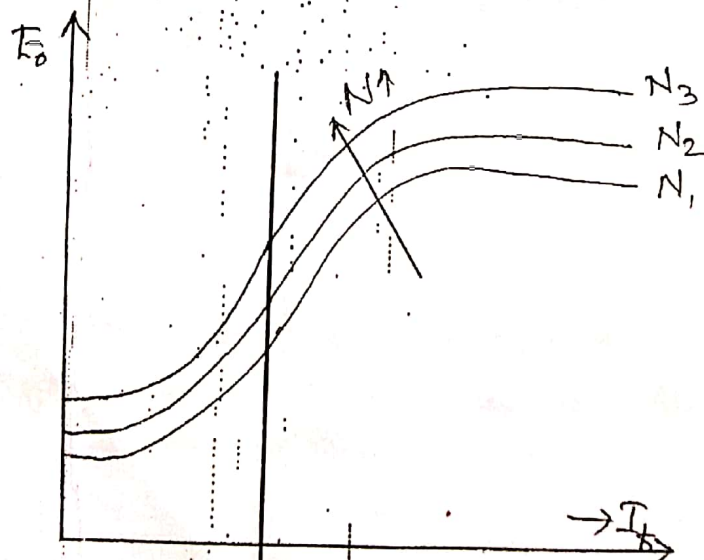
$\Rightarrow$ At low flux density, μ_r for iron is high so negligible reluctance.

μ_r reduces with increase in B, reluctance also increases.

③ $\Rightarrow$ After B, the reluctance of iron also increases and so it is not negligible. So the curve deviates from linear relationship.

④ $\Rightarrow$ After C, the magnetic saturation of poles begins and E_o tends to level off.

If the value of constant speed is increased, the steepness of the curve also increases

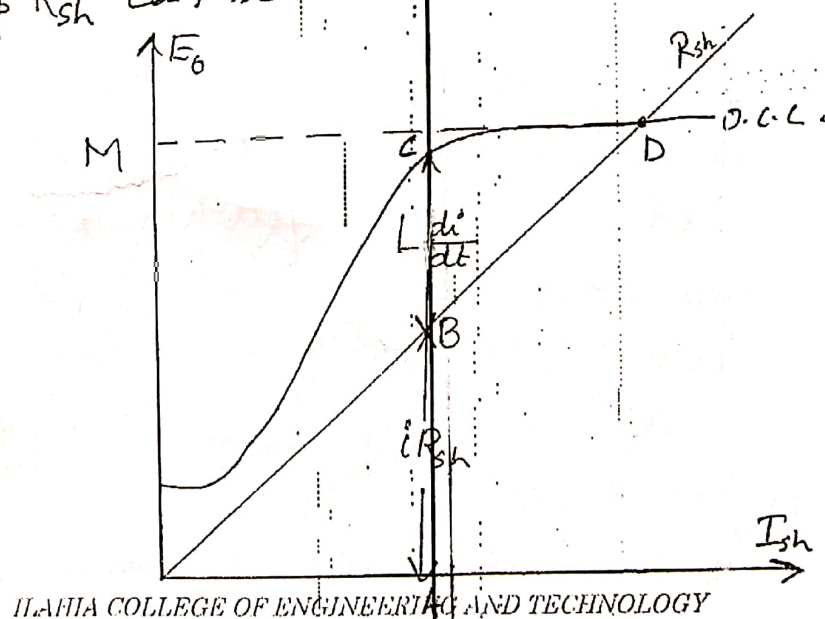


Voltage Build up is

Shunt Generator:

- Generator is run at constant speed.
- Some emf is generated due to residual magnetism in main poles.
- this small emf circulates a field current which in turn produces additional flux to reinforce the original residual flux.
- this process is continuous and the generator builds up the normal generated voltage.

The field resistance R_{sh} can be represented by a straight line passing through the origin. OCC & R_{sh} can be shown on the same diagram.



⇒ Since the field circuit is inductive there is a delay in the increase in current upon closing the field circuit switch.

→ Rate at the current increases depends on the voltage available for increasing it.

$$E_o = L \frac{di}{dt} + i R_{sh}$$

where $L \Rightarrow$ Inductance of field ckt.

$R_{sh} \Rightarrow$ Resistance.

Consider the instant, field current $i = 0A$

Total emf available is AC

$$AC = AB + BC$$

$i \Rightarrow$ Emf absorbed by + emf to overcome
Volt. drop $i R_f$ $L \frac{di}{dt}$

At pt D, the available voltage is OM & is all absorbed by $i R_{sh}$ drop. So the field current cannot increase further and the generator builds up stops.

⇒ Voltage build up of the generator is given by the point of intersection of OCC and field resistance line.

D is the pt of intersection of 2 curves and thus the generator will build up at OM.

Series Generator

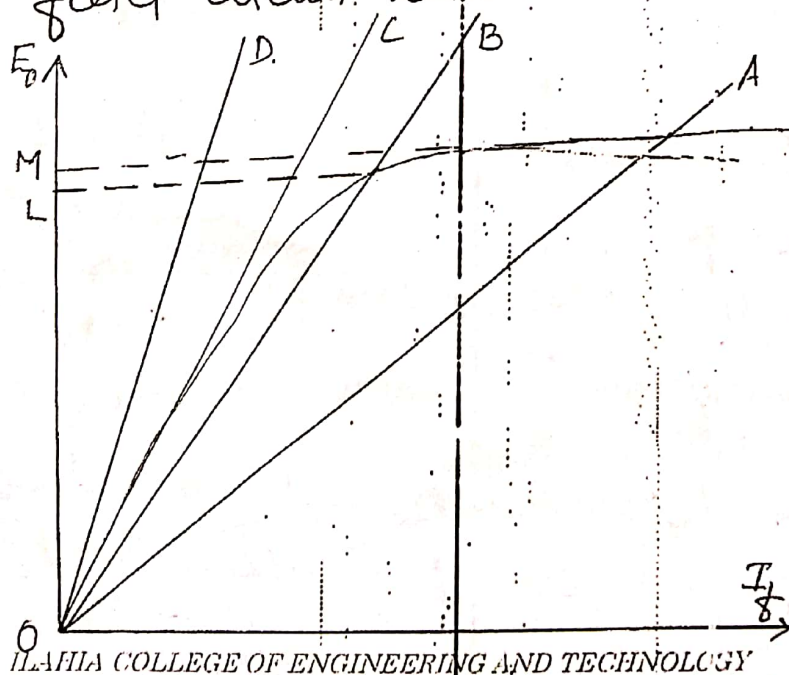
→ same as shunt generator

Compound Generator

- Start under no-load condition as the shunt field is effective at no-load only.
- When no-load voltage build up is achieved the generator is loaded.
- If the voltage rises, it is cumulatively compound.
- If the voltage drops, it is differentially compound.

Critical Field Resistance

→ Voltage build up in a shunt generator depends on field circuit resistance.



$\Rightarrow$ If field resistance is $R_1(OA)$ the generator builds up a voltage OM .

$\Rightarrow$ If field resistance is $R_2(OB)$ the generator builds up a voltage ON less than OM .

$\Rightarrow$ If the field resistance is increased, and the line becomes tangent (OC) to O.C.C generator would just excite.

$\Rightarrow$ If the field resistance is increased beyond this point (OD) generator will fail to excite.

The field circuit resistance represented by OC (tangent to O.C.C.) is called critical field resistance. R_c for shunt generator.

"Maximum field circuit resistance for a given speed with which the shunt generator would just excite is known as its critical field resistance."

$\Rightarrow$ Shunt generator will build up voltage only if field circuit resistance is less than critical field resistance.

Parallel Operations of DC Generators.

→ In a dc power plant power is usually supplied from several generators of small ratings connected in parallel instead of from one larger generator.

Need for Parallel Operation

(i) Continuity of service

If a single larger generator is used in power plant, then in the case of its breakdown the whole plant is shut down. If it is from a number of units operating in parallel, the continuity of supply can be maintained by healthy units.

(ii) Efficiency

Generators run most efficiently when loaded to their rated capacity. When load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded.

(iii) Maintenance and Repair.

Generators usually require routine maintenance and repair. If they are connected in parallel the routine or emergency operation can be performed by isolating the affected generator.

(iv) Increasing Plant capacity

When added capacity is required, the new unit can be simply paralleled with the old units.

(v) Non-availability of single large unit.

A single unit of desired large capacity may not be available. A number of smaller units can be operated in parallel will meet the requirement.

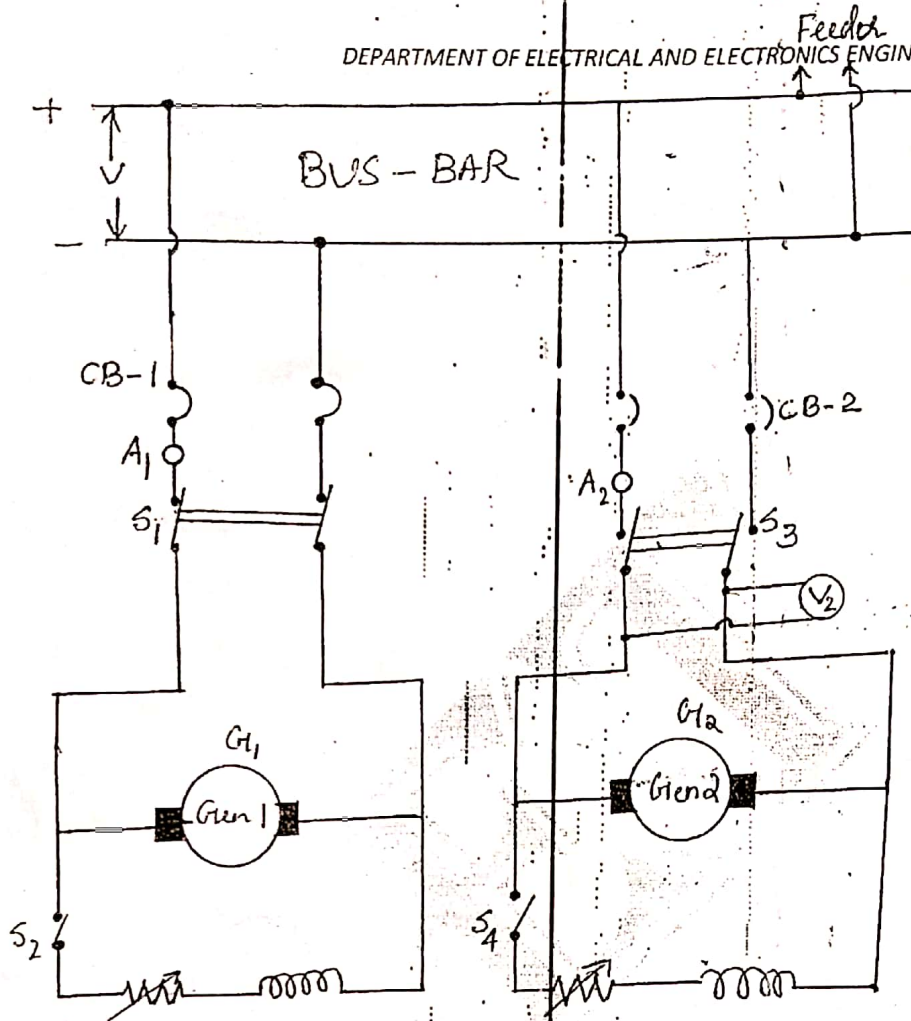
CONDITION FOR PARALLEL OPERATION

=> There are two main conditions

- (i) All the polarities must be correct.
- (ii) The terminal voltages of the generators being paralleled must be the same. (ideally).

CONNECTING SHUNT GENERATORS IN PARALLEL.

→ The generators of a power plant are connected in parallel through bus-bars. The bus-bars are heavy thick copper bars and they act as the +ve & -ve terminals. The positive terminals of the generators connected to the +ve side of bus-bars and negative terminals to the negative side.



→ The figure shows shunt generator G_1 , connected to the bus-bars and supplying load. When the load on the power plant increases beyond the capacity of this generator, the second shunt generator G_2 connected in parallel with the first to meet the increased load demand. The procedure for parallel operation is that

- (i) The prime mover of generator G_2 is brought upto rated speed. Now the switch S_4 in the field circuit of the generator G_2 is closed.

(ii) The circuit breaker CB-2 is closed and the excitation of generator G_2 is adjusted till it generates voltage equal to the bus-bar voltage. This is indicated by voltmeter V_2 .

(iii) Then generator G_2 is ready to be paralleled with generator G_1 . The main switch S_3 is closed, thus putting generator G_2 in parallel with generator G_1 . Note that generator G_2 is not supplying any load because its generated emf is equal to bus-bar voltage. This generator is said to be on floating (i.e. not supplying any load).

(iv) If generator G_2 is to deliver any current, then its generated voltage E should be greater than the bus-bar voltage V . The current supplied $I = \left[\frac{E-V}{R_a} \right]$.

By increasing the field current (thereby induced emf E) the generator G_2 can be made to supply proper amount of load.

(v) The load may be shifted from one shunt generator to another by adjusting the field excitation. Thus if generator G_1 is to be shut down the whole load can be shifted onto generator G_2 provided it has the capacity to supply that load. It reduces the current supplied by generator G_1 to zero (is indicated by ammeter A_1) open CB-1 & open the main switch S_1 .

Eddy current loss.

- due to voltages induced in armature core.
- this voltage produces circulating current in core. It is called eddy current & power loss due to this current is called eddy current loss.

- * If a continuous solid iron core is used.
 - Resistance to eddy current is small.
 - as the core has large cross-sectional area.
 - so magnitude of eddy current loss is high.

So care is made of this, round iron sheets called laminations.

Laminations are insulated from each other with varnish coating.

Thus laminating the core increases the core resistance which decreases the eddy current & hence eddy current loss.

$$P_e = K_e B_{max}^2 f^2 t^2 V \text{ Volts.}$$

K_e = Constant depending upon the electrical resistance of core &

ILAHIA COLLEGE OF ENGINEERING AND TECHNOLOGY system of units used.

$t \Rightarrow$ thickness of laminations in m.

$$P_c \propto t^2$$

So laminations thickness should be as small as possible.

Mechanical losses

$\rightarrow$ losses due to friction & windage.

Friction loss $\rightarrow$ Bearing friction,
Brush friction.

Windage loss $\rightarrow$ air friction of rotating parts.
 $\rightarrow$ depends on speed of m/c.

Iron loss + Mechanical loss $\Rightarrow$ Rotational losses
 $\Rightarrow$ Stray losses.

Constant losses & Variable losses

Constant loss

- $\rightarrow$ remains constant at all loads.
- $\rightarrow$ iron loss + mech. loss + shunt field cu loss.

Variable loss

- $\rightarrow$ Vary with load.
- $\rightarrow$ arm. cu loss + Series field cu loss.

Field cu loss is constant for shunt & Comp. Generators.

Total Loss $\rightarrow$ Constant loss + Variable Loss.

CONDITION FOR MAXIMUM EFFICIENCY

Efficiency of generator varies with load.

$$\text{Output} = VI_L$$

$$\text{Input} = \text{Output} + \text{losses.}$$

$$= VI_L + \text{Const. loss} + \text{Variable loss.}$$

$$= VI_L + W_c + I_a^2 R_a$$

$$= VI_L + W_c + (I_L + I_{sh})^2 R_a$$

I_{sh} is very small compared to I_L .

So I_{sh} is neglected.

$$\text{Input} \Rightarrow VI_L + W_c + I_L^2 R_a$$

$$\eta = \frac{\text{o/p.}}{\text{i/p.}} = \frac{VI_L}{VI_L + I_L^2 R_a + W_c}$$

$$\Rightarrow \frac{1}{1 + \left(\frac{I_L R_a}{V}\right) + \left(\frac{W_c}{VI_L}\right)}$$

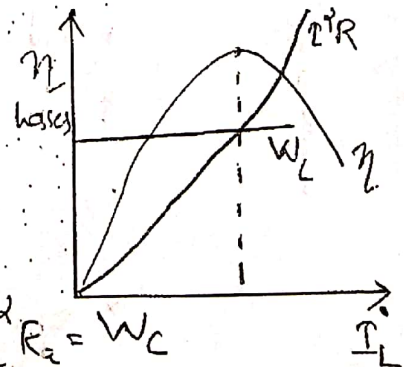
η is max. when denominator is minimum.

$$\text{i.e. } \frac{d}{dI_L} \left(\frac{I_L R_a}{V} + \frac{W_c}{VI_L} \right) = 0$$

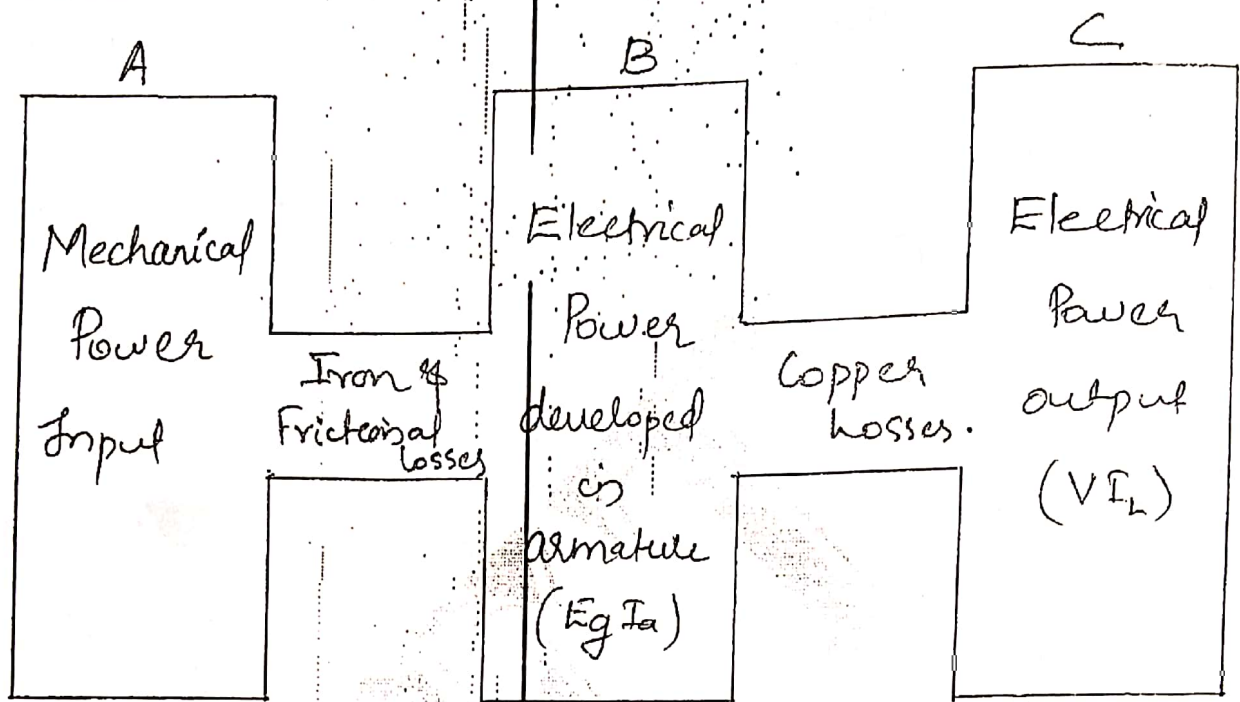
$$\frac{R_a}{V} - \frac{W_c}{VI_L^2} = 0$$

$$R_a = \frac{W_c}{I_L^2} \quad \text{i.e. } I_L^2 R_a = W_c$$

Variable loss = Constant loss



Power Flow Diagram



Mechanical Efficiency

$$\eta_m \Rightarrow \frac{B}{A} \Rightarrow \frac{E_g I_a}{\text{Mech. Power Input}}$$

Electrical Efficiency

$$\eta_e \Rightarrow \frac{C}{B} \Rightarrow \frac{V I_L}{E_g I_a}$$

Commercial/Overall Efficiency

$$\eta_c \Rightarrow \frac{C}{A} \Rightarrow \frac{V I_L}{\text{Mech. Power i/p}}$$

$$\eta_c = \eta_m \times \eta_e$$

$$\eta_c \Rightarrow \frac{C}{A} \Rightarrow \frac{\text{O/p}}{\text{i/p}} = \frac{\text{input} - \text{losses}}{\text{input}}$$

→ Consider a small piece ab of armature
⇒ When ab is under N-pole mag. lines
passes from a to b.

Half revolution later the same
armature ab is under S-pole and the mag. lines
passes from b to a.

⇒ So magnetism in the iron is reversed
in order to reverse continuously the molecular
magnets in the armature core, some power
has to be spent. This power loss is called
hysteresis loss.

Let P_h ⇒ Steinmetz formula.

Hysteresis loss P_h ⇒ $\eta B_{max}^{1.6} f V$ Watts.

where η ⇒ Steinmetz hysteresis coefficient.

B_{max} ⇒ Max. flux density in armature.

V ⇒ Volume of armature in m^3 .

f ⇒ freq. of magnetic reversal $\left(\frac{NP}{120}\right)$

P_h can be reduced by using materials
having low value of η for armature core.

Eg. - Silicon steel

Copper Losses

→ Due to change in current in various windings.

Armature Cu loss $\Rightarrow I_a^2 R_a$

Shunt Field Cu loss $\Rightarrow I_{sh}^2 R_{sh}$

Series Field Cu loss $\Rightarrow I_{se}^2 R_{se}$

→ Cu losses also occur in interpole field windings and also in compensating field winding.

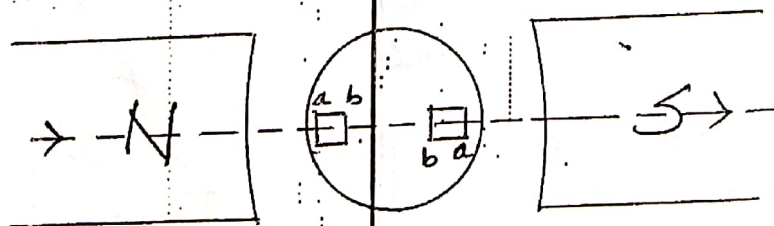
→ Brush contact losses due to brush contact resistance is also included in armature copper loss.

Iron Losses

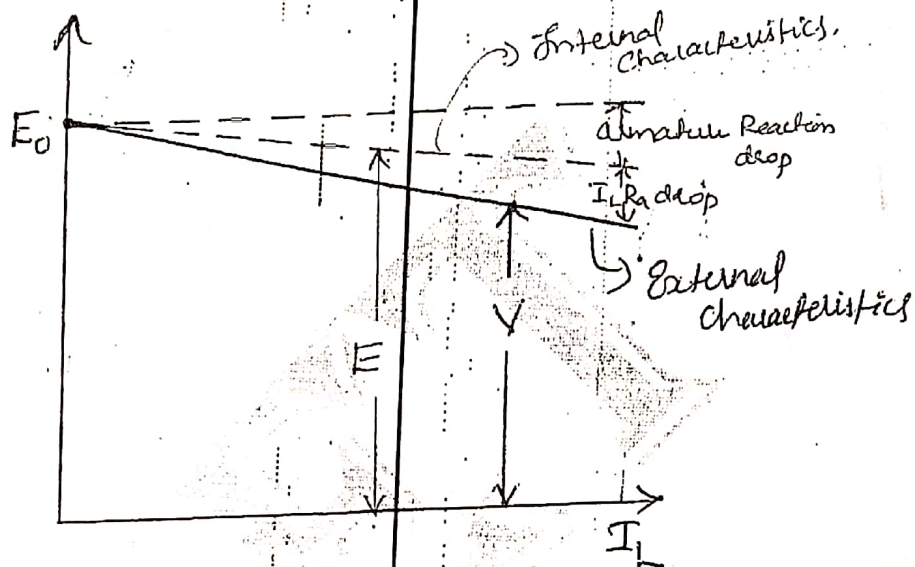
→ Due to the rotation of armature in the magnetic field of the poles.

Hysteresis Loss

→ Occurs as the armature is subjected to magnetic field reversals as it passes under successive poles.



2) Internal & External characteristics (load characteristics)



External charact. is plot b/w V & I_L

Internal charact. is plot b/w E_0 & I_L

$\Rightarrow$ As the load current increases, the terminal voltage falls due to

(i) Armature reaction weakens the main flux so that actual emf E on load is less than E_0 on no load.

(ii) Voltage drop due to arm. resistance
($I_L R_a = I_a R_a$)

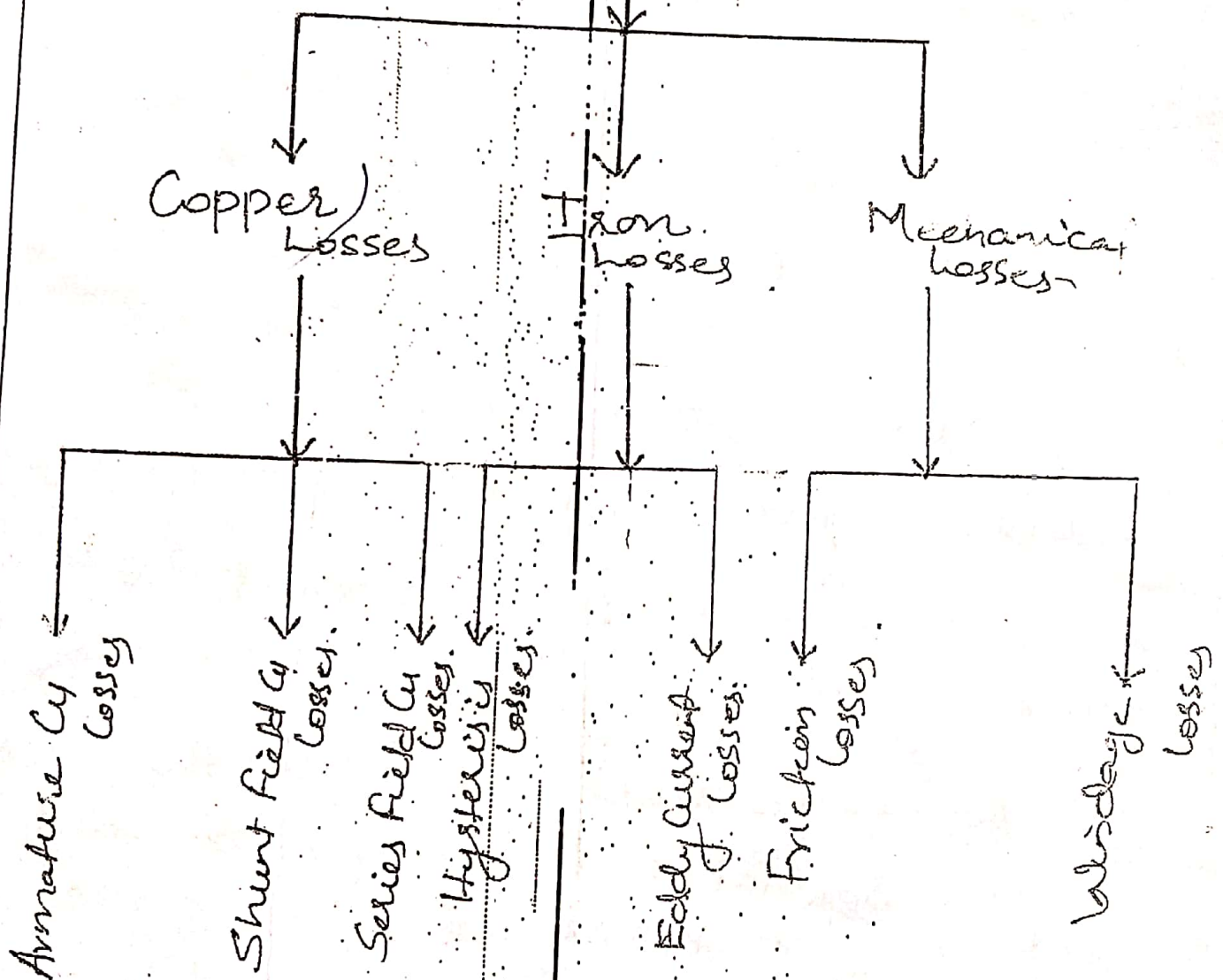
so the external charac. is dropping.

Internal charac. is determined from external charac. by adding $I_a R_a$ drop to external charac.

Losses and Efficiency

Losses in dc m/c are losses

$$\begin{aligned} \phi &= \frac{P}{f} \\ N &= \text{speed} \\ \frac{d\phi}{dt} &= \frac{60}{N} \cdot \frac{P}{f} \\ \frac{d\phi}{dt} &= \frac{P}{f} \cdot \frac{60}{N} \end{aligned}$$



→ These losses appear mainly as heat & thus raise the temperature of the machine.

→ Reduces the efficiency.

MODULE - III

DC MOTOR

→ It converts electrical energy into the mechanical energy. i.e. DC power into mechanical power.

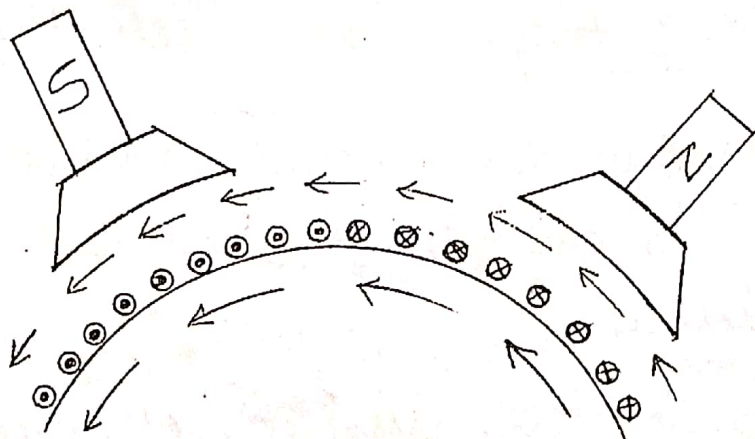
PRINCIPLE :-

→ When a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.

→ The direction of the force is given by Fleming's left hand rule. and the magnitude is given by.

$$F = B i l \text{ Newtons}$$

WORKING OF DC MOTOR



→ Consider a multipolar DC Motor. When DC supply is given.

(i) Field magnets are excited developing alternate N and S poles.

(ii) → armature conductors carry currents.

→ all conductors under N-pole carry current in one direction and under S-pole carry currents in opposite direction.

→ Each armature conductor is carrying current and is placed in the magnetic field. So the mechanical force acts on it.

→ Applying Fleming's left hand rule the force on each conductor is tending to rotate the armature in anticlockwise direction.

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

→ When the conductor moves from one side of brush to another, the current in that conductor is reversed.

→ So the direction of force on the conductor remains the same.

BACK/COUNTER EMF

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

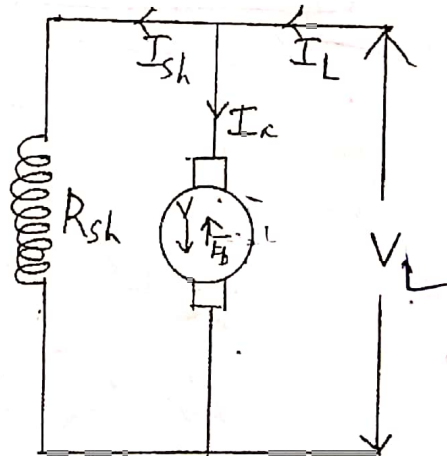
→ The induced emf acts in opposite direction to the applied voltage (V) by Lenz's law and is known as back emf or counter emf (E_b).

$E_b \Rightarrow \frac{\phi ZNP}{60A}$ is always less than the applied voltage V .

Net voltage across armature circuit.

$$\Rightarrow V - E_b$$

If R_a is the armature circuit resistance.



$$I_a = \frac{V - E_b}{R_a}$$

V & R_a are fixed, so E_b & I_a
If speed is high, E_b is high and motor draws less current and vice-versa.

SIGNIFICANCE OF BACK EMF

⇒ At starting $E_b = 0$

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

So at starting armature current is large. So in order to limit I_a , starters are used.

⇒ At no load, $V \propto E_b$

i.e. small torque is required to overcome friction and windage loss.

So I_a is small.

⇒ The presence of ^{E_b} back emf makes the dc motor self regulating.

When motor is loaded, the driving torque of the motor is not sufficient to meet the increased load torque.

So armature slows down.

So E_b falls down $N \propto E_b$.

Reduced E_b cause larger currents to flow through armature

$$I_a = \frac{V - E_b}{R_a}$$

Increase in I_a causes increase in electro-magnetic torque.

→ Motor continues to slow down till

$$T_L = T_m$$

⇒ When the load on motor falls, Torque developed by motor is excess of the load requirement.

So motor armature accelerates.
With the increase in armature speed,

E_b increases causes I_a to decrease.

I_a decreases causes decrease in Torque.
Steady state conditions are attained when

$$T_m = T_L$$

E_b acts like a generator.

i.e. It makes motor self regulating. So that it ~~draws~~ draws as much current as just required.

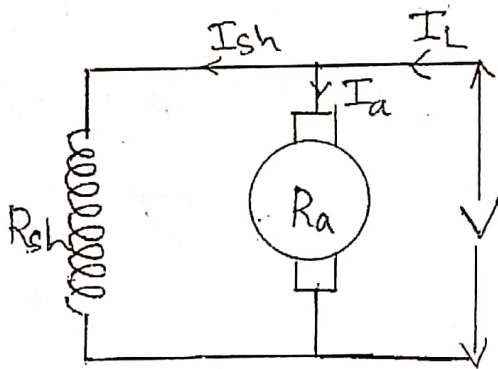
CLASSIFICATION

⇒ Manner in which the field winding is connected to armature. They are classified.

- 1) Shunt Wound Motor
- 2) Series Wound Motor.
- 3) Compound Wound Motor.

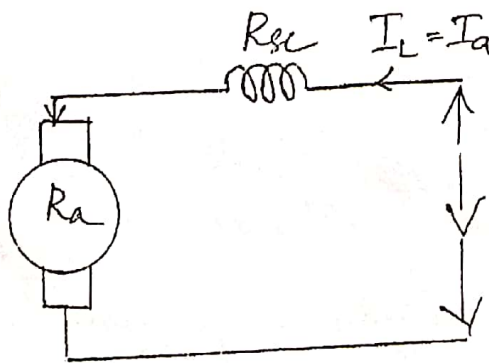
① Shunt Wound Motor.

- Field winding is connected parallel with armature.
- Shunt field windg have relatively large no: of turns of wire having high resistance.
- Shunt field current is small compared to I_a .



② Series Wound Motor.

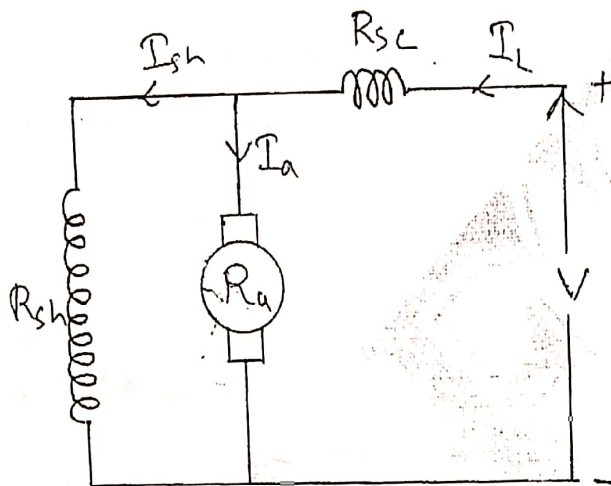
- Field windg is connected series with armature
- series field carries I_a .
- Series field windg has small number of turns of thicker wire and so it posses a low resistance.



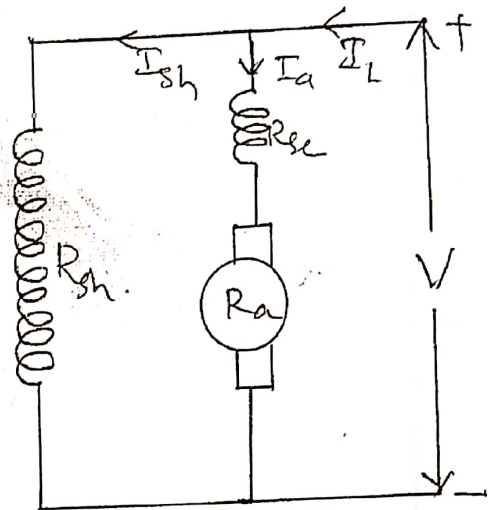
③ Compound wound Motor.

→ has 2 field windings.

→ One connected is parallel with armature and other is series with it.



Short-shunt connection.



Q₁. A 250V shunt motor takes a total current of 20A. R_{sh} and R_a are 200Ω & 0.3Ω resp.

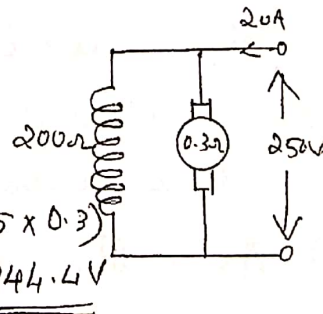
Determine (i) Back emf.

(ii) Gross Mech. Power in the arm.

$$I_{sh} = \frac{250}{200} = 1.25A$$

$$I_a = 20 - 1.25 \Rightarrow 18.75A$$

$$E_b = V - I_a R_a = 250 - (18.75 \times 0.3) \Rightarrow 244.4V$$



$$P_m = E_b I_a = 244.4 \times 18.75 \Rightarrow 4582.5W$$

Q₂. The counter emf of a shunt motor is 227 V, R_{sh} is 160Ω and field current is 1.5 A. If the line current is 39.5 A. Find R_a & I_a when motor is stationary.

$$V = I_{sh} R_{sh} \Rightarrow 1.5 \times 160 \Rightarrow 240V$$

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

$$\Rightarrow 39.5 - 1.5 \Rightarrow 38 A$$

$$V \Rightarrow E_b + I_a R_a \Rightarrow R_a = \frac{V - E_b}{I_a}$$

$$\Rightarrow \frac{240 - 227}{38} \Rightarrow \underline{\underline{0.342\Omega}}$$

When the motor is stationary, $E_b = 0$

$$I_a = \frac{V}{R_a} = \frac{240}{0.342} \Rightarrow \underline{\underline{701.5 A}}$$

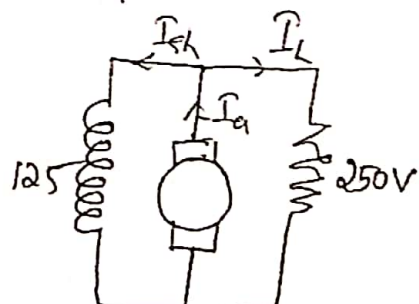
Q₃ · A 20 kW, 250 V dc shunt generator has R_a & R_{sh} of 0.1Ω & 125Ω resp. Calculate total arm. power developed when running

- (i) as a generator delivering 20 kW output.
- (ii) as a motor taking 20 kW output.

(i) As a Generator.

$$I_L = \frac{20 \times 10^3}{250}$$

$$\Rightarrow 80 A$$



$$I_{sh} = \frac{250}{125} = \underline{\underline{2 A}}$$

$$I_a = I_L + I_{sh} = \underline{\underline{82 A}}$$

$$E_g = V + I_a R_a = 250 + 82 \times 0.1$$

$$\Rightarrow \underline{\underline{258.2 V}}$$

Power developed in armature $\Rightarrow E_g I_a$

$$\Rightarrow 258.2 \times 82$$

$$\Rightarrow 21.17 \times 10^3 W \Rightarrow \underline{\underline{21.17 kW}}$$

(ii) As a Motor

$$I_L = 80 A$$

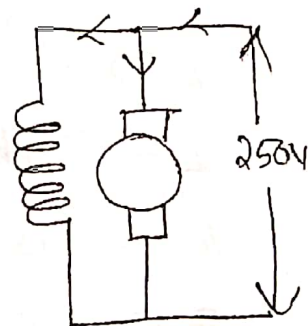
$$I_{sh} = 2 A$$

$$I_a = I_L - I_{sh} \Rightarrow 78 A$$

$$E_b = V - I_a R_a$$

$$= 250 - 78 \times 0.1$$

$$\Rightarrow \underline{\underline{242.2 V}}$$



Power developed in armature

$$\Rightarrow E_b I_a$$

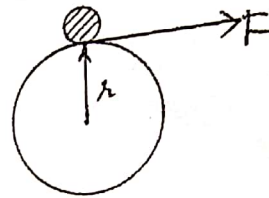
$$\Rightarrow 242.2 \times 78$$

$$\Rightarrow \underline{\underline{18.9 kW}}$$

ARMATURE TORQUE OF DC MOTOR

Torque is the turning moment of a force about an axis.

$$T = F \times r$$



In a DC motor, each conductor exerts a torque, tending to rotate the armature. The sum of the torque due to all conductors is known as gross or armature torque (T_a).

Let in a DC Motor,

$r \rightarrow$ avg. radius of arm. is m.

$l \rightarrow$ effective length of each conductor is m.

$Z \rightarrow$ Total no. of arm. conductors.

$A \rightarrow$ No. of parallel paths.

$B \rightarrow$ average flux density is wb/m^2 .

$\phi \rightarrow$ flux per pole is wb.

$P \rightarrow$ No. of poles.

$i \Rightarrow$ current in each conductor $\Rightarrow \frac{I_a}{A}$.

Force on each conductor, $F = B i l$ Newton.

Torque due to each conductor, $T = F \times r$ Nm

Total armature Torque : $T_a = Z F \alpha$.
 $\Rightarrow Z \cdot B l \alpha \text{ Nm.}$

where $\epsilon = I_a / A$ & $B = \phi / a$

i.e. $a = \frac{2\pi r l}{P} \Rightarrow$ cross-sectional area of flux path/pole at radius r .

$$\text{i.e. } T_a = Z \times (\phi / a) \times (I_a / A) \times l \times r$$

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

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

$$B = \phi / a$$

$$i = I_a / A$$

$$a = \frac{2\pi r l}{P}$$

$$\text{i.e. } T_a = 0.159 Z \phi I_a (P/A) \text{ Nm.}$$

If Z, P & A are fixed for a given m/c.

$$T_a \propto \phi I_a$$

For a shunt Motor

ϕ is practically constant.

$$T_a \propto I_a$$

For a series motor

$$\phi \propto I_a$$

$$T_a \propto I_a^2$$

Alternate Expression:-

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

$$T_a = 0.159 Z \phi I_a \left(\frac{P}{A} \right) \text{ Nm}$$

From (1)

$$Z \phi \left(\frac{P}{A} \right) = \frac{60 \times E_b}{N}$$

$$\therefore T_a = 0.159 \times \frac{60 \times E_b}{N} \times I_a \text{ Nm.}$$

$$T_a = 9.55 \frac{E_b I_a}{N} \text{ Nm}$$

Shaft Torque (T_{sh})

→ Torque available at the motor shaft for doing useful work.

→ T_a is armature of the motor is not available as T_{sh}



because a part of it are lost in overcoming iron & frictional loss in motor.

$$T_a - T_{sh} \Rightarrow \text{Lost torque.}$$

$$T_a - T_{sh} = 9.55 \frac{\text{Iron \& Frictional loss}}{N}$$

$$\therefore \text{O/p in Watts} \Rightarrow \frac{2\pi N T_{sh}}{60}$$

$$T_{sh} = \frac{\text{O/p in Watts}}{2\pi N/60} \text{ Nm.}$$

$$T_{sh} = 9.55 \frac{\text{O/p in Watts}}{N} \text{ Nm}$$

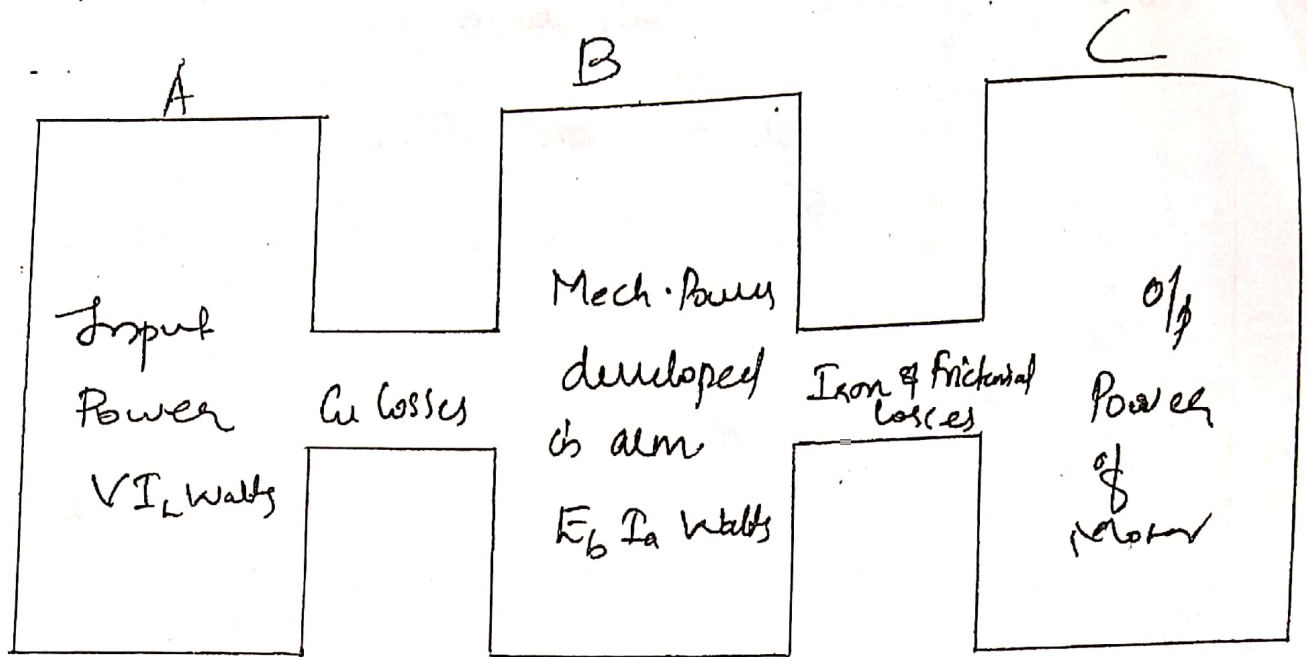
Brake Horse Power (BHP)

Horse power developed by shaft torque is known as brake horse power.

$$\text{BHP} \Rightarrow \frac{\text{O/p in Watts}}{746}$$

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

POWER FLOW DIAGRAM.



Overall efficiency, $\eta_c = C/A$

Electrical efficiency, $\eta_e = B/A$

Mechanical efficiency, $\eta_m = C/B$

Speed of a DC Motor.

$$E_b = V - I_a R_a$$

$$E_b = \frac{P\phi ZN}{60A}$$

$$\frac{P\phi ZN}{60A} = V - I_a R_a$$

$$N = \frac{(V - I_a R_a)}{\phi} \times \frac{60A}{PZ}$$

$$= K \frac{(V - I_a R_a)}{\phi}$$

where $K = \frac{60A}{PZ}$

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

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

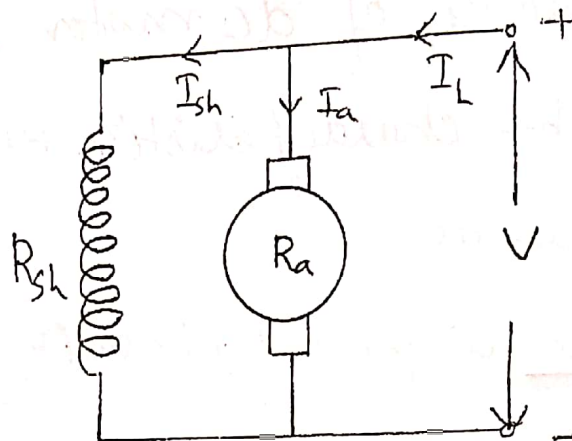
DC MOTOR CHARACTERISTICS :-

Performance of dc motor can be judged from the characteristics known as motor characteristics.

Most three important charact. of DC Motor are:-

- ① Torque and Armature current characteristics (T_a/I_a)
 - curve b/w T_a & I_a of dc motor.
 - also known as electrical characteristics of dc motor.
- ② Speed and armature current characteristics (N/I_a)
 - Curve b/w N & I_a .
 - Deciding factor is the selection of the motor for a particular application.
- ③ Speed and Torque characteristics (N/T_a)
 - curve b/w N & T_a .
 - also called mechanical characteristics.

Characteristics of DC SHUNT Motors:-



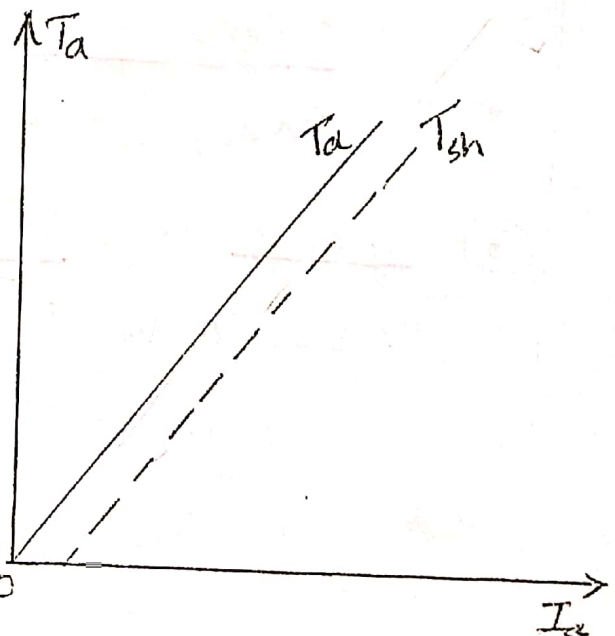
Field current I_{sh} is constant since field winding is directly connected to supply voltage V . Hence ϕ is a shunt motor is approximately constant.

(i) T_a/I_a characteristics.

$$T_a \propto \phi I_a$$

ϕ is constant, $\therefore T_a \propto I_a$

Hence T_a/I_a charac. is a straight line passing through the origin.



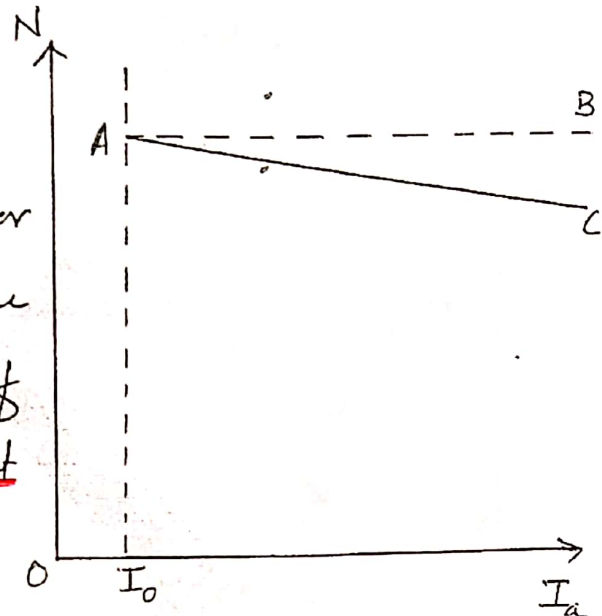
T_{sh} is less than T_a and is shown by dotted line.

→ Large current is required to start heavy load. So shunt motor should not be started on heavy load.

(ii) N/I_a characteristics :

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

E_b and ϕ is a shunt motor is almost constant under the normal conditions. So speed of shunt motor remain constant as I_a varies. (dotted line AB)



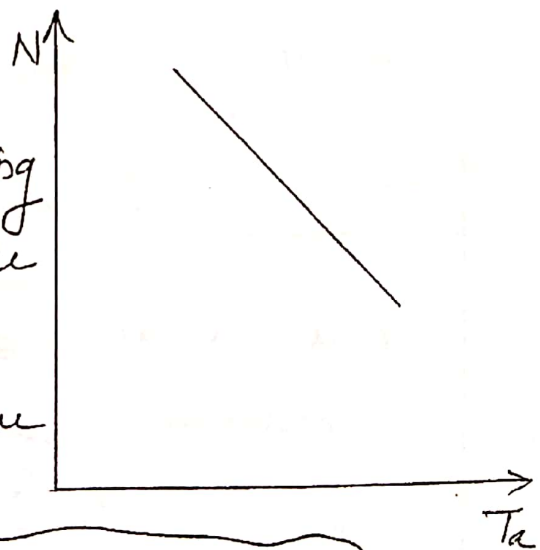
→ But when load is increased, E_b & ϕ decreases due to armature resistance drop and armature reaction respectively.

→ So speed of motor decreases slightly with load (line AC).

(iii) N/T_a characteristics.

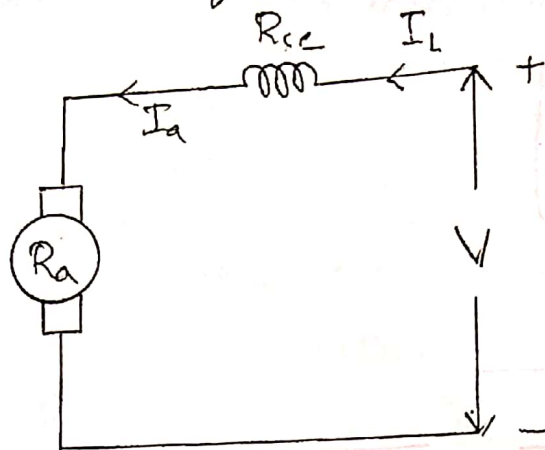
Curve obtained by plotting N and T_a for various armature current.

Speed falls as load torque increases.



Essentially a constant speed motor
Starting torque is not high as $T_a \propto I_a$

Characteristics of DC series motor:



Current through the field winding is same as armature current.

So flux increases with increase in I_a and vice versa.

(ii) T_a / I_a characteristics.

$$T_a \propto \phi I_a$$

$\phi \propto I_a$, upto magnetic saturation.

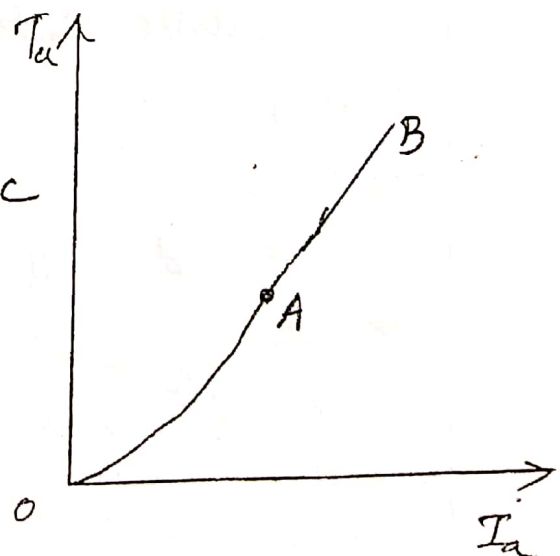
$$T_a \propto I_a^2$$

ϕ is constant, after magnetic saturation

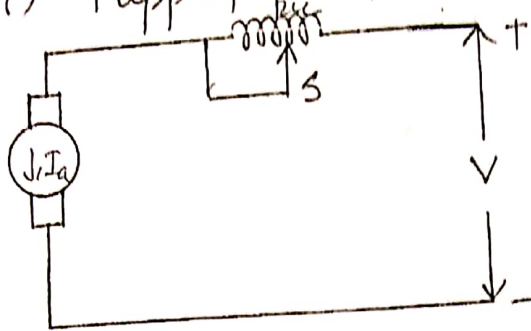
$$T_a \propto I_a$$

Upto magnetic saturation

$$T_a \propto I_a^2$$



(iii) Tapped field control



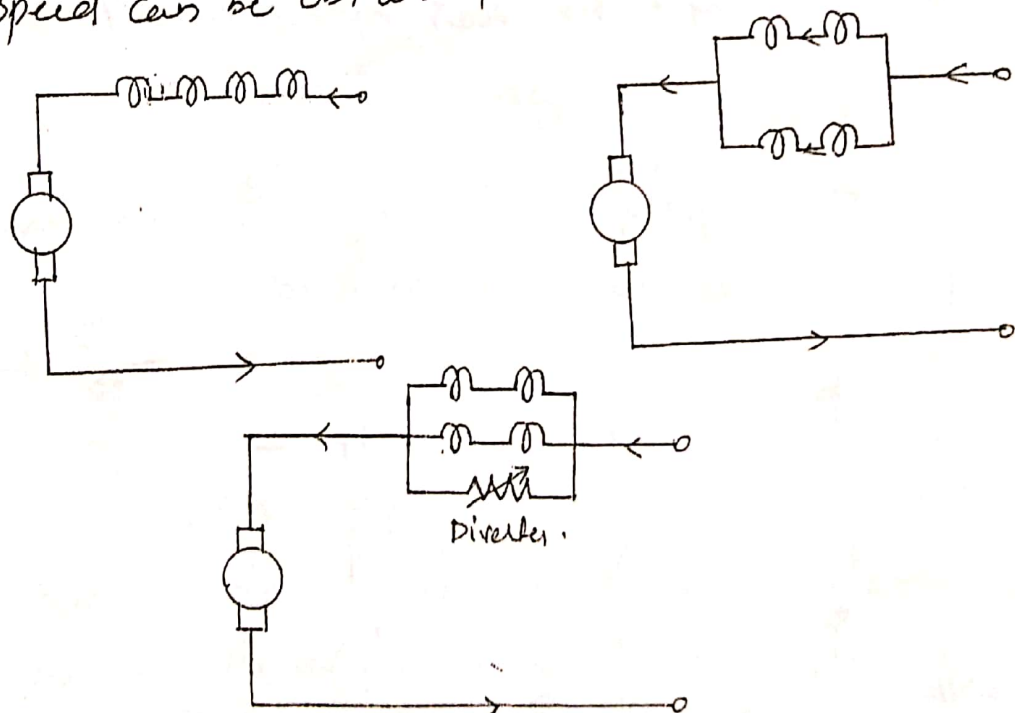
→ Flux is reduced & hence speed is increased by decreasing the number of turns of the series field winding.

→ The switch S can short cut any part of the field windg; thus decreasing flux & raising the speed.

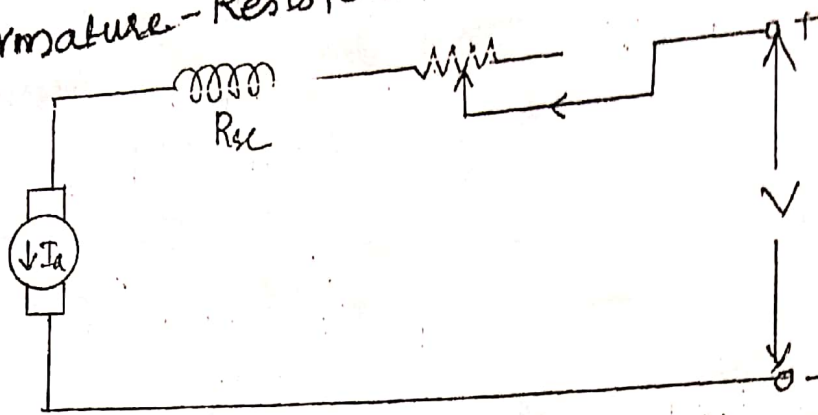
(iv) Parallelising Field coils.

→ This mtd is employed in the case of fan motors.

→ By regrouping the field coils several fixed speed can be obtained.



2. Armature-Resistance Control..



→ A variable resistance is directly connected in series with the supply to the motor.

→ This reduces the voltage across armature.

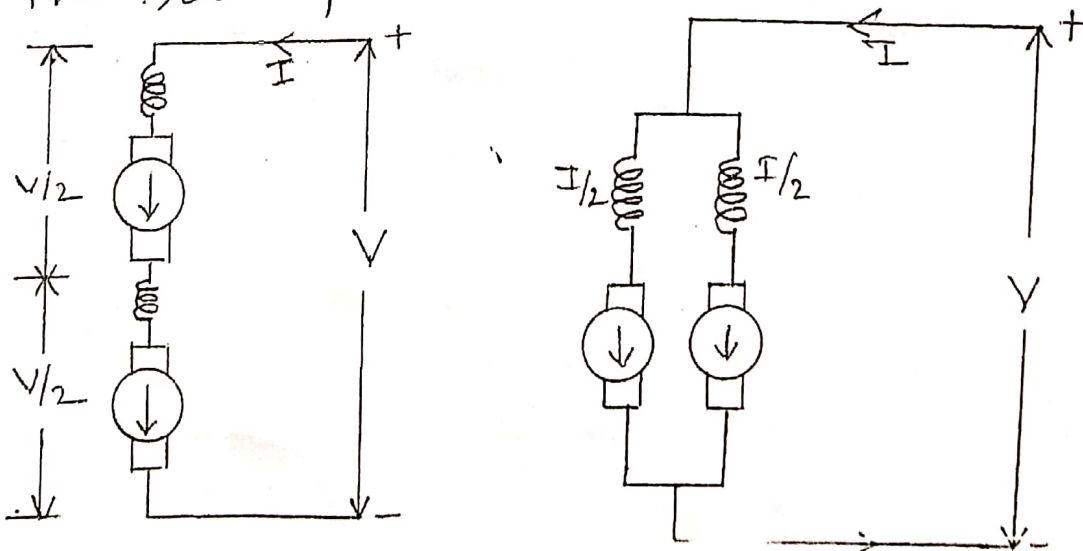
→ Hence speed reduces.

→ By changing the value of resistance speed can be changed.

→ This mtd has poor speed control. & regulation.

3. Series-Parallel control.

→ The speed control of d.c series motor is the series-parallel method.



Characteristics of DC Compound Motor.

→ Compound motor has both series field and shunt field windings.

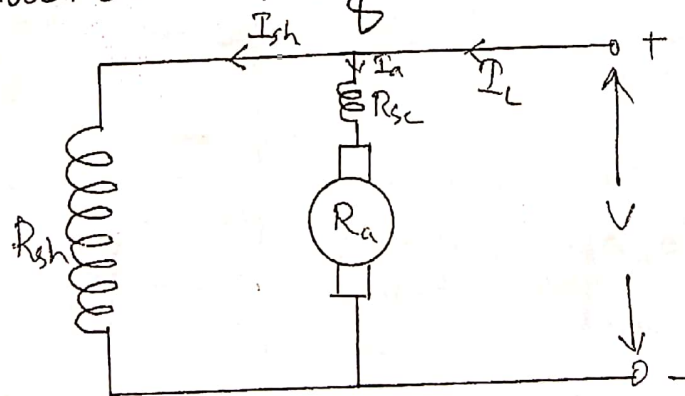
→ Compound motors are mainly of two types

(i) Differential Compound Motors.

(ii) Cumulatively Compound Motors.

Differential compound motors are rarely used due to their poor torque characteristics at heavy loads.

Characteristics of Cumulatively Compound Motor.



→ Each pole carries a series field and shunt field winding.

→ Series field aids shunt field.

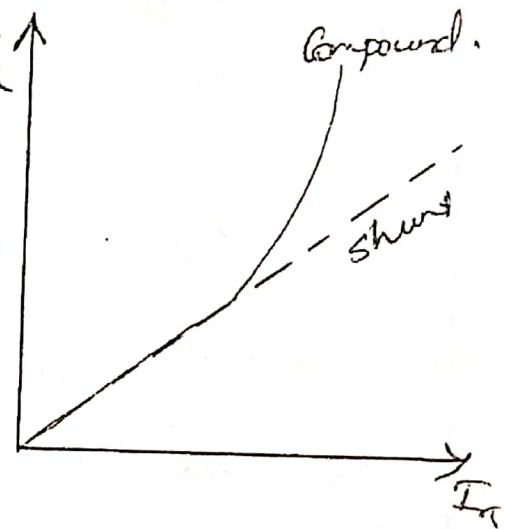
(i) T_a/I_a characteristics.

$$T_a \propto \phi I_a.$$

→ As load increases, series field increases but shunt field remains constant.

So total flux is increased T_a and hence T_a .

→ Torque of a cumulatively compound motor is greater than that of shunt motor, due to series field.

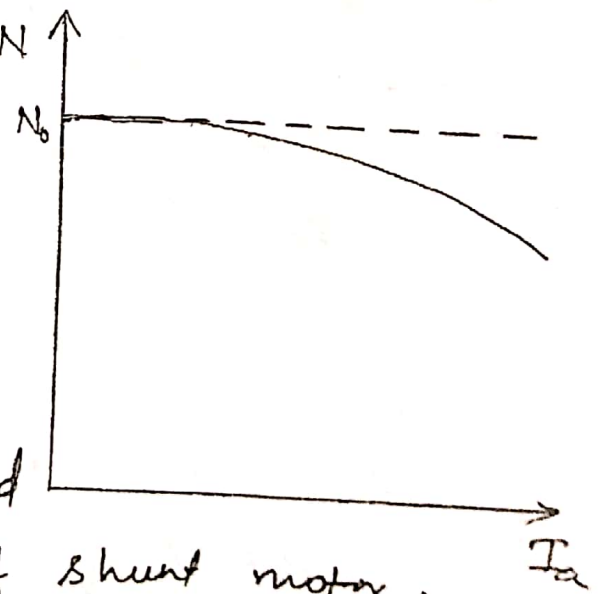


(ii) N/I_a characteristics.

→ As load increases, total ϕ increases.

$N \propto \frac{1}{\phi}$. So speed falls as load ϕ increases.

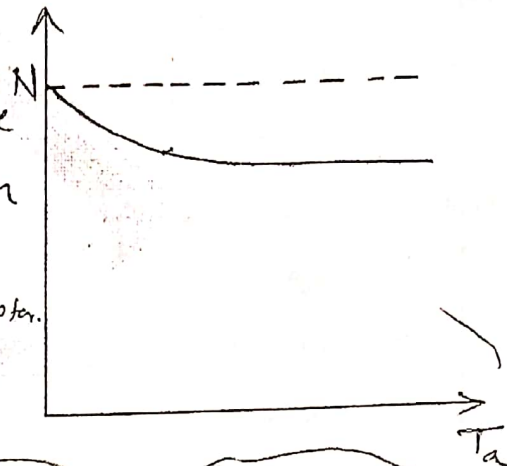
→ Speed regulation of the cumulatively compound motor is poorer than that of shunt motor.



→ Due to shunt field, motor has a definite no load speed and can be operated safely at no load.

(iii) N/I_a Characteristics.

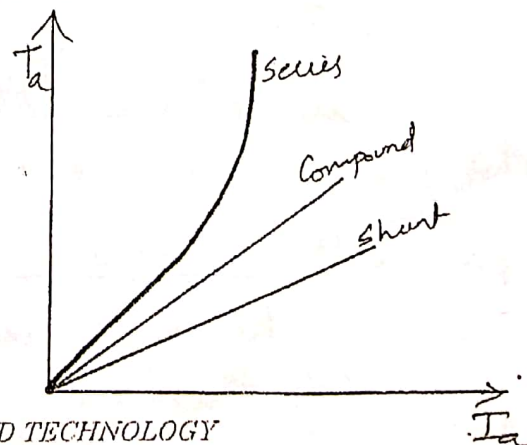
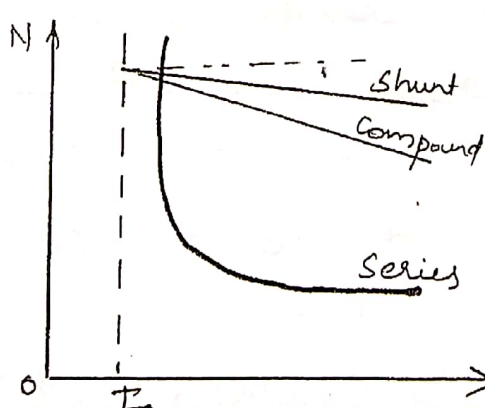
→ For a given armature current, T_a of the cumulative compound motor is more than that of shunt motor but less than that of series motor.



⊛ Starting torque is increased due to series field.

⊛ Motor is prevented from running away at no-load due to shunt field.

COMPARISON OF 3 MOTORS



- ① $\Rightarrow$ Speed reg. of shunt motor is better than series motor and speed reg. of cumulative comp. motor lies b/w shunt & series motor.
- ② $\Rightarrow$ Starting torque of series motor is more than shunt motor. Starting torque of cumulative comp. motor lies b/w shunt & series motor.
- ③ $\Rightarrow$ Both shunt and cumulative comp. motor have definite no load speed. But series motor has dangerously high speed at no load.

NECESSITY OF D.C. MOTOR STARTER.

$\rightarrow$ At starting when the motor is stationary.
there is no back emf in the armature.

$\rightarrow$ If the motor is directly switched on to the mains.

$\rightarrow$ Because of small armature resistance armature will draw a heavy current.

This will result in :-

- (i) Burning of armature due to excessive heating effect.
- (ii) Damaging the commutator and brushes due to heavy sparking.

(iii) Excessive voltage drop in the line to which the motor is connected.

TYPES OF DC. MOTOR STARTERS

→ The starting operation of a dc motor consists in the insertion of external resistance into the armature circuit to limit the starting current taken by the motor and the removal of this resistance in steps as the motor accelerates.

→ There are two principal types of dc motor starters.

a) Three-point starter.

b) Four-point starter.

a) Three-Point Starter.

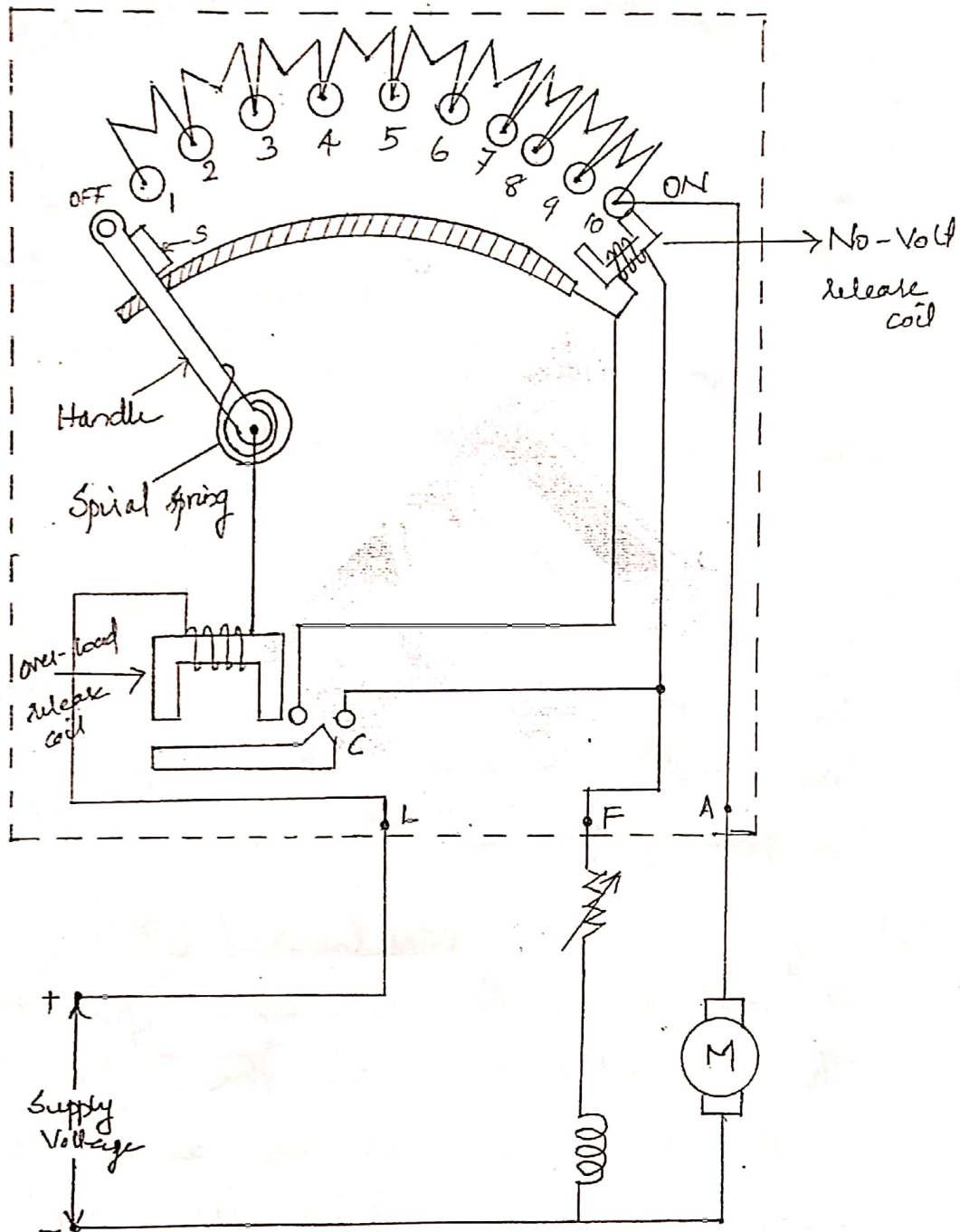
→ This type of starter is widely used for starting & compound motors.

→ The three-point starter for a shunt motor with protective devices.

→ It has three terminals L, Z & A.

→ The starter consists of starting resistances divided into several sections and connected in series with the armature.

- The tapping points of the starting resistance are brought out to a number of studs.
- The three terminals L, Z & A of the starter are connected respectively to the positive line terminals, shunt field terminals and armature terminals.
- The armature and shunt field windings are connected to the negative terminals of the supply.
- The no-volt release coil is connected in the shunt field circuit.
- One end of the handle is connected to the terminals L through the over-load release coil.
- The other end of the handle moves against a spiral spring and makes contact with each stud during starting operation, cutting out more & more starting resistance as it passes over each stud in clockwise direction.



Operation

- To start, the d.c supply is switched on with handle OFF position.
- The handle moved clockwise to the first stud. As soon as it comes in contact.

with first stud, the shunt field winding is directly connected across the supply. The whole starting resistance is inserted in series with the armature circuit.

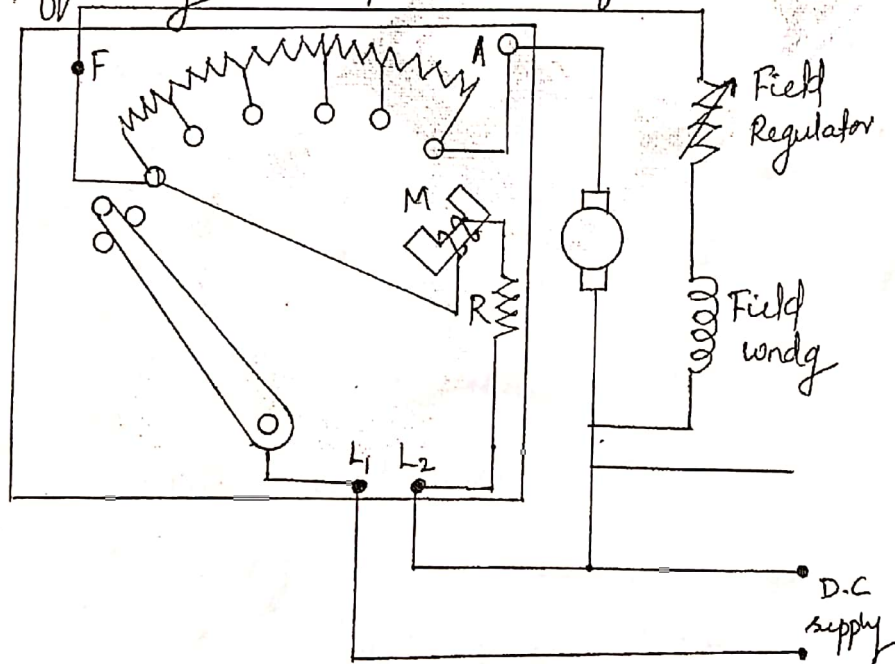
(iii) As the handle is gradually moved over to the final stud, the starting resistance is cut out of the armature circuit in steps.

(iv) If the supply voltage is suddenly interrupted or if the field excitation is accidentally cut, the no-volt release coil is demagnetised and the handle goes back to the OFF position under the pull of the spring.

(v) If the motor is overloaded (or a fault occurs) it will draw excessive current from the supply. This current will increase the ampere-turns of the over-load release coil and pull the armature C. thus short-circuiting the no-volt release coil. The no-volt coil is demagnetised and the handle is pulled to the OFF position by the spring.

b) Four-Point Starter.

- In a four-point starter, the no-volt release coil is connected directly across the supply line through a protective resistance R .
- No-volt release coil circuit is independent of the shunt field circuit.
- Proper speed control can be exercised without affecting the operation of no-volt release coil.



- The only difference b/w a three point starter and a four-point starter is the manner in which no-volt release coil is connected.

- The working of the two starters are the same.
- The three-point starters also provides protection against an open-field circuit.
- Protection is not provided by the four-point starter.

SPEED CONTROL OF D.C. MOTORS

⇒ The d.c motor is of considerable industrial importance. The principal advantage of a d.c motor is that its speed can be changed over a wide range by a variety of simple methods.

The speed of DC motor

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

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

where $R = R_a = R_{at} + R_{sc}$

the main three methods of speed control.

- (i). By varying the flux per pole (ϕ). This is known as flux control method.
- (ii). By varying the resistance in the armature circuit. This is known as armature control Method.
- (iii). By varying the applied voltage V . This is known as voltage control method.

SPEED CONTROL OF D.C. SHUNT MOTORS

→ Speed of a shunt motor can be changed by

- 1) flux control method
- 2) armature control method.

3) Voltage control method.

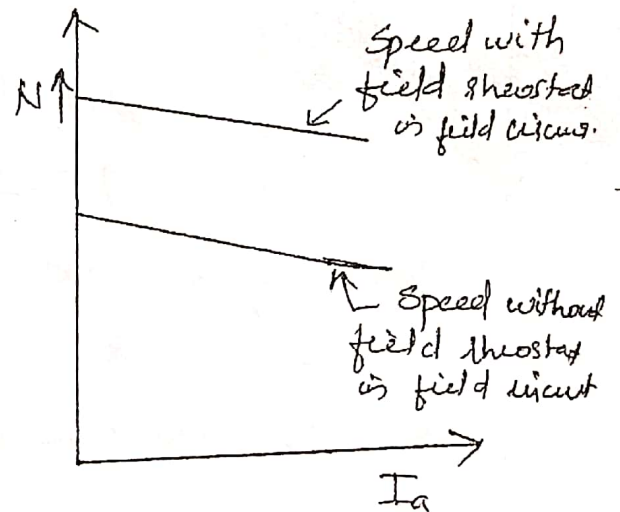
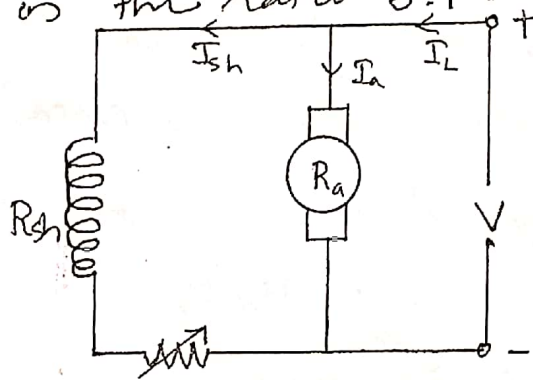
i) Flux Control Method

→ By varying the flux ϕ , the motor speed ($N \propto 1/\phi$) can be changed and hence the name flux control method.

→ A variable resistance (known as shunt field rheostat) is placed in series with shunt field winding.

→ The shunt field rheostat reduces the shunt field current I_{sh} & hence the flux ϕ . & the raise the speed of the motor above the normal speed.

→ This method permits to increase the speed is the ratio 3:1



Advantages.

→ This is an easy and convenient mtd.

→ It is an inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of I_{sh} .

(iii) The speed control exercised by this method is independent of load on the machine.

Disadvantages.

(i) Only speeds higher than the normal speed can be obtained since the total field circuit resistance cannot be reduced below R_{sh} .

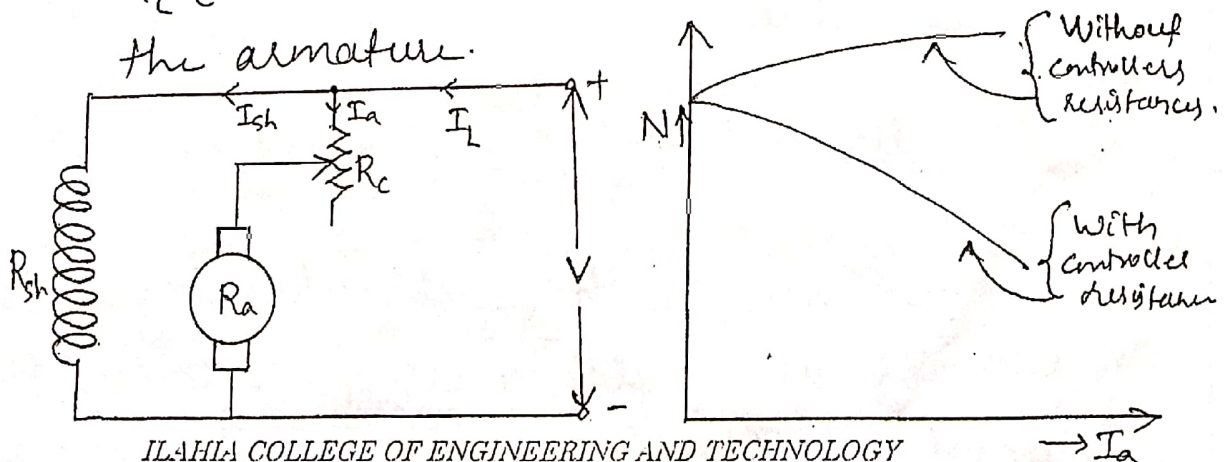
(ii) There is a limit to the maximum speed obtained by this method. It is because if the flux is too much weakened.

2) Armature control Method.

→ This method is based on the fact that by varying the voltage available across the armature.

→ The back emf and hence the speed of the motor can be changed.

→ This is done by inserting a variable resistance R_c (known as controller resistance) in series with the armature.



→ The voltage drop in the controller resistance, the back emf (E_b) is decreased.

→ Since $N \propto E_b$, the speed of the motor is reduced.

→ The highest speed obtainable is that corresponding to $R_c = 0$. i.e. normal speed.

Disadvantages.

- (i) A large amount of power is wasted in the controller resistance since it carries full armature current I_a .
- (ii) The speed varies widely with load since the speed depends upon the voltage drop in the controller resistance and hence on the armature current demanded by the load.
- (iii) The output and efficiency of the motor are reduced.
- (iv) Results in poor speed regulation.

⇒ Due to these disadvantages, this method is seldom used to control the speed of shunt motor.

3. Voltage Control Method.

→ The voltage source supplying the field current is different from that which supplies the armature.

→ This method avoids the disadvantages of poor speed ^{regulation} and low efficiency as in armature control method.

(i) Multiple Voltage control.

→ The shunt field of the motor is connected permanently across a fixed voltage source.

→ The armature can be connected across several different voltages through a suitable switchgear.

→ The voltage applied across the armature can be changed. The speed will be approximately proportional to the voltage applied across the armature.

(ii) WARD-LEONARD SYSTEM

→ The adjustable voltage for the armature is obtained from an adjustable-voltage generator while the field circuit is supplied from a separate source.

→ The armature of the shunt motor M (whose speed is to be controlled) is connected directly to a d.c. generator G driven by a constant-speed a.c. motor A .

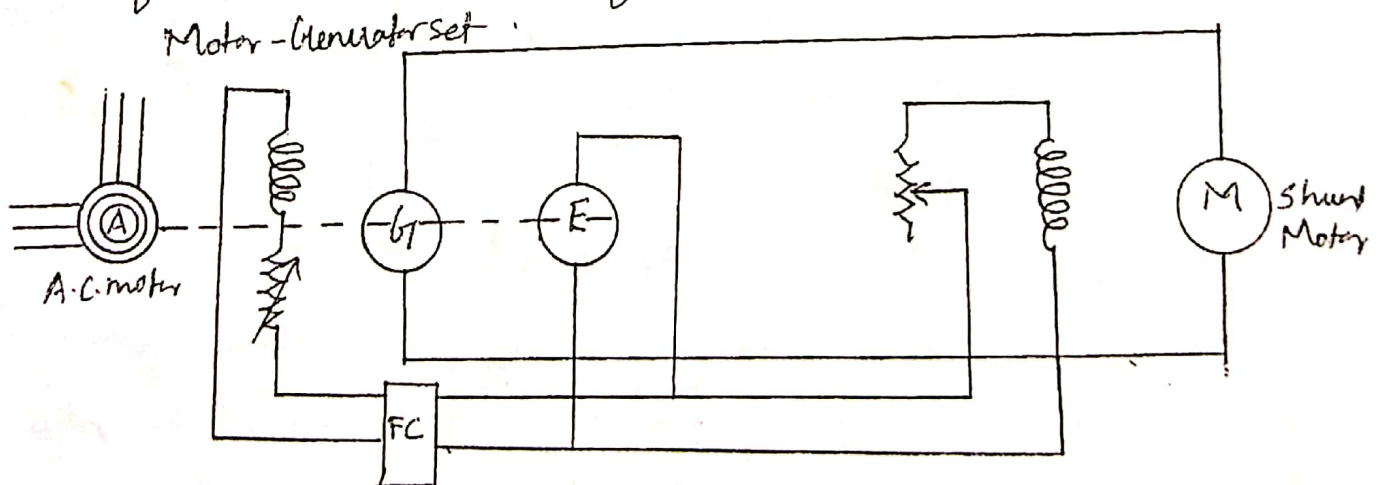
→ The field of the shunt motor is supplied from a constant-voltage exciter E .

→ The field of the generator G is also supplied from the exciter E .

→ The voltage of the generator G can be varied by means of its field regulator.

→ By reversing the field current of generator G by controller FC , the voltage applied to the motor may be reversed.

→ Field regulator is included in the field circuit of shunt motor M for additional speed adjustment.



Advantages

- It has high efficiency
(i.e. speed can be adjusted to any range without resistance losses).
- The motor can be brought to standstill quickly, simply by rapidly reducing the voltage of generator(G).
- This method is used for speed control of large motors when dc supply is not available.

Disadvantages

- Special motor-generator set is required for each motor.
- Losses in this set is high if the motor is operating at light loads for long period.

Speed Control of DC series Motor.

- The speed control methods of DC series motor are.

1) Flux control Method

- The flux produced by the series motor is varied and hence the speed. Variation of flux

can be achieved by

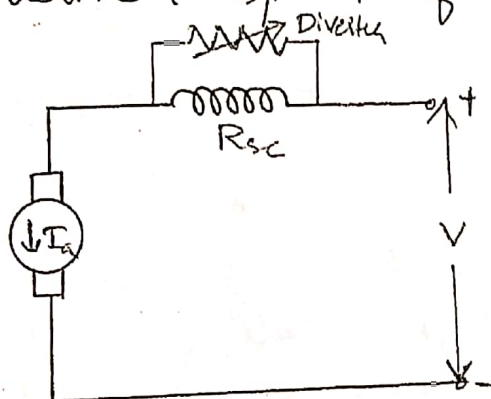
(i) Field Diverters.

→ Variable resistance (called field diverters) is connected parallel with series field winding.

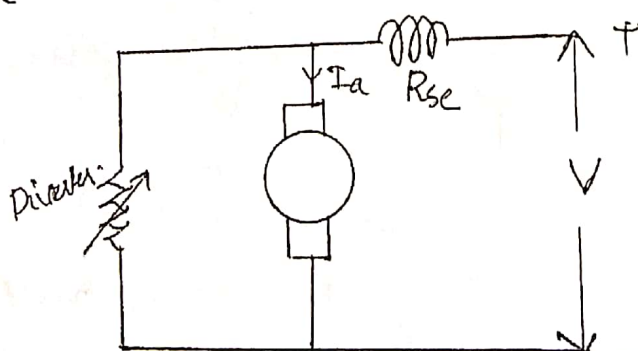
Here ($N \propto 1/\phi$)

→ The lowest speed obtainable is that the corresponding to zero current in the diverter.

→ The lowest speed obtainable is the normal speed of motor.



(ii) Armature Diverter



→ A variable resistor called armature diverter is connected in parallel with the armature.

→ The diverter shunts the currents (line), thus reducing armature current.

$I_a \propto \phi I_a$
thus P_a reduces

$N \propto 1/\phi$
the motor speed reduces

- When the motors are connected in series motor armature will receive one-half the normal voltage.
- The speed will be low.
- When the motors are connected in parallel, each motor armature receives the normal voltage & the speed is high.
- Thus two speeds obtain.
- Four times the speed when the machines are in parallel.

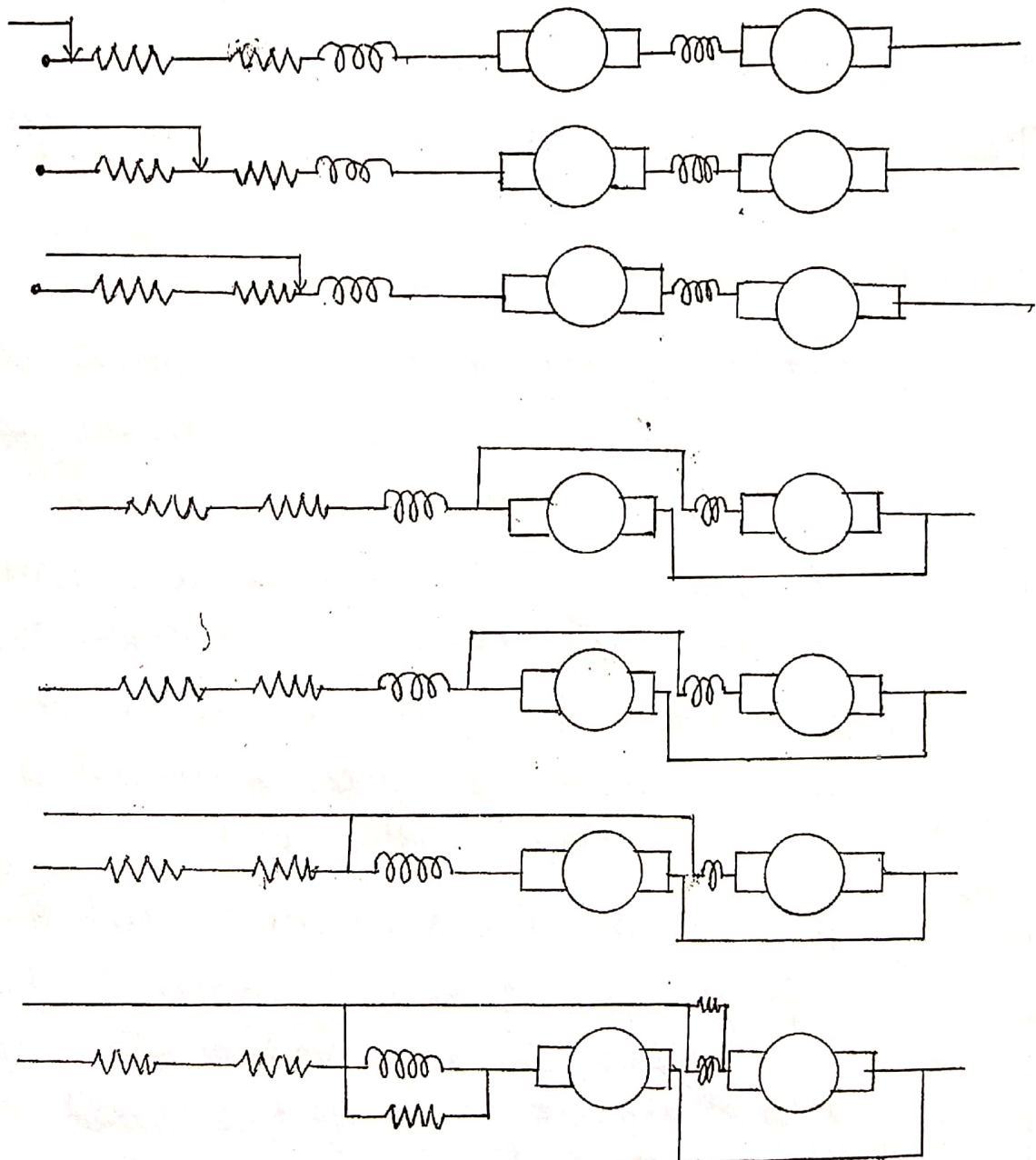
Series-Parallel & Resistance Control.

- Series parallel method is usually combined with resistance method of control in electric traction.

(i) At standstill, the motor are connected in series via starting rheostat. The motors are started up in series with each other and starting resistance is cut out step by step to increase the speed.

⇒ When all the resistance is cut out, the voltage applied to each motor is about one-half of the line voltage. The speed is then about one-half of the rated.

(ii) To increase the speed further, the two-motors are connected in parallel and at the same time starting resistance is connected in series with the combination. The starting resistance is again cut out step by step until full speed is attained.



TESTING OF DC MOTOR

→ The most important performance tests to be conducted on dc m/c are :-

→ Direct loading Methods.

→ Indirect loading Methods.

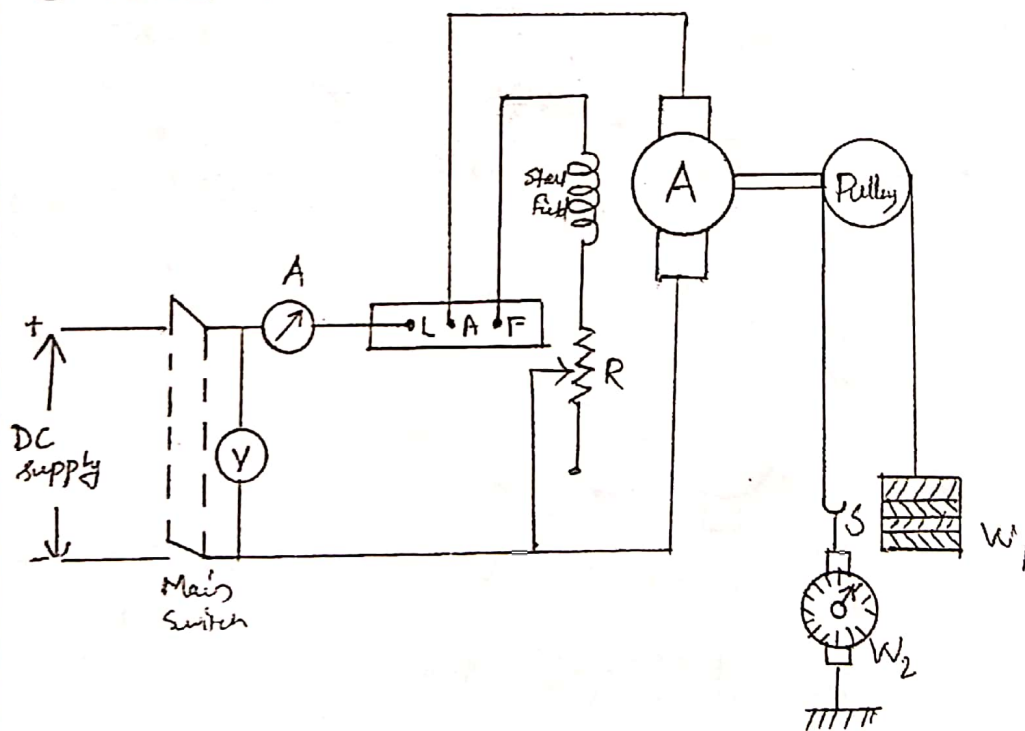
⇒ Direct loading Methods.

→ This method the efficiency and losses of only small m/c can be determined

→ Full load is applied to the m/c and o/p is directly measured.

→ In this m/c power loss is larger.

BRAKE TEST



- This test is applied to small motors.
- Brake is applied to pulley mounted on the shaft.
- One end is connected to earth through spring, S and other end is connected to suspended weight w_1 .
- Mechanical load is varied by adjusting weight.

Let

Supply voltage = V volts.

Input current $\rightarrow I$ Amps.

Weight = w_1 kg & Spring balance = w_2 kg.

Speed = N rpm.

Radius of pulley or shaft $\Rightarrow r$ metre

Thickness of belt = t metre.

$$\text{I/p} \Rightarrow T \propto \frac{2\pi N}{60} \text{ kg-m/s}$$

$$\Rightarrow (w_1 - w_2) \times r \times g \times \frac{2\pi N}{60} \text{ kg-m/s}$$

$$\text{Let } g = 9.81 \text{ m/s}^2$$

$$\text{O/p Power} = (w_1 - w_2) \times r \times g \times \frac{2\pi N}{60} \text{ Nm/s}$$

$$\text{I/p Power} = VI \text{ Watts.}$$

$$\eta_m = \frac{\text{O/p}}{\text{I/p}} = \frac{(w_1 - w_2) \times r \times g \times \frac{2\pi N}{60}}{V \times I}$$

⇒ In - Direct loading Method.

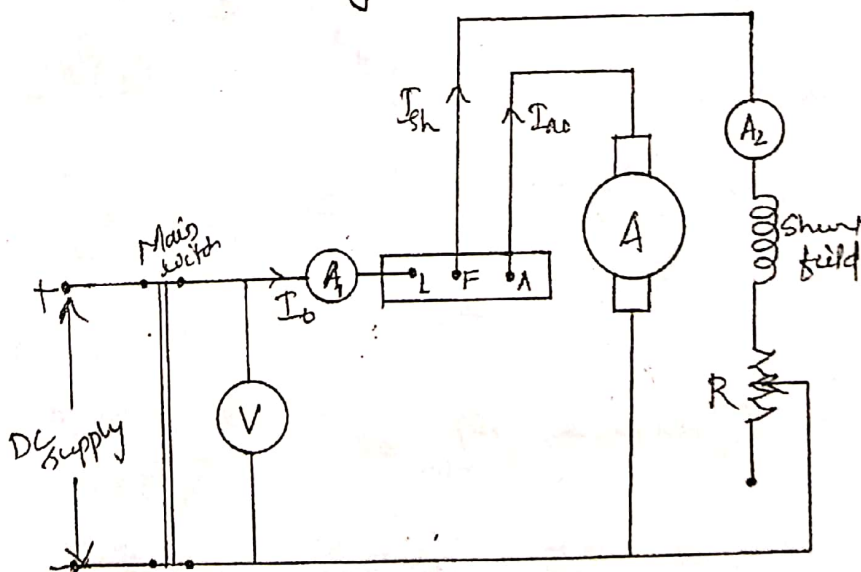
→ This method enables the determination of losses without actually loading the m/c.

→ The power loss is less & required to supply losses only.

SWINBURNE'S TEST

→ It is the simplest method (indirect) of testing dc m/c's in which the losses are measured separately and efficiency at any load is pre-determined.

→ The m/c is normally run as a motor on no load, the excitation is adjusted to give normal speed and normal (rated) voltage is applied across the motor terminals. The connection diagram is shown below.



Let

Input Power $\Rightarrow$ VI_0 Watts

Shunt field loss $\Rightarrow$ VI_{sh} Watts.

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

No-load power i/p to armature $=$ $VI_{a0} = V(I_0 - I_{sh})$.

Constant losses, $W_c =$ Input to motor $-$ Armature Cu loss.

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

Armature current $I_a = I - I_{sh}$ for motoring

$I + I_{sh}$ for generating.

Since the constant losses are known, the efficiency of the machine at any load can be determined.

Efficiency when Running as a Motor

Input Power to motor $\Rightarrow VI$

$$\text{Armature Cu loss} = I_a^2 R_a = (I - I_{sh})^2 R_a.$$

Constant losses $\Rightarrow W_c$

$$\text{Total losses} = (I - I_{sh})^2 R_a + W_c$$

$$\therefore \text{Motor Efficiency, } \eta_m = \frac{\text{Input} - \text{Losses}}{\text{Input}}$$

$$\Rightarrow \frac{VI - (I - I_{sh})^2 R_a - W_c}{VI}$$

Efficiency when running as generator.

O/p of generator $\Rightarrow VI$

Armature Cu loss $\Rightarrow (I + I_{sh})^2 R_a$

Constant losses $\Rightarrow W_c$

Total losses $\Rightarrow (I + I_{sh})^2 R_a + W_c$

$\therefore$ Generator efficiency $\Rightarrow \eta_g = \frac{\text{o/p}}{\text{o/p} + \text{losses}}$

$$\Rightarrow \frac{VI}{VI + (I + I_{sh})^2 R_a + W_c}$$

Advantages of Swinburn's Test.

- $\rightarrow$ The power required to carry out the test is small because it is a no-load test. This method is quite economical.
- $\rightarrow$ The efficiency can be determined at any load because constant losses are known.
- $\rightarrow$ Test is very convenient.

Disadvantages of Swinburn's Test

- $\rightarrow$ It doesnot take into account the stray load losses that occur the machine is loaded.
- $\rightarrow$ Test doesnot enable us to check the performance

of the machine on full-load. It does not indicate whether commutation on full-load is satisfactory if the temperature rises.

→ Test does not give quite accurate of the machine. It is because iron losses under actual load or greater than those measured.

REGENERATIVE OR HOPKINSON'S TEST.

→ The method of determining the efficiency of a d.c. machine saves power and give more accurate results.

→ Two identical d.c. shunt machines are mechanically coupled and connected in parallel across the d.c. supply.

→ The field excitation of the machines, one is run as a motor and as a generator.

→ The electrical power taken from the d.c. supply is the sum of motor and generator losses and this can be measured directly by a voltmeter and an ammeter.

→ The supply is equal to the power required to supply the losses of the two machines.

[illegible]
$$\text{Motor i/p} = V(I_1 + I_2)$$

(i) Assuming that both machines have the same η .

$\rightarrow \eta(V(\mathbb{P}^1, \mathbb{I}_0)) = \text{Generator } i/p$

$$\Rightarrow \eta \times \eta \vee (F_1 + F_2)$$

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But generator o/p $\Rightarrow V I_1$

$$\eta^2 V (I_1 + I_2) = V I_1$$

$$\eta = \sqrt{\frac{I_1}{I_1 + I_2}}$$

(ii) Assuming that iron, friction and windage losses are same in both machines.

Let R_a = armature resistance of each machine.

I_3 = Field current of generator G.

I_4 = Field current of motor M.

Armature Cu loss in generator = $(I_1 + I_3)^2 R_a$

Armature Cu loss in motor = $(I_1 + I_2 - I_4)^2 R_a$

Shunt Cu loss in generator = $V I_3$

Shunt Cu loss in motor = $V I_4$

Power drawn from the d.c supply is $V I_2$ & is equal to the total losses

Iron, friction and windage losses of two m/c (M & G)

$$\Rightarrow V I_2 - [(I_1 + I_3)^2 R_a + (I_1 + I_2 - I_4)^2 R_a + V I_3 + V I_4] = W \text{ (say)}$$

$\therefore$ Iron, friction & windage losses of each m/c = $W/2$

For Generator

$$\text{Output of generator} = VI_1$$

$$\text{Total losses} = \frac{W}{2} + (I_1 + I_3)^2 R_a + VI_3 = W_g (\text{say})$$

$$\therefore \text{Generator efficiency, } \eta_g = \frac{VI_1}{VI_1 + W_g}$$

For Motor.

$$\text{Input to motor} \Rightarrow V(I_1 + I_2)$$

$$\text{Total losses} = (I_1 + I_2 - I_4)^2 R_a + VI_4 + \frac{W}{2} = W_m (\text{say})$$

$$\therefore \text{Motor efficiency, } \eta_m = \frac{\text{Input} - \text{losses}}{\text{Input}}$$

$$\Rightarrow \frac{V(I_1 + I_2) - W_m}{V(I_1 + I_2)}$$

Advantages:

- (i) The total power required to test the two machines is small compared with the full-load power of each machine.
- (ii) The machines can be tested under full-load conditions, so that commutation qualities and temperature rise can be checked.
- (iii) It is more accurate to measure the loss directly than to measure it as the difference of measured i/p & o/p.

(iv) All the measurements are electrical which are simpler and more accurate than mechanical measurements.

MODULE - IV

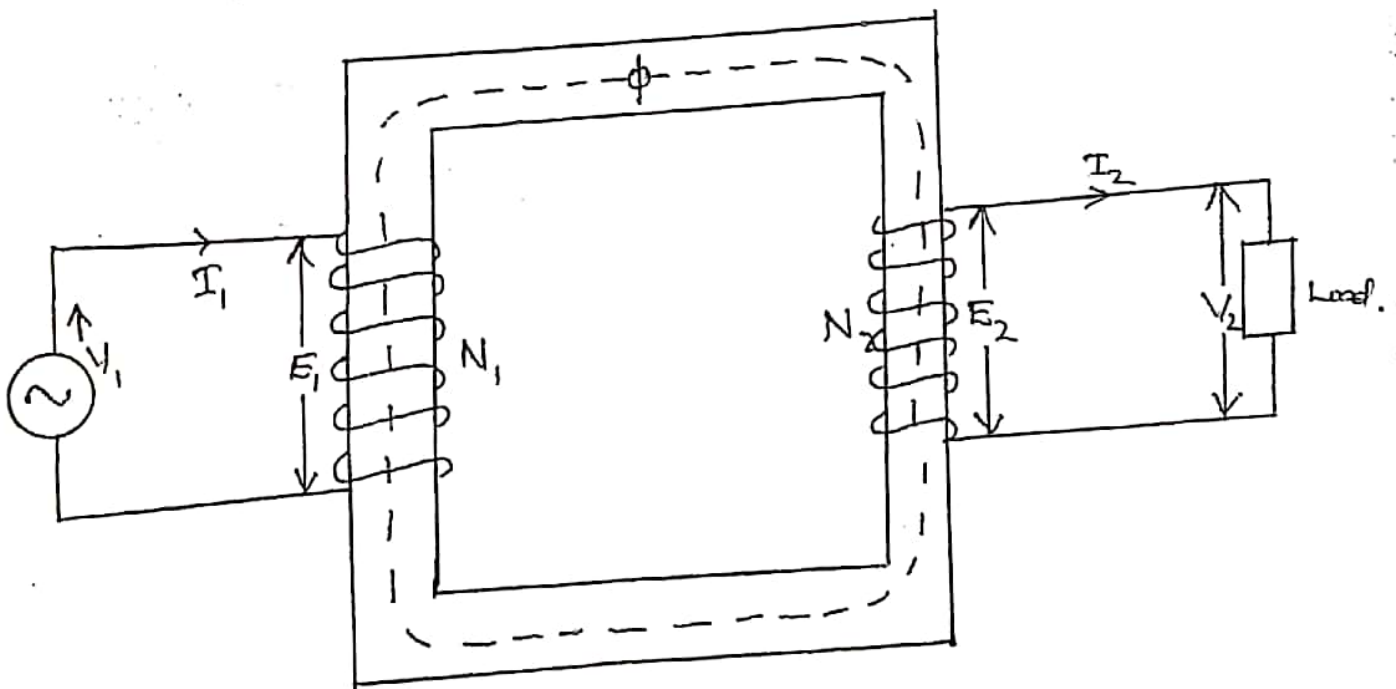
TRANSFORMER

→ A transformer is a static device which is used to step up & down voltages. without any change in frequency.

→ It mainly consists of two windings the primary and secondary, wound on a common laminated magnetic core.

→ The winding connected to the a.c. source is called primary winding.

→ One connected to load is called secondary winding.



WORKING

- When an alternating voltage V_1 is applied to the primary, an alternating flux ϕ is the core.
- Alternating flux links both the windings and induces emf E_1 and E_2 is then according to Faraday's laws of electromagnetic induction.
- Let $E_1 = -N_1 \frac{d\phi}{dt}$
 $E_2 = -N_2 \frac{d\phi}{dt}$
$$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$
- Magnitude of E_2 & E_1 depend upon the number of turns on the secondary and primary resp.
- If $N_2 > N_1$, then $E_2 > E_1$ (or $V_2 > V_1$) and a step-up transformer.
- If $N_2 < N_1$, then $E_2 < E_1$ (or $V_2 < V_1$) and a step-down transformer.
- Load is connected across the secondary winding the secondary emf E_2 will cause a current I_2 to flow through the load.

- (i) The transformer action is based on the laws of electromagnetic induction.
- (ii) There is no electrical connection b/w the primary and secondary. The a.c power is transferred from primary to secondary through magnetic flux.
- (iii) There is no change in frequency.
- (iv) The losses that occur in a transformer are.
 - (a) Core losses.
 - (b) Copper losses.

TYPES.

→ On the mode of construction transformers are classified into two types.

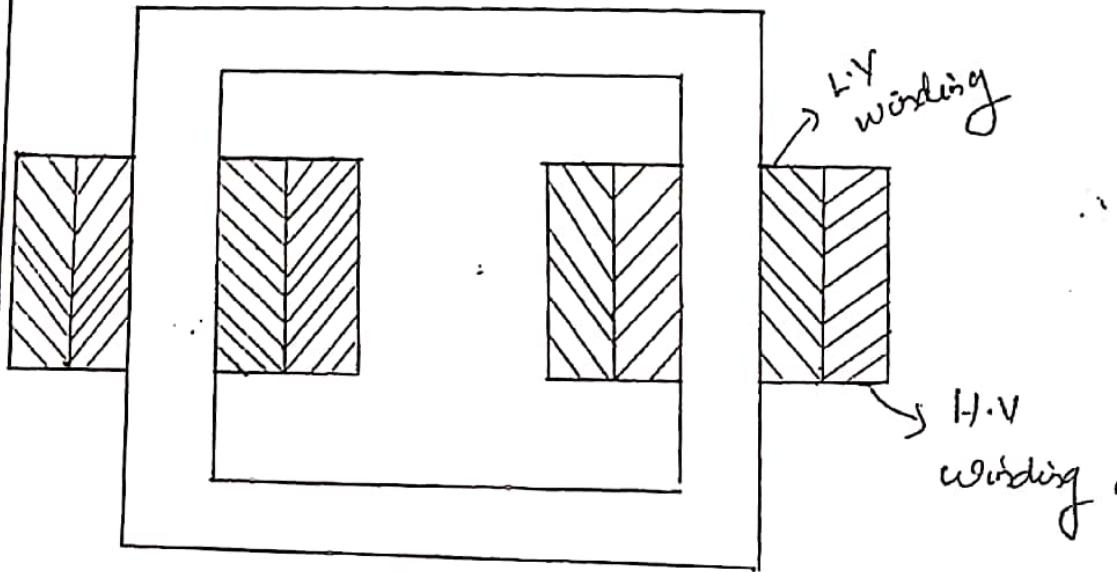
- 1) Core Type Transformers.
- 2) Shell Type Transformers.

1) Core Type Transformers.

→ Core-type transformer, half of the primary winding and half of the secondary winding

are placed around each limb.

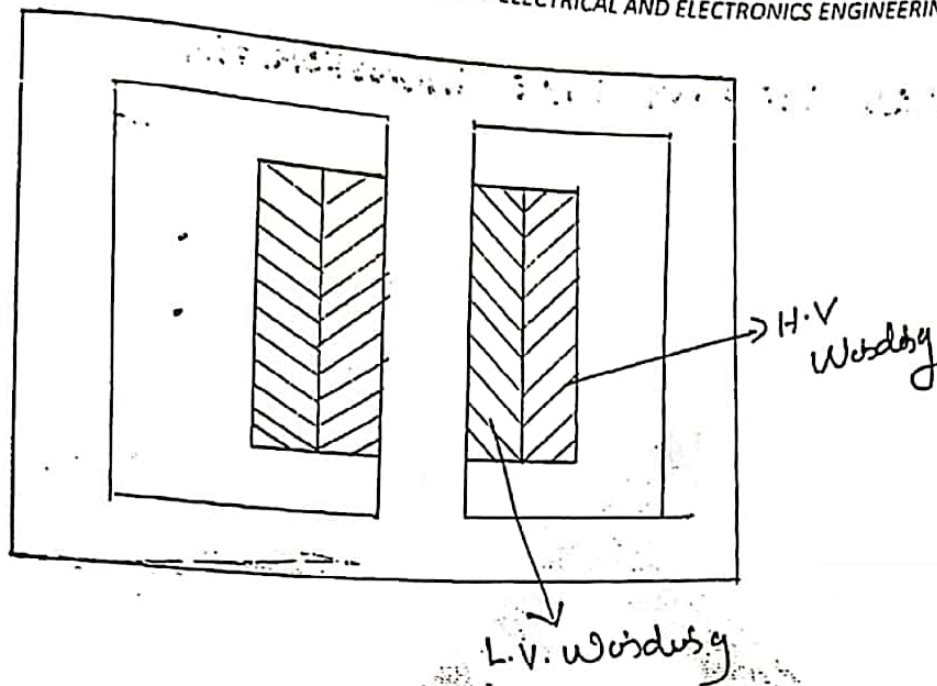
→ This reduces the leakage flux. It is usual practice to place the low-voltage winding below the high-voltage winding for mechanical considerations.



2) Shell-Type Transformer.

→ Method of construction involves the use of double magnetic circuit.

→ Both windings are placed around the central limb. The other two limbs acting simply as a low-reluctance flux path.



→ The choice of type will not greatly affect the efficiency of the transformer. The core type is generally more suitable for high voltage and small o/p while the shell-type is generally more suitable for low voltages and high o/p.

DRY TYPE TRANSFORMER.

→ Dry type transformer never uses any insulating liquid where its winding with core be immersed. Rather windings with core are kept within a sealed tank that is pressurized with air.

TYPES OF DRY TYPE TRANSFORMER

The dry type transformer is of two type

- 1). Cast Resin Dry type transformer. (CRT)
- 2). Vacuum pressure Impregnated Transformer. (VPI)

1) Cast Resin Dry Type Transformer. (CRT)

→ Cast Resin dry type transformer (CRT) is used in the high moisture prone areas. It is because of its primary and secondary windings are encapsulated with epoxy resin. This encapsulation helps to prevent moisture to penetrate to affect the winding material.

→ Complete protection is achieved by this cast resin encapsulation so that the transformer can work without disruption. is highly moisture prone area. Thus this transformer is non-hygroscopic.

Advantages.

- 1). Better over load capacity.
- 2). Low partial discharge along with low loss. Hence efficiency is very good.
- 3). It is non inflammable winding insulation. It offers zero risk to fire hazards. So it is suitable for indoor installation.

4). Be fitted outdoor in IP 45 enclosure.

2) Vacuum Pressure Impregnated Transformer (VPI)

→ This type of transformer is made with minimum flammable material as insulation of windings. The windings of this transformer are made in foil or strip in a continuous layer.

→ But for higher voltages, the windings is made of disks that are connected in series or parallel as per power rating with respect to voltage level.

→ The insulation of the winding is void free impregnation that is made with class H polyester resin. The primary and secondary winding with core are placed safely within a vacuum protective box.

→ This type of transformer are available from 5 kVA to 30 MVA with insulation grade F (155°C) & H (180°C)

Advantages.

- 1) High mechanical strength.
- 2) Void free insulation.
- 3) No temperature fluctuation.
- 4) Easy Maintenance

5) Less prone to fire hazard.

Advantages of Dry Type Transformer.

- 1) Safety for people & property.
- 2) Maintenance and pollution-free solution.
- 3) Easy installation.
- 4) Side clearance is less.
- 5) Environmentally friendly.
- 6) Excellent capacity to support overloads.
- 7) Reduced cost on installation.
- 8) No fire hazard.
- 9) Suited for damp and contaminated areas.

Disadvantages.

- 1) Dry type transformer is long lasting and with less chance of winding failure. But once it fails whole set up is to be changed i.e. complete change of high voltage & low voltage winding with loss.
- 2) For same power and voltage ratings, dry type transformer is costlier than oil cooled transformer.

Application

- 1) chemical, oil & gas industry. c) Fire risk areas.
- 2) Environmentally sensitive areas (e.g. forest)
[e.g. water protection areas].
- 3) Inner-city substations.
- 4) Indoor & underground substations.
- 5) Renewable generation.

COOLING OF TRANSFORMERS

→ In all electrical machines, the losses produces heat and means must be provided to keep the temperature low.

→ In generators and motors, the rotating unit serves as a fan causing air to circulate and carry the heat.

→ Transformers has no rotating parts. some other methods of cooling must be used.

→ Heat is produced in transformer by the iron losses in the core and I^2R loss in the windings.

(i) In small transformers (below 50 KVA) natural air cooling is employed i.e. the heat produced is carry away by the surrounding air.

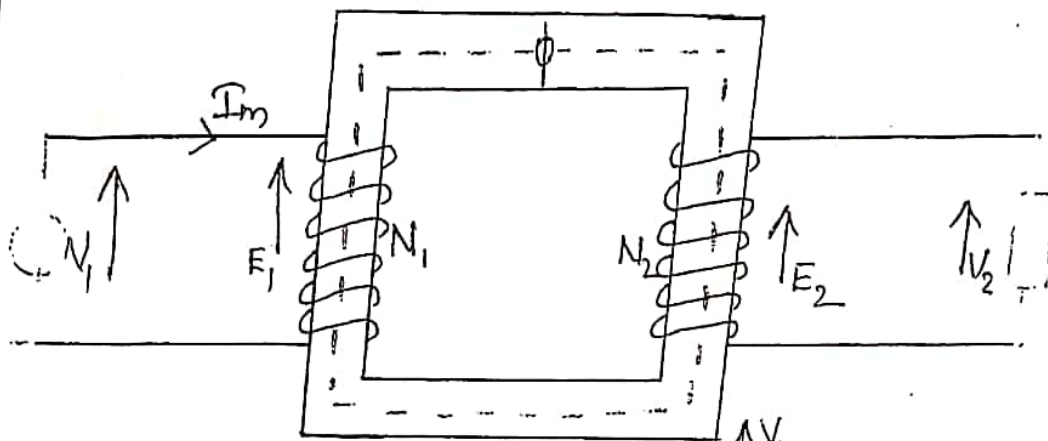
(ii) Medium size power or distribution transformers are generally cooled by housing them in tanks filled with oil. The oil serves a double purpose, carry the heat from the windings to the surface of the tank & insulating from the secondary.

(iii) For large transformers, external radiators are added to increase the cooling surface of the oil filled tank. The oil circulates around the transformer and moves through the radiator. Some times cooling fans blow air over the radiator to accelerate the cooling process.

IDEAL TRANSFORMER

An ideal transformer is one that.

- (i) No winding resistance.
- (ii) No leakage flux i.e. the same flux links both the windings.
- (iii) No iron losses i.e. eddy current and hysteresis losses in the core.

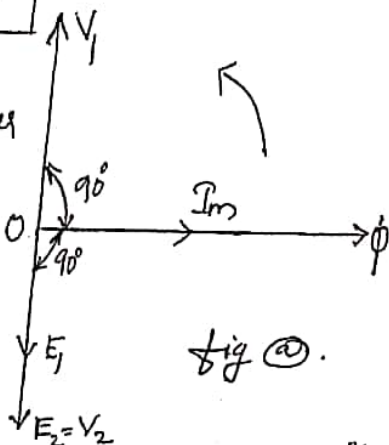


→ Consider an ideal transformer on no load.

i.e. secondary is open-circuited.

⇒ Under such condition the primary is pure inductor. When an alternating voltage V_1 is applied to the primary, it draws a small magnetising current I_m which lags behind the applied voltage by 90° . Thus an alternating flux ϕ_m is proportional to and in phase with it.

⇒ Thus ϕ links with both windings and induces emf E_1 in the primary and emf E_2 in



the secondary. The primary emf E_1 is at every instant equal to and is opposition to V_1 (Lenz's law). Both emf E_1 & E_2 lag behind flux ϕ by 90° .

→ The figure @ represents the phasor diagram of an ideal transformer on no load. Since flux ϕ is common to both the windings, it has been taken as reference phasor.

→ The Ist emf E_1 and IInd emf E_2 lag behind the flux ϕ by 90° .

→ E_1 & E_2 are in phase. But E_1 is equal to V_1 & 180° out of phase with it.

TRANSFORMATION RATIO.

→ In any transformer, the secondary & primary induced emfs are related to each other by the ratio of the number of secondary and primary turns.

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

The constant K is called voltage transformation

ratio.

Let $V_2 > V_1$ or Voltage transformation ratio $K > 1$

$V_2 < V_1$ or Voltage transformation ratio $K < 1$

$\Rightarrow$ In ideal transformer, the losses are negligible. So the Volt-ampere input to the primary & Volt-ampere output from secondary can be the approximately equated.

$$\text{Output VA} = \text{Input VA}$$

$$\text{or } V_2 I_2 = V_1 I_1$$

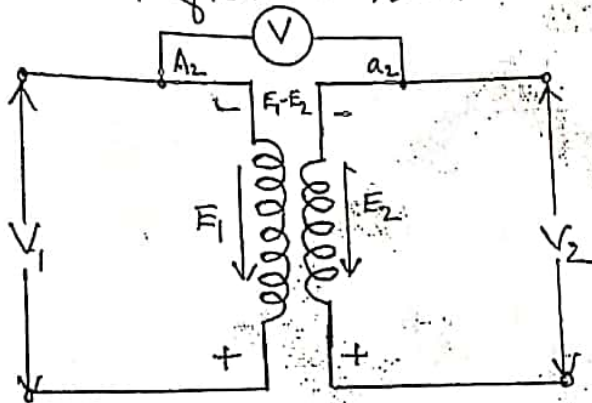
$$\text{or } \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{1}{K}.$$

i. Primary & secondary currents are inversely proportional to their respective turns.

POLARITY TEST

- $\rightarrow$ On the primary side of a two winding transformer, one terminal is positive with respect to the other one at any instant.
- $\rightarrow$ One terminal of the secondary winding is positive w.r. to other one.
- $\rightarrow$ Polarity test is performed to determine the terminals having the same instantaneous polarity.
- $\rightarrow$ The relative polarities of the primary and secondary terminals at any instant must be known for connecting windings of the same transformer in parallel.

→ For determination of relative polarity of the two windings of a transformer, the two windings are connected in series across a voltmeter. One of the windings (preferably HV winding) is excited from a suitable ac voltage source.



→ The polarities of the windings are as marked on the figure. When the transformer has a subtractive polarity the voltmeter will read the difference E_1 & E_2 . If the voltmeter read $E_1 + E_2$, the polarity markings of one of the windings must be interchanged.

→ In subtractive polarity the voltage b/w A_1 & a_1 or $(A_2$ & $a_2)$ is reduced. The leads connected to these terminals and the two windings are not subjected to high voltage stress.

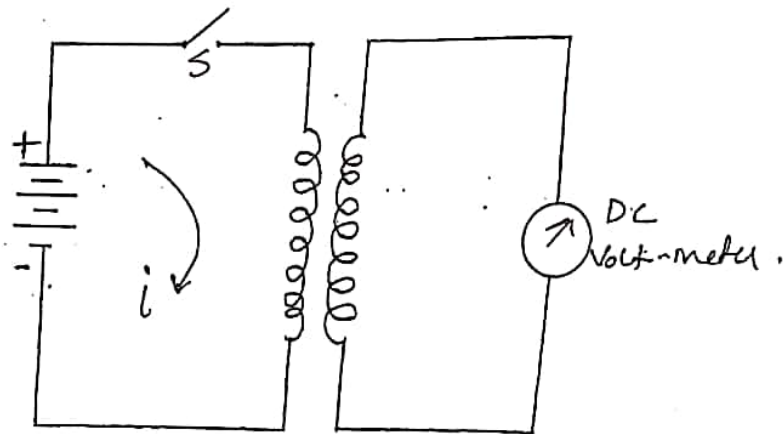
→ In additive polarity the two windings and leads connected to A_1 , A_2 , a_1 and a_2 are

subjected to high stresses voltages.

→ The above test may not be convenient for determination of relative polarities of the turns of two winding of a transformer field.

→ Polarity test is the field can be conveniently carried out by using a dc battery, a switch and a dc (permanent magnet type) voltmeter.

→ The circuit diagram is shown below.



→ The switch on the primary side is closed. the i^o current increases and so the flux linkage of both windings, inducing emfs in them.

→ The positive polarity of this induced emf on the primary is at the end to which the battery is connected (according to Lenz's Law). The end of secondary which simultaneously acquires the positive polarity.

→ The reverse happens on the opening of the switch i.e. similar polarity end is that end which acquires negative potential.

- $\Rightarrow$ Here E_1 & E_2 lag behind the mutual flux ϕ by 90° .
- $\Rightarrow$ The current I_2' represents the 1° current to neutralize the demagnetizing effect of secondary current I_2 .
- $\Rightarrow$ Let $I_2' = k I_2$ and is antiphase with I_2 .
 I_0 is the no-load current of transformer.
- $\Rightarrow$ The phasor sum of I_2' & I_0 gives the total primary current I_1 .

$$\text{Primary P.f.} \Rightarrow \cos \phi_1$$

$$\text{Secondary P.f.} \Rightarrow \cos \phi_2$$

$$1^\circ \text{ input power} \Rightarrow V_1 I_1 \cos \phi_1$$

$$11^\circ \text{ output power} \Rightarrow V_2 I_2 \cos \phi_2$$

(ii) Transformer with resistance and leakage reactance.

$\rightarrow$ In this transformers having winding resistance and leakage reactances. this is the actual condition exist in a transformer.

$\rightarrow$ There is voltage drop in R_1 & X_1 , so the 1° emf E_1 is less than the applied voltage V_1 .

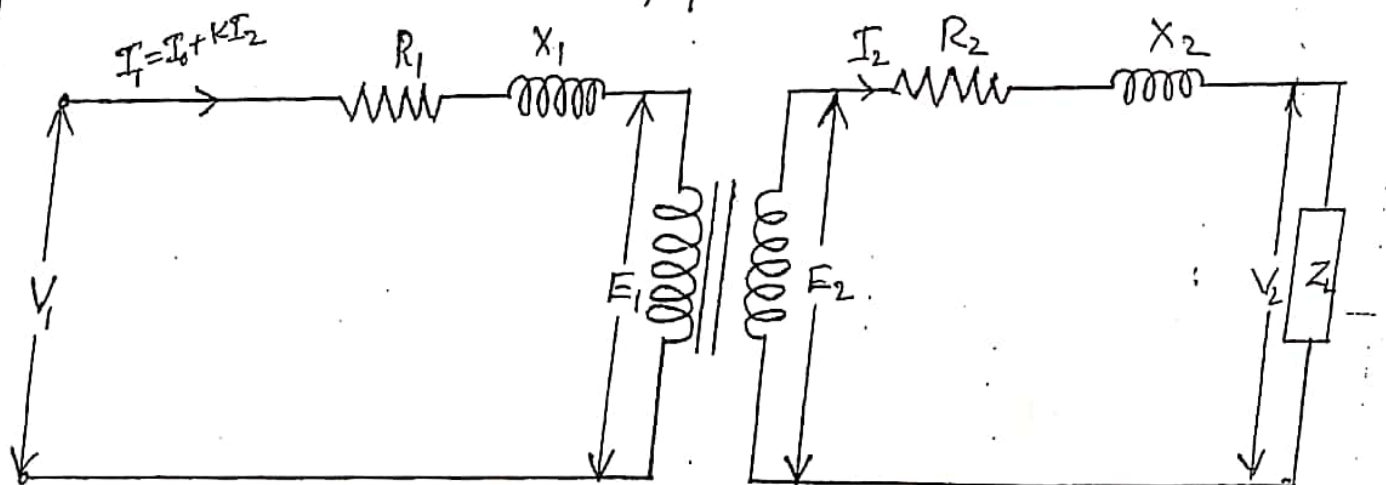
$\rightarrow$ There is voltage drop in R_2 & X_2 so that secondary terminal voltage V_2 is less than the secondary emf E_2 .

→ The usual case of inductive load which causes the secondary current I_2 to lag behind the secondary voltage V_2 by ϕ_2 . The total 1° current I_1 must meet two requirements.

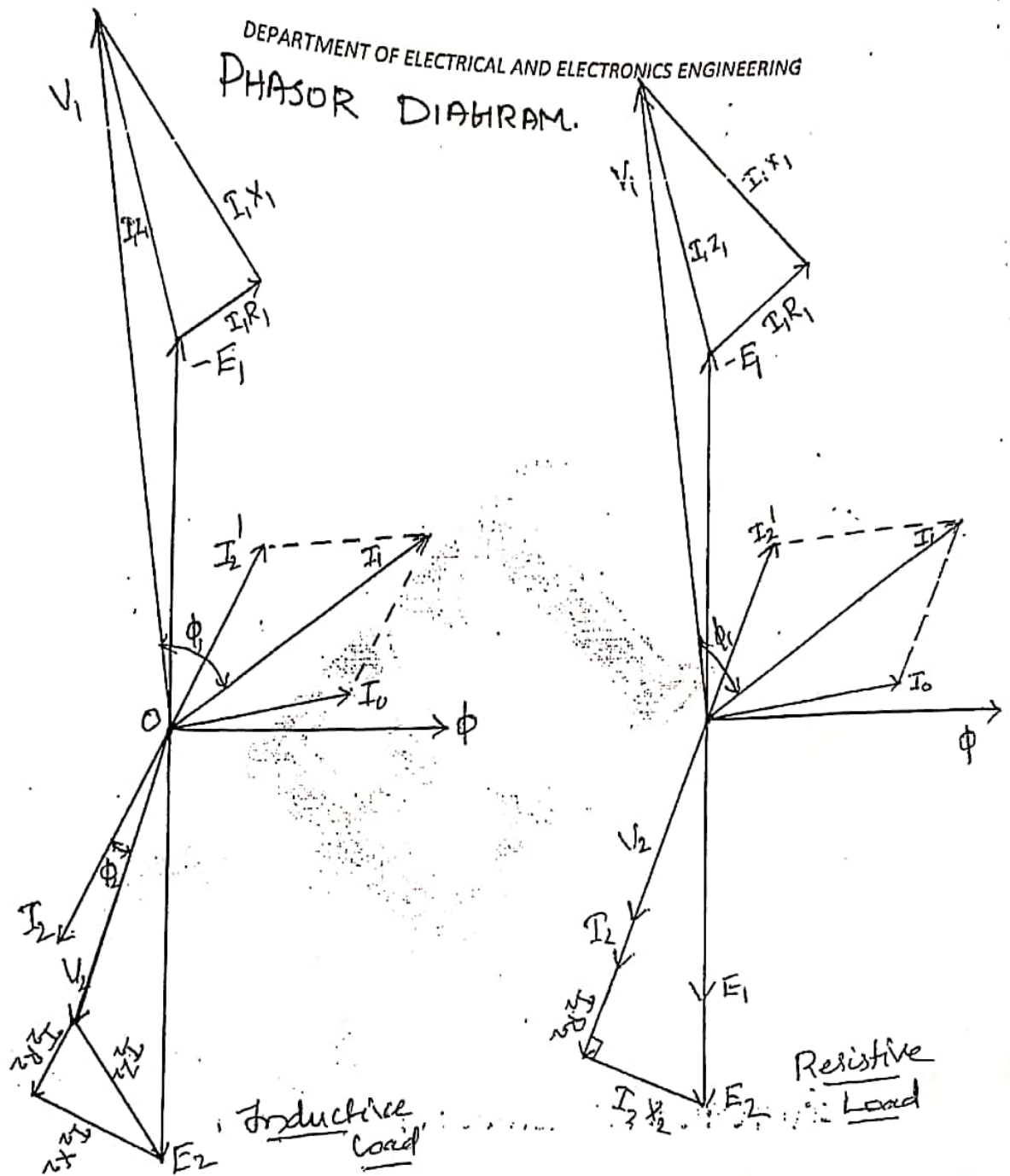
- (a) The supply the no-load current I_0 to meet the iron losses in the transformer and to provide flux in the core.
- (b) It must supply a current I_2' to counteract the demagnetizing effect of secondary current I_2 . The magnitude of I_2' will be

$$N_1 I_2' = N_2 I_2$$

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



DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
PHASOR DIAGRAM.



→ The phasor diagram of a practical transformer for inductive & resistive loads are shown in the figure above.

→ Both E_1 & E_2 lag the mutual flux ϕ by 90° .

→ The current I_2' represents the 1° current to neutralize the demagnetizing effect of I_2 .

$$a) I_0' = K I_2$$

then no load current I_0

the phasor sum of I_0 & I_2' gives I_1

→ the counter emf (E_1) opposes the applied voltage V_1 .

→ the drop $I_1 R_1$ is in phase with current I_1

→ $I_1 X_1$ (90° ahead of I_1) to $-E_1$.

→ E_2 represents secondary by the mutual flux ϕ .

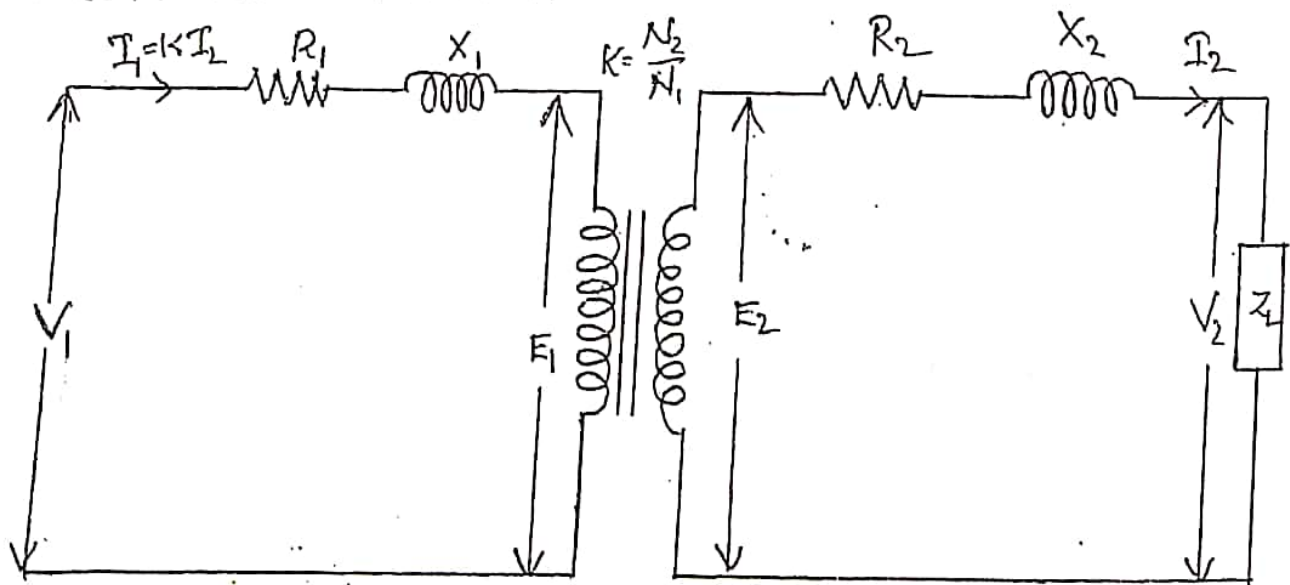
→ V_2 (terminal voltage) left after subtracting

$I_2 R_2$ & $I_2 X_2$ from E_2 .

$$V_1 \Rightarrow -E_1 + I_1(R_1 + jX_1)$$

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

EQUIVALENT CIRCUIT



MODULE - V

TRANSFORMER LOSSES AND EFFICIENCY

→ The power losses in a transformer are of two types.

1) Core or Iron losses.

2) Copper losses.

1) Core or Iron Losses.

→ These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux.

Hysteresis loss $\Rightarrow K_h f B_m^{1.6}$ watts/m³.

Eddy current loss $\Rightarrow K_e f^2 B_m^2 t^2$ watts/m³.

Hysteresis and eddy current losses depend upon

(i) maximum flux density B_m in the core.

(ii) supply frequency f .

Since transformers are connected to constant-frequency, constant voltage supply, both f & B_m are constant.

Iron or Core losses, P_i = Hysteresis loss + Eddy current loss

$\Rightarrow$ Constant losses.

$\Rightarrow$ Using ~~low~~ steel of high silicon content whereas eddy current loss can be reduced by using thin laminations

2) Copper losses (P_c).
→ These losses occur in both the 1st & 2nd winding due to their ohmic resistance.

$$\text{Total Cu losses } P_c = I_1^2 R_1 + I_2^2 R_2 \\ \Rightarrow I_1^2 R_{01} \text{ or } I_2^2 R_{02}.$$

i.e. Copper losses vary as the square of load current.

$$\text{Total losses in a transformer} \Rightarrow P_i + P_c \\ \Rightarrow \text{Constant} + \text{Variable losses.}$$

⇒ In a transformer, copper losses accounts for about 90% of the total losses.

EFFICIENCY

The efficiency of a transformer is defined as the ratio of o/p power (in watts or kW) to i/p power (watts or kW).

$$\text{Efficiency} = \frac{\text{Output Power.}}{\text{Input Power.}}$$

→ Efficiency can be determined by directly loading the transformer and measuring the input power and output power.

$\Rightarrow$ Considerable amount of power is lost during direct loading & losses will be high. Due to these drawbacks direct loading is seldom used to determine the efficiency of a transformer. Open-circuit & short-circuit tests are carried out to find the efficiency.

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

CONDITION FOR MAXIMUM EFFICIENCY

$$\text{Output power} = V_2 I_2 \cos \phi_2$$

If R_{02} is the total resistance of the transformer referred to secondary.

$$\text{Total cu loss, } P_c = I_2^2 R_{02}$$

$$\text{Total losses} = P_i + P_c$$

$$\text{Transformer } \eta = \frac{V_2 I_2 \cos \phi_2}{V_2 I_2 \cos \phi_2 + P_i + I_2^2 R_{02}}$$

taking I_2 outside

$$\eta = \frac{V_2 \cos \phi_2}{V_2 \cos \phi_2 + P_i / I_2 + I_2 R_{02}}$$

denominator should be minimum.

$$\frac{d}{dI_2} (\text{denominator}) = 0$$

$$\frac{d}{dI_2} (V_2 \cos \phi_2 + P_i/I_2 + I_2 R_{02}) = 0$$

$$0 - \frac{P_i}{I_2^2} + R_{02} = 0$$

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

i Iron loss = Copper losses.

VOLTAGE REGULATION

→ The voltage regulation of a transformer is the arithmetic difference between the no-load secondary voltage ($0V_2$) and the secondary voltage (V_2) on load expressed as percentage of no-load voltage.

$$\% \text{ Voltage Regulation} = \frac{0V_2 - V_2}{0V_2} \times 100\%$$

i $0V_2$ = No-load secondary voltage = KV_1

V_2 = Secondary voltage on load.

$$i \ 0V_2 - V_2 = I_2 R_2 \cos \phi_2 \pm I_2 X_{02} \sin \phi_2$$

Positive sign for lagging P.f.

Negative sign for leading P.f.

Q₁. A 10 KVA, 2000/400V single phase transformer has the following data.

$$R_1 = 5\Omega, X_1 = 12\Omega, R_2 = 0.2\Omega, X_2 = 0.48\Omega.$$

Determine the secondary terminal voltage at full-load, 0.8 p.f lagging when 1^o supplies voltage is 2000V.

$$K = \frac{V_2}{V_1} = \frac{400}{2000} = \frac{1}{5}$$

$$R_{02} = R_2 + K^2 R_1 = 0.2 + \left(\frac{1}{5}\right)^2 \times 5 = 0.4\Omega.$$

$$X_{02} = X_2 + K^2 X_1 = 0.48 + \left(\frac{1}{5}\right)^2 \times 12 = 0.96\Omega.$$

$$\text{F.L secondary current, } I_2 = \frac{10 \times 1000}{400} = 25\text{A.}$$

$$\cos \phi_2 = 0.8 \quad \therefore \sin \phi_2 = 0.6$$

$$\text{Voltage drop} = I_2 (R_{02} \cos \phi_2 + X_{02} \sin \phi_2).$$

$$= 25 (0.4 \times 0.8 + 0.96 \times 0.6)$$

$$= 25 (0.32 + 0.576) = \underline{\underline{22.4\text{V}}}$$

$\therefore$ Secondary terminal voltage at full-load

$$V_2 = 400 - 22.4 = \underline{\underline{377.6\text{V}}}$$

OC & SC TEST

→ The efficiency and voltage regulation of a transformer can be determined by two simple tests.

(i) Open-circuit test.

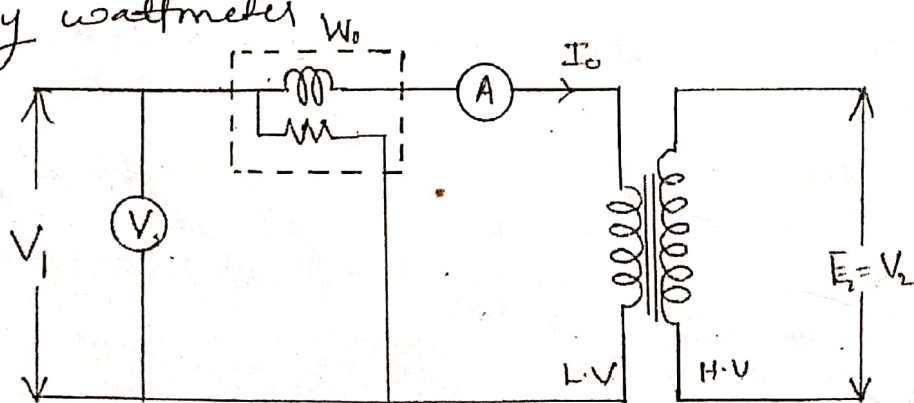
(ii) Short-circuit test.

→ These tests are very convenient as they provide the required information without actually loading the transformer.

Open Circuit Test

→ This test is conducted to determine the W₀ losses (or core losses) & parameters R₀ & X₀ of the transformer.

→ Rated voltage is applied to the primary while secondary is left open circuited. Let V_1 is measured by the voltmeter, the no-load current I_0 by ammeter and no-load i/p power W_0 by wattmeter.



Iron Losses, $P_i = \text{Wattmeter reading} = W_0$.

No load current = Ammeter reading = I_0

Applied Voltage = Voltmeter reading = V_1

Input power, $W_0 = V_1 I_0 \cos \phi_0$

No-load p.f., $\cos \phi_0 = W_0 / V_1 I_0$

$I_w = I_0 \cos \phi_0$, $I_m = I_0 \sin \phi_0$

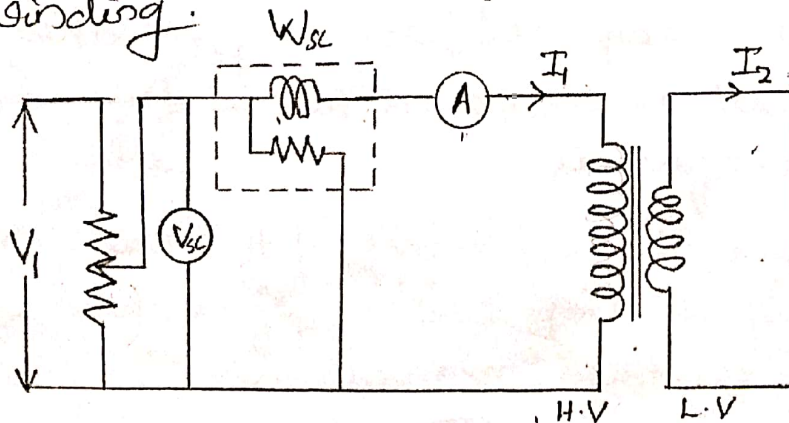
$R_0 = V_1 / I_w$ & $X_0 = V_1 / I_m$

Short-Circuit or Impedance Test.

→ This test is conducted to determine R_{01} or R_{02} and X_{01} or X_{02} and full-load copper losses of the transformer.

→ Rated current is applied to H.V side of the transformer and meter reading are noted.

→ Since ^{primary} ~~secondary~~ is short circuited full load current is flowing through the secondary winding.



the no-load current being neglected due to its smallness.

Full load cu loss $P_c \Rightarrow$ Wattmeter reading $= W_s$.

Applied Voltage = Voltmeter reading $= V_{sc}$.

F.L I° current = Ammeter reading $= I_1$.

$$P_c = I_1^2 R_1 + I_1^2 R_2' = I_1^2 R_{01}$$

$$R_{01} = P_c / I_1^2.$$

$\rightarrow$ Where R_{01} is the total resistance of transformer referred to I° .

Total impedance referred to I° , $Z_{01} = V_{sc} / I_1$.

Total leakage reactance referred to I° , $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

$$\text{Short-circuit p.f. } \cos \phi_s = \frac{P_c}{V_{sc} I_1}$$

Thus short-circuit test gives full-load cu loss,

R_{01} & X_{01} .

Advantages

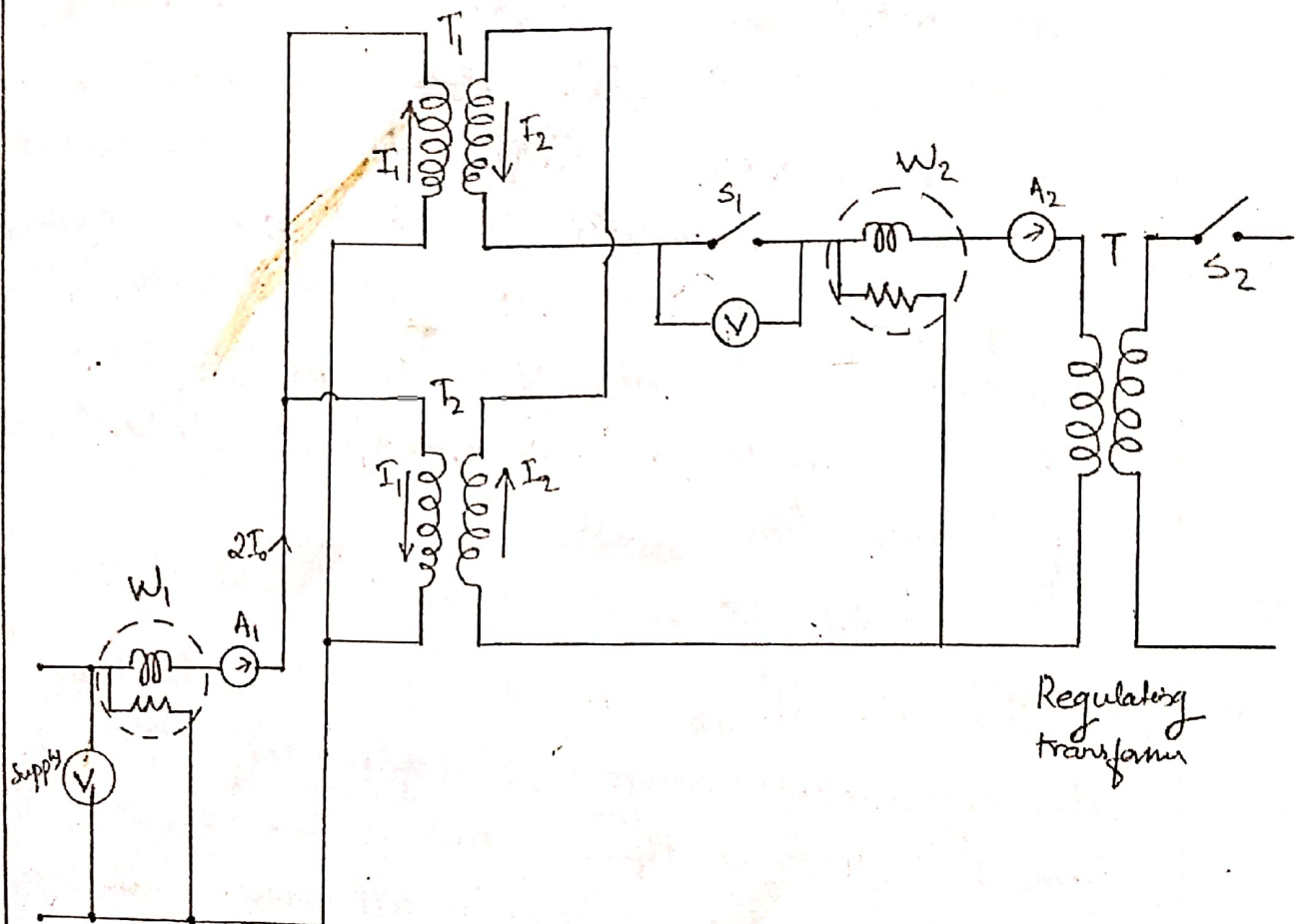
$\rightarrow$ The power required to carry out these tests is very small as compared to the full-load %p of the transformer.

$\rightarrow$ Determine the efficiency of the transformer accurately at any load & p.f without actually loading the transformer.

$\rightarrow$ The SC test enables us to determine R_{01} & X_{01} & R_{02} & X_{02} referred to I° & II° .

SUMPNER OR BACK-TO-BACK TEST.

→ Two identical transformers and provides the data for finding the efficiency, regulation and temperature rise. The main advantages of this test is that the transformer are tested under full-load conditions without much expenditure of power. The power required to conduct this test is equal to the losses of two transformers.



→ The connections for back-back test on two identical transformers T_1 & T_2 shown is fig above.

→ The primaries of two transformers are connected in parallel across the rated voltage V_1 , while the two secondaries are connected in phase opposition.

→ There will be no circulating current in the loop formed by the secondaries because their induced emf are equal and in opposition.

→

(i) The secondaries of the transformer are in phase opposition. With switch S_1 closed and switch S_2 open.

→ There will be no circulating current ($I_c = 0$) in the secondary loop circuit. It is because induced emf in the secondaries are equal and in opposition. (i.e. just like open ckt). The current drawn from the supply is $2I_0$ where I_0 is the no-load current. The reading W_1 will be equal to the core losses of two transformers.

$W_1 = \text{Core losses of two transformers.}$

(ii) The switch S_2 is also closed and o/p voltage of the regulating transformer is adjusted till full-load current I_2 flows in the secondary loop circuit. The full-load secondary current will cause full-load current ($I_1 = kI_2$) in the primary. The i^o current circulates in the P winding only & will not pass through W_1 .

→ Full-load currents are flowing through the 1° & 11° windgs. Readings of wattmeter W will be equal to the full-load copper losses of the two transformers.

W_2 = Full-load Cu losses of two transformers.

$W_1 + W_2$ = Total losses of two transformers at full-load.

⇒ The wattmeter W_1 gives the core losses of the two transformers while wattmeter W_2 gives the full-load copper losses of the two transformers. Power required to conduct this test is equal to the total losses of the two transformers.

⇒ ~~The~~ Transformers are not supplying any load yet full-load iron loss and full-load copper loss are occurring them.

⇒ There are two voltage sources and there is no interference between them. The supply voltages gives only $2 I_0$ while regulating transformer supplies I_2 and hence $I_1 (1 \ll I_2)$.

Advantages

- (i) The power required to carry out the test is small.
- (ii) The transformers are tested under full-load conditions.
- (iii) The iron losses and full-load copper losses are measured simultaneously.
- (iv) The secondary current (I_2) can be adjusted to any current value.
- (v) The temperature rise of the transformers can be noted.

ALL-DAY EFFICIENCY

The ordinary or commercial efficiency of a transformer is defined as $\eta_c = \frac{\text{output}}{\text{input}}$.

→ There are certain transformers whose performance cannot be judged by this efficiency. i.e. Distribution transformers, whose 1st is energized all the 24-hours, but secondaries supplies light loads during major portion of the day. The performance of each transformer on the basis of energy consumption during the whole day i.e. (24 hours) this is known as all-day or energy efficiency.

→ The ratio of output in kWh to the i/p in kWh of a transformer over a 24-hour period is known as all-day efficiency.

$$\eta_{\text{all-day}} \Rightarrow \frac{\text{kWh o/p in 24 hours}}{\text{kWh i/p in 24 hours}}$$

⇒ All-day efficiency is special importance for those transformers whose 1° are never open-circuited but the 11° carry little or no load much of the time during the day.

⇒ Such transformers, efforts should be made to reduce the iron losses which continuously occurs during the whole day.

AUTOTRANSFORMER

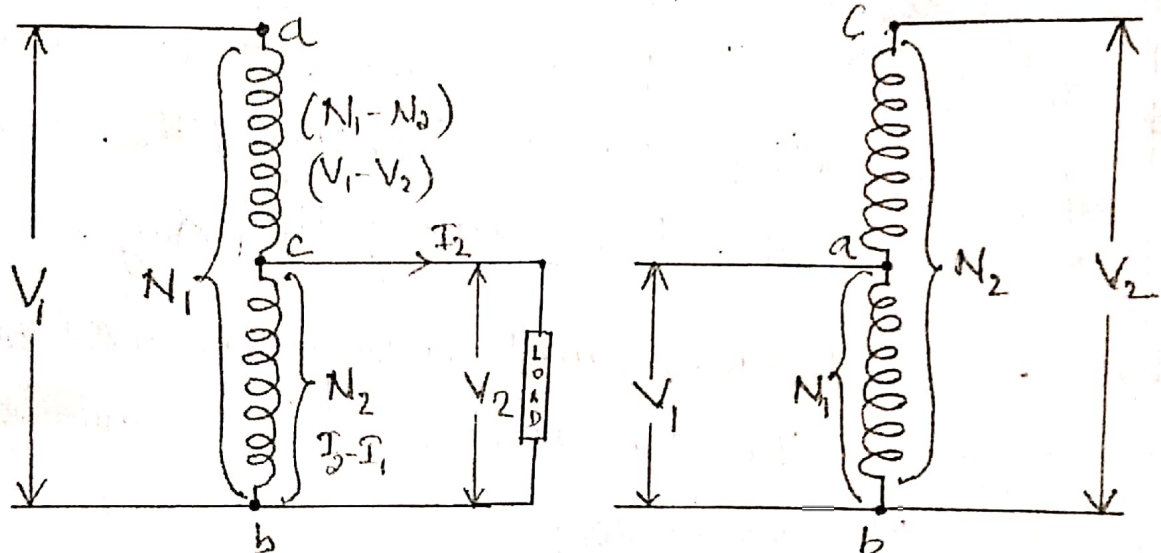
→ An autotransformer has a single winding on an iron core and a part of winding is common to both 1° & 11° circuits.

→ The circuit of autotransformer is shown in the figure below.

→ The winding ab having N_1 turns is the 1° winding and winding bc having N_2 turns is the secondary

winding. The 1^o & 2^o windings are connected electrically as well as magnetically. Power from the 1^o is transferred to the 2^o conductively as well as inductively (transformer action). The voltage transformation ratio k of an ideal autotransformer is

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



→ In an autotransformer input apparent power is equal to output apparent power.

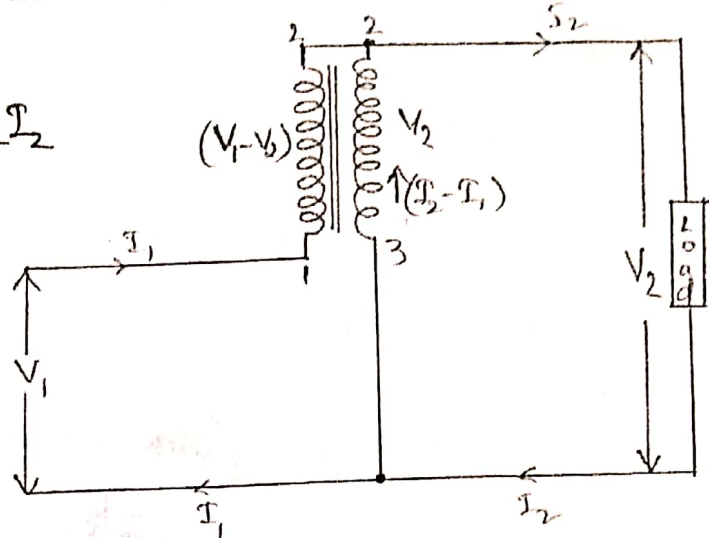
→ The 1^o and 2^o windings of an autotransformer are connected magnetically as well as electrically. The power from 1^o is transferred to the secondary inductively (transformer action) as well as conductively (i.e., conducted directly from source to the load).

Output apparent power $= V_2 I_2$

Apparent power transferred
inductively

$$\Rightarrow V_2 (I_2 - I_1) = V_2 (I_2 - k I_2)$$

$$\Rightarrow V_2 I_2 (1 - k) = V_1 I_1 (1 - k)$$



Power transferred inductively = Input $\times (1 - k)$.

Power transferred conductively = Input - Input $(1 - k)$

$$= \text{Input} [1 - (1 - k)]$$

$$\Rightarrow k \times \text{Input}.$$

Suppose the i/p power to an ideal autotransformer

is **SAVING OF COPPER**

→ The same o/p and voltage transformation ratio $k (N_2/N_1)$ an autotransformer requires less copper than an ordinary 2-winding transformer.

→ The length of copper required in a winding is proportional to the number of turns and the area of cross-section of the winding wire is proportional to the current rating.

→ $\therefore$ the volume and hence weight of copper required in a winding is proportional to current $\times$ turns

Weight of Cu required is a winding $\propto$ current $\times$ turns
2-Winding transformer.

Weight of Cu required $\propto (I_1 N_1 + I_2 N_2)$.

Autotransformer.

Weight of Cu required
is autotransformer (W_a) $\Rightarrow (1-k) \times$ Wt. in ordinary
transformer (W_o)

$$W_a = (1-k) \times W_o$$

$$\begin{aligned}\text{Savings in Cu} &= W_o - W_a = W_o - (1-k)W_o \\ &= kW_o.\end{aligned}$$

$$\begin{aligned}\text{Savings in Cu} &= W_o - W_a = W_o - (1-k)W_o \\ &= k \times \text{Wt. of Cu in ordinary transformer.}\end{aligned}$$

If $k=0.1$, the savings of Cu is only 10%

$k=0.9$, the savings of Cu is 90%.

$\therefore$ the value of k of autotransformer is nearer to 1
the saving of copper is greater.

APPLICATION

- Used as booster transformer.
- Used for reducing the voltage supplied to a.c. motors during the starting period.
- Used for continuously variable supply.

Current Rating and kVA Ratings.

→ Two winding transformer is connected as an autotransformer. Compare the volt-ampere ratings of the two.

$$\begin{aligned} \text{Voltage rating as two winding transformer} &= (V_1 - V_2) I_1 \\ &= (I_2 - I_1) V_2. \end{aligned}$$

When used as an auto-transformer.

$$\text{Voltage rating as an auto-transformer} \Rightarrow V_1 I_1 = V_2 I_2$$

Volt-ampere rating as an autotransformer

Volt-ampere rating as two winding transformer

$$\Rightarrow \frac{V_1 I_1}{(V_1 - V_2) I_1} = \frac{V_2 I_2}{V_2 (I_2 - I_1)}$$

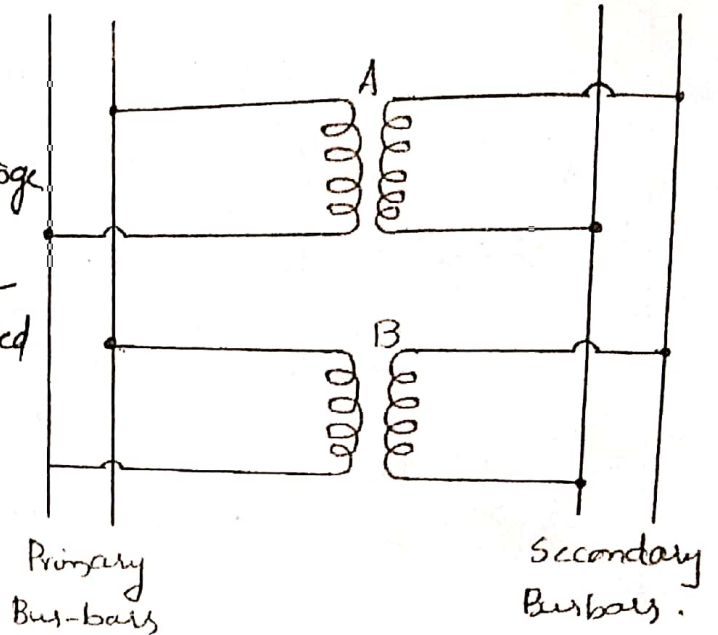
$$= \frac{1}{1 - k}$$

⇒ It is obvious that a two-winding transformer of a given volt-ampere rating when connected as an auto-transformer can handle high volt-ampere. This is because in the autotransformer connection part of VA is conducted directly from

PARALLEL OPERATION OF 1ϕ TRANSFORMERS

→ If two transformers are to be connected in parallel if the 1° windings are connected to supply Busbars and 2° are connected to load bus bar.

→ Figure shows the parallel connection of two transformers A & B.



→ It is essential that their terminals of similar polarities are joined to the same busbars.

→ The wrong connections may be damaged unless the transformer and dead short-circuit protected by fuses or circuit breakers.

→ There are three principal reasons for connecting transformers in parallel. If one transformer fails, the continuity of supply can be maintained.

→ Load on the sub-station becomes more than the capacity of the existing transformer another transformer can be added in parallel.

If any transformer can be taken out of the circuit for repair/maintenance without interrupting supply to the consumers.

CONDITION FOR SATISFACTORY PARALLEL OPERATION.

→ The transformers work satisfactorily in parallel, the following conditions should be satisfied.

- (i) Transformers should be properly connected with regard to their polarities.
- (ii) The voltage ratings and voltage ratios of the transformers should be the same.
- (iii) The per unit or percentage impedance of the transformer should be equal.
- (iv). The reactance/resistance ratios of the transformer should be the same.

ON LOAD AND OFF LOAD TAP CHANGERS.

→ Tap changing involves changes in leakage reactance, copper loss and core loss and possibly some difficulty in operating transformer in parallel.

OFF LOAD TAP CHANGERS

→ The tappings may be changed with the transformer isolated from the supply on both sides. This is called off-load tap changing. Arrangement is used for occasional adjustment, as in distribution transformers which are provided $\pm 5\%$ & $\pm 2\%$ taps.

ON LOAD TAP CHANGERS

Transformers special arrangements are made to avoid interruption of supply so that tap-changing is effected with the transformer energized or on load. This is called on-load tap changing. Daily and short-term adjustments are made with the help of on-load tap changing gear.

MODULE VI

THREE PHASE TRANSFORMER

→ 3ϕ s/m is used to generate and transmit electric power. 3ϕ voltages are raised or lowered by means of 3ϕ transformer.

→ A 3ϕ transformers can be built in two ways.

- (i) By suitably connecting a bank of 3 single phase transformers.
- (ii) By constructing a 3ϕ transformer on a common magnetic structure.

(i) Bank of 3 single phase transformer.

→ 3 similar 1ϕ transformers can be connected to form a 3ϕ transformer.

→ Primary and secondary windings may be connected in star (Y) or delta (Δ) arrangement. The 1° & 11° windings shown parallel to each other belong to same 1ϕ transformer. The ratio of secondary phase voltage to primary phase voltages is the phase transformation ratio k .

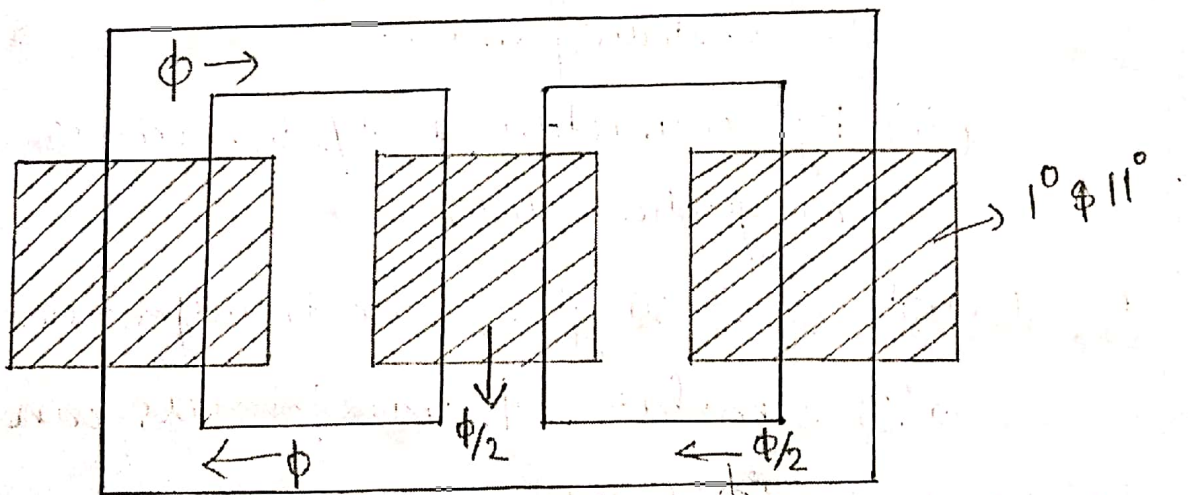
Phase transformation ratio, $k \Rightarrow \frac{\text{Secondary phase voltage}}{\text{Primary phase voltage}}$

$$\Rightarrow \frac{N_2}{N_1}$$

(ii) THREE PHASE TRANSFORMER

→ A three phase transformer can be constructed by having three primary and three secondary windings on a common magnetic circuit.

3 ϕ Core type Transformer.

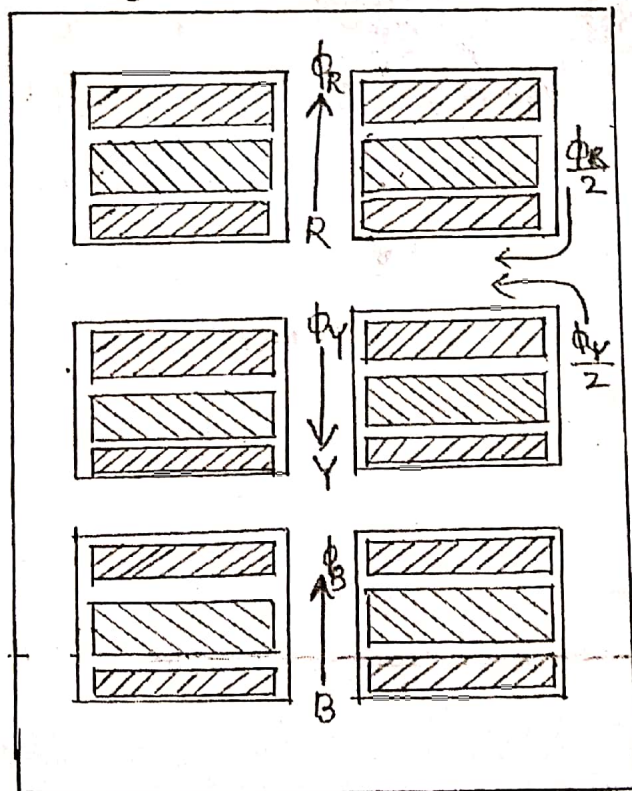


→ The figure above shows the ckt diagram of a 3 ϕ core type transformer. Each with windings (1 ϕ & 11 ϕ) on only one leg, have their unwound legs combined to provide a path for the returning flux.

→ If the 1 ϕ & 11 ϕ may be connected in star or delta.

→ If the ϕ is energized from a 3ϕ supply, the central limb carries the fluxes produced by the 3ϕ ϕ windings. Since the phasor sum of three fluxes passing through the central limb is 3ϕ currents at any instant is zero. Hence no flux exists in the central limb and it may be eliminated. This modification needs three leg core-type 3ϕ transformer.

3ϕ Shell Type Transformer.



→ A shell type transformer which is not commonly used.

→ It appears like three single phase shell type cores built on top of one another.

→ The joint use of the magnetic paths b/w the coils, there is less iron as this type of transformer than is 3 equivalent ϕ per

→ the common yoke section further can be affected by reversing the middle coils.

→ The flux carried corresponds to the phasor sum of the two phasors $\phi_{R/2}$ and $\phi_{Y/2}$.

→ Each phase has a magnetic circuit independent of others. If saturation effects in the common paths are neglected.

→ One advantage is that the former one can be operated in open delta should one of the windings be damaged.

3 ϕ Transformer Connections.

→ The primary and secondary windings may be connected in either star (Y) or delta (Δ) arrangement. The four most common connections are

→ Y-Y (Star-Star)

→ Δ - Δ (Delta-Delta).

→ Y- Δ (Star-Delta)

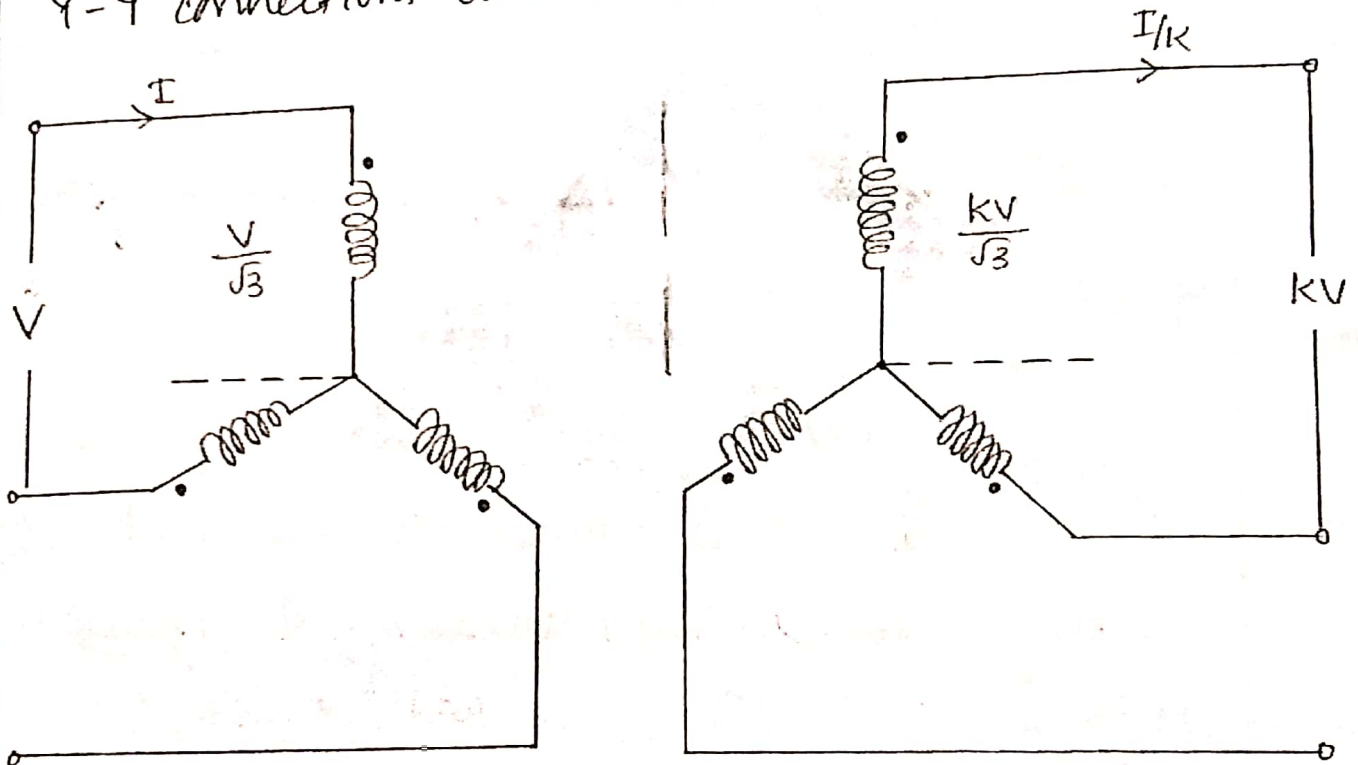
→ Δ -Y (Delta-Star)

→ V-V Connection.

1) Y-Y (Star-Star) Connection.

→ Y-Y is shown in the figure shown below. 57.7% (or $\frac{1}{\sqrt{3}}$) of the line voltage is impressed upon each winding but full line currents flows

in each winding. Power circuits supplied from a Y-Y bank often create serious disturbances in communication circuits in their immediate vicinity.
 → Because of these & other some disadvantages Y-Y connections are seldom used.

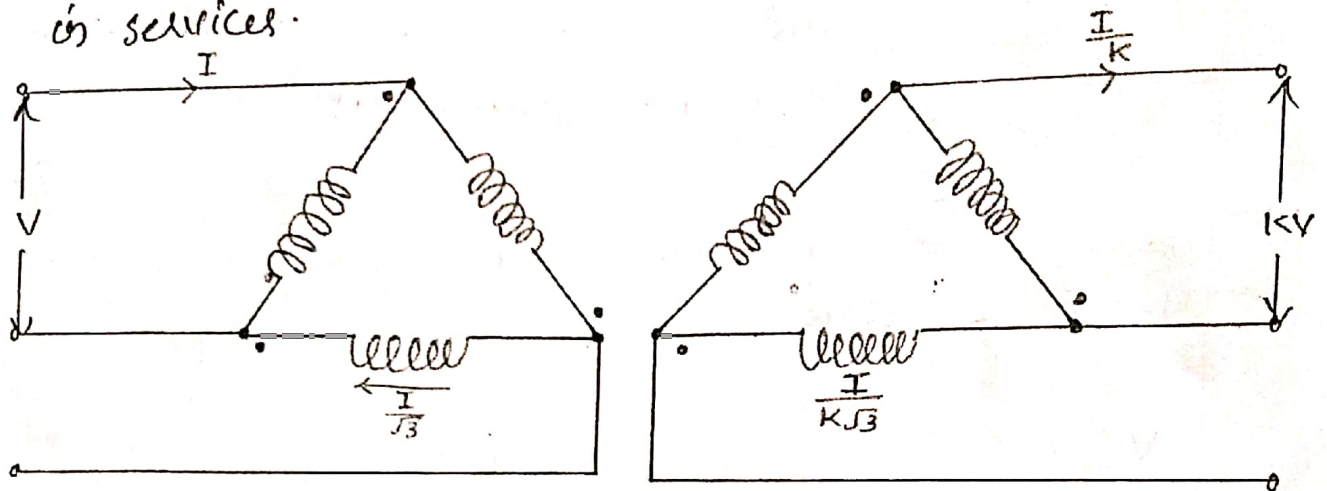


Y-Y Connection.

2) Δ - Δ Connection

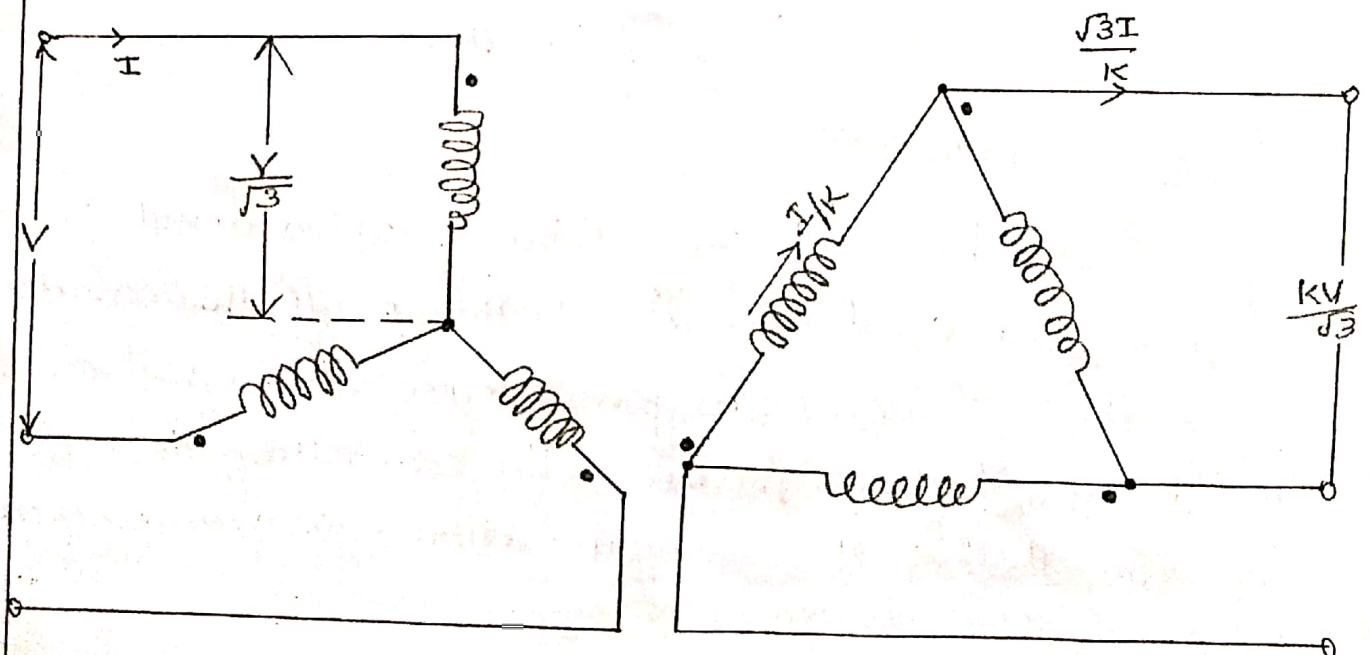
→ The Δ - Δ connection is often used for the moderate voltages. An advantage of this connection is that if one transformer gets damaged or is removed from service, the remaining two can be operated as the open-delta or V-V connection.

→ In this the bank still delivers three-phase currents and voltages in their correct phase relationship but the capacity of the bank is reduced to 57.7% of it with all three transformers in services.



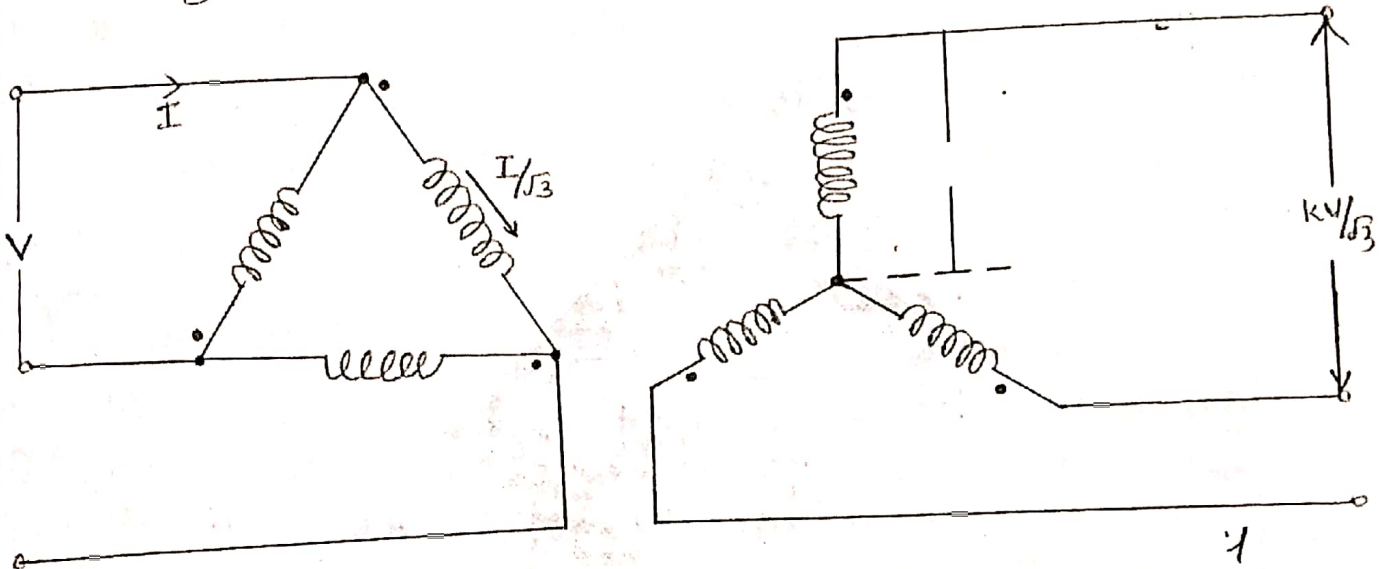
(ii) Y- Δ Connection.

The Y- Δ connection is suitable for stepping down a high voltage. The primaries are designed for 57.7% of the high-tension line voltages.



iv) Δ -Y connection.

→ The Δ -Y connection is commonly used for stepping up to a high voltage.



VECTOR GROUPING.

1) Star-Star (Yy0) connection.

→ This type of connection is most economical for small current and high voltage transformers.

Advantages.

→ The number of turns / phase and the amount of insulation is minimum because phase

$$\text{Voltage} \Rightarrow \frac{1}{\sqrt{3}} \text{ line Voltage}$$

→ There is no phase displacement b/w I^o & II^o Voltage.

→ Star points available on both sides it is possible to provide neutral connection.

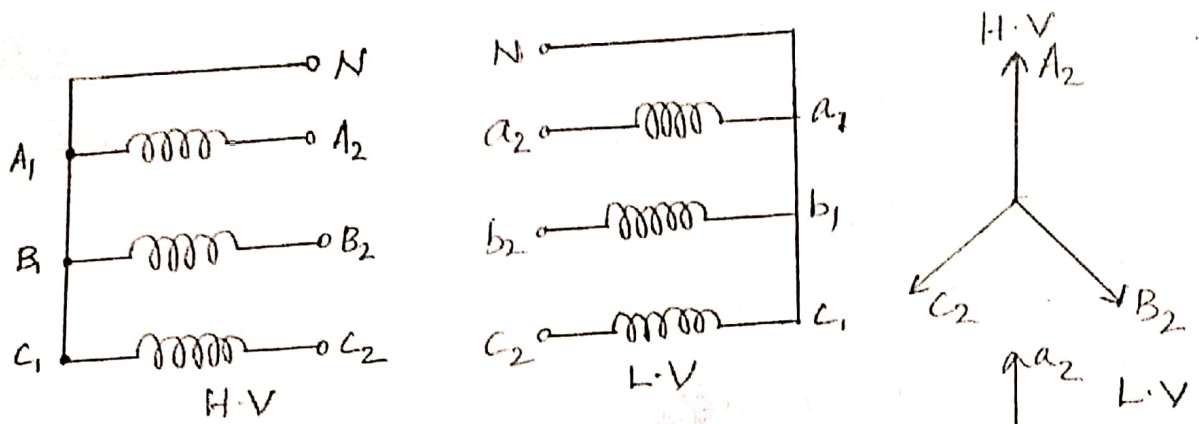
Disadvantages

→ If the load on the secondary side of the transformer is unbalanced, the phase voltages of the load side change unless the load star point is earthed. The difficulty of shifting neutral can be

overcome by connecting the primary star point to the star point of the generator.

ii The primary of the transformer draws a magnetizing current which has third and fifth harmonics. If neutral of primary winding is not connected to neutral of generator, the third and fifth harmonics currents cannot flow hence the flux in core cannot be of sinusoidal wave and, therefore, the voltages will be distorted. By connecting primary neutral to the generator neutral, the path for return of these third and fifth harmonics currents is provided and, therefore, the trouble of distortion of voltage is overcome.

iii Even if neutral point of primary is connected to neutral of generator or earthed, still if third harmonic is present in the alternate voltage form, it will appear on secondary side. Though the secondary line voltage do not contain third harmonic voltage; but the 3rd harmonic voltage are additive in the neutral and cause the current in the neutral of trippled frequency (3rd harmonic) which will cause interference to the nearby communication system.



2) Delta-Delta (Dd0) connection

→ This arrangement is mainly used in slm which carry large currents on low voltages and when continuity of service must be maintained even though one of the phase develops a fault.

→ When one of the phase is removed in $\Delta-\Delta$ connected transformers operation continues on it known as open delta.

→ By this the transformer delivers three phase current and voltage is their correct phase relationship but the capacity of the transformer is reduced to 57.7%.

Advantages

- 1) There is no phase displacement b/w 1° & 11° voltage
- 2) There is no distortion of flux.

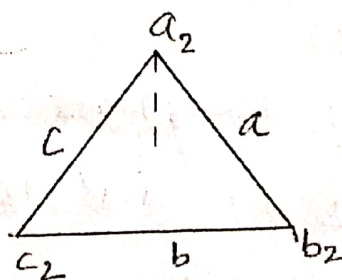
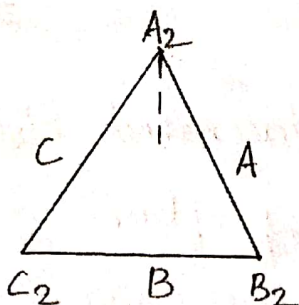
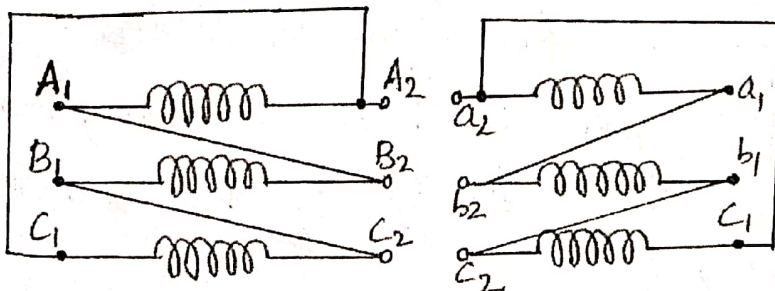
3) The cross section of conductor is reduced because the phase current is $\frac{1}{\sqrt{3}}$ times of line current.

A) No difficulty is experienced due to the unbalancing of load on secondary side.

Disadvantages.

1) Comparing with Y-Y connection more insulation is required.

2) The absence of the star point. If one line gets earthed due to fault, maximum voltage b/w windings and core will be full line voltage.

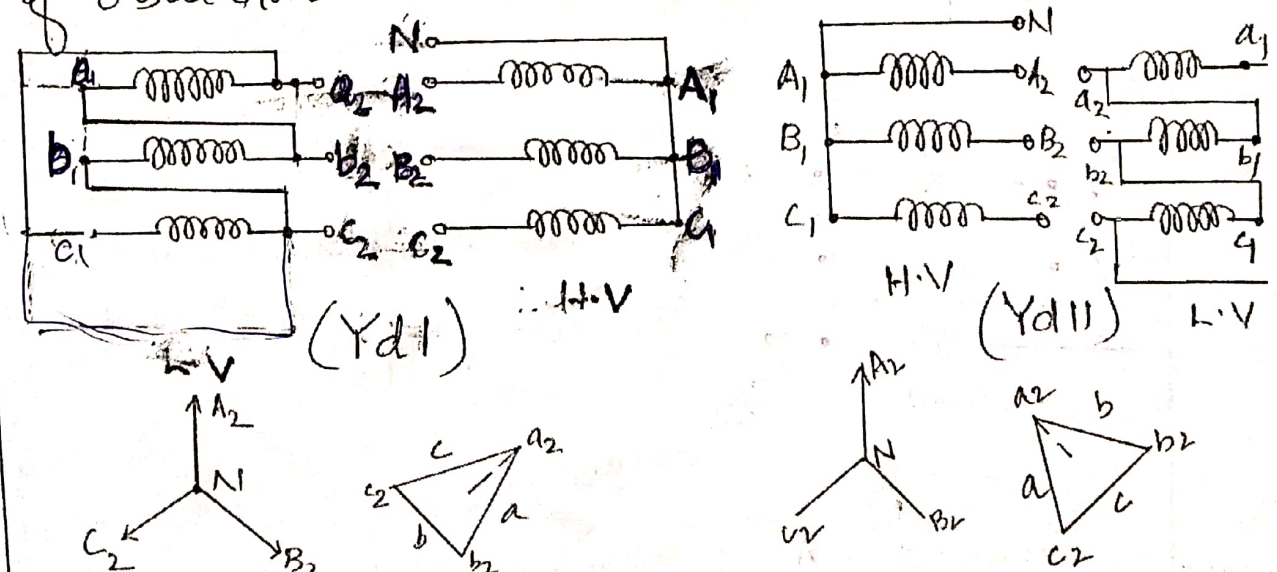


3) Star-Delta (Yd1 or Yd11) Connection.

→ These type of transformers connection is used principally, where the voltage is to be stepped down (i.e. at end of the transmission line). In this type transformers the neutral of the 1^o winding is earthed.

→ Line voltage ratio is $\frac{1}{\sqrt{3}}$ times of transformer turns ratio and secondary line voltage have a phase shift of $\pm 30^\circ$ w.r. to 1^o line voltages.

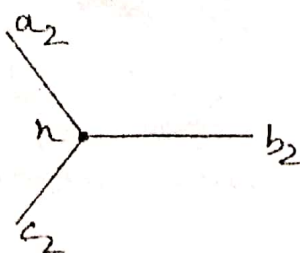
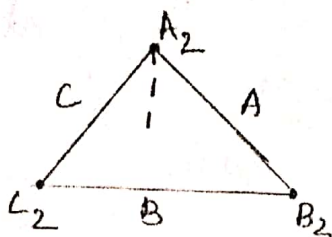
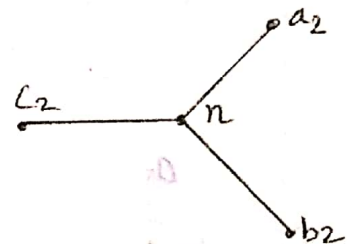
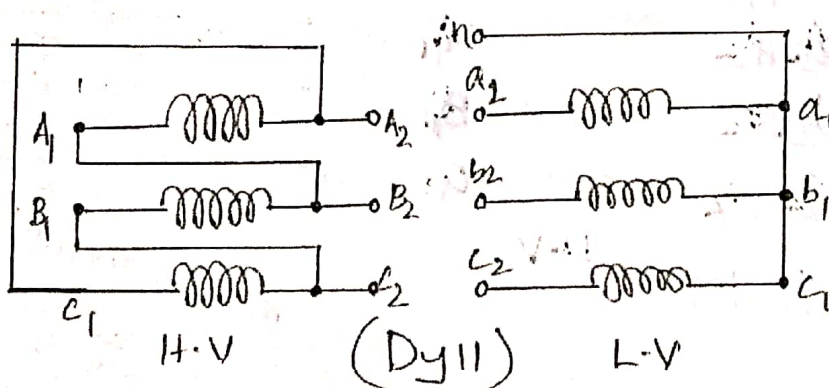
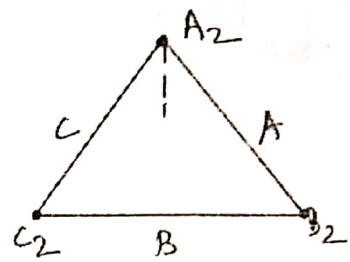
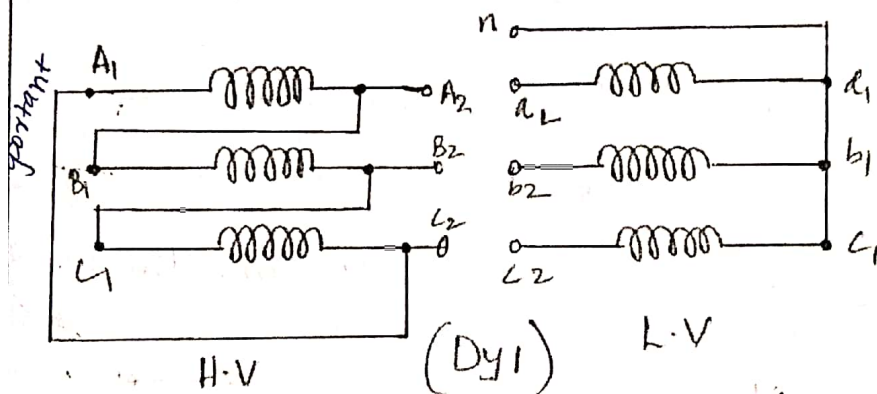
→ The hv side of the transformer, insulation is stressed only to the extend of 57.7% of the line voltage $\therefore$ some saving in the cost of insulation.



4) Delta-Star (Dy1 or Dy11) connection.

→ This connection is generally used is necessary to step up the voltages. i.e. at the beginning of a HT transmission line. On the high voltage side of the transformer, insulation is stressed out only to the extent of 57.7% of line to line voltage.

→ Neutral point is stable and will not float when load is unbalanced. There is no distortion of flux because the existence of a Δ connection.



SCOTT CONNECTION OR T-T CONNECTION

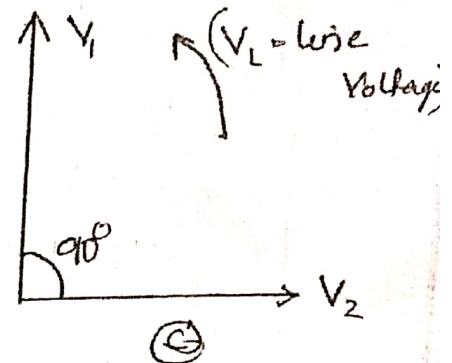
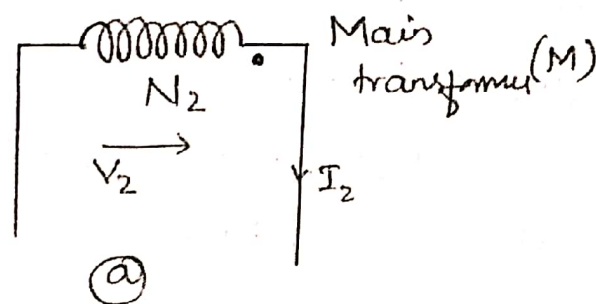
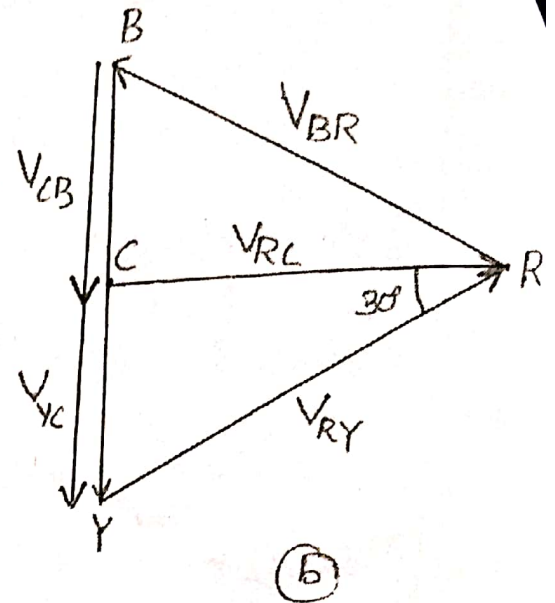
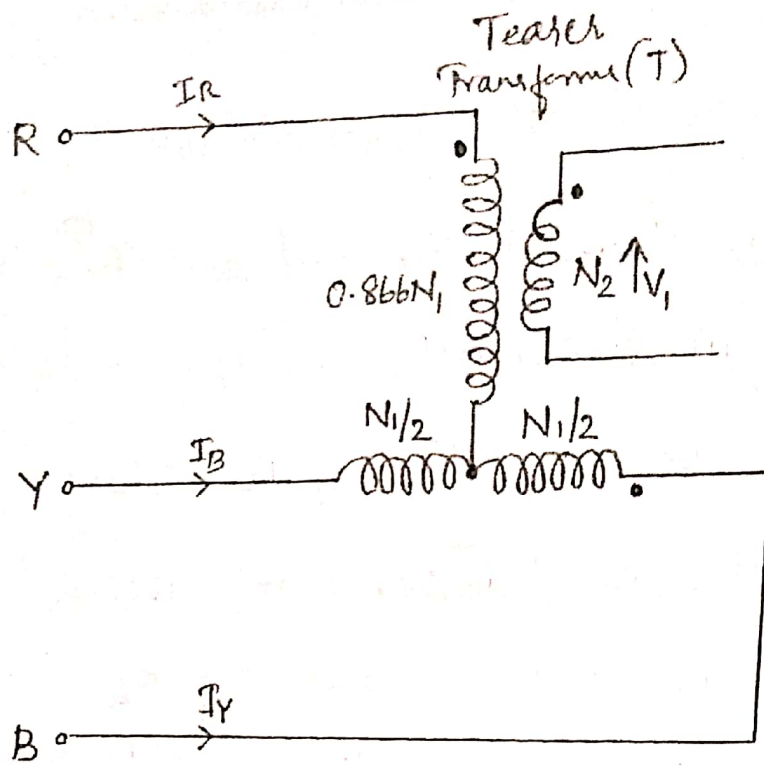
→ For 2 phase transmission and distribution s/m 2 ϕ supply is required. Convert 3 ϕ supply into 2 ϕ supply through Scott or T-T connection of two 1 ϕ transformers.

→ One is called main transformer (M) which has a centre tapped primary. The primary of this transformer has N_1 turns and is connected b/w the terminals B & Y of the 3 ϕ supply. The other transformer is called teaser transformer T. & its primary has $0.866 N_1$ turns.

→ One end of this 1 o is connected to centre-tap C & the other end to the terminal R of the 3 ϕ supply. The number of turns (N_2) of the secondary windings of the two transformer are equal.

→ The voltage across the secondaries are equal or magnitude having a phase difference of 90° .

→ Thus Scott connection convert 3 ϕ supply into a 2 ϕ supply.



→ The fig (a) shows the centre-tapped 1^o of the main transformer has a line voltage of V_{YB} applied to its terminals.

→ The 11^o terminal voltage V_2 of the main transformer

$$V_2 = \frac{N_2}{N_1} V_{YB} = \frac{N_2}{N_1} V_L$$

→ The fig (b) shows the relevant phasor diagram. The line voltages of the 3 ϕ s/m V_{RY} , V_{YB} and V_{BR} are balanced and are shown on the phasor diagram as a closed equilateral triangle.

- The voltage across the two halves of the centre tapped 1° of the main transformer, V_{CB} and V_{YC} are equal and in phase with V_{YB} .
- V_{RC} leads V_{YB} by 90° . This voltage (i.e. V_{RC}) is applied to the 1° of the teaser transformer.
- The 11° voltage V_1 of the teaser transformer will lead the 11° voltage V_2 by 90° as shown in fig. (c).

$$V_{RC} \Rightarrow V_{RY} \cos 30^\circ = \frac{\sqrt{3}}{2} V_L = 0.866 V_L \quad 1)$$

$$\begin{aligned} V_1 &= \frac{N_2}{0.866 N_1} V_{RC} = \frac{N_2}{0.866 N_1} \times 0.866 V_L \\ &= \frac{N_2}{N_1} V_L = V_2 \end{aligned}$$

- Thus voltages V_1 & V_2 constitute balanced 2- ϕ s/m consisting of two voltages of equal magnitude having a phase difference of 90° .

TERTIARY WINDINGS also called three winding transformer

- In addition to 1° & 11° windg transformers may be built with a third winding, called the tertiary winding or triple wound (3 winding) transformers.

→ The tertiary winding may serve any of the following purposes.

- (i) To supply the substation auxiliaries at a voltage different from the 1° & 11° windgs.
- (ii) To supply phase compensating devices, such as condensers operated at a voltage which is different from both 1° & 11° voltage.
- (iii) To interconnect three supply s/m operating at different voltages.
- (iv) To load large split-winding generators.
- (v) To measure voltage of an HV testing transformer.

→ The tertiary winding is called the auxiliary

PRINCIPLE OF OPERATION.

→ The operating principle of a 3 winding (or triple wound) transformer is essentially same as for the two-winding type

→ The 1° wndg of a 3 wndg transformer acts as the magnetizing wndg and its current produces the main magnetic flux.

→ The flux links the 11° and 111° winding and induces emfs in them in proportion to the number of turns in windings.

→ When loads are connected across the 11° and 111° windings, current I_2 & I_3 flows in them.

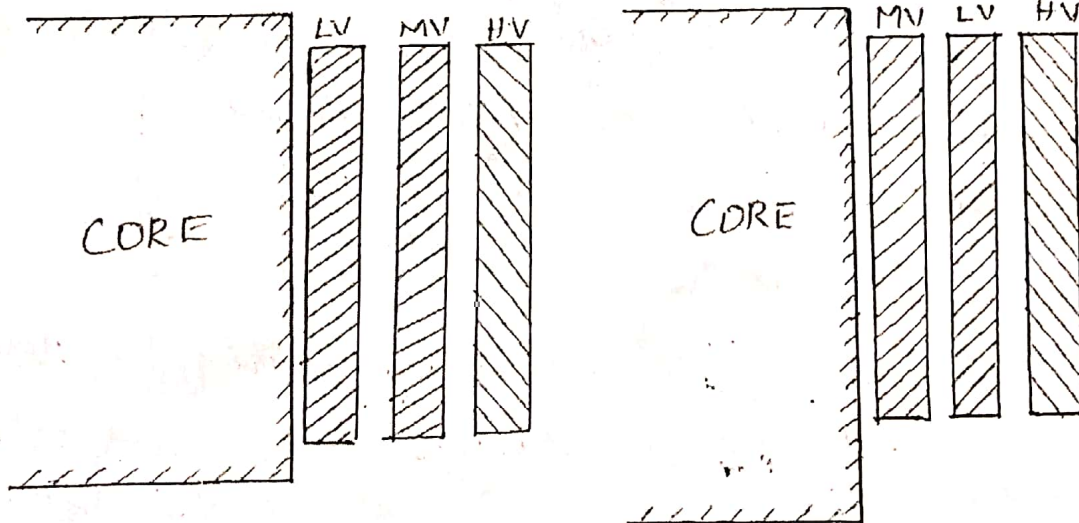
→ The demagnetizing effect of these currents will be determined by the geometrical sum of the forces of the 11° & 111° winding.

$$\text{i.e. } I_1 N_1 = (-I_2 N_2) + (-I_3 N_3) + I_0 N_1$$

$$\text{or } I_1 = I_2' + I_3' + I_0$$

$$\rightarrow \text{where } I_2' = -I_2 \frac{N_2}{N_1} \text{ or } I_3' = -I_3 \frac{N_3}{N_1}$$

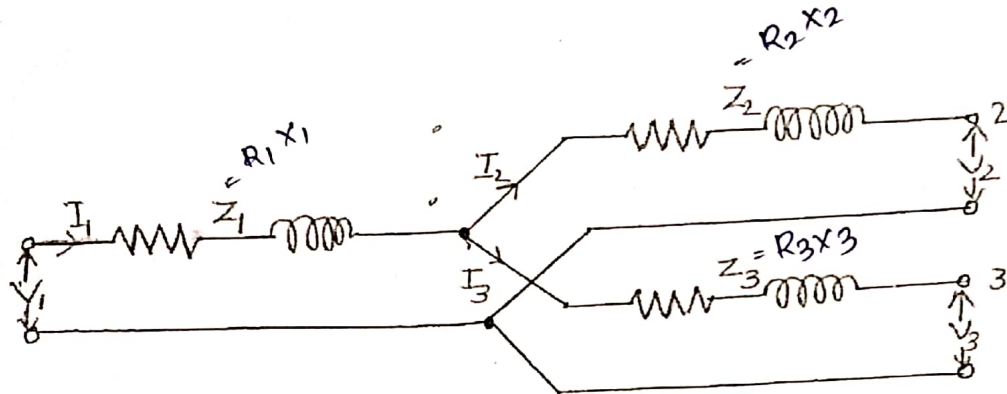
CONSTRUCTION.



→ A three winding transformer consist of three sets of windings (1° , 11° & tertiary). Three winding transformer may be either 3 ϕ units or 1 ϕ units connected in 3 ϕ bank.

- Such transformers have a large KVA rating.
- Three windings are operated at three different voltages, may be termed as high voltage, medium voltage & low voltage windings.
- Two alternative arrangements of windings of a 3 winding transformer. The hv winding in both cases is the outermost winding because of insulation consideration.
- The lv and mv windings are placed adjacent to each other with either of the two nearer to the core.
- Thus the two possible winding arrangements for windings from core outwards are
 - (i) lv, mv, hv
 - (ii) mv, lv, hv.
- In two-winding transformers, the kVA ratings of both 1° & 2° windings are same but it is not so in case of 3-winding transformers.
- The rating of tertiary winding depends upon the intended application. If it's provided for supply of additional load, the winding is designed and calculated on the same basis as the 1° and 2° .

EQUIVALENT CIRCUIT



→ The equivalent circuit of a 3-winding transformer can be drawn with each winding represented by its own resistance and leakage reactances.

$$Z_1 = \frac{1}{2} [Z_{12} + Z_{13} - Z_{23}]$$

$$Z_2 = \frac{1}{2} [Z_{23} + Z_{12} - Z_{13}]$$

$$Z_3 = \frac{1}{2} [Z_{13} + Z_{23} - Z_{12}]$$

PARALLEL OPERATION OF 3 ϕ TRANSFORMER

⇒ All the conditions for the successful parallel operation of 1 ϕ transformers is same and apply to the parallel running of 3 ϕ transformers but with following additions.

- (i) The secondaries of all transformers must have the same phase sequence.

(i) The phase displacement b/w 1° & 11° line voltages must be the same for all transformers which are to be operated in parallel.

(ii) The secondaries of all transformers must have the same magnitude of line voltage.

→ If these conditions are not complied with, the secondaries will simply short-circuit one another and no output will be possible. The main difficulty arising from the parallel connection of 3 ϕ transformer is to ensure that condition (ii) is satisfied. Transformers in the same group should be connected in parallel.