

**LECTURE NOTES
ON
ENERGY CONVERSION-1(TH-1)
DIPLOMA COURSES
4TH SEMESTER
ELECTRICAL ENGINEERING**

PREPARED BY- ER. BISWAJIT MALLIK(SR. LECT. ELECTRICAL)

DEPT. OF ELECTRICAL ENGINEERING

GOVT. POLYTECHNIC BALASORE

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Th1. ENERGY CONVERSION – I

Name of the Course: Diploma in Electrical Engineering			
Course code:		Semester	4 th
Total Period:	75 (60L + 15T)	Examination	3 hrs
Theory periods:	4P / week	Internal Assessment :	20
Tutorial:	1 P / week		
Maximum marks:	100	End Semester examination:	80

A. RATIONALE

Energy Conversion-I deals with DC machines and transformers. The application of DC generators and motors in modern industries are still in practice. The electrical technicians have to look after the installation, operation, maintenance and control of such machine. So the knowledge of these machines is felt essential. Transformers of various voltage ratios and KVA ratings are in wide use in industries as well as in distribution and transmission.

B. OBJECTIVES

After completion of this subject the student will be able to:

1. To acquire knowledge of construction, characteristic and control of the DC machines.
2. To acquire knowledge on performance of DC machines and transformers.
3. To acquire knowledge of testing and maintenance of transformers and DC machines.

C. TOPIC WISE DISTRIBUTION OF PERIODS		Periods
SI. No.	Topic	
1.	DC GENERATORS	17
2.	DC MOTORS	15
3.	SINGLE PHASE TRANSFORMER	20
4.	AUTO TRANSFORMER	03
5.	INSTRUMENT TRANSFORMERS	05
TOTAL		60

D. COURSE CONTENT IN TERMS OF SPECIFIC OBJECTIVES

1. D.C GENERATOR

- 1.1. Operating principle of generator
- 1.2. Constructional features of DC machine.
 - 1.2.1. Yoke, Pole & field winding, Armature, Commutator.
 - 1.2.2. Armature winding, back pitch, Front pitch, Resultant pitch and commutator-pitch.
 - 1.2.3. Simple Lap and wave winding, Dummy coils.
- 1.3. Different types of D.C. machines (Shunt, Series and Compound)
- 1.4. Derivation of EMF equation of DC generators. (Solve problems)
- 1.5. Losses and efficiency of DC generator. Condition for maximum efficiency and numerical problems.

- 1.6. Armature reaction in D.C. machine
 - 1.7. Commutation and methods of improving commutation.
 - 1.7.1. Role of inter poles and compensating winding in commutation.
 - 1.8. Characteristics of D.C. Generators
 - 1.9. Application of different types of D.C. Generators.
 - 1.10. Concept of critical resistance and critical speed of DC shunt generator
 - 1.11. Conditions of Build-up of emf of DC generator.
 - 1.12. Parallel operation of D.C. Generators.
 - 1.13. Uses of D.C generators.
2. **D. C. MOTORS**
- 2.1. Basic working principle of DC motor
 - 2.2. Significance of back emf in D.C. Motor.
 - 2.3. Voltage equation of D.C. Motor and condition for maximum power output(simple problems)
 - 2.4. Derive torque equation (solve problems)
 - 2.5. Characteristics of shunt, series and compound motors and their application.
 - 2.6. Starting method of shunt, series and compound motors.
 - 2.7. Speed control of D.C shunt motors by Flux control method, Armature voltage Control method. Solve problems
 - 2.8. Speed control of D.C. series motors by Field Flux control method, Tapped field method and series-parallel method
 - 2.9. Determination of efficiency of D.C. Machine by Brake test method(solve numerical problems)
 - 2.10. Determination of efficiency of D.C. Machine by Swinburne's Test method(solve numerical problems)
 - 2.11. Losses, efficiency and power stages of D.C. motor(solve numerical problems)
 - 2.12. Uses of D.C. motors
3. **SINGLE PHASE TRANSFORMER**
- 3.1 Working principle of transformer.
 - 3.2 Constructional feature of Transformer.
 - 3.2.1 Arrangement of core & winding in different types of transformer.
 - 3.2.2 Brief ideas about transformer accessories such as conservator, tank, breather, and explosion vent etc.
 - 3.2.3 Explain types of cooling methods
 - 3.3 State the procedures for Care and maintenance.
 - 3.4 EMF equation of transformer.
 - 3.5 Ideal transformer voltage transformation ratio
 - 3.6 Operation of Transformer at no load, on load with phasor diagrams.
 - 3.7 Equivalent Resistance, Leakage Reactance and Impedance of transformer.
 - 3.8 To draw phasor diagram of transformer on load, with winding Resistance and Magnetic leakage with using upf, leading pf and lagging pf load.
 - 3.9 To explain Equivalent circuit and solve numerical problems.
 - 3.10 Approximate & exact voltage drop calculation of a Transformer.
 - 3.11 Regulation of transformer.
 - 3.12 Different types of losses in a Transformer. Explain Open circuit and Short Circuit test.(Solve numerical problems)
 - 3.13 Explain Efficiency, efficiency at different loads and power factors, condition for maximum efficiency (solve problems)
 - 3.14 Explain All Day Efficiency (solve problems)
 - 3.15 Determination of load corresponding to Maximum efficiency.
 - 3.16 Parallel operation of single phase transformer.

4. AUTO TRANSFORMER

- 4.1. Constructional features of Auto transformer.
- 4.2. Working principle of single phase Auto Transformer.
- 4.3. Comparison of Auto transformer with an two winding transformer (saving of Copper).
- 4.4. Uses of Auto transformer.
- 4.5. Explain Tap changer with transformer (on load and off load condition)

5. INSTRUMENT TRANSFORMERS

- 1.1 Explain Current Transformer and Potential Transformer
- 1.2 Define Ratio error, Phase angle error, Burden.
- 1.3 Uses of C.T. and P.T.

Syllabus coverage up to Internal assessment

Chapters: 1 and 2.

Learning Resources:

Sl.No	Title of the Book	Name of Author	Publisher
1	Electrical Technology – II	B. L. Thareja and A. K. Thareja	S.Chand
2	A Textbook of Electrical Machines	K R Siddhapura, D B Raval	Vikas
3	Electrical Technology	J. B. Gupta	S.K.Kataria and Sons
4.	Electric Machine	Ashfaq Husain	Dhanpat Rai and Sons
5.	Electrical Machine	S. K. Bhattacharya	TMH
6.	Electrical Machines	D P Kothari, I J Nagrath	Mc Graw Hill
7	Electrical Machines	Prithwiraj purakait and Indrayudh Bandyopadhyay	OXFORD

Introduction to Electrical Machines

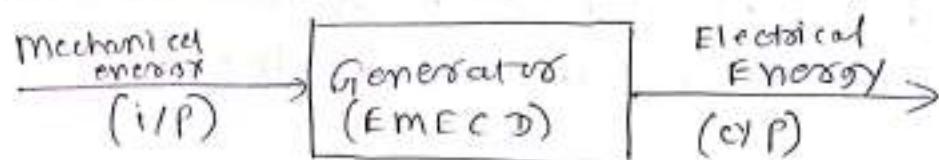
①

Electro-mechanical Energy conversion devices

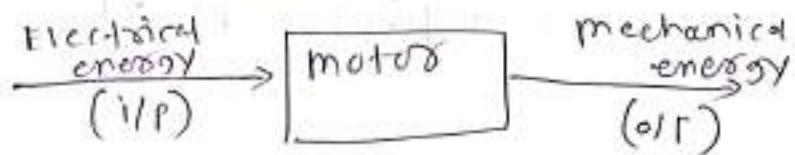
An electro-~~magnetic~~^{mechanical} energy conversion device is one which converts electrical energy into mechanical energy or mechanical energy into electrical energy.

Generators

The electrical machine which converts mechanical energy into electrical energy is called generators.



Motors The electrical machine which converts electrical energy into mechanical energy is called a motor.



An electro-mechanical energy conversion device is a link between an electrical & mechanical system.

BASIC Electromagnetic laws

(2)

① Faraday's laws of Electromagnetic induction

a) Faraday's 1st law

It states that whenever the ~~magnetic~~ conductor cuts magnetic field an emf is induced in the conductor, this emf causes a current to flow in the conductor if the circuit is closed.
b) Whenever there is a relative motion b/w the conductor & magnetic field an emf is induced in the conductor.

FLUX (ϕ) or No. of Field lines

Flux linkage (Ψ)

Total amount of flux passing through N turn of a coil $\boxed{(\Psi) = N \phi}$

b) Faraday's 2nd law

It states that the magnitude of induced emf is directly proportional to the rate of change of flux linkages

$$e = \frac{d\Psi}{dt} = \frac{d}{dt}(N\phi)$$

$$\boxed{e = -N \frac{d\phi}{dt}}$$
 Volt \therefore -ve sign is used to satisfy Lenz's law.

(5)

$$\text{if } \theta = \text{const.} \quad [e = 0]$$

Necessary conditions to produce induced emf

- 1) magnetic field
- 2) set of conductors
- 3) relative motion b/w magnetic field
 & conductors

(2)

Lenz's law

This law states that direction of induced emf is such that the current produced by it sets up a magnetic field which opposes the cause of production.

$$[e = -N \frac{d\phi}{dt}]$$

-ve sign indicates that emf induced opposes the cause that produces it.

(1)

(2)

③ Fleming's Right hand rule (LHRR)

It states that if we stretch the thumb, middle finger and fore finger (index) of right hand in such a way that they are mutually perpendicular to each other, then Thumb represents direction of motion of conductor, middle finger represents the direction of induced current & fore finger represents the direction of magnetic flux.

Ex: Used in case of DC Generators to find the direction of motion of induced emf.

④ Fleming's Left hand rule (LHHR)

It states that if we stretch the thumb, middle finger & fore finger of left hand in such a way that they are mutually perpendicular to each other then thumb represents direction of force, middle finger represents direction of current & fore finger represents direction of magnetic field.

Ex: Used in DC motor to find the direction of force.

(b)

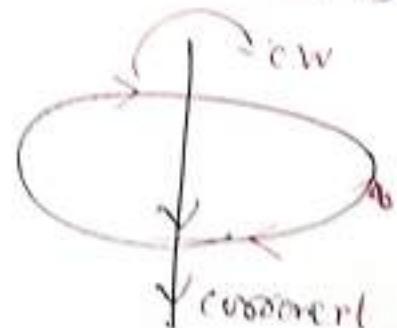
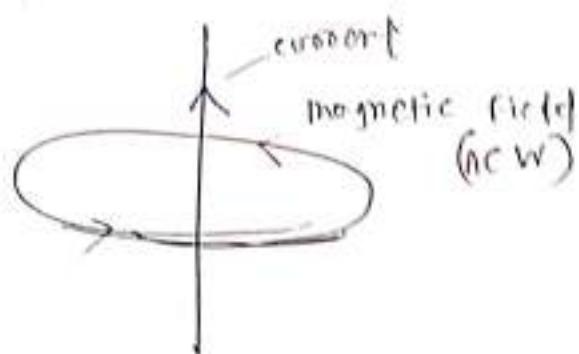
Condition for Parallel motion in DC machine

There must be two stationary magnetic field. These two fields should be stationary w.r.t. each other. Due to interaction torque produced there must be some displacement b/w these two fields. To reduce space displacement torque is produced. The space displacement angle is called *angle between field axis & armature axis*.

Machinist Right hand thumb rule

Suppose we hold an electric wire with our right hand. Assuming current flows in direction of thumb from (bottom to top).
 \rightarrow direction of magnetic field will be in direction as in which our fingers curl.

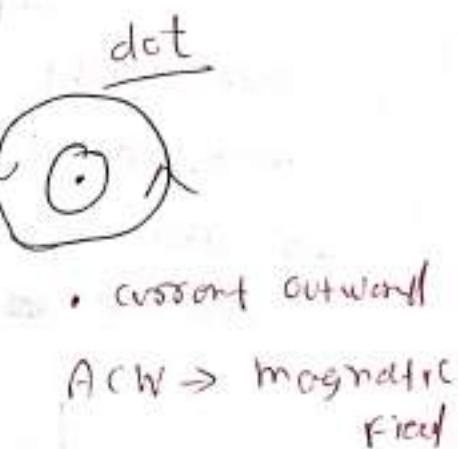
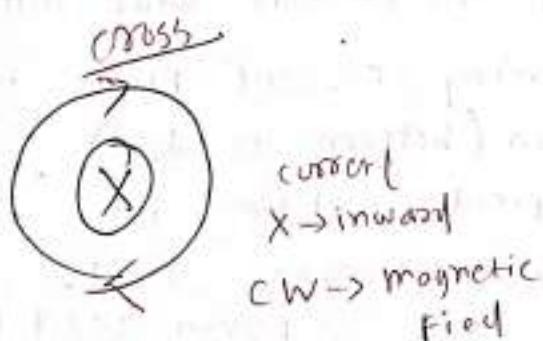
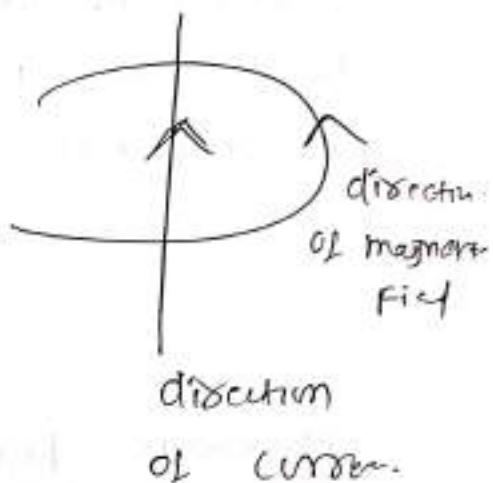
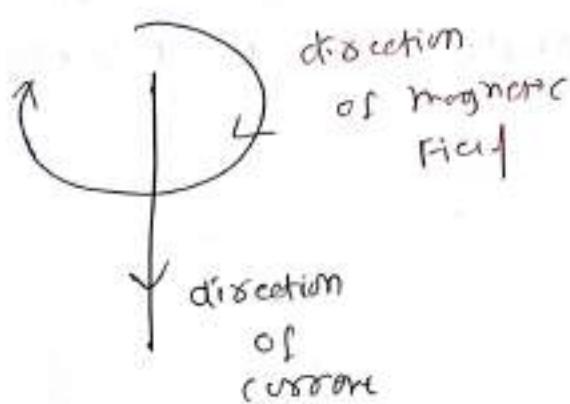
(From left to right)



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Corkscrew rule

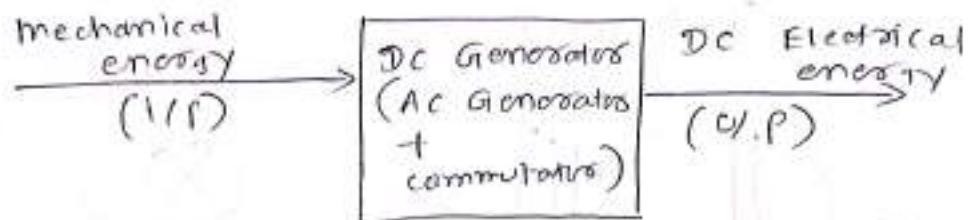
Suppose we have a corkscrew. Point the pointed tip of the corkscrew in the direction in which the current is flowing. The direction in which the screw rotates clockwise is the direction of magnetic field.



DC Generator

3.1 operating principle of generator

- A generator works on the principle of the production of dynamically induced e.m.f.
- whenever a conductor cuts magnetic flux, dynamically induced emf is produced in the conductor according to faraday's laws of electro-magnetic induction. The induced emf causes current to flow if the conductor circuit is closed.
- The direction of induced e.m.f (or current) is given by Fleming's right hand rule (FRHR).



Simple loop Generators

a) with slip rings

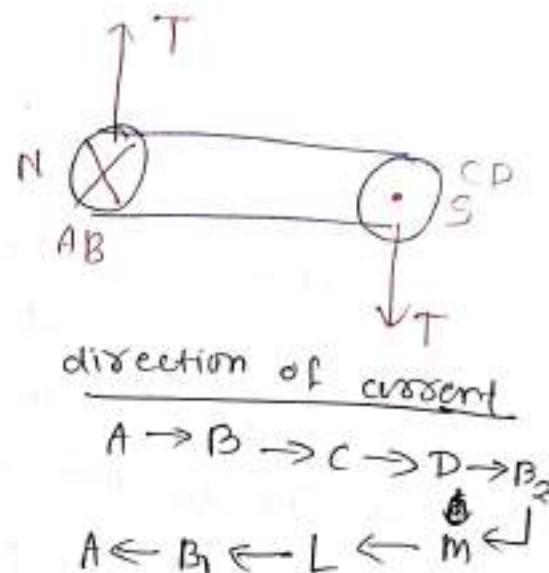
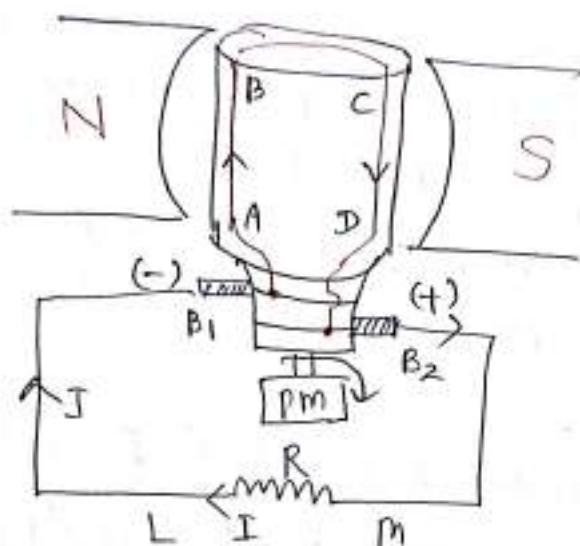
construction:-

- i) consider a single-turn rectangular copper coil ABCD rotating about its own axis in a magnetic field provided by either permanent magnet or electromagnets.
- ii) The two ends of the coil are joined to two slip-rings which are insulated from each other & from the central shaft.

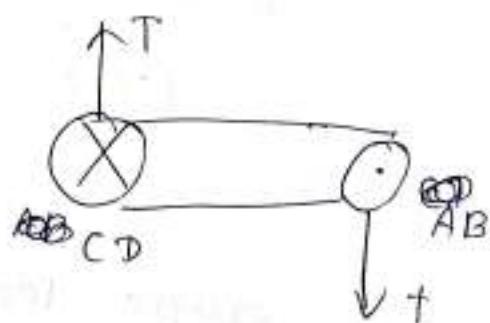
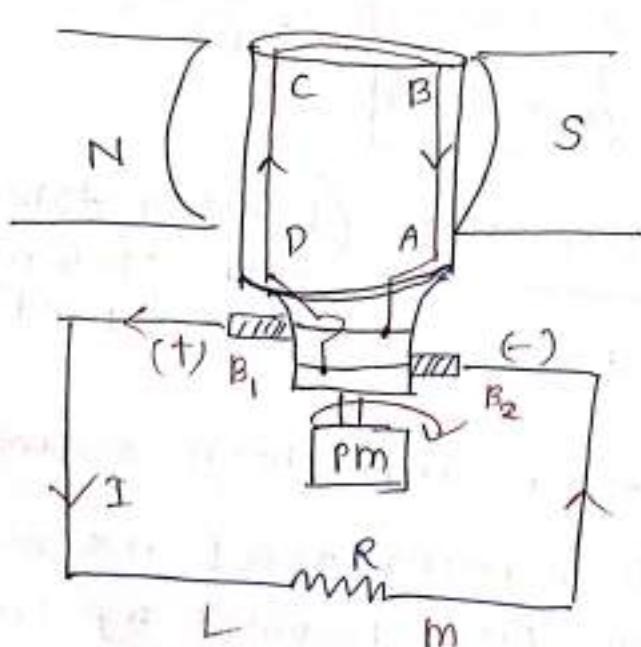
(Rotating Armature
with stationary
field)

iii) Two collecting brushes (of carbon or copper) press against the slip rings. ②

Case - I ($0^\circ - 180^\circ$)



case - II ($180^\circ - 360^\circ$)



⊗ → inwards

∅ → outwards

direction of current
 $D \rightarrow C \rightarrow B \rightarrow A \rightarrow B_1 \rightarrow L \rightarrow m$
 $D \leftarrow B_2 \leftarrow$

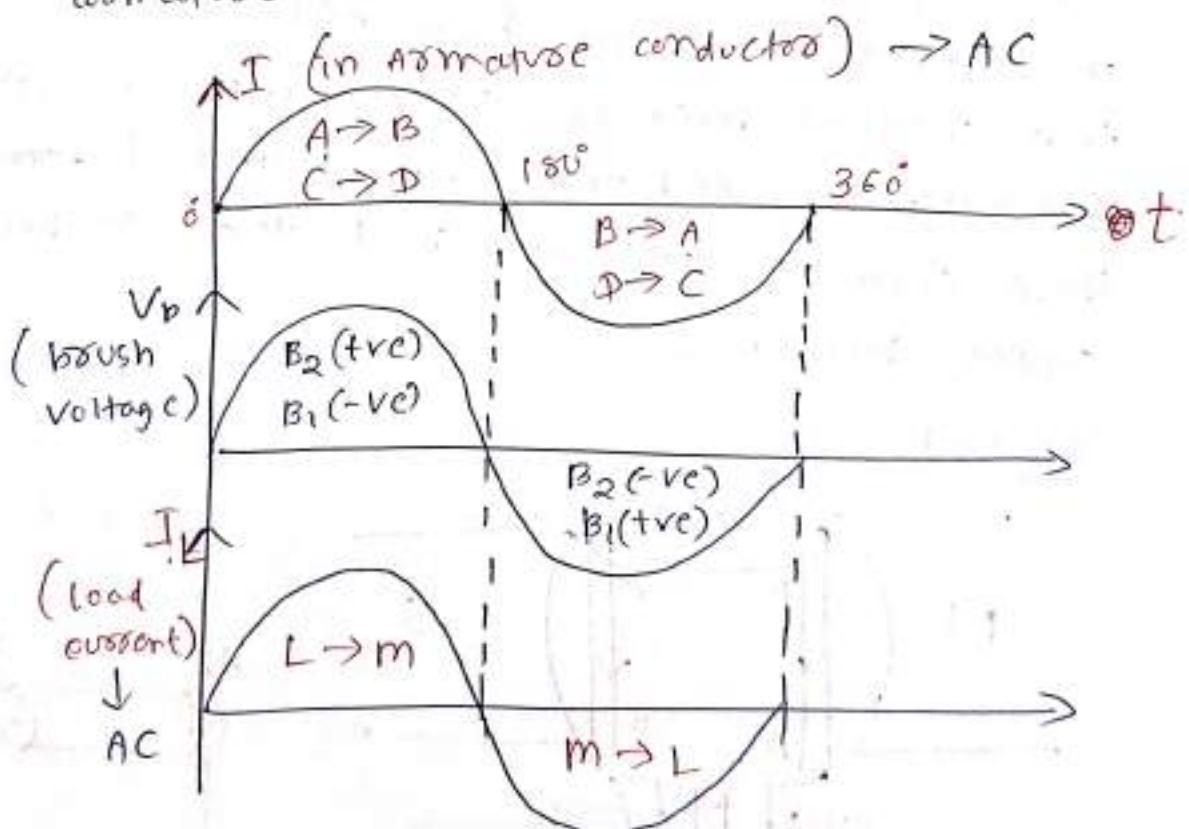
iv) with slipping brush B_1 is always in contact with conductors AB whether it exists under North pole or South pole & brush B_2 is always in contact with

(3)

conductors CD.

v) If conductor AB is under N' pole, the current in it is \times & brush B_1 polarity becomes -ve. After half cycle rotation, conductor AB comes under south pole. The induced current in it is \odot & brush B_1 polarity becomes +ve. It is observed that the brush polarity is alternating.

vi) Therefore with slip rings the brush voltage, load current & current inside the armature conductors are AC.

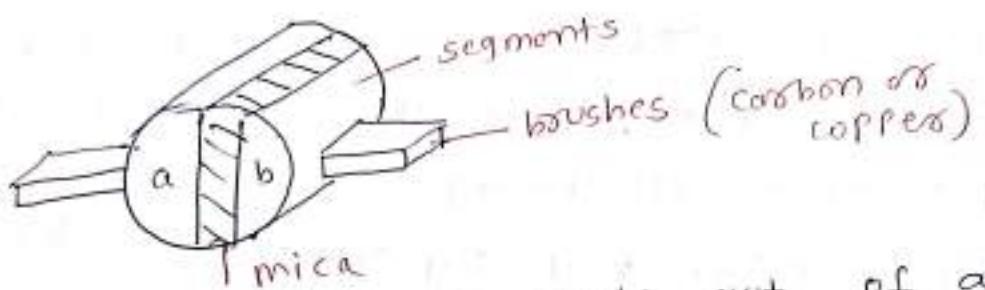


→ We found that, current obtained in a simple loop generator reverses its direction after every half revolution. It is AC in nature.

(1)

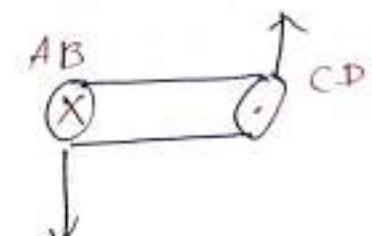
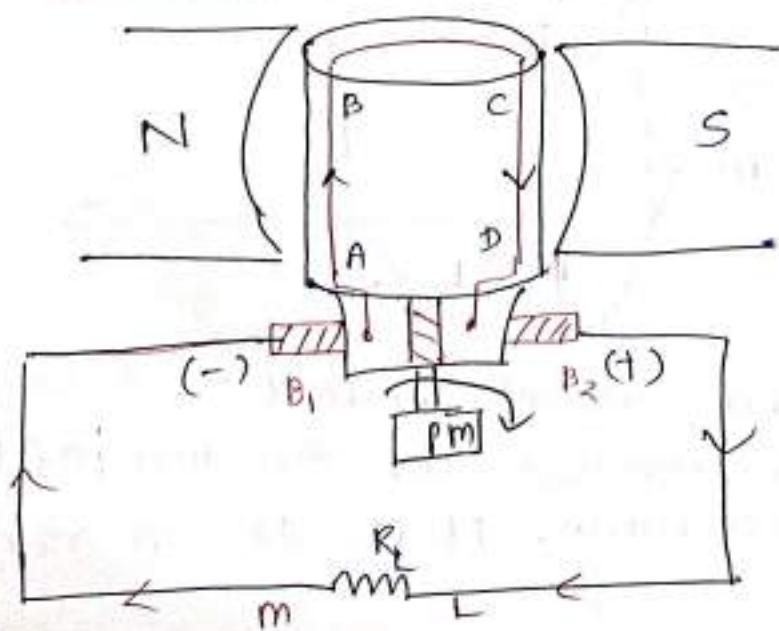
b) with split rings / commutators

For making the flow of current unidirectional in the load circuit, the slip rings are replaced with split rings.



The split rings are made out of a conducting cylinder which is cut into two ~~halves~~ or segments insulated from each other by a thin sheet of mica or some other insulating material. The coil ends are joined together on these segments on which rest the carbon or copper brushes.

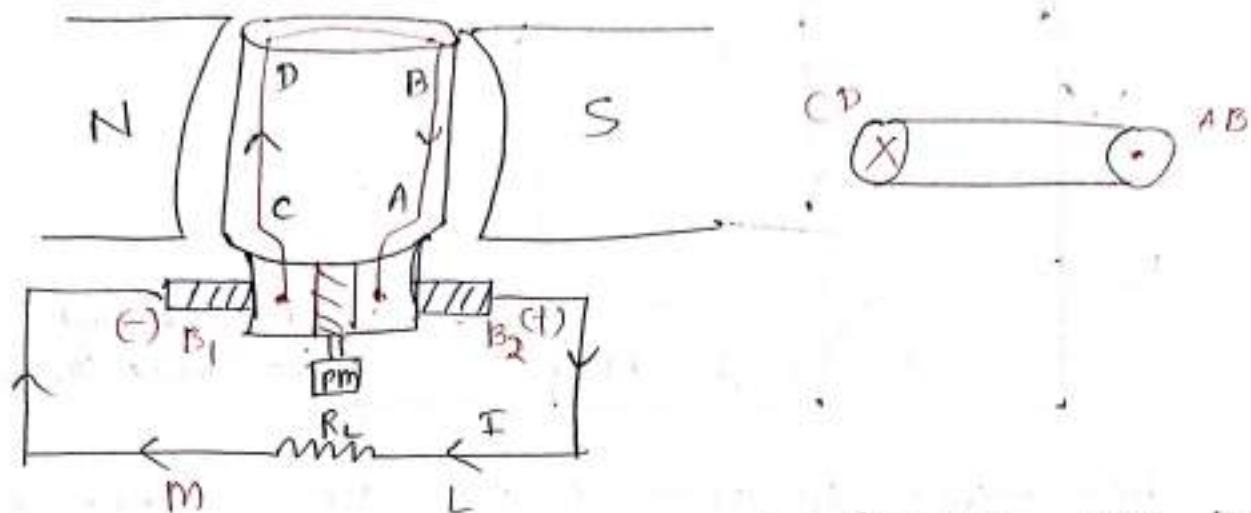
case - 1



$$\begin{array}{l}
 A \rightarrow B \rightarrow C \rightarrow D \rightarrow B_2 \\
 A \leftarrow B_1 \leftarrow m \leftarrow L
 \end{array}$$

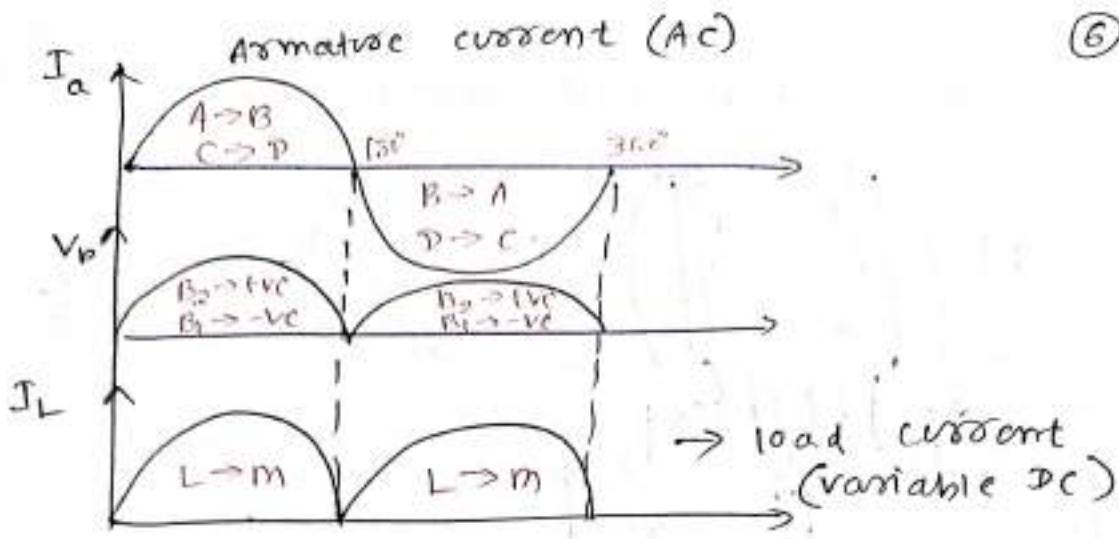
(5)

Case-II (after half cycle)

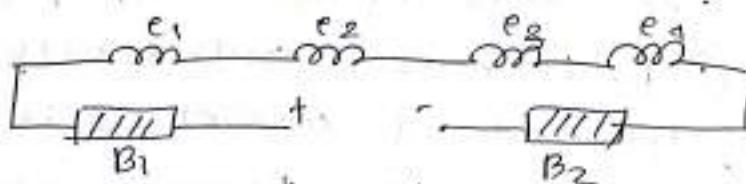


- i) The brush B_1 is always in contact with the conductor that exists under North pole only & brush B_2 is always in contact with the conductor that exists under South pole only.
- ii) In case ① B_1 brush is in contact with AB conductor, the induced current in it is \textcircled{X} . & the brush B_1 polarity becomes -ve.
- iii) After half cycle rotation conductor CD comes under North pole, the induced current in it becomes \textcircled{X} . Brush B_1 is in contact with conductor CD through commutator segment ② therefore B_1 brush polarity is -ve, from the above it is observed that the brush polarity is fixed i.e. uni-directional.

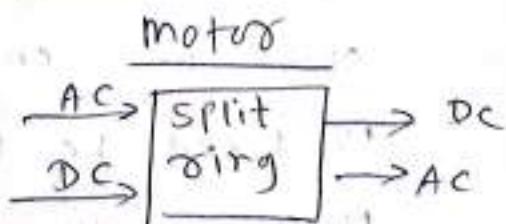
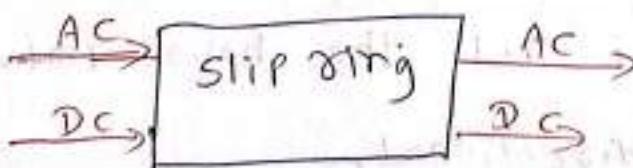
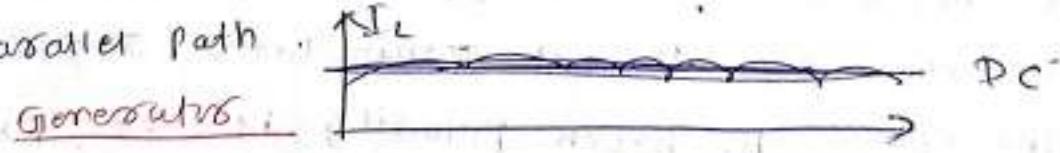
Note - with split rings, the brush voltage & load currents are uni-directional, but the current inside the armature conductors is AC.



The methods to increase DC O/P Voltage & to reduce ripples in the DC O/P Voltage are i) by connecting more No. of armature coils in series ~~with~~ in each parallel path



ii) by Using flat topped main field Flux distribution. The No. of pulses in the DC O/P voltage for every 180° rotation = the no. of armature coils connected in series in each parallel path.



(7)

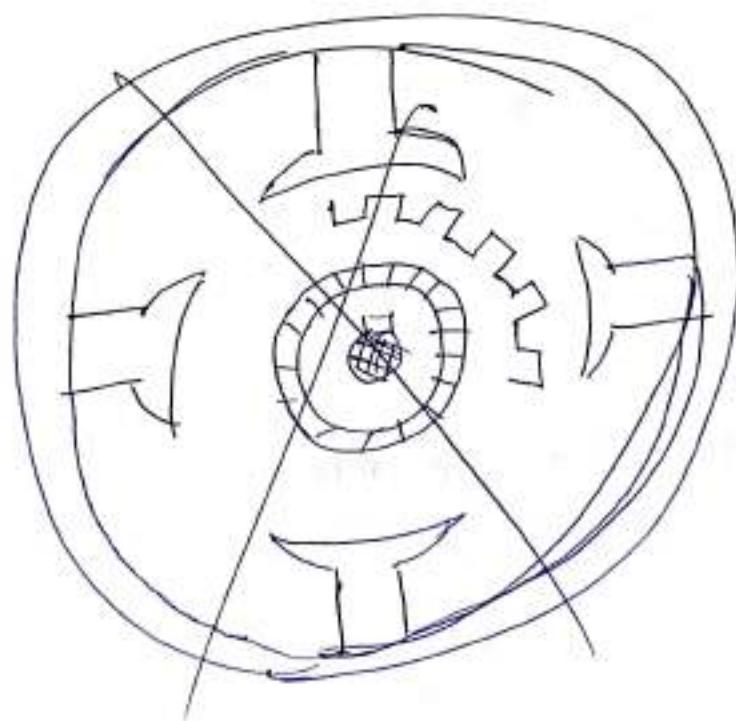
1.2 constructional features of DC machine

Practical DC Machine

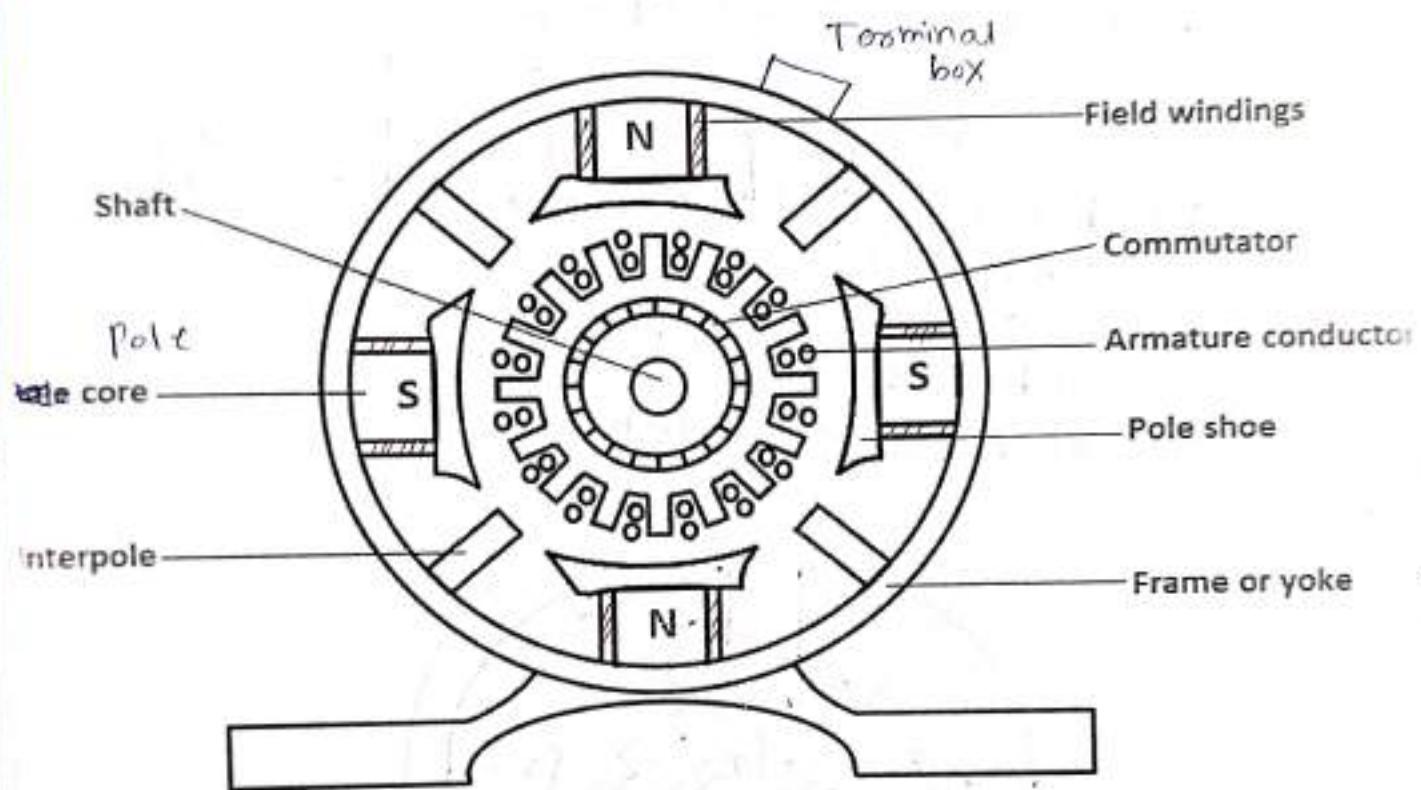
Basically DC machine consists of two main parts .

- Stator
- Rotor

- a) Stator
 - Yoke / Frame
 - Field poles
 - Pole core
 - Pole shoe
 - Field winding
 - interpoles
 - compensating poles
- b) Rotor
 - i) Armature core
 - ii) commutators
 - iii) brushes
 - iv) Armature windings .



(6)



Parts of a DC m/c

Explain with the help of a diagram.

(9)

Stator A stator is the static part of the DC machine that houses the field windings and receives the supply.

a) Yoke / Frame

It is the outer cylindrical frame of the machine.

Functions

- i) It provides mechanical support for the poles.
- ii) ^{and} It acts as a protective cover for entire machine.
- iii) It provides return path to the main

Field FLUX

- Material
- Cast iron (small DC machine)
 - cast steel (large DC machine)

(\because since the Flux carried by yoke is stationary (i.e. constant), it is not laminated)

b) Field Poles

Pole core : cast steel

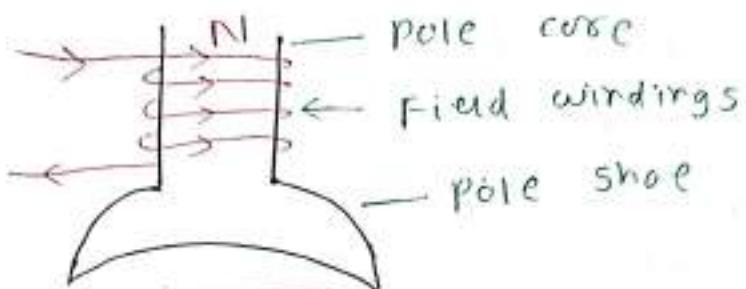
Function i) It carries Field winding & it provides mechanical support to the pole shoe.

ii) It acts as an electromagnet when the Field windings are excited.

Pole Shoe : cast steel laminations

Function i) It supports the exciting coils (or Field coils)

- ii) They spread out the flux in the air gap
 Due to larger cross-section, it reduces the reluctance of the magnetic path.



(c) Field (or exciting) winding

The field coils or pole coils which consists of copper wire.

- i) For DC shunt machine, large number of turns of small cross-section are used.
- ii) For DC series machine, small number of turns of large cross-section are used.
- iii) For dc compound machine, both shunt (thin wire) and series (thick wire) field windings are used.

Interpoles

These are fixed to the yoke in between the main poles of DC machine. These are usually tapered with sufficient sectional area at the root to avoid magnetic saturation. The interpole winding, consisting of a few turns of a thick wire is connected in series with the armature so that

its ~~magnetic~~ mmf is proportional to armature current.

Compensating windings

These windings are placed in the slots cut in the pole faces of DC machine. compensating winding is also connected in series with the armature circuit. This winding is however, used in large DC machine only.

Rotor

A rotor is the ~~stationary~~ ^{rotating} part of the DC machine that ~~never~~ brings about the mechanical rotation.

Armature core

→ silicon steel laminations are used in order to reduce both hysteresis loss & eddy current loss.

- Function
 - i) it accommodates armature windings.
 - ii) It provides low reluctance path to the main field flux.

Armature windings

- i) The armature winding is made from copper. It consists of large ~~no.~~ no. of insulated coils, each coil having one or more turns.

(12)

- ii) These coils are placed in slots and appropriately connected in series and parallel depending upon the type of winding required.
- iii) There are basically two winding types
 - a) LAP winding \rightarrow ($A = P$, No. of parallel paths = No. of poles)
 - b) wave winding \rightarrow $A_{\text{w.w.}} = 2$

commutator

- i) It contains no. of commutator segments
- ii) commutator segments are made with hard segments of high conductivity hard-drawn copper to reduce its wear and tear.

No. of commutator segments = No. of armature coils

- iii) commutator segments are insulated from each other by mica insulation.

brushes

brushes are made of carbon for small DC machines, electrographite for all DC machine and copper-graphite for low voltage & high current DC machine.

Function

It collect the current from armature conductors through commutator segments or brushes send the current into armature conductors through a commutator segments.

(13)

Advantages of carbon brush over copper brush

- i) self lubricating property, due to this brush frictional losses become less, efficiency increased.
- ii) high thermal stability i.e. high melting point due to this current collection capacity of brush is increased.
- iii) it improves the commutation i.e. less sparking at the buses.
- iv) brush drop is constant because it has -ve temp. co-efficient.

disadvantages : more brush drop

Bearings : The ball or roller bearing are fitted in the end housing. The function of the bearings is to reduce friction between the stationary and rotating parts of the machine and have less wear & tear.

Shaft

The shaft is made up of mild steel with maximum breaking strength. The shaft is used to transfer mechanical power from or to the machine. The rotating parts like armature core, commutator are mounted to the shaft.

(19)

End housing End housing are attached to the ends of the main frame and support bearings.

Armature windings

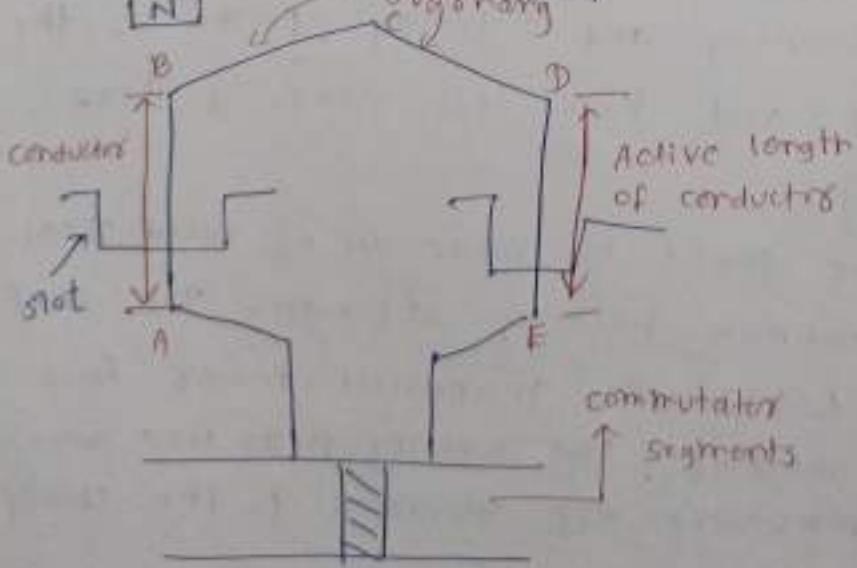
Terms used in winding

Conductors It is the active length of copper wire which takes active part in the energy conversion process, emf is induced if coil is rotated.

Turn A turn basically consists of conductors connected end to end by a wire called end conductors. $1 \text{ turn} = 2 \text{ conductors}$

coil coil contains any no. of turns but it has only 2 coil sides

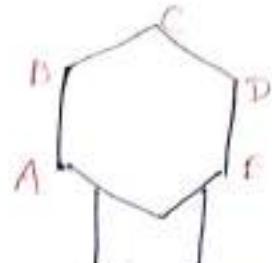
conductors in each coil side = turns of a coil.



a) Single turn coil



two multi-turn coil



(15)

AB, DE → coil sides

BCD → overhang or end-connection

conductors in a coil = $2 \times \text{turns}/\text{coil}$

conductors = Active copper

overhang = inactive copper

Types of armature windings based on coil sides / slot :

i) single layer winding

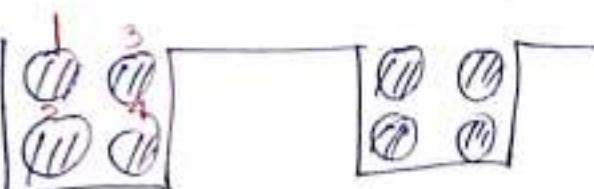


one coil side occupies the entire slot area.

ii) $S = \text{Slots}, c = \text{coil}$

$$c = \frac{s}{2}$$

Used in small AC m/c

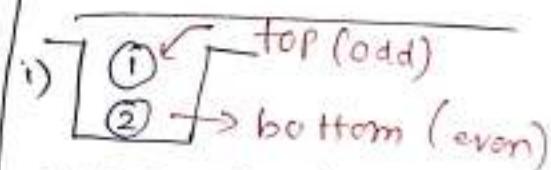


4 coil sides per slot

$$u = \text{coil sides}/\text{slot}$$

$$c = \frac{1}{2} u s$$

double layer winding



even no. of coil sides in two layers.

ii) $S = \text{slot} = \text{coil}$

$$c = s$$

used in commutator m/cs (dc m/cs) & large AC m/c.

more common in ^{above} 5kW machines.
(two coil sides per slot)

$$u = 2 \text{ (default)}$$

(16)

Advantage of double layer winding over single layer winding!

- easier to house the winding in slots during repairs.
 - lower-leakage reactance, so better performance.
 - better e.m.f waveform in case of generators.
 - more economical.
- Q) How many commutator segments are required in 4 pole, 36 slots DC m/c?
- 18
 - 36
 - 72
 - 194

~~Ans~~ $c = \frac{1}{2} vs$ $v = 2$

$$= \frac{1}{2} \times 2 \times 36$$

$$= 36$$

~~Unit pitch~~
Pole pitch: i) It is defined as the peripheral distance between identical points on two adjacent poles.

- Pole pitch = 180° (always) electrical degrees
- $PP = \frac{\text{conductors}}{\text{pole}}$

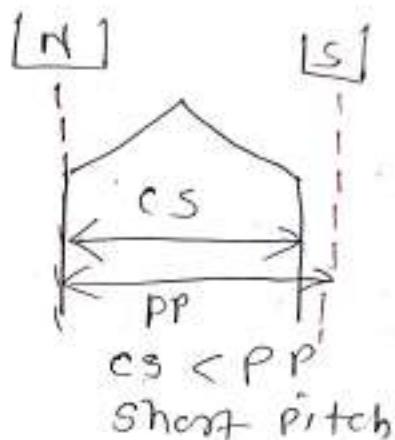
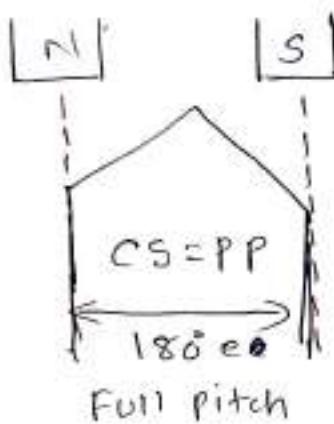
Ex: Conductors = 48, pole = 6

$$PP = \frac{48}{6} = 8 \text{ conductors per pole, the}$$

(17)

Coil span or coil pitch) The distance between the two coil-sides of a coil is called coil span or coil pitch.

ii) It is usually measured in terms of teeth, slots or electrical degrees.



if coil span = PP \rightarrow Full pitch wdg

coil span < PP \rightarrow Short pitch wdg

(\therefore NB \rightarrow short pitched windings are used in DC m/c in order to improve the commutation.)

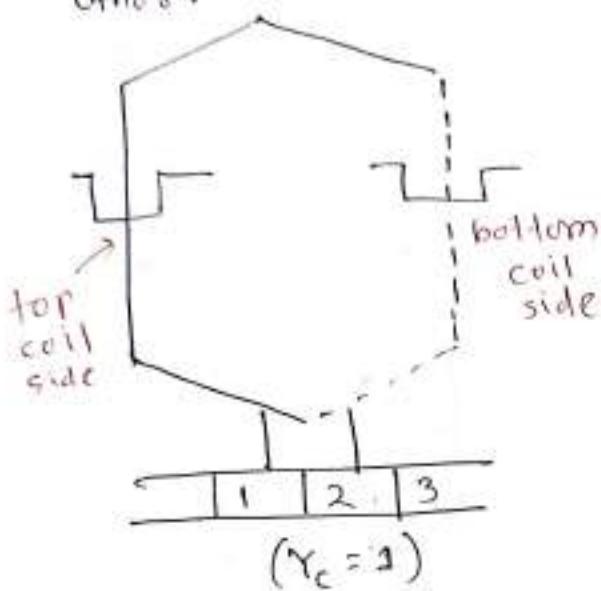
Types of Armature windings based on armature coil end connection:

- a) LAP winding
- b) Wave winding

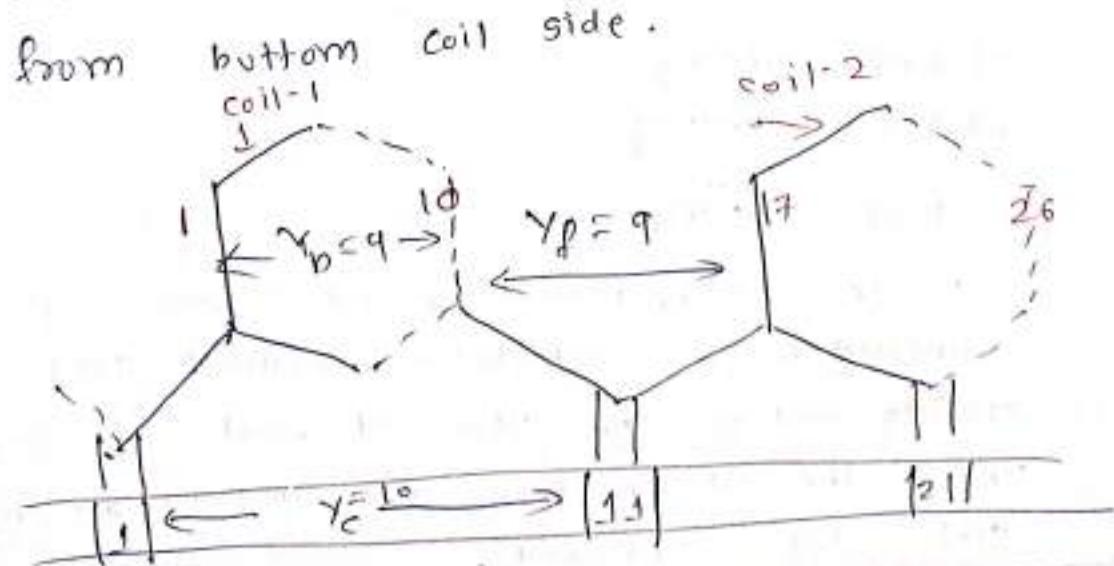
a) LAP winding

In lap winding, Finishing end of one coil is connected to a commutator segment and to the starting end of the adjacent coil situated under the same pole and similarly all the coils are connected.

This winding is known as lap winding because the sides of successive coils overlap each other.



b) wave winding the two coil-ends are bent in opposite directions and connected to the commutator segments which are approximately two pole pitch i.e. (36° e). each commutator segment has two coil-ends connected to it one from the top coil side and the other from the bottom coil side.



commas ~~sides~~ top or bottom, coil-sides as the

(19)

Closed winding teams

Back pitch (y_b)

- The distance b/w top and bottom coil sides of one coil, measured at the back of the armature is called back pitch.
- It may be expressed in terms of teeth, slots or in terms of coil sides.

ex. Top coil-sides 1,3,5 For coil 1

$$\text{bottom coil sides } 8,10,12 \quad \begin{array}{l} 1 \text{ top } \\ 8 \text{ bottom } \end{array} \quad y_b = 8 - 1 = 7$$

For coil-2 for coil-3

$$y_b = 10 - 3 = 7 \quad y_b = 12 - 5 = 7$$

∴ Note : y_b is always odd, $\left[y_b = \frac{2c}{p} \pm k \right]$
 $(k = \text{integer or fraction which makes } y_b \text{ odd})$ $= \frac{\text{coil-sides}}{\text{per pole}} \pm k$

Front pitch (y_f) : The distance between the two coil-sides connected to the same commutator segments, is called front pitch (y_f).

∴ y_f = always odd

if $y_b > y_f \rightarrow$ progressive winding i.e. Left \rightarrow Right
or clockwise direction

if $y_b < y_f \rightarrow$ retrogressive winding i.e. Right \rightarrow Left
or ccw direction.

Winding pitch (y_w)

The distance b/w consecutive coils
and similar ~~is~~ top or bottom, coil-sides as the

(20)

winding progresses -

→ it is in terms of coil-sides -

$$\rightarrow Y_w = Y_b - Y_F \rightarrow \text{lap winding}$$

$$= Y_b + Y_F \rightarrow \text{wave winding}$$

→ Y_w = always even

$$Y_w = 2 Y_c$$

commutator pitch (Y_c)

The distance b/w two commutator segments to which the two ends of one coil are joined, is called the commutator pitch.

→ always expressed in terms of commutator segments.

$Y_c = \frac{1}{2} \pm 1$ → for simplex lap winding

$$= \frac{c \pm 1}{p/2} \rightarrow \text{for simplex wave winding}$$

+ → progressive
- → retrogressive

- (Q) For a commutator machine with 6 poles & 40 coils, determine for a simplex lap winding
- the no. of commutator segments
 - back pitch & front pitch
 - commutator pitch

A: a) since one commutator segment is required for each coil, the no. of commutator = no. of coils

$$\therefore c = 40$$

b) back pitch, $Y_b = \frac{2c}{p} \pm k = \frac{2 \times 40}{6} \pm k$

(21)

$$Y_b = \frac{10}{3} \pm \frac{1}{3}$$

$$Y_b \text{ must be odd, so } Y_b = \frac{10}{3} - \frac{1}{3} = 3$$

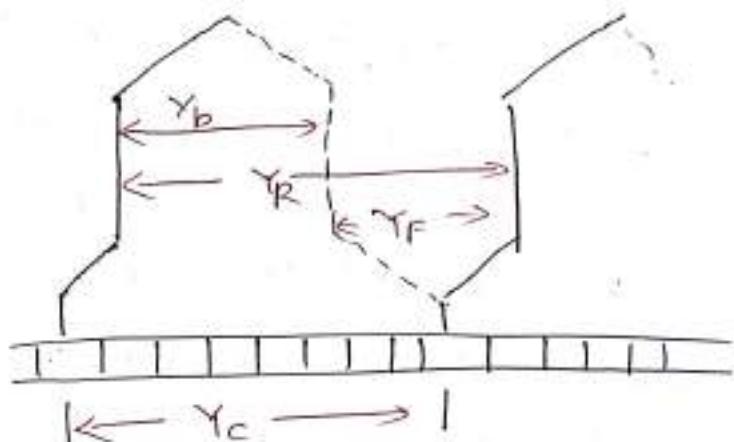
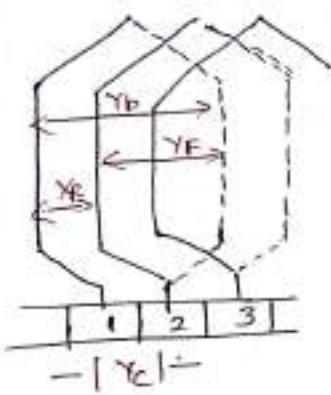
$$\text{but } Y_b - Y_F = 12$$

$Y_F = 13 - 3 = 11$, For progressive winding

$= 13 + 2 = 15$, for retrogressive winding

c) commutator segments pitch, $Y_c = \pm 1$.

Resultant pitch (Y_R) it is the distance between the beginning of one coil & the beginning of the next coil to which it is connected.



Dummy coils

- If commutator pitch Y_c is an integer, dummy coils are not required, otherwise dummy coils are required.
- In lap winding, $Y_c = \pm m$, always integer so dummy coils not required.
- In wave winding, $Y_c = \frac{c \pm m}{P/2}$ may be integer or fraction. If it is integer, dummy coils are not required, if it is not integer, dummy coils are required.

→ dummy coils are used to provide mechanical balance, dummy coils are electrically isolated coils i.e. they are not connected to the commutator.

Equalizer rings

→ In lap winding, each parallel path is distributed under one pole only, due to flux unbalance, e.m.f induced in the parallel paths are unequal & the circulating currents come into picture

→ due to circulating currents, some brushes are over-loading, commutation becomes poor (sparking at brushes)

→ To avoid over-loading of brushes & to reduce the flux unbalance effect equalizer rings are used in the lap windings.

→ Equalizer rings are not required with wave windings.

→ Equalizer rings are made with copper & are placed on the backside of armature. The equipotential points of the armature wdgs are connected to the equalizer rings.

Position of brushes

Brush positions can be located by determining the direction of current flowing in various coil sides.

Advantages of wave winding over lap winding:

- wave
 i) A wave winding requires only two brushes whereas lap winding requires brushes equal to the no. of poles.
 ii) LAP winding m/c require equalized rings for obtaining better commutation, it is not required in wave winding.
 iii) since lap connected m/cs require more brushes and equalized rings, these m/cs are more costly as compared to wave connected machines.

LAP winding = low voltage, High current
 (medium power 50 to 500 kW)
 (and high power > 500 kW)

wave winding = high voltage, low current
 (low-power < 50kW) & medium power m/cs.

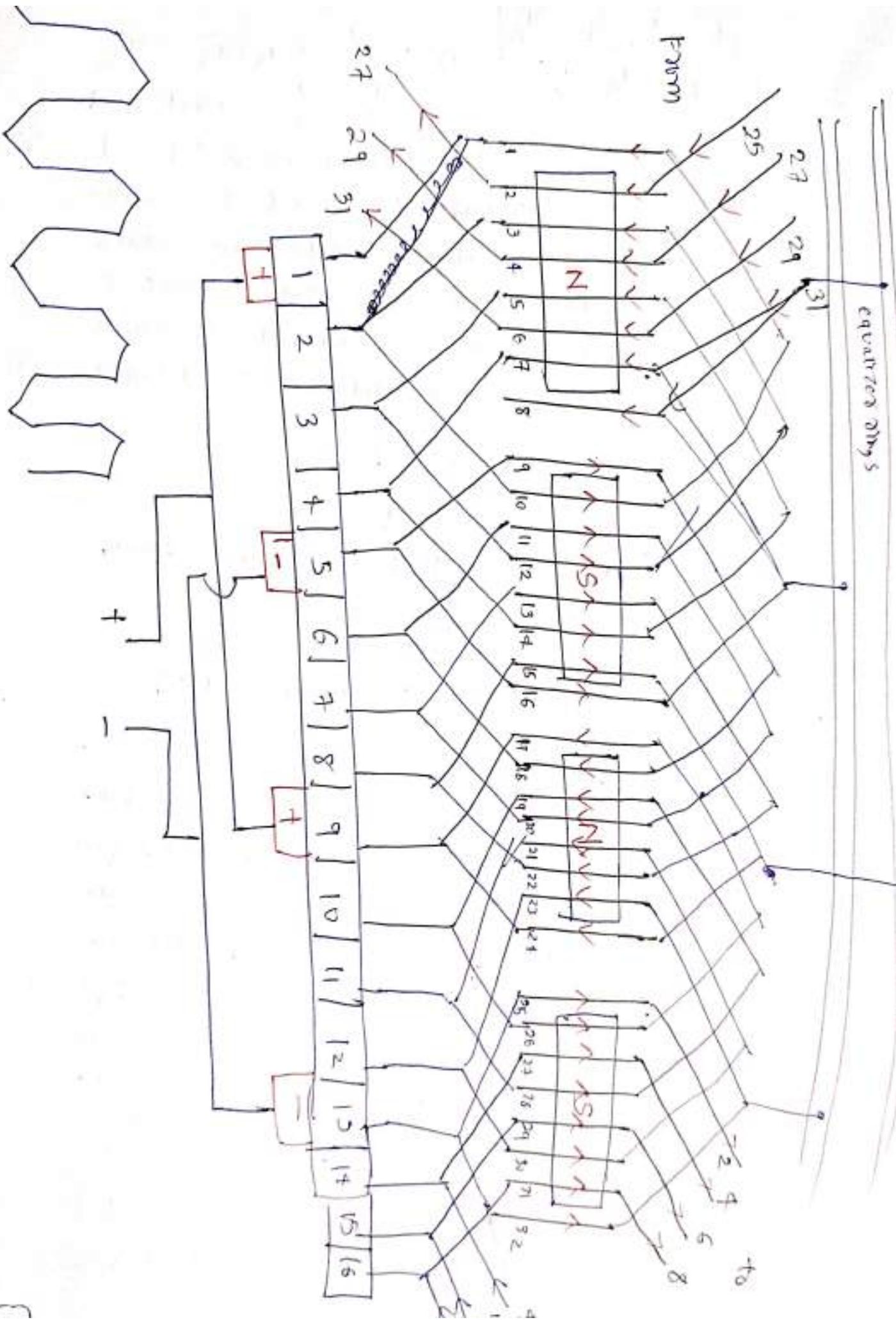
- b) Develop a simple lap winding for a DC m/c armature having 32 armature conductors & 4 poles. Also show connections to equalizer rings. Also show direction of current in the coils & brush position.

A: $P = 4$, conductors = $Z = 32$ slots = 32 (single layer)

$$\text{Pole pitch} = \frac{S}{P} = \frac{32}{4} = 8$$

$$Y_{av} = \frac{Y_b + Y_F}{2} = \frac{S}{P} \quad \dots (i)$$

$$\begin{aligned} Y_b - Y_F &= +2 \\ Y_b &= 9, Y_F = 7 \end{aligned}$$



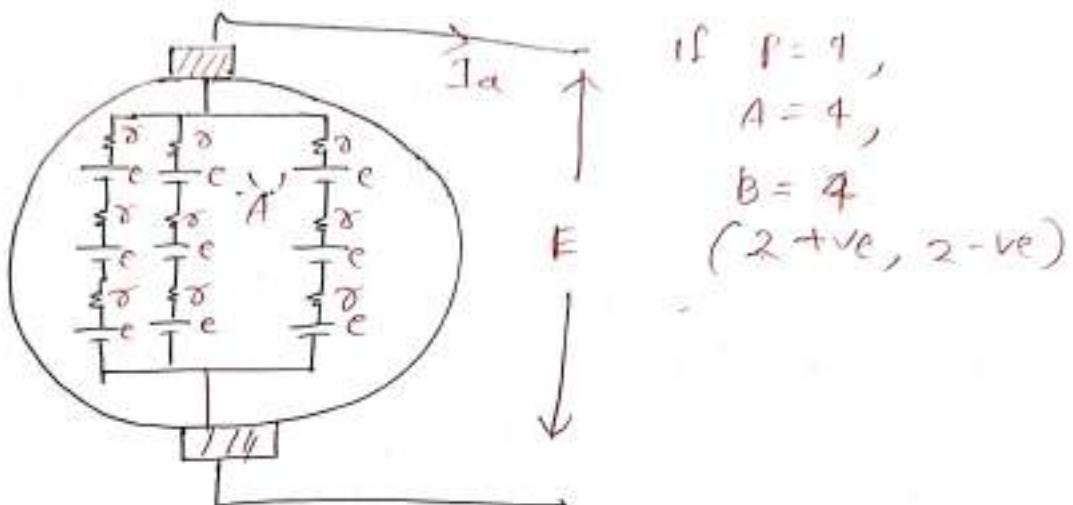
(25)

Circuit model of a DC MIC

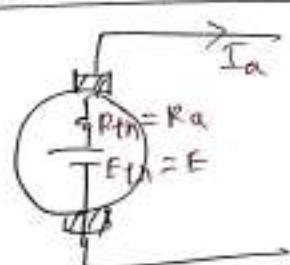
Let $Z = \text{total conductors}$

$A = \text{No. of parallel path}$

each conductor \rightarrow cell (σ, e)



Thevenin equivalent circuit



$$E_{th} = E_{oc} = E$$

$$E = e \times \frac{Z}{A}$$

$$E \propto \frac{1}{A}$$

$$\boxed{\frac{E_{loop}}{E_{wave}} = \frac{A_{wave}}{A_{Lap}}}$$

$$\Rightarrow \boxed{\frac{E_{loop}}{E_{wave}} = \frac{2}{P}}$$

⑥ $R_{th} = R_a$, Path resistance $R_p = (\sigma) \frac{Z}{A}$

$$R_a = \frac{R_p}{A} = \frac{\sigma Z}{A} = R_a = \sigma \frac{Z}{A^2}$$

$$\boxed{\frac{R_a(\text{wave})}{R_a(\text{loop})} = \left(\frac{A_{Lap}}{A_{wave}} \right)^2 = \left(\frac{P}{2} \right)^2}$$

$$R_a \propto \frac{1}{A^2}$$

⑦ $I_a = A I_c$

$$\boxed{\frac{I_{aL}}{I_{aw}} = \frac{A_L}{A_w} = \frac{P}{2}}$$

$$\therefore P_{loop} = P_{wave}$$

(26)

1.3 Different types of DC machines

1.4 Emf eqn of a DC machine

Let ϕ = Flux per pole in wb

P = No. of poles

Z = Total No. of armature conductors

A = No. of parallel path

N = Rotation speed of the armature
in r.p.m

Flux cut by one conductor in one revolution
of the armature, $d\phi = P\phi$ webers

Time taken to complete one

revolution, $dt = \frac{60}{N}$ seconds

in 60 sec = N revolu,

1 sec = $\frac{N}{60}$ revolu

induced emf is proportional to time rate of
change of magnetic flux. $e = \frac{d\phi}{dt}$

Emf generated per conductor $e = \frac{d\phi}{dt} = \frac{P\phi}{(60/N)}$ volts

No. of armature conductor per parallel path $= \frac{Z}{A}$

The total emf generated b/w the terminals

E_g = Avg. emf induced in one conductor \times No. of conductors
 \times in each parallel path

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

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

(27)

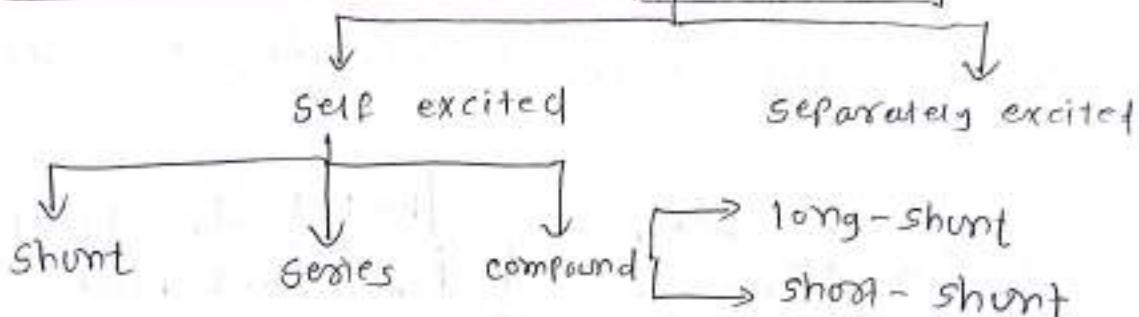
$$E \propto \phi N \Rightarrow \frac{E_2}{E_1} = \frac{\phi_2}{\phi_1} \times \frac{N_2}{N_1}$$

→ For lap winding, $A = P$, $E = \frac{\phi ZN}{60}$ volt

→ For wave winding, $A = 2$, $E = \frac{P\phi ZN}{120}$ volt
 ↳ $E \propto P$

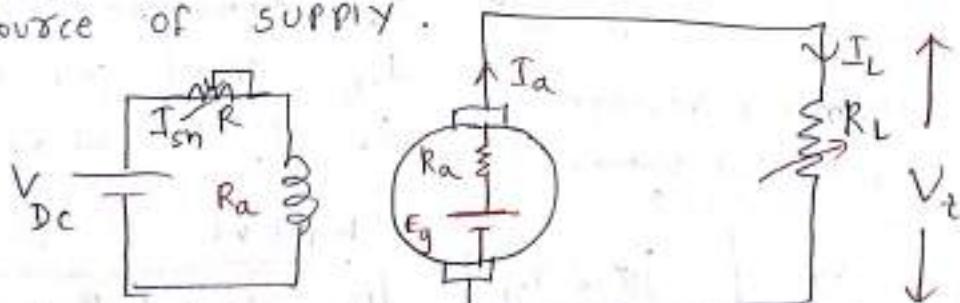
(1.3) Types of DC generators

DC Generators



Separately excited DC Generator

These are generators whose field ~~magnets~~ windings are excited from some external source of supply.



$$I_a = I_L, V_t = I_L R_L, E_g = V_t + I_a R_a + \text{Brush drop}$$

$\phi \propto I_a$. After saturation $\phi = \text{const.}$

I_a = Armature current

R_a = Armature resistance

E_g = Generated e.m.f

V = terminal voltage across load

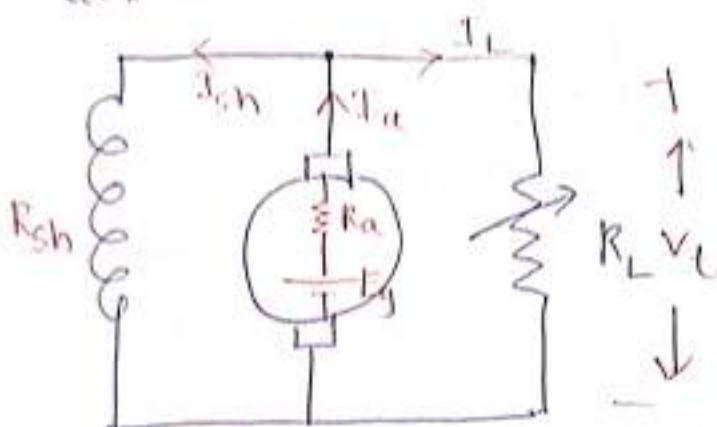
Brush drop = brush contact voltage.

gets excited by magnetizing

These are the generators whose field winding is energized by the current supplied by their own armature. The field poles must have residual magnetism.

DC shunt generator

The field windings are connected across or in parallel with the armature conductors and have the full voltage of the generator applied across them.



V_t = terminal voltage

E_g = generated voltage
e.m.f

$$I_{sh} = \frac{V_t}{R_{sh}} \quad | \phi \propto I_{sh}$$

[by KCL $I_a = I_L + I_{sh}$]

R_{sh} = shunt field resistance

R_a = armature resistance

R_L = load resistance

I_a = armature current

I_{sh} = shunt current

I_L = load current

by KVL

$$E_g = V_t + I_a R_a + B.D$$

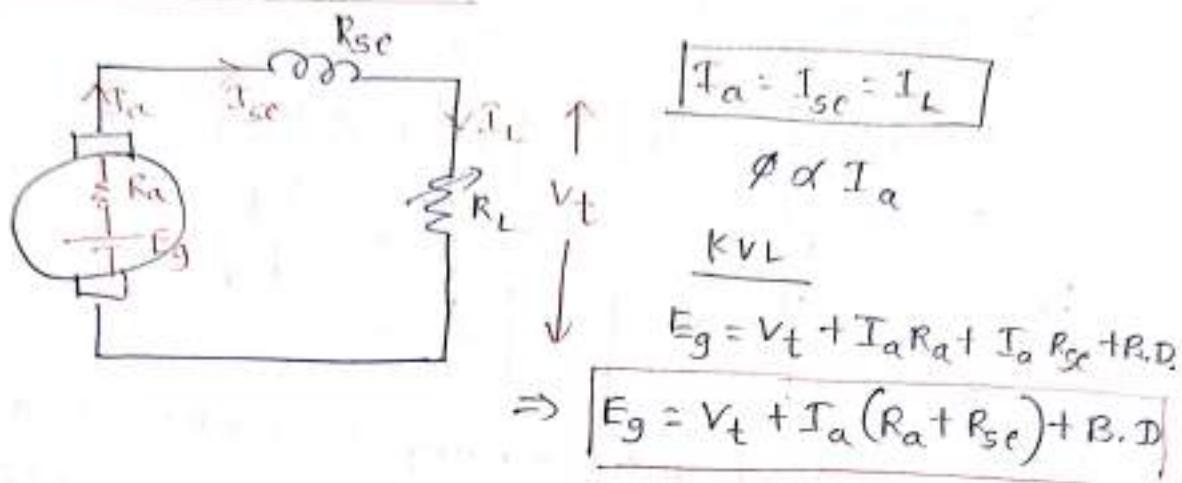
Power developed in armature = $P_a = E_g I_a$

Power delivered to load = $P = V_t I_L$

(∴ The field winding (R_{sh}) consists of large No. of turns of ^{thin} wire)

DC Series Generator

(29)



The field winding consists of a few turns of thick wire & is connected in series with the armature.

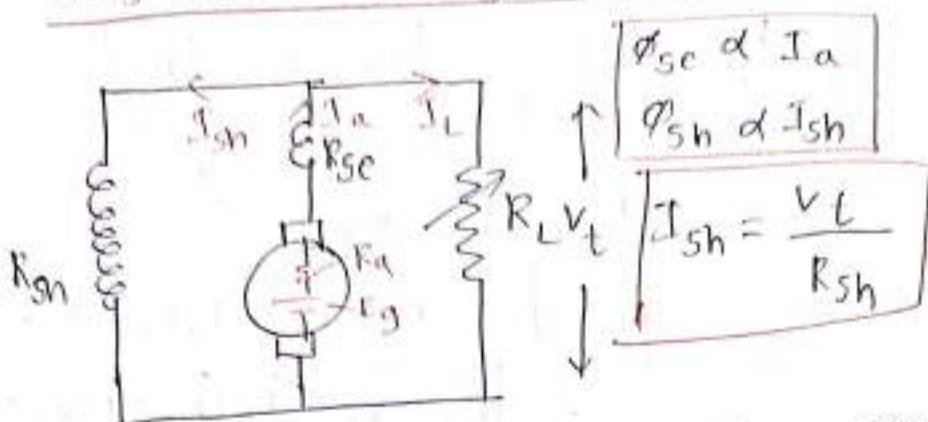
Power developed in armature, $P_a = E_g I_a$

Power delivered to load, $P = V_t I_L$

DC compound generator

- It is a combination of a few series and few shunt shunt windings and can be either short-shunt or long-shunt.
- In compound generators, the shunt Field is stronger than series field.
- In series field aids the shunt field, generator is said to be cumulatively-compound. On the other hand if it opposes the shunt field, the generator is said to be differentially compound.

long-shunt DC generator



If the shunt field winding is connected across both the armature and series field winding, then it is called long shunt dc generator.

KCL

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

KVL

$$E_g = I_a R_a + I_a R_{se} + V_t + B.P$$

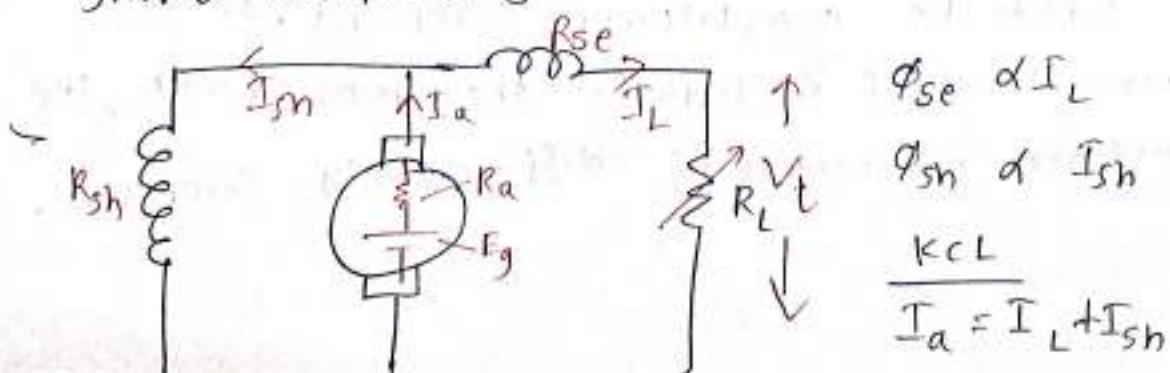
$$E_g = V_t + I_a (R_a + R_{se}) + B.P$$

Power developed in armature, $P_a = E_g I_a$

Power delivered to the load, $P = V_t I_L$

short-shunt DC generator

→ If the shunt field winding is connected across the armature circuit only, it is called short shunt compound generator.



$$\frac{\text{KCL}}{I_a = I_L + I_{sh}}$$

$$I_{sh} = \frac{V_t + I_a R_{se}}{R_{sh}}$$

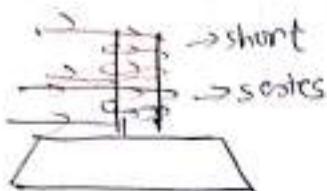
KVL

(31)

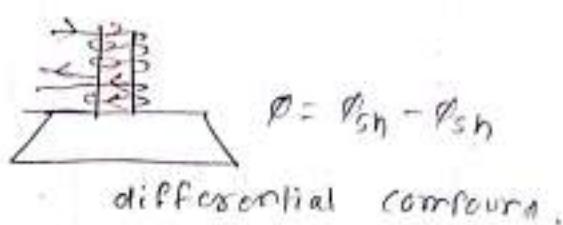
$$E_g = V_t + I_a R_{se} + I_a R_{sh} + B.P$$

Power developed in armature, $P_a = E_g I_a$

Power delivered to the load, $P = V_I L$



$\phi = \phi_{sh} + \phi_{se}$
cumulative compound



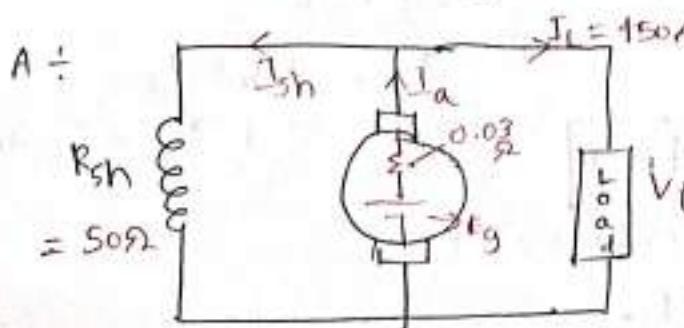
brush contact drop

it is the voltage drop over the brush contact resistance when current passes from commutator segments to brushes and finally to the external load.

0.5V → For metal graphite brush

2.0V → For carbon brush

Q.) A shunt generator delivers 450A at 230V and the resistance of the shunt field and armature are 5Ω and 0.03Ω respectively. Calculate the generated e.m.f?



Given

$V_t = 230V$

$I_L = 450A$

$R_{sh} = 5\Omega$

$R_a = 0.03\Omega$

$E_g \equiv ?$

A: current through shunt field winding is

$$I_{sh} = \frac{V_t}{R_{sh}} = \frac{230}{50} = 4.6 \text{ Amp}$$

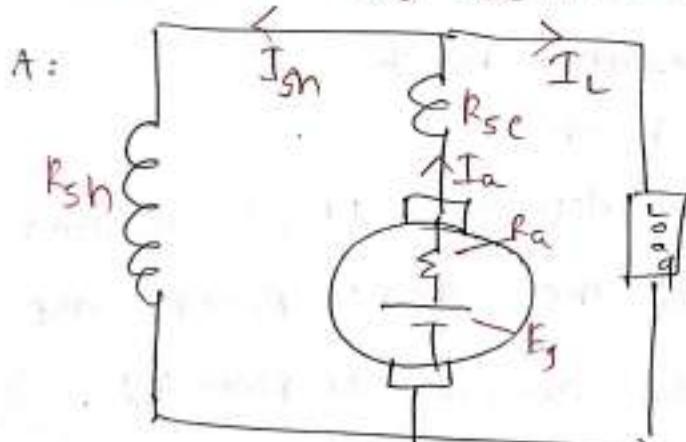
load current, $I_L = 150 \text{ Amp}$

by KCL, $I_a = I_L + I_{sh} = 150 + 4.6 = 154.6 \text{ Amp}$

(B.d = not given = 0)

$$\boxed{E_g = V_t + I_a R_a} \Rightarrow E_g = 230 + 154.6 \times 0.03 \\ \Rightarrow \boxed{E_g = 243.638 \text{ Volt}}$$

Q) A long-shunt compound generator delivers a load current of 50A at 500V and has armature, series field & shunt field resistance of 0.05Ω, 0.03Ω & 25Ω. Calculate E_g , I_a . Allow 1V per brush for contact drop.



Given
 $R_a = 0.05\Omega$ $E_g = ?$
 $R_{se} = 0.03\Omega$ $I_a = ?$
 $R_{sh} = 25\Omega$
 $I_L = 50A, V_t = 500V$
brush drop = $1 \times 2 = 2V$

$$I_{sh} = \frac{V_t}{R_{sh}} = \frac{500}{250} = 2 \text{ Amp} \quad \text{by KCL}$$

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

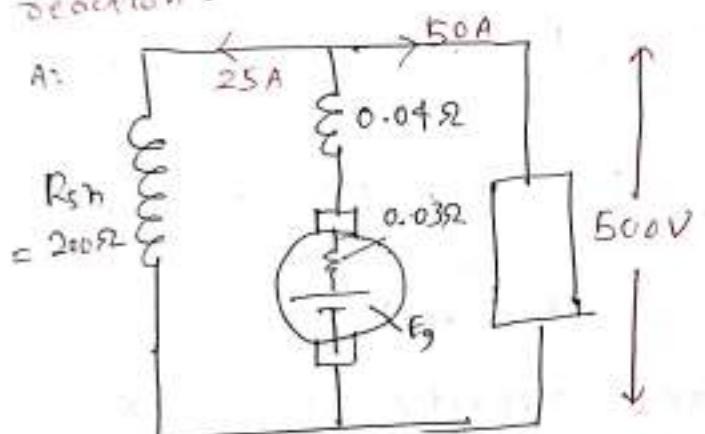
$$\boxed{E_g = V_t + I_a(R_a + R_{se}) + \text{B.D.}} \quad = 2 + 50 = 52 \text{ Amp}$$

$$\Rightarrow E_g = 500 + 52(0.05 + 0.03) + 2 \\ = 506.16 \text{ Volt.}$$

(33)

Q) A 4 pole, long short lap wound generator supplies 25 kW at a terminal voltage of 500V. The armature resistance is 0.03Ω, series field resistance is 0.01Ω and short field resistance is 200Ω. The brush drop may be taken as 1.0 V per brush. Determine Eg. Calculate also the No. of conductors if the speed is 1200 r.p.m and flux/pole is 0.02 wb. Neglect armature reaction.

Solution -



$$V_t I_L = 25 \times 10^3 \text{ Watt}$$

$$\Rightarrow I_L = \frac{25000}{500} = 50 \text{ Amp}$$

$$I_{sh} = \frac{V_t}{R_{sh}} = \frac{500}{200} = 2.5 \text{ Amp}$$

$$E_g = V_t + I_a (R_a + R_{se}) + B.D$$

$$= 500 + 62.5 (0.04 + 0.03) + 2$$

$$= 505.675 \text{ volt}$$

$$\text{Also we know, } E_g = P \phi Z N$$

$$\text{For lap } A=P, \quad E_g = \frac{\phi Z N}{60}$$

$$\Rightarrow Z = \frac{E_g \times 60}{\phi N} = \frac{505.675 \times 60}{0.02 \times 1200} = 1269$$

Given, LAP winding

$$A = P$$

$$V_t = 500 \text{ Volt}$$

$$V_t I_L = 25 \text{ kW}$$

$$R_a = 0.03 \Omega$$

$$R_{se} = 0.04 \Omega$$

$$R_{sh} = 200 \Omega$$

$$B.D = 2 \times 1 = 2 \text{ Volt}$$

$$N = 1200 \text{ r.p.m}$$

$$\phi = 0.02 \text{ wb}$$

$$\frac{E_g}{I_a}$$

$$= I_L + I_{sh}$$

$$= 50 + 2.5 = 52.5 \text{ Amp}$$

Q) A 4 pole, generator, having wave wound armature winding has 51 slots, each slot containing 20 conductors. What will be the voltage generated in the m/c when driven at 1500 rpm assuming the flux per pole to be 7×10^{-3} mwb?

A: slots = 51, each slot contains 20 conductors.

$$\text{Total no. of conductors } (Z) = 51 \times 20 = 1020$$

wave winding, $A = 2$, $P = 4$, $N = 1500 \text{ rpm}$

$$N = 1500 \text{ rpm}, \phi = 7 \times 10^{-3} \text{ wb}$$

$$E_g = \frac{P\phiZN}{60 \times A} = \frac{4 \times 7 \times 10^{-3} \times 1020 \times 1500}{60 \times 2}$$

$$= 357 \text{ volt.}$$

Q) An 8-pole dc shunt generator with 778 wave connected armature conductors and running at 500 rpm supplies a load of 12.5Ω resistance at terminal voltage of 250V.

$$R_a = 0.2 + 2, R_{sh} = 250 \Omega, I_a = ?, E_g = ?, \phi = ?$$

$$A: I_L = \frac{\text{load current}}{\text{constant}} = \frac{V}{R} = \frac{250}{12.5} = 20 \text{ A}, A = 2, Z = 778$$

$$I_{sh} = \frac{250}{250} = 1 \text{ Amp} \quad N = 500$$

$$I_a = I_L + I_{sh} = 20 + 1 = 21 \text{ Amp}$$

$$E_g = V_t + I_a R_a \quad \phi = 9.83 \text{ mwb}$$

$$= 250 + 21 \times 0.29$$

$$= 255.09 \text{ Volt}$$

$$\text{Now, } E_g = \frac{P\phiZN}{60A}$$

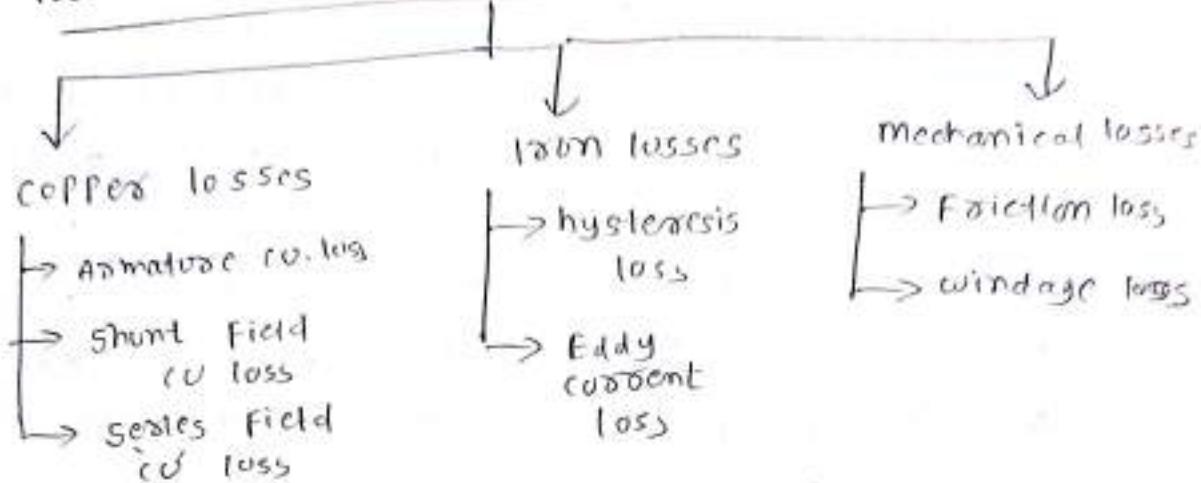
$$\Rightarrow \phi = \frac{E_g \times 60A}{P\phiZN}$$

11

8

MC

1.5 Losses in DC Machine



a) Copper losses (electrical losses)

$$\text{i) Armature copper losses} = I_a^2 R_a$$

where R_a = resistance of armature, interpoles
~~& series field winding~~

$$\text{ii) Series field cu loss} = I_a^2 R_{se}$$

$$\text{iii) Shunt field cu loss} = I_{sh}^2 R_{sh}$$

$I_a^2 R_a = 30\%$ of total F.L losses

b) Magnetic losses (also known as iron or core loss).

a) Hysteresis loss (W_h)

This loss is due to reversal of magnetisation of the armature core.

$$W_h = \gamma B_{max}^{1.6} f V \text{ Watts}$$

$$\begin{aligned} W_h &\propto f \propto N \\ \therefore W_h &\propto f \\ W_h &\propto N \end{aligned}$$

V = Volume of core
 $\text{in } m^3$

γ = hysteresis co-efficient

f = frequency of magnetic

B_{max} = max^m reversal flux density

(36)

b) Eddy current loss (W_e)

when armature core rotates, it also cuts the magnetic flux. Hence an e.m.f is induced in the body of the core according to the laws of electromagnetic induction. This e.m.f though small, sets up large current in the body of the core due to its small resistance. This current is known as eddy current. The power loss due to the flow of eddy current is known as eddy current.

$$W_e = K B_{\max}^2 f^2 t^2 V^2 \text{ watt}$$

$$W_e \propto f^2 \propto N^2$$

$$W_i = W_e + W_h$$

B_{\max} = max^m Flux density

f = Frequency of magnetic reversal

t = thickness of each laminations

V = Volume of each core

→ eddy current loss is

reduced by using laminated core.

→ W_h is reduced by using silicon steel which have low hysteresis co-efficient also possess high electrical resistivity.

These losses are practically constant for shunt and compound generators, because field current is almost constant.

→ These losses total upto 20 to 30% of F.L loss.

c) mechanical losses

These consists of

- i) Friction loss at bearings and commutators
~~be referred~~
 - ii) air-friction or windage loss of rotating armature.
~~be referred~~

These are about 10 to 20% F-L losses.

stay losses

Stray losses magnetic and mechanical losses are collectively known as stray losses or rotational losses.

Constant or Standing losses: The losses which remains constant at all loads are known as constant losses.

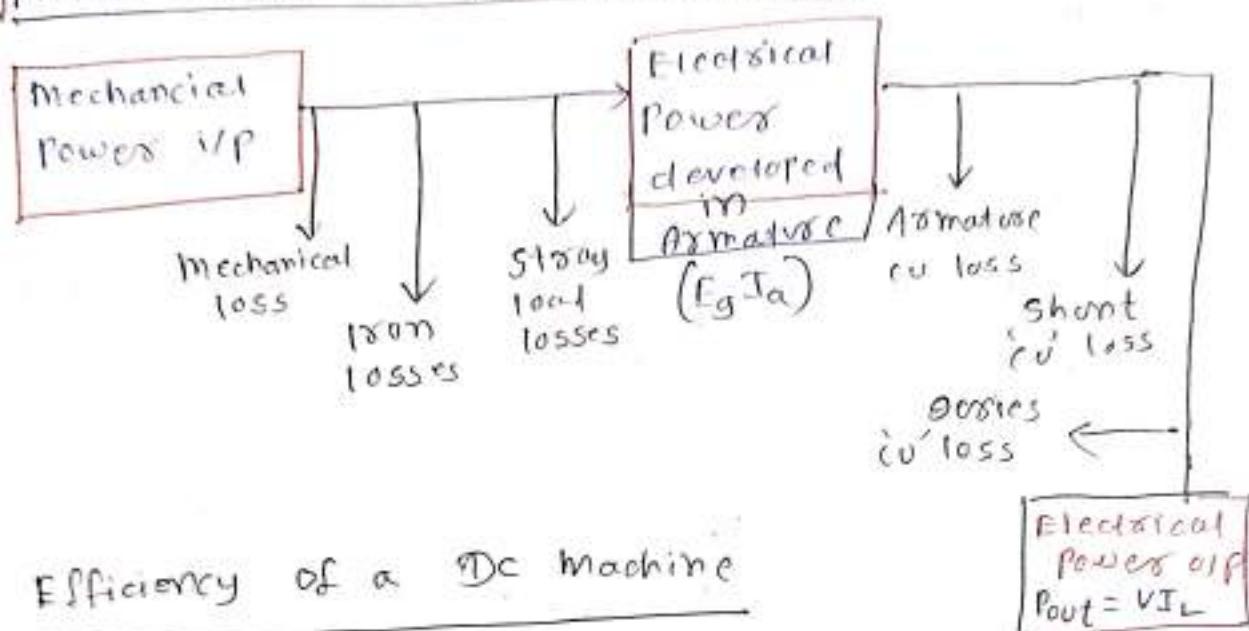
- 1) Iron losses (w_h & w_c)
 - 2) Mechanical losses
 - 3) Shunt field losses ($I_{sh}^2 R_{sh}$)

Variable loss The losses which vary with load are called variable loads.

- 1) copper loss in armature winding ($I_a^2 R_a$)
 - 2) copper loss in series field winding (~~$I_{sh}^2 R_{sh}$~~ $I_{se}^2 R_{se}$)

Total losses in a Dc Mc = Variable loss + constant loss

Power stages in DC Generators



Efficiency of a DC machine

The ratio of output power to the i/p power of a dc machine is known as efficiency.

$$\text{efficiency} = \eta = \frac{\text{O/P}}{\text{i/p}} = \frac{\text{O/P}}{\text{O/P} + \text{losses}}$$

$$\eta = \frac{\text{O/P}}{\text{i/p}} \times 100$$

NOTE

1. Mechanical efficiency

$$\eta_m = \frac{\text{Total watts generated in armature}}{\text{mechanical power supplied}} = \frac{E_g I_a}{\text{mechanical power supplied}}$$

2. Electrical efficiency

$$\eta_e = \frac{\text{Watts available in load circuit}}{\text{total watts generated}} = \frac{V I_L}{E_g I_a}$$

3. Overall or commercial efficiency

$$\eta_c = \frac{\text{Watts available in load circuit}}{\text{mechanical power supplied}}$$

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

Condition for maximum efficiency

Generated O/P = VI_L

Generated I/P = $O/I + \text{losses}$ (Variable loss + constant loss)
 $= VI_L + I_a^2 R_a + \text{constant losses}$

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

~~The~~ I_{sh} = negligible as compared to load current, then $I_a = I_L = I$

$$\eta = \frac{O/I}{I/P} = \frac{VI}{VI + I_a^2 R_a + W_c} = \frac{1}{1 + \left(\frac{I R_a}{V} + \frac{W_c}{VI} \right)}$$

Now, efficiency is maximum when denominator is

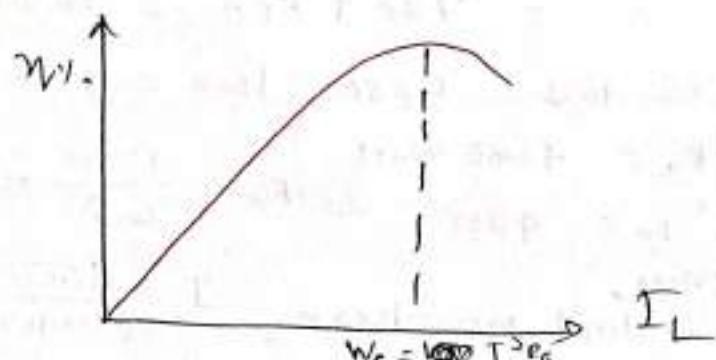
minimum i.e. when $\frac{d}{dI} \left(\frac{I R_a}{V} + \frac{W_c}{VI} \right) = 0$

$$\Rightarrow \frac{R_a}{V} = \frac{W_c}{VI^2} \Rightarrow I_a^2 R_a = W_c$$

Hence generator is maximum when

variable loss = constant loss

The load current corresponding to maximum efficiency is given by $I_a^2 R_a = W_c \Rightarrow I_a = \frac{W_c}{R_a}$



(90)

- c) A short generator has a F.L. current of 196A at 220V. The stray losses are 720W and the short field coil resistance is 55Ω. If it has a full load efficiency of 88%, Find the armature resistance. Also find the load current corresponding to maximum efficiency?

$$A: I_L = 196, V_t = 220V, O/P = V_t I_L \\ = 220 \times 196 = 43,120 \text{ Watt}$$

Full load efficiency, $\eta = 88\%$.

$$\gamma. \eta = \frac{O/P}{i/P} \times 100 \\ \Rightarrow i/P = \frac{O/P}{\gamma \eta} \times 100 = \frac{43120}{88} \times 100 = 49000 \text{ W}$$

$$\text{Total losses} = i/P - O/P = 49000 - 43120 \\ = 5,880 \text{ Watt}$$

$$I_{sh} = \frac{V_t}{R_{sh}} = \frac{220}{55} = 4 \text{ Amp}, I_L = 196 \text{ Amp}$$

$$I_a = I_{sh} + I_L = 196 + 4 = 200 \text{ Amp}$$

$$\text{shunt co' loss} = I_{sh}^2 R_{sh} = (4)^2 \times 55 = 880 \text{ W}$$

$$\text{stray losses} = 720 \text{ Watt}$$

$$\text{constant losses} = \text{stray loss} + \text{shunt co' loss} \\ = 720 + 880 = 1600 \text{ Watt}$$

$$\text{armature co' loss} = 5880 - 1600 = 4280 \text{ Watt}$$

$$I_a^2 R_a = 4280 \text{ Watt} \\ \Rightarrow (200)^2 R_a = 4280 \Rightarrow R_a = \frac{4280}{(200)^2} = 0.10792$$

For maxm efficiency,

$$I_a^2 R_a = \text{constant loss} = 1600 \text{ W}, I = \sqrt{\frac{1600}{0.107}} = 122.39$$

Armature Reaction

→ The effect of armature flux on the main field flux distribution is called armature reaction.

→ The armature flux produces two undesirable effects on main field flux

a) It demagnetises or weakens the main field

Reduction in the main ~~field~~ flux per pole reduces the generated voltage and reduces torque. $\Phi_{net} \downarrow, E_g \downarrow, T \downarrow$

b) Cross-magnetisation or distortion

due to distortion of flux distribution of main field, Poor commutation occurs i.e. Sparking occurs at brushes.

Geometric Neutral axis (GNA)

i) Geometric Neutral axis is the axis which is always perpendicular to the main field flux or direct-axis (d-axis)

ii) The GNA is itself quadrature axis (q-axis) and also called brush axis, since the brushes are always fixed along the GNA.

iii) GNA is also called axis of commutation, since commutation process takes place along the brush axis GNA.

Magnetic neutral axis (MNA)

(42)

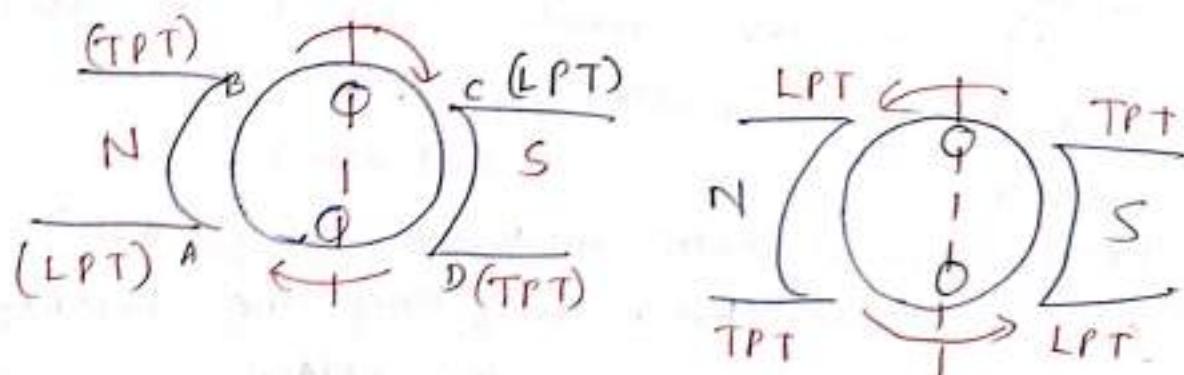
- It is defined as the axis along which no e.m.f is produced in the armature conductors because they move parallel to the lines of flux.
- It is always perpendicular to resultant flux distribution.

Leading pole tip (LPT)

It is the pole end at which the armature conductors are entering into the magnetic field.

Trailing pole tip (TPT)

It is the pole end at which the armature conductors are leaving from the magnetic field.
 if one travels along the assumed direction of rotation
 (i.e. from left to right for generator operation &
 from right to left for motor operation)



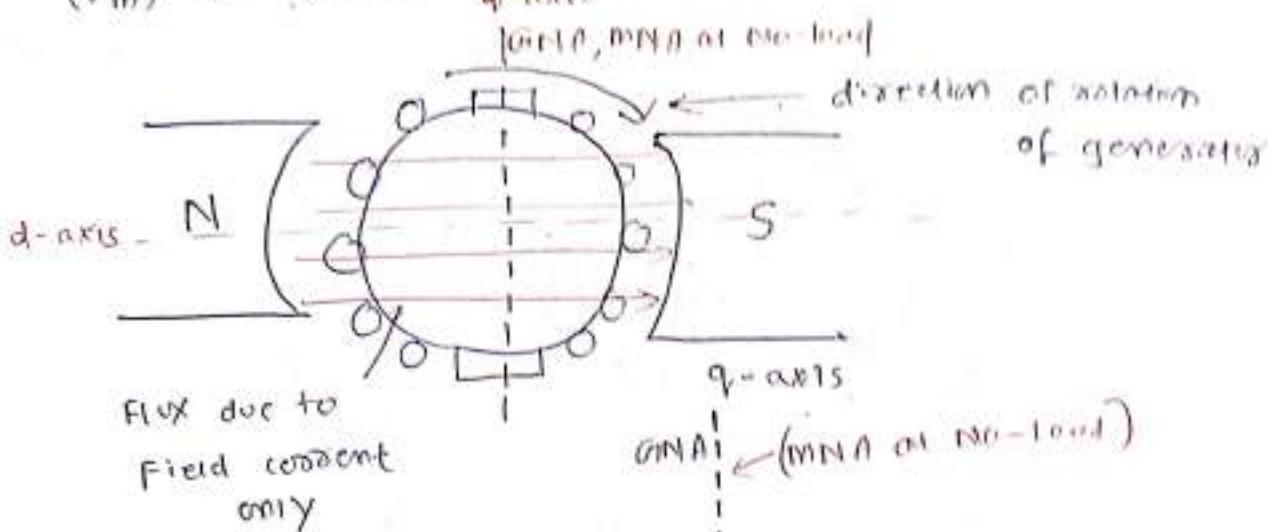
Consider a 2-Pole DC machine

(12)

Case-1

At no-load ($I_f \neq 0, I_a = 0$)
 $(\Phi_m \neq 0, \Phi_a = 0)$

only Field current (I_f) & hence main field flux (Φ_m) is considered



- i) Under No-load conditions, there is no electric current flowing through the armature winding ($I_a = 0$)
- ii) so in this case, there is only a main field flux (Φ_m) in the machine produced by the magnetic field system. • since there is no armature flux ($\Phi_a = 0$), hence the main flux (Φ_m) is distributed symmetrically w.r.t. Polar axis
- iii) In this case, the magnetic Neutral axis (MNA) and geometrical Neutral axis (GNA) coincide with each other.

(44)

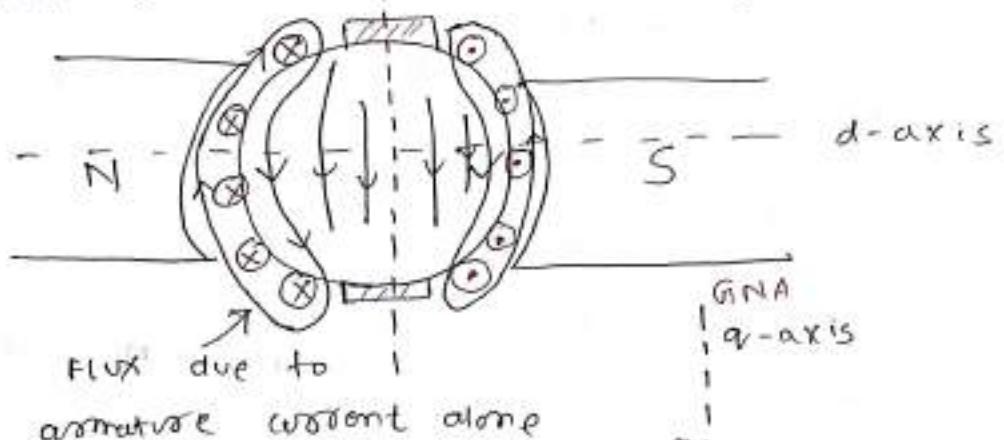
CASE-II when armature conductors carrying current with no current in field coils

on-load condition (only armature current is

$$(I_f = 0, I_a \neq 0) \quad \text{considered}$$

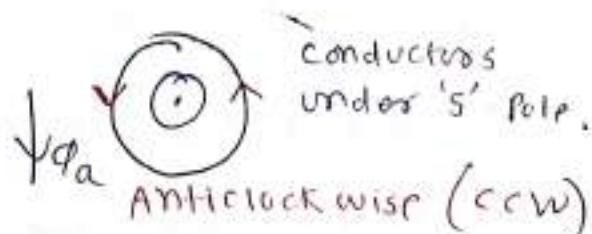
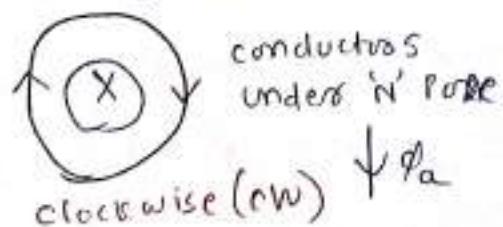
$$(\phi_m = 0, \phi_a \neq 0)$$

$\times \rightarrow$ inward
 $\circ \rightarrow$ outward



i) In this case, the magnetic flux produced in the machine due to armature current only is called the armature flux (ϕ_a).

ii) we can determine the direction of the armature flux by the cork-screw rule.



Thus we can observe that all the armature flux is in the downward direction.

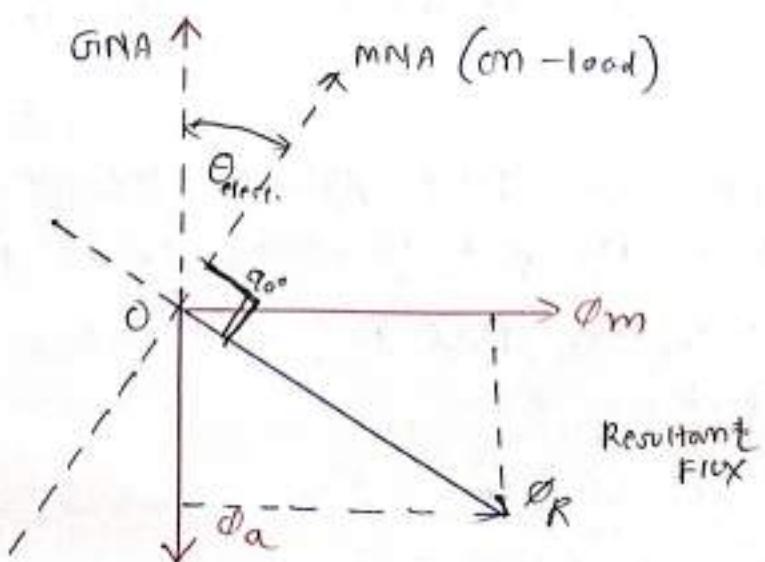
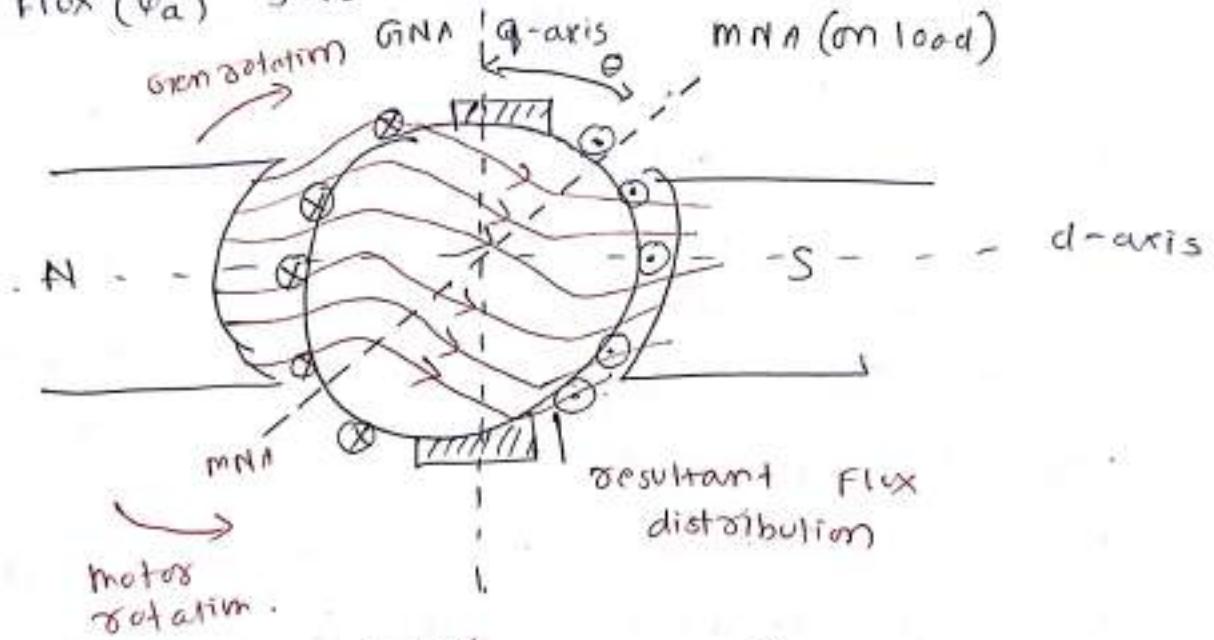
(16)

Case-III (on-load condition) (Practical case)

$$\left(I_f \neq 0, I_a \neq 0 \right)$$

$$\left(\phi_m \neq 0, \phi_a \neq 0 \right)$$

- i) both field current (I_f) & armature current (I_a) are considered. Hence two fluxes exist inside the generator when both armature winding & field winding carry electric current simultaneously. The combination of main field flux (ϕ_m) & armature flux (ϕ_a) gives resultant flux (ϕ_R) in the machine.



- ii) It is seen that armature Flux aids the main field flux at upper end of North pole and at the lower end of S-pole. Therefore at these two ~~flux~~ pole ends (tips) the armature flux strengthens the main field flux. Likewise the armature flux weakens the main field flux at lower end of N-pole & at upper end of S-pole.
- iii) If there is no magnetic saturation, then the strengthening & weakening of the main field flux are equal and the resultant flux per pole remains unaltered from its no-load value. But magnetic saturation occurs, as a consequence, the strengthening effect is less as compared to the weakening effect and the resultant flux is decreased from its no-load value. This is called de-magnetising effect of armature flux.
- iv) Armature flux crosses the main field flux. Hence this flux is called cross flux & effect due to this flux is called cross-magnetising effect.

Adverse effects of Armature Reaction in DC Generator:

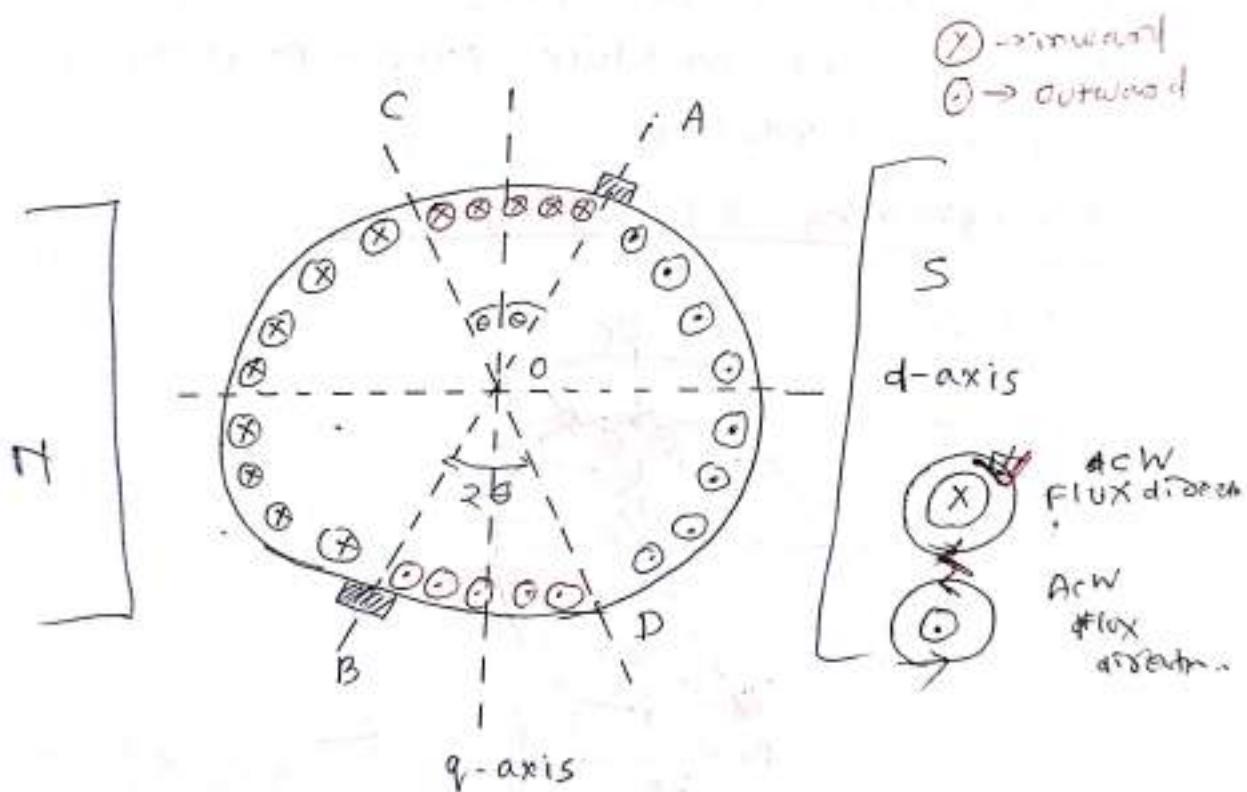
- The total magnetic flux created by each pole is reduced, which in turn reduces the induced e.m.f in the generator.
- The MNA is shifted in the direction of rotation of the armature, this shifting of MNA is due to shifting in the axis of resultant flux.
- The armature reaction causes a magnetic flux in the Neutral zone which induces a voltage in the armature winding which causes commutation problems.

In order to achieve sparkless commutation, the brushes must lie along the MNA. consequently the brushes are shifted through an angle θ so as to lie along the new MNA. due to brush shift, armature flux (ϕ_a) 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 result is that armature flux (ϕ_a) will no longer be vertically downward but will be rotated in the direction of rotation through an angle θ .

(19)

demagnetising & cross-magnetising conductors

i) The exact conductors which produce these distorting (cross-magnetising) & de-magnetising effects are shown where both the brushes axis has been given a forward lead of θ so as to lie along the new position of m.n.m.



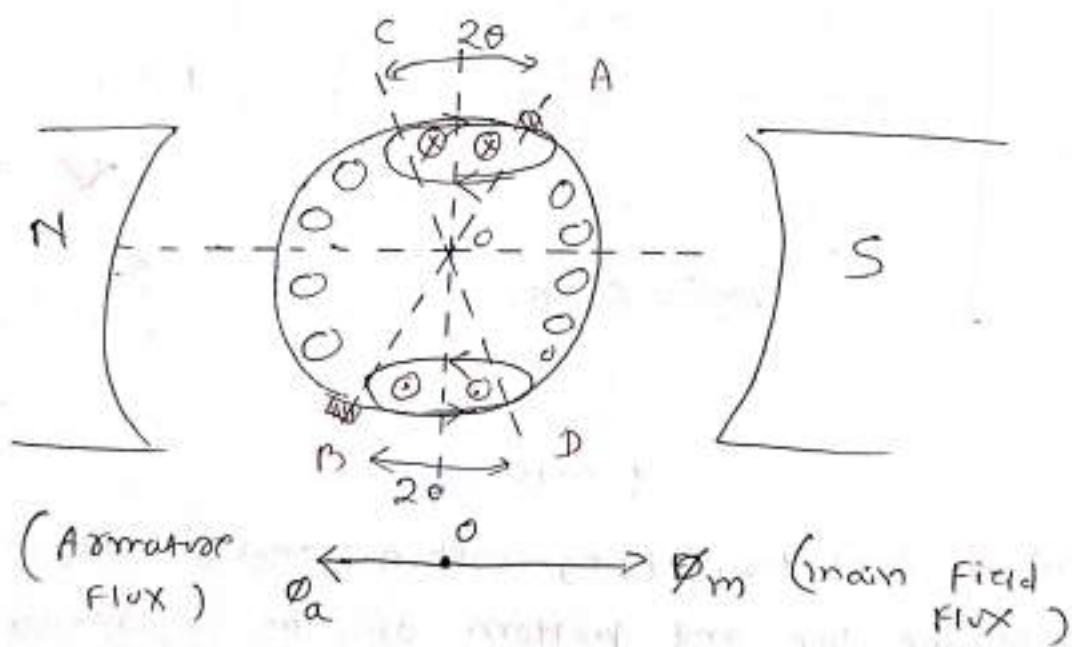
ii) All conductors lying within angles $AOC = BOD = 2\theta$ at the top and bottom of the armature, are carrying current in such a direction to send the flux through the armature from right to left. It is these conductors which act in direct opposition to

(5)

the main field and hence called demagnetising armature conductors.

iii) Now the conductors lying betw AOD & COP carry current in such a direction as to produce a combined flux pointing vertically downwards i.e. at right angles to the main field flux. This results in distortion of the main field. Hence, these conductors are known as cross-magnetising conductors and constitute cross-magnetising ampere-conductors.

Demagnetising AT per pole



since armature demagnetising ampere-turns are neutralized by adding extra ampere-turns to the Main Field winding, it is essential to calculate their number. The no. of turns is equal to half the no. of conductors because

two conductors constitute one turn.

Let Z = total no. of armature conductors

I = current in each armature conductors

$$I_{a/A} = I_a/2 \quad \dots \text{For simplex wave winding}$$

$$= I_a/P \quad \dots \text{For simplex lap winding}$$

θ_m = forward lead in mechanical or geometrical or angular degrees

Total no. of armature conductors in angles AOC

$$\& \text{ BOD is } \frac{4\theta_m}{360} \times Z.$$

As two conductors constitute one turn,

$$\therefore \text{Total no. of turns in these angles} = \frac{2\theta_m}{360} \times ZI$$

\therefore demagnetising amp-turns per pair of

$$\text{poles} = \frac{2\theta_m}{360} \times ZI$$

$$\therefore \text{demagnetising amp-turns/pole} = \frac{\theta_m}{360} \times ZI$$

$$\therefore \frac{\theta_e}{\theta_m} = \frac{P}{2} \Rightarrow \theta_m = \theta_e \times \frac{2}{P}$$

$$\boxed{AT_d/\text{pole} = ZI \times \frac{\theta_m}{360}}$$

$$AT_d/\text{pole} = \frac{ZI}{P} \times \frac{\theta_{\text{elect.}}}{360}$$

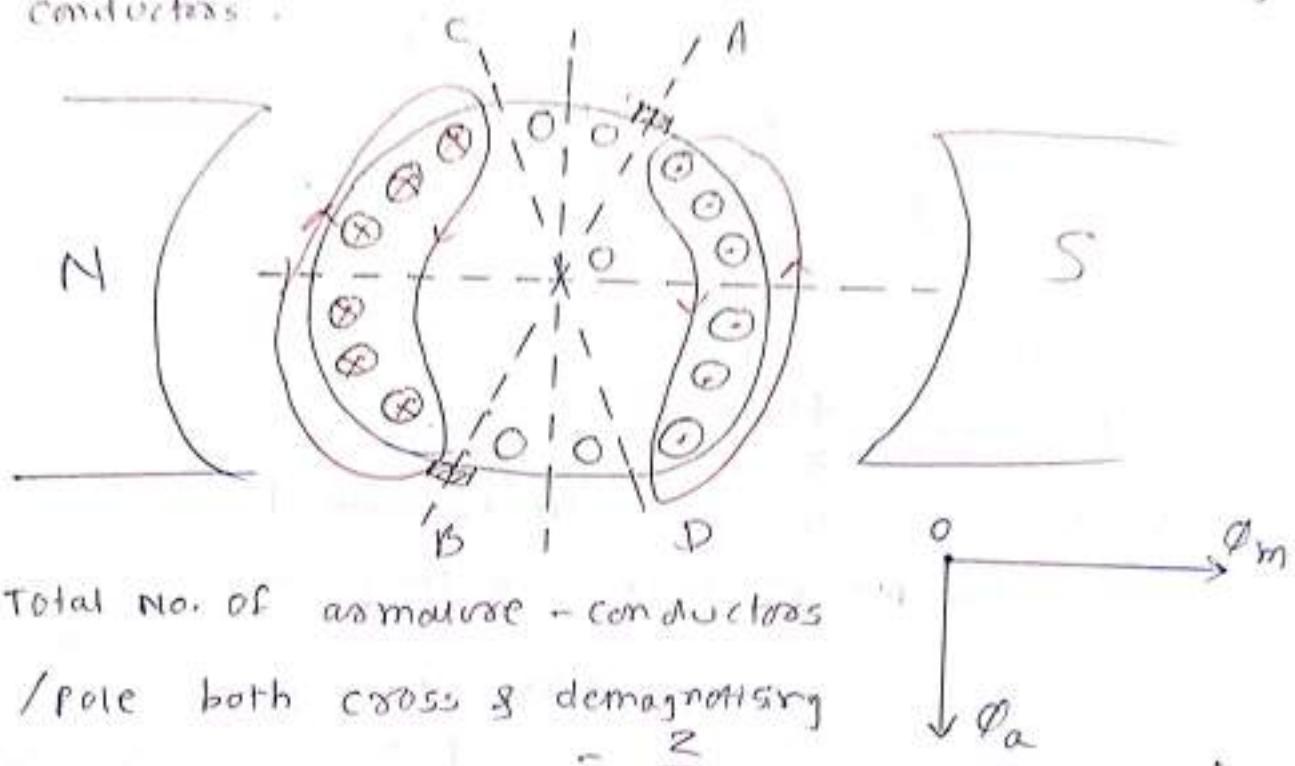
$$AT_d/\text{pole} = \frac{200}{180} \frac{2\theta_{\text{elect.}}}{180} \left[\frac{I_a}{A} \times \frac{Z}{2P} \right]$$

AT

(52)

Cross-magnetising At per pole

The conductors lying between angles AOD & BOC constitute distorting or ~~cross~~^{demagnetising} conductors.



Total No. of armature conductors

$$/\text{pole both cross \& demagnetising} = \frac{Z}{P}$$

$$\text{demagnetising conductors/pole} = Z \frac{20m}{360}$$

$$\text{cross-magnetising conductors/pole} = \frac{Z}{P} - Z \times \frac{20m}{360}$$

$$= Z \left(\frac{1}{P} - \frac{20m}{360} \right)$$

$$\boxed{\frac{AT_c}{\text{pole}} = Z I \left(\frac{1}{2P} - \frac{0m}{360} \right) \text{ At}}$$

$$\boxed{\frac{AT_c}{\text{pole}} = \frac{180 - 20c_{10c}}{180} \left(\frac{I_a}{A} \times \frac{Z}{2P} \right) \text{ At}}$$

(53)

The demagnetising amp-turns of armature reaction can be neutralized by putting extra turns on each pole of the generator.

$$\therefore \text{No. of extra turns/pole} = \frac{AT_d}{I_{sh}} \text{ for a shunt generator}$$

$$= \frac{AT_d}{I_a} \text{ for series generators}$$

~~These~~

The demagnetising effect can be overcome by adding extra turns to the main field winding or by increasing cross-section of field winding copper wire. This method requires more copper, cost of the machine increase, field copper losses increase, efficiency of the machine is decreased.

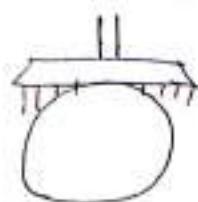


Methods to limit cross-magnetising effect

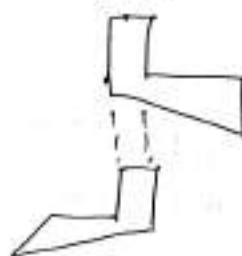
① by using high reluctance pole tips

This is achieved by using the following methods

- by using eccentric poles or chamfered poles



- by arranging pole shoe laminations left & right alternately



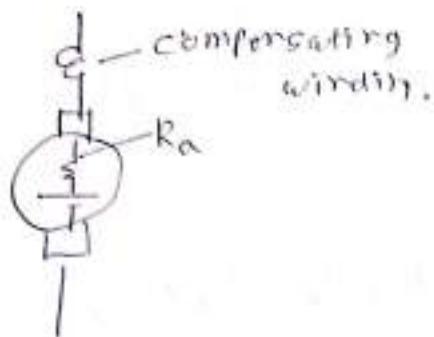
② by using compensating winding / compoles

→ compensating winding is inserted in the slots made on the pole faces.

→ compensating winding is connected in series with the armature winding.

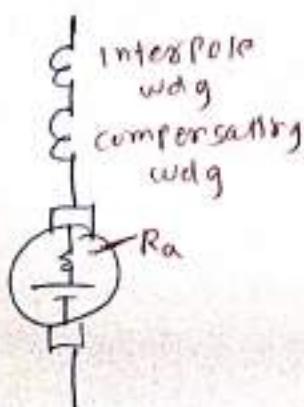
→ MMF produced by the compensating winding is acting opposite to the armature MMF. Therefore armature MMF under the pole is neutralised.

→ compensating winding is preferred in the DC m/c which are subjected to variable load i.e. drilling m/c, punching m/c's, in order to avoid flashovers.



(3) by Using interpoles

- Interpoles are placed along the inter-polar or quadrature axis, its field winding is connected in series with armature winding.
- Interpoles flux along the brush axis is acting opposite to the armature flux. Therefore the cross magnetising effect at interpoles region is neutralized.
- No. of interpoles required is equal to the main poles P' but in order to reduce the cost of small m/c's no. of interpoles used ~~is~~ is equal to $\frac{P}{2}$.
- In generator, the polarity of interpole is same as the main pole ahead of it in the direction of generator rotation.



(56)

- ④ shifting the brushes in the direction of generation,

resultant flux \downarrow , $\phi_{res} \downarrow$, $T_{em} \downarrow$, $V \downarrow$,
→ commutation improved
→ less sparking

Commutation

The process of current reversal in the armature coils/windings by means of commutator segments & brushes is called commutation.

→ No. of parallel path = A

$$\text{current in each coil} = I_c = \frac{I_a}{A}$$

→ during commutation process, current in coil changes from $+I_c$ to $-I_c$. or vice versa.

④ The currents induced in armature conductors of a d.c. generators are alternating, to make their flow unidirectional in the external circuit, commutator is used. ~~conductors~~ current flows in one direction when armature conductors are under N-pole and in the opposite direction when they are under S-pole. As conductors pass out of the influence of a N-pole and enter that of S-pole, the current in them is reversed. This reversal of current takes place along M.N.A axis or brush axis. This process by which current in the short-circuited coil is reversed while it crosses the M.N.A is called commutation.

(15)

commutation period: it is the time required for commutator segment 'a' to advance one commutator segments, (T_c)

W_b : brush width

W_c : commutator segment width

W_m : mica insulation width

$$T_c = \frac{W_c}{v_c} \text{ sec} \approx \frac{W_b}{v_c}$$

v_c : peripheral velocity

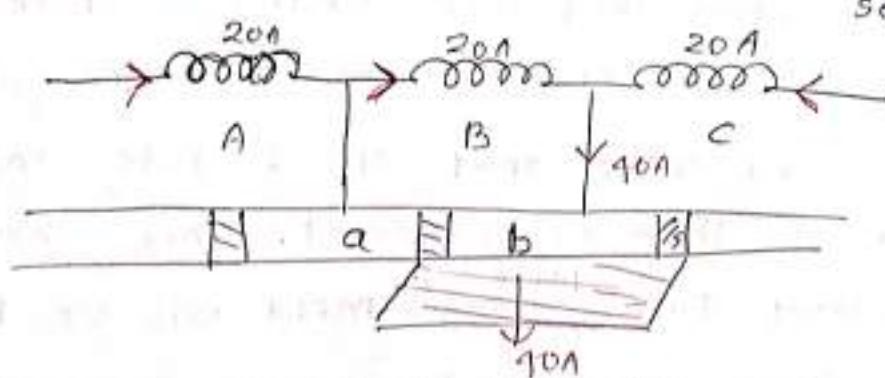
$$= \frac{\pi D N}{60} \text{ m/s}$$

if $t = T_c \rightarrow$ ideal commutation

if $t > T_c \rightarrow$ delayed commutation / under commutation

if $t < T_c \rightarrow$ fast commutation / over commutation process of commutation

Position - 3 Brush is completely in contact with segment 'b'



It is assumed that each coil carries

20A, so that brush current is 40 Amp.

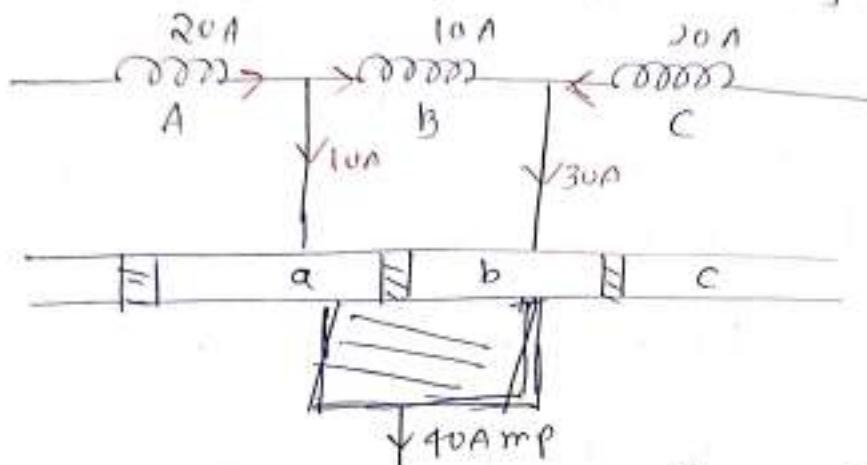
coil 'A' current = 20 Amp (from Left to Right)

coil 'B' current = 20 Amp (from Left to Right)

coil 'C' current = 20 Amp (from Right to Left)

(59)

Position - 2 brush is in contact with 70% with segment 'b', 30% with segment 'a'.



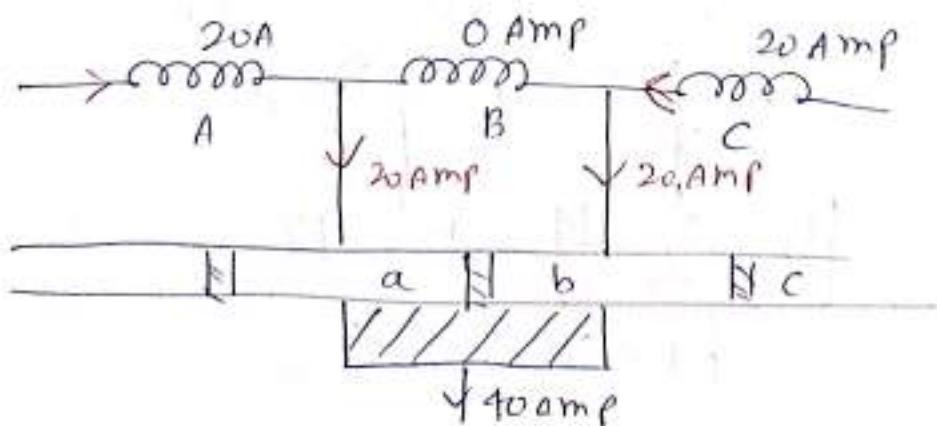
$$\text{coil } A' \text{ current} = 20\text{A} \quad (\text{L to R})$$

$$\text{coil } B' \text{ current} = 10\text{A} \quad (\text{L to R})$$

$$\text{coil } C' \text{ current} = 20\text{A} \quad (\text{R to L})$$

The current through coil B' has reduced from 20A to 10A because the other 10A flows via segment 'a'. As area of contact of the brush is more with segment 'b' than with segment 'a', it receives 30A and 'a' receives 10A, total being 40Amp.

Position - 3 brush is equally in contact with Segment 'a' & 'b'



(60)

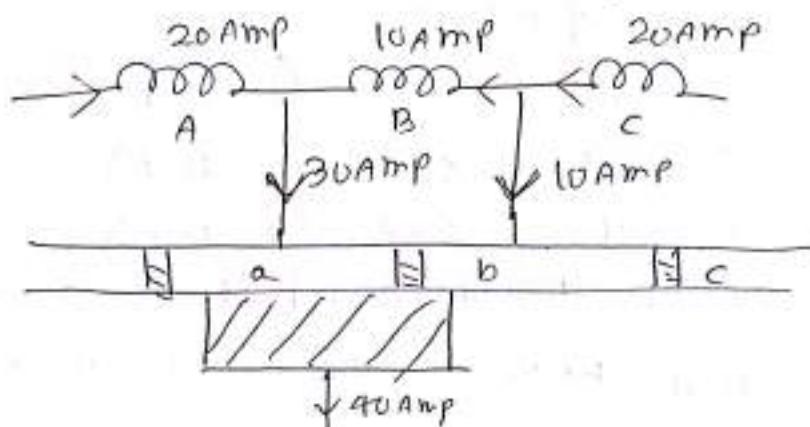
current through coil 'A' = 20 Amp (L to R)

current through coil 'B' = 0 Amp

current through coil 'C' = 20 Amp (R to L)

The current through coil 'B' is reduced to be zero. The brush contact areas with the two segments 'b' and 'a' are equal.

Position - 4 brush is in contact with 70% part of segment 'a' & 30% of segment 'b'

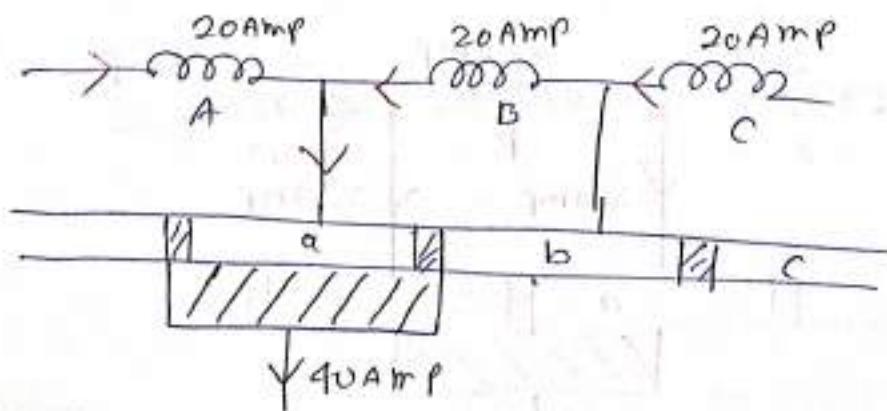


current in coil 'A' = 20 Amp (L to R)

current in coil 'B' = 10 Amp (R to L)

current in coil 'C' = 20 Amp (R to L)

Position - 5 brush is in complete contact with segment 'a'



(c)

current in coil 'A' = 20Amp (L to R)

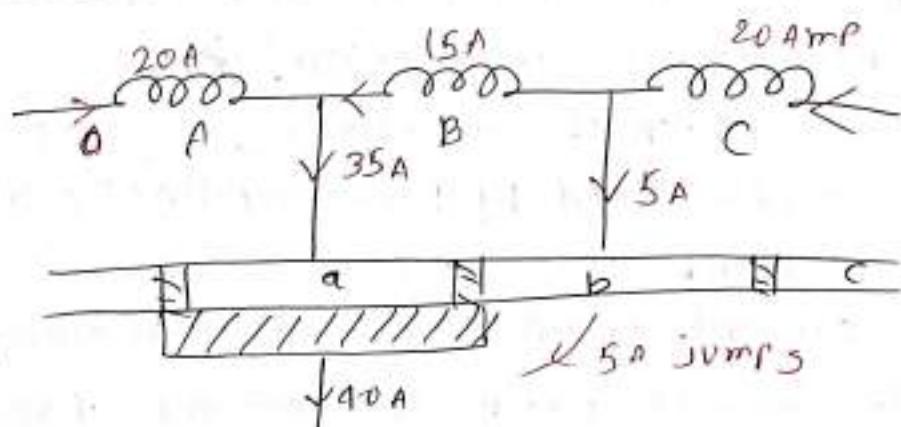
current in coil 'B' = 20Amp (R to L)

current in coil 'C' = 20Amp (R to L)

Here we have concluded

- i) current in coil 'B' reverses its direction from 20Amp (L to R) to 20Amp (R to L). with the rotation of armature.
- ii) Thus coil 'B' has undergone commutation. Each coil undergoes commutation in this way as it passes the brush axis. during commutation, the coil under consideration remains short circuited by the brush.

Practical case

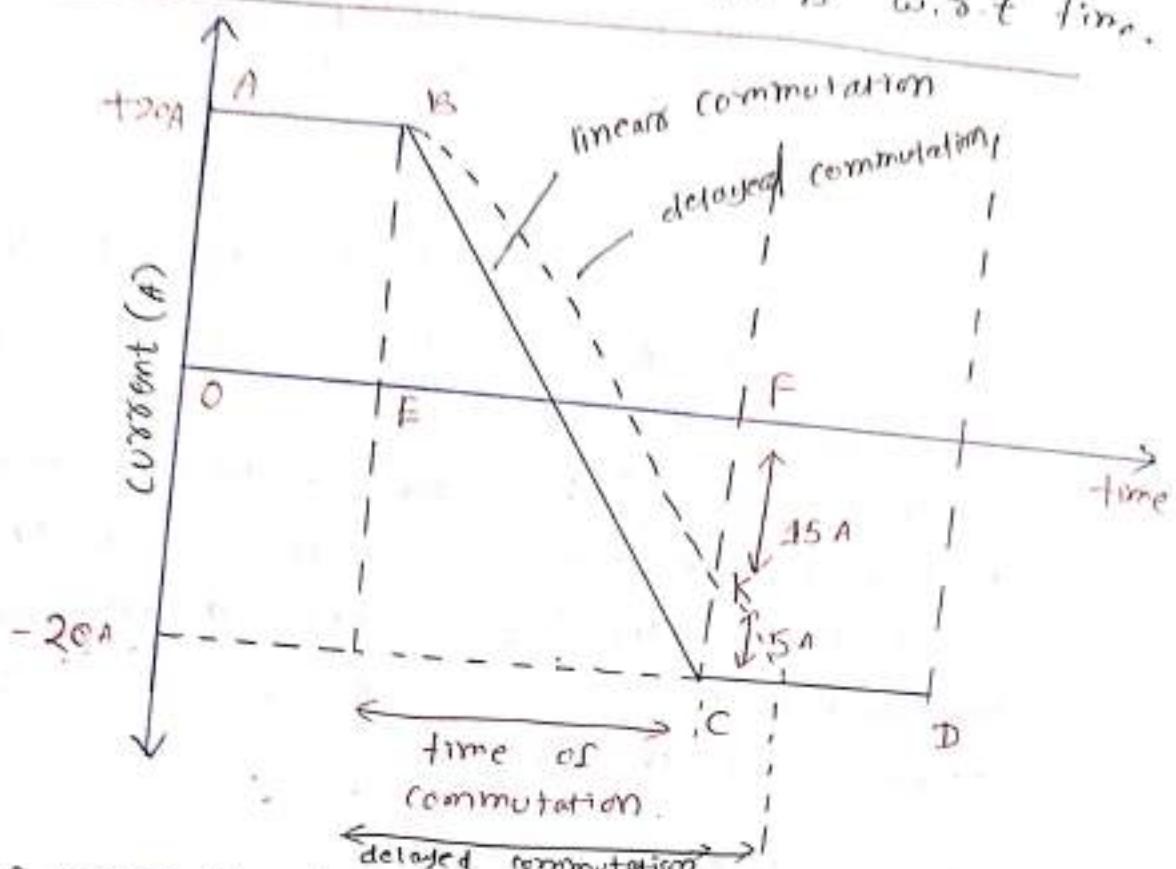


Now coil 'B' carries 15A (instead of 20Amp).

The difference of current b/w coils C and B i.e. $20 - 15 = 5$ Amp jumps directly from segment b to the brush through air thus producing spark.

(6)

Plot of change of current in coil B w.r.t time.



- (AB) constant current of 20 A upto time of beginning of commutation. (6)
- From finish of commutation, current is ~~constant~~ is represented by horizontal line (CD). Current value again is $EC = 20\text{ Amp}$ but current is in reverse direction.
- The way in which the current changes from its positive value 20 A ($= BE$) to zero and then to its -ve value of 20 A ($= CF$) depends on the condition under which the coil B goes commutation. However if current varies in a straight line - it is called linear commutation

1) Resistance commutation (by armature -

(6)

→ However due to production of self-induced e.m.f. in the coil, the variations follow the dotted line of core. It is seen that current in coil 'B' has reached to only a value of $I_B = 15A$ in the reverse direction, the difference of $(30 - 15 = 15A)$ passes as a spark.

practical DC machine has delayed commutation. The reasons for delayed commutation are

- i) cross-magnetising effect of Armature reaction
 - ii) self inductance property of a coil
- ① cross-magnetising effect of Armature reaction

due to this effect, flux exists along the brush axis, the coil undergoing commutation cuts the magnetic flux, dynamically induced e.m.f. This voltage drive the current in the local circuit same as its old direction which causes delayed commutation.

② Due to self-inductance property of a coil

during commutation process, the coil is said to be short-circuited, the current changes from $+I_c$ to $-I_c$ and during the commutation period a stancially emf is induced called Reactance Voltage.

(G1)

Reactance voltage opposes the current reversal according to Lenz's law. The current reversal is being opposed by reactance voltage causes delayed commutation.

$$\begin{aligned}\text{Reactance-Voltage } e_x &= e_x = L \frac{di}{dt} \\ &= L \left[\frac{I_c - (-I_c)}{T_c} \right] \\ e_x &= \frac{2LI_c}{T_c} \text{ Volts}\end{aligned}$$

~~Reasons for improving commutation~~

due to above 2 reasons at the end of commutation period some current remains with segment-2 but lower brush is in contact with commutator segment-1. This current is called residual current. Residual current ionises the air medium b/w the commutator segment & the brush & is reached to brush through the ionised air in the form of Sparking.

Methods for improving commutation

- i) Resistance commutation
- ii) e.m.f. commutation

i) Resistance commutation (by using high carbon brush resistance)

→ This is achieved by using carbon brushes instead of copper brushes. This method is suitable for DC machine only.

→ with carbon brushes, the time constant of the local circuit is decreased & the response from coil decays at a faster rate i.e. local circuit current & the current reversal takes place at a faster rate.

ii) e.m.f commutation (by using interpoles / compoles)

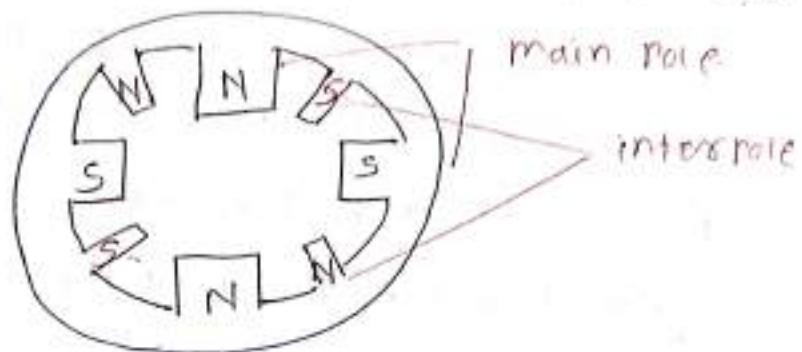
→ In this method, arrangement is made to neutralize the reactance voltage by producing a reversing e.m.f in the short-circuited coil under commutation.

→ This is achieved by using interpoles. This method is suitable for both large & small DC m/c.

→ The direction of interpole flux is acting opposite to the armature flux along the brush axis. Therefore cross-magnetising effect in b/w the poles is neutralized. Therefore dynamically induced emf produced in the commutated coil due to cross-magnetising effect becomes zero.

(66)

- The coil undergoing commutation cuts the interpole flux & dynamically induced emf is produced in it.
- This emf is acting in phase opposition to the reactance voltage present in the coil. Therefore reactance voltage effect is also neutralized.



No. of interpoles = No. of main field poles

For small m/c, No. of interpoles = $\frac{1}{2} \times$ No. of main field poles
interpoles are connected in series with armature.

Note

Equalizer rings is used to avoid unequal distribution of current at the brushes thereby helping to get sparkless commutation.

Characteristics of DC Generators

(67)

① open-circuit characteristics (o.c.c) E_o vs I_f | $N = \text{const.}$

- i) This curve shows the relationship between the generated e.m.f at No-load (E_o) and the field current (I_f) at constant speed.
- ii) It is also known as magnetisation characteristics or No-load characteristics.

② internal characteristics (E_g vs I_a) | $N = \text{const.}$

- i) This curve shows the relationship b/w the generated emf on load (E_g) & the armature current (I_a).
- ii) This emf (E_g) is less than (E_o) due to magnetisation demagnetising effect of armature reaction.
Therefore, this curve will lie below the o.c.c.

③ External characteristics (V_t vs I_L) | $N = \text{const.}$

- i) This curve shows the relationship b/w the terminal voltage (V_t) & load current (I_L).
- ii) The terminal voltage (V_t) will be less than E_g due to voltage drop in the armature circuit.
Therefore, this curve will lie below the internal characteristics.

Note i) open-circuit characteristics or magnetisation characteristics or no-load characteristics

$$E_o \propto \Phi N$$

$$E_o \propto I_f N$$

$$E_o \propto I_f \quad | N = \text{const.}$$

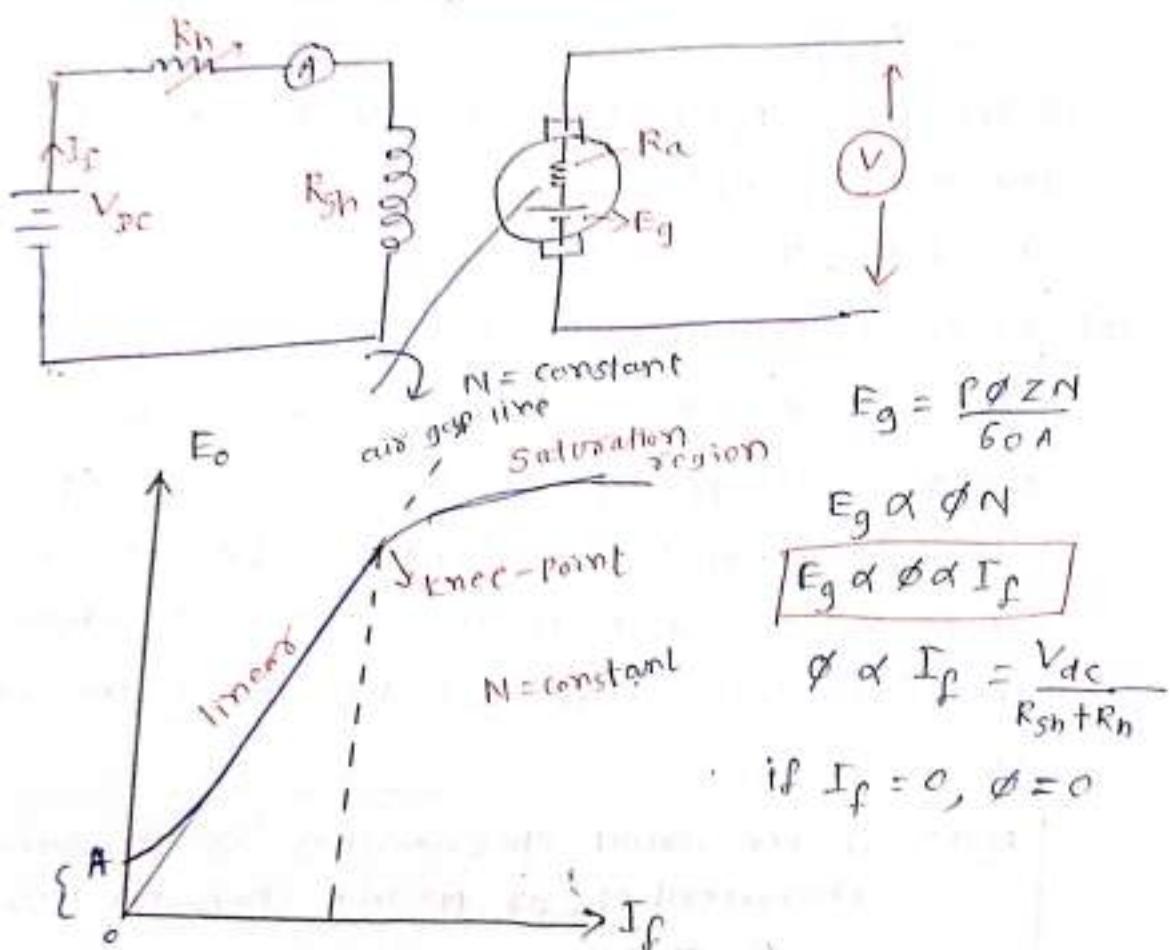
(62)

ii) internal characteristics or total characteristics

$$E_g \text{ vs } I_a \quad | N = \text{const.}$$

iii) external characteristics or load characteristics or voltage regulation characteristics or performance characteristics

$$V_t \text{ vs } I_L \quad | N = \text{const.}$$

Characteristics of Separately excited DC Generator1. [o.c.c] $[E_o \text{ vs } I_f \text{ } | N = \text{const.}]$  $OA = \text{residual voltage}$

if $I_f = 0$; $\phi = \phi_\infty$ (residual flux); $E = E_\infty = \frac{\text{residual flux}}{\text{Voltage}}$
 $= (2-6)\% \text{ of } E_o$

Before Saturation

$$\phi \propto I_f \therefore E_o \propto I_f$$

→ The curve ~~shows~~ is a straight line starting from zero so long as the poles are unsaturated.

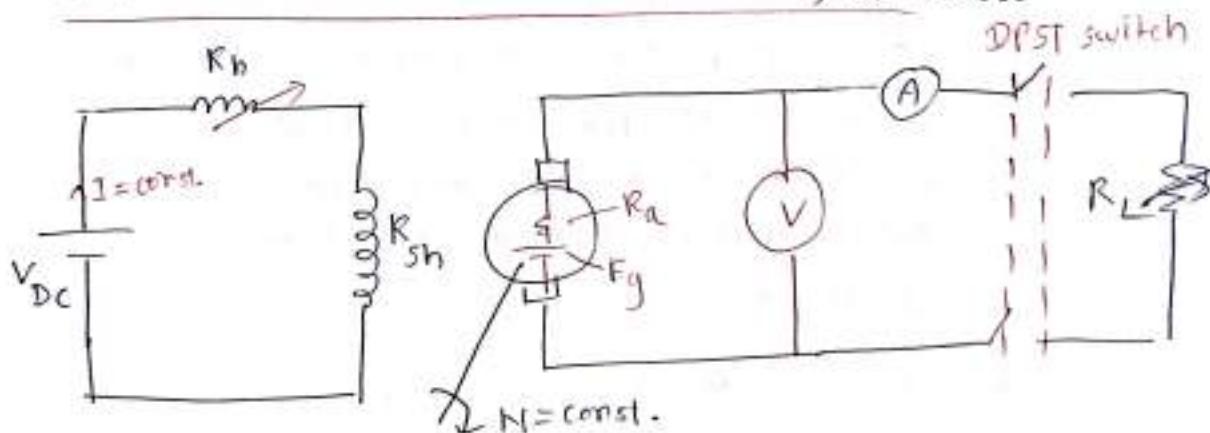
After Saturation

→ As the flux density increases, the poles become saturated.

→ So increase in I_f will not increase E_o accordingly.

$$\boxed{\phi = \phi_{sat} = \text{constant}} \quad \text{so} \quad \boxed{E_o = \text{constant}}$$

Q. External characteristics (V_t vs I_L) $|N = \text{const.}$ & internal characteristics (E_g vs I_a) $|N = \text{const.}$



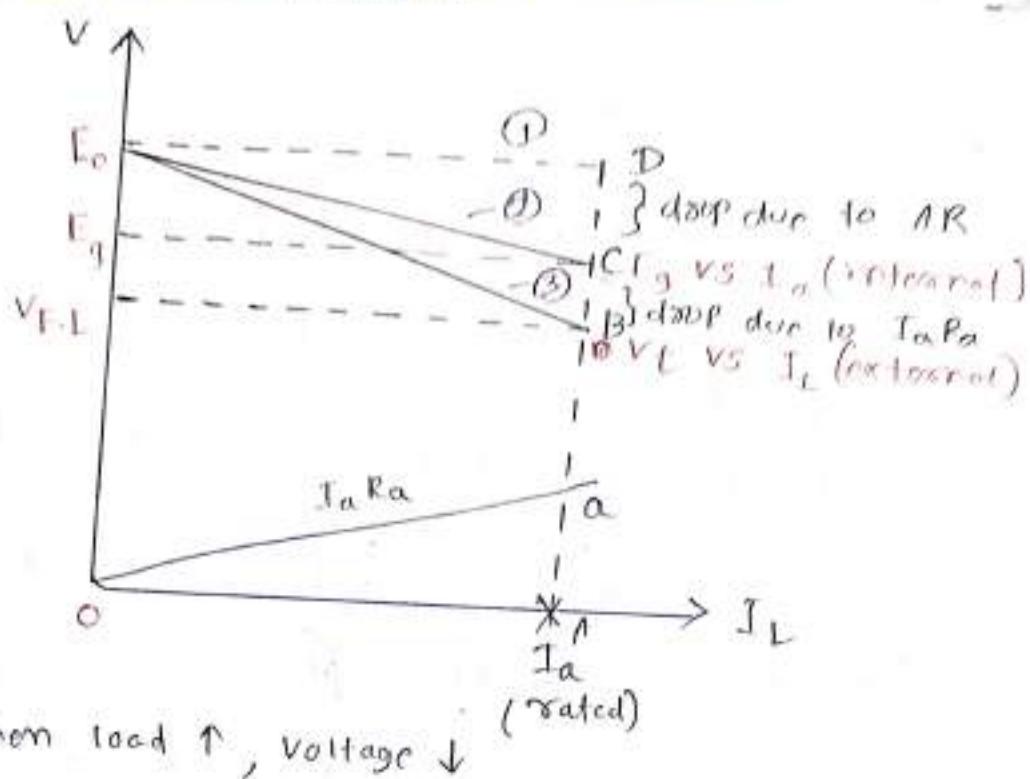
→ When DPST = open, $I_a = 0$, $\phi = \phi_{\text{rated}}$
 $N = N_{\text{rated}}$

$$E = V + I_a R_a$$

$$V_{\text{No-load}} = E = E_0$$

→ When DPST = close

$$\text{vary } R_L \text{ in steps} \quad \text{record } V_t \& I_L \quad \boxed{I_L = \frac{V_t}{R_L}}$$



$$AB = V_{FL} = \text{Full load voltage}$$

$$B_C = I_a R_a \text{ drop} \quad (\text{Armature drop})$$

$C_D = \text{drag due to Aromatic group}$

WAVE-1 \Rightarrow Na-lead Wallace

curve-1 → No-load voltage

Cube-2 → internal characteristics

$\cos(\ell-3) \rightarrow$ external characteristics

curve 'a' \rightarrow I_aR_a drop

Reasons for ~~V~~ Voltage drop

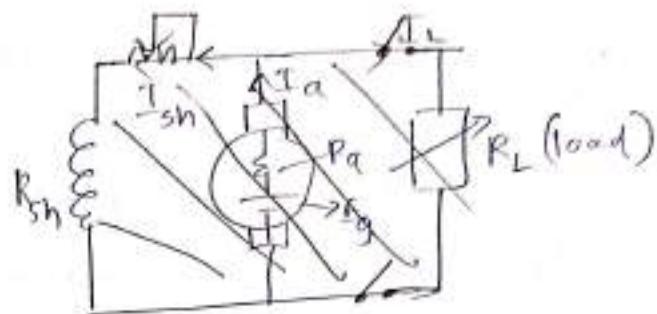
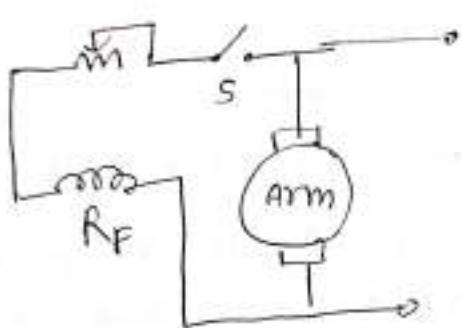
- i) $I_a R_a$ drop
 ii) drop due to immature reaction

→ due to above 2 reasons, the external characteristics is a drooping curve (curve-3)

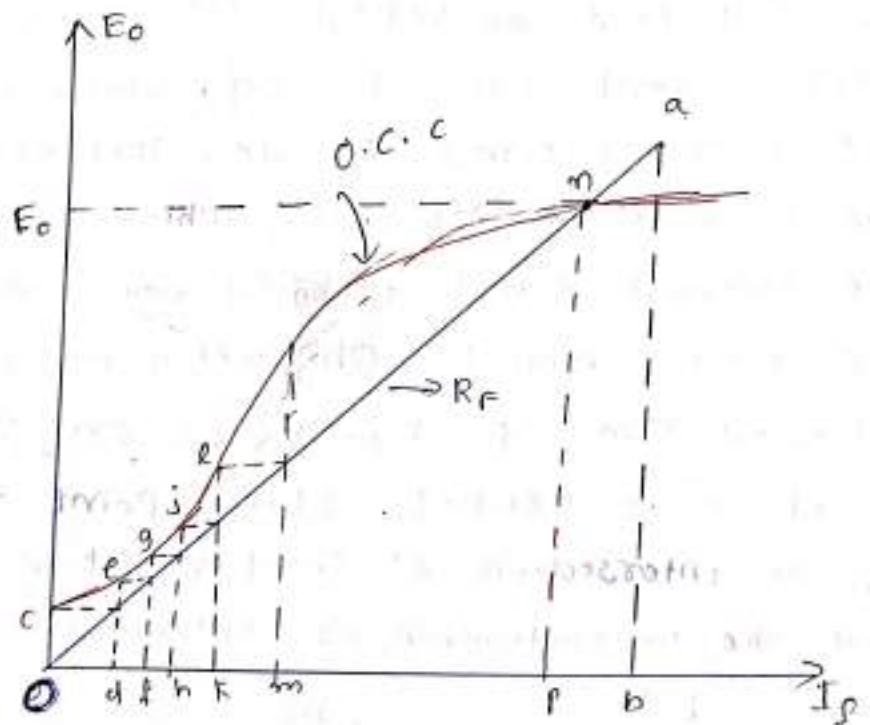
→ The internal characteristics can be determined from external characteristics by adding I_{Ra} drop to the external characteristics. curve-2 is the internal characteristics of the generator and should obviously lie above the external characteristics.

Voltage build-up process in a self-excited generator:

a) shunt generator



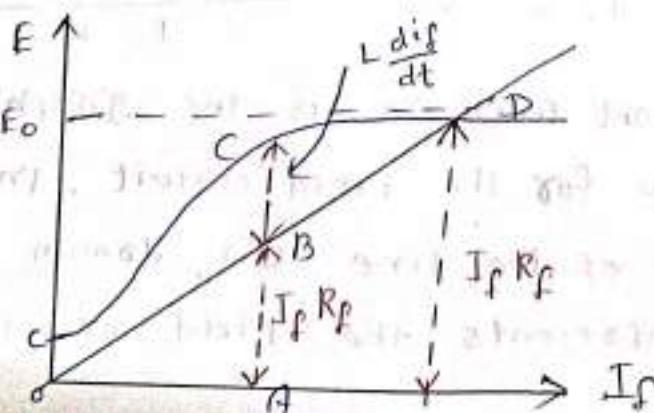
consider an unloaded shunt generator



The straight line Oa is the graphical plot of Ohm's law for the field circuit. In other words, the slope of the line Oa, drawn through origin, represents the field resistance R_F .

$$\tan \angle aOb = \frac{\text{Voltage } ba}{\text{current } Ob} = R_f \text{ (Field resistance in ohms)}$$

- When the armature is driven at a speed at a speed for which the magnetisation curve is given, the residual flux generates a small voltage Oc , with switch 'S' open i.e. with zero field current.
- When switch 'S' is closed, residual flux voltage Oc produces a small field current. If the flux produced by this small field current, adds to the residual flux, still larger voltages are generated.
- Residual flux \propto voltage Oc produces small field current equal to ' Od ', which in turn increases the generated e.m.f. to de . This voltage de raises the field current to Oe , which further raises the generated e.m.f. to dg , now e.m.f. dg raises the field current to Oh , which in turn increases the generated e.m.f. to hi & so on, till stable point 'n' is reached. Stable point 'n' is determined by the intersection of field resistance line Oa and the magnetisation or saturation-curve.



(13)

since the field circuit is inductive, there is a delay in the increase in current upon closing the field circuit switch. The rate at which the field current increases depends upon the voltage available for increasing it.

→ An amount \propto AB of the e.m.f \propto AC is absorbed by the voltage drop iR_f and the remainder part BC is available to overcome $L \frac{di}{dt}$.

② Series generator

During initial operation, with no current yet flowing, a residual voltage will be generated exactly as in the case of shunt generator.
i) The residual voltage will cause a current to flow through the whole series circuit when the circuit is closed. There will then be voltage build up to an equilibrium point exactly analogous to the build up of a shunt generator. The voltage build up graph will be similar to that of shunt generators except that now load current (instead of field current for shunt generator) will be taken along X-axis.

③ compound generator

i) When a compound generator has its series field flux aiding its shunt field flux, the machine is said to be cumulative compound. When the series field is connected in reverse so that its field flux opposes the shunt field flux, the generator

(71)

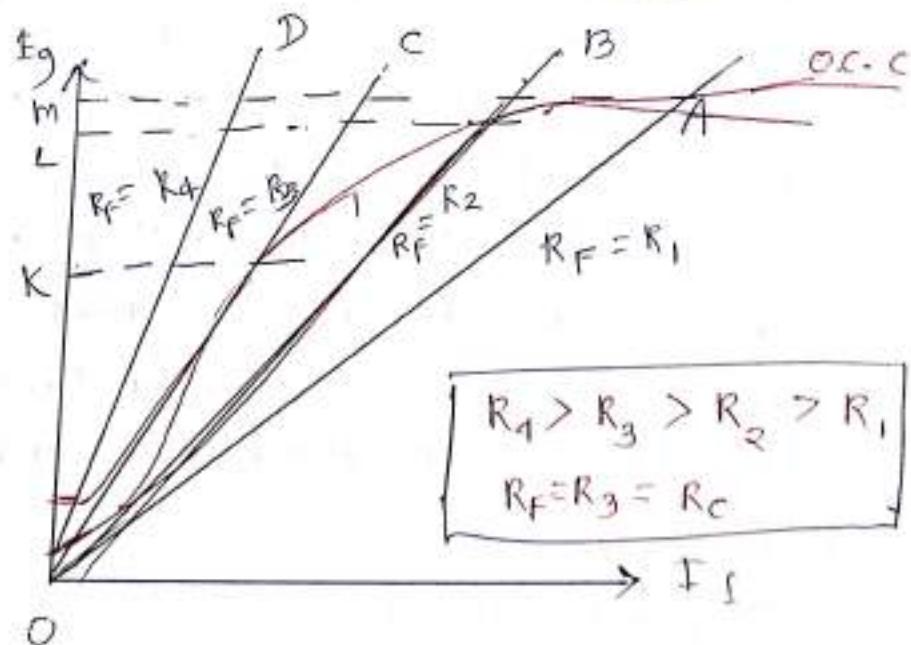
is then called differential compound.

v) The easiest way to build up voltage in compound generator is to start no-load conditions. At no load, only the short field is effective. When no-load voltage build up is achieved, the generator is loaded. If under load, the voltage rises, the series field connection is cumulative. If the voltage drops significantly, the connection is differential compound.

Critical Field Resistance for a Shunt generator

(R_C)

It is the maximum value of field circuit resistance at a given speed beyond which the generator fails to build up voltage.



- If R_F (Field circuit resistance) is R_1 (OA), the generator will develop a voltage OM .
- If R_F is increased to R_2 (OB), the generator will develop a voltage OL .

(75)

→ As the field circuit resistance is increased, the slope of the line R_f also increases.

→ When the field resistance line becomes tangent (line OC) to O.C.C, the generator would just excite. If the field circuit resistance is increased beyond the line (OD), the generator will fail to excite. $R_c \propto N$

$$\therefore R_f = R_3 = R_c \text{ (critical Field Resistance)}$$

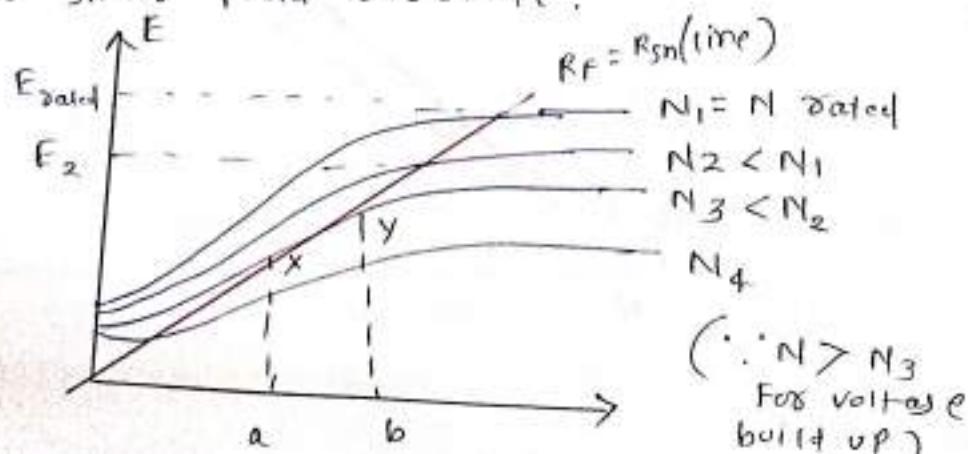
Note: The shunt generator will build up voltage only if field ~~current~~ circuit resistance is less than critical Field Resistance (R_c)

$$\therefore R_f < R_c \text{ (should be)}$$

Critical Speed (N_c)

→ It is the minimum speed of generator below which the generator fails to build up voltage with no external resistance in the field circuit.

→ At critical speed, critical field resistance is equal to shunt field resistance.

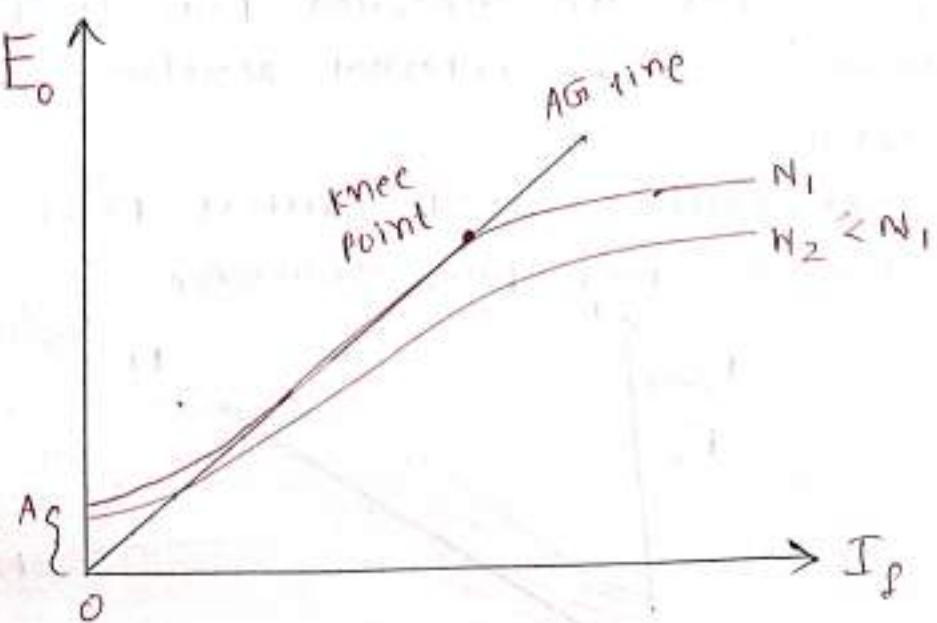


Conditions for voltage build up of a self excited D.C. generator:

- i) There must be some residual magnetism in generator poles. Due to ~~retentivity~~ property.
- ii) The connections of the field winding should be such that the field current strengthens the residual magnetism.
- iii) The field resistance should be less than critical field resistance ($R_f < R_{Cf}$)
- iv) ~~Critical speed~~ The speed of the generator should be higher than the critical speed ($N_0 > N_c$)
- v) When the generator build-up voltage under load condition, the load resistance must be more than the critical load resistance (R_{Lc}).

Characteristics of D.C. shunt generators

a) Open circuit characteristics (O.C.C) E_0 vs I_f | $N = \text{const}$



(17)

when $I_f = 0$, $\phi = \phi_\infty$, $E = E_o = 0V$

$\Rightarrow 0V = \text{residual flux voltage (2-6%)} \text{ of } I_o$

before saturation

$$\phi \propto I_f$$

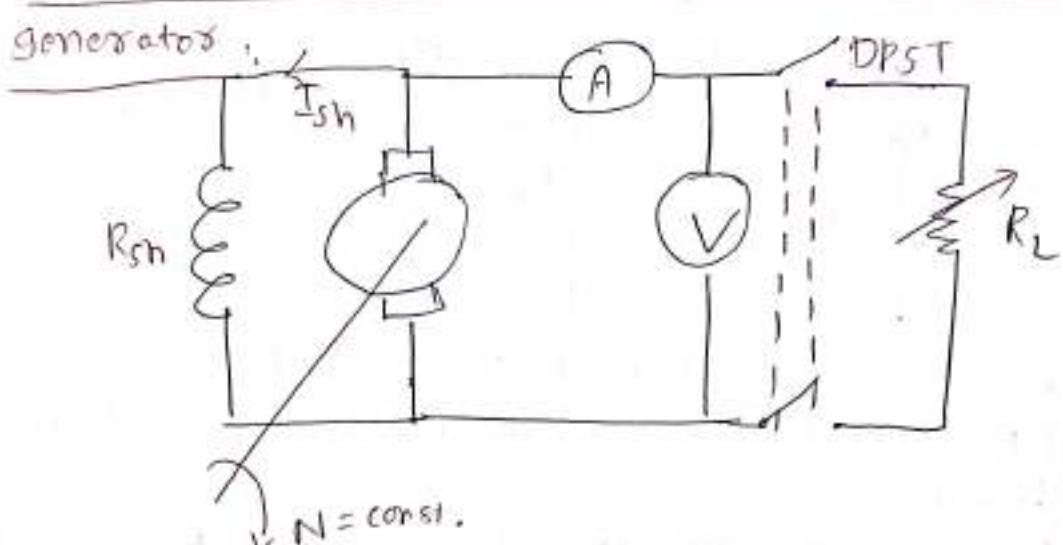
$$E_o \propto I_f$$

After Saturation

$$\phi = \phi_{\text{sat}} \quad \text{const.}$$

$$E_o = \text{const.}$$

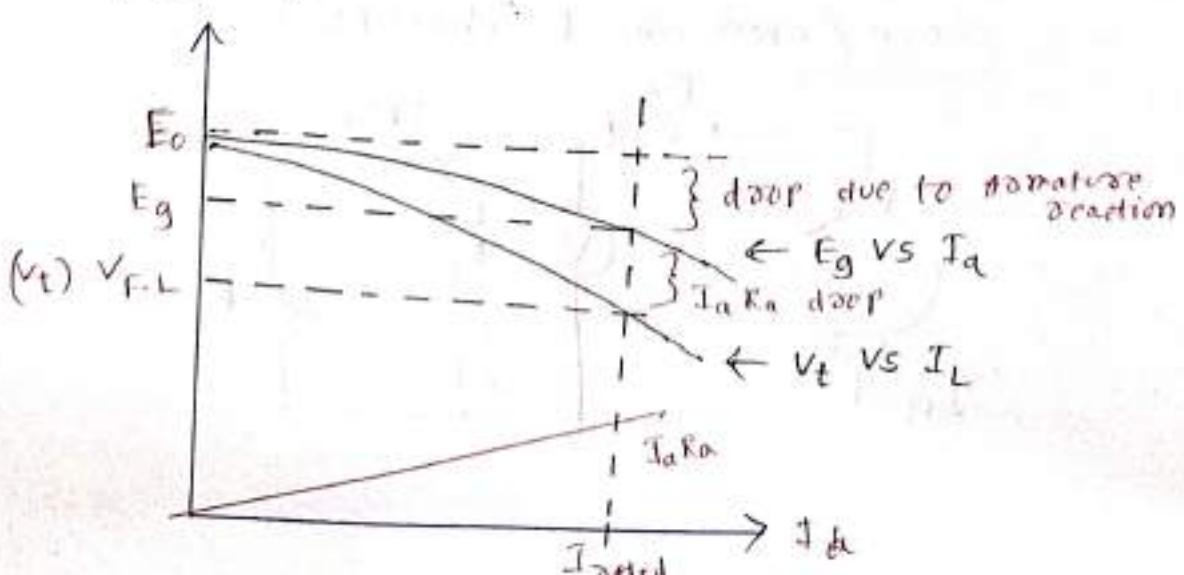
External & internal characteristics of shunt generator



when DPST switch open, $I_a \approx 0$

$$V = E_g - I_a R_a$$

$$V_{N.L} = E_g = E_o$$



(76)

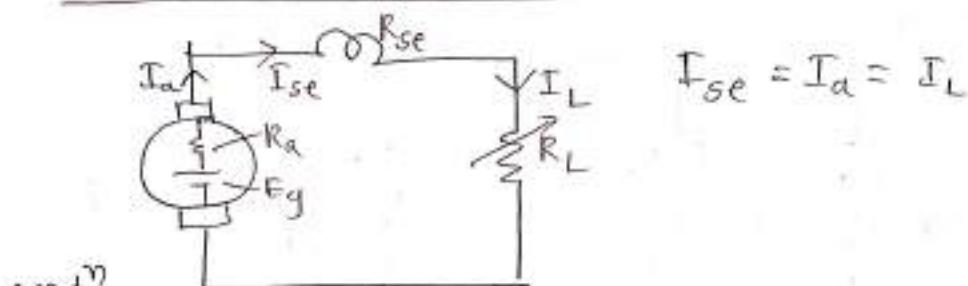
when load increases, voltage decreases

Reason for Voltage drop

- I_aR_a drop (drop due to armature reaction)
- drop due to armature reaction
- drop due to reduction field current,

Characteristics of Series Generator

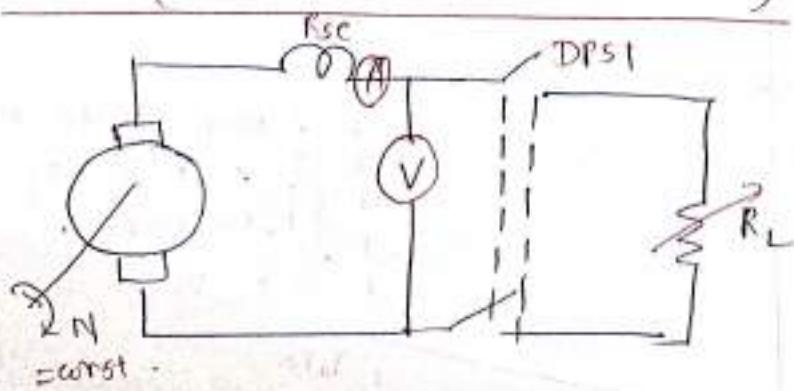
Voltage build up condition

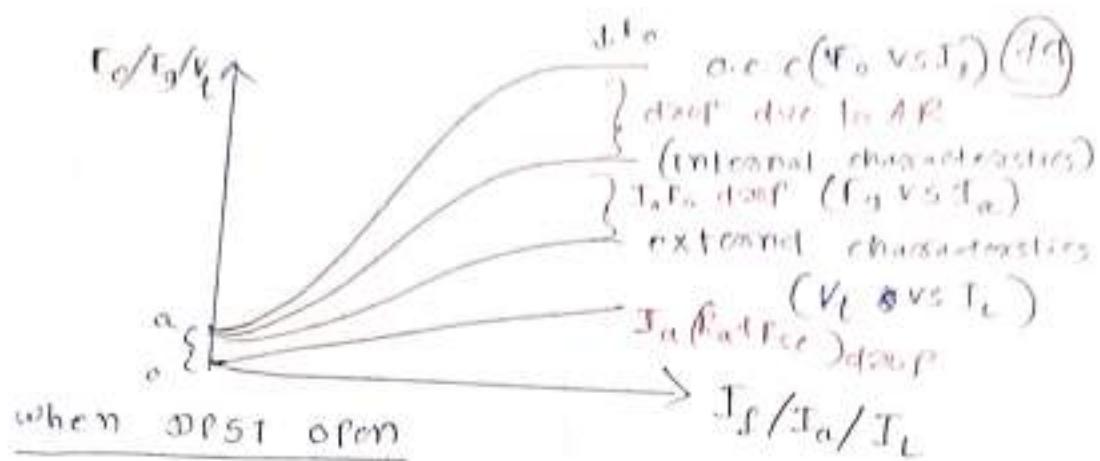


condⁿ

- Generator must have residual flux.
- Field terminals are properly connected to the armature.
- The total series circuit resistance should be less than critical resistance (R_c).
- The speed of prime mover should be greater than critical speed.

O.C.C (open circuit characteristics)





$$I_a = 0, V_{N.L} = E_g = E_\infty = (2 - G)I_L \text{ or } I_o$$

D.P.S.T Vary R_L in steps & record I_L .

load \uparrow , $V \uparrow \rightarrow$ rising characteristics.

compound generators

Compound generators voltage build up process is same as shunt generators.

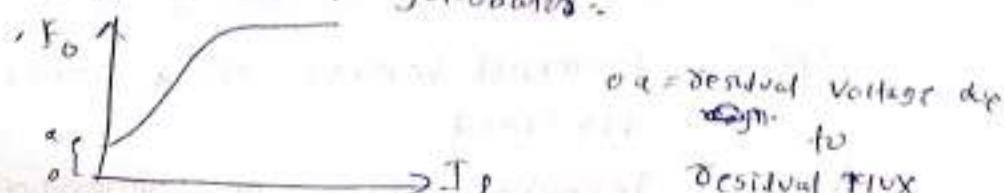
a) cumulative compound $\phi = \phi_{sh} + \phi_{se}$, $\phi_{net} \uparrow$, $E_g \uparrow$, $V_t \uparrow$

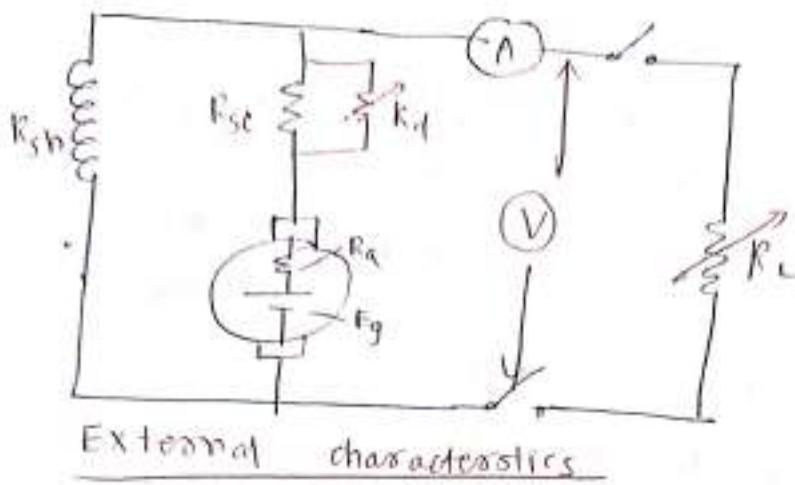
- over compound ($V > E_\infty$)
- under compound ($V < E_\infty$)
- flat / level compound ($V = E_\infty$)

b) differential compound $\phi = \phi_{sh} - \phi_{se}$, $\phi_{net} \downarrow$, $E_g \downarrow$, $V_t \downarrow$

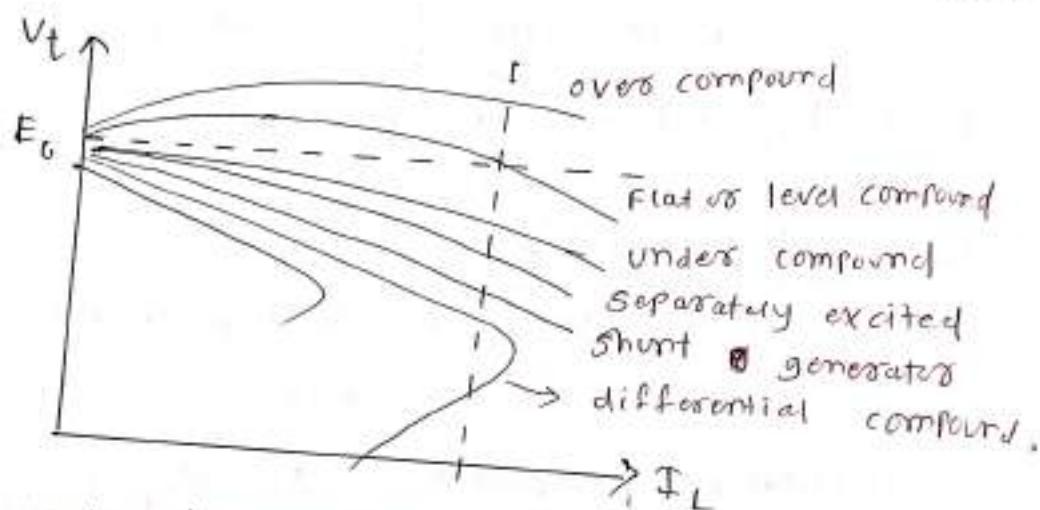
O.C.C / No-load characteristics

The no-load characteristics of a long shunt or short shunt compound generator is same as if it were a shunt generator.





when DPST open
 $I_a \approx 0, I_L = 0$
 $V_{NL} = E_g = F_g$
 DPST close
 & vary R_L in steps
 & record V_t & I_L .



Voltage characteristics

Voltage Regulation (%) VR)

The change in terminal voltage of a generator (at a constant speed) between full load & no-load expressed as percentage of full load.

$$\% \text{ VR} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

V_{NL} = terminal voltage of a generator at no-load

V_{FL} = terminal voltage of generator at full-load

(81)

If the change in voltage b/w no-load and Full-load is small, the generator is said to have good regulation, if the change in voltage is large, then it has poor regulation.

Note : $V_{N.L} = V_{F.L}$, then $\gamma \cdot VR = 0\%$.

$V_{N.L} > V_{F.L}$, then $\gamma \cdot VR = +ve \cdot V.R$

$V_{N.L} < V_{F.L}$, then $\gamma \cdot VR = -ve \cdot V.R$.

+ve, Voltage regulation generators \rightarrow under, separately, shunt, differential

-ve, VR generators \rightarrow series, over zero VR \rightarrow level compound

differential compound has high +ve V.R.

Very poor VR is in series generator.

level compound has very good VR.

Parallel operation of shunt DC generators

(2) (b)

Need of parallel operation of dc generators

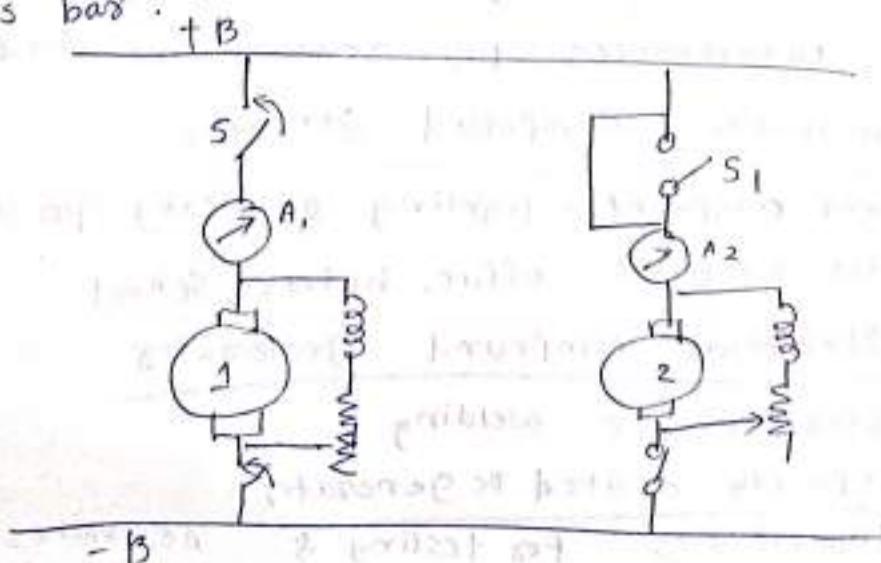
- i) continuity of service
- ii) Efficiency
- iii) maintenance and repair
- iv) addition of plant
- v) non-availability of single large unit.

Condition for parallel operation

- i) polarity of both the generators should be same.
- ii) voltage rating of both generators should be same.
- iii) load sharing between two generators should be equal.

Parallel operation of DC shunt generators

To connect two generators in parallel, their positive & negative terminals are must be connected with positive & negative terminals of the bus bar.



(81)

(82)

These bus-bars are heavy thick copper bars and they act as +ve & -ve power terminals of the power station.

If polarity of the incoming generator is not the same as the line polarity, as serious short circuit will occur when S is closed.

QUESTION

Uses of DC Generators

DC shunt generator

- used for lighting purpose
- used to charge the battery
- provide excitation to the alternator
- used for small power supply (portable generator)

DC series generator

- boosters in distribution system
- used for supplying field excitation current in DC locomotives for regenerative braking

Cumulative compound generator

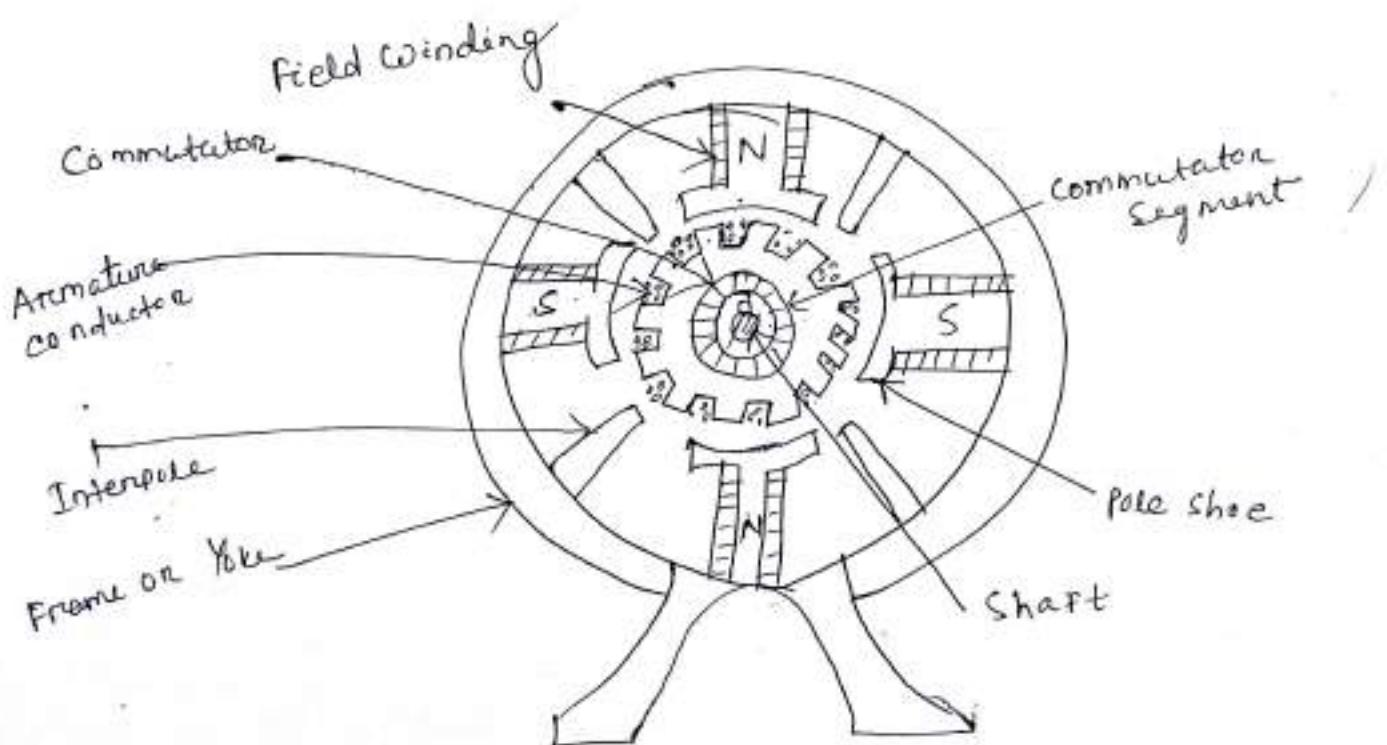
- over compound - lighting & heavy power supply
- flat compound - office, hotels, school

Differential compound generator

- used in arc welding

Separately excited DC generator

- laboratories for testing & researches
- used as a supply source of DC motor



Construction of D.C Generator

DC motor

(1)

An electric DC motor is a machine which converts electrical energy into mechanical energy.

Working principle of DC motor

- It works on the principle of Lorentz law.
- When a current carrying conductor is placed inside a magnetic field, it experiences a mechanical force whose direction is given by Fleming's left-hand rule, this force is Lorentz force.
- The magnitude of force $F = B I l$ Newton

where B = magnetic field strength in tesla
(Magnetic flux density) or (Wb/m^2)
 I = current in conductors in Amperes
 l = length of conductors in meters

Fleming's left hand rule, Thumb \rightarrow direction of force
Middle Finger \rightarrow direction of current
Fore Finger \rightarrow direction of Flux.

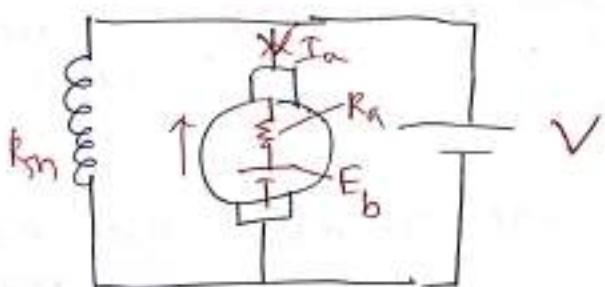
\rightarrow When the motor is connected to the DC supply mains, a direct current passes through the brushes and the commutator to the armature winding, while it passes through the commutator it is converted to AC so that the group of conductors under successive poles carry currents in the opposite directions.

(2)

Back e.m.f

When the motor armature rotates, the conductors also rotate and hence cut the Flux. In accordance with the laws of Electromagnetic induction, e.m.f is induced in them whose direction is found by Fleming's Right hand rule, is in opposition to the applied voltage. Because of its opposing direction, it is referred as counter or back e.m.f.

→ The direction of this induced e.m.f is such that it opposes the armature current (I_a) .



V = supply voltage

E_b = back emf

The rotating armature generates the back e.m.f E_b , put across supply mains of V Volts. Obviously, V has to drive I_a against the opposition of I_a . The power required to overcome this opposition is $E_b I_a$.

Significance of back emf

(3)

$$I_a = \frac{V - E_b}{R_a} \quad \therefore R_a = \text{armature resistance}$$

we know $E_b = \frac{P\phiZN}{60A}$ $\because E_b \propto N$ $\frac{T \propto I_a}{T \propto I_a}$

i) If speed is high ($N \uparrow$), Back e.m.f increases ($E_b \uparrow$)

If $E_b \uparrow$, $(V - E_b) \downarrow$, $I_a \downarrow$, $T \downarrow$, $N \downarrow$

* If speed increases above rated value, then less armature current flows, hence less torque is produced, speed decreases upto rated value.

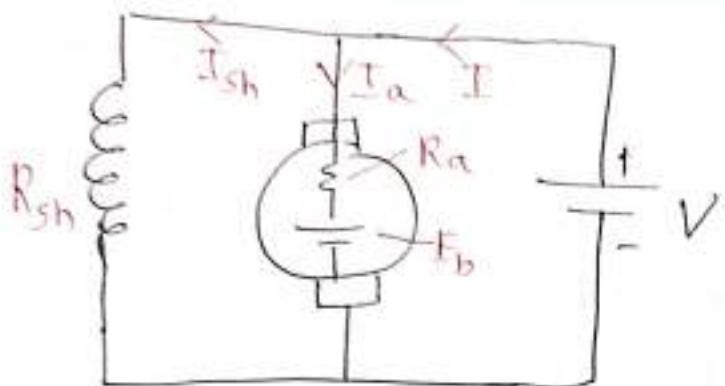
ii) If speed is low ($N \downarrow$), $E_b \downarrow$, $I_a \uparrow$, $T \uparrow$ so speed increases \uparrow .

* If speed is below rated value, more current flows which develops more torque, speed increases upto rated value.

* Hence E_b acts as a governor i.e. it makes a motor self regulating so that it draws as much current as it is necessary.

Voltage equation of a DC motor

(4)



The voltage V applied across the motor armature has to i) overcome the back e.m.f E_b & ii) supply the armature ohmic drop $I_a R_a$

$$V = E_b + I_a R_a \quad \text{Voltage eqn of a motor}$$

multiply I_a on both sides

$$VI_a = E_b I_a + I_a^2 R_a$$

VI_a = electrical power input to the armature

$E_b I_a$ = electrical equivalent of mechanical power developed in the armature

$I_a^2 R_a$ = w. loss in the armature

out of the armature i/p (VI_a), some is wasted in $I_a^2 R_a$ loss & the rest is converted into mechanical power within the armature.

motor efficiency = ~~Output Power developed by the armature~~
 $\frac{\text{i/p power in armature}}{\text{i/p power in armature}}$

$$\eta \% = \frac{E_b I_a}{V I_a} = \frac{E_b}{V} \times 100$$

∴ higher the value of E_b as compared to V , higher the motor efficiency.

Significance of back emf

(3)

$$I_a = \frac{V - E_b}{R_a} \quad \therefore R_a = \text{armature resistance}$$

we know $E_b = \frac{P\phi ZN}{60A}$ $\boxed{\therefore E_b \propto N}$ $\boxed{\frac{T \propto I_a}{T \propto I_a}}$

- i) If speed is high ($N \uparrow$), Back e.m.f increases ($E_b \uparrow$)
if $E_b \uparrow$, $(V - E_b) \downarrow$, $I_a \downarrow$, $T \downarrow$, $N \downarrow$

④ If speed increases above rated value, less armature current flows, hence less torque is produced, speed decreases upto rated value.

- ii) If speed is low ($N \downarrow$), $E_b \downarrow$, $I_a \uparrow$, $T \uparrow$ so speed increases \uparrow .

④ If speed is below rated value, more current flows which develops more torque, speed increases upto rated value.

- ④ Hence E_b acts as a governor i.e. it makes a motor self regulating so that it draws as much current as it is necessary.

(27)

(5)

$$P_{\text{mech}} = VI_a - I_a^2 R_a$$

Condition for maximum power

The gross mechanical power developed by the motor is $P_m = VI_a - I_a^2 R_a$

Differentiating both sides w.r.t I_a & equating the result to zero, we get

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

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

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

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

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

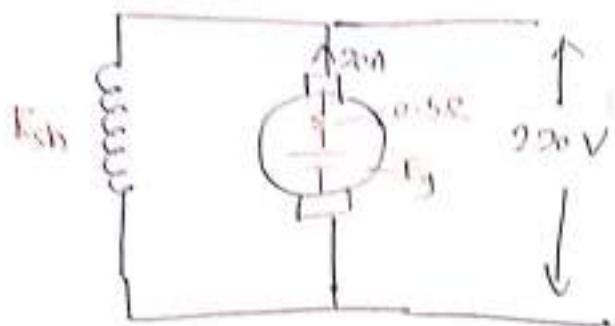
∴ Thus gross mechanical power developed by a motor is maximum when back e.m.f is equal to ~~the~~ half the applied voltage.

$$\% \text{ at } P_{\text{max}} = \frac{E_b}{V} \times 100 = \frac{V/2}{V} \times 100 = 50\%$$

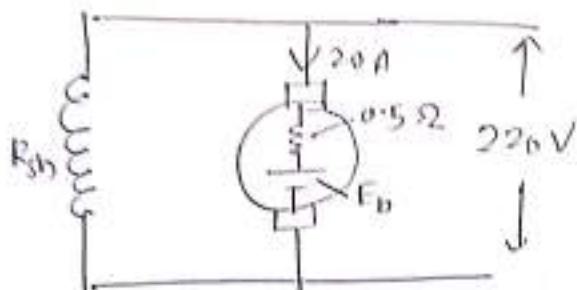
- Q) A 220V dc machine has an armature resistance of 0.5Ω . If full load armature current is 20 Amp. Find the induced e.m.f when the m/c acts as
 i) generator ii) motor

a) Generator

(6)

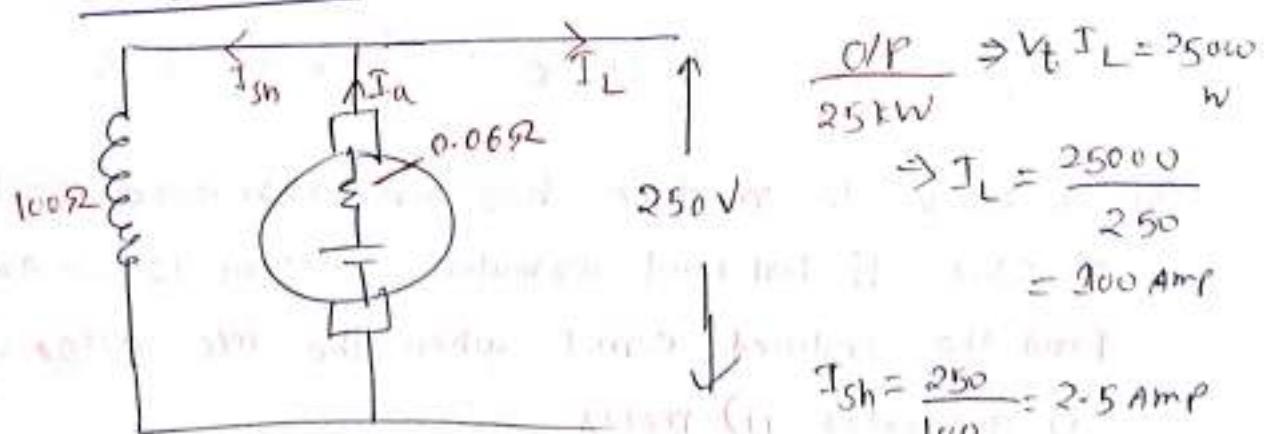


$$E_g = V + I_a R_a \\ = 220 + 0.5 \times 20 \\ = 230 \text{ volt}$$

i) b) motor

$$E_b = V - I_a R_a \\ = 220 - 0.5 \times 20 \\ = 210 \text{ volt}$$

- Q) A 25 kW, 250V dc shunt generator has an armature & field resistance of 0.06Ω & 100Ω respectively. Determine the armature power developed when working i) as a generator delivering 25 kW o/p
ii) as a motor taking 25 kW i/p

Ans: as generator

$$\frac{\text{O/P}}{25 \text{ kW}} \Rightarrow V_t I_L = 25000 \text{ W} \\ \Rightarrow I_L = \frac{25000}{250} \\ = 100 \text{ Amp}$$

$$I_{sh} = \frac{250}{100} = 2.5 \text{ Amp}$$

$$E_g = 0 V_t + I_a R_a$$

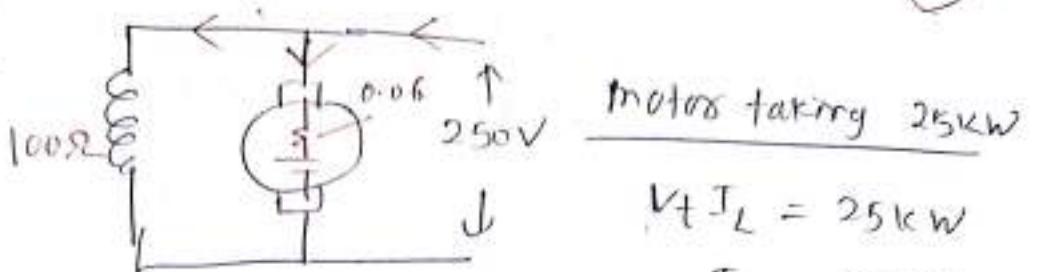
$$= 250 + 102.5 \times 0.06 = 256.15 \text{ volt}$$

$$I_d = I_L + I_{sh} = 102.5 \text{ Amp}$$

$$\text{Power developed in armature} \Rightarrow E_g I_a = 256.15 \times 102.5 \\ = 26.25 \text{ kW}$$

(b) as motor

(7)



$$I_{sh} = \frac{250}{100} = 2.5 \text{ Amp}$$

$$V_t I_L = 25 \text{ kW}$$

$$I_L = \frac{25000}{250} = 100$$

$$I_a = I_L - I_{sh} = 100 - 2.5 = 97.5 \text{ Amp}$$

$$E_b = V_t - I_a R_a = 250 - (97.5 \times 0.06)$$

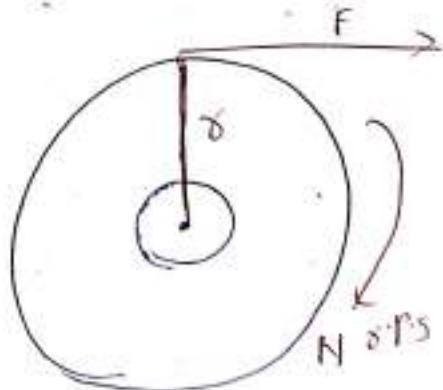
$$= 250 - 5.85 = 244.15 \text{ V.d.f}$$

$$\text{Power developed in armature} = E_b I_a = 244.15 \times 97.5 \\ = 23.8 \text{ kW}$$

Toque eqn

Toque is the turning or twisting moment of force about an axis. It is measured by the product of the force and the radius at which this force acts.

Consider a pulley of radius 'r' meter acted upon by a circumferential of F Newton which causes it to rotate at N r.p.m.



$$\text{Toque } T = F \times r \text{ Newton-metre (N-m)}$$

Workdone by this force in one revolution

$$= \text{Force} \times \text{distance}$$

$$= F \times 2\pi r \text{ Joule}$$

(8)

$$\text{Power developed} = F \times R \times N \text{ Joule/second or watt}$$

$$= (F \times \delta) \times 2\pi N \text{ watt}$$

Now $2\pi N$ = angular velocity ω in radian/second
and $F \times \delta$ = torque (T)

$$\therefore \text{Power developed} = T \times \omega \text{ watt}$$

$$\text{or } P = \omega T \text{ watt}$$

Moreover, if N is in r.p.m, then

$$\omega = \frac{2\pi N}{60} \text{ rad/sec}$$

$$P = \frac{2\pi N}{60} \times T \text{ or } P = \frac{2\pi}{60} \cdot NT$$

$$\text{or } P = \frac{NT}{9.55}$$

Armature torque of a motor (T_a)

Let T_a be the torque developed by the armature of a motor running at N r.p.s.

If T_a is in N/m, then power developed = $T_a \times 2\pi N$ watt ... (i)

→ we know that electrical power converted into mechanical power in the armature = $E_b I_a$ watt

$$\text{equating (i) & (ii)} \quad T_a \times 2\pi N = E_b I_a$$

$$\Rightarrow E_b = \phi Z N \times \left(\frac{P}{A}\right) \text{ volt, (iii)}$$

$$T_a \times 2\pi N = \phi Z N \left(\frac{P}{A}\right) \cdot I_a$$

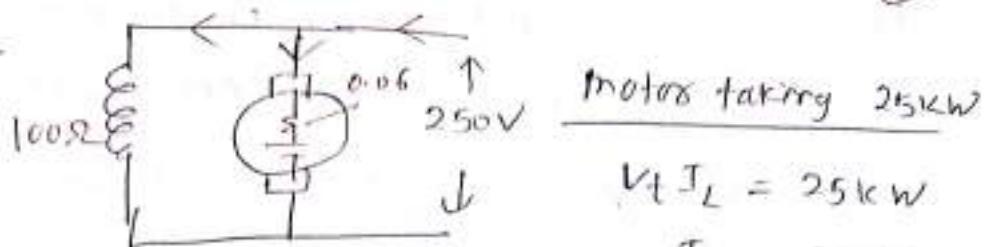
$$\text{or } T_a = \frac{1}{2\pi} \phi Z I_a \left(\frac{P}{A}\right) \text{ N-m}$$

$$= 0.157 \frac{\phi Z I_a}{A} \text{ N-m}$$

$$T_a = 0.157 \phi Z I_a \times \left(\frac{P}{A}\right) \text{ N-m.}$$

(7)

(b) as motor



$$V_t I_L = 25 \text{ kW}$$

$$I_L = \frac{25000}{250} = 100$$

$$I_{sh} = \frac{250}{100} = 2.5 \text{ amp}$$

$$I_a = I_L - I_{sh} = 100 - 2.5 = 97.5 \text{ amp}$$

$$E_b = V_t - I_a R_a = 250 - (97.5 \times 0.06)$$

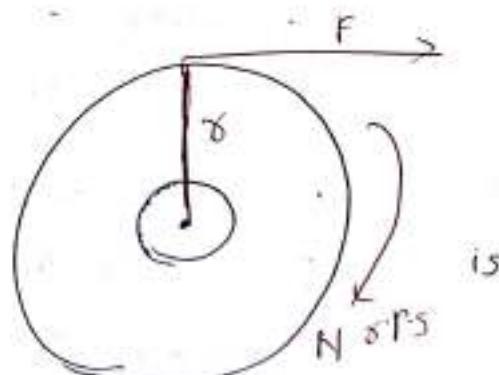
$$= 250 - 5.85 = 244.15 \text{ V.d.f}$$

$$\text{Power developed in armature} = E_b I_a = 244.15 \times 97.5 \\ = 23.8 \text{ kW}$$

Torque eqn

Torque is the turning or twisting moment of force about an axis. It is measured by the product of the force and the radius at which this force acts.

Consider a pulley of radius 'r' meter acted upon by a circumferential force F Newton which causes it to rotate at N r.p.m.



$$\text{Torque } T = F \times r \text{ Newton-metre (N-m)}$$

Work done by this force in one revolution

$$= \text{Force} \times \text{distance}$$

$$= F \times 2\pi r \text{ Joule}$$

(9)

$$T_a = 0.159 \phi Z I_a \times \left(\frac{P}{N}\right) \text{ N-m}$$

$$T_a \propto \phi I_a$$

a) in series motor

$$\phi \propto I_a \text{ (before saturation)}$$

$$\Rightarrow T_a \propto I_a^2$$

After saturation

$$T_a \propto I_a$$

b) in shunt motor $\phi = \text{constant}$

$$\therefore T_a \propto I_a$$

From eqn (iii), $T_a = \frac{E_b I_a}{2\pi N} \text{ N-m} \quad (\because N \text{ is in rps})$ if ~~N~~ is r.p.m. , then $T_a = \frac{E_b I_a}{(2\pi N/60)} = \frac{60}{2\pi} \left(\frac{E_b I_a}{N} \right)$

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

Shaft torque (T_{sh})

The torque which is available for doing useful work is known as shaft torque (T_{sh}). It is available at the shaft.

motor O/P = $T_{sh} \times 2\pi N$ Watt provided $T_{sh} = \text{N-m}$

$$T_{sh} = \frac{\text{O/P in watts}}{2\pi N} \text{ N-m} \quad (\because N = \text{rps})$$

$$= \frac{\text{O/P in watts}}{(2\pi N/60)} \text{ N-m} \quad (\because N = \text{rppm})$$

$$= \frac{60}{2\pi} \frac{\text{O/P}}{N} \quad \boxed{T_{sh} = 9.55 \frac{\text{O/P}}{N} \text{ N-m}}$$

$T_{lost} = T_a - T_{sh}$ = lost torque is due to iron & friction losses of the motor.

(27)

Brake horse power (bhp)

The mechanical power available at the shaft in horse power is known as brake horse power (bhp). $\text{O.P.M. in bhp} = \frac{Q \times N \times T_m}{60 \times 735.5}$

The value of back e.m.f (E_b) can be found from i) the equation $E_b = V - I_a R_a$
ii) the formula $E_b = \frac{P \phi Z N}{60 A}$ volt

Speed of a D.C. Motor

$$E_b = V - I_a R_a \text{ (or)} \frac{P \phi Z N}{60 A} = V - I_a R_a$$

$$\Rightarrow N = \left(\frac{V - I_a R_a}{\phi} \right) \times \frac{60 A}{Z P} \text{ r.p.m}$$

$$\Rightarrow N = \frac{E_b}{\phi} \times \left(\frac{60 A}{Z P} \right) \text{ r.p.m}$$

$$\Rightarrow \boxed{N = K \frac{E_b}{\phi}} \quad \text{where } K = \frac{60 A}{Z P}$$

$\Rightarrow \boxed{N \propto \frac{E_b}{\phi}}$ It shows that speed is directly proportional to back e.m.f (E_b) & inversely proportional to the flux ϕ or $N \propto \frac{E_b}{\phi}$

For series motor

Let N_1 = speed in the 1st case

I_{a1} = armature current in the 1st case.

ϕ_1 = flux/pole in the 1st case

N_2, I_{a2}, ϕ_2 = corresponding quantities in the 2nd case

(27)

Using the above ~~eqn~~ relation, we get

$$N_1 \propto \frac{E_{b1}}{\phi_1} \quad \text{where } E_{b1} = V - I_{a1} R_a \quad (ii)$$

$$N_2 \propto \frac{E_{b2}}{\phi_2} \quad \text{where } E_{b2} = V - I_{a2} R_a \quad (iii)$$

eqn (ii) / eqn (i)

$$\boxed{\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}}$$

before saturation, $\phi \propto I_a$.

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}$$

For shunt motor, $\phi = \text{const.}$

$$\boxed{\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}}$$

Speed regulation

The speed regulation is defined as the change in speed from No-load to full-load expressed as a percentage of full load speed.

$$\% \text{ Speed regulation} = \frac{\text{No-load speed} - \text{F.L. speed}}{\text{F.L. speed}} \times 100$$

$$\% = \frac{N_{NL} - N_{FL}}{N_{FL}} \times 100$$

→ Speed regulation of shunt motor is positive (10-15%).

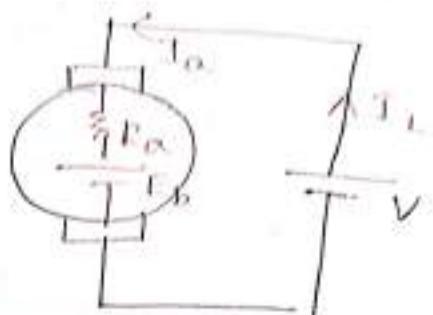
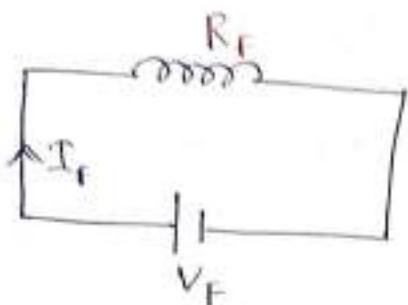
→ Speed regulation of series motor is positive (∞).
poorest speed regulation

→ Speed regulation of cumulative compound motor is positive range (20-25%).

→ S.R. of differential compound motor is negative (-5%).

Separately excited dc motor

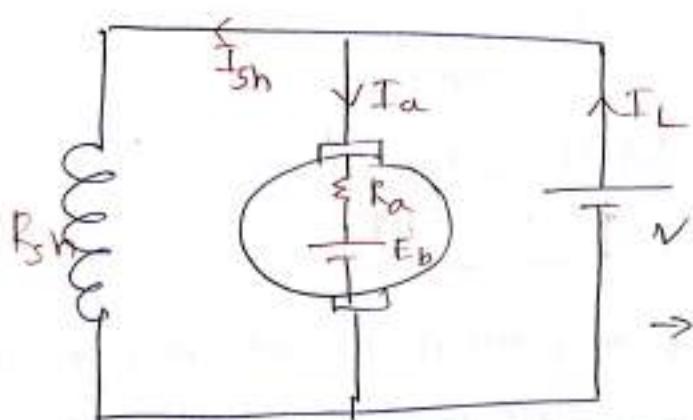
(12)



$$\boxed{E_b = V - I_a R_a - B \cdot D} \quad \boxed{I_L = I_a}$$

Bush drop neglected, $P_{in} = VI_L$

DC shunt Motor



KCL

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

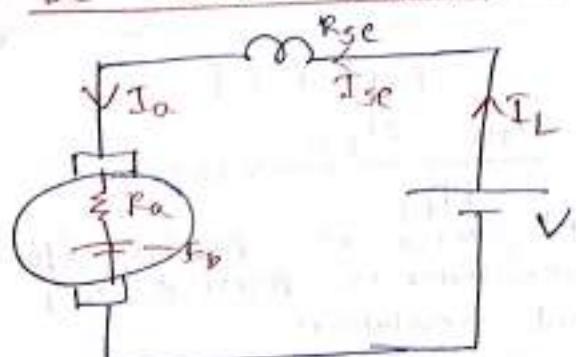
$$I_a = I_L - I_{sh}$$

$$\phi \propto I_{sh} = \frac{V}{R_{sh}} = \phi_{const.}$$

→ constant flux motor

$$\boxed{KVL \quad E_b = V - I_a R_a - B \cdot D}$$

DC ~~series~~ motor



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

KVL

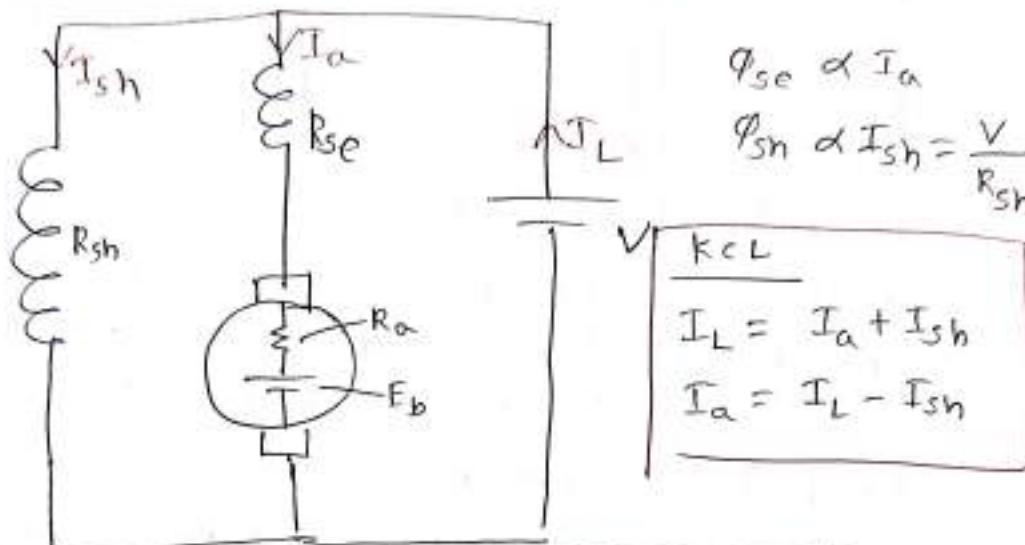
$$V = E_b + I_a R_a + I_{se} R_{se} + B \cdot D$$

$$E_b = V - I_a R_a - I_{se} R_{se} - B \cdot D$$

(27)

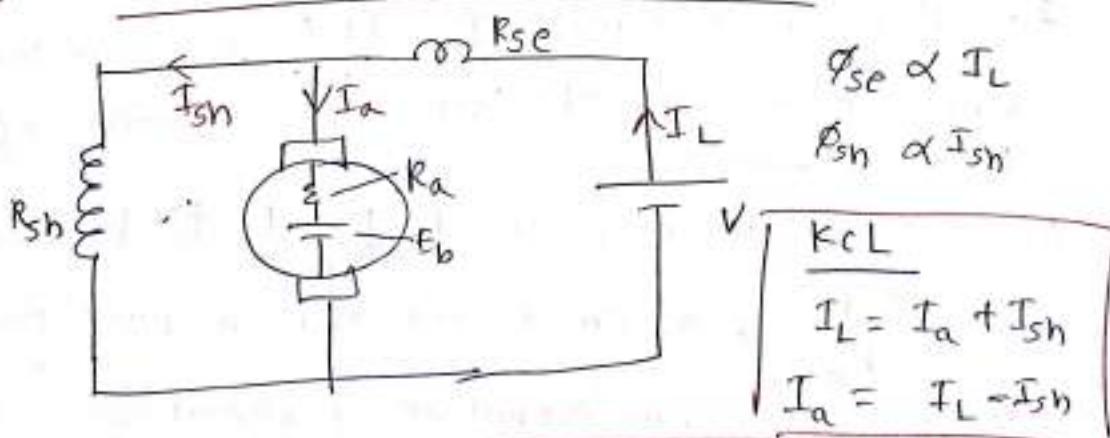
Compound motor

(13)

① long shunt compound motor

KVL

$$\left. \begin{aligned} V &= E_b + I_a R_a + I_a R_{se} + B.D \\ E_b &= V - I_a R_a - I_a R_{se} - B.D \end{aligned} \right\}$$

② shunt-shunt DC compound motor

KVL

$$\left. \begin{aligned} V &= E_b + I_a R_a + I_L R_{se} + B.D \\ E_b &= V - I_a R_a - I_L R_{se} - B.D \\ I_{sh} &= \frac{V - I_L R_{se}}{R_{sh}} \end{aligned} \right\}$$

(27)

(14)

Torque & speed of a DC motor

$$N = K \frac{V - I_a R_a}{\phi} = k \frac{E_b}{\phi} \quad [T_a \propto \phi I_a]$$

$$\left[N \propto \frac{E_b}{\phi} \right] \quad [T_a \propto \phi] \quad \left[\because E_b = \frac{N \phi}{K} \right]$$

→ If $\phi \uparrow, N \downarrow, T_a \uparrow$

→ it is seen that increase in flux would decrease the speed but increase in the armature torque. It can't be so because torque always tends to produce rotation.

→ if $T_a \uparrow, N$ (must increase) rather than decrease suppose the flux of a motor is decreased by decreasing the field current, then following events take place.

1. $\phi \downarrow$, back e.m.f $E_b = N \phi$ drops instantly (N remains constant because of inertia of the heavy armature)

2. due to decrease in $E_b \downarrow, I_a \uparrow$ because

$I_a = \frac{V - E_b}{R_a}$, a small reduction in flux produces large increase in armature current.

3. Hence, $T_a \propto \phi I_a$, small decrease in flux(ϕ) is more than counterbalanced by a large increase in I_a with the result that there is a net increase in T_a .

4. This increase in T_a produces increase in motor speed.

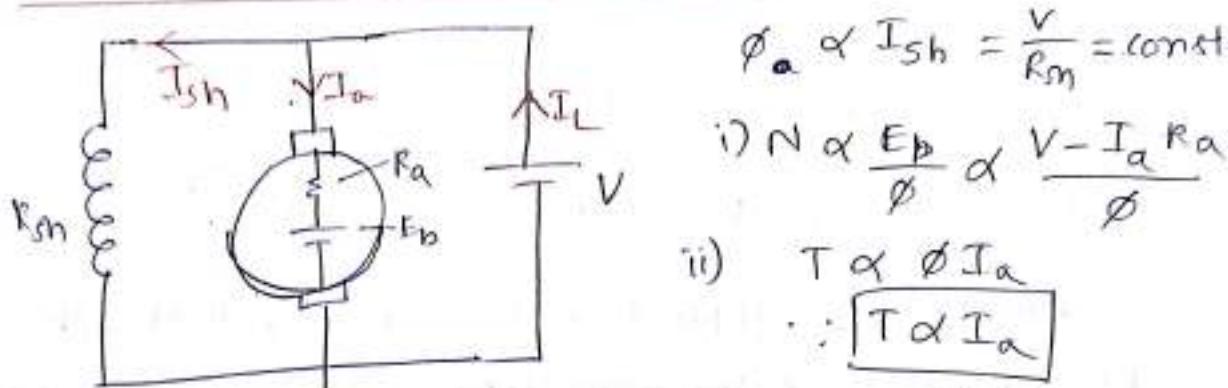
DC motor characteristics

- ① speed vs armature current (N vs I_a)
- ② Torque vs armature current (T_a vs I_a)
- ③ Speed vs torque (N vs T_a)

④ & ⑤ electrical characteristics

⑥ → mechanical characteristics

characteristics of DC shunt motor



$$\phi_a \propto I_{sh} = \frac{V}{R_m} = \text{const.}$$

$$\text{i) } N \propto \frac{E_b}{\phi} \propto \frac{V - I_a R_a}{\phi}$$

$$\text{ii) } T \propto \phi I_a$$

$$\therefore T \propto I_a$$

- ① Speed (N) vs armature current (I_a)

At No-load, $I_a \approx 0$ $\textcircled{N \propto V}$

~~when~~
Mechanical

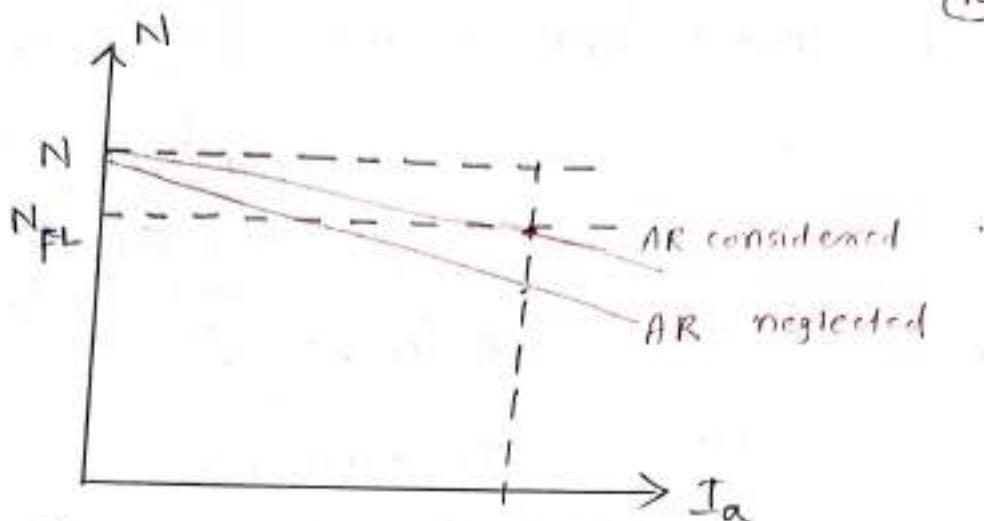
→ when mechanical load increases, $I_a \uparrow$, $\textcircled{N \propto V - I_a R_a}$
~~slightly decrease in speed.~~

~~when~~ load is there, due to armature reaction

$$, \phi \downarrow, \textcircled{T \propto \frac{1}{\phi}}$$

→ when load increases, E_b & ϕ decrease due to the armature resistance drop ($I_a R_a$) and armature reaction respectively, but E_b decreases slightly more than ϕ so that the speed of the motor decreases slightly with load.

(16)



$$I_{sh} = \frac{V}{R_{sh}} = \text{constant}, \quad \phi \propto I_{sh} \therefore \phi \approx \text{constant}$$

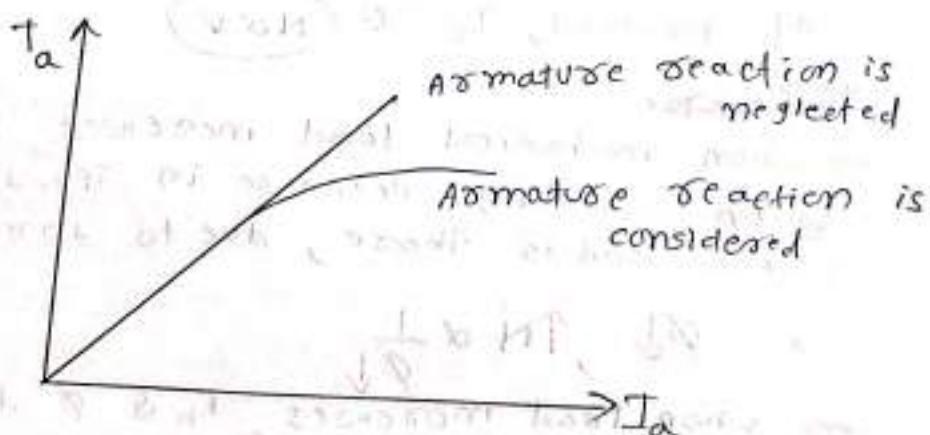
\therefore DC shunt motor is a ~~not~~ constant flux motor.

\rightarrow DC shunt motor is a constant speed motor.

② Torque (T_a) vs armature current (I_a)

$T \propto \phi I_a$. Applied voltage is constant. Therefore Flux is constant by neglecting armature reaction.

$\Rightarrow T \propto I_a$ $\therefore T_a$ vs I_a characteristics is linear



\rightarrow if Armature reaction & saturation is considered.

As load \uparrow , Flux decreases slightly \downarrow ,

Slightly \downarrow $T \propto \phi I_a \downarrow$

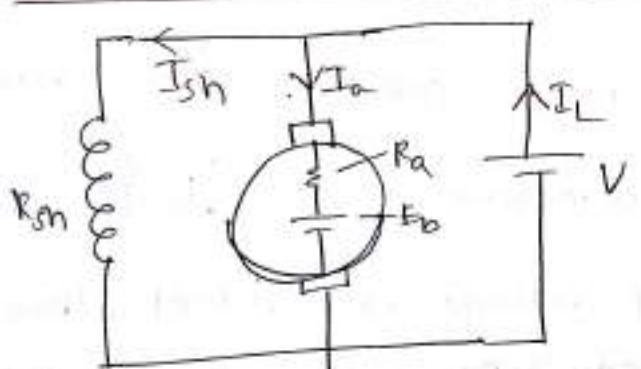
DC motor characteristics

- ① speed vs armature current (N vs I_a)
- ② Torque vs armature current (T_a vs I_a)
- ③ speed vs torque (N vs T_a)

① & ② → electrical characteristics

③ → mechanical characteristics

characteristics of DC shunt motor



$$\phi_a \propto I_{sh} = \frac{V}{R_{sh}} = \text{const.}$$

$$\text{i)} N \propto \frac{E_b}{\phi} \propto \frac{V - I_a R_a}{\phi}$$

$$\text{ii)} T \propto \phi I_a \\ \therefore T \propto I_a$$

- ① Speed (N) vs armature current (I_a)

At No-load, $I_a \approx 0$ $\therefore N \propto V$

- when load increases
→ when mechanical load increases, $I_a \uparrow$, $\therefore N \propto V - I_a R_a$
slightly decrease in speed.
- when load is there, due to armature reaction

$$, \phi \downarrow, N \propto \frac{1}{\phi}$$

- when load increases, E_b & ϕ decrease due to the armature resistance drop ($I_a R_a$) and armature reaction respectively. but E_b decreases slightly more than ϕ so that the speed of the motor decreases slightly with load.

(17)

Note: Never start the shunt motor with ~~load~~
heavy load as heavy starting load will need a
heavy starting current.

③ speed (N) vs torque (T_a) characteristics

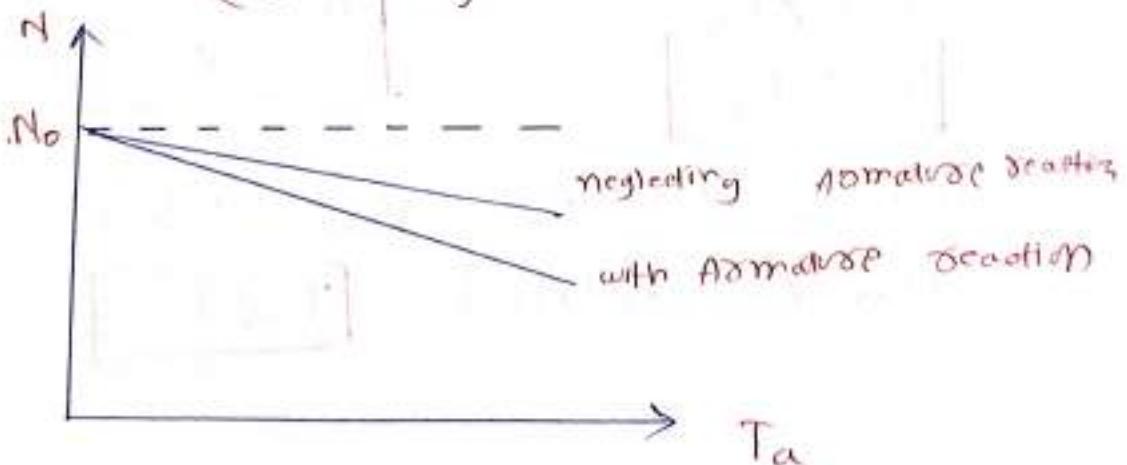
④ AR & saturation neglected, $\phi = \text{const.}$

$$T_a = k_1 \phi I_a \Rightarrow I_a = \frac{T_a}{k_1 \phi}$$

$$\begin{aligned} N &= k_2 \frac{E_b}{\phi} \Rightarrow N = k_2 \left(V - T_a R_a \right) \\ &\Rightarrow N = k_2 \left(V - \frac{T_a}{k_1 \phi} R_a \right) \\ &\Rightarrow N = N_o - \frac{T_a R_a}{(k_1 \phi)^2} \end{aligned}$$

⑤ with AR, $\phi \downarrow$ (slightly)

$$\downarrow N = N_o - \left(\frac{T_a R_a}{(k_1 \phi)^2} \right) \uparrow$$



$$T \propto \phi I_a \quad \therefore \phi = \text{const. in shunt motor}$$

$$T \propto I_a$$

\therefore Shunt motor has low starting torque.

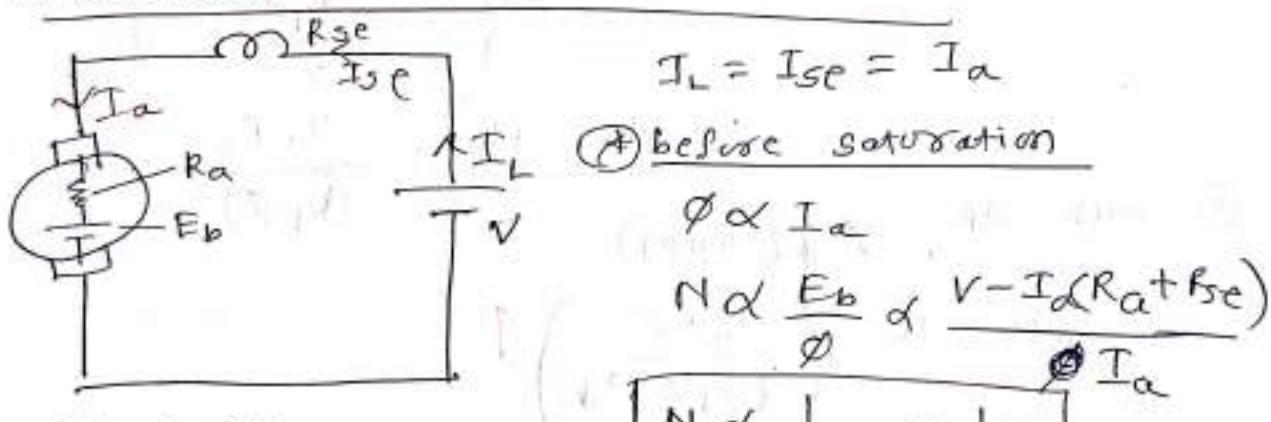
(18)

Application of shunt motor

Fan, centrifugal pumps, lathes, drills, machine shapers, spinning & weaving machine, tools.

Note The direction of rotation of D.C. motor can be reversed either by changing the field terminals or armature terminals but not both. At this condition, if the supply terminals are reversed the motor will rotate in the same direction.

Characteristics of series motor



* After saturation $\Phi = \Phi_{sat} = \text{constant}$

$$N \propto V - I_a(R_a + R_{se})$$

$$T \propto I_a$$

(constant power) on torque $\propto \frac{1}{I_a}$ $\propto \frac{1}{T}$

① Speed (N) vs armature current (I_a)

(1a)

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

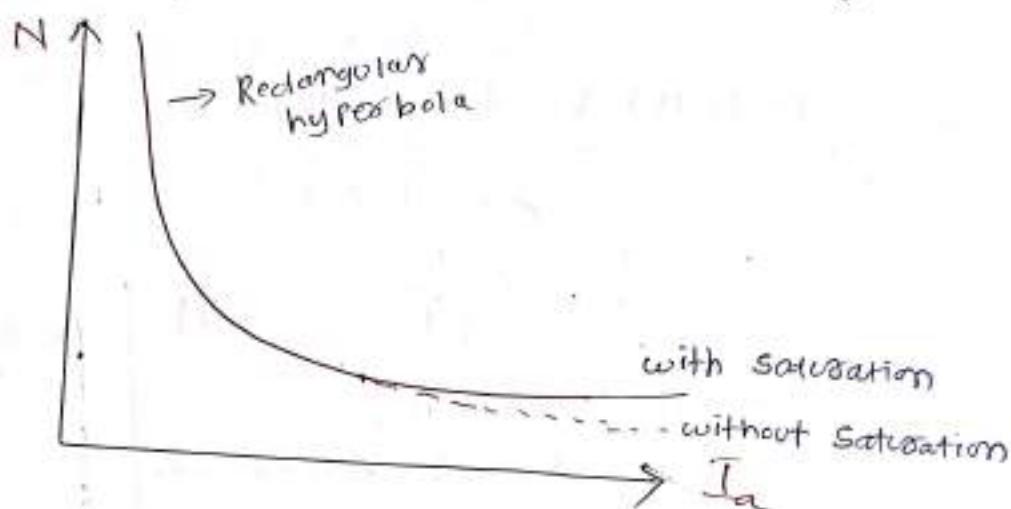
$$E_b = V - I_a(R_a + R_{se})$$

$$N \propto \frac{1}{\phi}$$

The drop $I_a(R_a + R_{se})$ is quite small under normal operating conditions.

$$N \propto \frac{1}{I_a}$$

If $N \propto \frac{1}{I_a \uparrow}$, or $N \propto \frac{1}{I_a \downarrow}$



Note:

∴ Series motor is a Variable Flux machine.

At No-load ($I_a \approx 0$)

$$\boxed{N \propto \frac{1}{I_a \downarrow(0)}}$$

i) No-load speed of DC series motor is dangerously high. So never start DC machine without load.

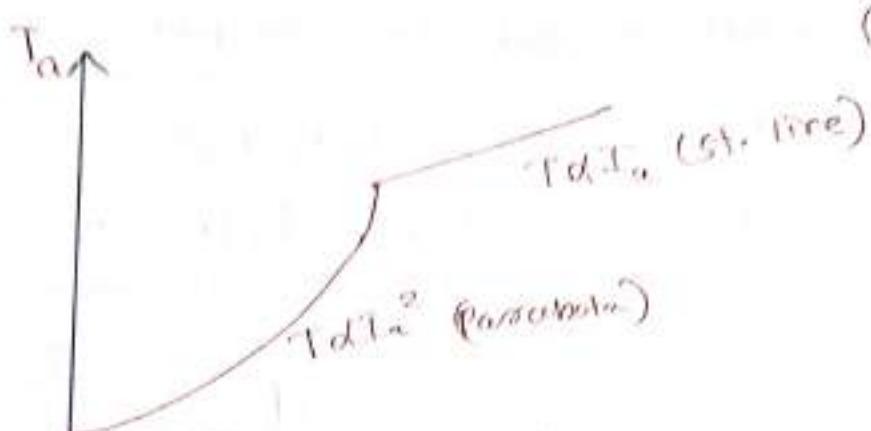
② Torque (T) vs armature current (I_a)

i) $T \propto I_a^2$, before saturation $(\phi \propto I_a)$

↳ characteristic is parabola

ii) $T \propto I_a$, after saturation, ($\phi = \text{constant}$)

↳ characteristics is linear



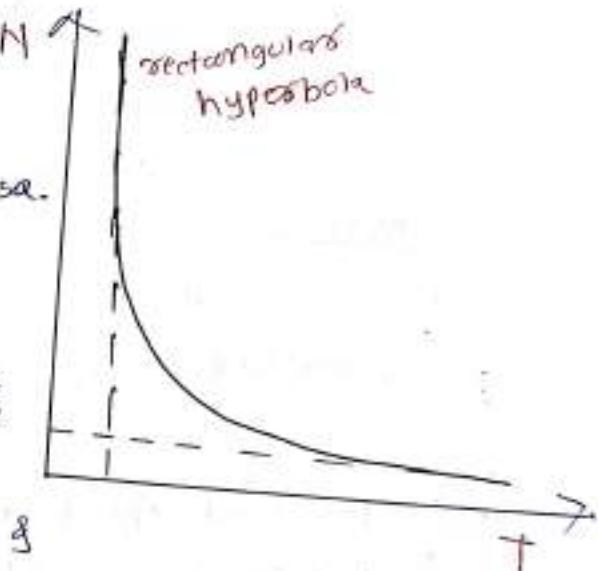
Note

- (3) Speed (N) vs torque (T_a)

In series motor, $T \propto I_a^2 \Rightarrow T_a \propto \sqrt{T}$

$$N \propto \frac{1}{I_a} \propto \frac{1}{\sqrt{T}}$$

when speed is high,
torque is low & vice-versa.



Applications

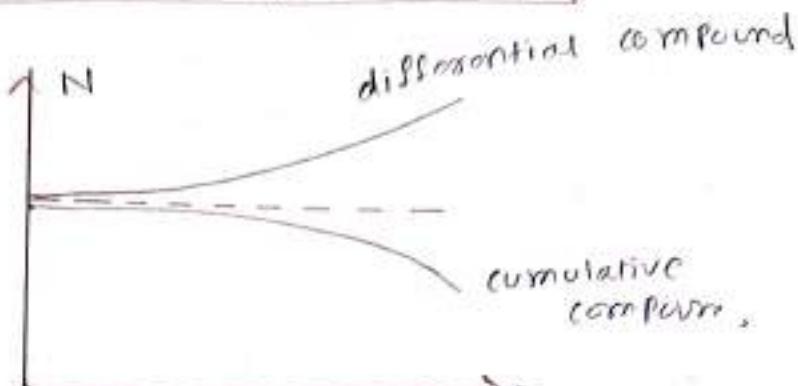
In elevators, air compressors, electric traction, cranes, vacuum cleaners, hair dryers & sewing machine.

Note: Series motor should never be started at No-load condition because it rotates at dangerously high speed. Series motor should be started with some load to keep the speeds within limits. Generally, series motors are connected with permanent load like traction & lifts.

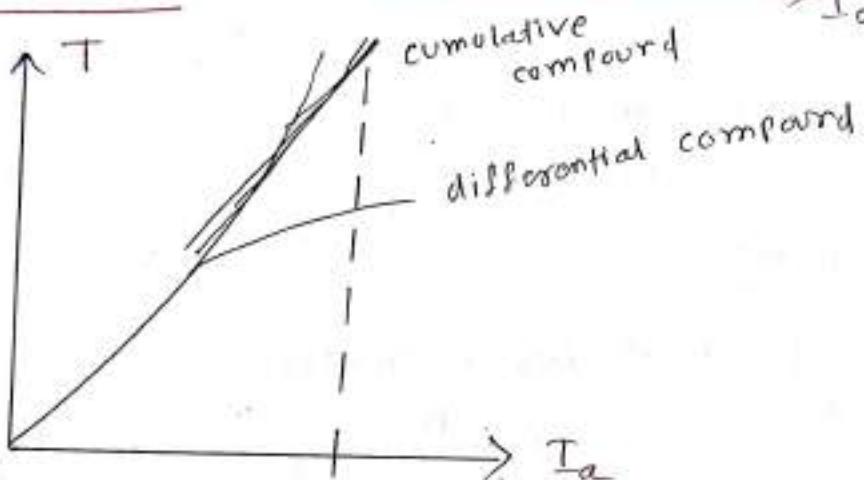
characteristics of D.C. compound motor

(2)

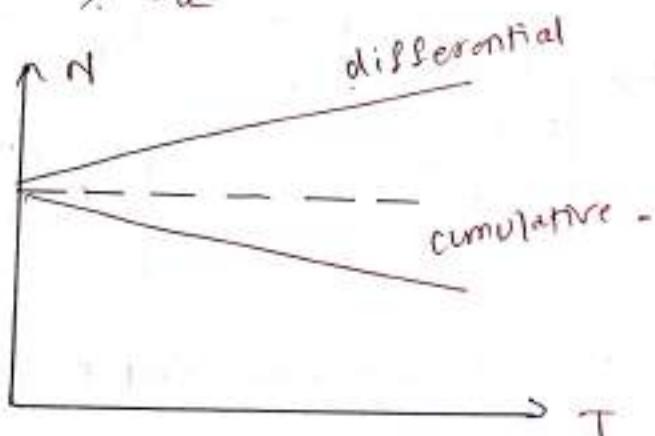
(1) N vs I_a



(2) T vs I_a



(3) N vs T



Application of DC compound motor

cumulative compound

- i) Punching m/c
- ii) drilling m/c
- iii) steel mills
- iv) cement mills
- v) Paper mills

No application for differential compound motor.

Losses & Efficiency

The losses taking place in the motor are the same as in generators. These are

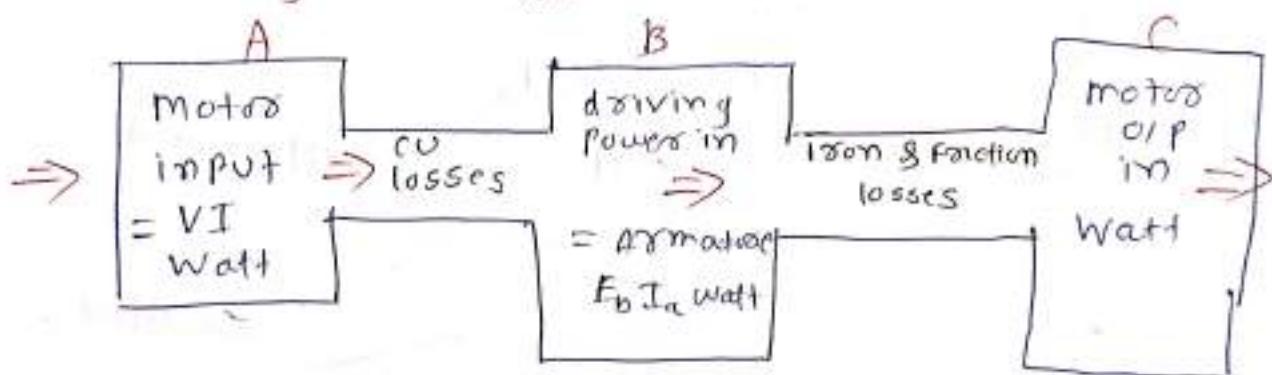
- i) copper losses
- ii) magnetic losses
- iii) mechanical losses

→ The condition for maximum power developed by the motor is $T_a R_a = \frac{V}{2} = F_b$

→ The condition for maximum efficiency is that armature cu. losses are equal to constant losses.

Power stages

Efficiency curve for a motor



$$\text{Overall or commercial efficiency } \eta_c = \frac{C}{A}$$

$$\text{Electrical efficiency, } \eta_e = \frac{B}{A}$$

$$\text{Mechanical efficiency, } \eta_m = \frac{C}{B}$$

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

$$A - B = \text{copper losses}$$

$$B - C = \text{iron \& Friction losses}$$

Speed control of DC Motors

(23)

$$\text{we know that } N = k \frac{E_b}{\phi} = k \left(\frac{V - I_a R_a}{\phi} \right)$$

V = supply voltage

I_a = armature current

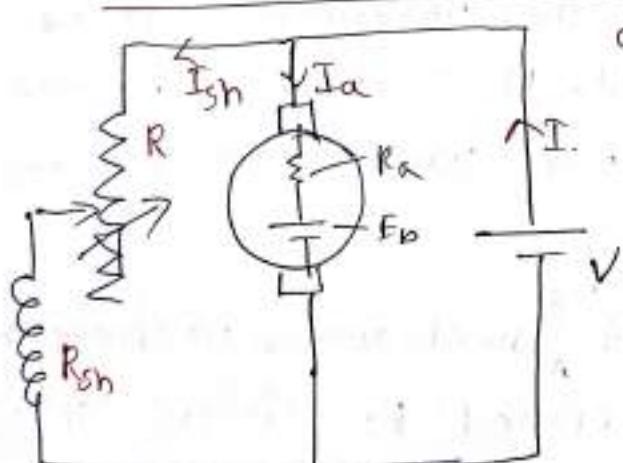
R_a = armature resistance

ϕ = flux/pole

The speed can be controlled by varying

- Flux/pole, ϕ (Flux control method)
- Resistance (R_a) of armature circuit
(Armature or Rheostatic control method)
- applied voltage (V) → Voltage control method

Speed control of shunt motors



a) Flux control method

$$N \propto \frac{1}{\phi}, \quad \phi \downarrow, N \uparrow$$

$$\phi \uparrow, N \downarrow$$

by decreasing the flux,
the speed can be increased
or vice-versa.

→ In this method, a variable resistance (known as Shunt field rheostat) is placed in series with the shunt field winding.

→ The shunt field rheostat reduces the shunt field current I_{sh} & hence the flux (ϕ).

Therefore by varying flux, above rated speeds are possible.

Advantages

- This is an easy & convenient method.
- It is an inexpensive method since very little power is wasted in the Shunt Field Rheostat due to relatively small value of I_{sh} .
- The speed control by this method is independent of load on the machine.

disadvantages

- only speeds higher than the normal speed can be obtained since the total field circuit resistance cannot be reduced below R_{sh} .
- There is a limit to the maximum speed obtainable by this method. It is because if the flux is too much weakened, commutation becomes poor.

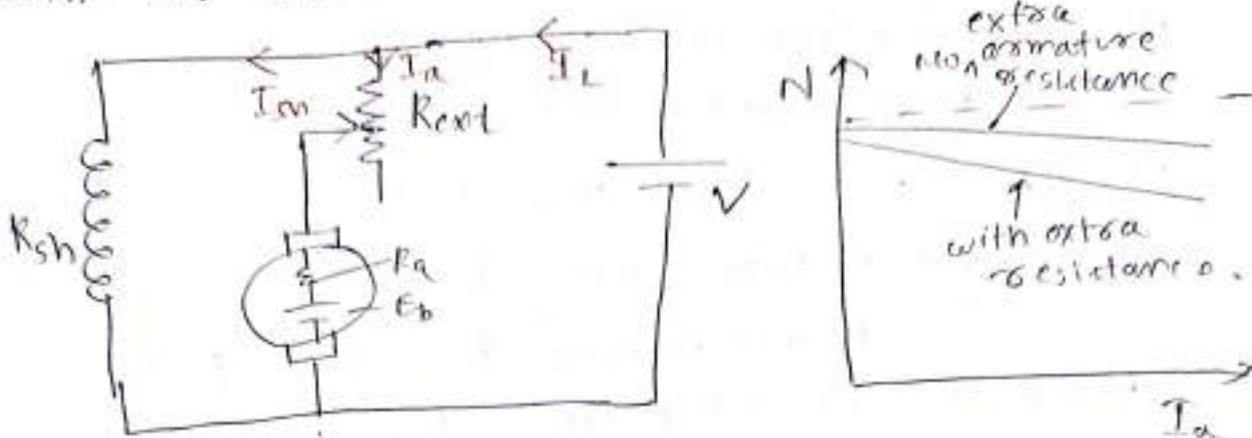
Note: The field of a ^{dc} shunt motor in operation should ~~be~~ never be opened because its speed will increase to an extremely high value.

(2) Armature or Rheostatic control method

This method is used when speeds below the no-load speeds are required. As the supply voltage is normally constant, the voltage across the armature is varied by inserting a variable rheostat or resistance in series

(25)

with the armature circuit.



due to voltage drop in the external resistance,
the back e.m.f is decreased.

disadvantages

- A large amount of power is wasted in the external resistance since it carries full armature current I_a .
- The speed varies widely with load since the speed depends upon the voltage drop in the resistance & hence the armature current demanded by the load.
- The O.P & efficiency of the motor are reduced.
- This method results in poor speed regulation.

due to this disadvantage, this method is rarely used in speed control of dc ^{shunt} motor.

③ Voltage control method

In this 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 & low

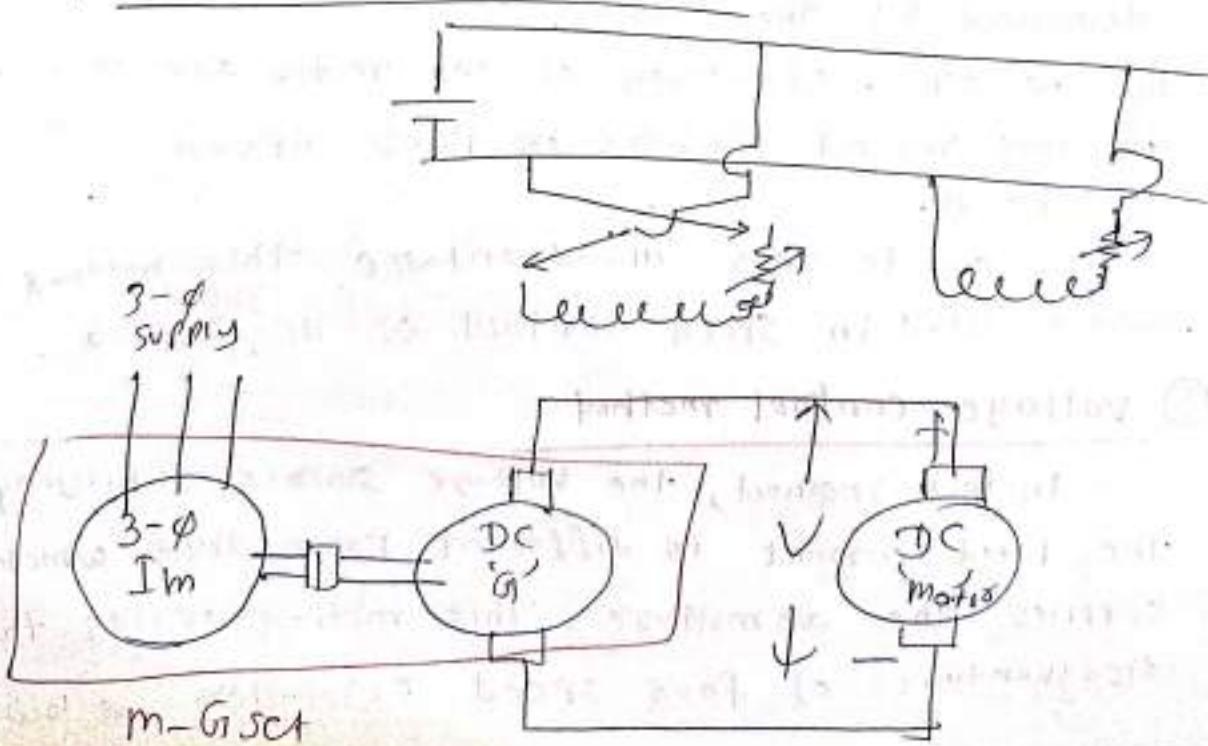
(26)

efficiency as in armature control method. However, it is quite expensive. So, this method of speed control is employed for large size motors whose efficiency is of great importance.

a) multiple voltage control

In this method, 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. In this way, voltage applied across the armature can be changed. The speed will be approximately proportional to the voltage applied across the armature. Intermediate speeds can be obtained by means of a shunt field regulator.

b) Ward - Leonard systems



(Q7)

- This system consists of a DC motor 'm' which is powered by a DC Generator 'G'. In this method the speed of the DC motor is controlled by applying variable voltage across its armature.
- This Variable Voltage is obtained using a motor-generator set consisting of a ~~no~~ 3- ϕ Induction motor (I_m) directly coupled ~~to~~ with the generator, G' .

Principle of Ward Leonard method

- The speed of the motor 'm' is to be controlled which is powered by the Generator G' . The shunt field of the motor 'm' is connected across the DC supply lines.
- Generator G' is driven by the induction motor whose speed is almost constant.
- When the O/P Voltage of the Generator is fed to the motor 'm', then the motor starts to rotate. When the O/P Voltage of the generator varies then speed of the motor also varies.
- Now controlling the O/P voltage of the generator the speed of the motor can also be controlled. For this purpose of controlling the O/P voltage, a field regulator is connected across the generator with the DC supply lines to control the field excitation.

Advantages of Ward Leonard system

(28)

1. It is a very smooth speed control system over a very wide range (from zero to normal speed of the motor)
2. The speed can be controlled in both the direction of rotation of motor easily.
3. The motor can run with uniform acceleration.
4. Speed regulation of DC motor in this system is very good.
5. It has inherent regenerative braking property.

disadvantages of Ward Leonard system

1. The system is very costly because two extra machines (motor-generator) set are required.
2. Overall efficiency of the system is not sufficient especially if it is lightly loaded.
3. Larger size & weight. Requires more floor area.
4. Frequent maintenance.
5. This drive produces frequent noise.

(29)

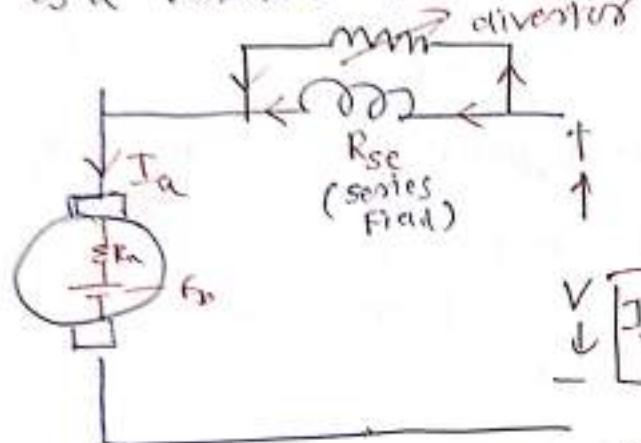
Speed control of DC series motor

a) Flux control method

Variation Φ in the flux of a series motor can be brought about in any of the following ways.

① Field diverter

In this method, the series winding is shunted by a variable resistance.



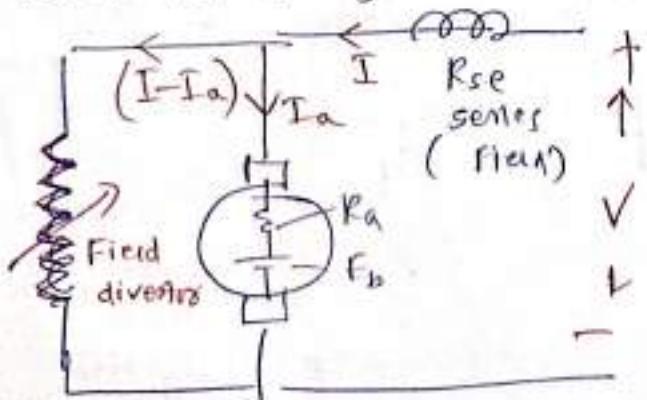
Any desired amount of current can be passed through the diverter by adjusting its resistance.

$$V \downarrow \boxed{I_{se} \downarrow, \Phi \downarrow, N \propto \frac{E_b}{\Phi} \uparrow}$$

Hence the flux can be decreased and consequently the speed of the motor is increased.

② Armature diverter

A diverter across the armature can be used for giving speed lower than normal speeds.



For a given constant load torque, if I_a is reduced due to armature diverter, Φ must increase.

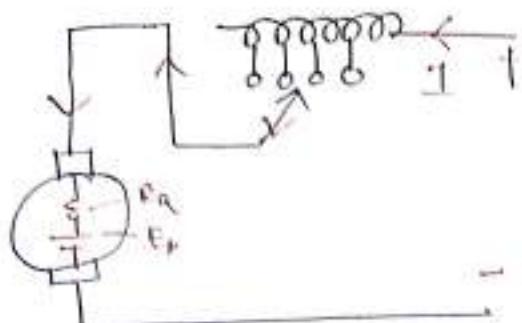
$$T \propto I_a \text{ and } I_a \text{ (const) if } I_a \downarrow, \Phi \uparrow \text{ (must)}$$

$$N \propto \frac{E_b}{\Phi} \uparrow$$

\therefore Hence speed is decrease.

(3)

③ Tapped field control field (Used in electric traction)



→ A no. of Taps are brought outside from the Series field.

→ The no. of Series field turns in the circuit can be changed.

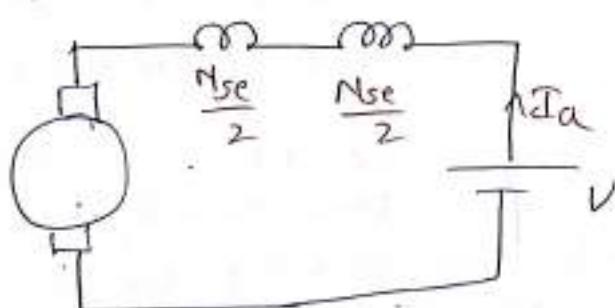
→ To decrease the ampere turns of Field, a No. of turns are shortened.

~~Because~~ No. of turns ↓, $\propto \frac{1}{N} I_a$, $\propto \frac{1}{\Phi}$, $\propto \frac{F_b}{\theta}$

→ with full field, the motor runs at minimum speed which can be raised in steps cutting out some of series turns.

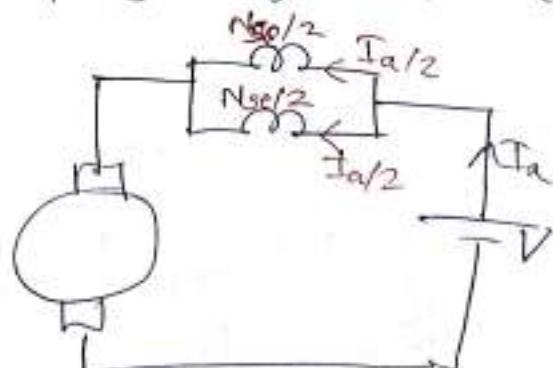
④ paralleling field coils

In this method, used for Fan motors, several speeds can be obtained by regrouping the field coils.



$$AT_{se} = I_a \frac{N_{se}}{2} + I_a \frac{N_{se}}{2} \\ = I_a N_{se}$$

$$N_p = 2 N_{se}$$

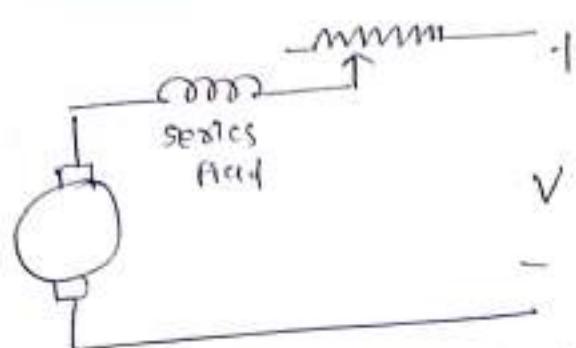


$$AT_p = \frac{I_a N_{se}}{2} + \frac{I_a N_{se}}{2} + \frac{I_a N_{se}}{2}$$

$$AT_p = \frac{I_a N_{se}}{2}$$

N_p , Φ , N ↑

(b) Voltage control method



by increasing the resistance in series with the armature, the voltage applied across the armature terminals can be decreased.

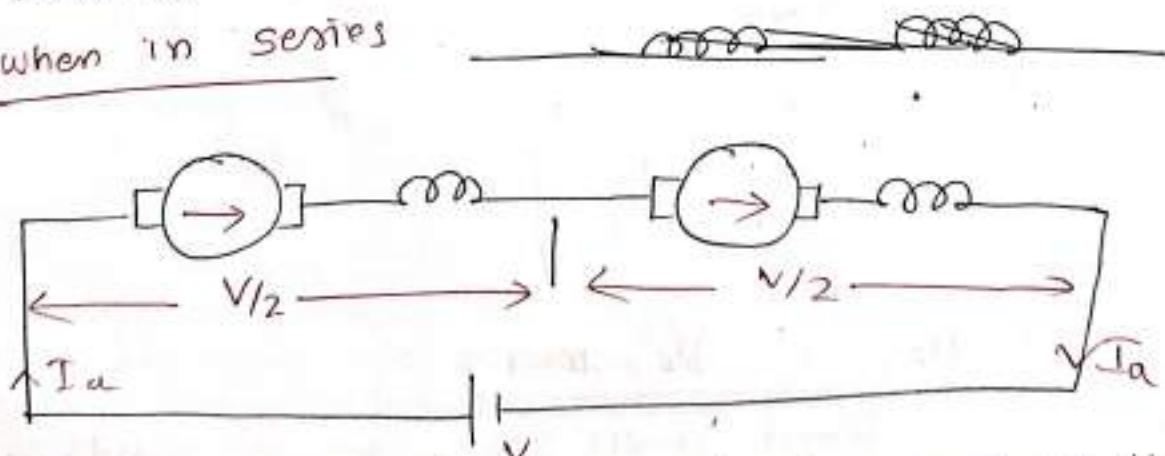
→ with reduced voltage across the armature, the speed is reduced. However, since full motor current passes through this resistance, there is a considerable loss of power in it.

(c) Series-parallel control

→ In this system of speed control, which is widely used in electric traction, two or more similar mechanical coupled series motors are employed.

→ At low speeds the motors are joined in series & for high speeds, motors are joined in parallel.

when in series



when in series, the two motors have the same current (I_a) passing through them, but

(3)

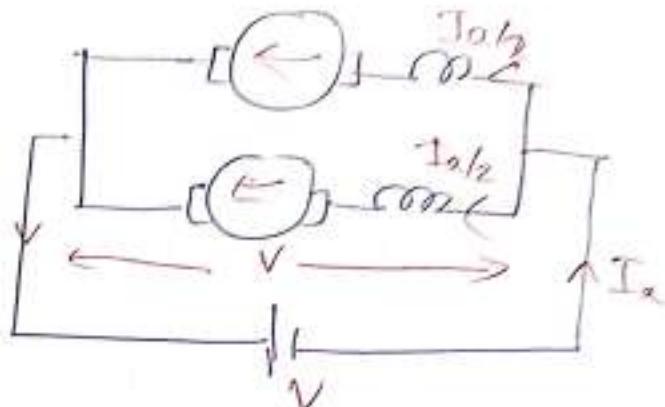
The voltage across each motor is $V/2$. i.e. half the supply voltage.

$$\text{Hence } N_p \propto \frac{E_b}{\phi} \propto \frac{V/2}{I_a} \propto \frac{V}{2I_a} \propto \frac{V}{2I} \quad \text{. (i)}$$

↑ $\propto I_a^2$ (iii)

When in parallel

When joined in parallel, voltage across each machine is V , the current drawn by each motor is $(I_a/2)$.



$$N_p \propto \frac{E_b}{\phi} \propto \frac{V}{(I_a/2)} \propto \frac{2V}{I_a} \propto \frac{2V}{I} \quad \text{. (ii)}$$

$$T_p \propto \left(\frac{I_a}{2}\right)^2 \quad \text{. (iv)}$$

$$\frac{\text{eqn (ii)}}{\text{eqn (i)}} \Rightarrow \frac{N_p}{N_{se}} = \left(\frac{2V/I}{V/2I} \right) = \frac{2V}{I} \times \frac{2I}{V} = 4$$

$$\Rightarrow N_p = 4 N_{se}$$

$$\frac{\text{eqn (iv)}}{\text{eqn (iii)}} \Rightarrow \frac{T_{se}}{T_p} = \frac{(I_a/2)^2}{(I_a)^2} = \frac{I_a^2}{4} \times \frac{1}{I_a^2}$$

$$T_p = \frac{T_{se}}{4}$$

Starting of DC motor

DC motor should never be connected directly across supply because it draws 5-7 times of full-load current at the time of

(33)

starting which can damage the motor.
 → so, starter is used to limit the high starting (I_{st})
 current of a motor & accelerate the motor.

Function of starter in the DC Motor

Necessity of Starter

The motor armature current is given by

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

Where V = Supply voltage ✓

E_b = Back emf and ✓

R_a = Armature resistance ✓

- When the motor is at rest, back emf developed across the armature winding is equal to zero.

- Let us consider a case of 230 V, 5 kW DC motor having armature resistance of 0.5 W and full load current of 27.0 A.

- If this DC motor is directly connected to supply mains, it will draw a starting current of 17 times its full load current.

$$(I_L = 5000 / (230 \times 0.8))$$

$$= 27.17 \text{ Amp}$$

Assume efficiency = 80%

$$I_L = 230 / 0.4$$

$$= 460.0 \text{ Amp}$$

Starting current drawn by motor

$$= 460 / 27.17$$

$$= 17 \text{ times full load current}$$

This excessive current (I) Blow out the fuses (II) Damage the commutator, brushes and also armature winding and (III) Produces large voltage drops in the supply voltage line.

- Therefore the motor must be protected against the flow of excessive current during starting period (say 5 to 10 seconds).
- A high resistance is connected in series with the armature winding in order to protect the motor which limit the starting current to a safe value.
- The starting resistance is gradually cut out as the motor gains speed and develops the back emf. As the motor attains its normal speed, additional resistance from the armature circuit is totally disconnected.

What is happened when the additional external resistance does not disconnect from the armature circuit?

- Large loss of power resulting in reduction efficiency
- Reduces the speed of the motor

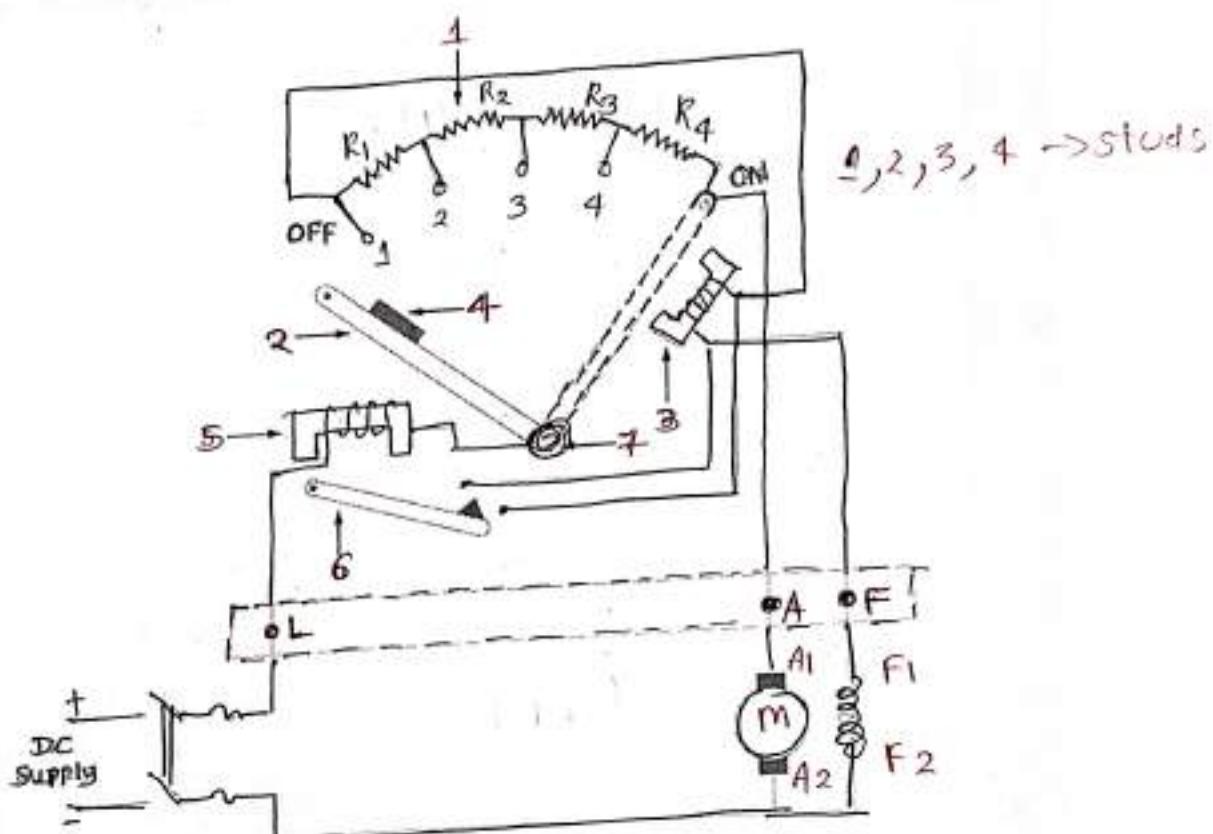
Why Fractional kW (Small) motors do not require any starter at starting ?

- The fraction HP motor does not require starter during starting because
- The resistance and inductance of small motors are sufficiently large to
- Limit the excessive current during starting
- Due to low moment of inertia it speeds up quickly.

Three Point Starter ✓

- The internal wiring diagram for such a starter is shown in the Figure A.
- It consists of starting resistance divided into several sections, holding coil (or NO volt release), overload release, brass arc and soft iron piece attached to starter arm.
- As there are three terminals (L – Supply line, F – Field, A – armature) available in the starter, it is called as three point starter.
- The positive supply terminal is connected to starter arm through path line terminal (L) and overload release.

- The negative supply terminal is connected to one end of the field winding and armature winding.
 - One end of the field winding is connected to brass arc through holding coil. One end of the armature winding is connected to starting resistance's last stud.
 - A spring is placed over the lever of the starter arm.



1. STARTING RESISTANCE	5. OVERLOAD RELAY / OLR
2. STARTING GARD / STARTER HANDLE	6. ARMATURE / lever
3. NVC (HOLD - ON COIL)	7. SPRING
4. SOFT IRON PIECE	L - LINE
A - ARMATURE OF MOTOR	F - FIELD WINDING

FIG A : THREE POINT STARTER OF DC SHUNT MOTOR

NVC → No-volt coil
OLR → over-load release

Operation

- The main switch is closed to start the DC motor and this will result in starting arm moves from left side to the right side.
- As soon as the starting arm makes contact with first stud, the field winding is directly connected to supply line through brass arc and whole of the starting resistance (R_s) is placed in series with the armature.
- As the starting arm is further moved to right side, the starting resistance is cut out in steps,.....and finally entire starting resistance is cut out.

Hold on coil or NO volt release (OLVc)

- As soon as the starter arm reaches the last stud, it is held against spring tension by attraction force between holding coil magnet and soft iron piece attached to the starter arm.
- The coil of NO volt release is connected in series with the field winding.
- When the supply fails / gets disconnected or break in the field winding, the holding coil is de-energized and so releases the starting arm which go back to OFF position (or first stud) due to spring tension.
- As a result motor gets disconnected from the supply mains.

Overload Release coil (OLR)

- It is connected in series with the supply line to protect the motor against overload.
- When the motor is overload, overload release coil is magnetize and it lifts the armature to the upward and short circuit the No volt release coil as shown in the figure A.
- As soon as the NO volt coil is short circuited, it demagnetized and releases the starting arm from 'ON' position.
- Therefore the motor is disconnected from the supply and protected against overload.
- The speed control of the DC shunt motor is achieved by connecting a variable resistance is in series with the field winding as shown in the Figure B.

- The speed of the DC shunt motor can be increased by weakening the field flux.
- The variation in the field flux is achieved by variable field resistance (R).
- There is limitation of field rheostat in order to achieve high speed if the field rheostat cuts too much rheostat.
- Too much weaken of field flux demagnetize the NO volt coil and thus starter arm moves from ON to OFF position consequently motor is shut down. Therefore the three point starter is not suitable for speed control.

Four Point Starter

- Figure B shows a four point starter with internal wiring diagram of a long shunt compound motor
- It will be noticed that NO volt coil has been taken out of the shunt field winding and has been connected directly across the supply line through a protecting resistance (R).
- When the starting arm touches first stud, the line current divides into three parts.

(I) One part through starting resistance, series field and armature winding.

(II) Second part passes through field rheostat and field winding.

(III) Third part passes through no volt coil and protecting resistance.

• It should be noted that any change of current in shunt field does not affect the function of the holding coil or NO volt coil.

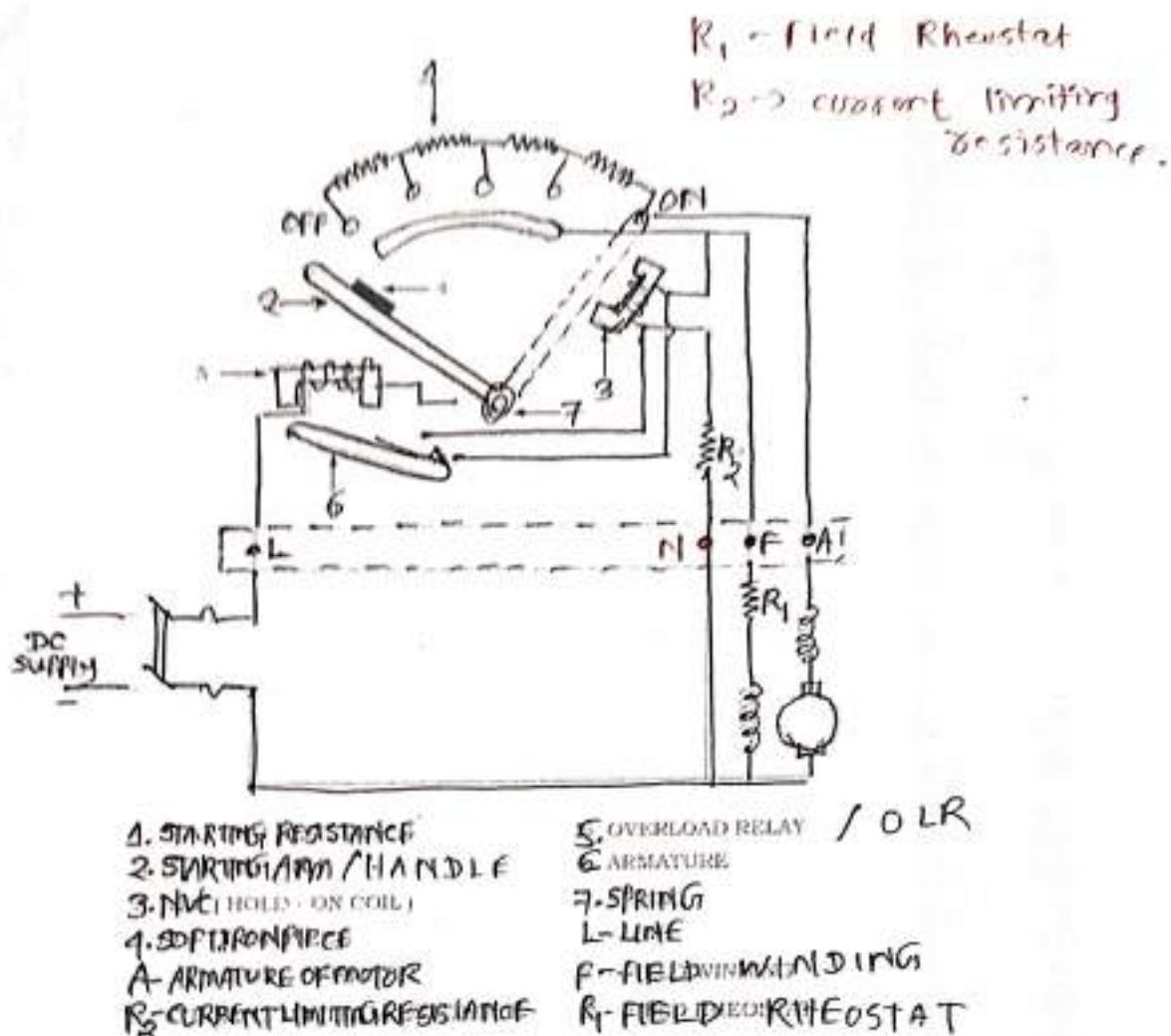


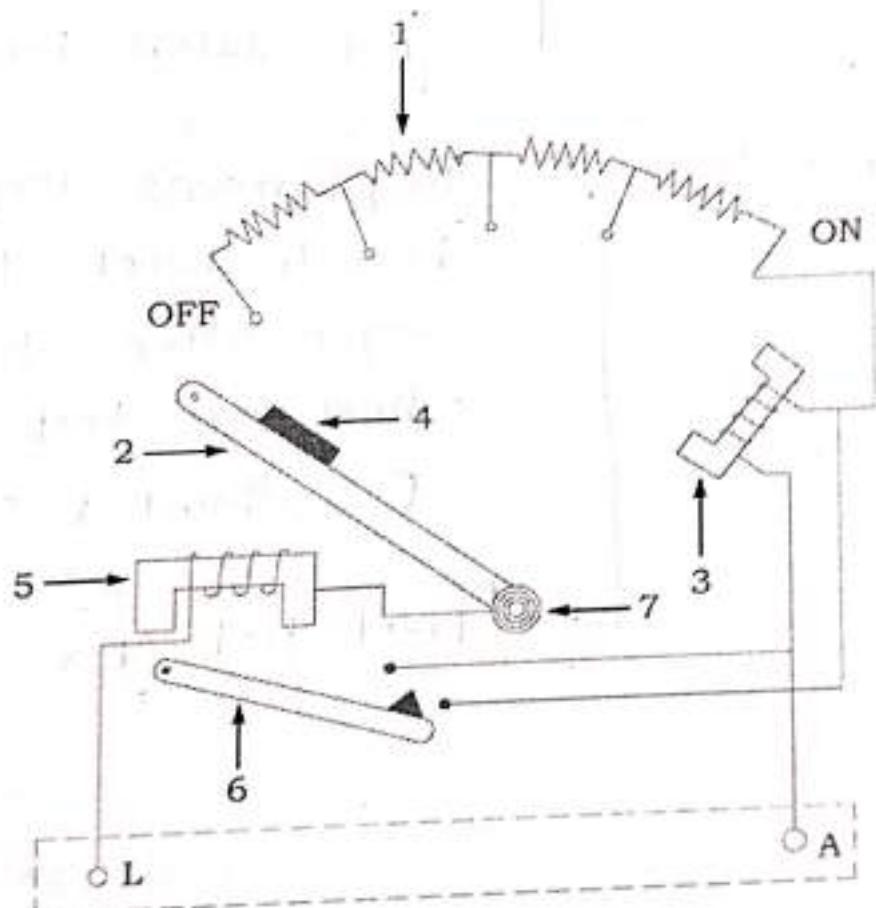
FIG B : FOUR POINT STARTER CONNECTION
DIAGRAM : LONG SHUNT COMPOUND MOTOR

$N \rightarrow$ connected to NVC
 NVC \rightarrow NO Volt coil
 OLR \rightarrow over load - release .

SERIES MOTOR STARTER

- Figure C shows a two point starter for DC series motor.
- The positive terminal is connected to starter arm through overload release and negative terminal is connected to armature of the DC series motor.
- The function of the NO volt coil and overload release is similar to that of we discussed in three point starter.

- The Operation of a two point starter is similar to that of three point starter but there is one important difference that the flux does not remain constant in the DC series motor but varies with the armature current.
- Therefore the back emf at any given speed depends on the current variation between upper limit and lower limits.
- As a result a series motor starter has a smaller numbers of steps than that of a shunt motor of the same rating with same upper and lower current limits.



1 STARTING RESISTANCE
 2 STARTING ARM
 3 NVC (HOLD - ON COIL)
 4 SOFT IRON PIECE
 A - ARMATURE TERMINAL

5 OVERLOAD RELAY
 6 ARMATURE
 7 SPRING
 L - LINE

FIG C : SERIES MOTOR STARTER

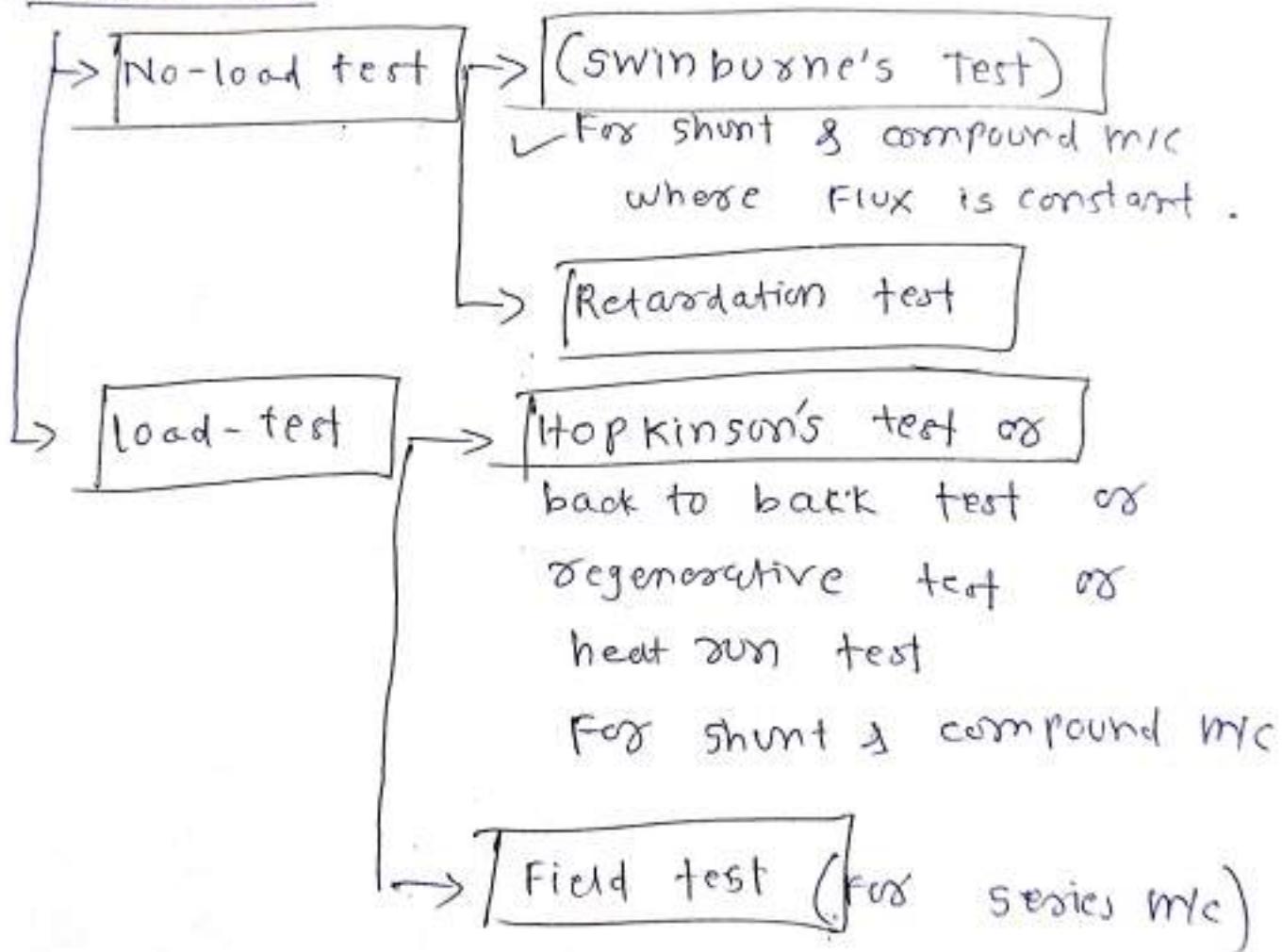
Testing of DC Machine

(10)

i) direct test

↳ Brake test → conducted for all machines up to 5HP or 5kW (small m/c)

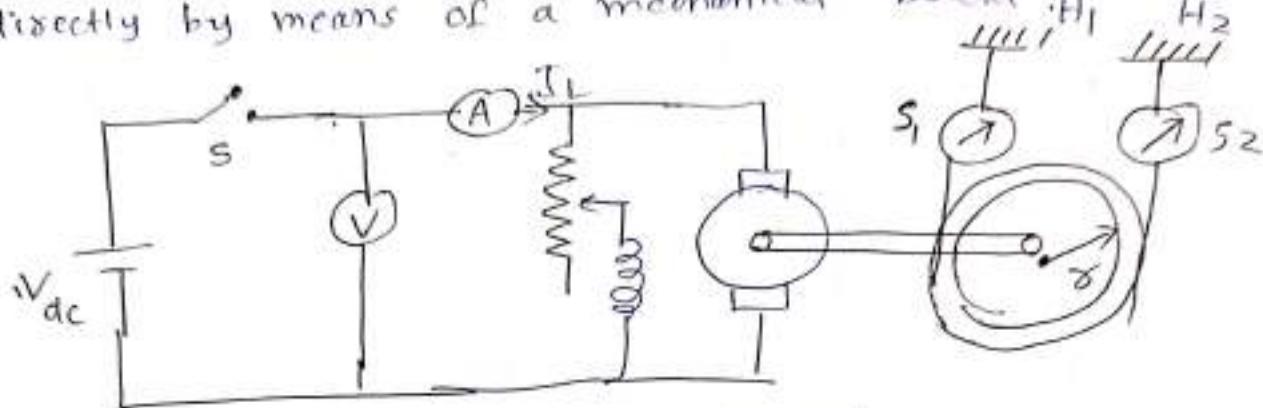
ii) indirect test



(41)

Brake Test (load test)

To determine directly the efficiency of comparatively small motors, the motor is loaded directly by means of a mechanical brake.

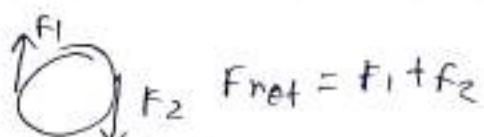
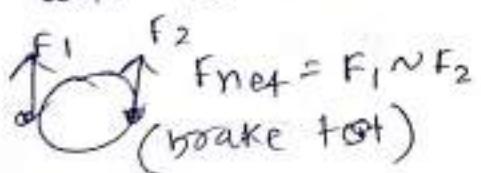


$S_1, S_2 \rightarrow$ spring balance in kg-wt.

$H_1, H_2 \rightarrow$ belt tightening wheel

$\gamma \rightarrow$ effective radius of pulley

→ A rope is wound round the pulley & its two ends are attached to two spring balances S_1 & S_2 . The tension on the rope can be adjusted with the swivels.



The force acting tangentially on the pulley is equal to the difference b/w the readings of the two spring balances.

$$F = (S_1 - S_2) \text{ kg-wt}$$

$$F = 9.81 (S_1 - S_2) \text{ Newton}$$

$$\text{Torque at the pulley is } T_{sh} = F \gamma \\ = 9.81 (S_1 - S_2) \gamma \text{ N-m}$$

$\omega = 2\pi N$ = angular velocity of pulley

then motor o/p = $P_{out} = \omega T_{sh}$

$$= 2\pi N (S_1 - S_2) \propto m \cdot g \cdot \omega t$$

$$P_{out} = 9.81 (S_1 - S_2) \propto (2\pi N) \frac{\text{Kgwt}}{\text{Watt}}$$

$$P_{out} = VI_L$$

$$\gamma. \eta = \frac{P_{out}}{P_{in}} \times 100$$

$$\boxed{\gamma. \eta = \frac{9.81 \times (S_1 - S_2) 2\pi N}{VI_L} \times 100}$$

The entire power is wasted in form of frictional losses. Therefore testing is costly.

disadvantage

This method can't be used for determining internal losses & efficiency of a large machine.

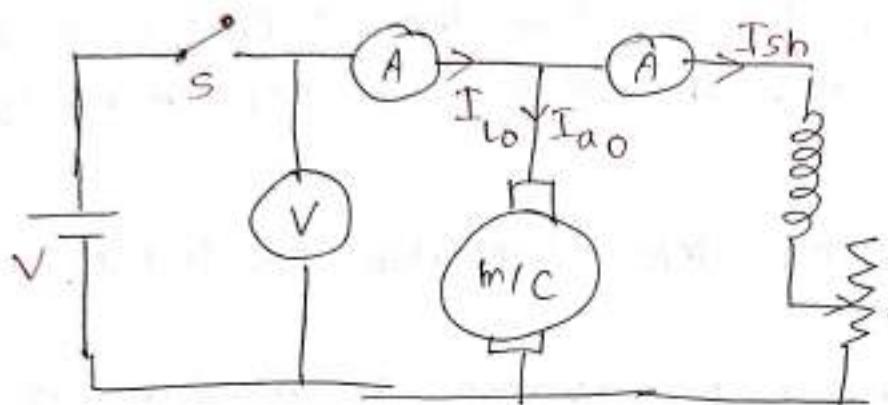
Swinburne's test (No-load test)

This method consists ~~in~~ in measuring the losses & then calculating the efficiency. So this test is indirect test.

(since this is no load test, it is not suitable for series motors because under no-load condition it rotates with dangerously high speed).

- This test is suitable for constant flux machine (Shunt & compound).
- The machine will be operated as a motor although it is a generator.

The machine is operated under No-load condition. Therefore the constant losses are measured and with the knowledge of constant losses, the efficiency can be predetermined at any desired load condition.



Rated No-load rotational losses are obtained from this test.

$$P_{in} = P_{out} + \text{losses}$$

$\hookrightarrow (P_{out} = 0, \text{ under No-load cond'n})$

$$VI_{L0} = 0 + \text{losses} \Rightarrow VI_{L0} = \text{losses} (\text{i.e. core loss} + \text{constant loss})$$

$$\Rightarrow VI_{L0} = I_{ao}^2 R_a + W_c$$

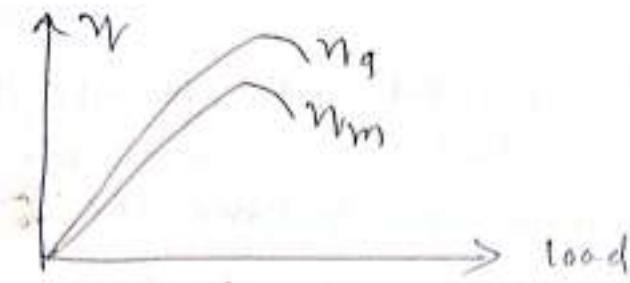
$$\Rightarrow \boxed{W_c = VI_{L0} - I_{ao}^2 R_a}$$

For generator

$$\eta_g = \frac{P_{out}}{P_{in}} = \frac{VI_L}{VI_L + I_a^2 R_a + W_c}$$

For motor

$$\begin{aligned} \eta_m &= \frac{P_{out}}{P_{in}} = \frac{P_{in} - \text{losses}}{P_{in}} \\ &= \frac{VI_L - I_a^2 R_a - W_c}{VI_L} \end{aligned}$$



Advantages

1. The power drawn from the supply is only to meet the losses. Therefore the experiment is economical.
2. Large rating m/c can also be tested.

disadvantages

The actual performance of machine is not verified, means temp. rise is not verified, commutation is not verified, stray load losses are not considered.

So efficiency is not accurate.

(v)

Starting of DC motor

DC motor should never be connected directly across supply because it draws 5-7 times of full load current at the time of starting which can damage the motor.

Necessity of DC motor starter

- At the time of starting, the motor is at stationary (i.e. $N=0$), we know that $E_b \propto N$ so $E_b=0$, so there is no back emf in the armature.

$$I_a = \frac{(V - E_b)}{R_a} \text{ i.e. } I_a \uparrow = \frac{V \uparrow}{R_a \rightarrow \text{constant}} \\ (\text{very small})$$

- Hence armature draws very heavy current as the armature resistance is very small. This high starting current may

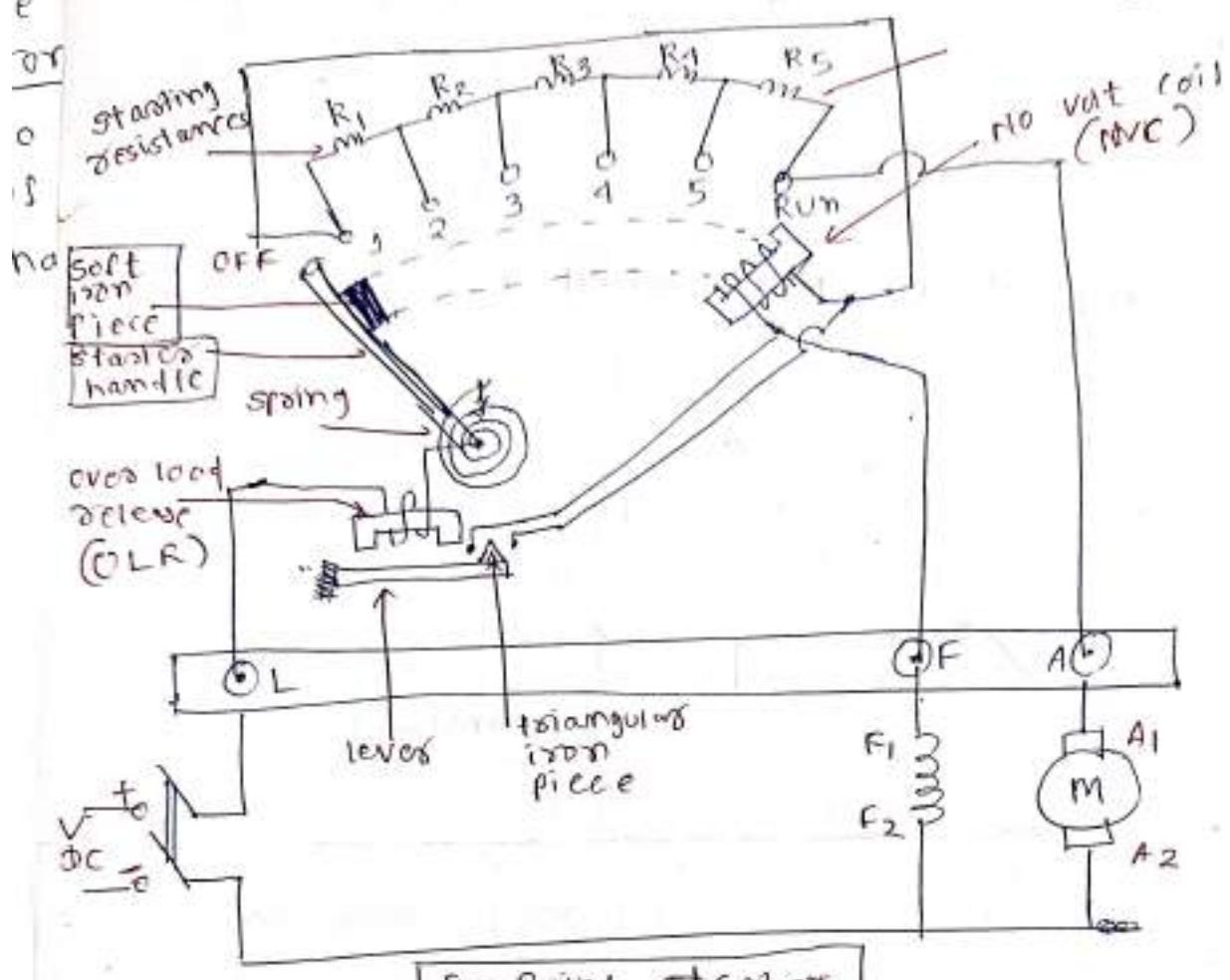
- i) burn the armature due to excessive heating.
- ii) damage the commutator & brushes due to heavy sparking
- iii) excessive voltage drop in the line to which the motor is connected.

- Hence starters (series resistances) are used to limit the high starting current into a safe value and gradually it is reduced as speed gains of the motor.

Types of DC motor starters

- ① 3-point starter
- ② 4-point starter

3-Point starter (used in DC shunt motor & DC compound motor) ②



construction:

- In this diagram of a three-point starter for a shunt motor with protective devices. It is called a 3-point starter because it has 3 terminals L, E & A i.e. Line, Field & Ammeter.
- The contact points 1, 2, 3, 4, 5 are sections of a variable resistance called studs.
- 'L' is connected to an electromagnet called overload release (OLR). The other end of OLR is connected to the lower end of conducting lever of starter handle where spring is attached.

③

The starter handle also contains a soft iron piece housed on it. This handle is free to move to the other side & run against the force of the spring. The spring brings back the handle to its original position OFF under the influence of its own force.

→ Another parallel path is derived from the stud '1' given to another electromagnet called No-volt coil (NVC) which is further connected to terminal 'F'. The starting resistance at starting is entirely in series with the armature. The OLR & NVC act as the two protecting devices of the starter.

Working

i) To start the motor, supply is switched on & the handle is in the OFF position. Then handle is slowly moved to stud no. '1'. At this point, field winding of the ~~short~~ motor gets supply through the parallel path provided to stud '1'. Through NVC. Here the entire series resistance comes in contact with the armature. Hence it limits the high starting current.

ii) As the handle is moved further, it goes on making contact with studs 2, 3, 4 etc thus gradually cutting off the series resistance from the armature circuit as the motor gains speed. At 'run' position the entire starting resistance is eliminated & it stays at that position till the motor is running & back emf develops fully.

Protective devices used in starters

①

(i) No-volt release coil (NVC)

- i) The soft-iron piece connected to the handle gets attracted by the magnetic force developed by NVC as it has been magnetised by field current.
- ii) thus NVC holds the handle in 'RUN' position against spring force till the supply is on. When supply is cut-off, NVC is demagnetised & can't hold the handle in RUN position. Hence it Handle returns to OFF position.
~~Hence it~~ If it would have stayed in RUN position & suddenly power is restored then there will be no starting resistances, resulting in excessive armature current. Hence NVC ~~protects~~ protects the motor.

(ii) over load release (OLR)

- i) If the motor is over-loaded, it will draw excessive current from supply. This will draw extra armature current & hence attracting power of the electromagnet increases, then the moveable arm is lifted & this short circuits the electromagnet! Hence the arm is released & returns to ~~safe~~ OFF position. Hence motor is protected from overload.

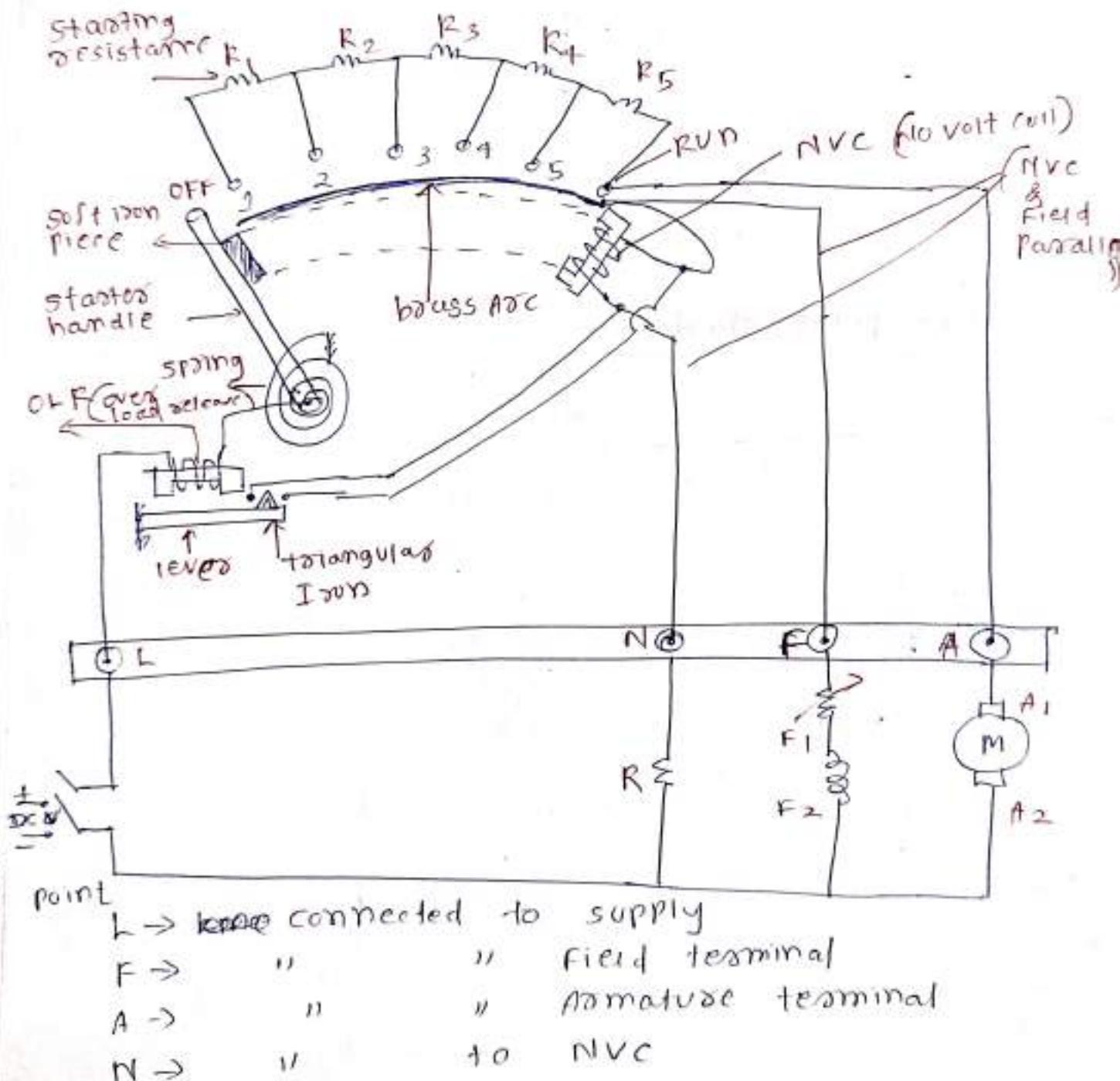
Drawbacks of 3-point starter

- i) While exercising the field control through field regulator, the field current may be weakened to such a low value that NVC may not be

(5)

able to keep the starter arm in the ON position. This may disconnect the motor from the supply when it is not desired. This drawback is overcome in the 4-point starter.

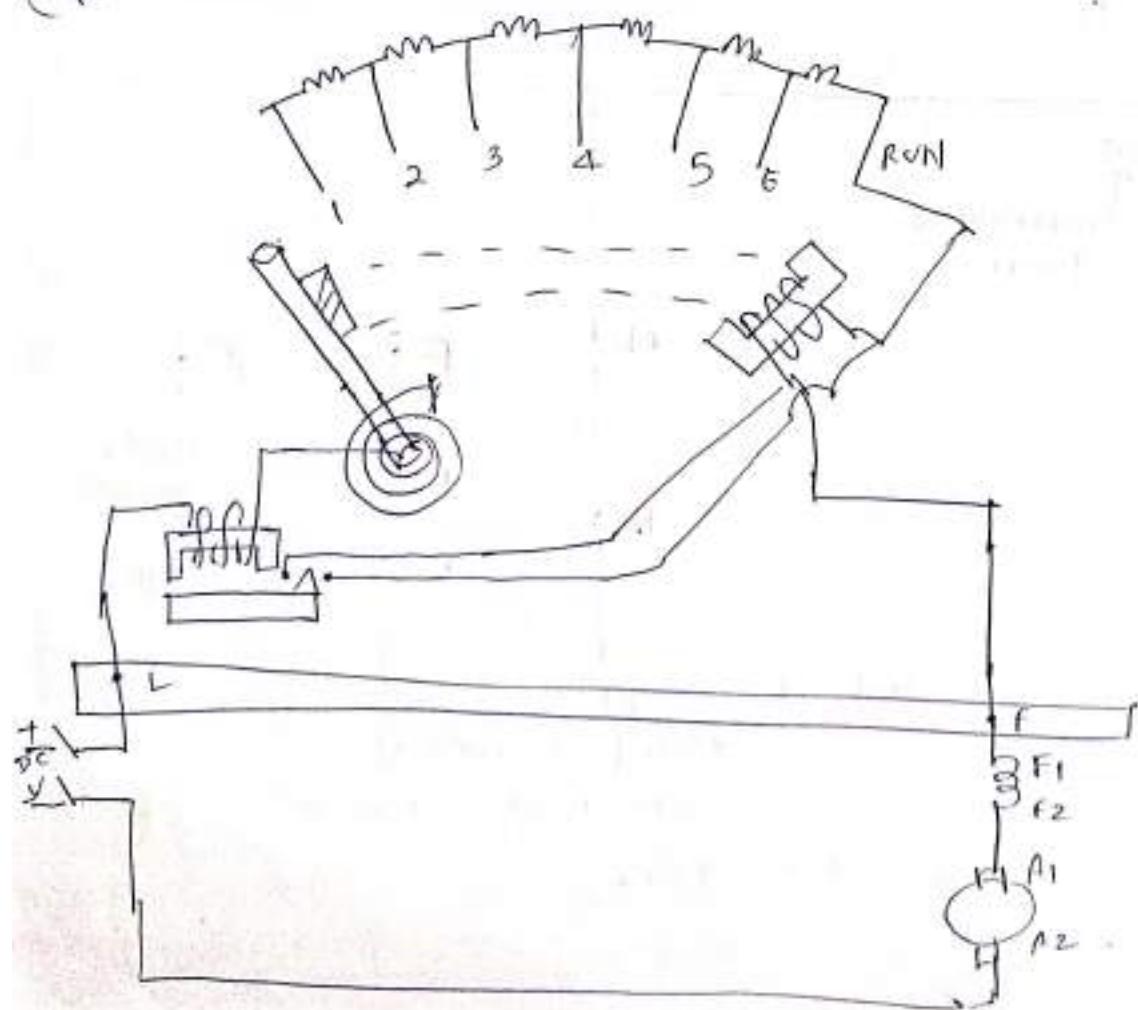
4 Point starters : (Used in DC shunt motors & DC compound motors)



(6)

- Here NVC is connected directly across the supply through fourth terminal called 'N'. Hence any change in field current will not bring any difference in the performance of NVC. Hence NVC always produces a force which is strong enough to hold the handle in its own position, against the closing force.
- The working of both 3-point & 4-point starters is the same. The 3-point starter ckt provides protection against an open field ckt but this is not available in 4-point starter.

(Not for DC motor) → used for ^{DC} series motor only



Single phase transformer

①

→ The transformer is a static device that transfers electrical energy from one electrical circuit to another electrical circuit through the medium of magnetic field and without change in frequency.

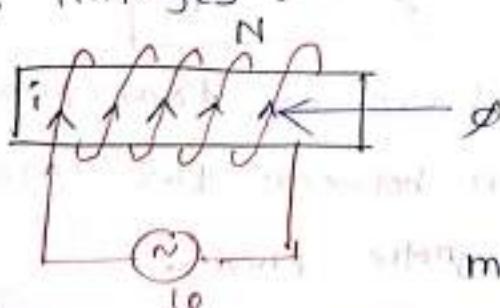
② As transformer doesn't change the frequency of the system, it can be treated as constant frequency device.

Working Principle

→ The transformer works based on "Faraday's law of electromagnetic induction".

→ According to Faraday's law, whenever there is a relative time variation between magnetic field and set of conductors statically induced e.m.f will be induced in the conductors.

→ According to Faraday's second law magnitude of statically induced e.m.f is equal to rate of change of flux linkages.



Let $N = \text{No. of turns in a coil}$
 $i = I_m \sin(\omega t)$

$$\text{mmf} = Ni$$

$$\text{Flux} = \frac{\text{mmf}}{\text{Reluctance}} = \frac{NI_m \sin(\omega t)}{\mu} = NI_m \sin(\omega t)$$

(2)

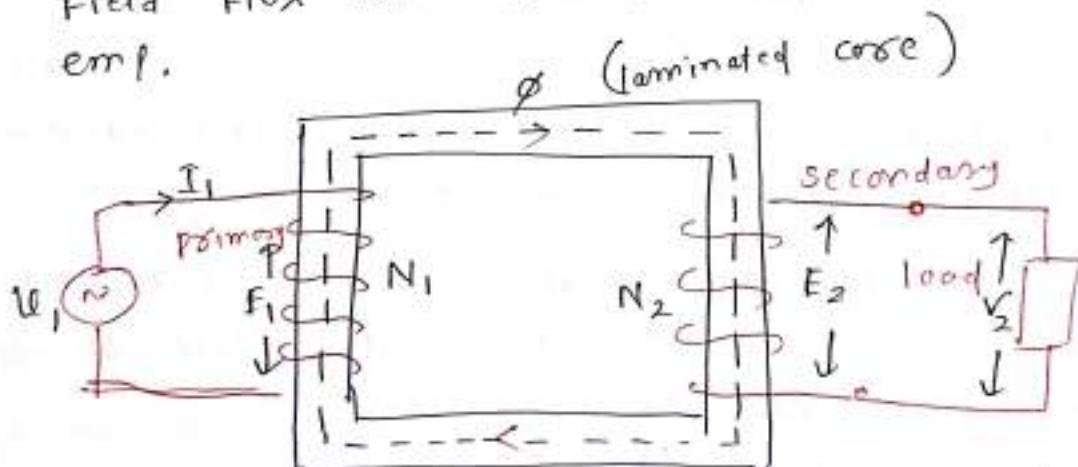
$$\text{FLUX } (\phi) = \rho_m \text{ area} \quad \rho_m = \frac{N I m}{S}$$

$N\phi$ = Flux linkages

$$E_s = \frac{d}{dt} (N\phi) \quad \boxed{F_s = -N \frac{d\phi}{dt}}$$

'-' sign represents direction of statically induced emf & it can be found by Lenz's law.

Lenz's law The direction of statically induced emf is such that the current due to this emf will flow through a closed circuit in such a direction that in turn it produce some flux & this flux must oppose the changes in main field flux which is the cause for production of emf.



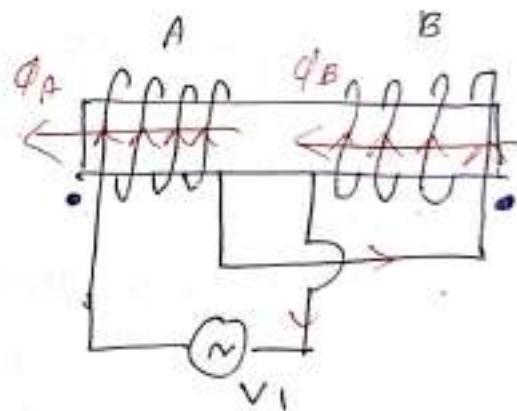
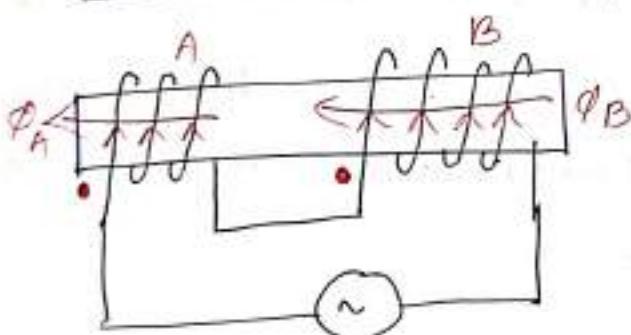
- The physical basis of transformer is mutual induction between two circuits linked by a common magnetic flux.
- two inductive coils are electrically separated but magnetically linked through path of low reluctance

(3)

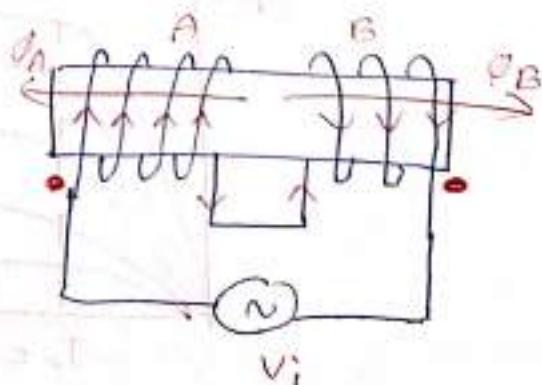
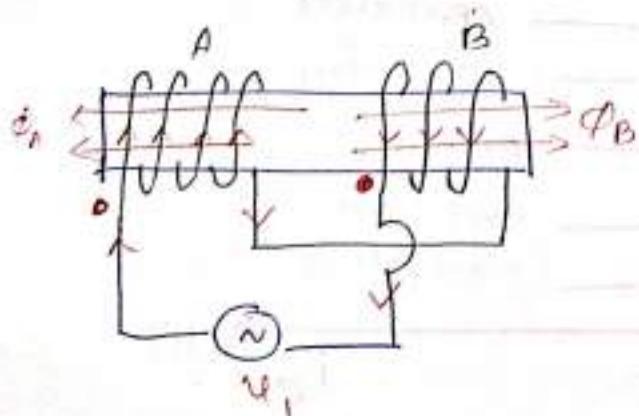
- When an alternating voltage V_1 is applied to the primary, an alternating flux (ϕ) sets up in the core, most of which linked with the other coil in which it produces mutually induced e.m.f (according to Faraday's laws of electromagnetic induction $e = M \frac{di}{dt}$)
- The alternating flux links both the windings & induces e.m.f E_1 & E_2 in Primary & Secondary respectively.

Types of magnetic coupling

① Positive coupling



② Negative coupling

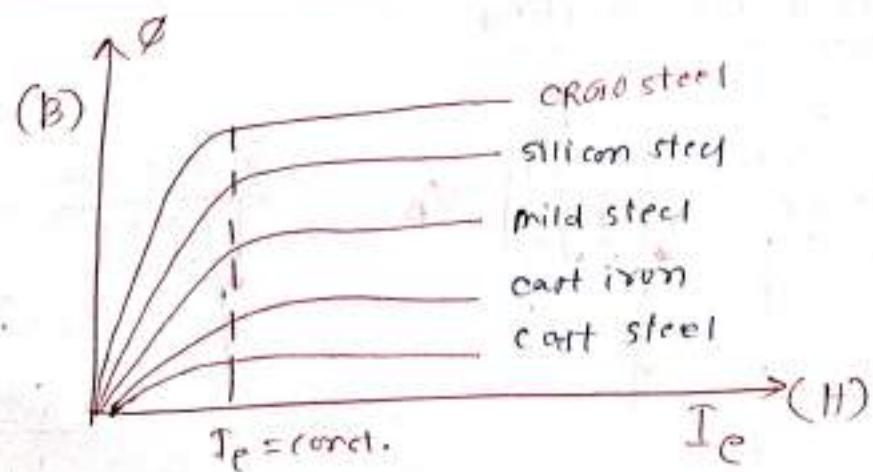


- ①
- The two coils are said to be Positively coupled, if the flux produced by two coils aiding one another in the magnetic circuit.
 - The two coils are said to be Negatively coupled, if the flux produced by two coils oppose one another in the magnetic circuit.

Transformer core

- The basic material used for making transformer core is silicon steel. silicon steel is a ferro-magnetic material. It has high permeability (μ) & low reluctance to flow & low hysteresis coefficient.
- Overall permeability of ~~steel~~^{Silicon} steel is increased by a process called "cold rolling grain orientation". The resulting steel is known as CRGO steel.
- As permeability of CRGO steel is higher than silicon steel, the transformer core is generally made of CRGO steel.

Magnetisation curve



Characteristics of Laminations

(1)

with CRGO steel higher flux densities can be achieved, so that size & weight of the transformer can be reduced.

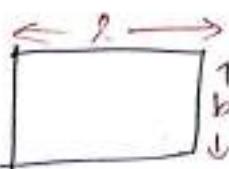
Importance of Laminations

Transformer core is generally made of thin strips called laminations to reduce eddy current loss.
Insulating material used

1. Oxide paint (Red oxide)
2. Inorganic Paints
3. Thin impregnated Paper

→ Gross cross section area of the core =
Area occupied by magnetic material +
Area occupied by insulating material

→ Net cross section of Area of the core = Area
occupied by only magnetic material



$$A_g = l \times b$$

$$\Phi = BA_n$$

A_n = net cross sectional area

Gating Factor (or) Iron Factor

$$k_s = \frac{\text{Net cross sectional area of core}}{\text{Gross cross sectional area of core}}$$

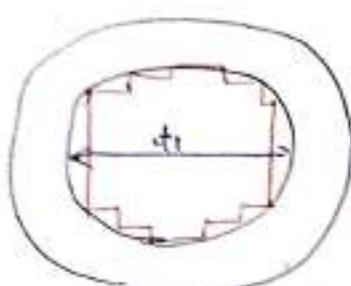
$$k_s = \frac{A_n}{A_{gross}} \Rightarrow A_{net} = k_s \times A_{gross}$$

Note The process of bunching of all laminations is called core staggering.

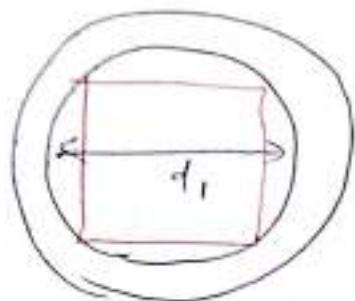
(G)

Note

The cross section of transformer core is made of steps instead of square shape.

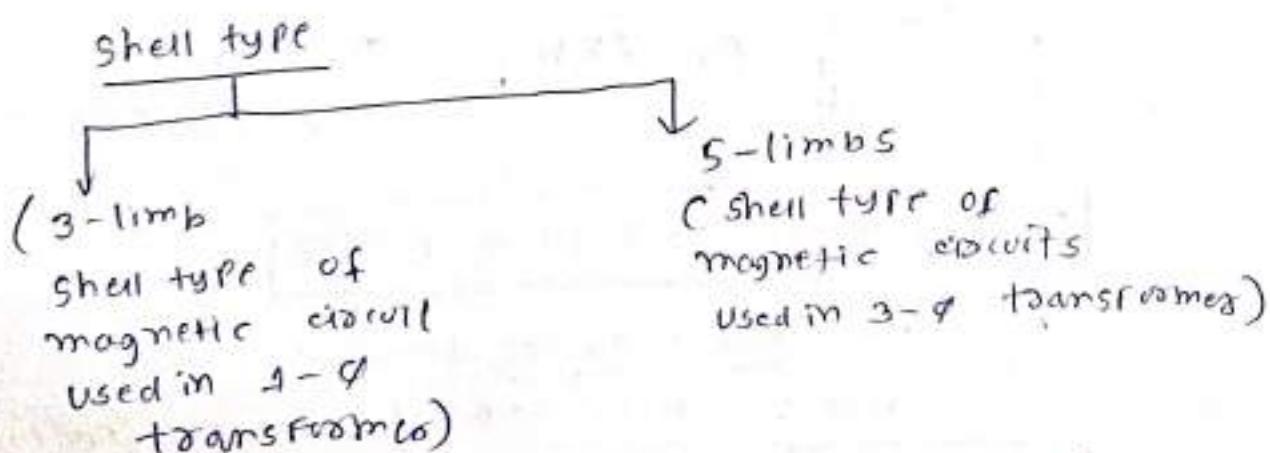
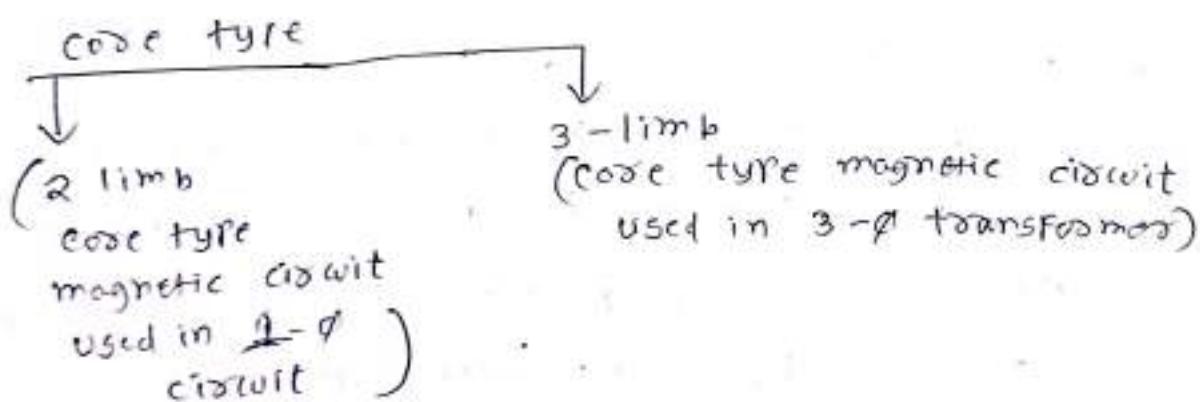


stepped core or
cruciform core



Types of magnetic circuits

- core type magnetic circuit
- shell type magnetic circuit



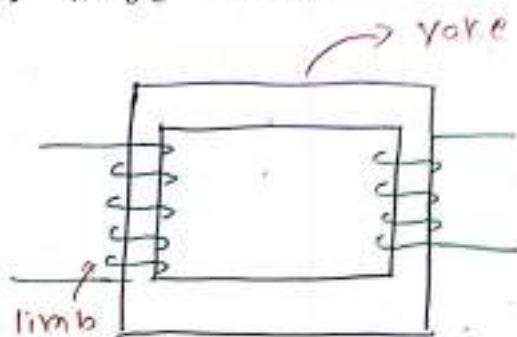
(D)

Limb: part of magnetic circuit in which winding is placed is called limb or leg.

④ vertical ~~one~~ portion of the core is called limb.

Yoke Horizontal portion of the core is called Yoke.

In practical case, yoke cross-sectional area is 20 to 30% more than limb cross-sectional area.

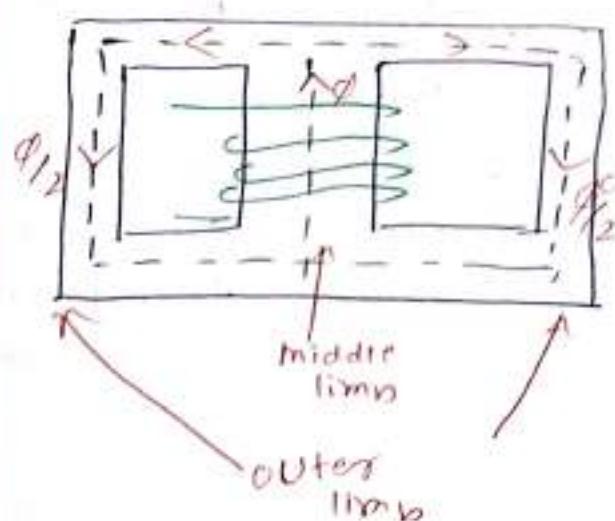
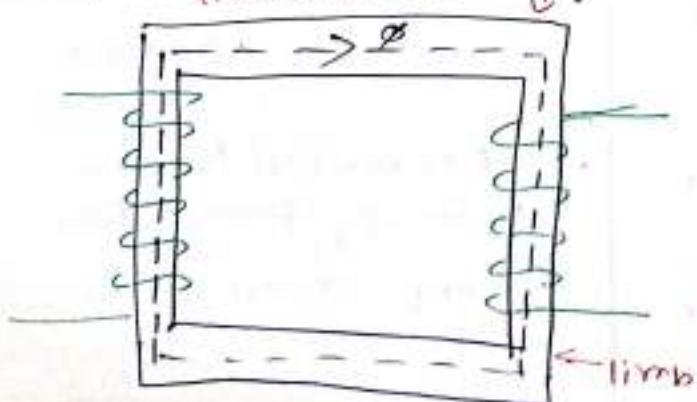


Type of transformers (based on core) \rightarrow core type transformer
 \rightarrow shell type transformer

core type transformer

shell type transformer

Horizontal Yoke



(6)

Core type

- Both the limbs are provided with windings and core is being surrounded by windings.
- It has two Yoke & two limbs.
- windings are less protected by core.
- leakage flux is more hence power transfer capability is less.
- series magnetic circuit.
- both the limbs ~~are~~ have same cross-sectional area.
- more amount of copper is required for winding.
- Requires less amount of insulating material
- Economical for high voltage, small KVA rating transformer

Shell type

- only middle limb is provided with winding & windings are surrounded by core.
- it has three limbs & two yokes.
- windings are more protected by core.
- leakage flux is less & power transfer capability is more.
- Parallel magnetic circuit.
- outer limbs cross-sectional area is half of the middle limb.
- less amount of copper required for windings.
- Requires more amount of insulating material.
- Economical for low Voltage, large KVA rating transformer

What is Transformer?

An electrical component known as a transformer is used to move electrical energy between one electrical circuit and another or between several circuits. A changing magnetic flux in the transformer's core results from a changing current in any of its coils.

As a result, any other coils wound around the same core experience a fluctuating electromotive force (EMF). AC voltage levels can be changed using transformers, classified as step-up or step-down types depending on whether they increase or decrease voltage level.

A transformer is composed of several unique components, each of which contributes to the overall performance of the transformer in a different way. The main components are the core, windings, insulating materials, transformer oil, tap changer, conservator, breather, cooling tubes, Buchholz Relay, and explosion vent.

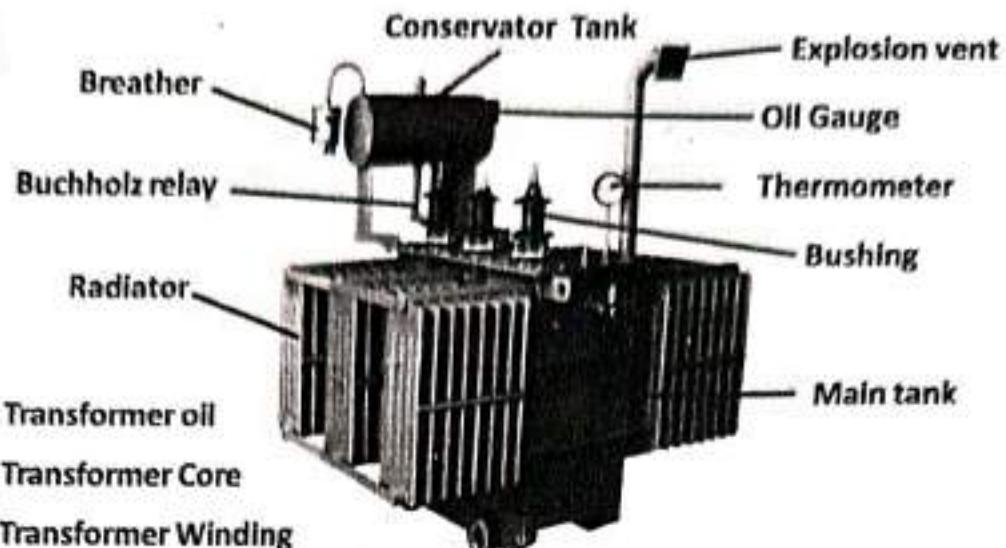
Nearly all transformers have a core, windings, insulating materials, and transformer oil; transformers with more than 50 KVA have other components. Let's discuss the working principle of these transformer parts.

Read Also: [Different Types of Transformers and Their Working \[Explained\]](#)

Parts of Transformer

Following are the main parts of transformer:

1. Core
2. Winding
3. Tank
4. Insulation
5. Transformer oil
6. Terminals and bushings
7. Breather
8. Tap changer
9. Radiators and fans
10. Cooling tubes
11. Buchholz relay
12. Explosion vent
13. Oil conservator
14. Temperature gauge



Parts of Transformer

#1 Core

Transformers are constructed using a core, which is the center of the transformer. These are used to support the windings. The primary and secondary windings are supported by the core, which offers an electromagnetic flux path with low reluctance.

It is constructed from thin sheets of premium grain-oriented steel separated by thin insulating materials. The carbon content of the core steel is kept below 0.1% to reduce hysteresis and eddy currents.

Improved core construction methods and highly permeable material help create a desirable, low reluctance flux path and confine flux lines to the core. Core type and shell type are the two different types of core constructions.

#2 Winding

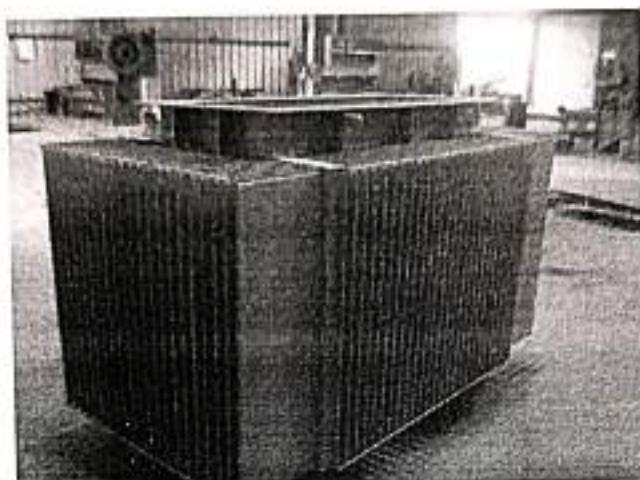
The windings, divided into several coils, enable voltage lowering between adjacent layers. Several turns of copper or aluminum conductors produce this winding and are insulated from the transformer core and one another.

Transformer winding types and configurations are determined by factors like current rating, short circuit power, temperature rise, impedance, and surge voltages. Primary and secondary windings are based on supply, which means they apply input and output voltages, respectively.

The primary and secondary winding is divided into two sections, the high voltage (HV) winding, and the low voltage (LV) winding. In contrast, high-voltage and low-voltage windings can be distinguished based on the voltage range. The number of turns and its current carrying capacity determine the winding to use.

Read Also: [Different Types of Capacitors and Their Applications \[PDF\]](#)

#3 Tank



Transformer tanks are used to hold, protect, and cool the windings and core in an electrical distribution transformer. It serves as a container for oil and support for all other transformer accessories and protects the core and windings from the outside environment.

Tank bodies are created by shaping rolled steel plates into containers and adding lifting hooks and cooling tubes. Aluminum sheets are also employed rather than steel plates to lighten the product and prevent stray losses.

#4 Insulation



Most power transformers have cellulose (paper/pressboard) and oil as insulation materials. Copper is used to make these windings due to their high conductivity and ductility. These components shield the transformer core and the primary and secondary windings from one another.

Insulation is required between the core and the windings, as well as between each winding turn and the tank for all current-carrying components. The insulators must withstand high temperatures, have good mechanical qualities, and have high dielectric strength.

Transformers can sustain the most severe damage if the insulation fails. Transformer insulation is generally made of synthetic materials, paper, cotton, and other materials. The most fundamental components of a transformer are its core, winding, and insulation.

Read Also: [Understand The Different Types of Electric Motors \[Complete Guide\]](#)

#5 Transformer Oil



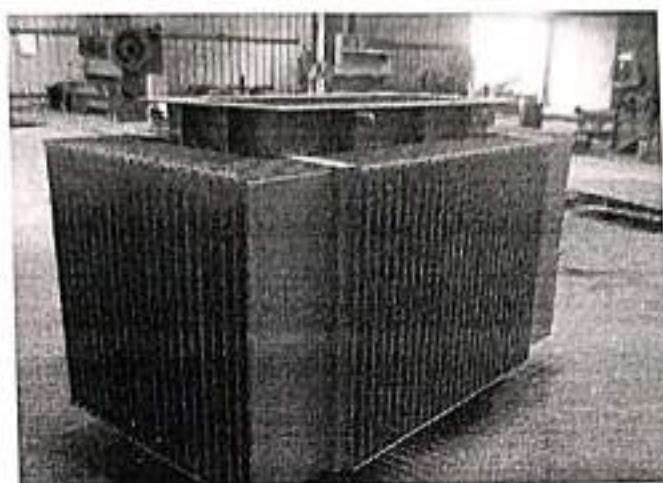
The core and coil assembly are insulated and cooled using the transformer oil. The transformer's core and windings must be completely submerged in the oil, which typically contains mineral oils with hydrocarbons.

Transformer oil provides additional insulation between conductor parts, improves heat dissipation, and detects faults, especially in oil-immersed transformers. Transformer oil has a 310°C flashpoint, a 2.7°C relative permeability, and a density of 0.96 kg/cm³.

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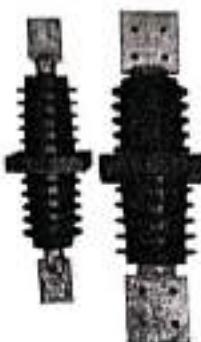
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#4 Insulation



#6 Terminals and Bushings



Transformers have terminals that are used for connecting incoming cables and cables leaving the transformer. Normally, they are mounted on the bushings and are connected to the ends of the windings by means of cables.

An insulator bushing is a type of device that forms a barrier between the terminals of the power source and the tank that contains it. They are positioned above the transformer tanks. For the conductors connecting terminals to windings, they provide a secure path. Porcelain or epoxy resins are used to create these devices.

Read Also: [Types of Insulators Used In Power Transmission Lines \[PDF\]](#)

#7 Breather



A breather is an add-on for liquid-immersed power transformers that are connected to the transformer tank. It is a crucial device for preventing moisture from getting into the oil. The breather is a cylinder filled with silica gel that is used to keep the air entering the tank dry.

This is because moisture can cause internal faults in the insulation when it reacts with the insulating oil, which is why it is essential to maintain dry air. This is why there shouldn't be any moisture in the air, and the breather accomplishes this.

#8 Tap Changer



A tap changer's job is to control a transformer's output voltage. This is accomplished by changing the number of turns in one winding, which affects the transformer's turn ratio. A de-energized tap changer and an on-load tap changer are the two different types of transformer tap changers (DETC).

On-load tap changers can operate while the current is still flowing to the load, whereas off-load tap changers can only operate when the transformer is not supplying any loads. These days, automatic tap changers are also accessible.

Read Also: [Understand The Working & Application of DC Generator](#)

#9 Radiators and Fans



The transformer is made up of exterior radiator tubes, which are cooled by air from fans installed on the tank's walls. Most of the time, heat is produced as a result of the power that is lost in the transformer. Most dry transformers use natural air cooling.

However, various cooling techniques are used when it comes to oil-immersed transformers. Radiators and cooling fans are mounted on the transformer tank based on the kVA rating, power losses, and level of cooling requirements.

The surrounding transformer oil absorbs the heat produced in the core and winding. At the radiator, this heat is released. Using cooling fans attached to the radiators, forced cooling is accomplished in bigger transformers.

#10 Cooling Tubes

In order to cool the transformer oil, cooling tubes are used, as their name suggests. It's possible for oil to circulate naturally or artificially inside the transformer.

When the oil temperature rises, the hot oil naturally rises to the top during natural circulation. In contrast, the cold oil naturally lowers, whereas an ~~internal~~ pump is used to move the oil between the hot and cold zones in forced circulation. ↳ ~~internal~~

Read Also: [Different Types of Inductors and Their Applications \[PDF\]](#)

#11 Buchholz Relay



Buchholz relays are critical components of oil-immersed transformers rated above 500kVA. Usually what happens, transformer oil short circuits produce enough heat to cause the oil to break down into gases like methane, carbon monoxide, and hydrogen.

Buchholz relays are mounted on the pipe connecting the conservator tank to the main tank. They sense these gases and activate the trip and alarm circuits. The trip circuit interrupts the current flow and activates the circuit breaker controlling the primary winding.

#12 Explosion Vent

An explosion vent, which is a component of the transformer, serves as a means for oil and air gases to escape during an emergency. It typically consists of a metallic pipe that is held just above the conservator tank and has a diaphragm at one end.

When there is an oil leak, the pressure inside the tank can reach dangerous peaks. When this happens, the diaphragm ruptures at a relatively low pressure, releasing the forces inside the transformer into the atmosphere.

#13 Oil Conservator



The oil conservator tank's purpose is to offer enough space for transformer oil to expand and contract. It varies in accordance with the fluctuation in the main tank's ambient temperature for transformer oil.

This cylindrical drum-shaped structure is mounted on top of the transformer's main tank. It has a Buchholz relay mounted on the pipe connecting it to the main tank. To show how much oil is in the conservator tank, a level indicator is also present on the oil conservator.

#14 Temperature Gauge

An instrument used to monitor the temperature of a power transformer is called a temperature gauge. It is placed on top of the tank to measure the temperature of the transformer. There is an alarm or light on this meter which alerts you when the temperature rises.

You might like to read more in our blog:

- ~~1. Understand The Different Types of Wind Turbines & Their Working~~
- ~~2. 25 Essential Electrician Tools and Their Applications [Full Guide]~~
- ~~3. Different Types Of Resistors Explained With Symbols~~
- ~~4. What is A.C Motors? Types, Working, Construction and Applications~~

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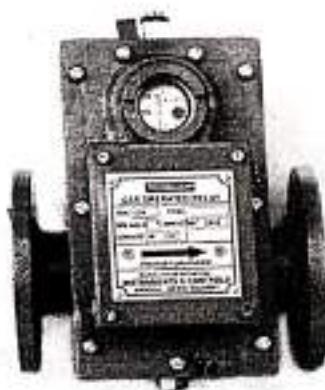
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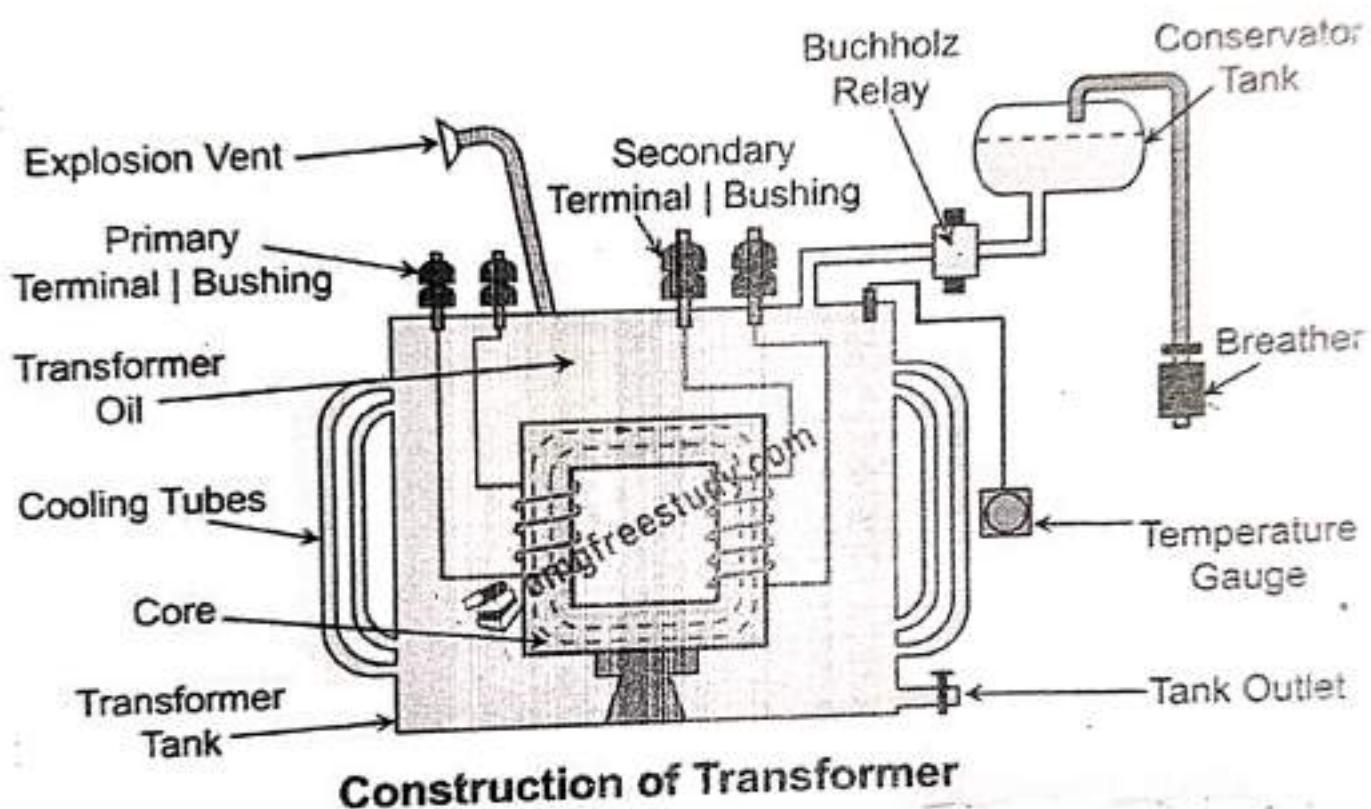


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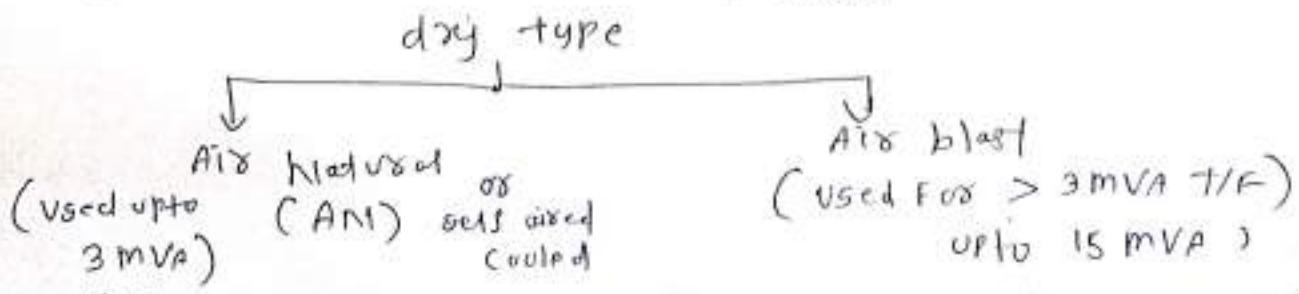
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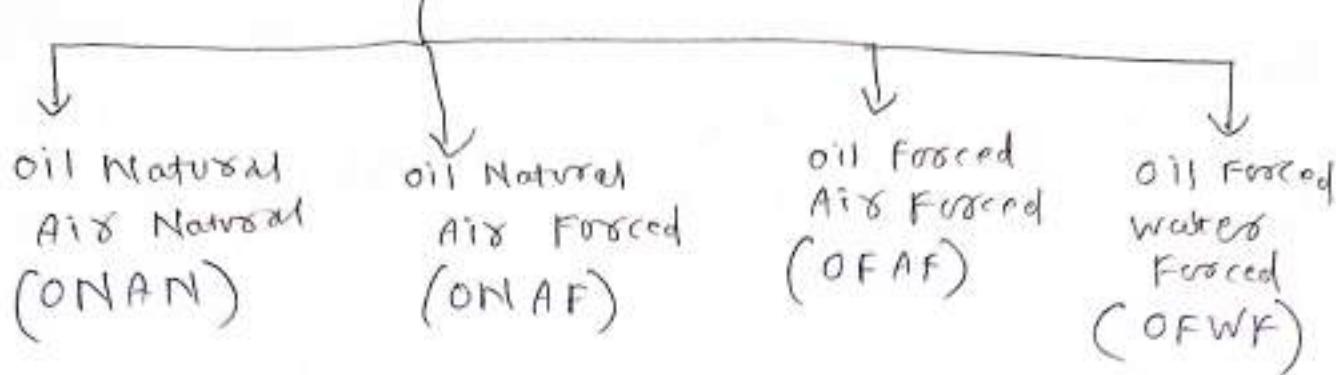
Types of transformer cooling

- ① dry type
- ② oil immersed transformer



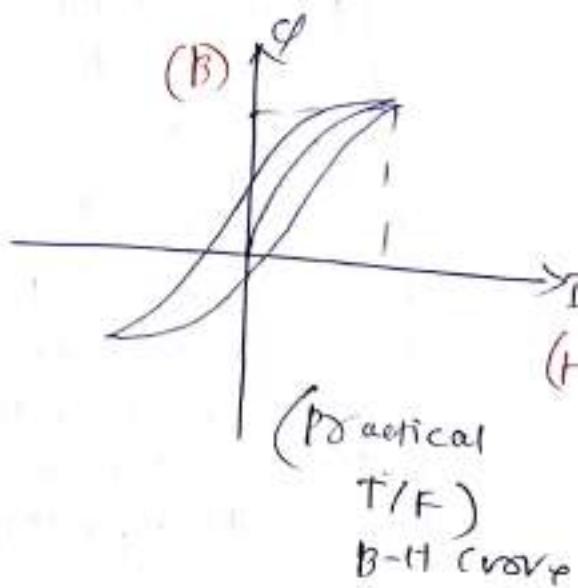
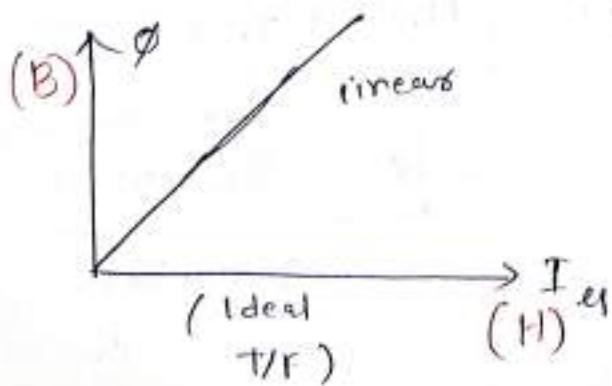
(18)

oil immersed transformer



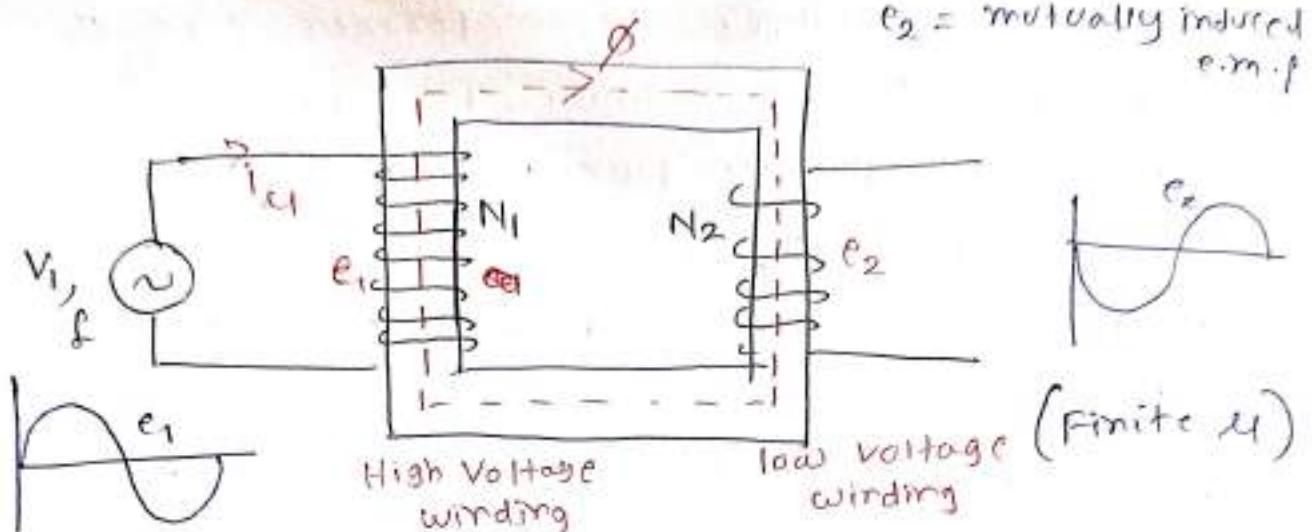
Ideal TransformerAssumptions

1. The permeability (μ) of transformer core is assumed to be infinity. i.e. Excitation current required to produce flux in the core is zero.
 $(\because \mu = \infty, I_{ex} = 0)$
2. Iron losses in transformer core are assumed to be zero.
3. Resistances of Transformer windings are assumed to be zero. (*i.e. purely inductive circuit*)
4. magnetic leakage flux in Transformer is completely zero ($k=1$, co-efficient of coupling)
5. The magnetisation curve of transformer core is assumed to be linear.



1st Assumption

Operation of transformer with finite permeability of core:



I_m = magnetising component of current for creating flux in the core / excitation current

$$I_m = I_m \sin \omega t$$

$$\text{primary MMF} = N_1 I_m = N_1 I_m \sin \omega t$$

$\text{FLUX} = \frac{\text{MMF}}{R}$
 $R = \frac{l}{\mu_0 M_\infty A}$
 $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$

Absolute permeability

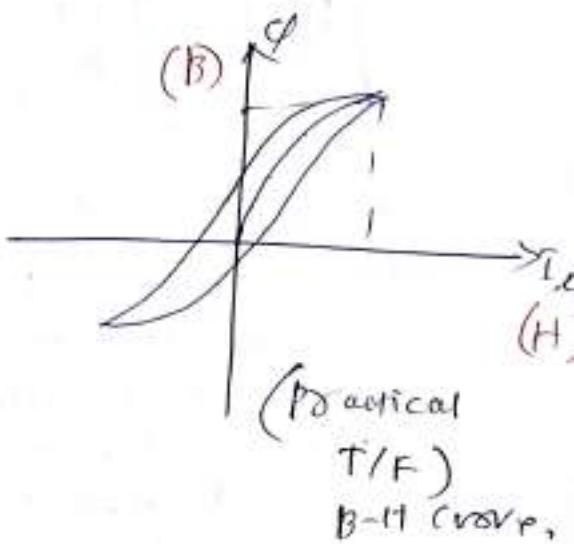
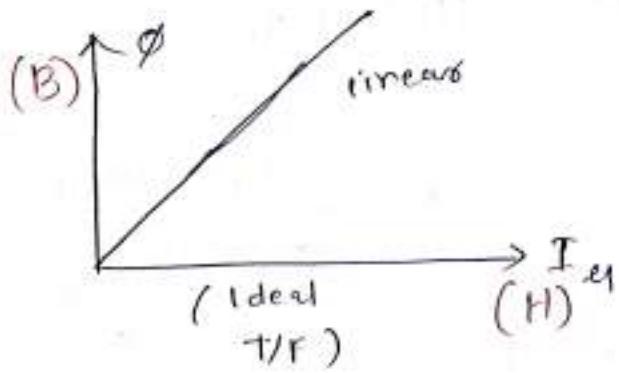
 $M_\infty = \text{relative permeability}$

$(\phi) = \left(\frac{N_1 I_m}{R} \right) \sin \omega t$
 $\Rightarrow \boxed{\phi = \phi_m \sin \omega t} \text{ cycles}$
 $\phi_m = \frac{N_1 I_m}{R}$

Ideal Transformer

Assumptions

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(21)

- consider an ideal transformer whose secondary is open circuited & primary is connected to sinusoidal alternating voltage V_1 .
- since the primary coil is purely inductive & there is no output (secondary being open) the primary draws the magnetising current I_M only.
- The function of this current is merely to magnetise the core, it is small in magnitude and lags V_1 by 90° .
- The current I_M produces an alternating flux (ϕ) which is proportional to the current I_M & hence is in phase with it. This flux (ϕ) links with both the primary & secondary windings.
- The self induced e.m.f E_1 is at every instant equal to and in opposition to V_1 . It is also known as counter e.m.f or back e.m.f of the primary.

From Faraday's second law

$$\begin{aligned} E_1 &= -N_1 \frac{d\phi}{dt} \\ &= -N_1 \frac{d}{dt} (\phi_m \sin \omega t) \\ &= -N_1 \phi_m \cos \omega t \cdot \omega \end{aligned}$$

$$E_1 = N_1 \phi_m \omega \sin(\omega t - 90^\circ)$$

Self induced e.m.f in primary winding is lagging behind the Flux exactly by 90° to satisfy Lenz's law.

At $\omega t = \pi$, emf is maximum

$$E_1 \text{ max} = N_1 \phi_m \omega$$

Rms value of induced emf $E_1 = \frac{E_{1 \text{ max}}}{\sqrt{2}}$

$$E_1 = 4.44 N_1 \phi_m f$$

$$\phi_m = B_{\text{max}} A_n$$

$$E_1 = 4.44 N_1 B_m A_n f \quad \dots (i)$$

where $A_n = \text{net cross-sectional area of the core}$

→ Similarly there is a mutually induced e.m.f E_2 produced in the secondary. This e.m.f is antiphase with E_1 & its magnitude is proportional to the rate of change of flux and the no. of secondary turns.

mutual induced emf in the secondary winding is also lag behind the flux in the core exactly by 90° , so that it always in phase with self induced emf of primary.

$$\text{At } \omega t = \pi, E_2 \text{ max} = N_2 \phi_m \omega$$

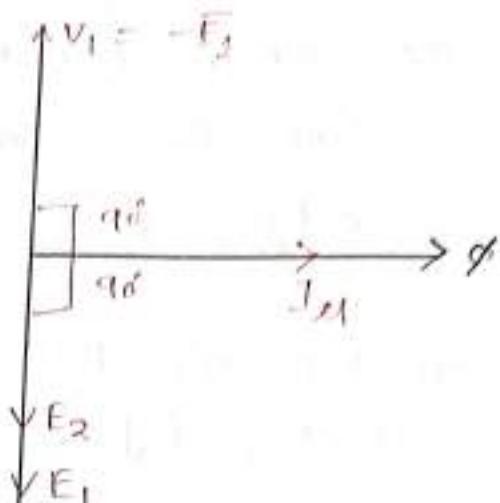
Rms value of $E_2 = 4.44 N_2 \phi_m f$

$$E_2 = 4.44 N_2 B_m A_n f \quad \dots (ii)$$

eqn (i) & (ii) are called emf equation of transformer.

Vector diagram

(Phasor diagram)



Observation of e.m.f equation of transformer

$$E_1 = 4.44 N_1 B_m A n f$$

$$E_2 = 4.44 N_2 B_m A n f$$

1. $\frac{E_1}{N_1} = 4.44 B_m A n f$

$$\frac{E_2}{N_2} = 4.44 B_m A n f$$

In transformer, emf per turn on both sides
is same.

$$\text{emf / turn} = 4.44 B_m A n f$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K \rightarrow \text{transformation ratio}$$

Turns ratio $\Rightarrow \frac{N_1}{N_2} = \frac{E_1}{E_2}$

Transformation ratio $= (K) = \frac{1}{\text{Turns ratio}(a)}$

2. Voltage rating mentioned on name plate of transformer represents induced e.m.f in the winding only.

(21)

- ③ during operation of transformer, the maximum flux density in the core is proportional to $\frac{V}{f}$ ratio.
if $\frac{V_1}{f} = \text{constant}$, $B_m = \text{constant}$.

$$B_{\max} \propto \frac{E_1}{f} \propto \frac{V_1}{f}$$

- ④ during operation of Transformer
 $V_1 = \text{constant}$, $f \downarrow < \text{rated}$

$\uparrow B_{\max} \propto \frac{V_1}{f} = \text{const.}$, overfluxing, $I_{\text{ut}} \uparrow$, deep saturation.

- ⑤ during design stage of transformer, f' is called design frequency.

$\uparrow \text{Rating of T/F} = \uparrow E_1 I_1$
= apparent power rating

(KVA or MVA) $E_1 \uparrow$ or $f' \uparrow$ (designed)
KVA rating increases.

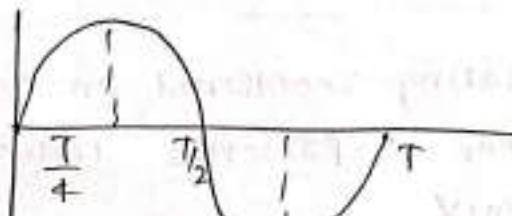
Emf equation of transformer

Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

ϕ_m = maximum flux in the core in webers
= $B_m \times A$

f = frequency of A.c. input in Hz.



(25)

FLUX increases from its zero value to maximum value (Φ_m) in one quarter of cycle i.e. $\frac{1}{4} f$ second.

$$\therefore \text{AVG. rate of change of Flux} = \frac{\Phi_m}{\frac{1}{4} f}$$

$$= 4f \Phi_m \text{ Wh/s or Volt.}$$

Rate of change of Flux per turn means

Induced e.m.f in Volts

$$\text{Average e.m.f/turn} = 4f \Phi_m \text{ volt}$$

\therefore If Flux ϕ varies sinusoidally, then r.m.s value of induced e.m.f is obtained by multiplying the average ~~max~~ Value ~~off~~ with Form Factor.

$$\text{Form Factor} = \frac{\text{r.m.s Value}}{\text{average Value}} = 1.11$$

$$\text{r.m.s Value of e.m.f/turn} = 1.11 \times 4f \Phi_m$$

$$= 4.44 f \Phi_m \text{ Volts}$$

Now r.m.s Value of induced e.m.f in the whole of primary winding

$$= (\text{Induced e.m.f/turn}) \times \text{No. of primary turns}$$

$$E_1 = 4.44 f N_1 \Phi_m = 4.44 f N_1 B_m A$$

Similarly r.m.s Value of the e.m.f induced in Secondary is

$$E_2 = 4.44 f N_2 B_m A$$

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 f \Phi_m$$

(26)

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = k$$

i) If $N_2 > N_1$, i.e. $k > 1$, the transformer is called step-up transformer.

ii) If $N_2 < N_1$, i.e. $k < 1$, the transformer is called step-down transformer.

For ideal transformation, input VA = o/p VA

$$V_1 I_1 = V_2 I_2$$

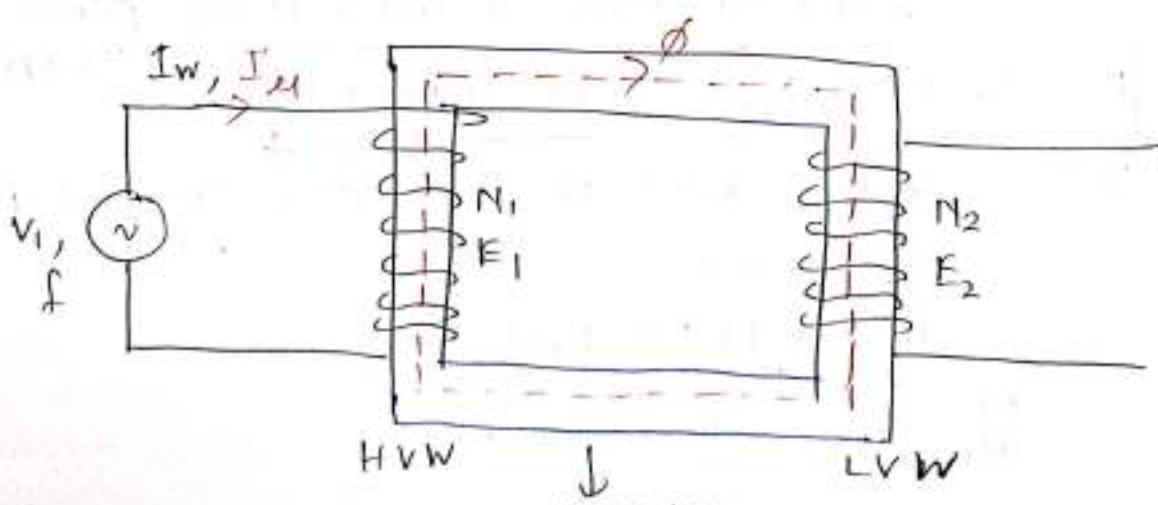
currents are in
the inverse ratio
of the Voltage.

$$\left\{ \text{or } \frac{E_2}{E_1} = \frac{V_1}{V_2} = \frac{1}{k} \right\}$$

2nd Assumption

operation of T/F with iron losses in T/F core.

→ consider a practical core, finite permeability.
due to iron losses in transformer core, the transformer draws an additional component of current from source which is called iron loss component of current.



I_w = iron loss component of current.

(21)

$$\vec{I}_o = \vec{I}_w + \vec{I}_u \rightarrow I_w \text{ & } I_u \text{ are 90° apart.}$$

 I_u

1. Reactive component of current (or) Wattless component of current.
2. It is always quadrature with applied voltage.
3. Its magnitude is about 4 to 5% of full load current.

4. $I_u \approx X_o$
 representing parameter
 For I_u is inductor,
 since I_u is quadrature
 with applied voltage

 I_w

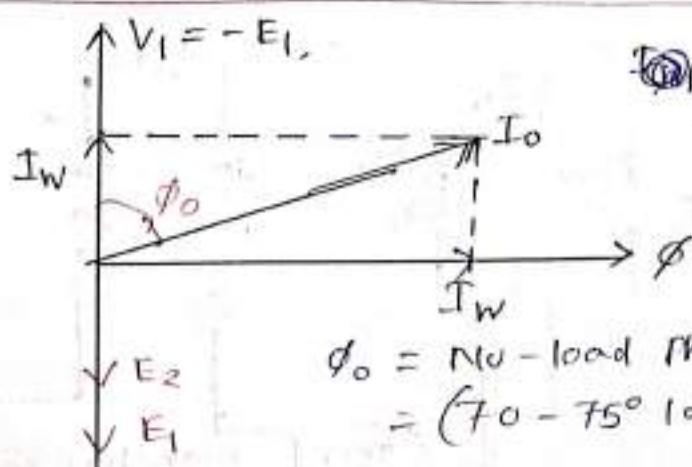
1. Active component of current (or) wattful component of current.
2. It is always in phase with applied voltage.
3. Its magnitude ϕ is about 1 to 2% of full load current.

4. $I_w \approx R_o$

representing parameter
 for I_w is resistor,
 since I_w is inphase
 with applied voltage.

$$I_o = \sqrt{I_u^2 + I_w^2}, I_o = 5\% \text{ of } I_{FL}$$

Vector diagram of a T/F under no-load condition



$$\begin{aligned} \phi_0 &= \text{No-load phase angle} \\ &= (70 - 75^\circ) \text{ lag} \end{aligned}$$

$$\cos \phi_0 = \text{No-load PF}$$

$$= 0.2 \text{ to } 0.25 \text{ lag}$$

→ T/F has poor No-load PF, because it draws more I_{ul} than I_w .

if $V_1 = \text{constant}$, $f \downarrow$ & I_{el} rated, $B_m \uparrow \propto \frac{V}{f} \downarrow$

→ overfluxing

→ deep saturation

→ $I_{ul} \uparrow$, $I_o \uparrow$, $\phi_0 \uparrow$, $\cos \phi_0 \downarrow$

but $\frac{V_1}{f} = \text{constant}$, $B_m = \text{constant}$, $I_{el} = \text{constant}$, $\cos \phi_0 = \text{constant}$ is

$$I_w = I_o \cos \phi_0$$

$$I_{el} = I_o \sin \phi_0$$

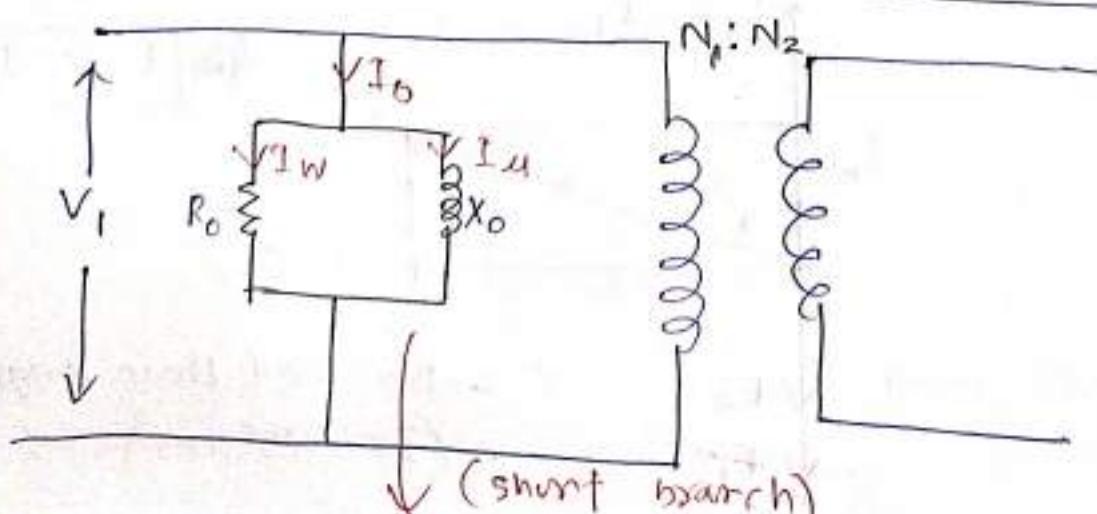
$$\boxed{\text{No-load power } V_1 I_o \cos \phi_0}$$

$$= V_1 I_w \approx \text{iron loss}$$

$$\boxed{\text{No-load power} \approx \text{iron losses}}$$

$$\text{No-load primary copper loss} = I_o^2 R_1 \quad (I_o = \underset{\text{very small}}{\text{neglected}})$$

equivalent circuit of T/F under no-loaded condition



Shunt branch parameters

$$\textcircled{i} \quad R_o = \frac{V_1}{I_w} \quad (I_{st} \gg I_w)$$

$$\textcircled{ii} \quad X_o = \frac{V_1}{I_{st}} \quad \textcircled{iii} \quad I_w = I_e \cos \phi_o$$

$$\textcircled{iv} \quad I_{st} = I_e \sin \phi_o$$

$$R_o \gg X_o$$

$\frac{1}{R_o} = G_o$ = shunt conductance

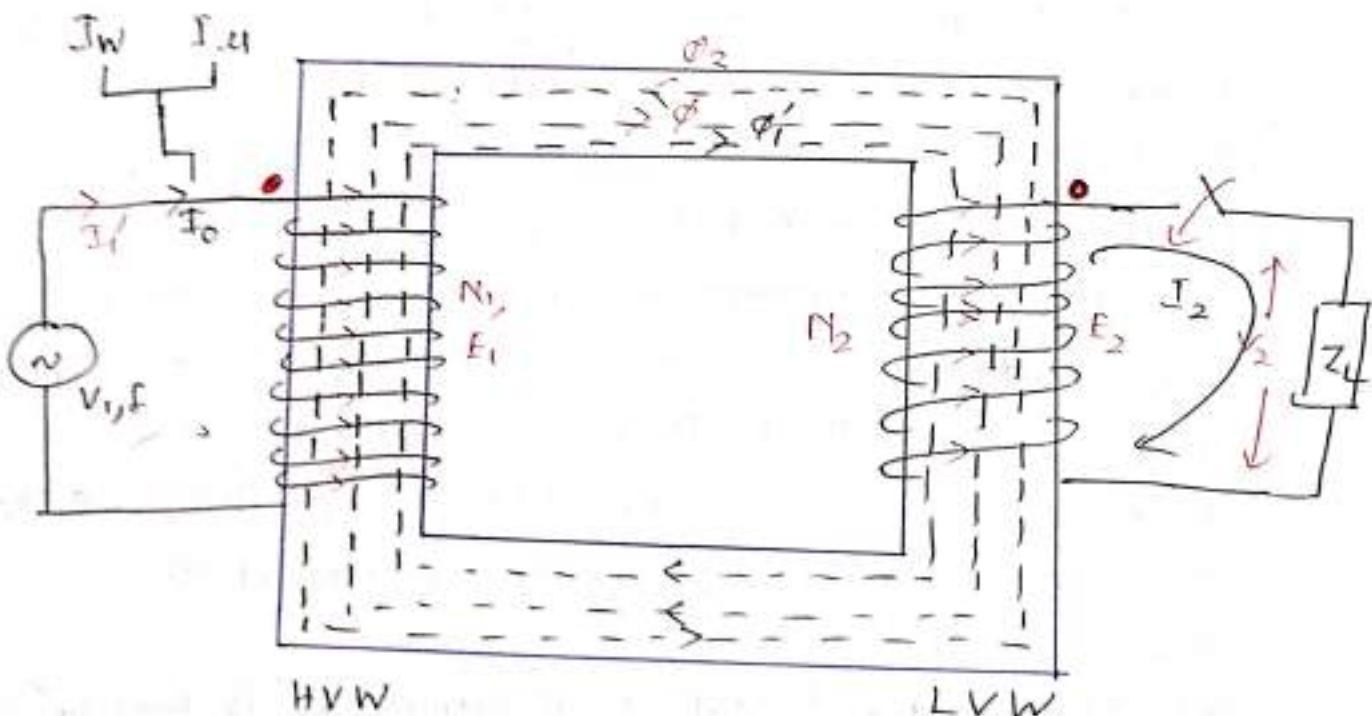
$$\text{because } I_w \ll I_{st}$$

$\frac{1}{X_o} = B_o$ = shunt susceptance

$$G_o \ll B_o$$

$$\text{Iron loss} = V_1 I_w = V_1 \cdot \frac{V_1}{R_o} = \frac{V_1^2}{R_o} = V_1^2 G_o$$

operation of transformer under load condition



$N_1 I_{st} = \text{primary mmf}$

$L \phi \hat{=} \text{primary Flux or main field flux / working flux}$

V_2 = Secondary terminal voltage (3)

I_2 = Secondary load current

$N_2 I_2$ = load ~~current~~ component of secondary mmf

ϕ_2 = load component of secondary flux.

- i) When the secondary is loaded, the secondary current I_2 is set up. The secondary current sets up its own m.m.f ($N_2 I_2$) and hence its own flux (ϕ_2) which is in opposition to main primary flux (ϕ) which is due to I_0 . The secondary ampere-turns ($N_2 I_2$) are known as demagnetising Amp-turns.
- ii) The opposing secondary flux ϕ_2 weakens the primary flux (ϕ) momentarily, hence primary back e.m.f. E_1 tends to be reduced. For a moment V_1 gains the upper hand over E_1 & hence causes more current to flow in primary.
- iii) Let the additional primary current I'_1 is called load component of primary current. This current is antiphase with I_2 . The additional primary ~~current~~ MMF $N_1 I'_1$ sets up its own flux ϕ'_1 which is in opposition to ϕ_2 (but is in the same direction as ϕ) and is equal to it in magnitude.
- iv) To satisfy transformer action, ϕ'_1 is used to nullify ϕ_2 so that resultant load component of flux in core is zero & therefore flux in the core is main flux only even under load condition.

(31)

(V) That means amount of flux in transformer core is always maintained constant irrespective of load across its secondary terminals, hence transformer can be treated as constant flux device.

$N_1 I_1'$ = load component of primary mmf

ϕ_1' = load component of primary flux

Total primary current under loaded condition $I_1' = I_0 + I_1'$

Power transfer condition $\phi_1' = \phi_2$

$$\Rightarrow N_1 I_1' = N_2 I_2$$

\Rightarrow load-component of Primary Amperes turn = load-component of Secondary Amperes turn

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

$$\text{we know } \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1'}{I_2} = K$$

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

$$I_1' = K I_2$$

$$\Rightarrow E_1 I_1' = E_2 I_2$$

\Rightarrow load-component of Primary VA = load-component of Secondary VA

if I_0 = neglected $I_1 \approx I_1'$

$$N_1 I_1 \approx N_2 I_2 \quad K \approx \frac{I_1}{I_2}$$

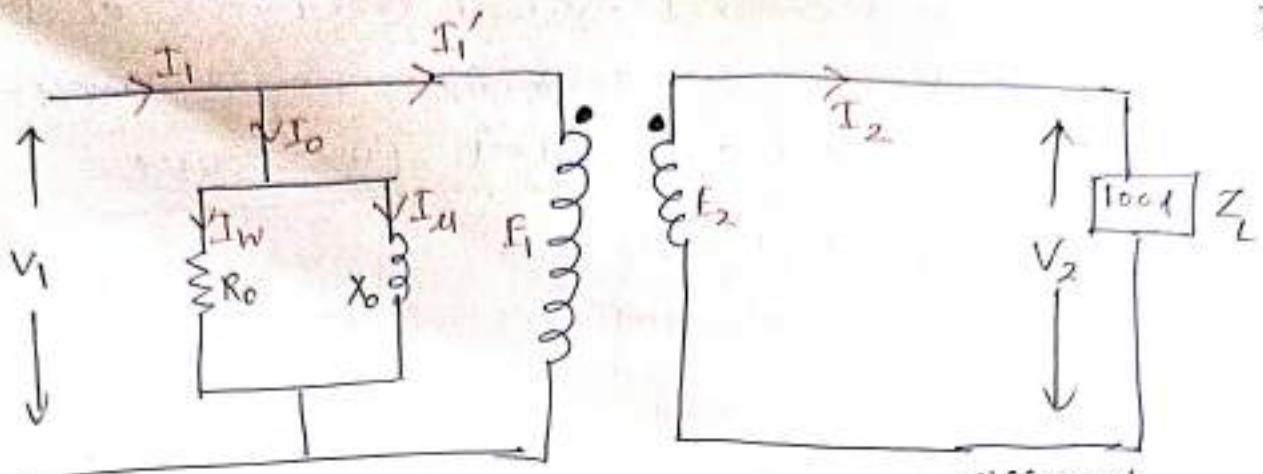
$$E_1 I_1 \approx E_2 I_2$$

\therefore So transformer is a constant power device.

$$\boxed{\begin{aligned} N_1 &= E_1 \\ E_2 &= V_2 \end{aligned}}$$

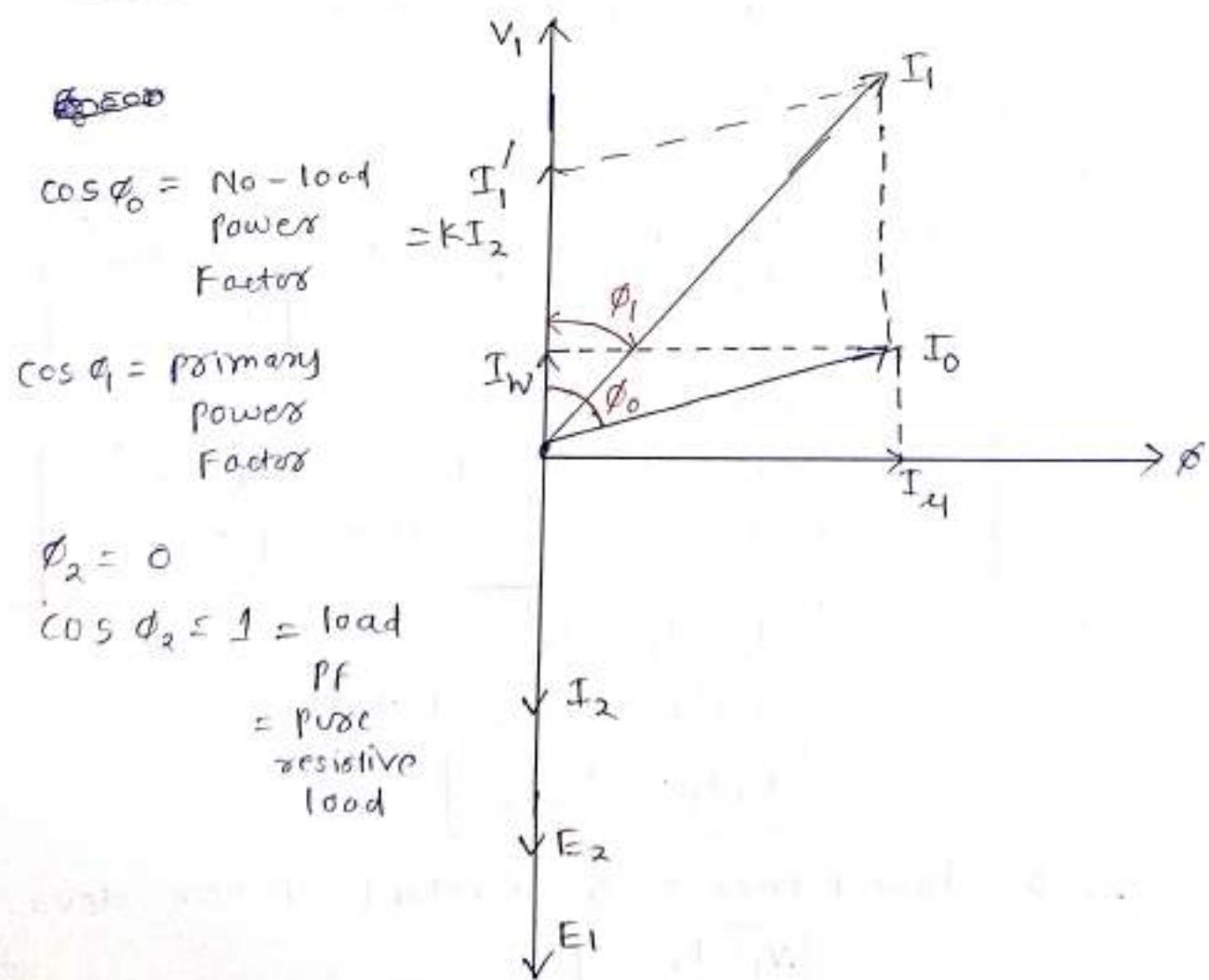
(32)

Equivalent circuit of transformer under load condition



vector diagram of transformer under different load

a) under UPF or pure resistive load



(33)

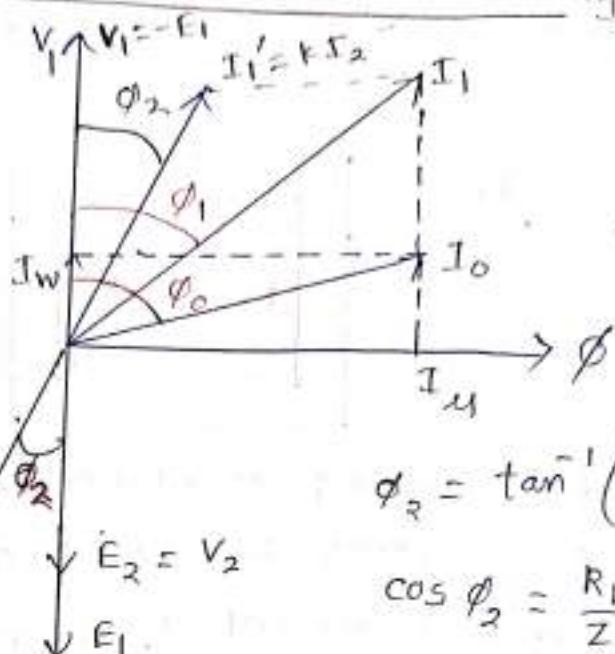
b) under lagging power factor ($R-L$) load ($\frac{R_L}{I_2 R} \frac{L}{X_L}$)

$$\begin{cases} \phi_1 > \phi_2 \\ \cos \phi_1 < \cos \phi_2 \end{cases}$$

$\cos \phi_0$ = No-load power factor

$\cos \phi_1$ = primary power factor

$\cos \phi_2$ = load power factor



$$\begin{aligned} \phi_2 &= \tan^{-1}\left(\frac{X_L}{R_L}\right) \text{ lag} \\ \cos \phi_2 &= \frac{R_L}{Z_L} \end{aligned}$$

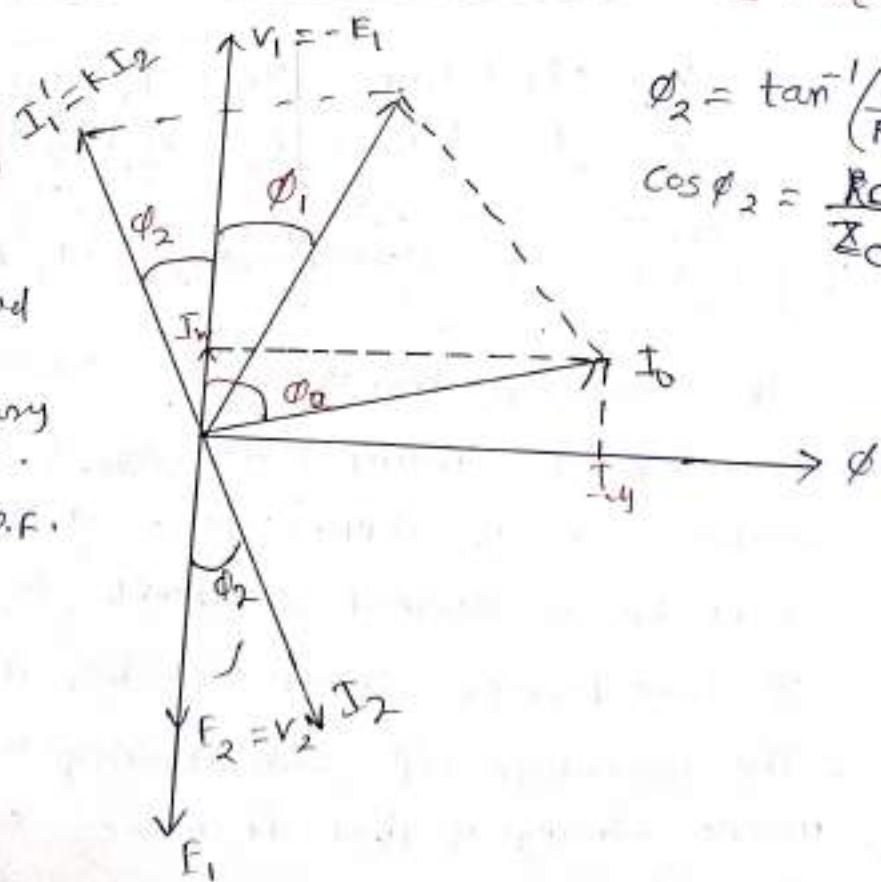
c) under leading power factor ($R-C$) load ($\frac{R}{I_2 R} \frac{C}{X_C}$)

$$\begin{cases} \phi_1 < \phi_2 \\ \cos \phi_1 > \cos \phi_2 \end{cases}$$

$\cos \phi_0$ = No-load p.f.

$\cos \phi_1$ = primary p.f.

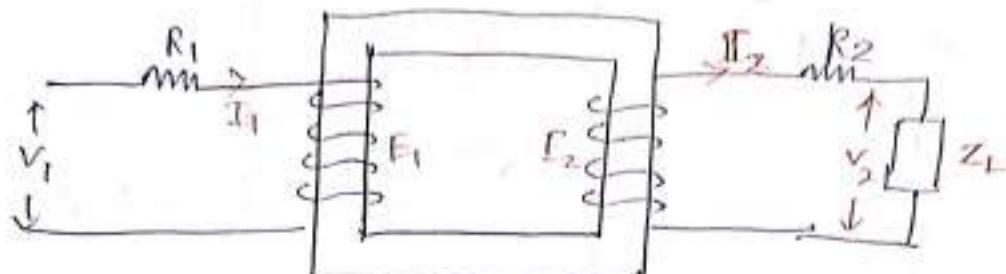
$\cos \phi_2$ = load p.f.



$$\begin{aligned} \phi_2 &= \tan^{-1}\left(\frac{X_C}{R_C}\right) \text{ lead} \\ \cos \phi_2 &= \frac{R_C}{Z_C} \text{ lead} \end{aligned}$$

(Q. 1)

Transformer with winding Resistance but no magnetic leakage reactance



R_1 = winding resistance of primary

R_2 = winding resistance of secondary

No-load current I_0 is neglected here

→ because of winding resistance, IR drop & I^2R drops are exists in transformer winding.

$$V_1 = E_1 + I_1 R_1 \Rightarrow \boxed{V_1 = E_1 + I_1 R_1}$$

$$V_2 = E_2 - I_2 R_2 \Rightarrow \boxed{E_2 = V_2 + I_2 R_2}$$

(Q.)
Total loss of Transformer $\propto I_1^2 R_1 + I_2^2 R_2$

→ The condition that must be satisfied while transferring winding resistance from one side to another side is copper loss of that resistance should be maintained constant so that performance of transformer should not be affected.

→ The advantage of concentrating both the resistances in one winding is that it makes calculations very simple & easy because it has to work in one winding only.

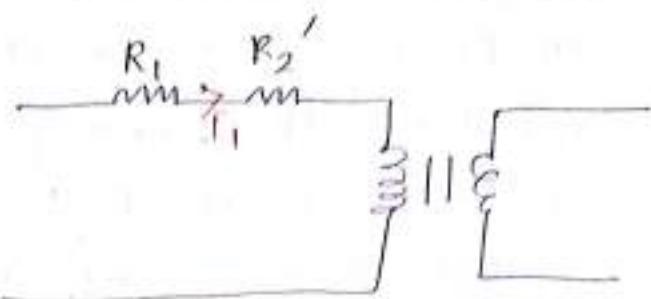
(95)

Secondary to resistance as referred to primary

$$I_2^2 R_2 = I_1^2 R_2'$$

$$\Rightarrow K_2' = \left(\frac{I_2}{I_1}\right)^2 R_2$$

$$\Rightarrow \boxed{R_2' = \frac{R_2}{K^2}}$$

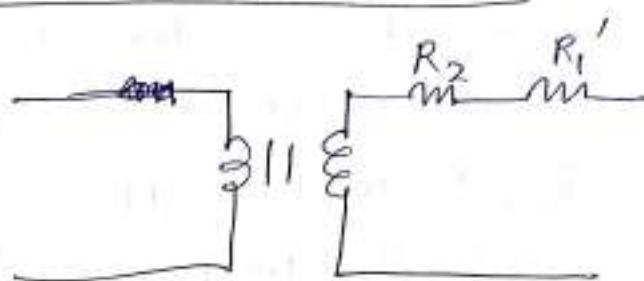


Primary resistance referred to secondary

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

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

$$\Rightarrow \boxed{R_1' = K^2 R_1}$$



Total resistance of transformer referred to primary side $\boxed{R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}}$

Similarly, Total resistance or equivalent resistance of transformer referred to secondary side

$$\boxed{R_{02} = R_2 + R_1' = R_2 + K^2 R_1}$$

Total cu-loss of transformer in primary side

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

Total cu-loss of transformer in secondary side $= I_2^2 R_{02}$

Total cu-loss of transformer $= I_1^2 R_{01} + I_2^2 R_{02}$

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

$$\text{or } = I_2^2 R_{02}$$

Magnetic leakage

- In practical, all the flux linked with primary does not link with secondary but part of it ϕ_{L1} completes its magnetic circuit by passing through air rather than around the core.
- This flux is known as primary leakage flux & is proportional to the primary ampere-turns alone because the secondary turns do not link to the magnetic circuit of ϕ_{L1} . The flux ϕ_{L1} is in time phase with I_1 . It induces an e.m.f e_{L1} in primary but not in secondary.
- Similarly Secondary ampere-turns ~~as (m.m.r.)~~ sets up leakage flux ϕ_{L2} which is linked with secondary winding alone (and not with primary turns). This flux ϕ_{L2} is in time phase with I_2 & produces a self-induced e.m.f e_{L2} in secondary.

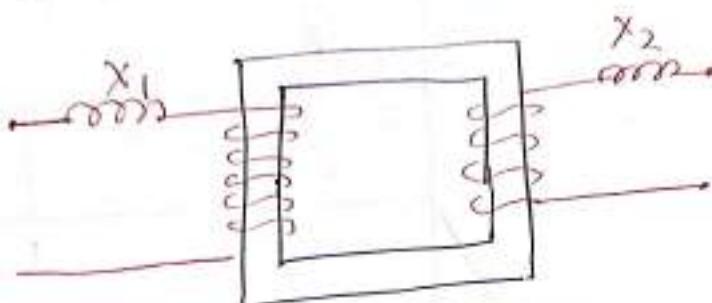
$$X_1 = \frac{e_{L1}}{\cancel{I}_1} = \text{primary leakage reactance}$$

$$X_2 = \frac{e_{L2}}{I_2} = \text{secondary leakage reactance.}$$

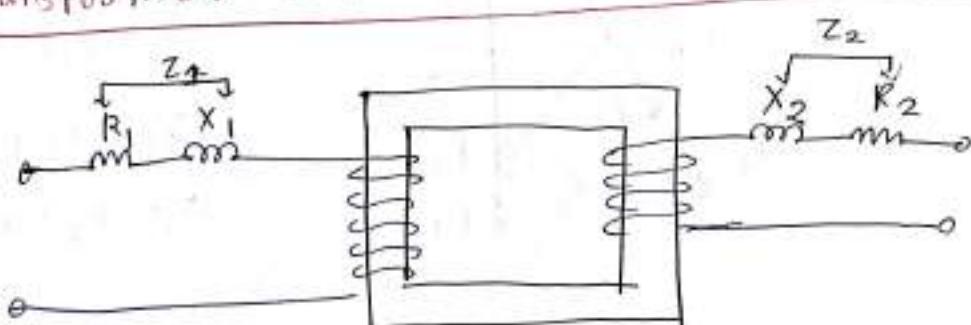
- i. The leakage flux links one or the other winding but not both, hence it in noway contributes to the energy from the primary to the secondary winding.

(11)

- Q. Transformer The primary voltage V_1 will have to supply reactive drop $I_1 X_1$ in addition to $I_1 R_1$. Similarly E_2 will have to supply $I_2 R_2$ & $I_2 X_2$.
3. In actual transformer, the primary & secondary windings are not placed on separate legs or limbs because due to their being separated, large primary & secondary leakage fluxes would result.



Transformer with Resistance & leakage reactance



$$Z_1 = \sqrt{R_1^2 + X_1^2} = \text{primary impedance}$$

$$Z_2 = \sqrt{R_2^2 + X_2^2} = \text{secondary impedance}$$

$$V_1 = E_1 + (R_1 + jX_1) I_1 = E_1 + I_1 Z_1$$

$$E_2 = V_2 + I_2 (R_2 + jX_2) = V_2 + I_2 Z_2$$

$$X'_2 = \frac{X_2}{k^2} \quad \& \quad X'_1 = k^2 X_1$$

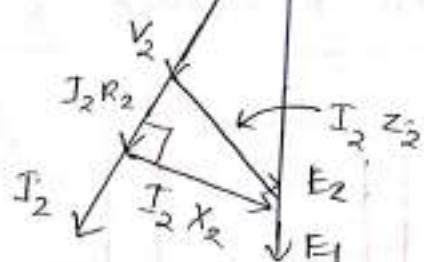
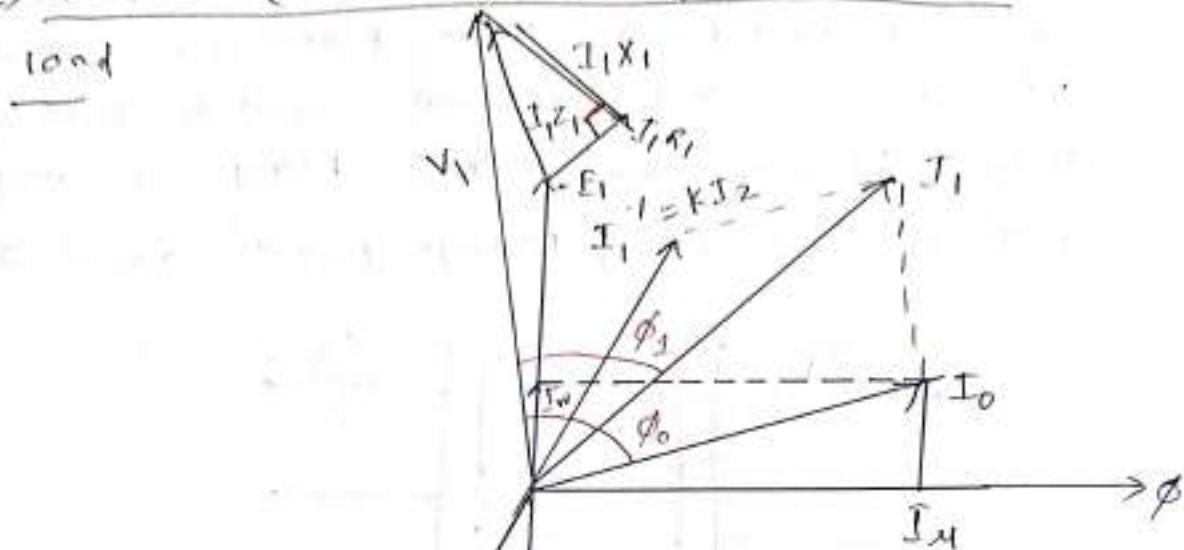
$$X_{01} = X_1 + X'_2 = X_1 + \frac{X_2}{k^2}$$

$$X_{02} = X_2 + X'_1 = X_2 + k^2 X_1$$

(36)

Phasor diagram / vector diagram on load with winding resistance & magnetic leakage reactance.

a) with UPF (unity power factor) or pure resistive load



$$Z_1 = R_1 + jX_1$$

$$V_1 = E_1 + I_1(R_1 + jX_1)$$

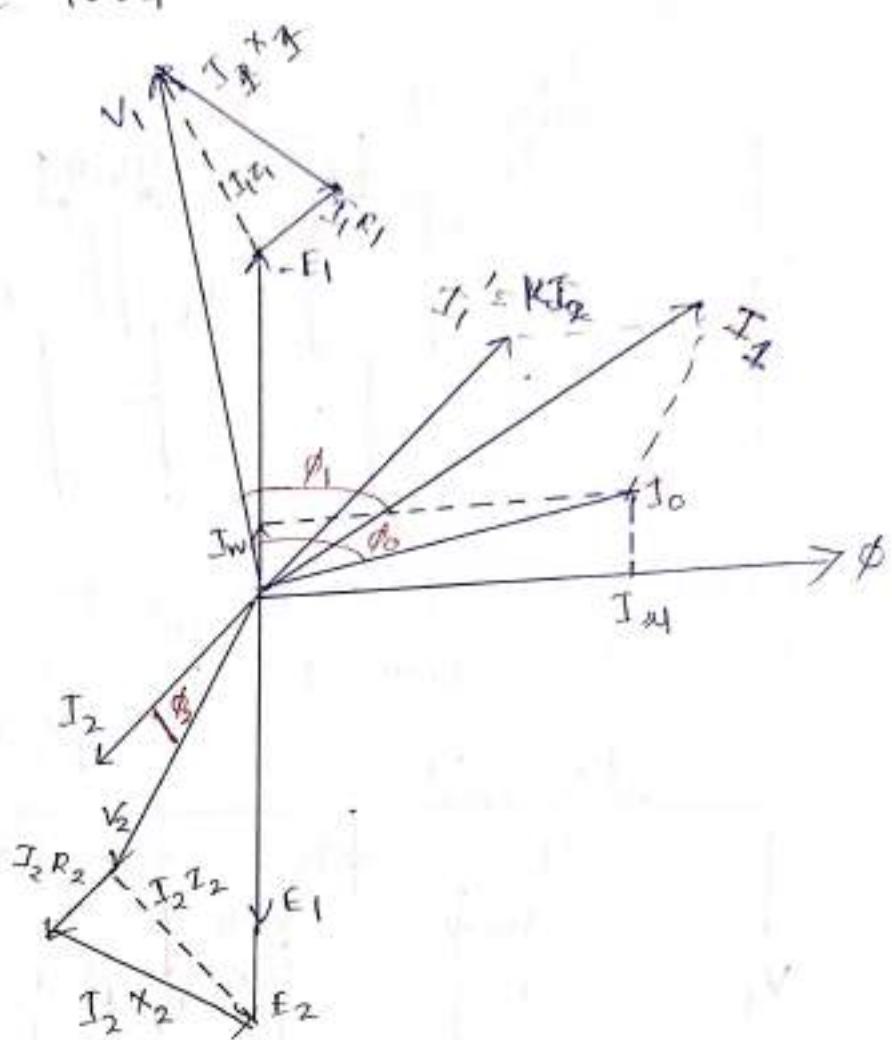
$$V_1 = E_1 + I_1 Z_1$$

R_1, R_2 = winding resistances
 X_1, X_2 = leakage reactances

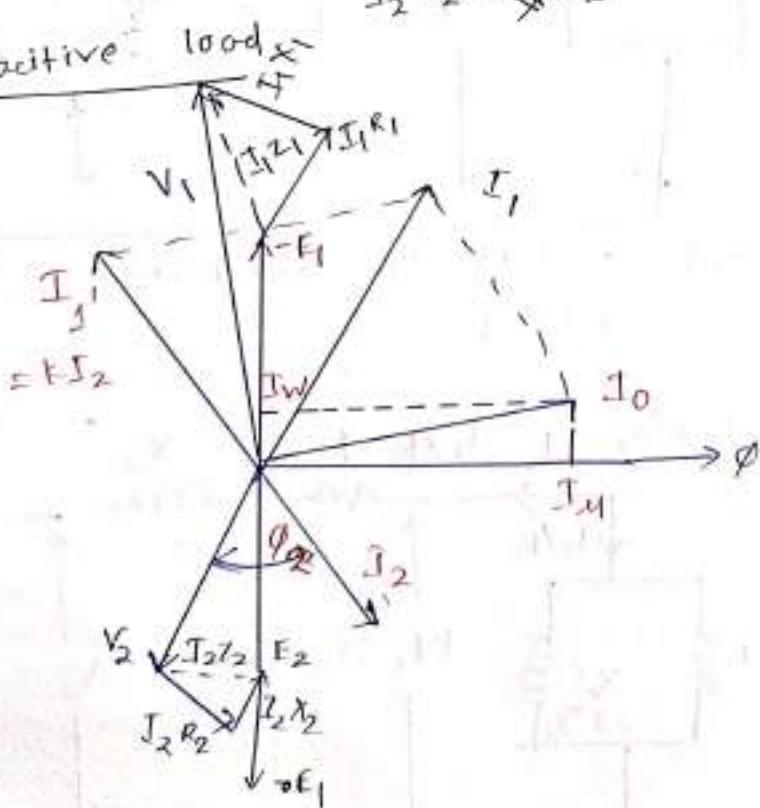
→ when the transformer is loaded there is voltage drop in R_1 & X_1 so that primary EMF E_1 is less than applied voltage V_1 . similarly there is voltage drop in R_2 & X_2 so that secondary terminal voltage V_2 is less than the secondary EMF E_2 .

→ E_1 & E_2 lag the mutual flux ϕ by 90° . the counter EMF opposes the applied voltage V_1 is $-E_1$.

(31)

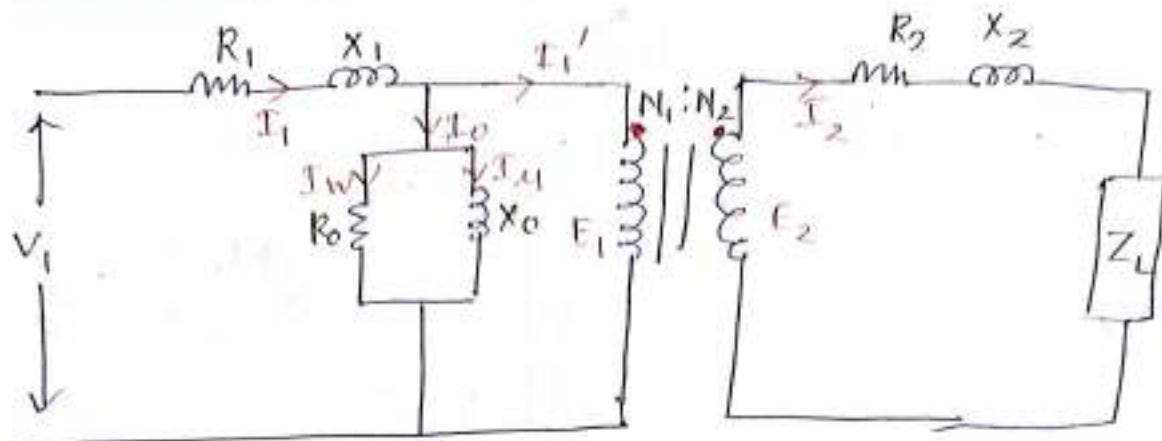
b) ~~pure~~ inductive load

c) capacitive load

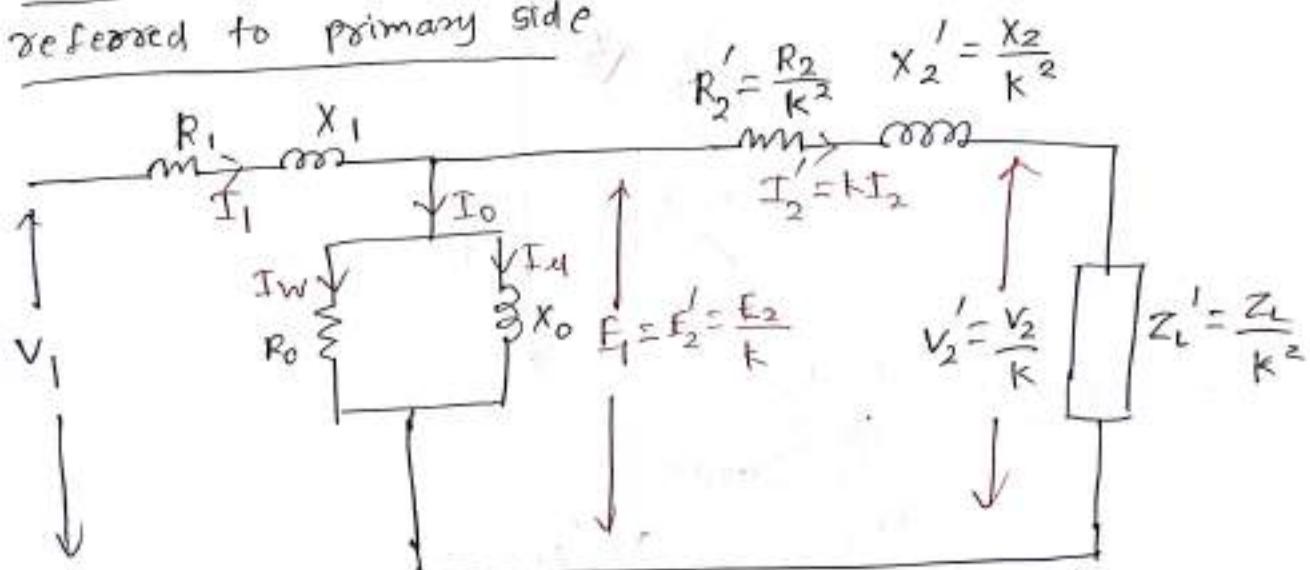


Exact equivalent circuit of transformer

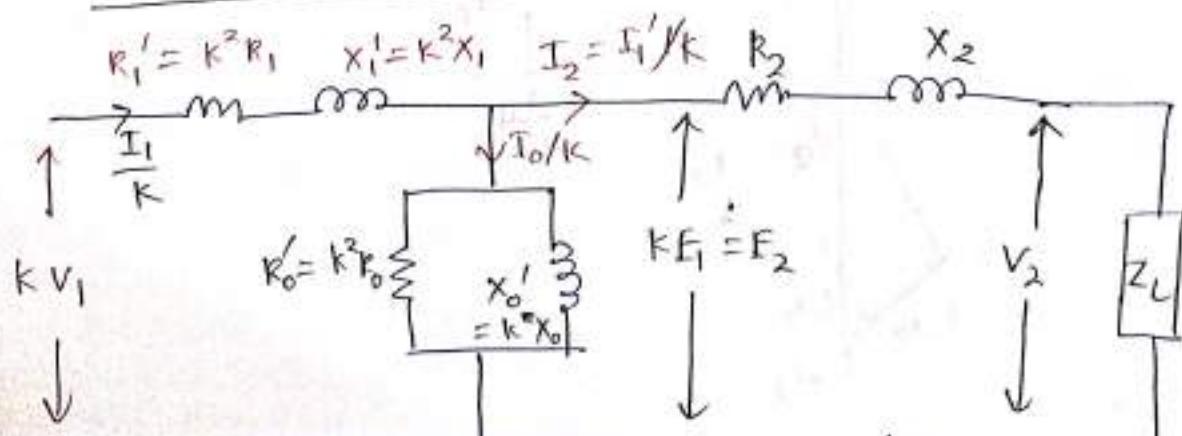
(c)



Exact equivalent circuit of transformer when referred to primary side



exact equivalent circuit of transformer when referred to secondary



(10)

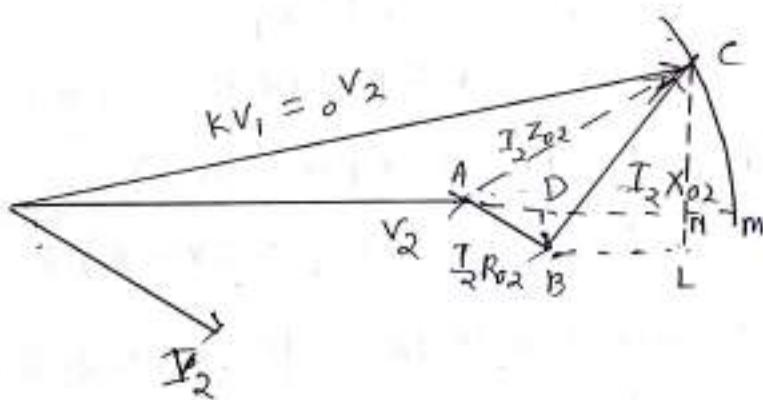
Total approximate voltage drop in a transformer

→ When transformer is on no-load, then V_1 is approximately equal to E_1 .

$$\frac{E_2}{E_1} = K \Rightarrow E_2 = K E_1 = KV_1.$$

Also $E_2 = oV_2$ = secondary terminal voltage at no-load
 $= KV_1$

→ on load, secondary voltage is V_2 . The difference between the two is $I_2 Z_{02}$.



$$\begin{aligned}\text{Approximate voltage drop} &= AN = AD + DN \\ &= I_2 R_{02} \cos \phi + I_2 X_{02} \sin \phi\end{aligned}$$

In general, approximate voltage drop is

$$(I_2 R_{02} \cos \phi \pm I_2 X_{02} \sin \phi)$$

- + → lagging load
- → leading load

(12)

Exact voltage drop

$$= (I_2 R_{02} \cos \varphi + I_2 X_{02} \sin \varphi) + \frac{(I_2 X_{02} \cos \varphi + I_2 R_{02} \sin \varphi)^2}{2 \sigma V_2}$$

+ → lag load

- → lead load.

- Q) A 230/460 v transformer has a primary resistance of 0.252 & reactance of 0.552 & the corresponding secondary values are 0.75Ω & 1.8Ω respectively. Find the secondary terminal voltage when supplying 30A at 0.8 p.f. lagging?

A): $K = \frac{460}{230} = 2, R_{02} = R_2 + K^2 R_1$
 $= 0.75 + 2^2 \times 0.2 = 1.55 \Omega$

$$X_{02} = X_2 + K^2 X_1$$
 $= 1.8 + 2^2 \times 0.5 = 3.8 \Omega$

Voltage drop = $I_2 (R_{02} \cos \varphi + X_{02} \sin \varphi)$
 $= 10 (1.55 \times 0.8 + 3.8 \times 0.6) = 35.2 \text{ volt}$

Secondary terminal voltage = $460 - 35.2 = 424.8 \text{ volt}$

Various losses in T/F

① Copper losses or ohmic losses

These losses occur due to ohmic resistance of the transformer winding.

Total copper loss of a T/F = $I_1^2 R_1 + I_2^2 R_2$
 $\text{or } \sigma = I_1^2 R_{01}$

$\text{or } \sigma = I_2^2 R_{02}$

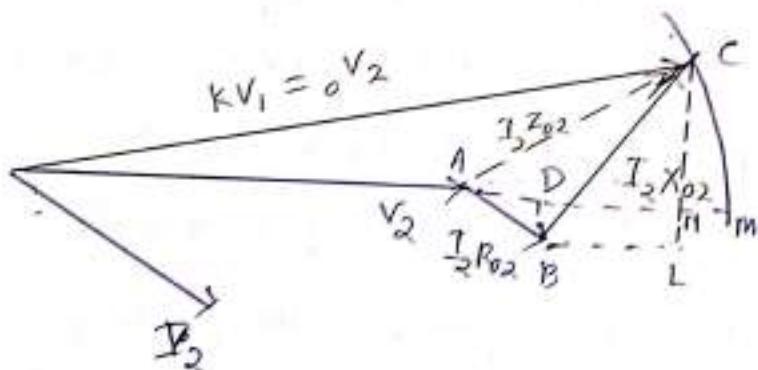
* Total approximate voltage drop in a ⁽¹⁾ transformer

→ When transformer is on no-load, then v_1 is approximately equal to E_1 .

$$\frac{E_2}{E_1} = k \Rightarrow E_2 = k E_1 = k V_1.$$

Also $E_2 = v_o$ = secondary terminal voltage at no-load
 $= k V_1$

→ on load, secondary voltage is V_2 . The difference between the two is $I_2 Z_{o2}$.



$$\text{Approximate voltage drop} = AN = AD + DN$$

$$= I_2 R_{02} \cos \phi + I_2 X_{02} \sin \phi$$

In general, approximate voltage drop is

$$(I_2 R_{02} \cos \phi \pm I_2 X_{02} \sin \phi)$$

+ → lagging load

- → leading load

(13)

$$\text{Full load copper loss} = I_1^2 R_{\phi 1} \text{ (or)} I_2^2 R_{\phi 2}$$

Copper losses \propto square of load current

$$\propto I_1^2 \propto I_2^2$$

$$\boxed{\text{Cu-loss at } \frac{1}{2} \text{ F.L.} = \frac{1}{4} \times \text{F.L. Cu-loss}}$$

$$\boxed{\text{Cu-loss at fraction } x \text{ of F.L.} = x^2 \times \text{F.L. Cu-loss}}$$

\rightarrow Copper loss is a variable loss, because it varies with load.

② Iron losses or core losses

Iron loss is caused by the alternating flux in the core & consists of hysteresis & eddy current loss.

ⓐ Hysteresis loss It is due to reversal of magnetisation of transformer core whenever it is subjected to alternating nature of magnetising force. This power is dissipated in terms of heat and is known as hysteresis loss.

Hysteresis loss per cycle = Area enclosed within one hysteresis loop

$$W_h = \pi B_{max}^2 f V \quad \alpha = \text{hysteresis co-efficient}$$

(range 1.5 to 2.5)

V = volume of core $\alpha = 1.6$ for silicon steel

π = Steinmetz's co-efficient

f = frequency of magnetisation or supply frequency

During operation of transformer

$$\boxed{B_{max} \propto \frac{V_1}{f}}$$

(44)

Case-I $\frac{V_1}{f} = \text{constant}$, $B_m = \text{constant}$

$$W_h \propto f \Rightarrow [W_h = A f]$$

Case-II $\frac{V_1}{f} \neq \text{constant}$, $B_m \neq \text{constant}$

$$W_h \propto N \left(\frac{V_1}{f} \right)^2 f \cdot V \quad (\gamma = 1.6) \quad W_h \propto V_1^{1.6} f^{-0.6}$$

$$[W_h = A V_1^{1.6} f^{-0.6}]$$

Case-III $V_1 = \text{constant}$, f is decreased

$$\uparrow B_m \propto \frac{V_1}{f} \downarrow \quad [W_h \propto f^{-0.6}]$$

(b) eddy current loss

Eddy current loss is basically $I^2 R$ loss present in the core due to production of eddy currents in the core, because of its conductivity.

$$[W_e = k B_m^2 f^2 t^2]$$

B_{\max} = maximum flux density

f = frequency of eddy current
(Supply frequency)

t = thickness of lamination

Case-I

$$B_{\max} \propto \frac{V_1}{f} \quad \left(\frac{V_1}{f} = \text{const.} \right) \quad W_e \propto f^2 \Rightarrow [W_e = B f^2]$$

Total iron loss = $W_i = W_h + W_e$

$$[W_i = A f + B f^2]$$

Case-II $\frac{V_1}{f} \neq \text{constant} \Rightarrow B_m \neq \text{constant}$

$$W_e \propto k \left(\frac{V_1}{f} \right)^2 f^2 t^2 \quad W_e \propto V_1^2 \Rightarrow [W_e = B V_1^2]$$

Total iron loss $\Rightarrow W_i = W_h + W_e$

$$\Rightarrow W_i = A V_1^{1.6} f^{-0.6} + B V_1^2$$

(15)

Case-III $V_1 = \text{const}$, $\downarrow \text{frequency decreases}$

$\uparrow B_m \propto \frac{V_1}{f} \Rightarrow B_m \neq \text{const.}$ $W_c \propto V_1^2 = \text{const.}$

$W_h \propto f^{-0.6} \Rightarrow W_h \uparrow$

Note

\therefore As iron losses depends on applied voltage and independent of load current, this loss can be treated as constant loss, since applied voltage is maintained constant.

Testing of transformer

1. Open circuit test 2. No-load test

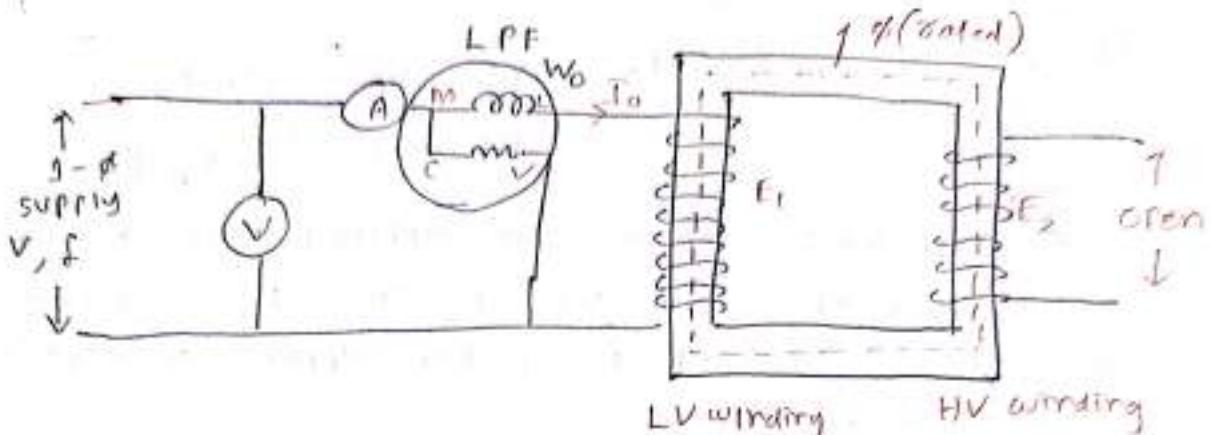
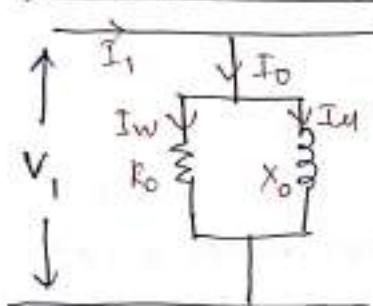
Objectives of open circuit test are

1. To find out shunt branch parameters of circuit i.e. R_o & X_o .
2. To find out constant losses in a transformer.
3. To separate iron losses into hysteresis & eddy current loss.

→ open circuit test should be conducted at rated flux in the transformer core which can be achieved by exciting transformer at rated voltage and frequency and by keeping other winding terminals open. $B_m \propto \frac{V_1(\text{rated})}{f_{\text{rated}}} \Rightarrow \phi \text{ is rated}$

→ This test is conducted on LV side, low range meters are sufficient to conduct the test i.e. low range voltmeter & wattmeter. Here Low power factor wattmeter is generally used.

(16)

1. To find out R_0 & X_0 .

$$R_0 = \frac{V_1}{I_0}, X_0 = \frac{V_1}{I_2}$$

$$I_w = I_0 \cos \phi_0$$

$$I_2 = I_0 \sin \phi_0$$

$$\cos \phi_0 = \frac{W_0}{V_1 I_0} \quad \text{& } \sin \phi_0 = \sqrt{1 - \cos^2 \phi_0}$$

2. To find out constant losses

$$W_0 = \text{No-load Power}$$

= losses in T/F under N.L condition

= constant losses + No-load primary copper loss

$$\text{constant loss} = W_0 - I_0^2 R_1 \quad (\because I_0^2 R_1 \text{ is neglected as } I_0 \text{ is small})$$

Wattmeter reading = iron losses of T/F

3. Separation of iron loss

$$\frac{V_1}{f} = \text{const.}, B_m = \text{const.}$$

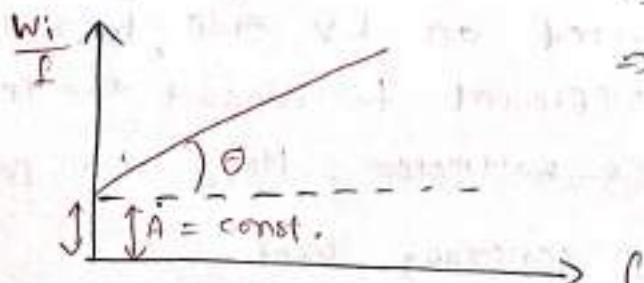
$$W_i = Af + Bf^2$$

$$\Rightarrow \frac{W_i}{f} = A + Bf$$

$$\Rightarrow y = mx + c$$

$$B = \tan \theta$$

= slope of st. line



(1)

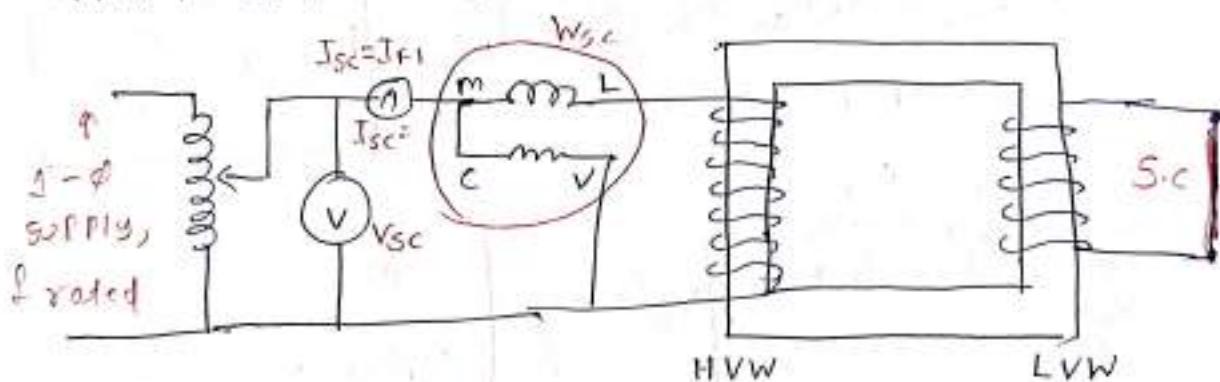
$$\left. \begin{array}{l} W_h \text{ at rated } f = A \times f \\ W_e \text{ at rated } f' = B \times f'^2 \end{array} \right\}$$

Short circuit test

objective

- To findout Variable losses in transformer.
- To findout series branch Parameters of equivalent circuit (total R & X w.r.t winding in which test is conducted)
- To find out $\gamma.R$, $\gamma.X$ & $\gamma.Z$ of T.F.

→ This test is done on H.V. side , low voltage is applied on HV side .



Steady short circuit current

This is the amount of current that would flow through transfer windings under short circuit condition corresponding to rated applied voltage.

Rated short circuit current (I_{sc})

It is the rated current in the windings under short circuit condition with reduced applied voltage .

(18)

$$I_{sc}(\text{steady}) \gg I_{sc}(\text{rated})$$

\downarrow
under V_{rated}

\downarrow
under reduced voltage

V_{sc} = Voltage required to get rated S.C current
 ≈ 5 to 8% of V_{rated}

$\phi = 5$ to 8% of rated : B_{\max}

Procedure to find out variable loss

W_{sc} = losses in T/F under short circuit condition

= F.L. cu losses + stray load losses

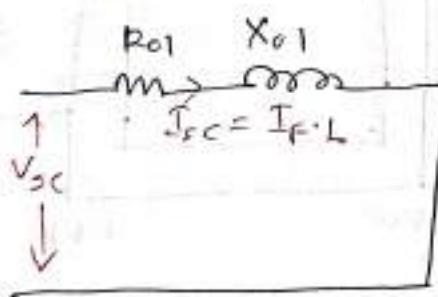
+ small amount of iron loss $\rightarrow V_{sc}$

$$\text{Variable loss} = W_{sc} - (\text{iron loss})$$

~~$(W_{sc}) = (W_{sc})_{\text{oc}} \times \left(\frac{X_{sc}}{V_{\text{rated}}} \right) R_{F.V}$~~

$$W_{sc} = \text{F.L. cu loss} \quad \Rightarrow$$

$$R_{01(2)} = \frac{W_{sc}}{I_{sc}^2}$$



$$Z_{01(2)} = \frac{V_{sc}}{I_{sc}}$$

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

Q) Why transformer Rating in kVA?

A) CU loss of a transformer depends on current & iron loss on voltage.. Hence, total transformer loss depends on Volt-ampere (VA) and not on on phase angle b/w voltage & current i.e. it is independent of load power factor. That is why rating of transformer is in kVA and not in kW.

$$\left. \begin{array}{l} W_b \text{ at rated } f = A \times f \\ W_e \text{ at rated } f = B \times f^2 \end{array} \right\}$$

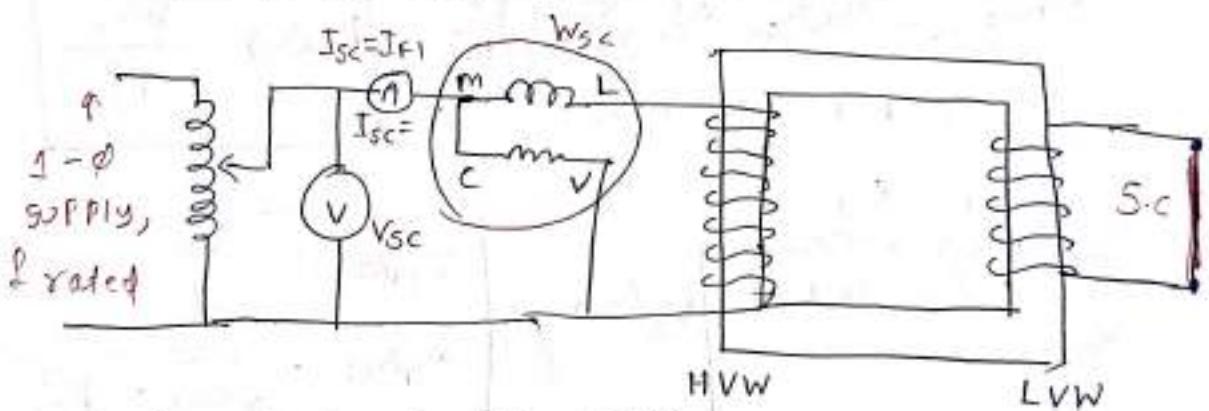
(47)

Short circuit test

Objective

- To findout Variable losses in transformer.
- To findout series branch Parameters of equivalent circuit (total R & X w.r.t winding in which test is conducted)
- To find out $\gamma.R$, $\gamma.X$ & $\gamma.Z$ of T/F.

→ This test is done on H.V. side, low voltage is applied on HV side.



Steady short circuit current

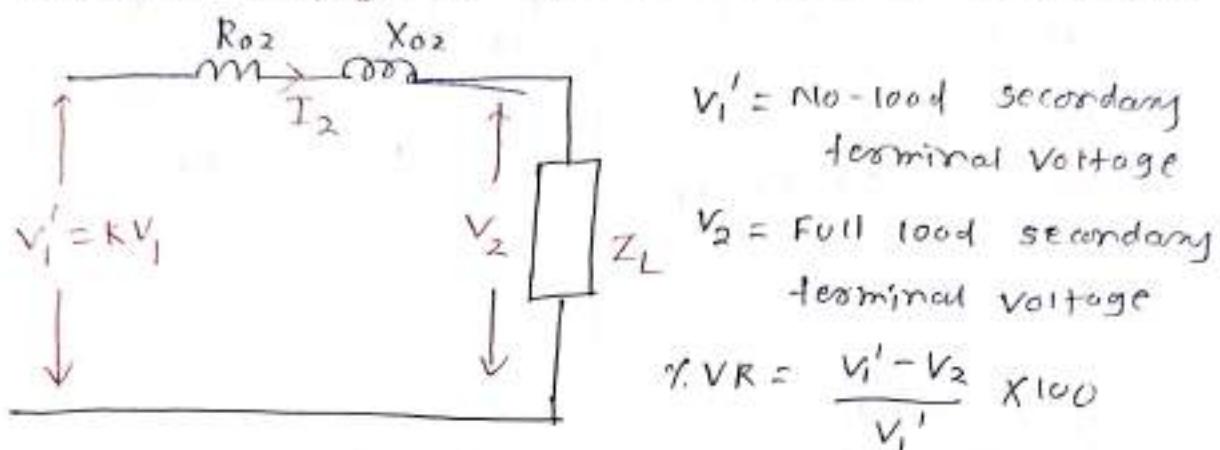
This is the amount of current that would flow through transfer windings under short circuit condition corresponding to rated applied voltage.

Rated short circuit current (I_{sc})

It is the rated current in the windings under short circuit condition with reduced applied Voltage.

(19)

Voltage regulation change in terminal voltage from no-load to full load at specific power factor of load is expressed as fraction of either no load secondary terminal voltage or full load secondary terminal voltage is known as voltage regulation.



Voltage drop at specific power factor of transformer load is $\pm I_2 R_{02} \cos \phi_2 \pm I_2 X_{02} \sin \phi_2$

$$\% VR = \frac{I_2 R_{02} \cos \phi_2 \pm I_2 X_{02} \sin \phi_2}{V_1'}$$

Condition for maximum regulation

$$\tan \phi = \frac{X_{02}}{R_{02}}$$

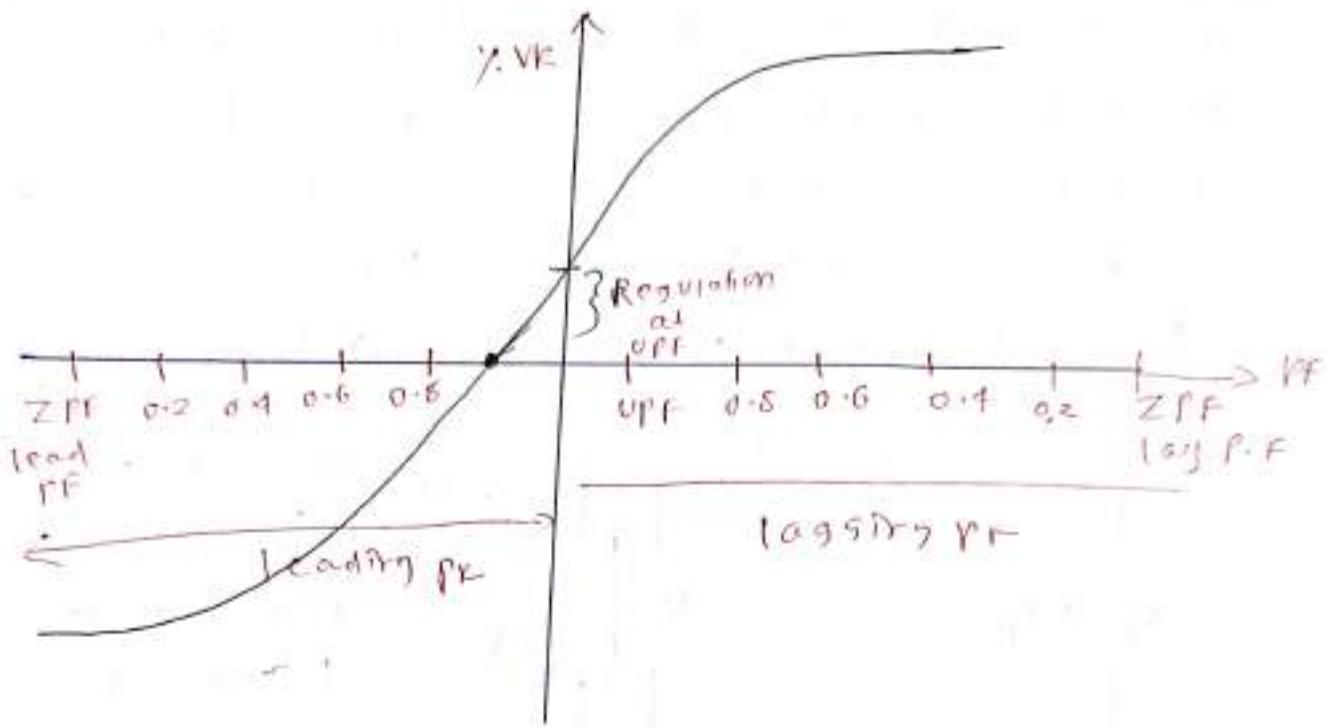
maximum regulation occurs at lagging power factor.

Condition for zero regulation

$$\tan \phi = -\frac{R_{02}}{X_{02}}$$

The -ve sign indicates that zero regulation occurs at a leading power factor.

50

Efficiency

$$\eta = \frac{\text{O/P Power}}{\text{I/P Power}} = \frac{\text{O/P Power}}{\text{O/P Power} + \text{losses}}$$

$$\eta_{F.L.} = \frac{E_2 I_2 \cos \phi_2}{E_2 I_2 \cos \phi_2 + I_2^2 R_{02} + W_i}$$

$$\eta_{\alpha \text{ of F.L.}} = \frac{\alpha (E_2 I_2 \cos \phi_2)}{\alpha (E_2 I_2 \cos \phi_2) + \alpha^2 I_2^2 R_{02} + W_i}$$

Condition for maximum efficiency

$$\eta = \frac{\alpha P}{\alpha P + \alpha^2 P_c + P_i} \quad L. \text{ } (i)$$

$$P = E_2 I_2 \cos \phi_2$$

P_i = total iron loss

P_c = full-load copper loss

α = fraction of full-load kVA

(51)

differentiating both sides of eqn ①

$$\frac{dW}{dx} = \frac{(xP + x^2P_c + P_i)P - xP(P + 2xP_c)}{(xP + P_i + x^2P_c)^2}$$

$$= \frac{P(P_i - x^2P_c)}{(xP + x^2P_c + P_i)^2}$$

efficiency will be maximum, when $\frac{dW}{dx} = 0$

$$\text{or } P_i = x^2P_c$$

$$\text{or } x^2P_c = P_i$$

$$\Rightarrow x^2(I_2^2R_{02}) = W_i$$

$$\Rightarrow \boxed{\text{cu. loss} = \text{iron loss}}$$

$$x = \sqrt{\frac{W_i}{\text{F.L. cu loss}}}$$

Output KVA corresponding to maximum efficiency

$$= 2 \times \text{Rated KVA}$$

$$= \text{Rated KVA} \times \sqrt{\frac{\text{iron loss}}{\text{F.L. cu loss}}}$$

O/P KVA or load KVA

$$\text{corresponding to maximum efficiency} = \text{F.L. KVA} \times \sqrt{\frac{\text{iron loss}}{\text{F.L. cu loss}}}$$

secondary

current corresponding to maximum efficiency

$xI_2 = I_{2m}$ = secondary current corresponding to maximum efficiency

$$I_{2m}R_{02} = W_i \Rightarrow \boxed{I_{2m} = \frac{W_i}{R_{02}}} \quad R_{02} = R_2 + R_1'$$

(52)

Variation of efficiency with power Factor

$$\eta = \frac{O/P}{I/P} = \frac{I/P - \text{losses}}{I/P} = 1 - \frac{\text{losses}}{I/P}$$

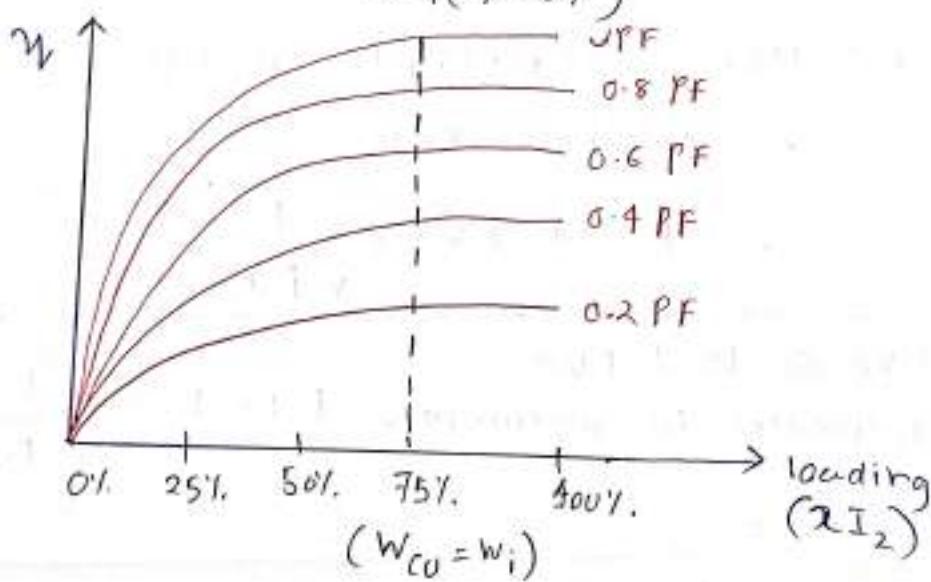
$$= 1 - \frac{\text{losses}}{(V_2 I_2 \cos\phi + \text{losses})}$$

Let $\frac{\text{losses}}{V_2 I_2} = \lambda$

$$\eta = 1 - \frac{\lambda}{\cos\phi + \lambda}$$

$$\eta = 1 - \frac{\lambda}{\cos\phi + \lambda}$$

$$= 1 - \frac{\lambda / \cos\phi}{1 + (\lambda / \cos\phi)}$$



Ques.

energy efficiency / all day efficiency / operational efficiency - used to know performance of distribution T/F

Differentiating both sides of eqn ①

$$\frac{d\eta}{dx} = \frac{(\chi P + x^2 P_c + P_i) P - x P (P + 2x P_c)}{(x P + P_i + x^2 P_c)^2}$$

$$= \frac{P (P_i - x^2 P_c)}{(x P + x^2 P_c + P_i)^2}$$

Efficiency will be maximum, when $\frac{d\eta}{dx} = 0$

$$\text{or } P_i = x^2 P_c$$

$$\text{or } x^2 P_c = P_i$$

$$\Rightarrow x^2 (I_2^2 R_{02}) = W_i$$

$$\Rightarrow \boxed{\text{cu. loss} = \text{Iron loss}}$$

$$x = \sqrt{\frac{W_i}{F.L. - \text{cu. loss}}}$$

Output KVA corresponding to maximum efficiency

$$= 2 \times \text{Rated KVA}$$

$$= \text{Rated KVA} \times \sqrt{\frac{\text{Iron loss}}{F.L. - \text{cu loss}}}$$

O/F KVA or load KVA

$$\text{corresponding to maximum} = F.L. \text{ KVA} \times \sqrt{\frac{\text{Iron loss}}{F.L. - \text{cu loss}}}$$

Secondary

Current corresponding to maximum efficiency

$x I_2 = I_{2m}$ = Secondary current corresponding to maximum efficiency

$$I_{2m} R_{02} = W_i \Rightarrow \boxed{I_{2m} = \frac{W_i}{R_{02}}} \quad R_{02} = R_2 + R_1'$$

(53)

$$\text{Ordinary or commercial efficiency} = \frac{\text{output in watts}}{\text{input in watts}}$$

↳ used to know performance of power transformer

All-day efficiency

$$\begin{aligned}\eta_{\text{all-day}} &= \frac{\text{output energy in kWhr}}{\text{input energy in kWhr}} \quad | \text{ 1 day} \\ &= \frac{\text{OIP energy in kWhr}}{\text{OIP energy in kWhr + losses in kWhr}} \quad | \text{ 1 day}\end{aligned}$$

$$\eta_{\text{all-day}} < \eta_{\text{commercial}}$$

- To find all-day efficiency or energy efficiency, we have to know the load cycle on the transformer, how much & how long the transformer is loaded during 24 hours.
- distribution transformers are energized for 24 hours, but they deliver very light loads for major portion of the day. Thus iron or core loss occurs for the whole day but the copper loss occurs only when the transformer is loaded. The performance of such a transformer must be judged by its all-day efficiency.

Q) Find the all-day efficiency of 500 kVA distribution transformer whose copper loss & iron loss at full load are 4.5 kW & 3.5 kW respectively. During a day of 24 hours, it is loaded under 0.3

No. of hours	Loading in kW	Power Factor
6	400	0.8
10	300	0.75
4	100	0.8
4	0	-

At load of 400 kW at 0.8 PF lagging i.e. $\frac{400}{0.8} = 500 \text{ kVA}$
 300 kW at 0.75 PF means $\frac{300}{0.75} = 400 \text{ kVA}$
 100 kW at 0.8 PF means $\frac{100}{0.8} = 125 \text{ kVA}$

i.e. one-fourth of full load

Cu loss at F.L. of 500 kVA = 4.5 kW

Cu loss at 400 kVA = $4.5 \times \left(\frac{400}{500}\right)^2 = 2.88 \text{ kW}$

Cu loss at 125 kVA = $4.5 \times \left(\frac{125}{500}\right)^2 = 0.281 \text{ kW}$

Total Cu loss in 24 hrs = $(6 \times 4.5) + (10 \times 2.88) + (4 \times 0.281) + (9 \times 0) = 56.924$

The iron loss takes place throughout the day irrespective of the load on the transformer because its primary is energized all the 24 hours.

Iron loss in 24 hours = $24 \times 3.5 = 84 \text{ kWh}$

Total transformer loss = $56.924 + 84 = 140.924 \text{ kWh}$

Transformer O/P is 24 hrs = $(6 \times 400) + (10 \times 300) + (4 \times 100)$
 $= 5800 \text{ kWh}$

$\eta_{\text{all-day}} = \frac{\text{O/P}}{\text{O/P + losses}} = \frac{5800}{5800 + 140.924} = 0.976 \approx 97.6\%$

(1)

(53)

$$\text{ordinary or commercial efficiency} = \frac{\text{output in watts}}{\text{input in watts}}$$

↳ used to know performance of power transformers

All-day efficiency

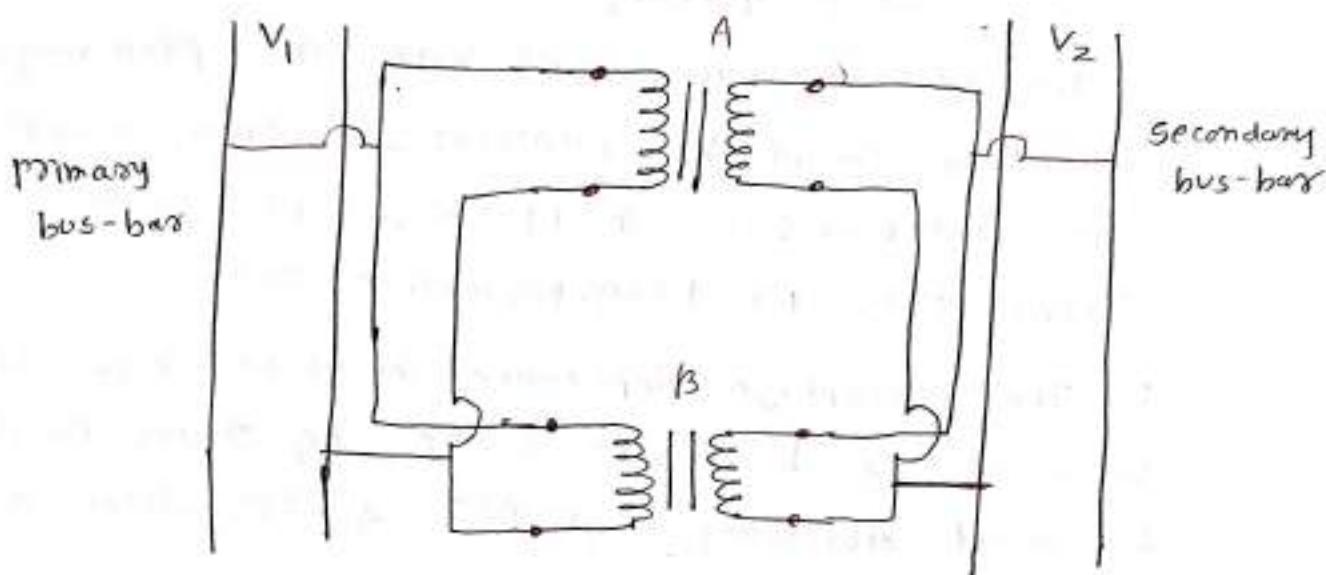
$$\begin{aligned}\eta_{\text{all-day}} &= \frac{\text{output energy in kWhr}}{\text{input energy in kWhr}} \quad | \text{ 1 day} \\ &= \frac{\text{oip energy in kWhr}}{\text{oip energy in kWhr + losses in kWhr}} \quad | \text{ 1 day}\end{aligned}$$

$$\eta_{\text{all day}} < \eta_{\text{commercial}}$$

- To find all-day efficiency or energy efficiency, we have to know the load cycle on the transformer i.e., how much & how long the transformer is loaded during 24 hours
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Parallel operation of single-phase transformer

Two transformers are said to be connected in parallel if the primary windings are connected to supply bus bars and secondary windings are connected to load bus bars.



In connecting two or more Transformers in parallel, it is essential that their terminals of similar polarities are joined to the same bus bar if not done, two two e.m.f.s of secondaries which are parallel with different polarities, will act together in the local secondary circuit even when supplying no-load and hence dead short circuit will happen.

Condition for Satisfactory parallel operation

These are certain definite conditions which must be satisfied in order to avoid any local circulating currents & to ensure that

(56)

the transformers share the common load in proportion to their KVA ratings.

1. primary windings of the transformers should be suitable for the supply system voltage & frequency.
2. The transformers should be properly connected with regard to polarity.
3. The voltage ratings of both the primary & secondary should be identical .in other words, the transformers should have the same turns ratio or transformation ratio.
4. The percentage impedance should be equal in magnitude & have the same X/R ratio in order to avoid circulating currents & operation at different power factors.
5. with transformers having different KVA ratings, the equivalent impedances should be inversely proportional to the individual KVA rating if circulating currents are to be avoided.

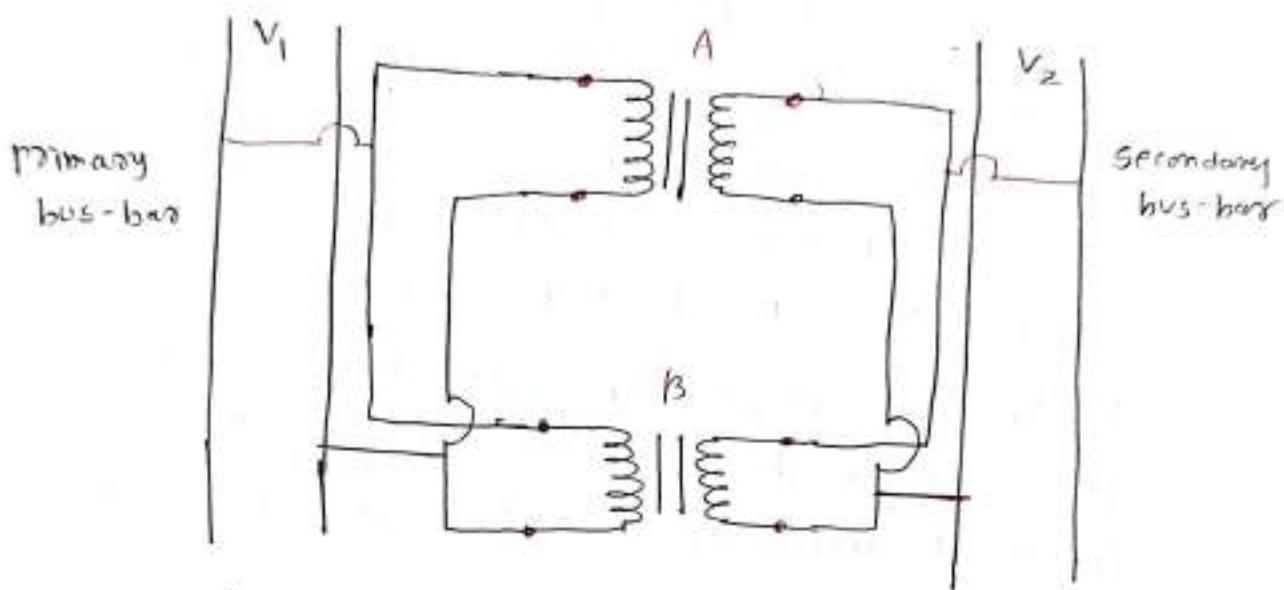
a) Case-1 → Ideal case

consider the ideal case of two transformer having the same voltage ratio & having impedance voltage triangles identical in size & shape.

Parallel operation of single-phase transformer

(55)

Two transformers are said to be connected in parallel if the primary windings are connected to supply bus bars and secondary windings are connected to load bus bars.

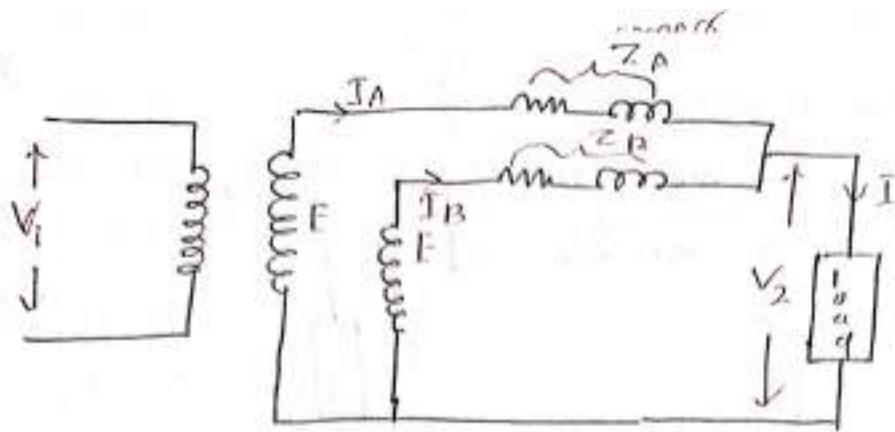


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Condition for Satisfactory parallel operation

These are certain definite conditions which must be satisfied in order to avoid any local circulating currents & to ensure that

(57)



$$I = I_A + I_B$$

$$V_2 = E - I_A Z_A \quad \text{Also} \quad I_A Z_A = I_B Z_B$$

$$= E - I_B Z_B$$

$$= E - \pm Z_{AB}$$

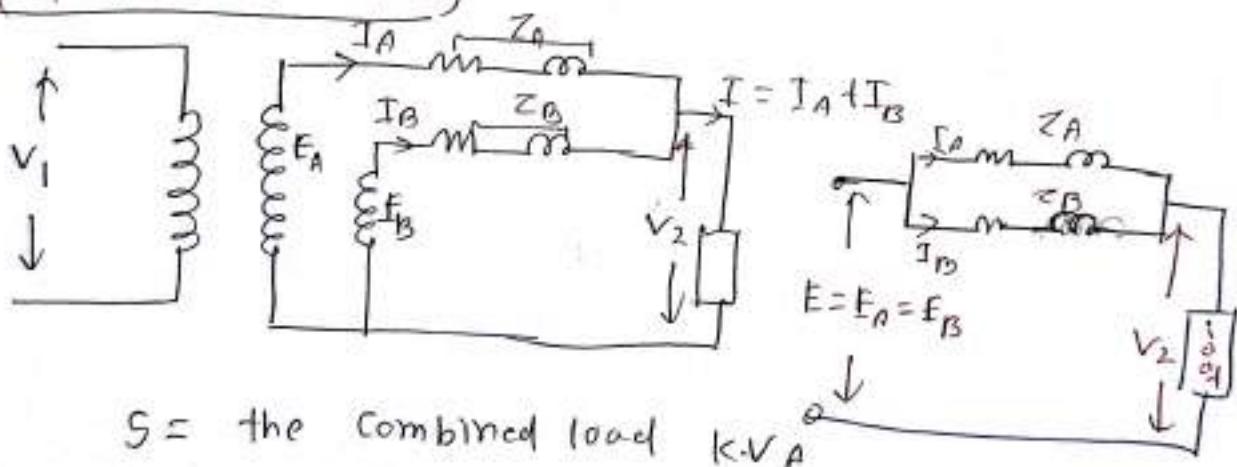
$$\therefore \frac{I_A}{I_B} = \frac{Z_B}{Z_A}$$

$$I_A = I \left(\frac{Z_B}{Z_A + Z_B} \right)$$

$$I_B = I \left(\frac{Z_A}{Z_A + Z_B} \right)$$

Case - 2

(equal voltage ratios)



S = the combined load kVA

The kVA carried by each transformer is

$$S_A = S \frac{Z_B}{Z_A + Z_B} = S \frac{1}{1 + \left(\frac{Z_A}{Z_B} \right)}$$

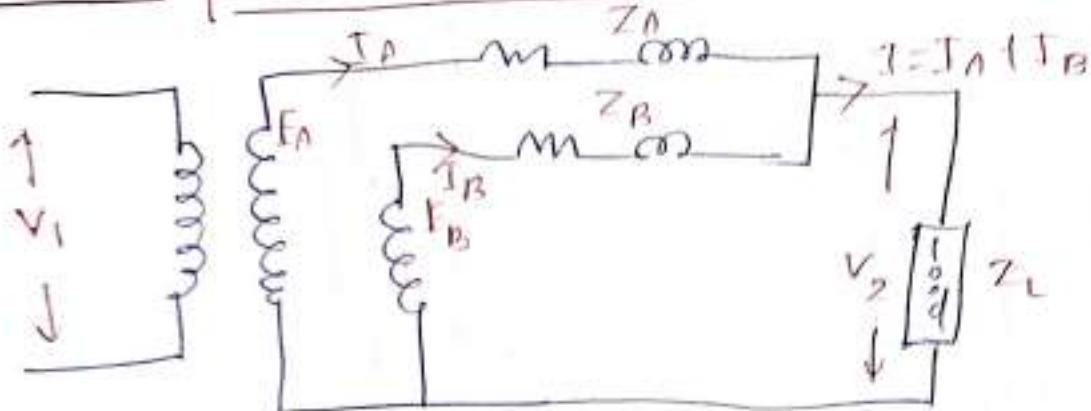
$$S_B = S \frac{Z_A}{Z_A + Z_B} = S \frac{1}{1 + \left(\frac{Z_B}{Z_A} \right)}$$

S_A & S_B are obtained in magnitude as well as in phase.

(56)

Case-3

[Unequal Voltage Ratios]



$$I = I_A + I_B = \frac{E_A z_B + E_B z_A}{z_A z_B + Z_L(z_A + z_B)} \quad V_2 = I Z_L$$

$$I_A = \frac{E_A z_B}{Z_L(z_A + z_B)} + \frac{E_A - E_B}{z_A + z_B}$$

$$I_B = \frac{E_B z_A}{Z_L(z_A + z_B)} - \frac{E_A - E_B}{z_A + z_B}$$

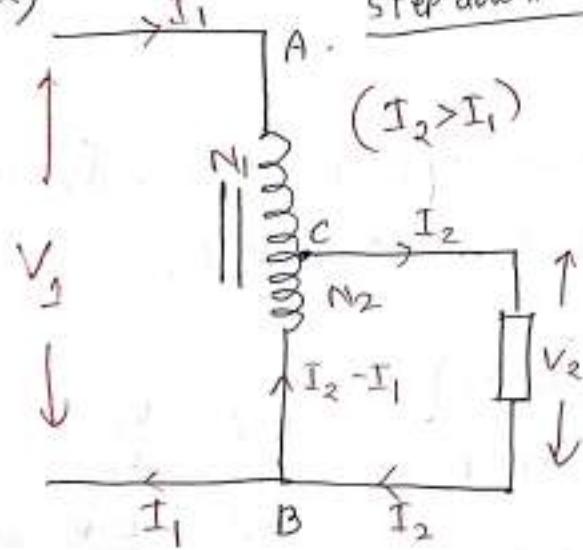
(1)

Auto-transformer

Auto-transformer is a transformer in which

- Part of the winding is common to both primary & secondary i.e. it is a transformer with one winding only.
- In this transformer, the primary & secondary are not electrically isolated from each other as in case of a two-winding transformer.

a) Step down auto T/F



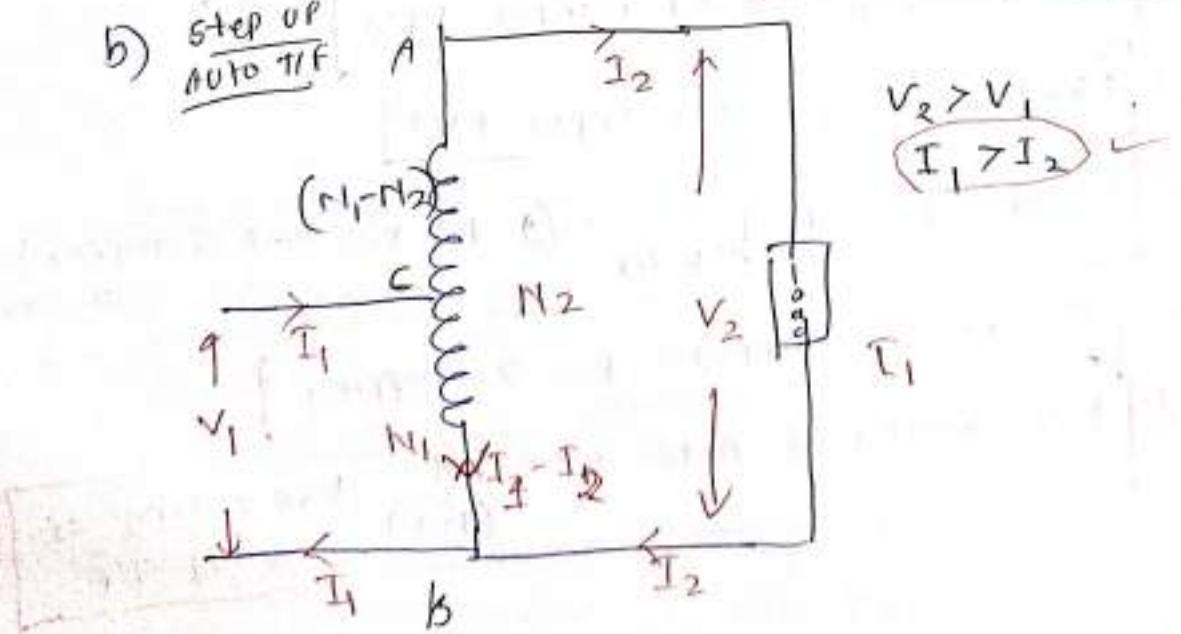
AB = Primary winding
with N_1 turns

BC = Secondary winding
with N_2 turns

Neglecting iron loss &
no-load current.

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

b) Step up auto T/F



(2)

- For step down Auto T/F, $I_2 > I_1$, so $I_2 - I_1$ flows through the common part of the winding.
- For step up Auto T/F, $I_1 > I_2$, hence $I_1 - I_2$ current flows in the common part of the winding.

Note

In Auto transformer power is not only transferred by induction process but also by conduction process.

For step-down transformer

$$\text{KVA transfer by induction process} = (V_1 - V_2) I_1$$

$$\text{input KVA} = V_1 I_1$$

$$\frac{(\text{KVA})_{\text{induction}}}{\text{input KVA}} = \frac{(V_1 - V_2) I_1}{V_1 I_1} = 1 - \frac{V_2}{V_1}$$

$$= 1 - \frac{L \cdot V}{H \cdot V} = 1 - K$$

i) $(\text{KVA})_{\text{induction}} = (1-K) \times \text{input KVA}$

ii) $(\text{KVA})_{\text{conduction}} = K \times \text{input KVA}$

iii) $\frac{(\text{weight of copper})_{\text{Auto T/F}}}{(\text{weight of copper})_{\text{2-wdg T/F}}} = (1-K) \times \frac{(\text{weight of copper})}{(\text{weight of copper})_{\text{2-wdg T/F}}}$

iv) $\text{Saving of copper} = k = \% \text{ tapping}$

v) $\text{KVA rating of Auto T/F} = \frac{1}{(1-K)} \text{ KVA rating of 2-wdg T/F}$

(2)

Uses

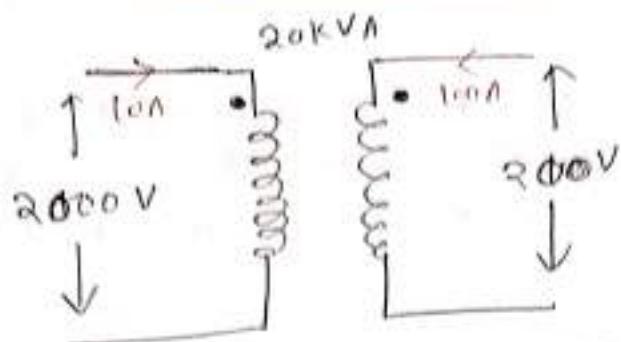
As said early auto transformer are used when k is nearly equal to unity and where there is no objection to electrical connection b/w Primary & Secondary.

1. to give small boost to a distribution cable to correct the voltage drop.
2. as auto-~~or~~ starters transformers give upto 50% to 60% of full voltage to an induction motor during starting.
3. as Furnace transformers for getting a convenient supply to suit the furnace winding from a 230-V. supply.
4. as interconnecting transformers in 132 kV/330 kV system.
5. in control equipment for 1-phase & 3-phase electrical locomotives.

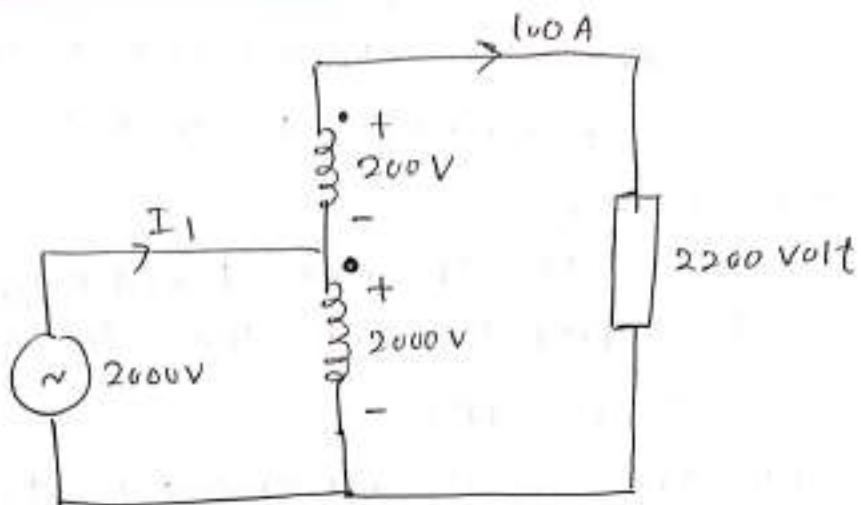
conversion of auto transformer from two-winding transformer

By using two winding transformer we can realize two different auto T/Fs one with series additive polarity & other with series subtractive polarity.

(1)



(a) Series - additive polarity



(1) Voltage rating of Auto transformer

$$= \frac{2000}{2200} V \Rightarrow k = \frac{10}{11}$$

(2) kVA rating of Auto T/F

$$I_1 (\text{rated}) = \frac{20000}{2000} V_p = 10 \text{ Amp}$$

$$I_2 (\text{rated}) = \frac{20000}{200} VA = 100 \text{ Amp}$$

$$\begin{aligned} \text{kVA rating of Auto T/F} &= V_2 I_2 = 2200 \times 100 \\ &= 220 \text{ kVA} \end{aligned}$$

(2)

3. Primary current of Auto transformer

$$I_1 = \frac{220 \times 10^3}{2000} = 110 \text{ A}$$

4. Current in common part of Auto T/F along with direction; apply KCL at node A'

$$\begin{aligned} I_1 &= I_{A \text{ to } B} + I_2 \\ \Rightarrow I_{A \text{ to } B} &= 10 \text{ A} \end{aligned}$$

5. $(\text{kVA})_{\text{induction}} = 200 \times 100 = 20 \text{ kVA}$

$(\text{kVA})_{\text{conduction}} = 220 - 20 = 200 \text{ kVA}$

(b)

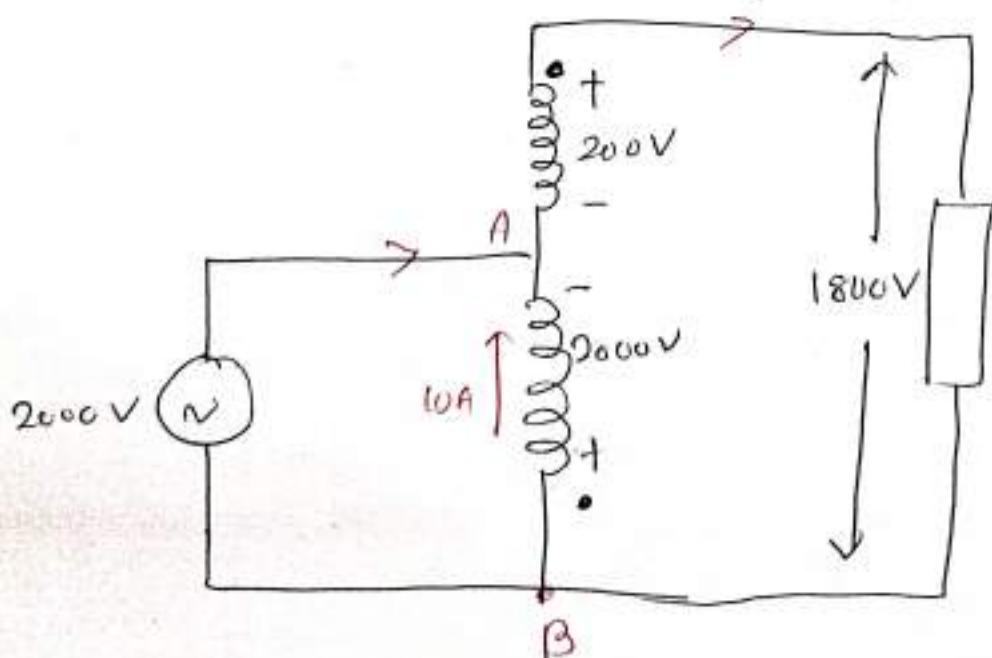
Series subtractive polarity

1. Voltage Rating of Auto Transformer
 $= 2000 / 1800 \text{ volt}$

2. KVA Rating of Auto T/F

$$I_1 \text{ rated } = \frac{20 \times 10^3}{2000} = 10 \text{ A}$$

$$I_2 = 100 \text{ A}$$



(6)

$$I_2 (\text{rated}) = \frac{20 \times 10^3}{200} = 100 \text{ A}$$

$$(kVA)_{\text{Auto T/F}} = V_2 I_2 \\ = 1800 \times 100 = 180 \text{ kVA}$$

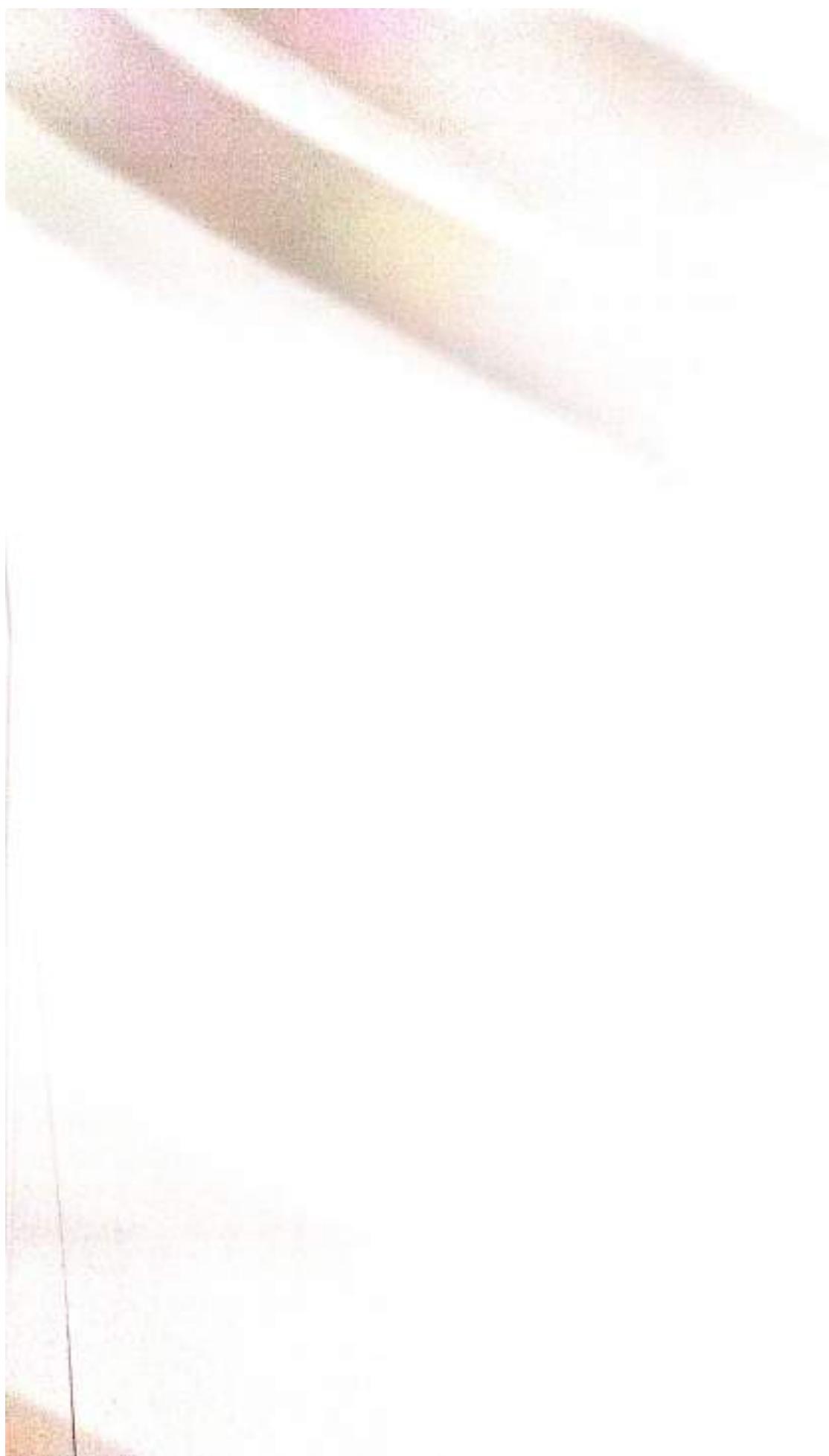
3. primary current of Auto T/F

$$I_1 = \frac{180 \times 10^3}{200} = 90 \text{ A}$$

4. current in common part of Auto T/F along with
the direction = 10 A from B to A

$$5. (kVA)_{\text{induction}} = 200 \times 100 = 20 \text{ kVA}$$

$$(kVA)_{\text{conduction}} = 180 - 20 = 160 \text{ kVA}$$



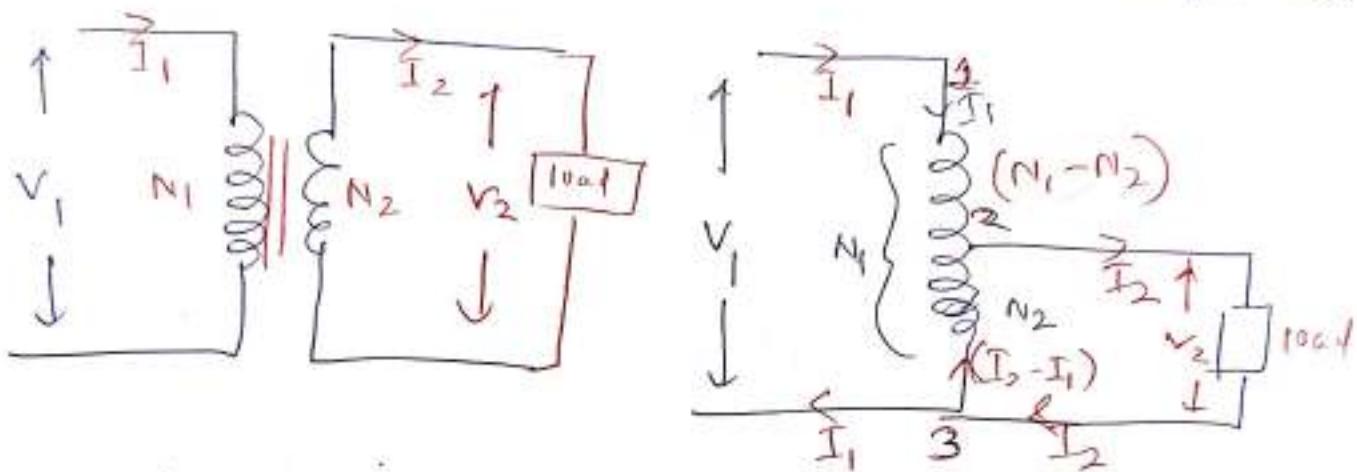
(4)

∴ Saving of 'cv' = $k \times$ wt. of 'cv' in
if $k=0.1$, Saving of cv is $\frac{1}{10}$ of ordinary T/F

(7)

Saving of copper in Auto T/F

For the same off g voltage transformation ratio $k \left(\frac{N_2}{N_1} \right)$, an autotransformer requires less copper than an ordinary two-winding transformer.



weight of copper required in a winding
of current \propto turns

Two winding T/F

weight of cu. required $\propto (I_1 N_1 + I_2 N_2)$

Auto T/F

weight of cu. required in section 1-2 $\propto I_1 (N_1 - N_2)$

weight of cu. required in section 2-3 $\propto (I_2 - I_1) N_2$

Total weight of cu. required

$$\propto I_1 (N_1 - N_2) + (I_2 - I_1) N_2$$

(8)

Weight of cu. in Auto T/F

Weight of cu. in two-winding T/F

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

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

$$= \frac{N_1 I_1 + N_2 I_2 - 2N_2 I_1}{N_1 I_1 + N_2 I_2}$$

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

$$= 1 - \frac{N_2}{N_1} = 1 - k$$

\therefore wt. of 'cu' in Auto T/F (w_a) = $(1-k) \times$ wt. of cu. in ordinary T/F (w_o)

$$\text{or } w_a = (1-k) w_o$$

Saving of copper = $w_o - w_a$

$$= w_o - w_o(1-k)$$

$$= w_o [1 - (1-k)]$$

$$= k w_o$$

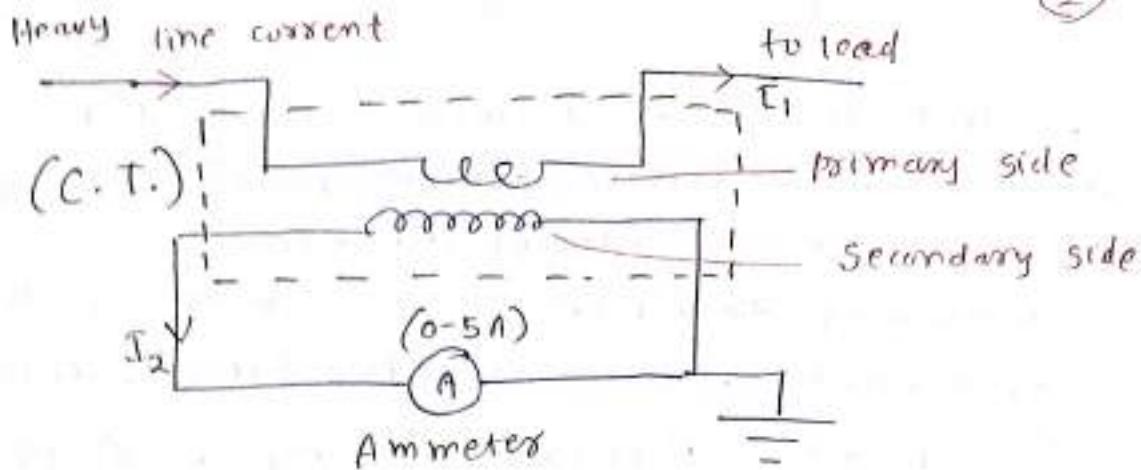
Instrument + transformer

(1)

- Instrument + transformers are used for A.c. measurement i.e. voltage, current, power & energy in conjunction with the relevant instruments.
- Instrument + transformers are small capacity transformers. There are two types of instrument transformer
 - i) current transformer (CT)
 - ii) potential transformer (PT)

current transformer (For measuring large alternating currents)

- i) These instruments or transforms are used with low range ammeters to measure currents in high-voltage alternating current circuits where it is not practicable to connect instruments & meters directly to the lines.
- ii) In addition to ~~the~~ insulating the instruments from the high voltage line, they ~~current~~ step down the current in a known ratio.
- iii) The current transformer (CT) has a primary coil of one or more turns of thick wire connected in series with the line whose current is to be measured. The secondary consists of a large No. of turns of fine wire & is connected across the ammeter terminals



if we want to measure 100 Amp

$$CT \text{ used (ratio)} = 20:1$$

so Ammeter will show = 5 Amp

Note: The secondary circuit of a C.T. should never be kept open, when the primary winding is carrying a current, if the secondary winding of C.T is kept open, high e.m.f might be induced in the secondary winding which causes excessive heating of core & windings, causing accident to human life & damage to C.T.

Burden on secondary of C.T

The product of Voltage & current on the secondary side when the CT is supplying the instruments with its maximum rated value of current, is known as rated burden & is measured in Volt-amperes. The usual rating of a CT is very small 15 VA & in

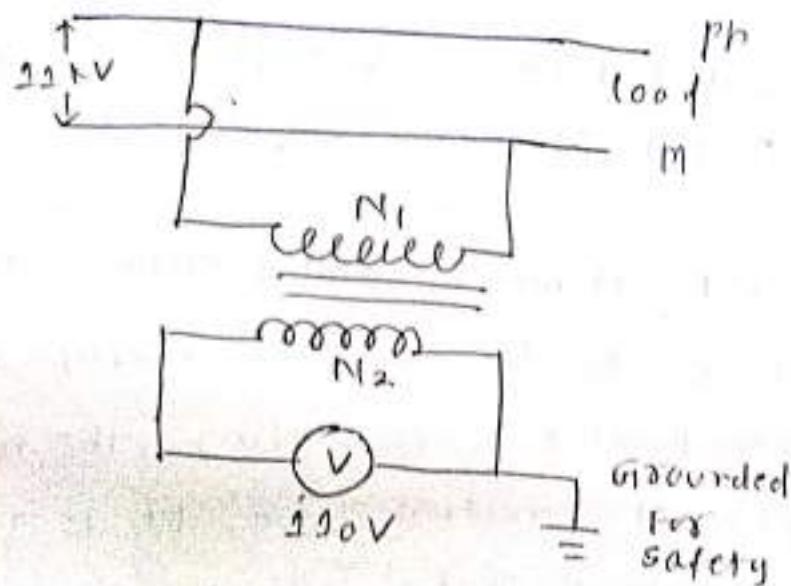
Applications of CT

(3)

- To measure large load currents, such as transmission lines with low range ammeters.
- To operate protective relays.
- To increase the current range of instruments such as wattmeters, energy meter etc.
- To provide necessary electrical isolation between test instruments from the supply.

Potential Transformer (PT) (for measuring high voltages)

- It is a step-down transformer and its principle of operation is same as that of two winding transformer.
- The primary winding of a potential transformer is connected to the system whose voltage is to be measured. The secondary winding of potential transformer is connected to Voltmeter as shown.



(iii) Suppose that the voltage of a system is to be measured be 11 KV. A P.T. of 1:100 turns is used which will step down the voltage from 11 KV to 110 volt.

Applications of PT

- i) To measure high voltage with low voltage voltmeter potential transformer is used.
- ii) used to operate the pilot lights.
- iii) to operate relays,
- iv) to increase the voltage of instruments like wattmeter, energy meter etc.

Nominal transformation ratio (k_n)

It is the ratio of rated primary to the rated secondary current (or voltage).

$$k_n = \frac{\text{rated Primary current } (I_1)}{\text{rated secondary current } (I_2)} \dots \text{for CT}$$

$$= \frac{\text{rated Primary Voltage } (V_1)}{\text{rated secondary Voltage } (V_2)} \dots \text{for PT}$$

In case of CT, it may be stated either as a fraction such as 500/5 or 100/1 simply as the number ~~corresponding~~ representing the numerator of the reduced fraction 100. It is also known as marked ratio.

(3)

Actual transformation ratio

The actual transformation ratio or just ratio under any given condition is

$$k = \frac{\text{primary current} (I_p)}{\text{corresponding secondary current}}$$

$k \neq k_n$ (practical case), For ideal T/F $k=k_n$ for all condition of loadings.

Ratio error (r)

$$r = \frac{k_n - k}{k} = \frac{\text{nominal ratio} - \text{actual ratio}}{\text{actual ratio}}$$

so ratio error may be defined as the difference b/w the primary current reading (assuming the nominal ratio) and the true primary current divided by true primary current.

Ratio correction Factor (RCF)

$$\text{R.C.F} = \frac{\text{actual ratio}}{\text{nominal ratio}} = \frac{k}{k_n}$$

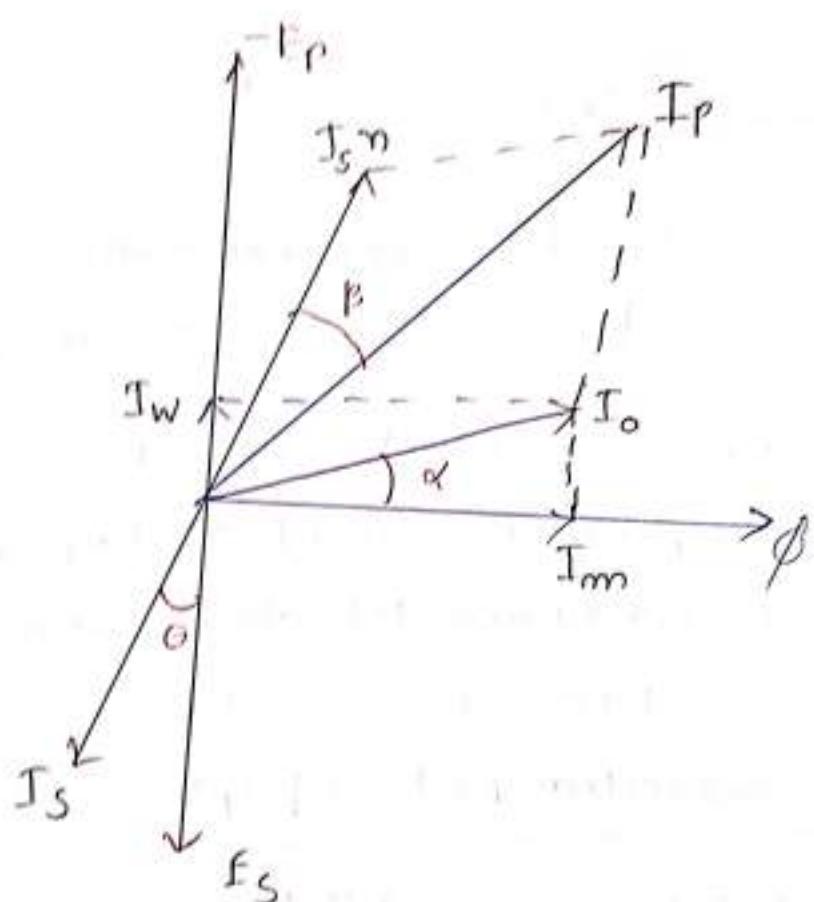
Phase angle error

- In practice, the secondary current of the CT must be in exact phase opposition with the primary current i.e. exactly by 180° phase difference.
- At the time of power measurement, there exists a difference in the phase angle b/w

(6)

Primary & Secondary currents.

- This is due to the fact that primary current has to supply core loss & magnetising components of the CT for which it loses some phase angle.
- The phase angle error can be understood by below phasor diagram of a current transformer.



where I_p = Primary current

I_s = Secondary current

n = turn ratio

I_o = excitation current

I_w = core-loss component

I_m = magnetising component.

(7)

E_p = Primary induced emf

E_s = Secondary induced emf

ϕ = Flux developed

θ = Phase angle error

α = Borden angle

β = Angle b/w flux & excitation current.

→ In the phasor diagram, by taking flux as the reference. If load is connected to the lagging power factor, then the secondary current I_s lags behind the secondary emf E_s .

→ The primary has to supply excitation current components i.e. I_m & I_w . The secondary current can be referred to as primary by multiplying it with turns ratio i.e. nI_s . The vector sum of nI_s & I_o gives the primary current I_p .

→ The phase angle error is given by

$$\theta = \frac{180}{\pi} \left[\frac{I_m \cos \delta - I_w \sin \delta}{nI_s} \right] \text{ degrees}$$

→ In practice, most of the loads (delay or instrument or pilot lights) connected across secondary are inductive in nature.

(8)

→ For inductive loads, δ is +ve but very small.
 Therefore, $\sin \delta \approx 0$ & $\cos \delta \approx 1$. By substituting in
 the above eqn we get,

$$\Theta = -\frac{180}{\pi} \left[\frac{I_m}{nI_s} \right] \text{ degrees.}$$

