WORKING PRINCIPLE OF D.C GENERATOR

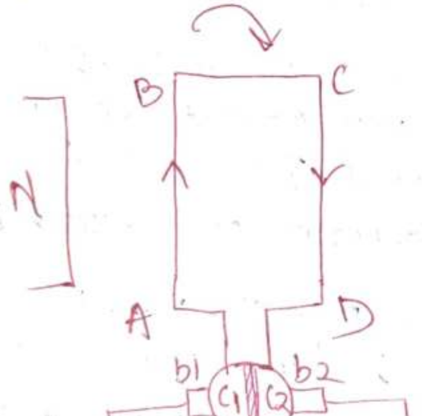
Working of a DC generator based on the principle of Faraday's law of electromagnetic induction. According to Faraday's law of electromagnetic induction, whenever a conductor cuts magnetic flux emf is induced in it.

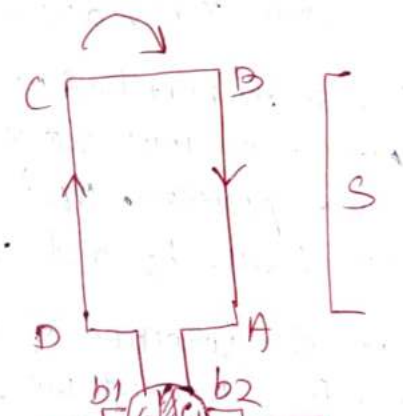
OR

Whenever there is a rate of change of flux in a conductor, emf is induced in it.

This emf causes a current to flow if the conductor circuit is closed.

Let a single turn rectangular coil ABCD is rotating about it's own axis in a magnetic field produced by either a permanent magnet or electromagnet.

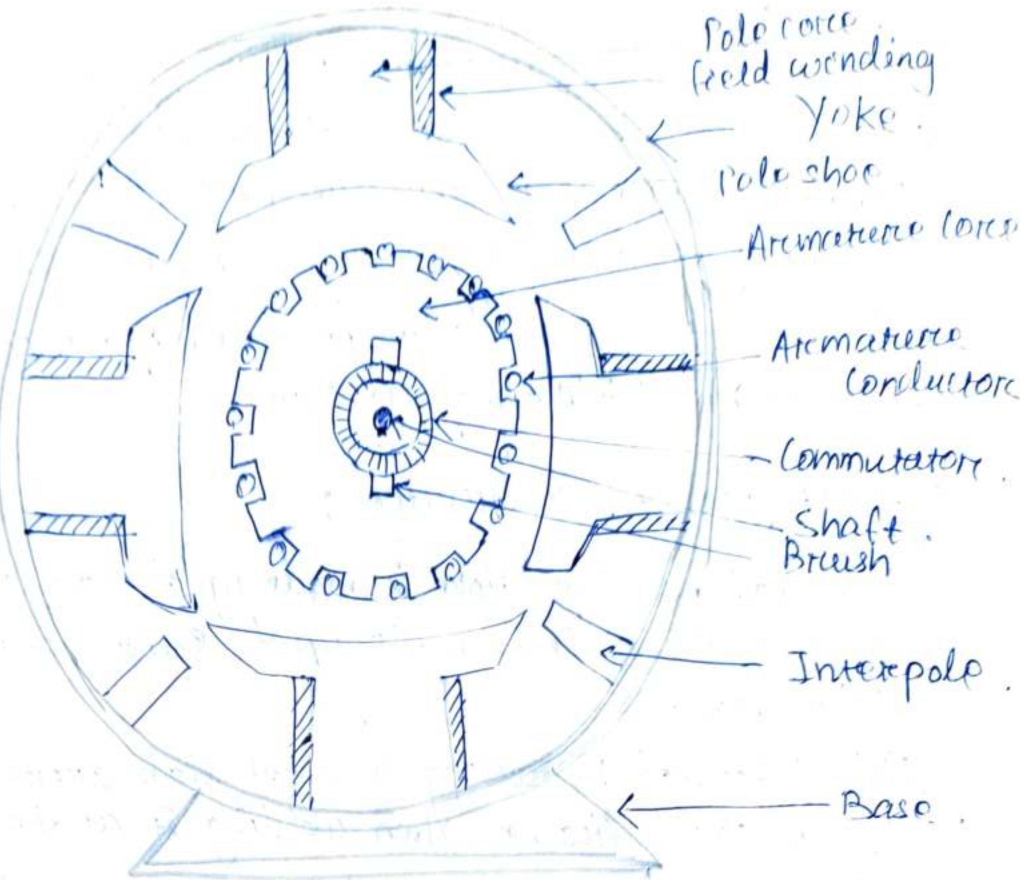




* Two ends of the coils are jointed to the commutator segments i.e. conductor AB is connected to C_1 and conductor CD is connected to C_1. Two collecting brushes are pressed against the commutator segments.
* Let the coil is rotating in clockwise direction. When plane of the coil is right angle to lines of flux as shown in ~~fig a~~, flux linked with the coil is maximum but rate of change of flux is minimum.

* Because in this position the coil sides AB and CD do not cut the flux as they move parallel to the flux. Hence there is no induced emf in the conductor. (at $\theta = 0^\circ$) ($\theta = 0^\circ$ to $\theta = 90^\circ$)
* When the coil moves in clockwise direction, rate of change of flux starts to increase. As a result induced emf also increases.
* When the coil plain is horizontal to the lines of flux, flux linked with the coil is minimum, but rate of change of flux linkage is maximum (fig-2). Hence maximum emf is induced here.
* In the next quarter revolution i.e from $\theta = 90^\circ$ to $\theta = 180^\circ$, flux linkage gradually increases and rate of change of flux decreases. As a result emf decreases from maximum value to zero.
* According to Flemings Right hand rule, direction of current flow is AB-XY-CD. Current through the load resistance is from X to Y during first half revolution.
* But in the next half revolution i.e from $\theta = 180^\circ$ to $\theta = 360^\circ$ both conductors along with the commutator segment change their position. Now commutator segment C_1 is connected with brush b_2 and segment C_2 is connected with brush b_1.
* Now the direction of current flow is DC-XY-BA. But current through the load resistance is from X to Y which is same as first half revolution. So output current is unidirectional but not continuous like pure direct current.

CONSTRUCTION OF DC MACHINE



The main parts of a DC machine are.

(i) Yoke.
(ii) Pole core and pole shoe.
(iii) Field winding
(iv) Armature core.
(v) Armature winding or conductor.
(vi) Commutator.
(vii) Brushes and bearing
(viii) Interpole
(ix) Shaft.
(x) Slot
(xi) Base.

YOKE

Yoke is the outermost covering of a DC machine. It is also called as Frame.

Function:-

(i) It provides mechanical support for poles.

(ii) It provides protection to whole machine from harmful atmospheric elements like dust, moisture, SO_2, Acid etc.

(iii) It also provide protection against mechanical injury.

(iv) It carry the magnetic flux produced by the poles or it provides path for the magnetic flux.

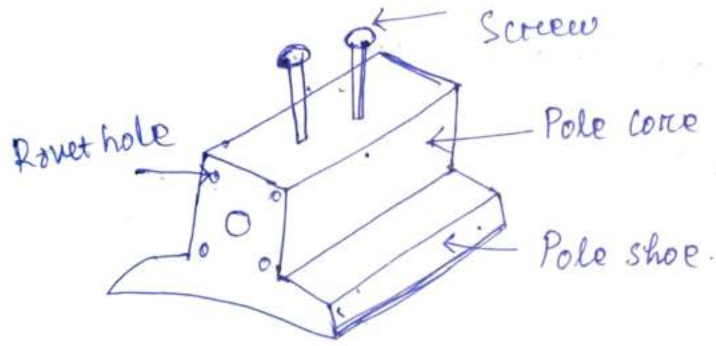
Material used and construction:-

(i) For small machine Yoke is made up of cast iron and for large machine it is made up of Silicon steel or Cast steel.

(ii) It is formed by rolling a steel slab around a cylindrical frame, then welding it at the bottom.

(iii) Then the feet and terminal box etc are welded to the frame.

POLE CORE AND POLE SHOE



(i) The Field magnet consist of pole core and pole shoe.

(ii) The pole cores are fixed to the magnetic frame or Yoke by the screw/bolt.

(iii) Each pole core has a curved surface which is called as pole shoe.

Function :-

(i) It supports and hold the field winding.

(ii) Pole shoe increases the cross-sectional area of magnetic ckt. As a result reluctance of the magnetic path is reduced.

(iii) Due to pole shoe, the magnetic flux spread in the air gap uniformly.

Material used and Construction:-

(i) The pole core and pole shoe are made of thin lamination of cast steel which are rivetted togethere undere hydraulic pressure.

(rivet → passing metal pins through holes in two or more metal plates to held them together)

(ii) The thickness of the lamination varied from 0.25 mm to 1 mm.

(iii) Lamination of core is required to reduce eddy current loss..

FIELD WINDING

(i) Field winding are used to form electromagnet and wound on the pole core with a definite direction.

(ii) Field winding carry current to form electromagnet and to produce necessary flux.

(iii) Field coils are connected in series with each othere and in such a direction pole core so that alternate 'N'-pole and S-pole are formed.

(iv) Generally field winding is made up of copper.

ARMATURE CORE.

(i) It is the rotating part of DC machine and connected to the shaft.

(ii) A prime-mover is connected to the shaft to move the armature.

Functions:—

(i) It holds the armature conductor and causes them to rotate, so the armature conductors cut the magnetic field and an emf is induced in them.

(ii) It provides a path of very low reluctance to the flux through the armature from N-pole to S-pole.

Material used and construction:-

(i) It is cylindrical or drum shape and made of circular laminated silicon steel sheet or disc.

(ii) The thickness of the lamination varied from 0.25mm to 1mm.

(iii) The slots are punched on the outer periphery of the disc.

(iv) The lamination are perforated for air ducts which permits axially flow of air through the armature for cooling purpose.

(v) The purpose using lamination is to reduce eddy current loss.

(vi) If the laminations are thinner, then resistance offered to the current is greater. Hence I^2R loss in core is less.

ARMATURE WINDING.

(i) Armature winding is interconnection of armature conductors placed in the slots.

(ii) Armature winding are made up of copper and insulated from each other and from armature core.

(iii) Armature winding can be done by two method

(1) Wave winding

(2) Lap winding

(iv) In lap winding number of parallel path is equal to no of pole but in wave winding no of parallel path is equal to 2.

COMMUTATOR:-

(i) The function of commutator is to collect current from the armature conductors.

(ii) It convert AC induced in the armature conductor into unidirectional current.

(iii) It is of cylindrical structure and made up of wedge shaped segment of hard drawn copper.

(iv) These segments are insulated from each other by thin layer of mica.

BRUSHES AND BEARINGS:-

(i) The function of brushes is to collect current from the commutator and supplied it to the external ckt.

(ii) Brushes are placed in brush holder which are rest on the commutator.

(iii) Brushes are usually made of carbon and are in the shape of a rectangular box.

(iv) The function of bearing are to reduce friction between rotating and stationary part of the machine.

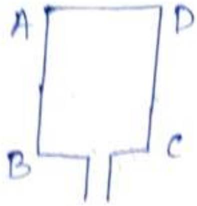
SHAFT

(i) Rotating parts like armature core, commutator, cooling fans are mounted on the shaft.

(ii) Shaft is made of mild steel with a maximum breaking strength or mechanical strength.

ARMATURE WINDING

Conductor:- The length of wire laying in the magnetic field and in which emf is induced is called a conductor.

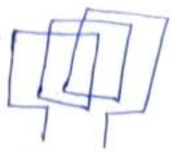


AB = CD = Conductor.

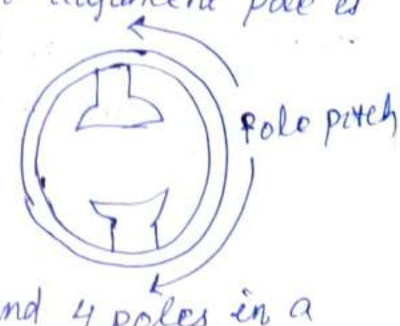
Coil:-

→ Two conductors AB and CD along with their end connection constitute one coil of the armature winding.

→ Coil may be of two types

(1) Single turn  (2) Multi turn 

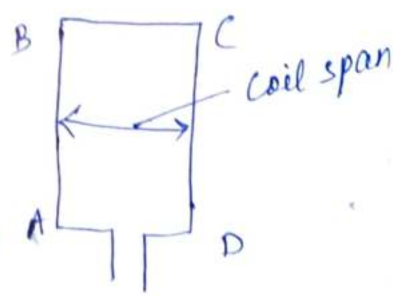
Pole Pitch:- The distance between two adjacent pole is called Pole pitch.



→ It is equal to the no of armature conductors or armature slots per pole.

e.g → If there are 48 conductors and 4 poles in a generator, then pole pitch = $\frac{48}{4} = 12$.

Coil Pitch/Coil Span:-



→ The distance between two sides of a coil is called coil pitch.

→ According to length of coil pitch winding of armature is divided into two types

(1) Full Pitch winding

(2) Fractional Pitch winding.

Full-Pitch Winding:-

(i) If coil pitch is equal to pole pitch, then the winding is called full pitch winding.

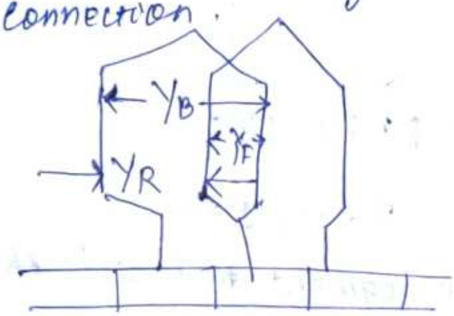
(ii) In this case the coil sides lies under opposite pole, hence induced emf in them are additive in nature.

Fractional-Pitch Winding:-

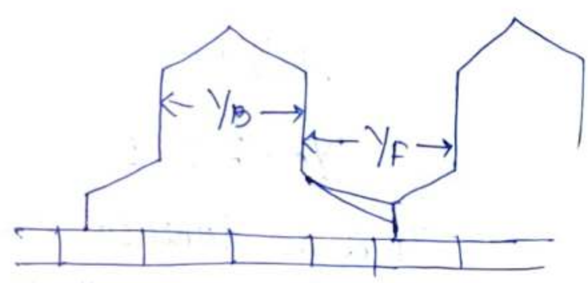
(i) If coil pitch is less than pole pitch, then the winding is called fractional pitch winding.

(ii) In this case, there is a phase difference between the emf in two sides of the coil. So total emf is the vector sum of emf in the two coil sides.

(iii) The main advantage of is saving of copper at the end connection.



$Y_R = Y_B - Y_F$



$Y_R = Y_B + Y_F$

Back Pitch:—

→ The distance covered by a coil on the back side of the armature is called back pitch.

→ It is denoted by 'Y_B'.

Front Pitch:—

→ The number of armature conductor covered by a coil on the front end of the armature is called Front Pitch.

→ It is denoted by 'Y_F'.

→ Front Pitch may be defined as the distance between second conductor of one coil and the first conductor of another coil.

Resultant Pitch:-

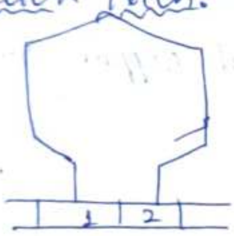
→ It is the distance between first side of first coil and first side of the second.

→ It is denoted by Y_R.

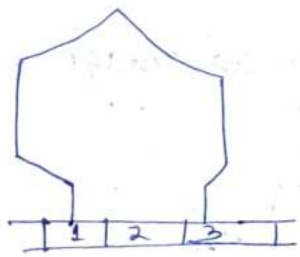
For lap winding $Y_R = Y_B - Y_F$

For wave winding $Y_R = Y_B + Y_F$

Commutator Pitch:-



$Y_C = 2-1 = 1$



$Y_C = 3-1 = 2$

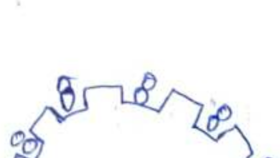
→ It is the distance between the segment to which the two ends of a coil are connected.

→ It is denoted by Y_C.

Single layer winding:-

→ In which winding, one conductor or one coil sides is placed in each armature slots is called single layer winding

Two layer winding:-



→ In this type of winding there are two conductor or coil sides per slot arranged in two layers.

SIMPLEX LAP WINDING

Rules:-

(i) Both front Pitch and back Pitch should be odd, otherwise it would be difficult to place the coil properly on the armature.

(ii) No of commutator segment is equal to no of slots or coil because the front end of the conductors are joined to the segment in pairs.

(iii) The Back Pitch and front pitch can not be equal, they differ by two or some multiple of two.

$$Y_B = Y_F \pm 2m \quad (m = 1, 2, 3)$$

1 → Simplex 2 → Duplex 3 - Multiplex

(iv) Both Front Pitch and Back Pitch should be nearly equal to pole pitch.

(v) Commutator Pitch (Y_C) is equal to ±1.

(vi) No of slots for a two layer winding is equal to the no of coils.

(vii) The no of parallel path in the armature is equal to no of poles.

(viii) (a) Progressive winding

$$Y_F = \frac{Z}{P} - 1 \qquad Y_B = \frac{Z}{P} + 1 \qquad (Y_B > Y_F)$$

(b) Retrogressive winding

$$Y_F = \frac{Z}{P} + 1 \qquad Y_B = \frac{Z}{P} - 1 \qquad (Y_F > Y_B)$$

WAVE WINDING.

Rules:-

(i) Both back pitch and front pitch are odd.

(ii) Back Pitch and front pitch are nearly equal to pole pitch, they may be equal or differ by two.

(iii) Resultant Pitch : $Y_R = Y_B + Y_F$

(iv) Commutator Pitch $Y_C = Y_A$

(v) $Y_C = \frac{\text{no of commutator bar} \pm 1}{\text{No of pair of poles}}$

(vi) Average pitch $Y_A = \frac{Z \pm 2}{P}$

or $\frac{\text{No of commutator bars} \pm 1}{\text{No of pairs of poles}}$

EMF EQUATION OF DC GENERATOR.

Let, P = No of poles

Z = Total No of armature conductors

ϕ = Flux per pole

N = Speed of the armature in RPM.

A = No of parallel path.

According to Faraday's law of electromagnetic induction, induced emf

$$E = \frac{d\phi}{dt} \quad \text{--- (1)}$$

Since, the flux per pole is ϕ, each conductor cuts flux in one revolution equal to $P \times \phi$

$$\text{so, } d\phi = P \times \phi$$

N revolution in 1 min/60 sec.

1 revolution in = $\frac{60}{N}$ sec.

So, $dt = \frac{60}{N}$ sec.

Now putting the value of $d\phi$ and dt in equation 1

Induced emf $E = \frac{P\phi}{60/N} = \frac{P\phi N}{60}$ Volt

(It is the induced emf per conductor)

Total generated emf will be determined from no of armature conductor in series in any one path between the brushes.

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

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

for wave winding A = 2

$$E_g = \frac{P\phi Z N}{60 \times 2} = \frac{P\phi Z N}{120}$$

For lap winding (A = P)

$$E_g = \frac{P\phi ZN}{60\,A\times P} = \frac{\phi ZN}{60}$$

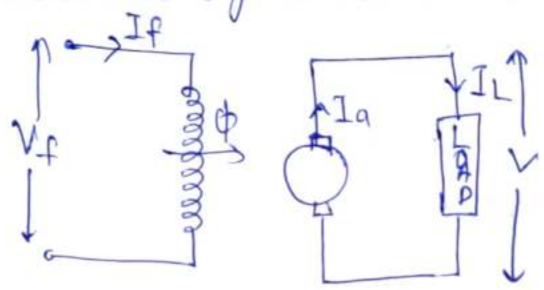
Classification of DC Generators:-

Depending upon the excitation of field, DC generator is divided into two types.

(1) Separately excited DC generator.

(2) Self excited DC generator.

Separately Excited DC generator.



$E_g = I_aR_a + V + V_B$

(i) In separately excited DC generator a separate voltage source is used to excite the field.

(ii) The field and armature circuits are electrically isolated and magnetically coupled.

(iii) This type of generator can give wide range of voltage. Output voltage of the generator can be easily changed by changing the field current.

Self Excited Generator.

i) In self excited generator the field winding is excited by the current produced by the generator itself.

ii) A part of current or entire current produced can be used for excitation of field winding.

(iii) Due to residual magnetism some magnetic flux always remains present in the coil of magnetic poles to start the generator.

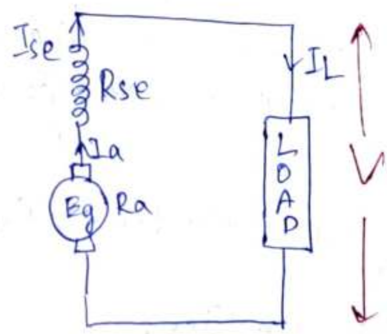
(iv) There are three types of self excited generator

(1) Series Generator.
(2) Shunt Generator.
(3) Compound Generator.

SERIES GENERATOR.

(i) In series generator field winding is connected in series with the armature.

(ii) Field winding is made up of thick wire with less no of turns.



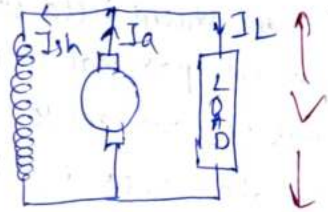
$$E_g = I_aR_a + I_{se}R_{se} + V + V_b$$

$$I_a = I_{se}.$$

SHUNT GENERATOR.

(i) In shunt generator field winding is connected in parallel to the armature.

(ii) The field winding is made up of thin wire with more no of turns.



$$E_g = I_aR_a + V + V_b$$

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

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

COMPOUND GENERATOR.

(i) In a Compound generator both series and shunt field are present.

(ii) Series winding has less no of turns and shunt winding has more no of turns.

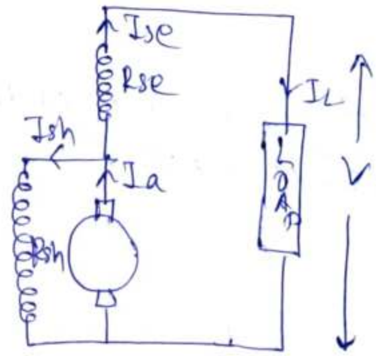
(iii) According to the connection compound generator is divided into two type.

(1) Short shunt compound generator.

(2) Long shunt compound generator.

Short shunt Compound generator.

If shunt field winding is only connected parallely with the armature, then the generator is called short shunt gen.



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

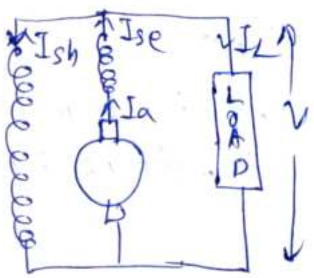
$I_a = I_{sh} + I_{se}$.

$I_{se} = I_L$.

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

Long shunt Compound gen.

If the shunt field winding is ~~only~~ connected parallally both with armature and series field winding, then the generator is called as long shunt DC generator.



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

$I_a = I_{sh} + I_L$.

$I_{se} = I_a$.

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

* According to the nature of flux compound generator is divided into two types
  (1) Cumulatively Compounded generator
  (2) Differentially Compounded generator.

* When the series field aids the shunt field, the generator is said to be cummulatively compounded generator.

* If series field opposes the shunt field, then the generator is said to be differentially compounded generator.

LOSSES OF DC MACHINE

- Copper loss
  - Series field cu loss
  - Shunt field cu loss
  - Armature cu loss
- Iron loss
  - Hysteresis loss
  - Eddy current loss
- Mechanical loss
  - Frictional losses
  - Windage losses

Iron loss

Due to rotation of the armature core in the magnetic flux of field poles, some losses takes place continuously in the core and are known as Iron loss.

There are two types of irons loss.

⇒ Eddy current loss.

⇒ Hysteresis loss.

Eddy current loss:-

⇒ When a armature core rotates it also cuts the magnetic flux. Hence an emf is induced on the surface of the armature according to Faraday's law of electro magnetic induction

⇒ This emf is small, but set up circulating current (leakage current) on surface of armature due to it's low resistance.

⇒ This current is known as eddy current and losses due to flow of this current is known an eddy current loss.

⇒ In order to reduce this loss, the core is built up of thin laminations. These laminations are insulated from each other by thin coating of Varnish.

⇒ When the core body is a single continuous iron piece, the magnitude of eddy current is large, because the armature cross-sectional area is large and resistance is small.

⇒ ~~Eddy current loss rises~~ When the core is laminated, the cross sectional area decreases and resistance increases.

As a result eddy current loss get reduced.

⇒ Eddy current loss rises the temperature of core and reduces the the efficiency of the generator

$$We = K B_{max}^2 f^2 t^2 V^2 \text{ Watt}$$

f = frequency of magnetic reversal
Bmax = flux density.
t = thickness of lamination
V = volume of core

Hysteresis loss:—

⇒ Hysteresis loss is due to reversal of magnetisation of armature core.

⇒ When the armature core exposed to one pair of pole, it undergoes one complete rotation of magnetic reversal.

⇒ The portion of the armature which is under N pole, after ~~one~~ completing half revolution it will be under S Pole.

⇒ This constant process of magnetic reversal in the armature core, consume some amount of energy which is called hysteresis loss

⇒ The frequency of magnetic reversal is given by

$$f = \frac{PN}{120}$$

⇒ The loss depends upon the volume and grade of iron, frequency of magnetic reversal, value of flux density.

$$W_h = \eta B_{max}^{1.6} f V \text{ Watt}$$

where η = Steinmetz hysteresis constant.
Bmax = flux density.
f = frequency of magnetic reversal.
V = Volue of core.

⇒ Hysteresis loss can be reduced by using Silicon steel to made armature core.

COPPER LOSS

When current flows through the conductor I^2R loss (~~and~~ heat loss) takes place in them. This loss is known as copper loss.

Armature Cu loss:-

I^2R loss in the Armature conductor is known as Armature Cu loss. Armature cu loss $= I_a^2 R_a$

where I_a = Armature current
R_a = Armature Resistance.

Shunt Cu loss:-

I^2R loss in the shunt field winding is called shunt cu loss.

Shunt Cu loss $= I_{sh}^2 R_{sh}$.

where I_{sh} = Shunt field current.
R_{sh} = Shunt field resistance.

Series cu loss:-

I^2R loss in series field winding is called series field cu loss.

Series field Cu loss $= I_{se}^2 R_{se}$

where I_{se} = Series field current
R_{se} = Series field resistance.

* With change in load Armature cu loss and series field cu loss vary. So they are variable losses. But shunt field cu loss almost remains constant with change in load. So shunt Cu loss is called as constant loss.

Mechanical Loss.

Mechanical loss consist of

(1) Friction loss at bearing, commutator, brushes (moving parts of machine)

(2) Air friction or windage loss of due to friction of rotating armature and air.

If speed of a generator is constant, then this type of ~~generator is~~ loss is almost constant. So it is also called as constant loss.

STRAY LOSS → Generally mechanical loss and Iron loss are collectively known as stray loss. They are produced due to rotation of the armature. Therefore these are also known as rotational losses.

| Stray loss = Mechanical loss + Iron loss |

Constant loss

⇒ Value of these losses don't change with change in load.

⇒ Shunt cu loss and stray losses together known as constant loss.

| Constant loss = Shunt cu loss + Stray loss |

Variable loss

⇒ Value of these losses. ~~do not~~ changes with change in load.

⇒ Armature cu loss and series cu loss together known as variable loss.

| Variable loss = Armature cu loss + series cu loss |

Power flow diagram/Power stages of DC generator.

Mechanical i/p or o/p of Driving engine or primover → Mechanical loss & Iron loss → Electric power developed in armature. $= E_g I_a$ Watt →

Total Cu loss → Electrical power output $P_{o/p} = V I_L$ Watt

Mechanical efficiency $= \frac{\text{Electric power developed in armature.}}{\text{Mechanical i/p}}$

$= \frac{E_g I_a}{\text{Mechanical power i/p}}$

Electrical efficiency $= \frac{\text{Electrical power output}}{\text{Electrical power developed in armature}}$

$= \frac{V I_L}{E_g I_a}$

overall efficiency $= \frac{\text{Electrical power o/p}}{\text{Mechanical power i/p}} = \frac{V I_L}{\text{Mechanical power i/p}}$

overall efficiency $= \eta_m \times \eta_e$

Condition for maximum efficiency (shunt generator)

Generator output $= V I_L$ Watt

Generator input = output + losses

$= V I_L$ + Constant losses + Variable losses

$= V I_L + W_c + I_a^2 R_a$

Efficiency $= \frac{P_{o/p}}{P_{i/p}}$

$$\eta = \frac{VI_L}{VI_L + W_c + I_a^2 R_a}.$$

$$= \frac{VI_L}{VI_L\left(1 + \frac{W_c}{VI_L} + \frac{I_a^2 R_a}{VI_L}\right)}.$$

for a shunt generator $I_a \simeq I_L$ (as I_{sh} is small)

so $$\eta = \frac{1}{1 + \frac{W_c}{VI_L} + \frac{I_L^2 R_a}{VI_L}}$$

$$\Rightarrow \eta = \frac{1}{1 + \frac{W_c}{VI_L} + \frac{I_L R_a}{V}}$$

Now η is maximum when it's denominator is minimum.
i.e when $\frac{d}{dI_L}\left[\frac{W_c}{VI_L} + \frac{I_L R_a}{V}\right] = 0$.

$$\Rightarrow -\frac{W_c}{V} \times \frac{1}{I_L^2} + \frac{R_a}{V} = 0$$

$$\Rightarrow \frac{R_a}{\cancel{V}} = \frac{W_c}{\cancel{V} I_L^2}$$

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

or $$\Rightarrow \boxed{W_c = I_a^2 R_a}$$

$\Rightarrow$ **Constant loss = Variable loss**.

Therefore efficiency of a generator is maximum it's constant loss is equal to variable loss.

Power flow diagram/power stages of DC generator

First Mechanical Energy is given to shaft of the DC generator through a primover. The primover may be a Driving engine, a motor or a turbine. So we can say Output of Prime-mover = Mechanical i/p to the generator

$$\boxed{\text{Output of Prime-mover} = P_{i/p}}$$

Then the armature starts to rotate. As a result all rotational losses (iron loss + Mechanical loss) takes place. After rotational losses/stray losses rest amount of mechanical power converted to electrical power at the armature. So generated electrical power is given by $E_g I_a$.

Mechanical input to generator = Stray losses + generated electrical power at armature

$$\Rightarrow \boxed{P_{i/p} = \text{stray losses} + E_g I_a}$$

When current flows through the windings of the generated some of generated electrical power will be wasted in copper loss. After copper loss rest electrical power will move to load. $P_{o/p} = V I_L$

So $$\boxed{E_g I_a = \text{Copper loss} + V I_L}$$

$E_g I_a$ = generated electrical power.

$V I_L$ = Output power at load.

Stray loss = Mechanical + Iron loss

Copper loss = $I_a^2 R_a + I_{se}^2 R_{se} + I_{sh}^2 R_{sh} + I_a^2 R_I$

(according to type of generator)

ARMATURE REACTION

⇒ Armature reaction is the effect of magnetic field set up by the armature current on the main flux of generator.

OR

In a DC machine two kinds of flux are present i.e. ~~are~~ armature flux and main field flux. The effect of armature flux on the main flux is called Armature reaction.

MNA (Magnetically neutral axis)

⇒ An Emf is induced in the armature conductors when they cut magnetic field lines.

⇒ But there is an axis along which armature conductors move parallel to the magnetic flux and there is no induce emf along this axis. This axis is known as magnetically neutral axis.

⇒ So MNA may be defined as the axis along which no EMF is generated in the armature conductors.

⇒ Brushes are always placed along MNA axis. Because reversal of current takes place in this axis.

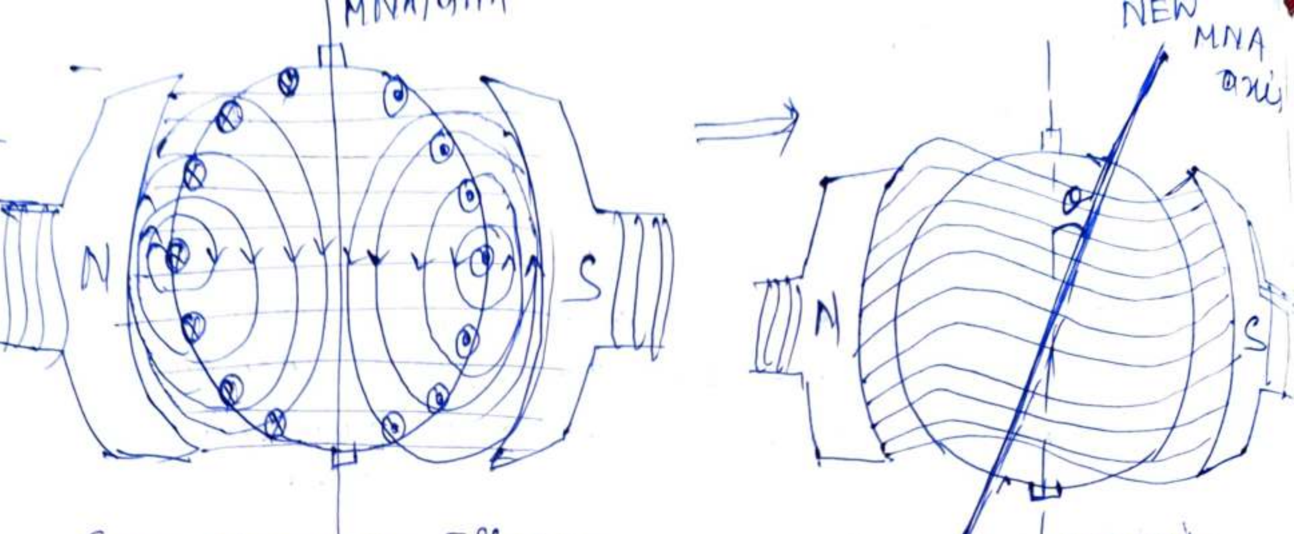
GNA (Geometrically neutral axis)

⇒ GNA is defined as the axis which is perpendicular to the main field axis.

⇒ Consider no current is flowing through armature conductor and only field winding is energised. In this case flux lines due to main field pole are uniform. So MNA coincides with GNA as shown in fig-1.

But when the generated is loaded, armature current starts to flow which causes armature flux. Now the armature flux super imposed with the main flux and disturb it. This is called armature Reaction. Armature Reaction has two effects.

1) Cross magnetising effect.
2) De magnetising effect.



Cross Magnetising Effect :-

⇒ At no load condition ~~Magne~~ MNA coincides with GNA. But when the generator is loaded current starts flowing through the armature conductor. Direction of the current found by Flemings Right hand Rule.

⇒ So current direction is inward in the conductor under 'N' pole and outward under 'S' pole.

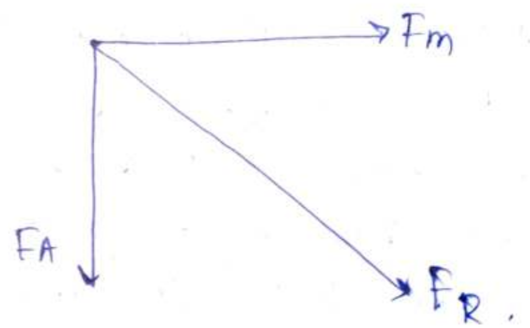
⇒ The direction of lines of force around the Armature conductor can be found by applying Right hand thumb rule.

⇒ According to Right hand thumb rule direction of Armature flux under 'N' Pole is clockwise and under S pole is anticlockwise.

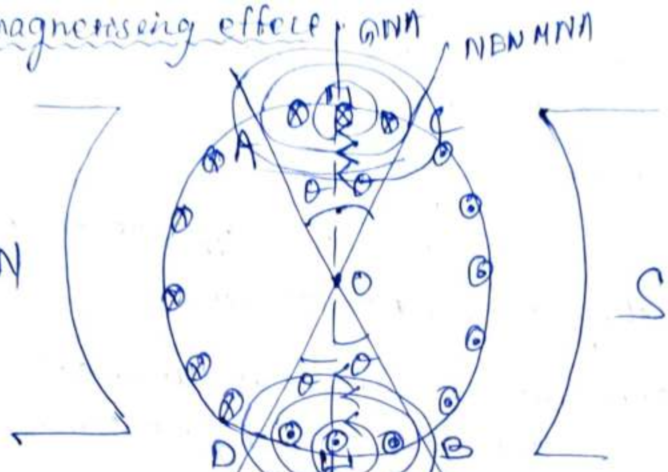
⇒ Now it is seen that the main flux through the armature is No longer uniform.

⇒ Now the MNA axis will shift to a new position, as a result spark will produce at Brushes.

⇒ Here angle between main field and armature field is 90°. So the Resultant field is found by vector addition of main flux and armature flux.



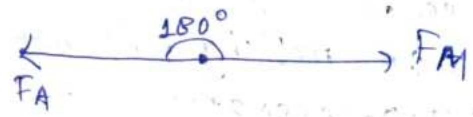
Demagnetising effect



⇒ Due to cross-magnetising effect, MNA is shifted to a new position which is at angle θ from GNA.

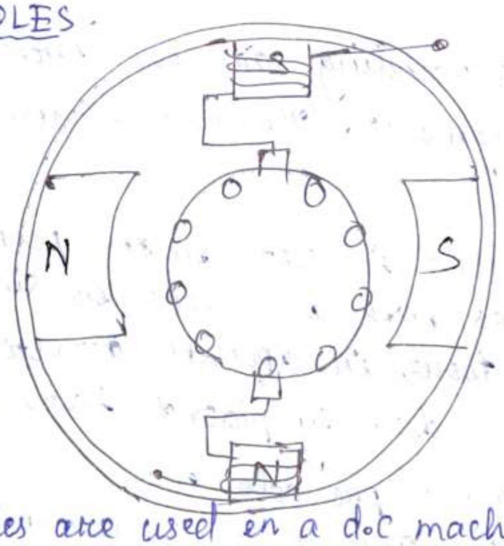
⇒ Conductors in regions AOC and BOD at the top and Bottom of the armature carry current in such a direction that direction of armature flux is from right to left. So the main flux get reduced.

$F = F_m - F_A$



HOW TO REDUCE ARMATURE REACTION

① INTERPOLES.



⇒ Interpoles are used in a d.c machine to reduce armature Reaction. Interpoles are small poles fixed to YOKE and placed in between the main poles.

⇒ Interpole winding is connected in series with the armature winding so that they can carry full armature current to neutralise the armature reaction.

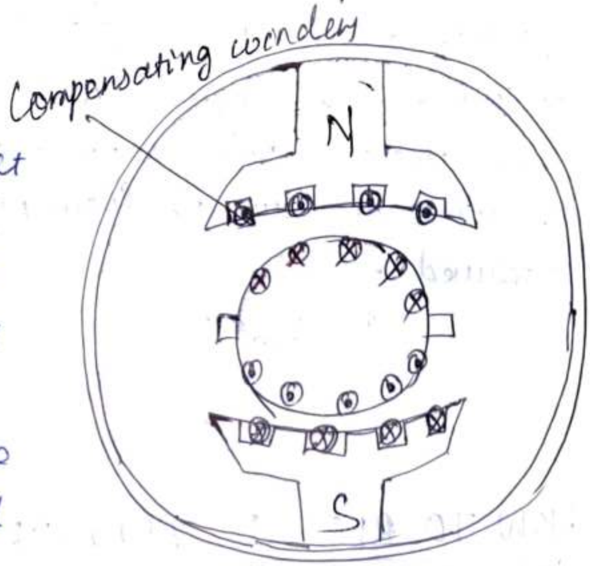
⇒ Their polarity is same as that of main pole ahead in the direction of rotation.

⇒ The function of interpole is to neutralise the cross-magnetising effect of armature reaction. Hence the MNA axis can not shift from it's original position.

⇒ Here flux produced by the interpole is just opposite to the armature flux. Hence they cancel each other.

⇒ This cancellation of cross magnetisation is automatic and for all loads. Because both are produced by the same armature currents.

2) COMPENSATING WINDING



⇒ These are used for large direct current machines which are subjected to large fluctuations in load i.e. rolling mill motor and turbo-generator.

⇒ Their function is to neutralize the cross magnetizing effect of armature reaction.

⇒ In absence of compensating winding arc can strick between consecutive commutator segments. This may further short circuit the armature.

⇒ These windings are placed in slots in the pole shoes and are connected in series with armature in such a way that current in them flows in opposite direction to that of armature conductors directly placed below the poles.

⇒ Compensating winding must provide sufficient emf so as to counterbalance the armature conductor.

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

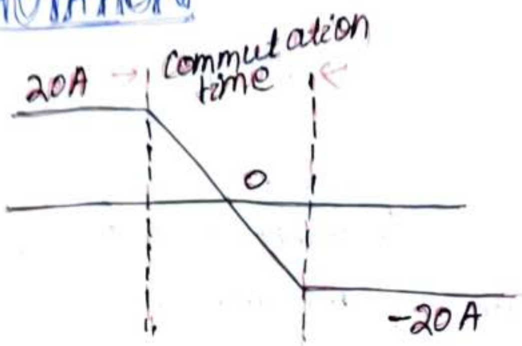
Z_c = no of compensating conductor/pole

Z_a = No of active armature conductor/pole

I_a = Total Armature Current.

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

COMMUTATION



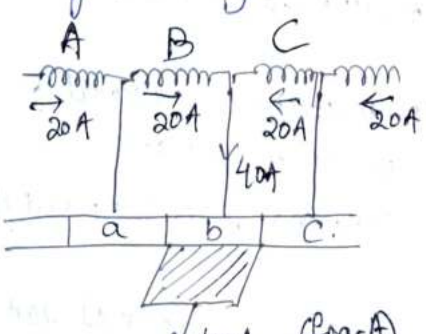
⇒ Current induced in the armature conductors are alternating in nature. To make their flow unidirectional in the external circuit we need a commutator.

⇒ Current flow in one direction when armature conductors are under 'N' pole and in opposite direction when they are under 'S' pole. As conductors pass out from the influence of a 'N' pole and enter the S-pole, current in it is reversed.

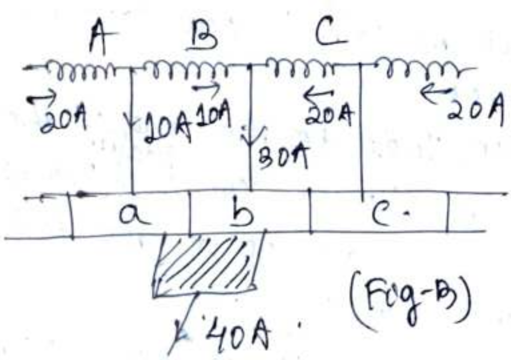
⇒ This reversal of current takes place along the MNA axis. The process by which current is reversed in a conductor while it passes the MNA axis is called commutation.

⇒ Total time required for this process is called as commutation period.

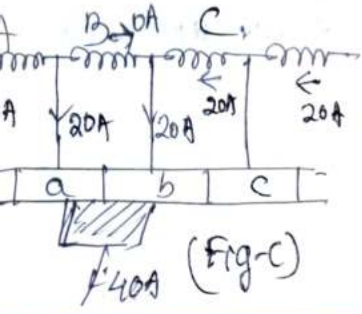
Let us consider that brush width is equal to one commutator segment of a simp generator having simple ring winding. Here we will observe coil 'B'.



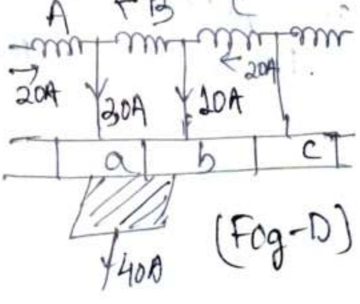
(Fig-A)



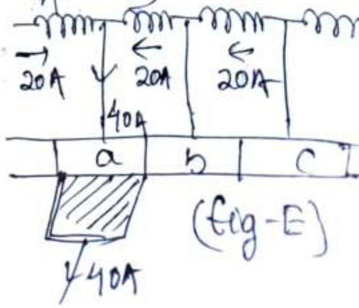
(Fig-B)



(Fig-C)



(Fig-D)



(Fig-E)

⇒ If current reversal (change of current from +I to -zero and to -I) is completed in commutation period, then the Commutation is called ideal.

⇒ If current reversal is not completed with in commutation period, then the commutation is ~~call~~ not ideal and sparking takes place between brushes and commutator.

⇒ It is assumed that each coil carries 20A current so that output of brush is 40A.

⇒ In fig-~~A~~ the coil B is going short circuited because the brush is about to come in contact with commutator segment (a). Here current through coil B is 20 Amp and total current output is 40A.

⇒ In fig-B 1/3 (one third) of the brush is in contact with commutator segment 'a' and the remaining 2/3 part with segment 'b'. As a result current in the coil B reduced from 20 A to 10 A. Because other 10A current flows through commutator segment 'a' to the brush as shown in fig 'B'.

⇒ Fig(C) shows coil B in the middle of it's commutation period or short circuit period. Now current through the coil is reduced to zero.

⇒ In fig(d) 1/4 part of brush of b will be in contact with commutator b, and 3/4 part in contact with the segment 'a'. As a result the coil 'B' now carries 10A current in reverse direction

⇒ Fig (e) Indicates the end of the commutation period. Now the Brush comes totally in contact with commutator segment 'a' and hence the coil 'B' carries 20A current in reverse direction.

⇒ But if coil B carries 15A current in place of 20A, even after commutation period, current jumps directly from segment 'b' to brush through air. This produces ~~arc~~ spark

METHODS OF IMPROVING COMMUTATION

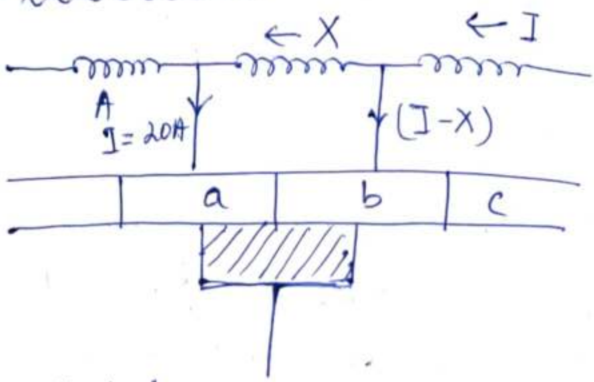
There are two practical ways of improving commutation. By improving commutation current reversal in short circuited coil can be done without spark.

The two methods are

1 → Resistance commutation

2 → EMF commutation.

Resistance commutation.



⇒ In this method low resistance copper brushes are replaced by high resistance carbon brush.

⇒ In the above figure it is seen that current 'I' in the coil 'C' has two paths to reach the brush. The first path is straight commutator segment 'b' to brush and other is via coil 'B' to commutator segment 'a' and then to the Brush.

⇒ If Cu brushes are used, they have low resistance. So I will choose the shortest path to flow. As a result poor commutation occurs.

⇒ But if carbon brushes are used, flow of current will depend upon the contact area of the Brush with the commutator segment.

⇒ If contact area is larger then Resistance offered by the brush will be less and more current will flow. Therefore reversal of current is completed within commutation time period.

EMF Commutation

⇒ In this method, arrangement is made to neutralise the reactance voltage by inducing a reversing emf in the short circuited coil under commutation.

⇒ This reversing EMF is in opposition to the Reactance Voltage. If it is equal to the reactance emf, quick reversal of current is done in short circuited coil.

⇒ The reversing EMF may be produced by
- → giving the brushes a forward lead.
- → by using interpoles.

Brush shifting Method.

In this method brushes are shifted in forward direction. As a result the short circuited coil comes under the influence of opposite polarity.. So a reversing flux is produced.

Compensating winding

Using Interpoles-

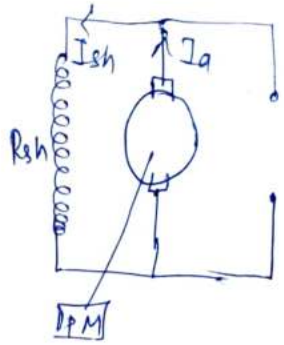
→ Small poles are placed in between the main poles to improve commutation. These poles are called as interpole.

→ These interpoles induce an emf in the short circuit coil during the commutation period which oppose the reactance voltage and give spark-less commutation.

Critical Resistance of a Shunt Generator:-

Critical Resistance is the value of field Resistance above which if it is increased, then voltage build up in a shunt generator will be zero.

VOLTAGE BUILD UP of Shunt Generator:-



⇒ Before loading a shunt generator it is first allowed to build up it's voltage.

⇒ Usually there is always present some residual magnetism in the poles, Hence when we rotate the armature a small emf is produced initially.

⇒ This emf circulate a small current in the field circuit which increases the pole flux.

⇒ When flux is increased, generated emf is increased which further increases the flux and so on.

⇒ This process is called as Voltage build up of shunt generator.

⇒ As there is no load, generated emf only give supply to field resistance. If generated emf is greather than the ohmic drop ($I_{sh} R_{sh}$) energy would continue to stored in field pole.

⇒ If field resistance is greater then critical resistance, generator will fail to excite.

Condition for voltage build up:-

(i) There must be some residual magnetism in generator poles.

(ii) If excited on open circuit, it's shunt resistance should be less then critical resistance.

(22) For the given direction of rotation, the shunt field coils should be correctly connected to the armature so that flux due to field current and residual magnetism are in same direction .

CHARACTERISTICS OF DC GENERATOR

A DC generator generally has three types of characteristics.

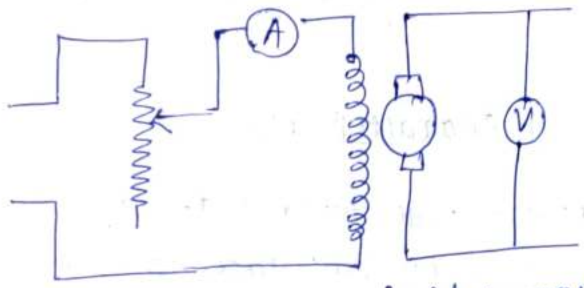
1) No load saturation characteristics or open circuit characteristics
⇒ It shows the relation between No-load generated EMF in the armature and field current at a fixed speed. It is just like the magnetisation curve for the material of a electromagnet.

2) Internal Characteristics
⇒ It gives the relation between actual emf induced in the armature (E_g) and Armature current (I_a).

3) External Characteristics
⇒ It gives the relation between terminal voltage V and load current (I_L). This characteristics is important in judging which generator is suitable for which purpose.

Separately Excited Generator:

1) No load Characteristics or open Circuit characteristics.



⇒ In a separately excited DC generator, field current is obtained from an external independent DC source.
⇒ The value of Field current can be varied from zero to upward by using a variable Resistance 'R'.
⇒ We know that the voltage equation of a DC generator is

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

hence if speed is constant,

$$E_g \propto \phi$$

⇒ When I_f increase from its initial small value, generated emf E_g increases directly as long as the pole are unsaturated.

⇒ When the flux density increases the poles becomes saturated, then a greater increase in I_f is required to produce a small increase in Voltage.

⇒ Therefore lower portion of the curve is almost linear and upper portion bends down.

Internal Characteristics

⇒ The internal Characteristics of a separately excited DC generator is obtained by subtracting the voltage drop due to armature reaction from no load Voltage.

⇒ This curve will be slightly drooping. As armature current increases, drop also increases gradually.

⇒ In the above diagram AC line is indicating the actual generated volage E_g with respect to Armature current.

External Characteristics

⇒ External characteristics of separately excited DC generator is obtained by substracting the voltage due to Armature resistance (I_aR_a) from the generated Voltage E_g.

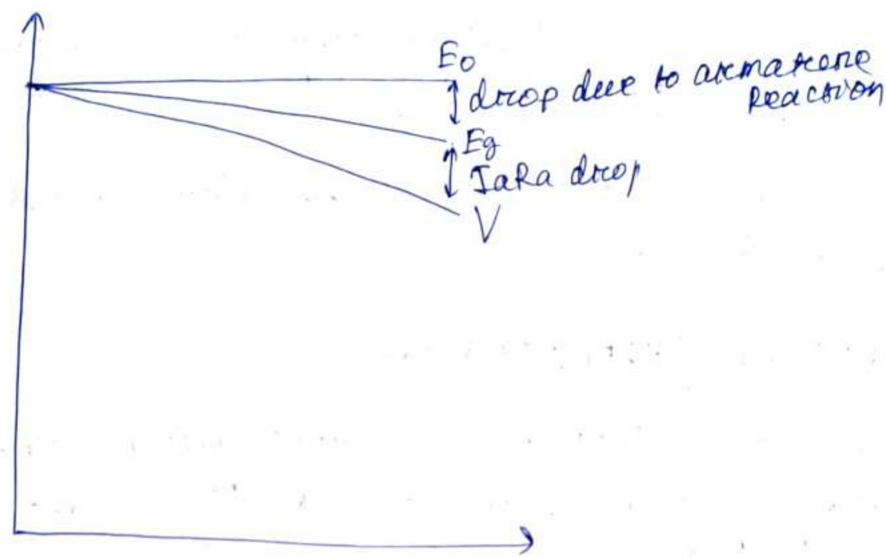
$$V = E_g - I_aR_a$$

⇒ So the external characteristic curve lies below the internal characteristics curve. 'AB' line in the above diagram is indicating the external characteristic curve.

⇒ It can be seen from the curve that when load current increases, the terminal voltage decreases slightly. This decrease in voltage can be maintained easily by increasing field current.

⇒ This type of generator can operates in stable condition with any field excitation and gives wide range of outpu voltage.

⇒ The main disadvantage of this type of generator is that it is very expensive to provide external supply source.



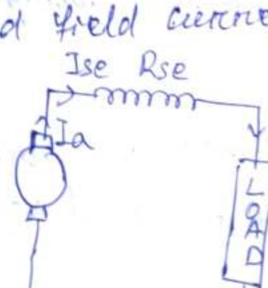
(SELF EXCITED) DC Series Generator Characteristics.

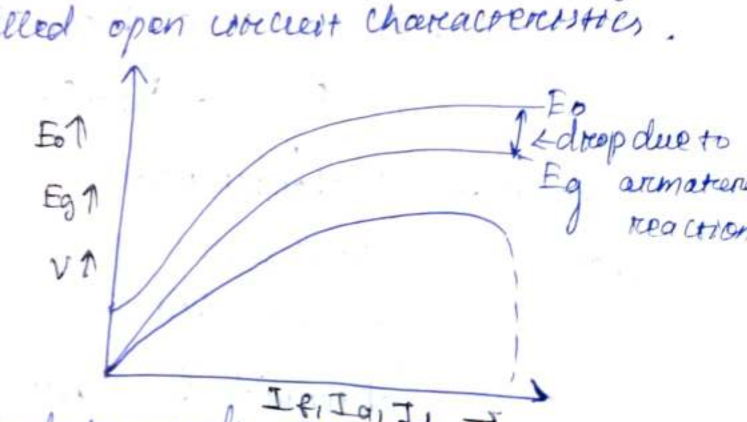
Open circuit characteristics.

⇒ In series generator the Armature winding, field winding, and external load circuit all are connected in series with each other. Therefore same current flows through all parts of the current i.e.

$I_a = I_{se} = I_L$,

⇒ The curve which shows the relation between No load Voltage and field current is called open circuit characteristics.





⇒ As during No load, the load terminals are open circuited, there will be no current in the field because the field winding, armature winding and load are connected in

⇒ So this curve can be obtained practically by exciting the DC generator by an external power.

⇒ Due to residual magnetism there will be a small critical voltage across the armature. That is why the curve started from point A not from the origin 'O'.

⇒ Initially the curve is linear but after saturation the curve bends down.

INTERNAL CHARACTERISTICS

⇒ The internal characteristics curve gives the relation between voltage generated in the armature 'E_g' and the armature current 'I_a'.

⇒ This curve is obtained by substracting the drop due to Demagnetising effect of Armature reaction from the No-load Voltage.

⇒ So the actual generated voltage E_g will be less then the no load Voltage E_0.

EXTERNAL CHARACTERISTICS

⇒ External characteristics shows the variation of terminal voltage (V) with load current (I_L).

⇒ Terminal voltage of this type of generator is obtained by substracting the ohmic drop due to Armature resistance and series field resistance from actual generated Voltage 'E_g'.

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

⇒ The external characteristic curve lies below the internal characteristic curve because the value of terminal voltage is less then generated Voltage.

⇒ It can be observed from the characteristics of series generator that with increase in load the terminal voltage of the machine increases.

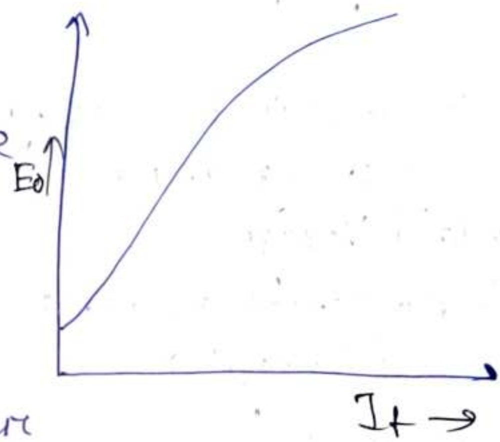
⇒ But after reaching it's maximum value it starts to decrease due to excessive demagnetising effect of Armature reaction and Voltage drop across armature and field resistance.

⇒ The dotted portion of the characteristics gives approximately constant current irrespective of external load.

⇒ Because increase in load tends to increase the load current, but decrease in load voltage tends to decrease load current according to Ohm's law. Due to these simultaneous effect there will be no significant change in load current.

SHUNT GENERATOR.

1) Open Circuit Characteristics.



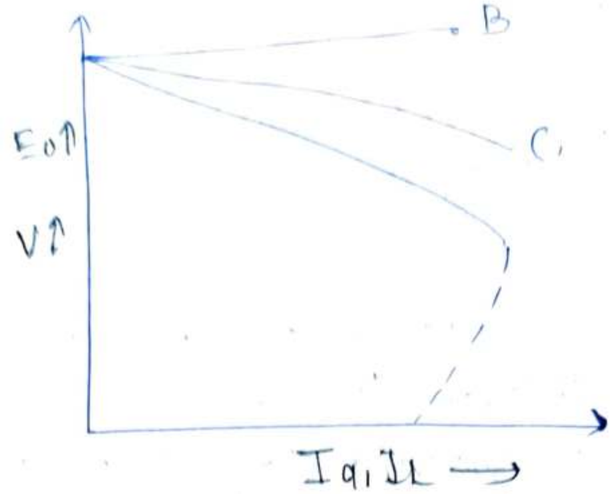
⇒ In shunt generator the armature winding, field winding and external load current all are connected in parallel with each other.

⇒ Therefore same voltage will occur across all parts of the circuit. Armature current equal to summation of load current and shunt field current. [$I_a = I_{sh} + I_L$]

⇒ The curve which shows the relation between No load Voltage and field current is called open circuit characteristics curve. (OCC)

⇒ Due to Residual magnetism there will be a small initial voltage across the armature. So that the curve started from a point A not from origin 'O'.

Internal Characteristics / External characteristics.



⇒ The internal characteristic curve gives the relation between the voltage generated in the armature 'E_g' and armature current 'I_a'.

⇒ This curve is obtained by subtracting the drop due to demagnetising effect of armature reaction from the No-load Voltage.

⇒ So the actual generated voltage E_g will be less than the no load Voltage E_0.

External Characteristics.

⇒ It shows the variation of terminal voltage with the load current.

⇒ This curve lies below the internal characteristic curve. Because the terminal voltage.

$$V = E_g - I_a R_a$$

⇒ When load Resistance of shunt generator decreases, load current of the generator increased as shown in the above figure.

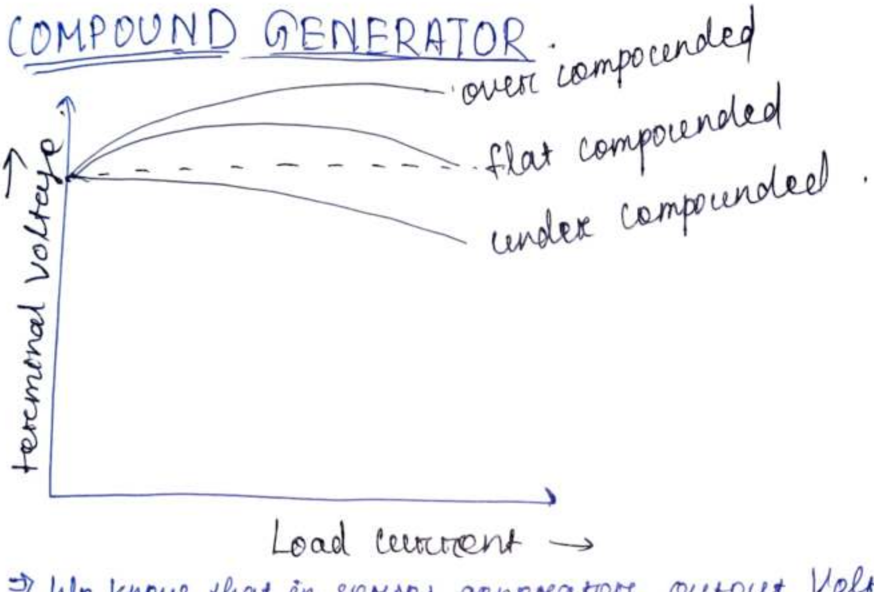
⇒ But load current can be increased to a certain limit upto a point C. Beyond this point the characteristics C is reversed.

⇒ Any decrease of load Resistance (increase in load) further results in reduction of load current.

⇒ As a result the External Characteristics curves turns back as shown in dotted line and ultimately the terminal voltage becomes zero.

⇒ When I_L increases, terminal voltage V decreases after certain limit. Due to heavy load current the terminal voltage decreases drastically. This drastic reduction of terminal voltage across the load results in drop of load current.

COMPOUND GENERATOR.



⇒ We know that in series generator output voltage is directional with load current and in shunt generator output voltage is inversely proportional with load current.

⇒ So in a compound generator the electric current in the shunt field winding produces a flux which causes fall in terminal voltage. But current in series field produces a flux which opposes the shunt field flux and compensate the drop in the terminal voltage and try to operate the machine at constant voltage.

⇒ If the series field turns are such that, the generator produces same voltage at rated load as no load, then the generator is flat compounded.

⇒ If the series field armature turns are such that the rated load voltage is greater than the no load voltage, then the generator is called as over compounded genera

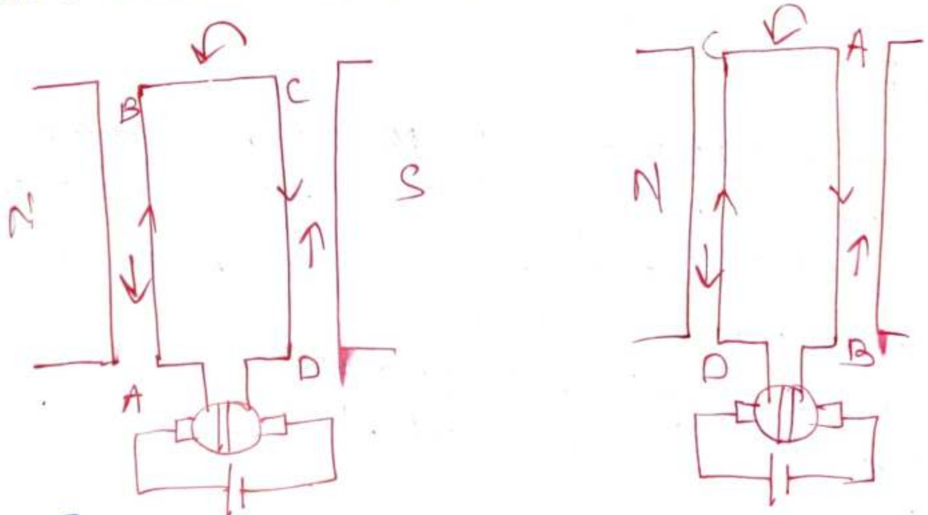
⇒ If the rated voltage is less then the no-load voltage, then the generator is called as under compounded.

DC MOTOR

A DC motor is a device which convert electrical energy into mechanical energy.

2.1 WORKING PRINCIPLE

The basic working principle of a DC motor is that when ever a current carrying conductor is placed in a magnetic field, then the conductor will experience a force. Due to this force conductor will starts to rotate in a definite direction.



In the above diagram when the armature winding is connected to a DC supply, current is setup in the winding. Here the field is provided by a pair of permanent magnet.

When the current carrying conductor is placed in magnetic field as shown in fig(1), it will experience a mechanical force. The direction of force can be determined by Fleming's left hand Rule. According to this rule if we streatch the fore finger, middle finger and thumb of our left hand perpendiculare to each other, then the direction of magnetic field is represented by fore finger, direction of current is represented by middle finger and direction of force is represented by thumb finger.

According to this rule a downward force is experienced by conductor AB and a upword force is experienced by CD, therefore the conductor starts to rotates in anticlock direction.

After completing half cycle of rotation conductor AB will be under 'S' pole and conductor CD will under 'N' pole. Now due to commutator the direction of flow of current in the conductor remains same.

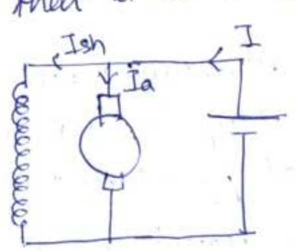
Now applying Fleming left hand rule we can observe that conductor CD will experience a downward force and conductor AB will experience a upward force.

Again the conductor will rotate in anticlockwise direction. In this way a continuous rotation in Anticlock wise direction is achieved.

2.2 BACK EMF

When the armature of motor rotates, armature conductors also cuts the magnetic flux and according to Faraday's law of Electromagnetic induction an emf is induced in Armature conductors.

It is denoted by E_b. The direction of back emf is such that it will oppose the supply.



$$V = I_a R_a + E_b$$

$$\Rightarrow I_a R_a = V - E_b$$

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

Significance of BACK EMF:-

i) Back emf makes a dc motor self regulating i.e. E_b makes motor to adjust I_a automatically when the load changes.

ii) We known that for a DC shunt motor $I_a = \frac{V - E_b}{R_a}$

here V, R_a are constant

therefore armature current I_a depends on E_b.

(iii) Again we know, $E_b = \frac{P\phi ZN}{60A}$. Therefore back emf is directly proportional to speed of the motor.

(iv) If load of the motor is suddenly increased, the motor starts to slow down. As the motor speed decreases back emf also decreases. As a result armature current starts to increase

(v) If load on the motor is suddenly reduced, speed of the motor will increase. As a result back emf is increased and armature current starts to decrease.

(vi) In this way a DC motor can regulates it's input automatically according to change in load.

2.4 TORQUE EQUATION OF A DC MOTOR

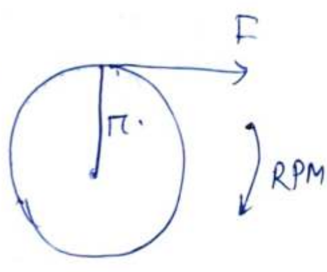
Torque is the measure of how much force is acting on an object to rotate it.

OR

It is twisting or turning moment of a force about an axis.

* It is measured by product of force and radius at which the force act.

Consider a pully of radius r m. A force of 'F' newton is acting upon it to rotate it at N RPM.



Torque developed on the pully is given by

$$T = F \times r$$

Work done by the force 'F' on one revolution

$$W = F \times \text{distance}$$

$$W = F \times 2\pi r \ Nm$$

Now power developed for one revolution is given by

$$P = \frac{\text{Workdone}}{\text{time}}$$

N revolution = 1 min / 60 sec.

1 " = $\frac{60}{N}$ sec.

$$P = \frac{\text{Workdone}}{\text{time}}$$

$$= \frac{2\pi r f}{\frac{60}{N}}$$

$$\Rightarrow P_m = \frac{2\pi r f N}{60}$$

$$\Rightarrow \boxed{P_m = \frac{2\pi T N}{60}}$$

$$\Rightarrow T = \frac{60}{2\pi} \frac{P_m}{N}$$

$$\Rightarrow \boxed{T = 9.55 \frac{P_m}{N}}$$

ARMATURE TORQUE

Let Ta be the torque developed by the armature of the motor running at N RPM. Then mechanical power is develop at armature is given by ~~$P_m = 2\pi$~~

$$P_m = \frac{2\pi}{60} T_a N$$

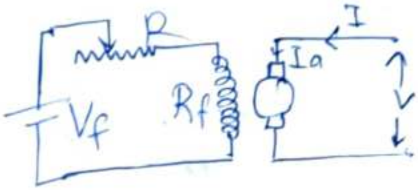
Electrical power input to the Armature is given by

$$P_e = E_b I_a \text{ watt}$$

We know that at armature ~~$P_e = E_b I_a$~~ the mechanical power developed is equal to total electrical input to the armature. So $T_a = 9.55 \frac{E_b I_a}{N}$ & $T_{sh} = 9.55 \frac{P_{o/p}}{N}$

(2.7) Types of DC MOTOR · Voltage equation of DC MOTOR.

Separately excited Motor.



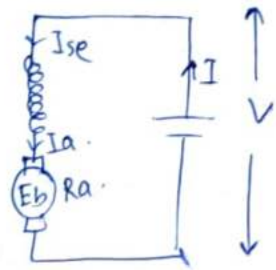
$\Rightarrow -V + I_aR_a + E_b = 0$

$\Rightarrow V = I_aR_a + E_b + V_b$

$\Rightarrow I = I_a$

Self excited Motor.

Series Motor.



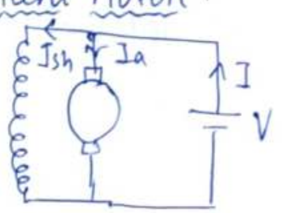
$I_a = I_{se} = I$

$-V + I_{se}R_{se} + I_aR_a + E_b + V_b = 0$

$\Rightarrow V = I_{se}R_{se} + I_aR_a + E_b + V_b$

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

Shunt Motor.



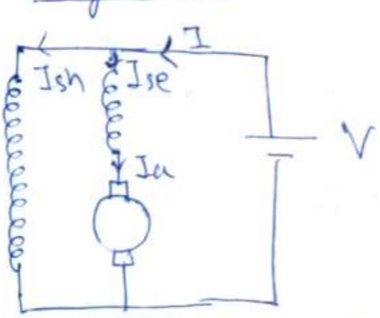
$-V + I_aR_a + E_b = 0$

$\Rightarrow V = I_aR_a + E_b + V_b$

$I = I_a + I_{sh}$, $I_{sh} = \frac{V}{R_{sh}}$

Compound motor.

(i) Long shunt.



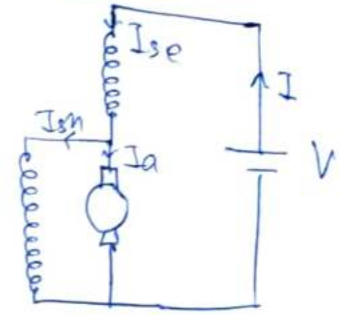
$-V + I_{se}R_{se} + I_aR_a + E_b + V_b = 0$

$\Rightarrow V = I_{se}R_{se} + I_aR_a + E_b + V_b$

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

$I_{se} = I_a$, $I_{sh} = \frac{V}{R_{sh}}$

(ii) Short shunt.



$V = I_{se}R_{se} + I_aR_a + E_b + V_b$

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

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

(2.11) POWER FLOW DIAGRAM.

Electrical input $P_{i/p} = VI$ → Cu loss I^2R → Power in Armature. $P_e = E_b I_a = P_m$

→ Iron loss + Mechanical loss → Mechanical power output. $P_{o/p}$ (at shaft).

⇒ Electrical power is given to the motor as input. Input electrical power is ~~converted to~~ given by

$$P_{i/p} = VI$$

where V = supply voltage (dc)
I = supply current.

⇒ When current flows through the armature and field winding due to supply voltage, Copper losses takes place.

Copper loss = Armature Cu loss + field Cu loss.

$= I_a^2 R_a + I_{se}^2 R_{se}$ (series motor)

$= I_a^2 R_a + I_{sh}^2 R_{sh}$ (shunt motor)

$= I_a^2 R_a + I_{se}^2 R_{se} + I_{sh}^2 R_{sh}$ (compound motor)

⇒ After copper loss, rest amount of input power is converted into mechanical power in the armature.

$$P_{electrical} = E_b I_a = P_{mechanical}.$$

⇒ When armature starts to rotate, mechanical and iron losses takes places.

~~Mechanical~~ Rotational loss = Iron loss + ~~Fri~~ Mechanical loss

⇒ Rest amount of mechanical power transferred to the shaft. This power is called as output power.

$$P_{o/p} = E_b I_a - \text{Rotational losses}$$

$P_{i/p} = VI$

$P_{i/p} = \text{Copper losses} + E_b I_a$

$E_b I_a = P_{o/p} + \text{Rotational losses}$

$$\text{Electrical efficiency} = \frac{\text{Electrical power at Armature}}{P_{i/p}\text{(electrical input power)}}$$

$$\eta_e = \frac{E_b I_a}{VI}$$

$$\text{Mechanical efficiency} = \frac{\text{Mechanical Output at shaft } (P_{o/p})}{\text{Mechanical power developed at armature}}$$

$$= \frac{P_{o/p}}{E_b I_a}$$

$$\text{Overall efficiency} = \frac{P_{o/p}}{P_{i/p}} = \frac{P_{o/p}}{VI}$$

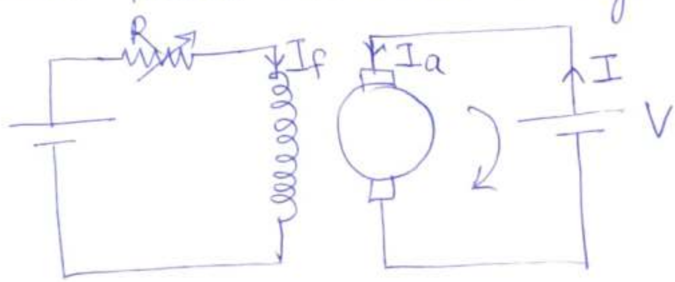
Losses:

CLASSIFICATION OF DC MOTOR

- DC MOTOR
  - Separately excited motor
  - Self excited motor
    - Series motor
    - Shunt motor
    - Compound motor
      - long shunt compound motor
      - short shunt compound motor

Separately excited motor.

If field winding and armature winding of a motor are electrically separated from each other, then the motor is called as separately excited motor. Here the field winding and armature winding are supplied from different voltage sources.



Applying KVL at armature circuit;

$$V = I_aR_a + E_b + V_b$$

where V = Voltage supply.

I_aR_a = Voltage drop at armature.

E_b = Back emf.

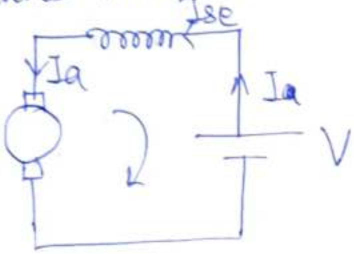
V_b = Brush drop.

Self excited Motor.

If field winding and armature winding are electrically connected with each other, then the motor is called as self excited motor. In this type of motor field and armature windings are connected to a single voltage source. There are three types self excited motor.

a) Series Motor

If the field winding and armature windings are connected in series with each other, then the motor is called as Series motor.



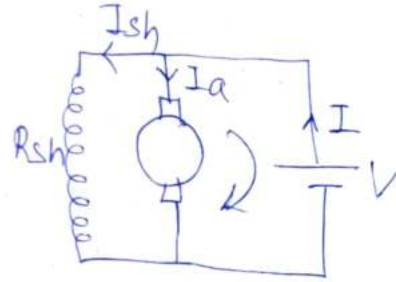
By apply KVL

$$V = E_b + I_aR_a + I_{se}R_{se} + V_b$$
(Voltage equation)

Here $I_a = I_{se} = I$.

b) Shunt Motor.

If the field winding and armature windings are connected in parallel with each other, then the motor is called as Shunt motor.



Voltage equation is given by

$$V = E_b + I_aR_a + V_b.$$

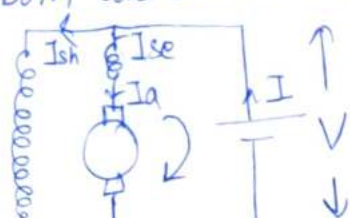
$$I = I_a + I_{sh} \quad \& \quad I_{sh} = \frac{V}{R_{sh}}.$$

c) Compound Motor.

If a motor has both series and shunt field winding then it is called compound motor.

(i) Long shunt Compound motor

Shunt field winding is connected in parallel across both armature & series field.



$I = I_a + I_{sh}$

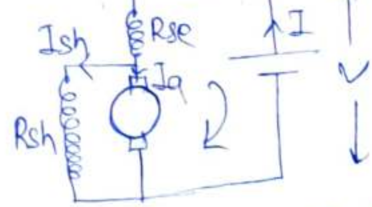
$I_{se} = I_a$.

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

$V = E_b + I_aR_a + I_{se}R_{se} + V_b$

(ii) Short shunt Compound motor

Shunt field winding is only connected across armature.



$I = I_a + I_{sh}$

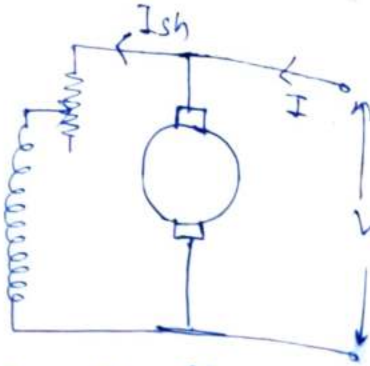
$I = I_{se}$

$$V = E_b + I_aR_a + I_{se}R_{se} + V_b$$

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

2.7 Speed Control of DC shunt motor:

1) Flux control Method



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

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

⇒ We know that $N \propto \frac{1}{\phi}$, so by decreasing the flux ϕ speed of the motor can be encreased and vice-versa.

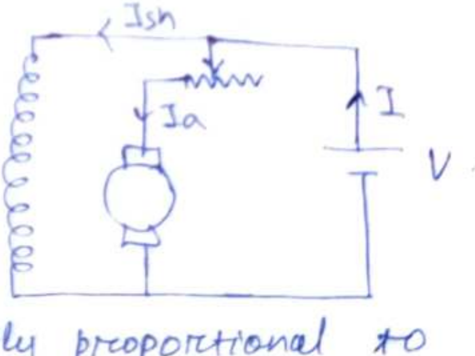
⇒ The flux of a DC motor can be changed by changing I_{sh} with the help of a shunt field Rheostat.

⇒ When the resistance of field rheostat is encreased, I_{sh} decreases. As a result flux decreases which results in encrease of speed.

⇒ In field control method speed of the motor can be encreased above the rated speed. But it can not be decreased below rated speed.

⇒ As magnitude of Ish is small, loss in the Rheostat ($I_{sh}^2 R_{sh}$) is small. Therefore this method is very efficient.

2) Armature Voltage Control Method



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

So, $N \propto E_b$

$N \propto V - I_a R_a$

⇒ We know that speed is directly proportional to armature voltage (E_b). So by changing the value of E_b we can change the speed of a motor.

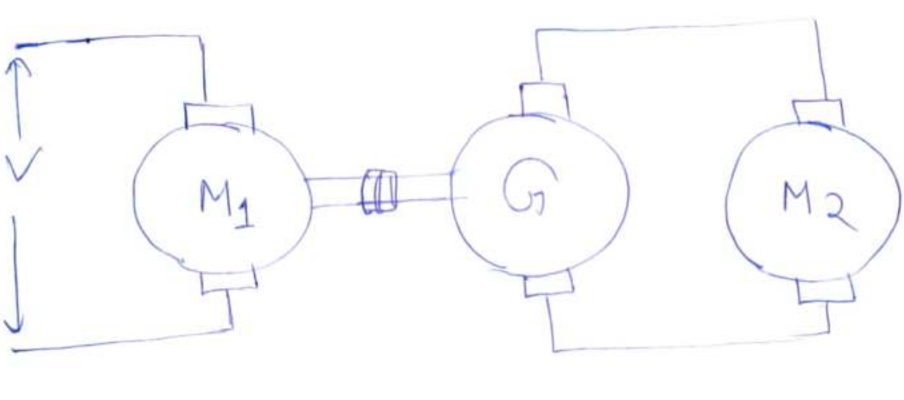
⇒ As the supply voltage is normally constant, voltage across the armature can be changed by inserting variable resistance in series with armature circuit.

⇒ As the variable resistance is increased, potential difference across the armature is decreased. As a result speed of the motor also decreases.

⇒ This method is used when speed is below rated speed is required.

⇒ In this method losses will be more because.

3) Ward Leonard method or System:

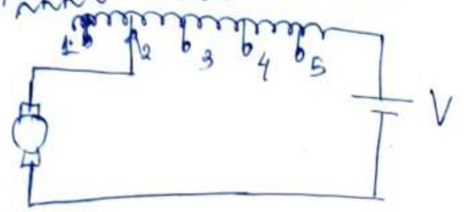


⇒ Here M_2 is the main motor whose speed control is required. The field of this motor is permanently connected across DC supply line. Now by changing the supply voltage of M_2 any desired speed can be obtained.

⇒ This variable voltage is supplied by a motor generator set which consist of a DC motor M_2 directly coupled to the generator 'G'.

⇒ The motor M_2 runs at approximately constant speed. Output of motor M_2 is given to generator G and output voltage of the generator is directly fed to the main Motor 'M1'. Output Voltage of Generator 'G' can be vary from zero to maximum by a field Regulator.

(3) Tapped field Method.



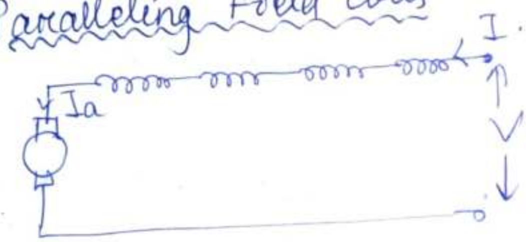
⇒ This method is mostly used in Electric traction.

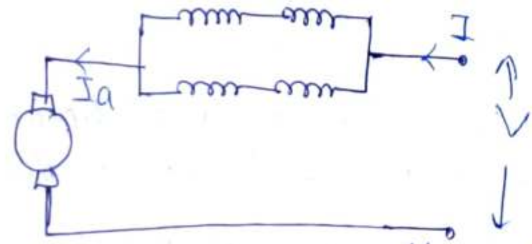
⇒ Here no of series field turn can be changed by tapping.

⇒ With full field turns the motor runs at it's maximum speed and when field turn is minimum it runs at maximum speed.

⇒ In the above fig. when the armature is connected to tapping 1, the motor will run at minimum speed. Because no of turns is maximum, which gives maximum flux. As a result speed will be minimum.

(4) Paralleling Field Coils

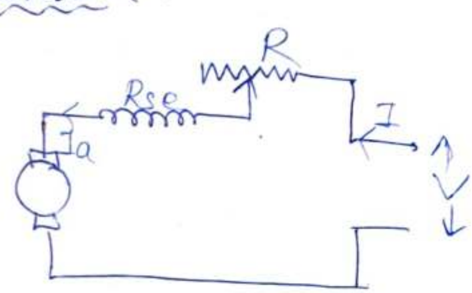




→ In series motor, the field winding can be divided into two or more equal parts. These parts are connected either in series or parallel. Due to different connection, total flux changes. As a result speed changes.

→ In this method we can not change the speed smoothly

(5) Variable Resistance in series with Armature.



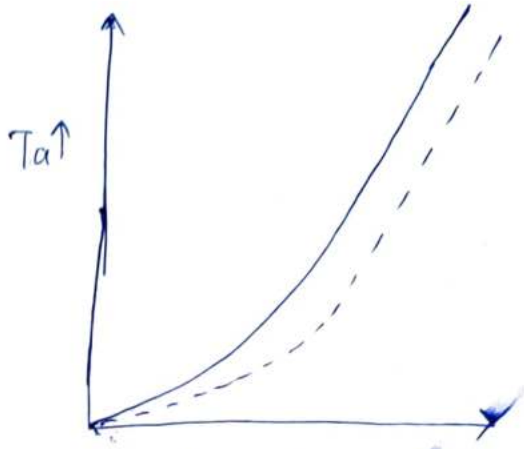
→ In this method, voltage applied across the armature terminals can be reduced by increasing the variable resistance R, connected in series with the armature.

→ As E_b is directly proportional to speed, with decrease in E_b speed decreases.

→ In this method full motor current passes through the resistance, power loss takes place.

2.5) CHARACTERISTICS OF SERIES MOTOR

1) T_a Vs I_a Characteristics



⇒ Before saturation Torque (T_a) is directly proportional to I_a^2

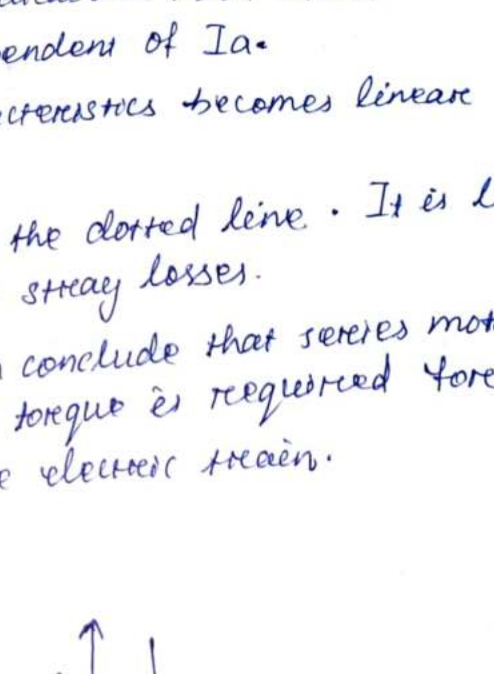
⇒ At light load I_a is small, hence flux is small. As I_a increases, Torque T_a also increases as the square of current.

⇒ Hence initially the curve is parabolic. But after saturation flux is almost independent of I_a. Hence $T_a \propto I_a$. So the characteristics becomes linear after saturation.

⇒ The shaft torque is shown by the dotted line. It is less then Armature torque due to stray losses.

⇒ From the characteristics we can conclude that series motor are used where high starting torque is required for accelerating heavy masses like electric train.

2) N Vs I_a Characteristics.



⇒ The variation of speed can be obtained from the formula

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

⇒ As load increases, I_a increases which increases the flux. Here change in E_b for various load current is very small. Hence speed varies inversely with armature current.

⇒ When load is heavy, I_a is large and speed is low.

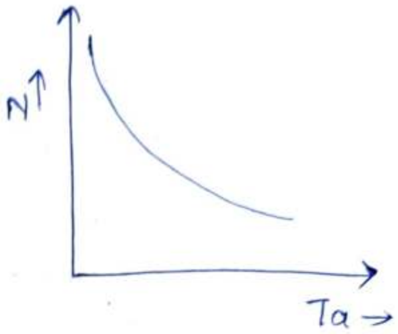
⇒ When load is small, I_a falls to ~~zero~~ a small value, as a result speed becomes very high.

⇒ Therefore a d.c series motor without load.

③ N Vs Ta characteristics.

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

& $T_a = 9.55 \cdot \frac{E_b I_a}{N}$ — ①



$\phi \propto I_a$ & $I_a \propto T_a$

so $I_a \propto T_a$ — or from eqn $T_a \propto \frac{1}{N}$.

$N \propto \frac{E_b}{T_a}$.

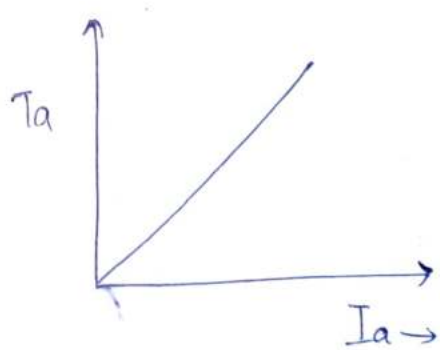
In a series motor speed is inversely proportional to Armature torque. So when speed is high, torque is low and vice-versa.

CHARACTERISTICS OF SHUNT MOTOR.

1) Ta Vs Ia characteristics.

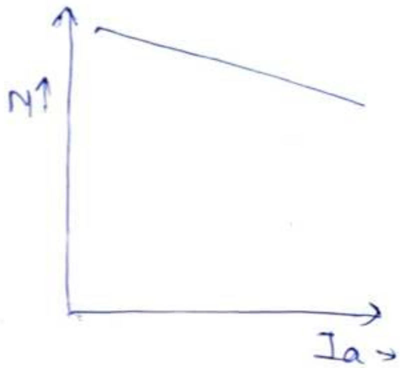
⇒ We know that Armature torque is proportional to ϕI_a.

⇒ But in shunt motor ϕ is almost constant. Only at heavy load ϕ decreases due to increase in Armature reaction.



⇒ Therefore in a shunt motor torque is directly proportional to Armature current ($T_a \propto I_a$). So the characteristics is a straight line through origin or linear.

② N vs Ia characteristics.



⇒ In a shunt motor ϕ is almost constant. Therefore

$N \propto E_b$

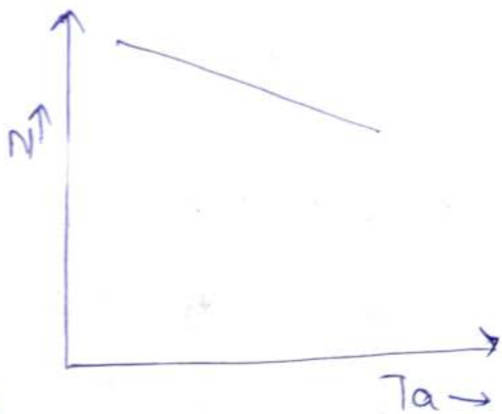
⇒ But practically both E_b and flux decreases with increase in load.

⇒ ~~From the characteristics~~

⇒ However E_b decreases more than flux, as a result there is some decrease in speed.

⇒ From the characteristics we can notice that there is no appreciable change in the speed of DC shunt motor from no load to full load. Therefore these motors are used where sudden change in the load takes place like wood cutting machine, Lath machine etc.

③ N Vs Ta characteristics.



We know that

$T_a \propto \phi I_a$

where ϕ is almost constant

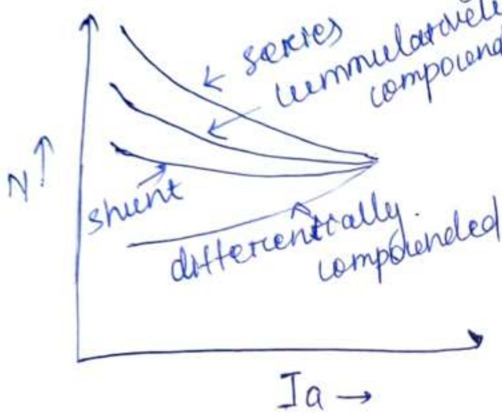
so $\boxed{T_a \propto I_a}$

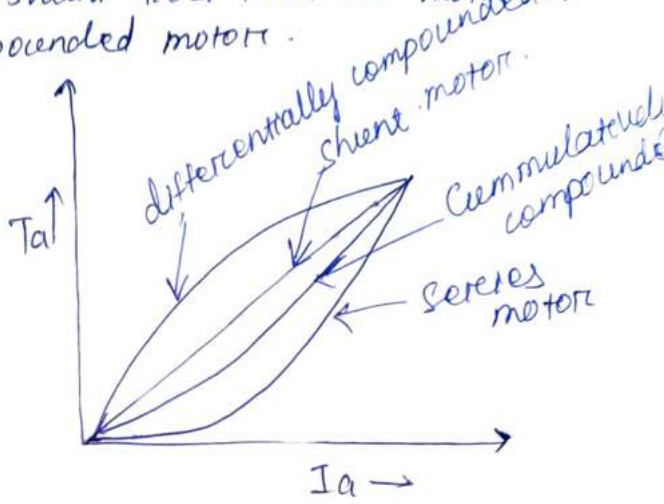
So graph/Relation betn N & Ta will be same as that of relation betn N Vs Ia.

CHARACTERISTICS OF COMPOUND MOTOR.

⇒ If series field flux is in the same direction with shunt field flux, then the motor is said to be cumulatively compound motor.

⇒ If the series field opposes the shunt field then the motor is said to be differentially compounded motor.





Cummulatively Compound motor.

⇒ These motor are used where properties of both series and shunt field winding is required.

⇒ This type of motor is generally used where high starting torque with continuous change in load is required. Due to shunt winding it can handle sudden change in load and due to series winding it will be able to take heavy load.

Differentially Compounded motor.

⇒ As series field opposes the shunt field, as load is applied to the motor the total flux will decreases.

⇒ This results in motor speed remaining constant or even increases with increase in load.

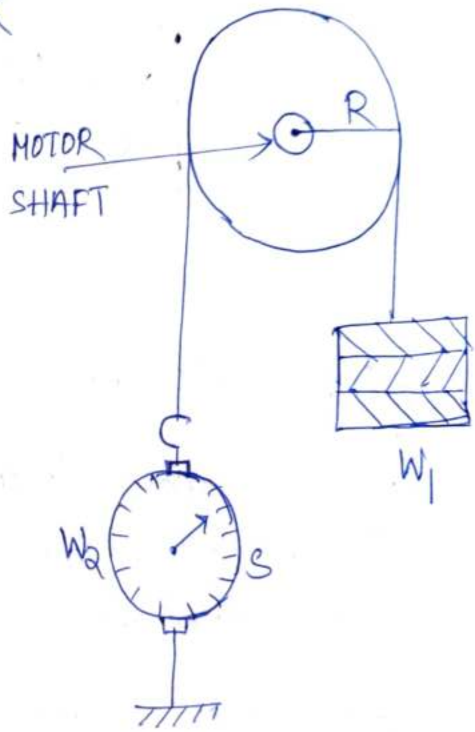
⇒ Therefore there is a decrease in the rate at which motor torque increases with load.

⇒ Such motors are not commonly used due to decrease in flux with increase in load.

Brake Test.

It is the direct method to calculate efficiency of a DC Motor. In this method load is applied to the motor and efficiency is calculated.

Consider a motor having a water-cooled pulley mounted on the motor shaft. Brake is applied to the pulley with the help of a brake band. One end of the band is connected with a wooden block and another end is connected with a spring balance 'S'.



Let W_1 = weight of wooden box.

W_2 = reading of spring balance.

Net pull on the Pulley due to the belt is

$$\text{Pull} = W_1 - W_2 \text{ kg}$$

$$= 9.81(W_1 - W_2) \text{ Newton}$$

If R = radius of pully in metre.

N = speed of motor or pully in rpm.

Then, shaft torque T_{sh} developed by the motor

$$T_{sh} = (W_1 - W_2)R \quad \text{N-m}$$

We know that $T_{sh} = 9.55 \dfrac{P_{o/p}}{N}$

$$\Rightarrow P_{o/p} = \frac{1}{9.55} T_{sh} \times N$$

$$\Rightarrow \boxed{P_{o/p} = .104\, T_{sh} N}$$

Let supply voltage is V, I = full-load current taken by the motor

then input power = VI watt.

$$\eta = \frac{P_{o/p}}{P_{i/p}}$$

$$= \frac{1.024\ T_{sh} N}{VI}$$

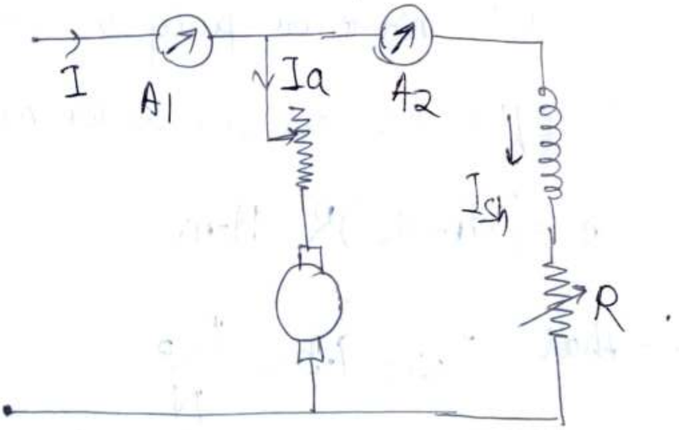
$$\boxed{\eta = \frac{1.02\ (W_1 - W_2) R N}{VI}}$$

Q-11) Swinburne's Test (No-load Test or Losses Method)

→ In this method losses are measured at no load condition. From the knowledge of losses efficiency at any desired load can be predetermined in advance.

* This test is applicable to those machines in which flux is practically constant.

Procedure.



→ First the motor started with no-load condition. Then the speed is adjusted to rated speed with the help of shunt regulators.

No load source current I_0 is given by ammeter A_1 and field current is given by ammeter A_2.

So the no load armature current is given by

$$I_{a0} = I_0 - I_{sh}.$$

If supply voltage = V volt.

no-load input $= VI_0$

$= V(I_0 - I_{sh})$

No-load power input to the motor gives

(i) constant losses, W_c

(Iron losses + Mechanical losses + Shunt field Cu loss)

(ii) Variable losses, W_v

Armature Cu loss $= I_a^2 R_a$.

* Constant losses are calculated in no-load test of the motor.

<u>Efficiency at any load, (current = I)</u>

Input $= VI$

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

Constant losses $= W_c$.

Total losses $= W_c + I_a^2 R_a$.

$$\eta = \frac{P_{o/p}}{P_{i/p}} = \frac{P_{i/p} - \text{losses}}{P_{i/p}} =$$

$$\boxed{\eta = \frac{VI - (W_c + I_a^2 R_a)}{VI}}$$

(2.3) Condition for Maximum power.

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

By differentiating both sides by I_a with respect to I_a and equating the result by zero, we get condition for maximum power.

$$\frac{dP_m}{dI_a} = \frac{d}{dI_a}\left[VI_a - I_a^2 R_a\right] = 0$$

$$\Rightarrow V - 2I_aR_a = 0$$

$$\Rightarrow V = 2I_aR_a$$

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

We know that, for a shunt motor.

$$V = E_b + I_aR_a$$

$$\& \Rightarrow I_aR_a = \frac{V}{2}$$

$$\text{so } V = E_b + \frac{V}{2}$$

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

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

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

SINGLE PHASE TRANSFORMER

Transformer is a static device that transfer electric power from one circuit to another with same frequency through the process of mutual induction. It is most commonly used to increase or decrease the voltage levels between the circuit

$$P_{i/p} \simeq P_{o/p}$$

3.2 CONSTRUCTION

⇒ A transformer mainly consist of two coils having mutual inductance and a laminated steel core. The two coils are insulated from each other and from steel core.

⇒ Other necessary parts are

1. → Transformer tank → Here transformer core and windings are placed.
2. Transformer oil → It insulate the core and winding from transformer tank.
3. Bushing
4. Conservator tank.
5. Breather.
6. Buchholz Relay etc.

⇒ TRANSFORMER CORE

→ Transformer core is mainly used for two purpose

(i) To provide mechanical support for the entire transformer

(ii) To provide a path for the flow of magnetic flux.

→ It is made up of silicon steel laminations. The laminations are cut in the form of L's, E's or I's. They are joined together and pivoted to avoid any

→ The laminations are insulated from each other by a coat of varnish or oxide layer. Thickness of these laminations varies from 0.35mm to 0.5mm.

→ High silicon content in the core reduces hysteresis loss and laminations reduces eddy current loss.

→ There are three types of core construction.
(i) Shell-type (ii) Core-type (iii) Berry type.

WINDINGS

→ A transformer has two windings i.e primary winding and secondary winding. Primary winding is connected to power supply and secondary winding is connected to the load.

→ In core type T/F windings are wound around two legs of and in shell type T/F windings are wound around middle leg.

→ Windings are made of solid or stranded copper. Proper insulation is given to the windings to prevent it from short circuit. Varnish, paper or cloth insulation are used.

TRANSFORMER TANK and INSULATING OIL

→ The transformer core and winding arrangement are immersed in a tank containing insulating oil.

→ The tank gives protection to the core and winding. Insulating oil act as an insulation medium for core and winding. It also absorbes the heat generated in the winding and core.

CONSERVATOR TANK.

→ The transformer tank is connected through a pipe to a small tank which is called as conservator tank.

→ It acts as a reservoir for the transformer oil. An increase in temperature causes the oil in the transformer tank to expand. Conservator tank provide space for this expansion of oil.

BREATHER.

→ During the change in temperature inside the tank, the oil inside the tank expands and contracts. So, atmospheric air get absorbed inside a transformer tank through Breather.

→ Breather consist of Silica gel which prevents any atmospheric moisture from entering the tank. All the moisture gets absorbed by the silica gel.

COOLING TUBES

→ Cooling tubes are used to remove the heat from the transformer oil and tank. The cooling method may be natural or forced, which depends on the size of a transformer.

BUSHING

→ All the transformer leads are brought out ~~of~~ from the transformer tank through suitable bushing.

→ Construction and size of bushing depends on the voltage level.

→ Bushing ~~the~~ are used to insulate the supply leads.

~~CLASSIFICATION OF TRANSFORMER~~

BUCHHOLZ RELAY

→ It is a device used to protect the transformer from faults occurring inside the tank.
→ It is placed between the transformer tand and conservator tank.
→ When fault occurs inside the T/F tank decomposition of oil occures which produces bubbles. There bubbes move towards the conservator tank and activate the relay.

Explosion Vent.

→ The transformer has an explosion vent to prevent any damage to the transformer tank caused by excessive pressure generated inside the T/F.

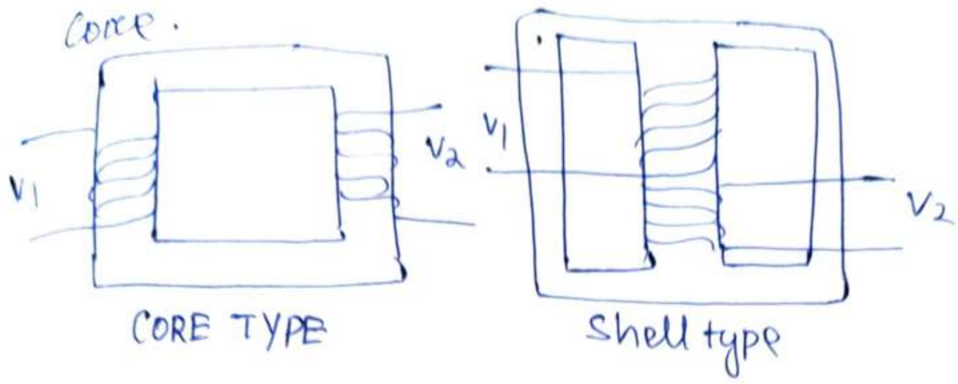
3.2.1 Arrangement of core & windings in different types of transformers

According to the construction of core, transformer is classified into three types.
(i) Core type (ii) Shell type (iii) Berry type.

CORE TYPE T/F

→ A core type transformer has two vertical legs or limbs with two horizontal sections named yoke. The core is rectangular in shape. with a common magnetic circuit.
→ The windings are placed on the both limbs. The windings/ coils may be circular, oval or rectangular.

→ Low voltage winding is placed nearest to the core.



SHELL TYPE T/F

→ A shell type transformer has a central limb and two outer limbs. It creats double magnetic path.

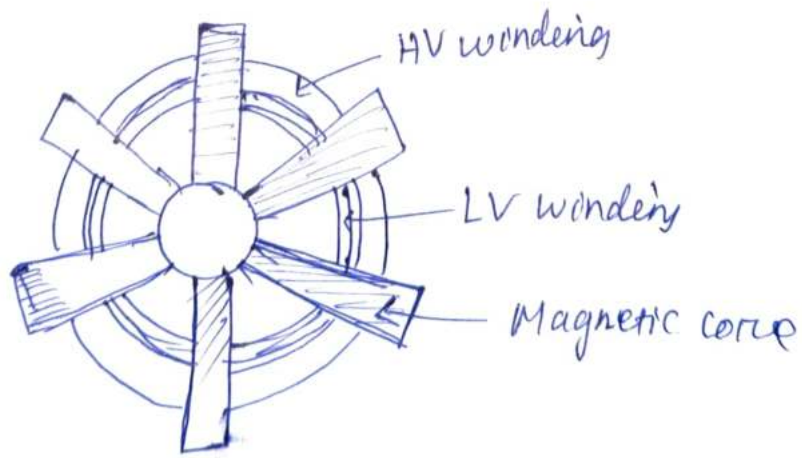
→ Both HV and LV coils are placed on the central limb.

BERRY TYPE T/F

→ The core looks like the spokes of a wheel.

→ Tightly fitted metal sheet tanks are used for housing this type of transformer, with transformer oil filled inside it.

→ It has more than two independent magnetic ckt.



3.1 Basic Operating Principle of A Transformer:

⇒ The basic working principle of a transformer is mutual induction between two circuit linked by a common magnetic field.

⇒ Let two inductive coils which are electrically separated but magnetically linked through a path of low reluctance (transformer core) as shown in the above figure.

⇒ If one coil is connected ~~two~~ to a source of alternating voltage, and alternating flux is set up in the laminated core. This alternating flux linked with another coil. According to Faraday's law of electro magnetic induction, emf is induced in it.

⇒ When this coil is connected to a load power will transferred to it.

⇒ The first coil to which voltage source is given is called Primary winding and from which coil energy is drawn is called secondary winding.

COOLING METHODS

Air Natural.

→ Used in small rating transformers (5 to 10 KVA) where coolant is air. or it is a dry transformer.
→ The external surface is sufficient to dissipate heat.
Ex- Instrument transformer.

Air Blast.

→ This method is also used for dry transformers.
→ External fans or blowers are used for a continuous blast of air through the winding and core of transformer.
→ It is used in transformers having ratting less than 25 KVA.

Oil Natural cooling

→ In this method of cooling, the winding and core of a transformer are emmersed in the oil. An iron tank is used as enclosure.
→ Heat produced in winding and core is transferred to the oil. The heated oil transfers heat to the tank surface and heat dissipates to it's surrounding.
→ In higher rated transformers radiators are used for natural cooling.

Oil Natural Air forced cooling

→ It is used for oil-immersed medium to large capacity T/F.
→ In this method cooling is provided by forcing air to the cooling surfaces like radiators or tubes.

Oil Natural Water forced cooling

→ In this method, winding and core are immersed in oil.

→ Water circulates through copper cooling coils to increase heat dissipation. The coils are mounted above the core and inside the surface.

→ Heat is transferred to the water and heated water is cooled in cooling tower.

Oil Forced Air Natural Cooling

→ This method is rarely used.

→ Here pump is used to circulate oil, heated oil is used in a heat exchanger by natural circulation of air.

→

Oil forced Air forced Cooling

→ In this method of cooling, the oil is circulated in the transformer with the help of a pump.

→ The heated oil is cooled in an external heat exchanger. For more cooling, air is blast with the help of fan.

Oil forced water forced cooling

→ Heated oil is carried out from the main tank and transferred to the heat exchanger with the help of a pump.

→ In a heat exchanger, oil is cooled by the water passing through the copper tubes.

Maintenance of Transformer.

There are many preventative maintenance actions to be performed on a power transformer. They can be on a daily, monthly, yearly, half-yearly basis. Some activities only need to be performed once in a 3 to 4 years interval.

Daily Basis maintenance.

→ Reading of MOG (Magnetic oil gauge) of main tank and conservator tank.

→ Color of silica gel in breather.

→ Leakage of oil from any point of a transformer.

Monthly Basis Maintenance

→ Oil level of transformer oil inside the bushing.

→ Breathing holes in silica gel. To be cleaned for proper breathing

→ Oil level in oil cap cender breather.

Yearly Basis Maintenance.

→ The auto, remote, manual function of cooling systems like oil pumps, fans etc.

→ All bushings to be cleaned

→ Oil condition of OLTC to be tested for dielectric strength and moisture content. If require then replaced.

→ Mechanical inspection of Buchholz relays.

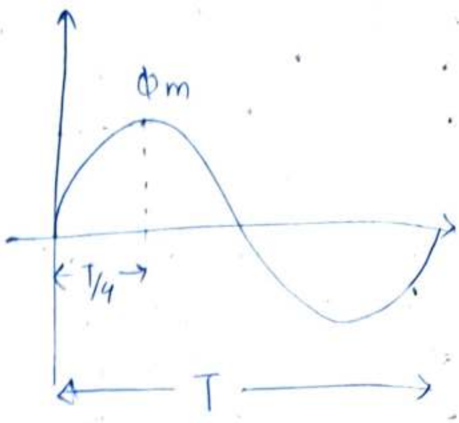
→ All relays, Alarms and control switches along with their circuit.

→ Insulation resistance and polarization index of T/F must be checked.

Half-yearly Maintenance.

→ Transformer oil must be checked half yearly basis for dielectric strength, moisture content, acidity, sludge content.

E-MF Equation of Transformer



Let

N_1 = no of turns in primary winding

N_2 = No of turns in Secondary winding

Φ_m = maximum flux in the Core

f = frequency of AC input in Hz

Flux increases from it's zero value to maximum value in one quarter of the cycle i.e. $\frac{1}{4f}$ sec.

$$\text{Here } d\phi = \Phi_m - 0 = \Phi_m$$

$$\& \; dt = T/4 - 0 = T/4 = \frac{1}{4f}$$

So average induced emf in one coil is given by

$$E_{avg}/turn = \frac{d\phi}{dt} = \frac{\Phi_m}{1/4f} = 4f\Phi_m \text{ Volt}$$

form factor for A sine wave is given by

$$\frac{\text{Rms Value}}{\text{Average Value}} = 1.11$$

So rms value of induced emf is obtained by multiplying Average value with form factor.

$$E_{rms}/turn = 1.11 \times 4f\Phi_m = 4.44\Phi_m \text{ Volt}$$

Now Rms value of induced emf in whole primary winding is equal to induced emf/turns x no of primary turns.

$$E_1 = 4.44 f\Phi_m \times N_1 \text{ Volt} \quad \text{—(1)}$$

Similarly Rms value of induced emf in secondary winding is $E_2 = 4.44 f\Phi_m \times N_2$ Volt —(2)

Voltage Transformation Ratio (K):-

It is the ratio between voltage at secondary winding to voltage at primary winding. It is denoted by K.

$$\frac{E_2}{E_1} = \frac{V_2}{V_1} = K$$

we know that

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

$$\Rightarrow \frac{E_1}{N_1} = 4.44 f \phi_m \text{ Volt} \quad — (1)$$

&

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

$$\frac{E_2}{N_2} = 4.44 f \phi_m \quad — (2)$$

from eqn (1) & (2) we get that

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

$$\Rightarrow \boxed{\frac{E_2}{E_1} = \frac{N_2}{N_1} = K}$$

So transformation ratio is also defined as ratio of no of turns in secondary winding to no of turns in primary winding.

Also in a transformer

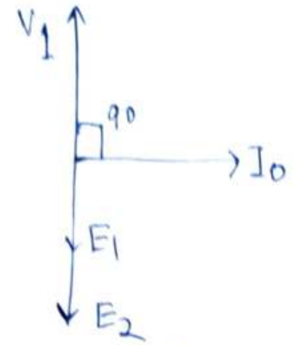
$$P_{i/p} = P_{o/p}$$

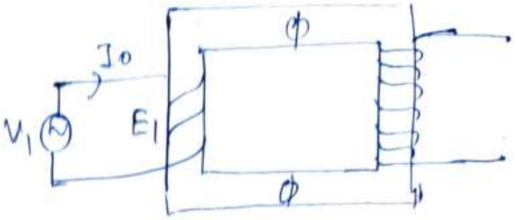
$$\Rightarrow V_1 I_1 = V_2 I_2$$

$$\Rightarrow \boxed{\frac{V_2}{V_1} = \frac{I_1}{I_2} = K}$$

Hence $$\boxed{K = \frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1}}$$

IDEAL TRANSFORMER (no load condition)



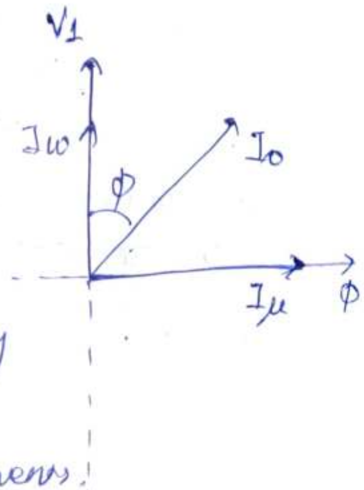


⇒ An ideal transformer is one which has no losses i.e it's winding has no resistance. In other words an Ideal transformer consist of two purely inductive coil wound on a loss free core.

⇒ As the winding is purely inductive in nature, the primary current I_0 laggs behind the supply voltage V_1 by 90°.

⇒ As the induced emf E_1 and E_2 opposes the supply voltage V_1, they lag behind V_1 by 180°.

NOT IDEAL TRANSFORMER.



⇒ But when the transformer is not ideal, then the windings are not purely inductive.

⇒ Hence the no load primary current I_0 is not at 90° behind V_1, but it lagg V_1 by an angle 'ϕ' which is less than 90°.

⇒ The primary current I_0 has two components:

(i) Active Component (I_w) ⇒ This component will be inphase with V_1. This component mainly supply Iron loss and some quantity of primary copper loss. This is also called as working component or Iron loss component.

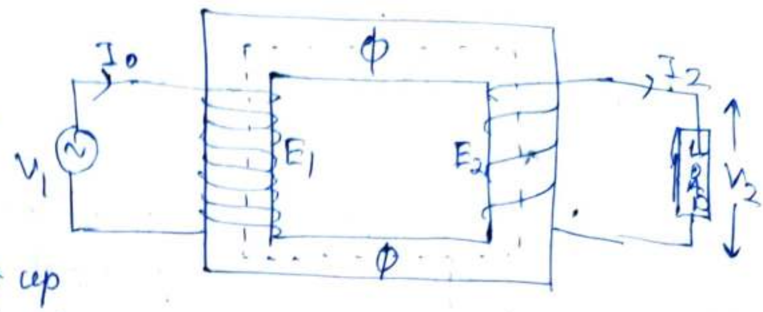
$$I_w = I_0 \cos\phi$$

(ii) Magnetising Component (I_μ) ⇒ This component laggs behind V_1 by 90°. Function of this component is to maintain alternating flux in the core.

$$I_\mu = I_0 \sin\phi$$

$$\vec{I_0} = \vec{I_w} + \vec{I_\mu} = I_0\cos\phi + I_0\sin\phi$$

NOT IDEAL TRANSFORMER AT LOAD



⇒ When the secondary is loaded, secondary current I_2 is set up.

⇒ The secondary current set up it's own flux Φ_2 which is in opposite direction to the main flux ϕ.

⇒ The opposing flux Φ_2 weaken the primary flux ϕ. Hence primary induced emf E_1 tends to reduce. As a result an additional primary current I_2' flows in the primary winding. It is known as load component of primary current.

⇒ This additional current I_2' set up it's own flux Φ_2' which is in opposite direction to Φ_2 but in same direction to ϕ.

⇒ Hence the two flux Φ_2 and Φ_2' cancel out each other. So we find the magnetic effect of secondary current I_2 is immediately neutralised by the additional primary current I_2'.

⇒ Hence what ever the load condition the net flux passing through the core is approximately same as the no load flux ϕ.

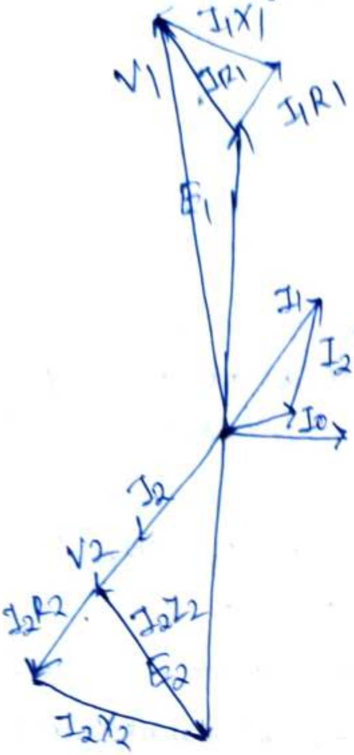
$$\Phi_2 = \Phi_2'$$

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

$$\Rightarrow \frac{I_2'}{I_2} = \frac{N_2}{N_1} = K \qquad \boxed{I_2' = K I_2}$$

3.8 Phasor Diagram of T/F on Load with winding resistance, and leakage Reactance.

LOAD having unity power factor.



→ Induced emf in primary and secondary winding will be 180° to each other

→ As load is resistive, load voltage and current will be in phase.

→ Primary winding →

$$V_1 = E_1 + I_1R_1 + jI_1X_1$$

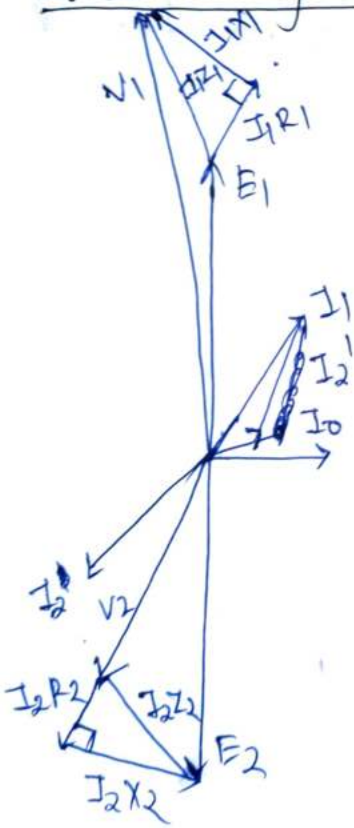
Secondary winding

$$E_2 = V_2 + I_2R_2 + jI_2X_2$$

→ $I_1 = I_0 + I_2'$

→ I_2X_2 will be in 90° to I_2R_2. Similarly I_1X_1 will be in 90° to I_1R_1.

Load having Lagging Power factor.



→ As load is inductive, I_2 lags behind V_2.

→ I_2R_2 will be in parallel with I_2. I_2X_2 is in 90° to I_1X_2.

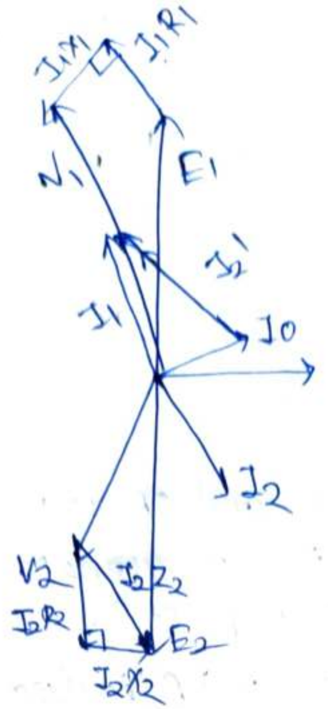
→ I_2' will be in opposite to I_2.

$$I_0 + I_2' = I_1$$

→ I_1R_1 will be in parallel to I_1. I_1X_1 is 90° to I_1R_1.

$$\vec{E_1} + \vec{I_1}R_1 + \vec{I_1}\vec{X_1} = \vec{V_1}$$

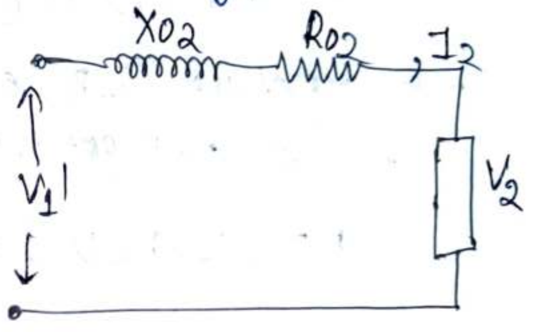
Load having leading power factor :



→ As load is capacitive I_2 lead V_2.
→ According the wave form changes.

Approximate Voltage of ~~in~~ a Transformer.

Equivalent circuit of a T/F w.r.t secondary is given below.



Here
R_{02} = Equivalent resistance of T/F w.r.t secondary
X_{02} = Equivalent ~~resistance~~ reactance of T/F w.r.t secondary.

Now applying KVL on the circuit we get

$$\vec{V_1'} = \vec{I_2}R_{02} + \vec{I_2}X_{02} + \vec{V_2}$$

$$= \vec{I_2}Z_{02} + \vec{V_2}$$

Here $\vec{I_2}Z_{02}$ is the voltage drop in the transformer.

Let the load is inductive.

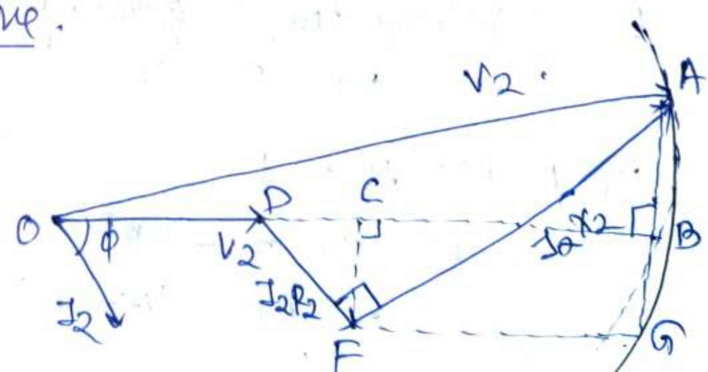


fig-1

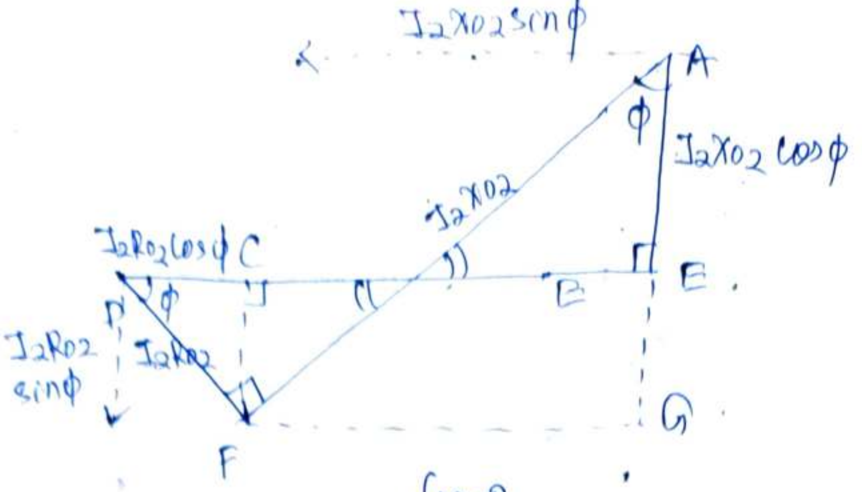


fig-2

- In fig 1 with O as centre and OA as radius an arc is drawn. OD vector ($\vec{V}$) is extended with dotted line which cut the arc at point B.
- From point F a perpendicular FE is drawn and from point A perpendicular AE is drawn on line OB.

Here Approximate voltage drop is DE.

$$DE = DC + CE$$

- By resolving $I_2 R_{02}$ and $I_2 X_{02}$ into two components as shown in fig-2, we get the value of DC and CE

$$DE = I_2 R_{02} \cos\phi + I_2 X_{02} \sin\phi$$

So
Approximate Voltage drop

$$= I_2 R_{02} \cos\phi + I_2 X_{02} \sin\phi \text{ (w.r.t secondary)}$$

$$= I_1 R_{01} \cos\phi + I_1 X_{01} \sin\phi \text{ (w.r.t Primary)}$$

Exact voltage Drop:

Exact voltage drop is given by DB.

$$DB = DC + CB.$$

In Δ AOB in fig-1.

$$AE^2 = OA^2 - OB^2$$

$$= (OA + OB)(OA - OB)$$

$$AE^2 = 2OA \times (OE + EB - OB)$$
$$= 2OA \times ED$$
$$\Rightarrow EB = \frac{AE^2}{2OA}$$
$$= \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2V_1'}$$

Exact voltage drop = DB

$$= DE + EB$$
$$= \text{Approximate voltage drop} + EB$$
$$= (I_2 R_{02} \cos\phi \mp I_2 X_{02} \sin\phi) + \left(\frac{I_2 X_{02} \cos\phi \pm I_2 R_{02} \sin\phi}{2V_1'}\right)^2$$

<u>If load is Resistive.</u>

Exact voltage drop and approximate voltage drop
$$= I_2 R_{02}$$

VOLTAGE REGULATION OF T/F

Voltage regulation of a transformer is the arithmetic difference between the no-load secondary voltage ($_0V_2$) and the secondary voltage on load (V_2) expressed as percentage of no-load voltage.

$$\%\ \text{Voltage Regulation} = \frac{_0V_2 - V_2}{_0V_2} \times 100$$

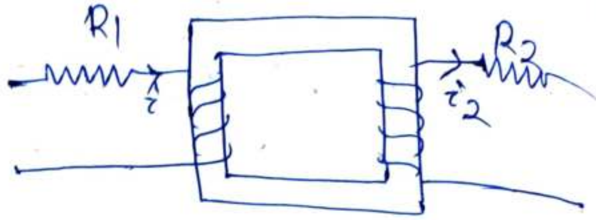
$_0V_2$ = No load secondary voltage

V_2 = Secondary voltage on load.

$$_0V_2 - V_2 = I_2 R_{02} \cos\phi_2 \pm I_2 X_{02} \sin\phi_2$$

3.7 Equivalent Resistance, Leakage Reactance and impedance of transformer.

Equivalent Resistance.



→ Let the primary and secondary winding of the have resistances of R_1 and R_2 respectively.

→ For simplicity in calculation, resistance of the two windings can be transferred to any one of the two winding.

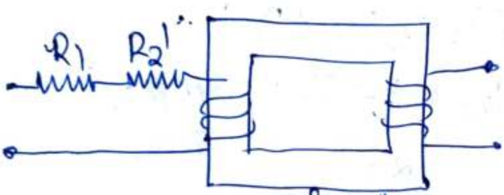


fig-1

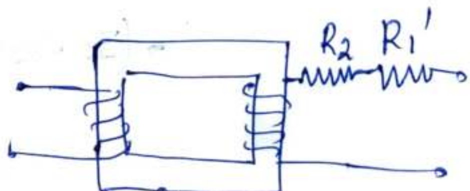


fig-2

→ Let the resistance of secondary winding is transferred to winding of primary as shown in fig-1.

The power loss in the resistance R_2 must be same after transfer from secondary to primary.

so $I_2^2 R_2 = I_1^2 R_2'$

$$\Rightarrow R_2' = \frac{I_2^2}{I_1^2} R_2 = \left(\frac{I_2}{I_1}\right)^2 R_2$$

$$\Rightarrow R_2' = \frac{R_2}{K^2}$$

So total Resistance of the transformer with reference to primary is

$$\boxed{R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}}$$

Similarly equivalent resistance of transformer with reference to secondary is

$$\boxed{R_{02} = R_2 + R_1' = R_2 + K^2 R_1}$$

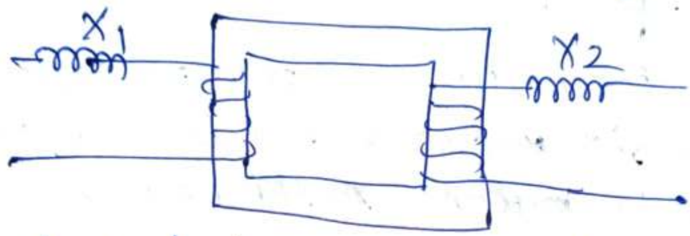
$I_1^2 R_1 = I_2^2 R_1'$

$\Rightarrow R_1' = \frac{I_1^2}{I_2^2} R_1 = K^2 R_1$

In the working principle of transformer it is assumed that flux linked with primary winding also links the secondary winding.

→ But in practice, all the flux linked with primary does not link the secondary. Because a part of total flux completes its path by passing through air. This flux is called as leakage flux.

→ This leakage flux produces a self induced e.m.f in coil. Hence it is equivalent to a small inductive coil in series with each winding.



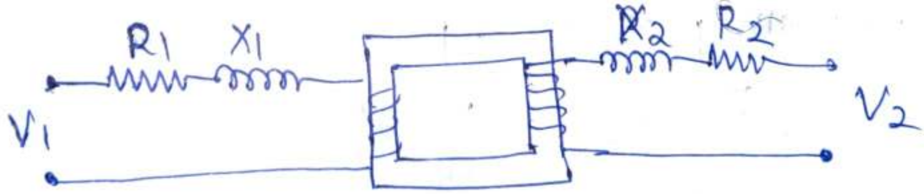
Equivalent leakage reactance of T/p w.r.t Primary

$$X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

and w.r.t secondary

$$X_{02} = X_2 + X_1' = X_2 + K^2 X_1$$

Impedance of Transformer.



Impedance of primary winding, $Z_1 = R_1 + iX_1$

$$Z_1 = \sqrt{R_1^2+X_1^2}$$

Impedance of secondary winding $Z_2 = R_2 + iX_2$

$$Z_2 = \sqrt{R_1^2+X_1^2}$$

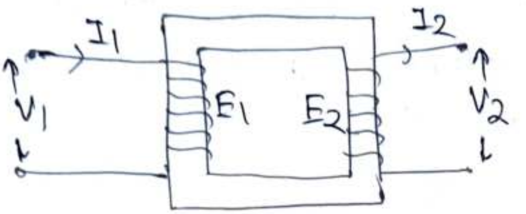
Equivalent impedance of T/F w.r.t primary

$$Z_{01} = Z_1 + Z_2' = Z_1 + \frac{Z_2}{K^2}$$

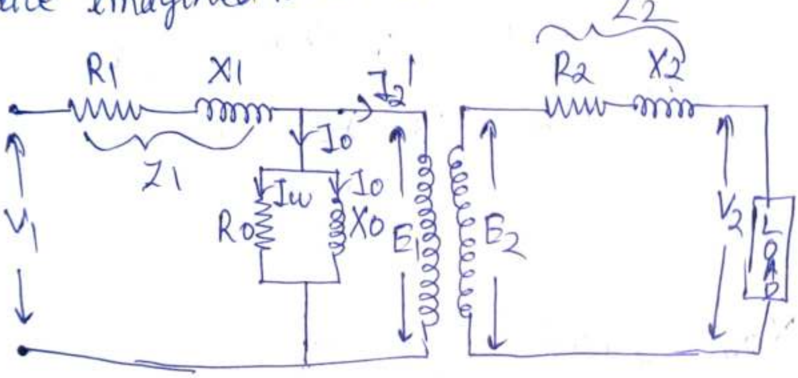
Equivalent impedance of T/F w.r.t secondary

$$Z_{02} = Z_2 + Z_1' = Z_2 + K^2 Z_1$$

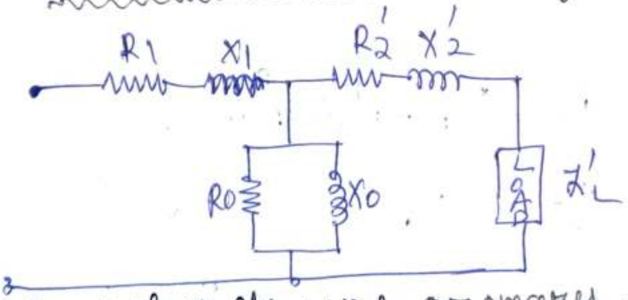
Equivalent Circuit of T/F.



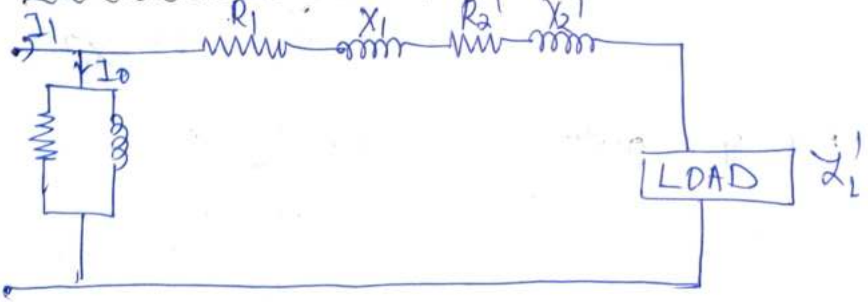
The transformer can be resolved into an equivalent circuit in which the resistance and leakage reactance are imagined to be external to the windings.



Equivalent ckt w.r.t primary.

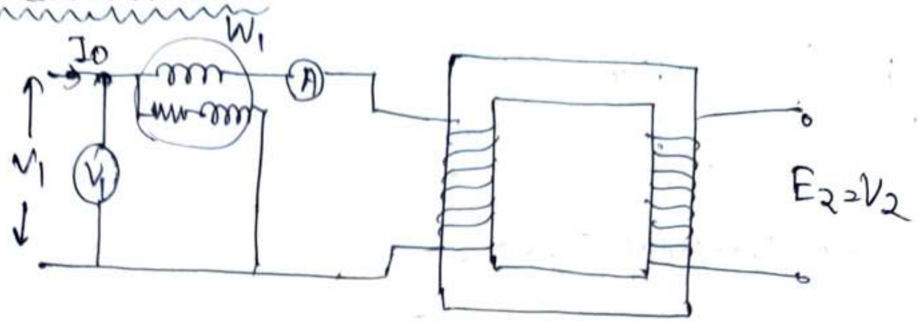


Equivalent ckt w.r.t primary.



TRANSFORMER TESTS

OPEN Circuit Test:



→ From this test we can determine no load loss or core loss, and no load current I_0. Value of I_0 is helpful to findout X_0 and R_0.

→ One winding of T/F (usually HV winding) is left open and other winding is connected to it's supply of normal voltage and frequency.

→ A wattmeter W_1, Ammeter A and Voltmeter V is connected in lowvoltage winding.

→ W_1 will measure the input power. As load is not connected

$$P_{in} = \text{Iron loss} + \text{Primary Cu loss}$$

→ Ammeter will measure no load current I_0 & voltmeter will measure input voltage V_1.

$$\text{Primary Cu loss} = I_0^2 R_1$$

So $\boxed{\text{Iron loss} = W - I_0^2 R_1}$

Primary Cu loss may be neglected.

We know that

$$P = V_1 I_0 \cos\phi$$

$$\Rightarrow \cos\phi = \frac{P_{in}}{V_1 I_0}$$

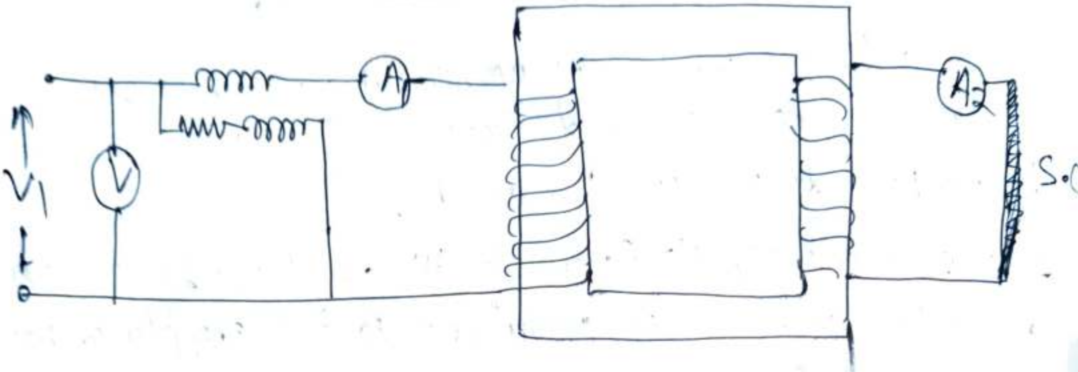
$$\Rightarrow \phi = \cos^{-1}\left[\frac{P_{in}}{V_1 I_0}\right]$$

$I_\mu = I_0 \sin\phi$

$I_w = I_0 \cos\phi$

$$R_0 = \frac{V_1}{I_w} \qquad X_0 = \frac{V_1}{I_\mu}$$

Short Circuit Test.



→ Short Circuit test is performed to determine

(i) Equivalent impedance Z_{01} or Z_{02}, equivalent reactance (X_{01} or X_{02}), equivalent Resistance (R_{01}, R

(ii) Cu loss at full load

(iii) Voltage regulation.

→ In this test the low voltage is short circuited by a thick conductor. Experiment is conducted in high voltage side i.e. wattmeter, voltmeter and ammeter are connected.

→ A low voltage is applied to the high voltage side and increased till full-load are flowing both in primary and secondary winding.

→ As a primary voltage is small percentage of normal voltage, mutual flux ϕ is also less. So core loss is very small that can be neglected.

so $W_1 = I_1^2 R_{01}$

$$R_{01} = \frac{W}{I_1^2}$$

$$Z_{01} = \frac{V_{sc}}{I_1}$$

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

Efficiency of A Transformer.

The efficiency of a T/F at a particular load and power factor is defined as o/p power divided by i/p power being measured in the same unit.

$$\eta = \frac{P_{o/p}}{P_{i/p}} = \frac{P_{o/p}}{P_{o/p} + losses} = \frac{P_{i/p} - losses}{P_{i/p}}.$$

Condition for maximum efficiency

$$V_{i/p} = V_1 I_1 \cos\phi$$

$$losses = W_i + W_c$$

With reference to primary

$$W_c = I_1^2 R_{01}$$

$$\eta = \frac{I_1 V_1 \cos\phi - (W_i + I_1^2 R_{01})}{V_1 I_1 \cos\phi}$$

$$= 1 - \left(\frac{W_i + I_1^2 R_{01}}{I_1 V_1 \cos\phi}\right)$$

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

for maximum efficiency

$$\frac{d}{dI}(\eta) = 0$$

$$\Rightarrow \frac{d}{dI}(\eta) = 0 + \frac{W_i}{I_1^2 V_1 \cos\phi} - \frac{R_{01}}{V_1 \cos\phi} = 0$$

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

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

For maximum efficiency $\boxed{W_i = W_c}$

→ There are mainly three types of losses

① Iron loss/ core loss < Hysteresis loss, Eddy current loss

② Copper loss < Primary Cu loss, Secondary Cu loss

③ Dielectric loss

Iron loss/ Core loss

→ The losses which occurs on the core of a T/F is called as core loss or Iron loss. This loss occurs due to the alternating current in the winding.

Hysteresis loss → This loss occurs due to continuous magnetisation and demagnetisation of iron core. This occurs due to the alternating flux flowing through the core. It is reduced by using silicon steel to make T/F core.

Eddy Cu loss → Due to the alternating flux in the core, circulating current flows on the surface of iron core which results in generation heat or power loss. It is called as Eddy Cu loss. It is reduced by using laminated sheet of silicon steel to make T/F core.

Copper loss

When current flows in the windings of T/F I^2R loss (in the form of heat) takes place. It is called Cu loss.

Cu loss of T/F w.r.t Primary → $I_1^2 R_{01}$

" Secondary → $I_2^2 R_{02}$

Dielectric loss

→ It occurs within the oil of transformer.

→ When oil quality diminishes, transformer efficiency will be affected.

ALL-DAY EFFICIENCY

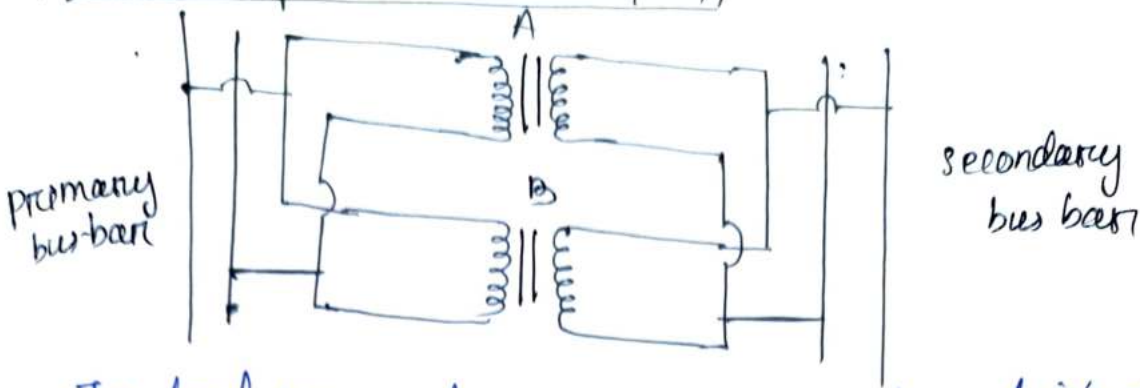
→ The ordinary or commercial efficiency of the T/F is given by the ratio

$$\eta = \frac{P_{o/p} \text{ in watt}}{P_{i/p} \text{ in watt}}$$

→ But in case of distribution T/F this formula is not applicable. Because load connected in the secondary winding changes through out the day, therefore in this case all day efficiency of the T/F is calculated

$$\eta_{all\ day} = \frac{P_{o/p} \text{ in kwh}}{P_{i/p} \text{ in kwh}} \text{ (for 24 hours)}$$

Parallel operation of 1-ϕ T/F



→ If load connected to a T/F increases beyond it's rating a second T/F may be connected in parallel with it to supply the extra load.

→ The primary windings are connected to the supply busbare and secondary windings are connected to load busbar.

→ Due to parallel operation of T/F maintanance of T/F is possible with interception of powere flow.

→ During fault in any T/F power flow to the load can be continued from other T/F.

Condition for parallel operation

① Polarity of the two T/Fs must be same. In other ward positive polarity of T/F 1 and T/F 2 are connected to positive ~~tor~~ line of busbar.

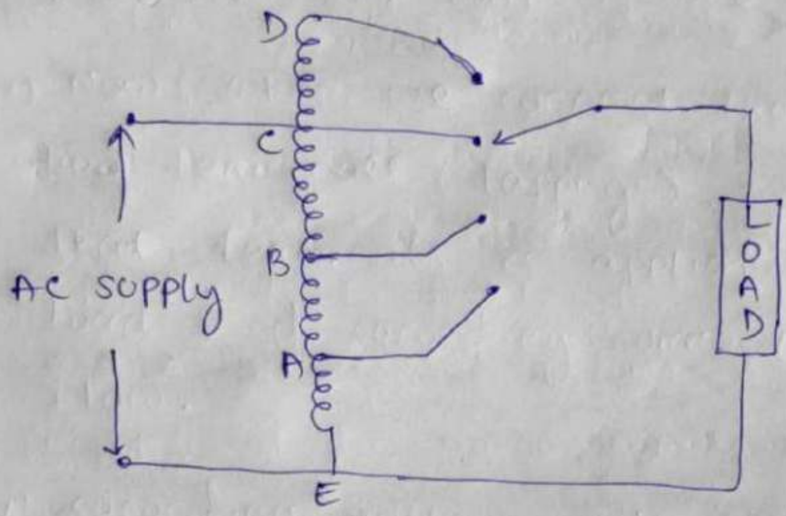
② Both T/F should have same transformation ratio.

③ Percentage impedance of both T/F should be same to abvoid circulating current.

Chapter-4 Auto Transformer.

Auto Transformer :-

An auto transformer is an electrical transformer having one winding with more than two terminals.



Advantages :-

(i) They are smaller in size.

(ii) cheap in cost.

(iii) low leakage reactance.

(iv) low exciting current.

construction :-

(i) An auto transformer consists of a single copper wire, which is common in both primary as well as secondary circuit.

(ii) The copper wire is wounded on a laminated silicon steel core with more than two tapping.

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both primary and secondary circuit share the same neutral point.

(iii) the above figure shows ckt diagram of a Auto transformer. we can see that variable turns on the secondary can be obtained by tapping of the winding.

(iv) Here the primary and secondary circuits are connected electrically as well as magnetically.

(v) The same Transformer can be used as step down or step-up transformer due to presence of tapping. for example, if the load is connected to tapping 'D', then the transformer will act as step-up Transformer. Because, here primary turns are 'CE' where as secondary turns are 'DE'. we can clearly see that CE < DE. So secondary voltage will be greater than primary. But if load is connected to tapping B or A, then it will act as a step down transformer.

Working principle of Auto transformer :-

(i) It's working principle and operation is similar to a two winding transformer.

(ii) when supply is given to the primary circuit

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AC current flows through the winding. Therefore an alternating flux is created around the conductor or winding.

(iii) According to Faraday's law of electromagnetic induction emf will induce in the coil.

(iv) Now, when we connect the load between two terminals (tappings), induced emf between that terminals is applied across the load and secondary current starts to flow.

(v) secondary voltage will depends on the number of turns and no. of turns depends upon tapping on winding.

Comparision between two winding T/F and Auto Transformer :-

Two winding T/F.	Auto T/F.
(i) It has two winding i.e primary and secondary.	(i) It has one winding only.
(ii) primary and secondary circuits are electrically separated but	(ii) primary and secondary circuits are connected electrically

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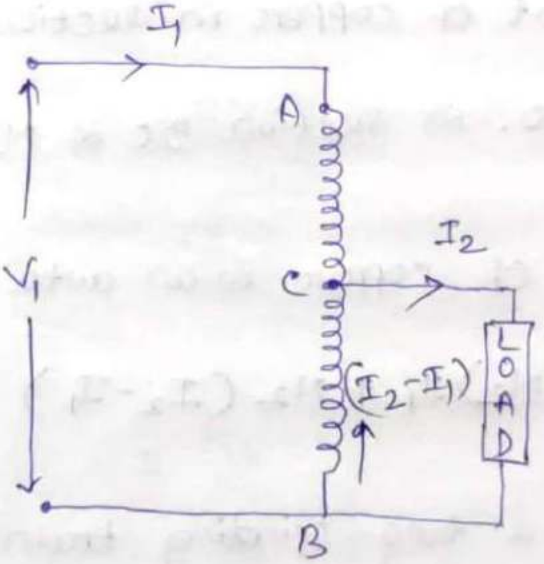
magnetically coupled	as well as magnetically.
(iii) size is large	(iii) size is small.
(iv) copper requirement is more	(iv) copper requirement is less.
(v) cost is more.	(v) cost is less.
(vi) Losses are more and efficiency is less.	(vi) Losses are Less and efficiency is more.
(vii) Poor voltage regulation.	(vii) Better voltage regulation.
(viii) output is constant.	(viii) output is variable.

Saving of copper in an Auto Transformer. :-



Here AB is the primary winding having N_1 turns and BC is secondary winding having N_2 no.of turns. so,

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$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K.$$

current in section BC is vector difference of I_2 and I_1. As it is a step down transformer $V_2 < V_1$ and $I_2 > I_1$. So current in section 'BC' is $I_2 - I_1$

we know that weight of copper is proportional to the length and area of cross-section of the conductors. Again length is proportional to no. of turns and cross-sectional area depends on current. Hence weight is proportional to the product of current and number of turns.

So, weight of copper in section $AC \propto (N_1 - N_2) I_1$

weight of Cu. in section $BC \propto N_2 (I_2 - I_1)$.

$\therefore$ Total weight of copper in an auto transformer

$$= (N_1 - N_2) I_1 + N_2 (I_2 - I_1).$$

let, we take a two winding transformer.

Here weight of copper in primary $\propto N_1 I_1$

Similarly weight of copper in secondary $\propto N_2 I_2$

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∴ Total weight of copper in a two winding

$$= N_1 I_1 + N_2 I_2.$$

$$\frac{\text{weight of cu. in auto T/F.}}{\text{weight of cu. in two winding Transformer}} = \frac{(N_1 - N_2) I_1 + N_2 (I_2 - I_1)}{N_1 I_1 + N_2 I_2}$$

$$\Rightarrow \frac{W_a}{W_0} = \frac{N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$\Rightarrow \frac{W_a}{W_0} = \frac{N_1 I_1 + N_2 I_2 - N_2 I_1 - N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$= 1 - \frac{N_2 I_1 - N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$= 1 - \frac{\frac{2 N_2 I_1}{N_1 I_1}}{\frac{N_1 I_1}{N_1 I_1} + \frac{N_2 I_2}{N_1 I_1}} \quad \left[\text{dividing by } N_1 I_1\right].$$

$$= 1 - \frac{2 \frac{N_2}{N_1}}{1 + \frac{N_2}{N_1} \times \frac{I_2}{I_1}}$$

$$= 1 - \frac{2 \times K}{1 + \frac{1}{K} \times K}$$

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$$\Rightarrow \frac{W_a}{W_o} = 1 - \frac{2K}{2}$$

$$\Rightarrow \frac{W_a}{W_o} = 1-K.$$

$$\Rightarrow W_a = (1-K) W_o$$

Saving of copper $= W_o - W_a$

$= W_o - (1-K)W_o$

$= W_o(1-1+K).$

$= K W_o.$

Saving = K X weight of ordinary or two winding transformer..

Here, Power transfered inductively $= (1-K) P_{i/p}$.

Power transfered conductively $= K P_{i/p}$.

Uses of Auto Transformer. :-

(i) To adjust AC supply voltage. By using it we can vary the AC voltage (voltage - regulator).

(ii) It is used as a starter for squirrel cage induction Motor.

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(iii) It is used in power transmission and distribution system.

(iv) It is also used in audio system and railways.

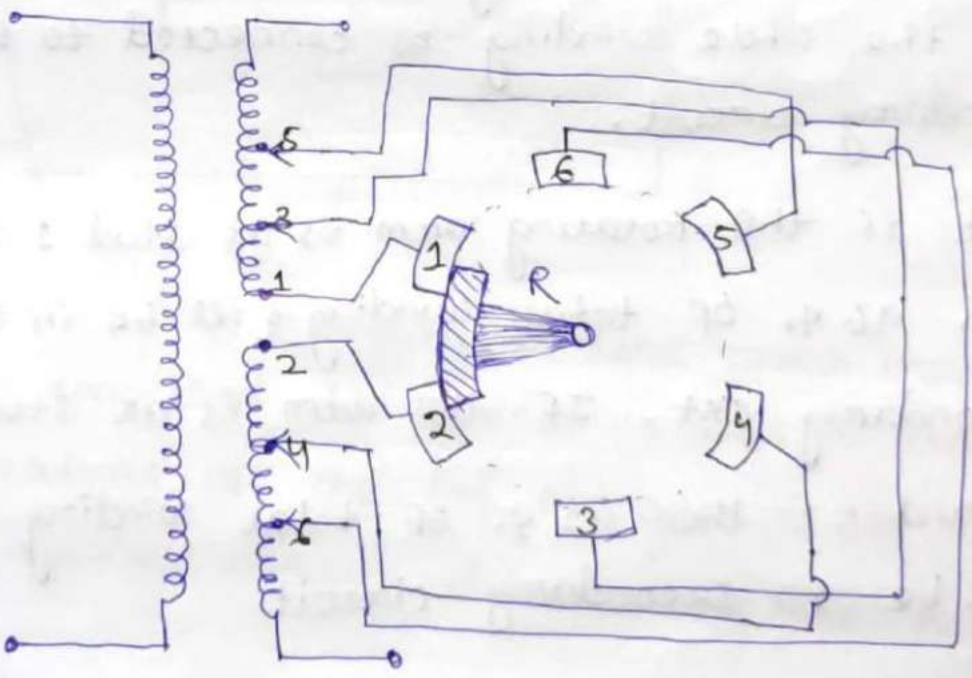
Tap changer :-

Mechanism used to change the tapping of a transformer is called tap changer. Tap changer is mainly classified in to two types.

(1) Off Load tap changer.

(2) ON-Load Tap changer.

1. Off Load Tap changer :-



(i) Here tap changing is done when the transformer is disconnected from the main supply. This tap changing is usually done manually.

(ii) The above fig. shows an off-load tap changer. The secondary winding is tapped from six location.

(iii) This tappings are connected to six studs arranged along a periphery of a cycle.

(iv) The rotable arm R can be rotated by a hand wheel mounted outside the transformer tank.

(v) Let, the tappings are at an interval of 2%. If position of rotating arm is at stud 1 and 2, the whole winding is connected to the secondary circuit.

(vi) But if the rotating arm is at stud 1 and 6 then 96% of total winding will be in the secondary ckt. If the arm is at stud 6 and 5, then 92% of total winding will be in secondary circuit.

(vii) In the process by moving the rotating arm, no. of turns in the secondary winding

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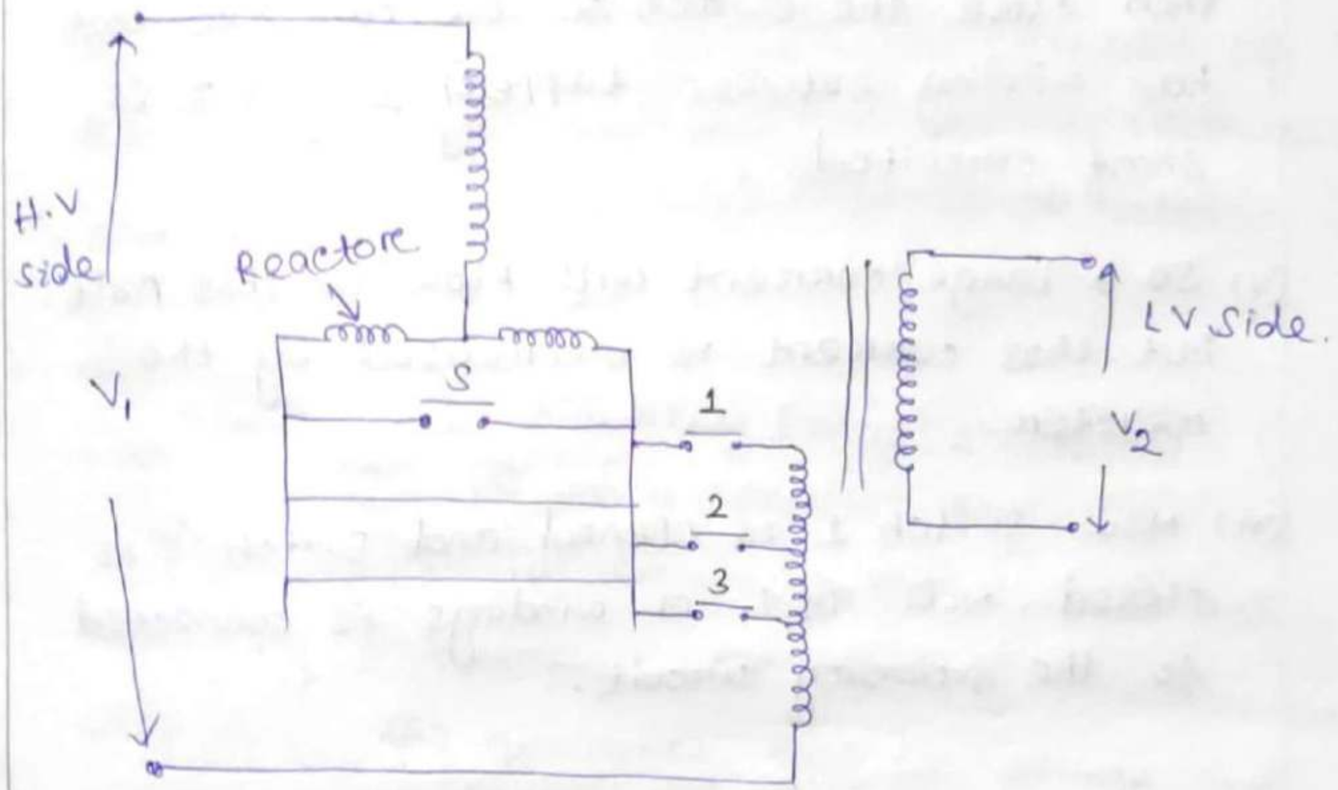
changes. As a result secondary voltage also changes.

(iii) This tap changer is only used in off condition of transformer. If we use it in on condition. then huge spark will produce.

ON-Load Tap changer :-



(i) Here Tap changing is done, when transformer is connected to source as well as load. Main feature of the tap changer is to change tapping without discontinuing the power supply.

(ii) In this type of tap changer a centre tapped reactor provided to prevent short circuit

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of the tap winding. During normal operation switch 's' remainly closed.

(iii) Let initially switch of tapping one is closed. So whole windings is connected. Now if I required less voltage, the tappers 2 is to be connected.

(iv) for this we have to first open the switch 's'. then close the switch 2. we can see that how winding between tapping 1 and 2 is short circuited.

(v) So a large current will flow to this part. But this current is decreased by the reactor.

(vi) Now switch 1 is opened and switch 's' is closed. Now 98% of windings is connected to the primary circuit.

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(Chapter-5) Instrument Transformers

Instrument transformers :-

(i) Instrument transformers are used in AC system for measurement of electrical quantities like current, voltage, power, energy etc.

(ii) Generally measuring instruments are of low ratings. So by using this instruments we can not measure high electrical quantities. It is very costly to design the measuring instrument for measurement of such high level voltage and current.

(iii) measurement of such very large electrical quantities can be made possible by using instrument transformer with these small rating measuring instruments. Instrument transformer step down the quantities that is voltage and current. so that they can be measured by low rating instruments.

(iv) Mainly there are two types of instrument transformer

(1) current transformer (C.T).
(2) Potential transformer (P.T).

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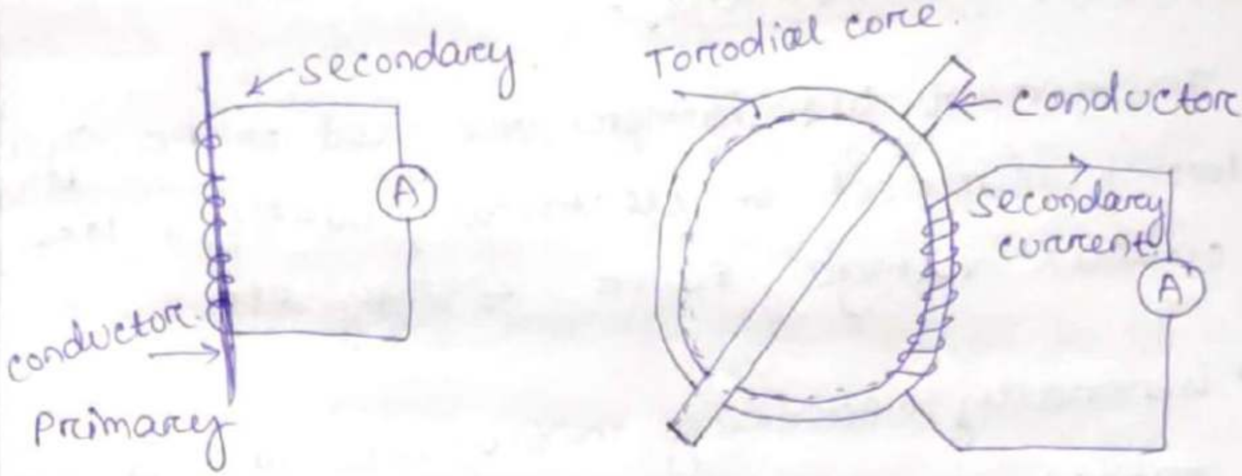
Current Transformer :-



(i) current transformer is used to step up the voltage or step down the current so that this stepped down current can be easily measured by measuring instruments.

(ii) Primary of C.T is having very few turns and secondary has large no.of turns. secondary winding is connected to measuring instrument.

(iii) current transformers are often constructed by passing a single primary turn (either an insulated cable or an uninsulated busbar) through a well insulated ring shaped (torodial) core wound with many no.of turns.

(iv) one terminal of the secondary is earthed to avoid the chance of insulation breakdown

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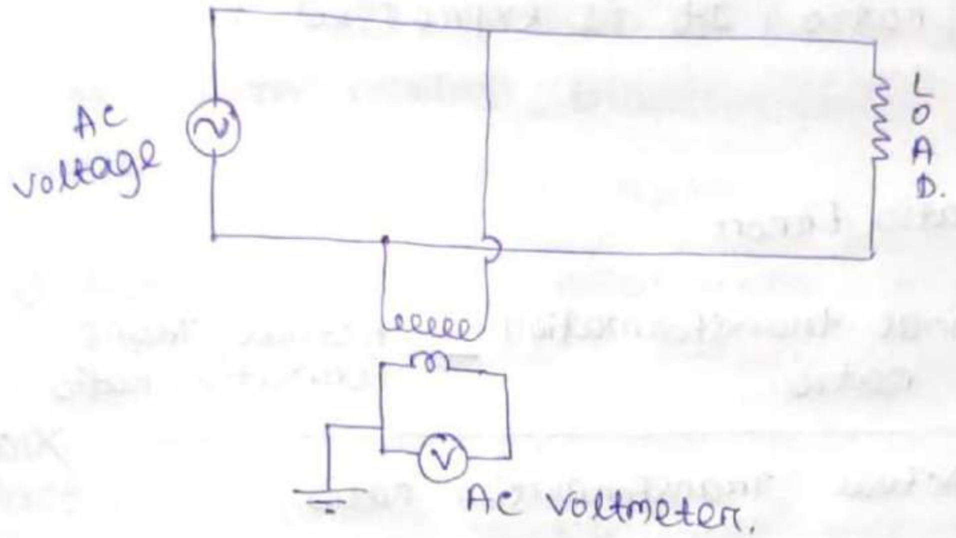
and also protect the operatore against high voltage

(v) Turns ratio of the transformer is

$$\text{Turns ratio} = \frac{N_p}{N_s} = \frac{I_s}{I_p} = \frac{V_p}{V_s}.$$

Potential Transformere (PT) :-



(i) Potential transformers are also known as voltage transformers and they are basically step down transformers.

(ii) They step down the voltage of high magnitude to a lower value. which can be measured with standard measuring instrument.

(iii) These transformers have large number of primary turns and less number of secondary turns.

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(iv) secondary winding is connected to a Voltmeter.

(v) one terminal of the secondary is connected to each for safety of operator.

Ratio Error of C.T. :-

Ratio error of C.T is defined as the per unit deviation in transformation ratio from nominal ratio. It is expressed in percentage.

Percentage Ratio Error

$$= \frac{\text{Nominal transformation ratio} - \text{Actual Transformation ratio}}{\text{Actual Transformation ratio}} \times 100$$

nominal transformation ratio = rated transformation ratio.

Phase angle error of CT :-

Ideally the angle between primary and secondary current should be 180 degree. But there is some deviation from 180°. This deviation is called phase angle error.

OR

It is defined as the phase difference between primary current and reversed secondary current.

Burden of CT or PT. :-

It is defined as the volt ampere (VA) of connected load across the terminals of secondary winding of CT and PT.

Ratio Error of PT. :-

Ratio error of PT is defined as the variation in nominal transformation ratio to actual transformation ratio.

$$\% \text{ Ratio Error} = \frac{\text{Nominal ratio} - \text{Actual ratio}}{\text{Actual ratio}} \times 100$$

Phase angle error of PT. :-

Ideally angle between primary and secondary voltage should be 180°. But practically there is same deviation from 180°.

OR.

It is defined as the phase difference between the primary voltage and reversed secondary voltage.

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Uses of current T/F :-

current transformers are used in a wide variety of applications ranging from power system control to the precise current measurement in industrial, medical, automotive and telecommunication system. Some of the application are.

(1) Extending the range of measuring instruments such as ammeter, energy meter, wattmeter etc.

(2) Over current fault protection.

(3) Distance protection in power transmission system.

Uses of Potential Transformer :-

Like C.T., potential transformers are also used in power system control, industrial, medical, automotive and telecommunication system.

① Extending the range of measuring instruments like voltmeter, energy meter, wattmeter, etc.

② Electrical protection system.

③ Distance protection of feeders

④ Impedance protection of generator.

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