Unit-III

3. Starting, Speed control and Testing of DC Machine

Speed control Methods of DC Machine:-

$$E_b = \frac{\phi Z N}{60}\left[\frac{P}{A}\right]$$

Z, P, A are constants

$E \propto \phi N$

$N \propto \frac{E}{\phi}$; $E_b = V - I_a R_a$, very small value negligible

$E_b \approx V$

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

Thus the factors effecting the speed of the DC-Motor are

1. The flux
2. voltage across the Armature
3. The applied voltage

Depending upon these factors the various speed control methods are

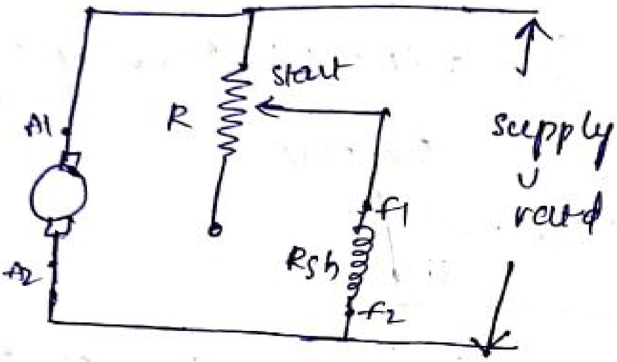
1. the change in the flux (ϕ) by controlling the current through the field winding is called Flux control method.

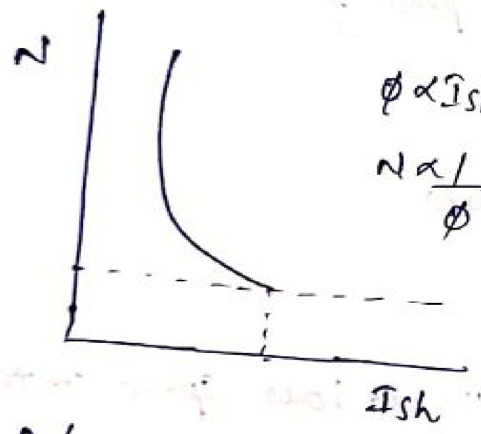
2. change in the armature path resistence which in turn changes the voltage applied across the Armature is called "rheostatic control Method or Armature control Method

3. change in the applied voltage called applied voltage control Method.

* Speed control of DC - Shunt Motor :—

* flux control Method :-





$\phi \propto I_{sh}$

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

this method is for above rated speed machines

(Rectangular hyperabola)

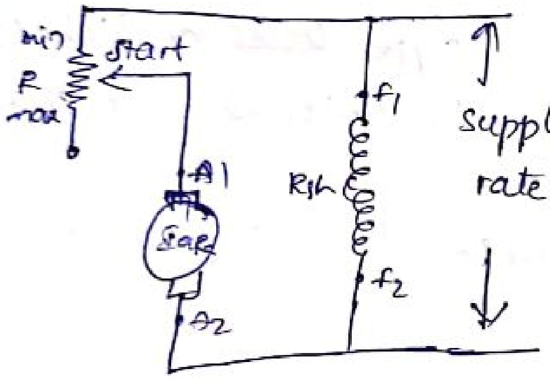
Advantages:-

- It provides relatively smooth and easy control.
- Speed control above rated speed is possible
- As field winding resistance is high, the field current is small. hence power loss is very small, which makes method more economical and efficient.
- As the field current is small the size of the rheostat is small

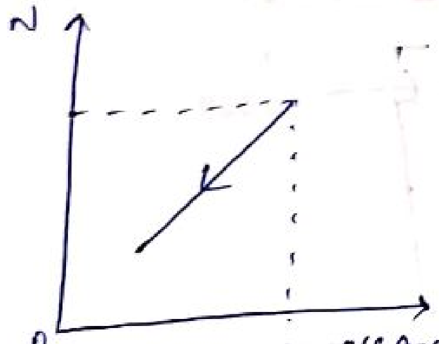
Disadvantages:-

- The speed control below normal rated speed is not possible as flux can be increased upto only its rated value.
- As flux reduces, speed increases. But high speed effects the commutation making motor operation unstable.

* Rheostatic control Method / Armature Control Method:-



$N \propto E_b \propto V - I_a R_a$

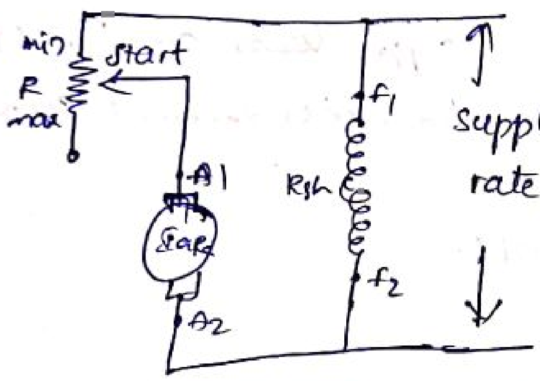


It doesn't support the armature to zero.

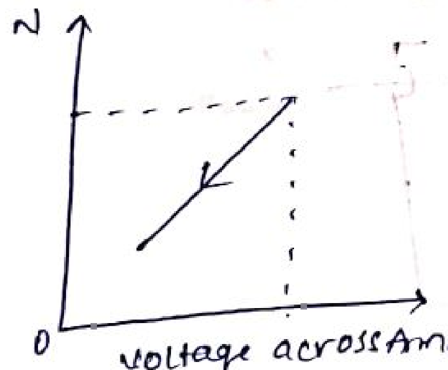
Disadvantages:-

- The speed control below normal rated speed is not possible as flux can be increased upto only its rated value.
- As flux reduces, speed increases. But high speed effects the commutation making motor operation unstable.

* Rheostatic control Method of Armature Control Method:-

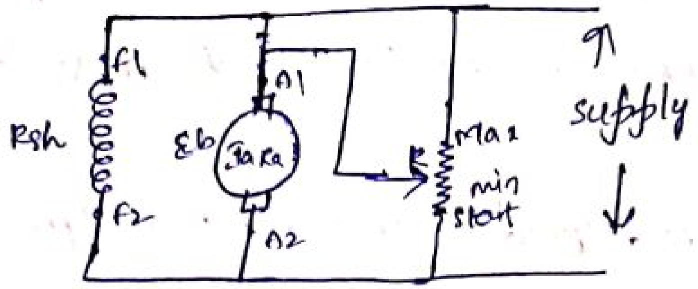


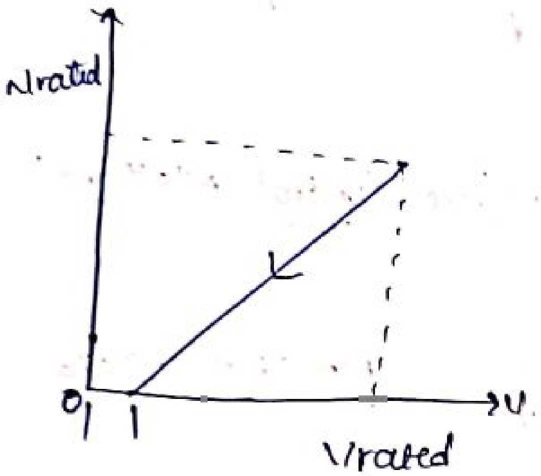
$N \propto E_b \propto V - I_a R_a$



It does not support the armature to zero.

* potential devider control:-

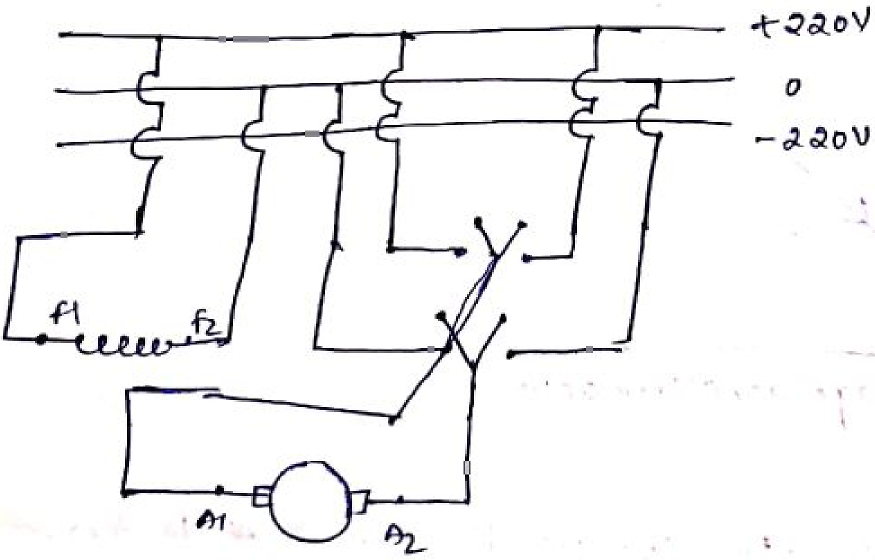




It take some time to start the motor. it doesn't becomes zero.

copper losses are high (I^2R) due to series Rheostat connection

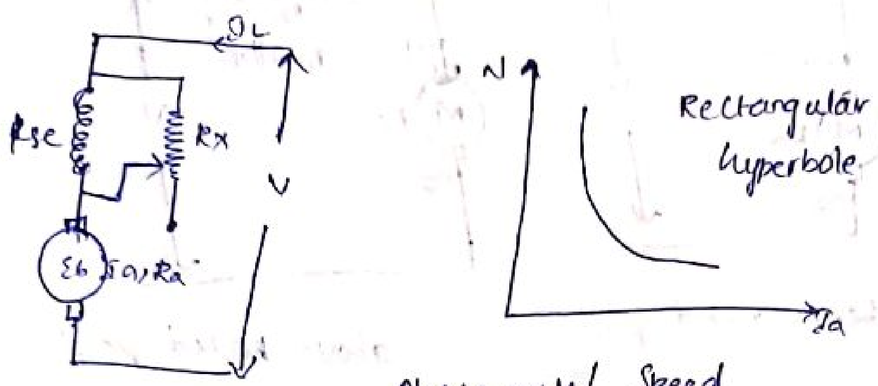
* Applied voltage Control:-



Speed control of DC- Series Motor:-

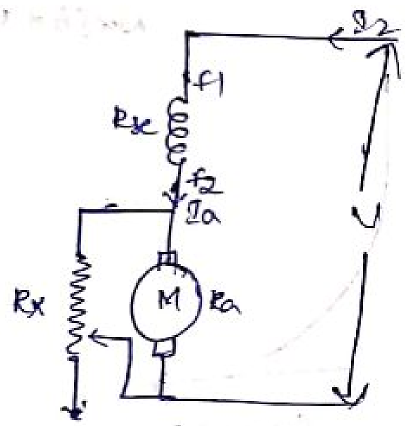
1) flux control Method

i) field diverter Method



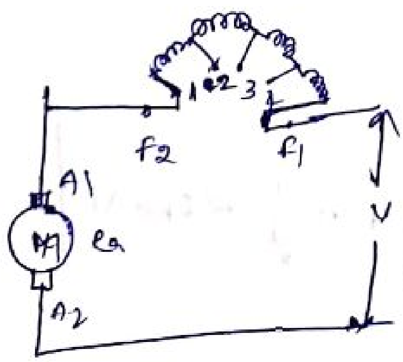
Above rated Speed

ii) Armature diverter Method:-



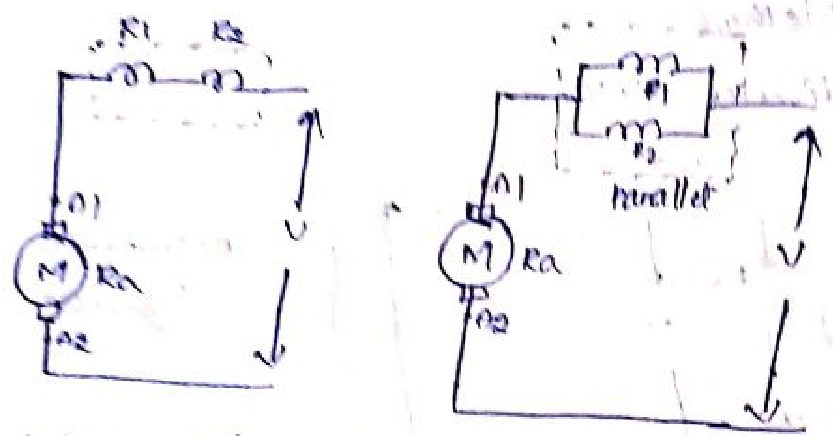
$T \propto \phi I_a$ (below rated speeds)

iii) Tapped field Method:-



above rated Speeds

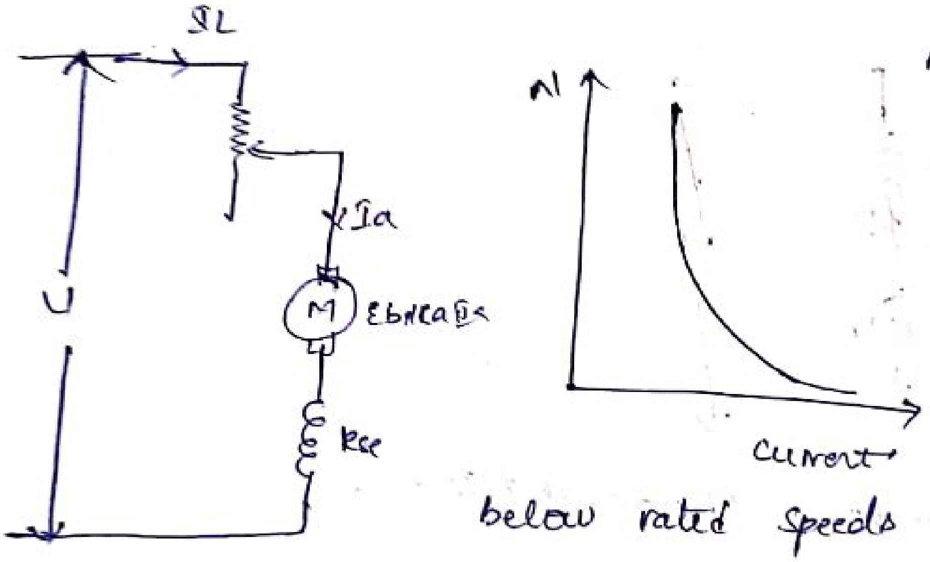
iv) Series parallel connection of field:



below rated speed

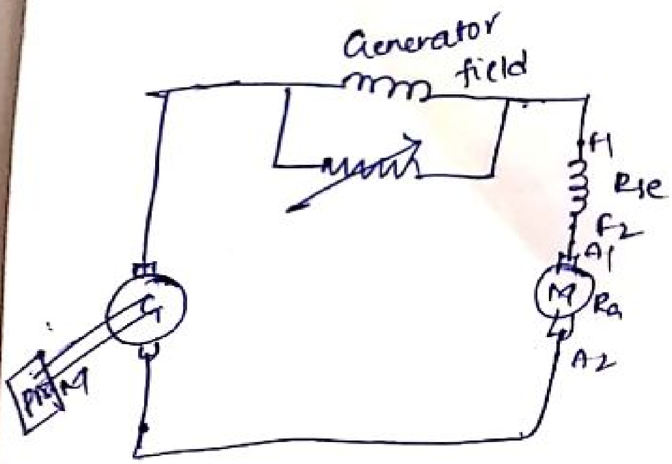
above rated speed

Armature Control Method (or) Rheostat control Method:-



below rated speeds

* Applied voltage control:-



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

* Starting Methods of D.C. Motor:—

$E_b = V - I_a R_a$

$E_b = 0$ (starting)

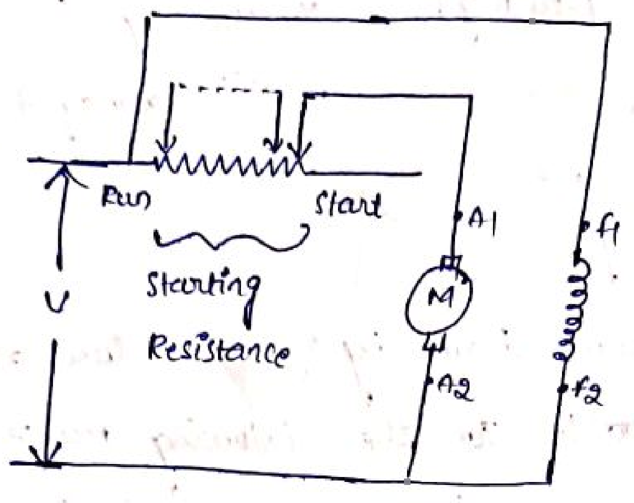
$V = I_a R_a$

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

due to high current at the starting the winding will be damaged.

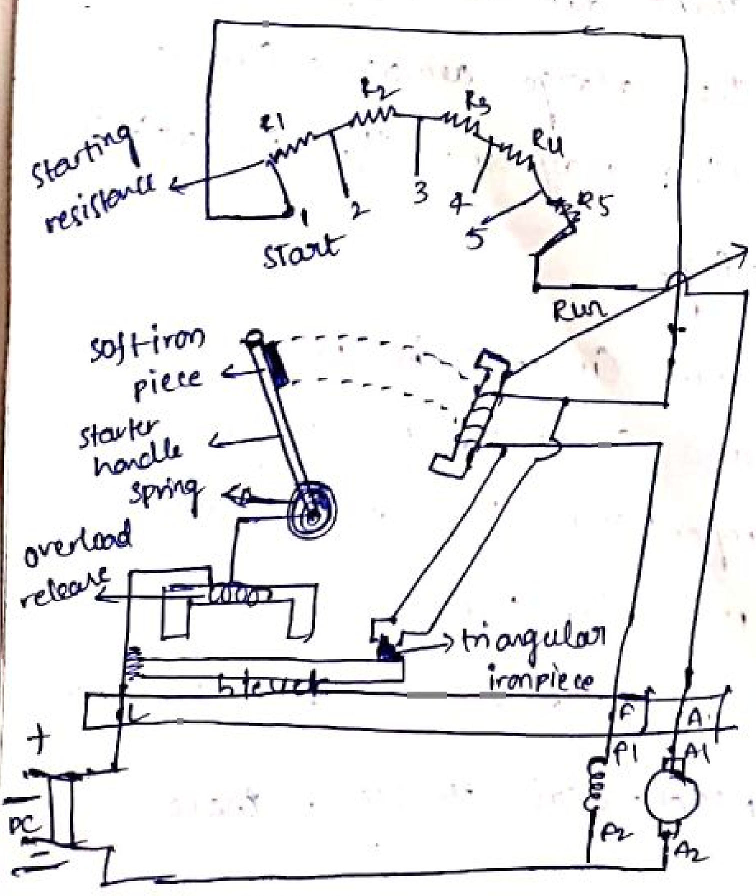
- Such high current drawn by the Armature at start is highly objectionable for the following reasons.
- In a constant voltage system, such high in rush currents may cause tremendous line voltage fluctuations this may effect the performance of other equipment connected to the same line.
- Such excessively high currents, blows out the fuses
- If motor fails to start due to some problems with the field winding, then a large armature current flowing for a longer time may burn the insulation's of the armature winding.
- As the starting Armature Current is 10-15 times more than the full load current, the torque developed which is proportional to the armature current will also be 10-15 times. Due to such high currents, the shaft and other accessories are there we subjected to large Machanical stresses. there

stresses may cause ferminent machanical damage to the motor.

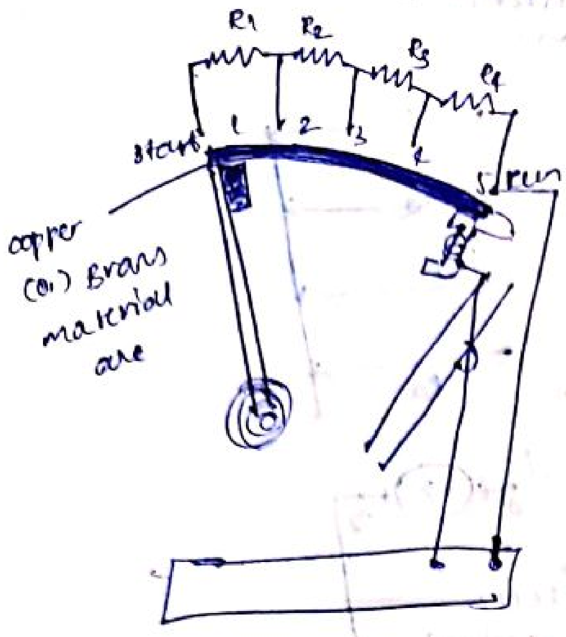


- There are two types of starters
  1. three point starter
  2. four point starter

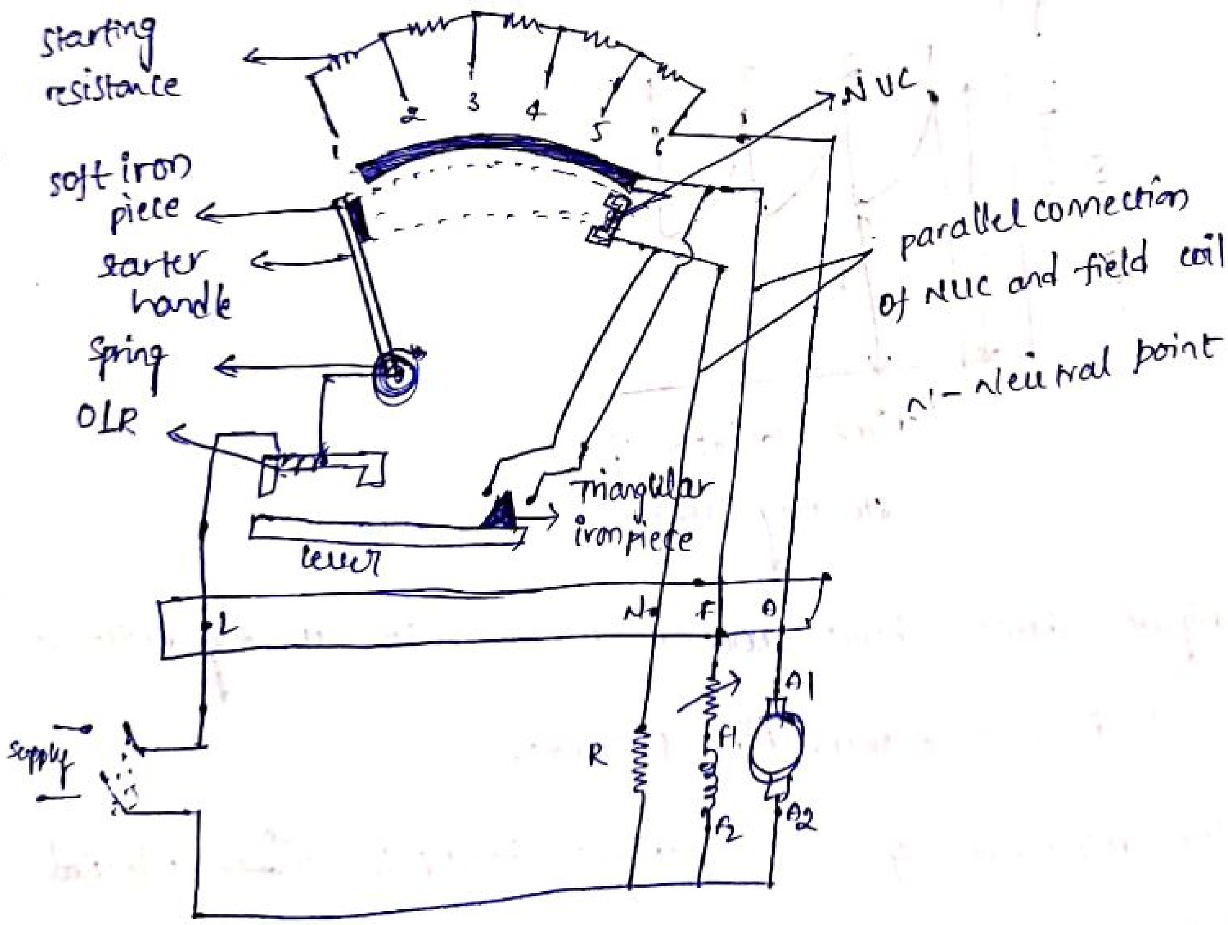
Three-point starter:-



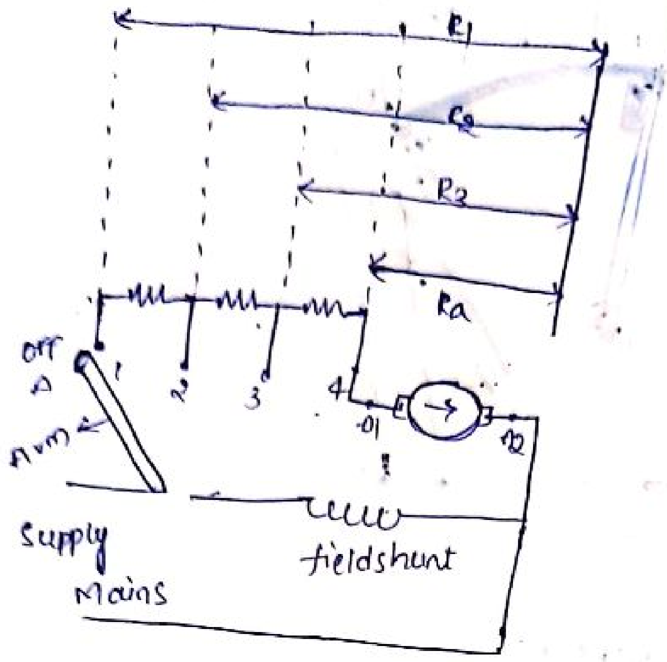
Tappings technically called as studs

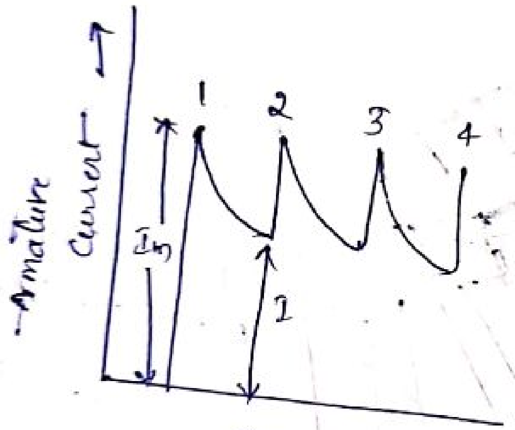


four-point starter:-



* Grading of the starting resistance:-





Time variation of starting current

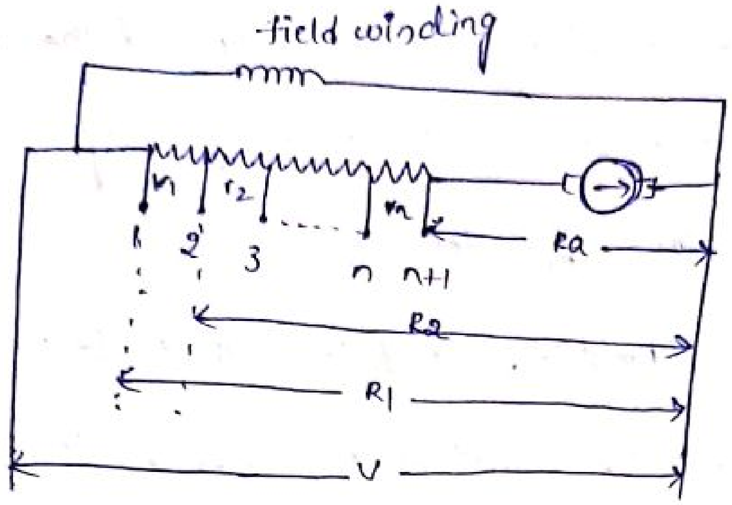
- figure shows shunt wound Motor with starting resistence divided into 3-sections b/n 4-studs.

- The resistence of these sections should be so selected that current during starting remains b/n im and i.

Im = Maximum value of current

i = Minimum value of current.

* Design of starter:-



- Figure shows a DC - shunt motor - starter with n - resistance section's and (n+1) studs.

- Let R_1 is the total resistance in the armature circuit when the starter arm is on stud-1.

- R_2 - total resistance in the Armature circuit when the starter arms is on stud-2. and so on...

- I_m - upper Current Limit

  I - Lower Current Limit

- n - no. of sections in the starter resistance.

  V - applied voltage

- R_a - Armature resistance

On stud-1 :-

When the starter arm moves to stud 1, the total resistance in the armature circuit is R_1 and the circuit current jumps to maximum value I_m given by.

$$I_m = V/R_1 \rightarrow (1)$$

Since, $T \propto \phi I_a$, it follows that the maximum Torque acts on the armature to accelerate it. As the armature accelerates, the induced emf increases and the armature current decreases. When the current has fallen to the predetermined value I, the starter arm is moved over to stud-2.

Let the value of back emf be E_{b1} at the instant of starter arm leaves the stud 1. then I is given as

$$I = \frac{V - E_{b1}}{R_1} \rightarrow (2)$$

On stud-2 :-

As the starter arm moves to stud-2, sufficient Resistance is cut out and current rises to maximum value I_m once again given by I_m

$$I_m = \frac{V - E_{b1}}{R_2} \rightarrow (3)$$

the acceleration continues and the back emf increases and the armature current decreases. when the current has fallen to the predetermined value I, the starter arm is moved over to stud-3. let E_{b2} be the value of back emf and the instant the starter arm leaves the stud-2.

then $$I = \frac{V - E_{b2}}{R_2} \longrightarrow (4)$$

on stud-3:-

As the starter arm moves to stud-3.

$$I_m = \frac{V - E_{b2}}{R_3} \longrightarrow (5)$$

As the starter arm leaves stud-3

$$I = \frac{V - E_{b3}}{R_3} \longrightarrow (6)$$

on nth stud:-

As the starter arm leaves nth stud

$$I_m = \frac{V - E_{bn}}{R_n}$$

on $(n+1)^{th}$ stud:-

when the starter arm moves over to $(n+1)^{th}$ stud, all the external resistance is cut out leaving only the armature resistance R_a then

$$I_m = \frac{V - E_{bn}}{R_a}, \quad I = \frac{V - E_b}{R_a}$$

Dividing (2)/(3)

$$\frac{I}{I_m} = \frac{U-E_{b1}}{R_1} \times \frac{R_2}{U-E_{b1}}$$

$$\frac{I}{I_m} = \frac{R_2}{R_1}$$

Dividing (4)/(5)

$$\frac{I}{I_m} = \frac{R_3}{R_2}$$

by continuously doing these divisions we have finally

$$\frac{I}{I_m} = \frac{R_a}{R_n}$$

let $\frac{I}{I_m} = k$ then $\frac{R_2}{R_1} = \frac{R_3}{R_2} = \cdots \frac{R_a}{R_n} = k$

If we multiply these n- equal ratio's together then

$$\frac{R_2}{R_1} \times \frac{R_3}{R_2} \times \frac{R_4}{R_3} \times \cdots \times \frac{R_a}{R_n} = k^n$$

$$\frac{R_a}{R_1} = k^n$$

$$k = \left[\frac{R_a}{R_1}\right]^{1/n}$$

The value of resistance elements can be obtained as

$$R_2 = R_1 \times k$$

$$R_3 = R_2 \times k$$

$r_1 = R_1 - R_2 = (1-k) R_1$

$r_2 = R_2 - R_3 = (1-k) R_2 = R_1 k (1-k)$

Knowing the values of n, I_1, R_a the above values can be obtained.

* A 2-pole lap wound dc shunt motor with 360 conductor operates at a constant flux level of 50mwb. The motor armature has a resistance of 0.12Ω and is designed to operate at 240V, taking a current of 60Amp at full load.

i) determine the value of external resistance to be inserted in the armature circuit so that armature current does not exceed twice its full load value at starting.

ii) The external resistance is completely cut out when the motor reaches its final speed, with full load value. calculate the armature current at full load value. calculate the motor speed under these conditions.

Sol:-

$P = 2$ $\quad V = 240V$

$Z = 360$ $\quad I_a = 60Amp$

$\phi = 50 \times 10^{-3}$ wb

$R_a = 0.12\Omega$

i) $I_{max} = 60 \times 2 = 120$

$120 = I = V / R_{ext} + R_a$

$120 = \frac{240}{R_{ext} + 0.12}$

ii) $E_b = \frac{\phi Z N}{60}\left[P/A\right]$

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

$E_b = V - I_a R_a$

$= 240 - 60 \times 0.12$

$= 232.8$

$= 776$ rpm

* A 200-volts shunt motor having armature resistance of 0.4 Ω and shunt field resistance of 100Ω drives a load at 500rpm taking 27Amp. it is desired to run the motor at 700rpm. Assuming the load torque to be constant, find the value of resistance to be used as field regulator. Neglect saturation effect.

Sol:-

$V = 200$ V $\quad I_L = 27$ Amp

$R_a = 0.4\Omega$

$N_2 = 700$

$R_{sh} = R_f = 100\Omega$

$N_1 = 500$

Initial condition's:-

$I_{sh_1} = \frac{V}{R_{sh}} = \frac{200}{100} = 2$ Amp

$I_{a_1} = I_L - I_{sh_1} = 27 - 2 = 25$ Amp

$E_{b_1} = V - I_{a_1} R_a = 200 - 25 \times 0.4$

$= 190$ V

$N_2 = 700 rpm$

$E_{b2} = V - I_{a2} R_a$

$T \propto \phi I_a$ (Torque constant)

$\phi_1 I_{a1} \propto I_{a2} \phi_2$

$\phi \propto I_{sh}$

$I_{sh1} I_{a1} \propto I_{a2} I_{sh2}$

$$I_{sh2} = \frac{I_{sh} I_{a1}}{I_{a2}}$$

$$= \frac{2 \times 25}{I_{a2}} = \frac{50}{I_{a2}}$$

WKT

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

$$N_1 \propto \frac{E_{b1}}{\phi_1}, \quad N_2 \propto \frac{E_{b2}}{\phi_2}$$

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

$$\frac{500}{700} = \frac{190 \times \frac{50}{I_{a2}}}{2 \times [200 - I_{a2} 0.4)} \quad [\phi = I_{sh}]$$

$$5 \times (2 \times (200 - I_{a2} 0.4)) = 7 (190 \times \frac{50}{I_{a2}})$$

$$2000 - 4 I_{a2} = \frac{66500}{I_{a2}}$$

$$2000 I_{a2} - 4 I_{a2}^2 = 66500$$

$$I_{a2}^2 - 500 I_{a2} + 16625 = 0$$

$I_{a1} = 464.18$ Amp

$I_{a2} = 35.81$ Amp

let consider $I_{a2} = 35.81$ Amp

No motor has the current 464 Amp

$I_{sh2} = \frac{50}{I_{a2}} = \frac{50}{35.81} = 1.39$ Amp

$R_{sh2} = \frac{V}{I_{sh2}} = \frac{200}{1.39} = 143.88 \Omega$

field rheostatic resistance $= 143.88 - 100$

$= 43.88 \Omega$

* A starter is required for a 250V shunt motor. the maximum current limit is to be 67 Amp and the minimum is 3/4th of this value. Armature resistance is 0.5Ω. Find the no. of section's of the starter and the resistance of each element.

sol:- $V = 250V$, $I_{1max} = 67A$ $K = 3/4$

$I_{min} = 67 \times 3/4$, $R_a = 0.5 \Omega$

$K^n = R_a / R_1$ $K = \left(\frac{R_a}{R_1}\right)^{1/n}$

$= \left(\frac{I_1 R_a}{I_1 R_1}\right)^{1/n}$

$$k = \left(\frac{S_1 R_a}{4}\right)^{1/n}$$

$$\left(3/4\right)^n = \frac{67 \times 0.5}{250}$$

$$\left(\frac{3}{4}\right)^n = 0.134$$

$$(0.75)^n = 0.134$$

$$n \log 0.75 = \log 0.134$$

$$n = \frac{-2.009}{-0.287}$$

$$n = 7$$

$$\frac{R_a}{R_L} = k^n$$

$$R_L = \frac{R_a}{k^n} = \frac{0.25}{(3/4)^7}$$

$$= \frac{0.5}{0.133} = 3.785\ \Omega$$

$$\frac{R_2}{R_L} = k \Rightarrow R_2 = R_1 k = 2.838\ \Omega$$

$$\frac{R_3}{R_2} = k \Rightarrow R_3 = R_2 k = 2.129\ \Omega$$

$$\frac{R_4}{R_3} = k \Rightarrow R_4 = R_3 \times k = 1.596\ \Omega$$

$$\frac{R_5}{R_4} = k \Rightarrow R_5 = R_4 \times k = 1.197\ \Omega.$$

$$\frac{R_6}{R_5} = k \Rightarrow R_6 = R_5 \times k = 0.898\ \Omega$$

$$\frac{R_7}{R_6} = K \Rightarrow R_7 = R_6 K \Rightarrow 0.673\,\Omega$$

$$\frac{R_8}{R_7} = K \Rightarrow R_8 = R_7 K \Rightarrow 0.504\,\Omega$$

$r_1 = R_1 - R_2 = \quad 0.947\,\Omega$

$r_2 = R_2 - R_3 = \quad 0.709\,\Omega$

$r_3 = R_3 - R_4 = \quad 0.533\,\Omega$

$r_4 = R_4 - R_5 = \quad 0.399\,\Omega$

$r_5 = R_5 - R_6 = \quad 0.299\,\Omega$

$r_6 = R_6 - R_7 = \quad 0.224\,\Omega$

* A 220V shunt motor has an Armature resistance of 0.4Ω the armature current at starting must not exceed 40Amp. If the no. of sections is 6. calculate the values of the resistor steps to be use in this starter.

Sol:- $V = 220V$

$R_a = 0.4\,\Omega$

$I_1 = I_a = 40mp$

$n = 6$

$K^n = R_a / R_1$

$$K = \left(\frac{R_a}{R_1}\right)^{1/n}$$

$$= \left(\frac{I_1 R_a}{I_1 R_1}\right)^{1/n}$$

$k = \left(\frac{I_1 R_a}{V}\right)^{1/n}$

$= \left(\frac{40 \times 0.4}{220}\right)^{1/6}$

$= ~~0.646886~~$

$= 0.646$

$\frac{R_a}{R_1} = k^n$

$R_1 = \frac{R_a}{k^n} = \frac{0.4}{(0.646)^6}$

$= 5.607$

$\frac{R_2}{R_1} = k \Rightarrow R_2 = kR_1 = 3.610$

$\frac{R_3}{R_2} = k \Rightarrow R_3 = kR_2 = 2.325$

$\frac{R_4}{R_3} = k \Rightarrow R_4 = kR_3 = 1.497$

$\frac{R_5}{R_4} = k \Rightarrow R_5 = kR_4 = 0.964$

$\frac{R_6}{R_5} = k \Rightarrow R_6 = kR_5 = 0.621$

$\frac{R_7}{R_6} = k \Rightarrow R_7 = kR_6 = 0.399$

$r_1 = R_1 - R_2 = 1.997$

$r_2 = R_2 - R_3 = 1.285$

$r_3 = R_3 - R_4 = 0.825$

$r_4 = R_4 - R_5 = 0.533$

$r_5 = R_5 - R_6 = 0.343$

$r_6 = R_6 - R_7 = 0.222$

* Testing of DC Machine:-

Losses in a DC Machine:-

The losses in a DC machine may be divided into 2-classes

i) Constant losses — [Core losses, Mechanical losses]

ii) Variable losses
↓
copper losses

Copper losses:- these losses occur due to current in the various windings of the machine. These are 3-types of losses.

i) Armature copper loss

ii) shunt copper loss

iii) Series field copper loss

Hysteresis Loss:-

Hysteresis losses occur in the dc-machine in the armature since any given part of the armature is subjected to magnetic field reversals as it passes under successive poles. it is given by "steinmetz" formula.

$$P_h = \eta B_{max}^{1.6} f v \text{ watts.}$$

where

B_{max} = maximum flux density in armature

f = frequency of magnetic reversals

v = volume of armature in m^3

η = Steinmetz coefficient

- In order to reduce the hysteresis loss, core is made off such materials which have a low value of steinmetz coefficient. Ex: silicon-steel

Eddy Current Loss:-

In addition to the voltages induced in the armature conductors, there are also voltages induced in the armature core. these voltages produce circulating currents in the armature core. These are called eddy currents and powerloss due to their flow is called Eddy current loss.

- To reduce the eddy current loss lamination's are used.

$$\therefore P_e = K_e B_{max}^2 f^2 t^2 v \text{ watts}$$

where

K_e = constant depending upon the electrical resistance of the core.

B_{max} = Max. flux density

f = frequency of magnetic reversals

t = thickness of the lamination

v = volume of the core

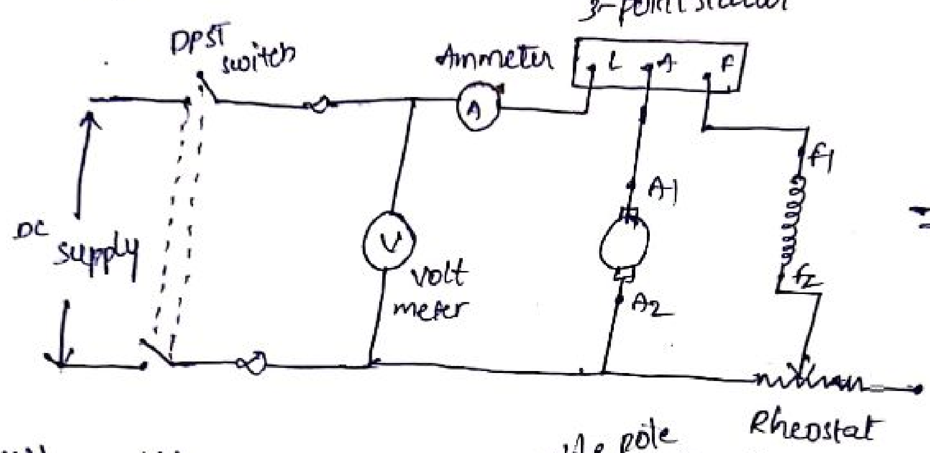
* Testing of a D.C. Machine:-

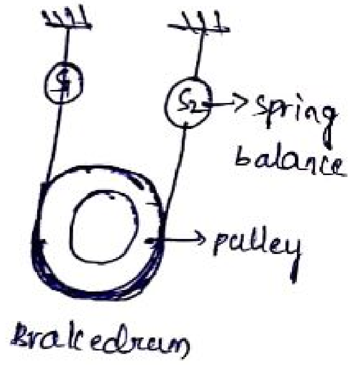
Direct Testing:-

(direct load testing)

Brake Test → By using Brake drum Testing we are doing Direct testing in a shunt motor.

Circuit diagram:-





DPST- double pole single throw

r is from circumference of circle = radius of brakedrum

$o/p = \frac{2\pi NT}{60}$

T = torque

$I/p = V \times I_L$ (volt × Ammeter)

voltmeter (V)	Ammeter (Amp)	S_1	S_2	$S_1 \sim S_2$	Speed (rpm)	$T = (S_1 - S_2) \times 9.81 \times r$	o/p	I/p	$\eta = \frac{o/p}{I/p}$

Advantages:-

1. The method gives the correct value of efficiency of the machine.
2. The Temperature rise and commutation conditions can be checked on the spot at full load.

Dis advantages:-

1. This method requires the application of load on the machine.

2. For machines of large rating, the loads of required size may not be available.

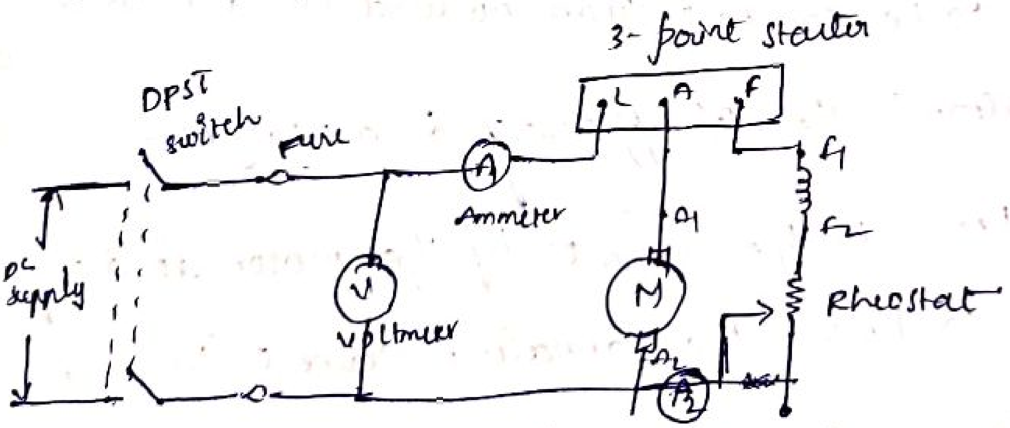
3. Even if it is possible to provide such loads, large power will be dissipated, making it an expensive method.

Indirect testing:-

(not applying load directly but indirectly we are applying)

- Swinburne's test:-
- Hopkinson's test
- Seperation of losses test
- Retardation test
- field test

*Swinburn's test / No load test / Pre determined Test:-



Voltmeter (V) (V1)	Line current (A1) (I_L)	field current (A2) (I_f)

Calculation of constant losses:-

- If I_0 is the no-load line current taken by the motor, I_f is the field current and V_L is line voltage, then the armature current on no-load I_{a0}.

$$I_{a0} = I_0 - I_f$$

- the Armature copper loss on no load = $I_{a0}^2 R_a$

since the test is only no load Test, the input to the motor on no-load will give the sum of the no-load, Armature copper loss and the constant losses

$$\text{no load input} = I_{a0}^2 R_a + \text{constant losses}$$

$$\text{constant losses} = V_L I_0 - I_{a0}^2 R_a$$

- The constant losses that are obtained consists of iron loss, shunt field loss and Mechanical loss are assumed to be constant from no load to full load.

→ predetermination of Efficiency as a Motor:-

let I be the current by the motor at any assumed load. then the armature current $I_a = I - I_f$

∴ Armature copper loss = $I_a^2 R_a$

total losses due to load $W_L = W_C + I_a^2 R_a$

Input to the motor $P_i = V_l \times I$

output of the motor P_o = Input - losses

$= V_l I - W_L$

$= V_l I - (W_c + I_a^2 R_a)$

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

$$= \frac{V_l I - (W_c + I_a^2 R_a)}{V_l I}$$

- for different values of I can be assumed and at each line current, the efficiency can be computed as indicated above.

- predetermination of efficiency as a Generator:-

If the machine runs as a Generator, it will supply load current. let 'I' be the load current then the Armature current is $I_a = I + I_f$

Armature copper loss on load $= I_a^2 R_a$

total loss under load $W_L = W_c + I_a^2 R_a$

out put of the machine when working as a Generator

$P_o = V_l I$

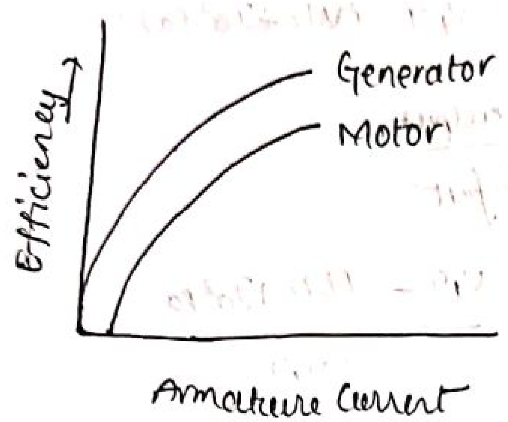
Input to the Generator = output + losses

$P_i = V_l I + W_L$

$= V_l I + W_c + I_a^2 R_a$

$$\text{Efficiency } \eta = \frac{o/p}{I/n}$$

$$= \frac{V_L I}{V_L I + W_c + I_a^2 R_a}$$



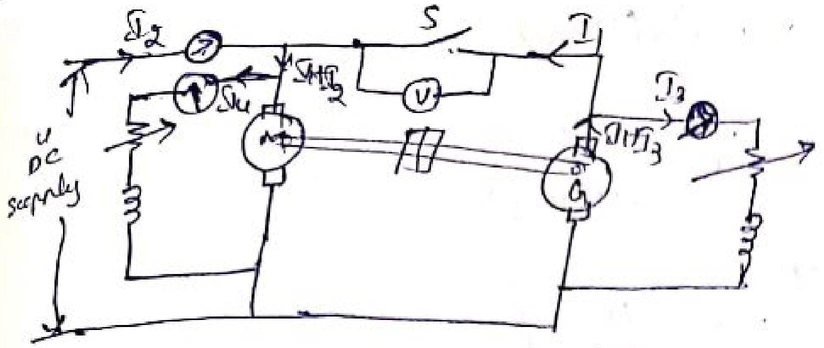
Advantages :-

- The power required to carry out the test is small because it is a no load Test. Therefore this method is quite economica
- The efficiency can be determined at any load because constant losses are known.
- It is very convenient.

Dis advantages:-

- It doesnot take into account the stray load losses that occur when the machine is loded.
- This test doesnot enable us to check the performance of the machine on full load.
- This Test does not give quite accurate efficiency of the machine. It is because iron losses under actual load
- It is 1 are greater than those measured. This is mainly due to armature reaction.

Hopkinson's Test / Regenerative Test :-



Calculations:-

$V \Rightarrow$ supply voltage

Motor input $= V(I_1+I_2)$

Generator output $= V(I_1)$

To find the efficiencies of the machines let us consider 2 cases.

1. Assuming that both the machines have the same efficiency.
2. Assuming Iron, friction and windage losses are same in both the machines.

Case-I:- Both have same Machines:-

Motor output $= \eta \times$ motor input

$= \eta \times V(I_1+I_2)$

$=$ Generator Input

Generator output $= \eta \times$ generator input

$= \eta \times \eta V(I_1+I_2)$

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

But generator output $= VI_1$

$$VI_1 = \eta^2 V(I_1+I_2)$$

$$\eta^2 = \frac{VI_1}{V(I_1+I_2)}$$

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

Conclusion: This expression gives the value of efficiency sufficiently accurate for a rough Test. However if greater accuracy is required the efficiencies of the two machines should be calculated seperately as indicated below.

Case 2:- Assuming constant losses are same in both machines

$R_a \Rightarrow$ armature resistance of each Machine

$I_3 \Rightarrow$ field current of Generator G.

$I_4 \Rightarrow$ field current of Motor M.

Armature copper losses in generator $= (I_1+I_3)^2 R_a$

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

shunt copper loss in Generator $= VI_3$

shunt copper loss in Motor $= VI_4$

Power drawn from the DC supply is $: VI_2 =$ total losses of the motor and Generator

VI_2 = Total loss of G & M

If we substract armature and shunt copper losses of the two machines from VI_2, we get iron, friction & windage losses of the two machines.

$$W_C = VI_2 - \left[(I_1+I_3)^2 R_a + (I_1+I_2-I_4)^2 R_a + VI_3 + VI_4\right]$$

Constant losses of each machine is $\frac{W_C}{2}$

Efficiency

for Generator:-

$$\text{output} = VI_1$$

$$\text{total losses} = \frac{W_C}{2} + (I_1+I_3)^2 R_a + VI_3 = W_g$$

$$\eta_g = \frac{VI_1}{VI_1 + W_g}$$

for Motor)

$$\text{input} = V(I_1+I_2)$$

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

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

Advantages:-

1. The total power required to test the two machines is small, compare with the full load power of each machine.

2. The Machines can be Tested under full load condition's so that commutation qualities and Temperature rise can be checked.

3. It is more accurate to measure the loss directly than to measure in as the difference of the measured input and output.

4. All the measurements are electrical which are simplar and more accurate than Mechanical Measurements.

Disadvantages:-

1. Two Similar DC Machines are required.

- Retardation Test / Running down Test:-

Case-I

⇒ If the supply to the Armature is cut off but the field remains normally excited, the motor slows down gradually and finally stops. The kinetic Energy of the Armature is used upto overcome friction, Windage and Iron losses.

Case-II

If the Supply to the Armature as well as Field Excitation is cut off, the motor again slows down and finally stops. Now the kinetic energy of the Armature is used to overcome only the friction and windage losses. This is expected, because in the absence of flux there will be no iron losses.

UNIT-IV Single-phase Transformers

Classification of Transformers:-

1. According to No. of phases:
   (a) Single phase transformer (b) Three phase transformer

2. According to construction:-
   (a) Core type transformer
   (b) Shell type transformer
   (c) Berry type transformer

3. According to Function:
   (a) Power transformers
      i. Step-up transformers ii. step-down transformer
   (b) Distribution transformers
      (i) Pole mounted transformer (ii) plinth mounted transformer
   (c) Instrument transformers
      (i) Current transformers (CT) (ii) Potential transformers (PT)

4. Special purpose Transformers:
   (a) Scott connection (b) Vee connection
   (c) Pulse transformer (d) Auto transformers
   (e) welding transformer

5. According to type of Cooling
   (a) Air cooled transformer (b) oil cooled transformer

6. According to location
   (a) Indoor transformers (b) outdoor transformer

7. According to frequency:

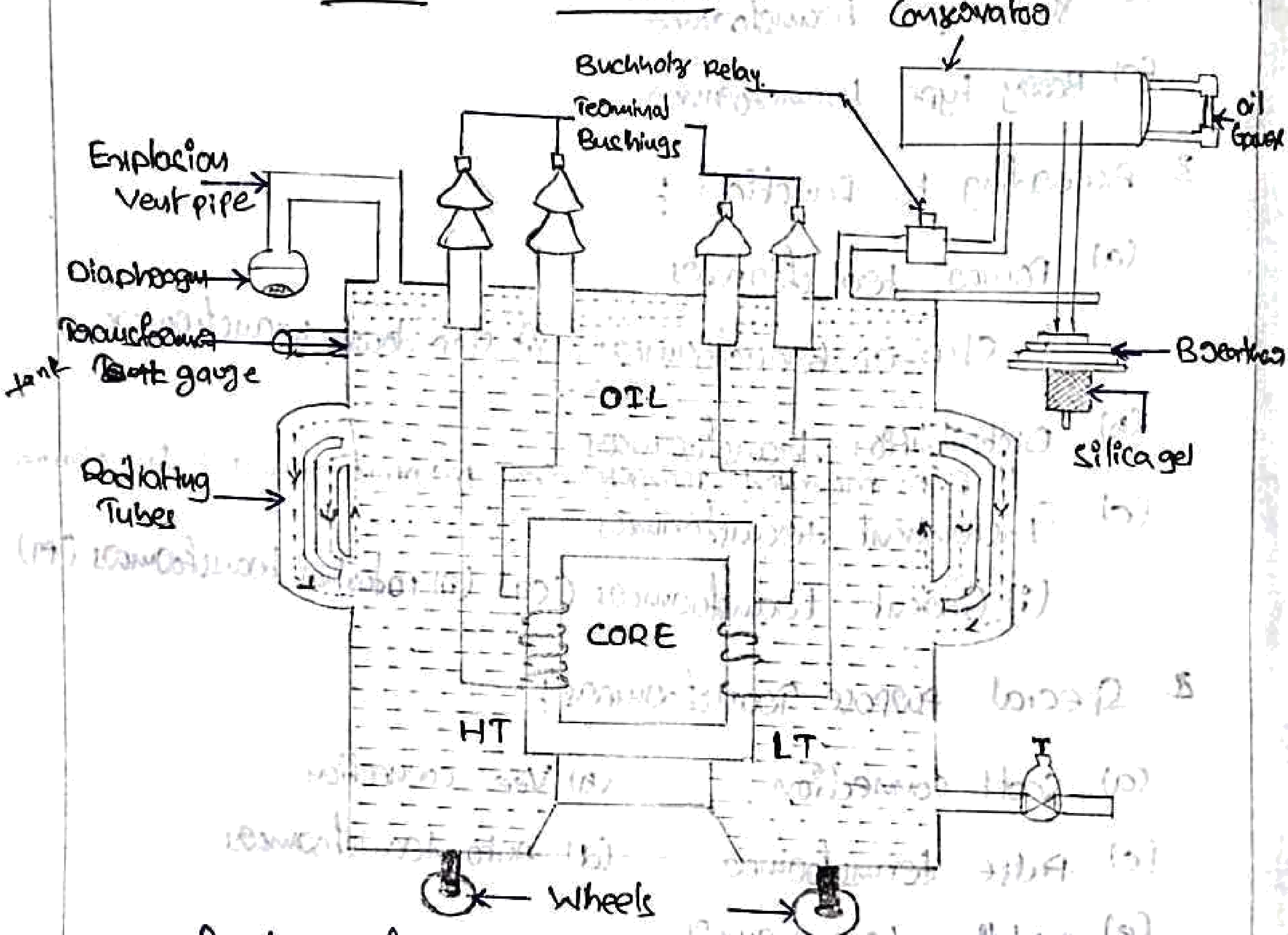
(a) low frequency (50Hz) (b) High frequency [HFT's Pulse transformer]

8. According to Rating:

a. low rating transformer b Medium rating transformer

c. High rating transformer.

Construction of a Transformer:



A transformer is a static device and it's construction is simple as there are no moving parts. The transformer has the following parts

1. Magnetic core: The purpose of core is to provide a path of low reluctance for the magnetic flux. Core is

laminated, stampings to reduce eddy current losses

2. Windings (or) Coils :

Windings are made up of copper conductors & are placed on the core. The winding which is connected to the supply is known as "primary winding", and the winding which is connected to load is known as "secondary winding".

3. Transformer Tank :

The transformer with core and windings is housed in proper container. Container transformer oil is called "transformer tank."

4. Transformer Oil :

The insulating oil which is used in the tank of a transformer is called transformer oil. It proves three functions

i. It cools away the heat produced in the core & winding

ii. Additional insulation for the windings

iii. Protects the insulation from dirt & moisture.

5. Conservator : Conservator performs the following functions

i) It maintain the oil level in the tank

ii) It provides space for the expansion of oil when the temperature of the transformer increases

iii) It reduces the rate of oxidation of oil because it ensures surface of the oil is less exposed to oil

6. Breather :-

The function of the breather is to prevent entry of moisture in the air and allows dry air into the transformer. Moisture reduces the dielectric strength of oil.

7. Terminal Bushings :-

Connections from the transformer windings are brought out by means of bushings mounted on the transformer tank.

8. Oil level indicator :-

For indicating the level of the oil in the conservator an oil level indicator is fit to it. It is essential that, the oil level in conservator is maintained above a predetermined minimum level

9 Buchholz Relay :-

It is used for protection of oil-filled transformers from incipient faults below oil level.

The two basic parts of transformer are :-

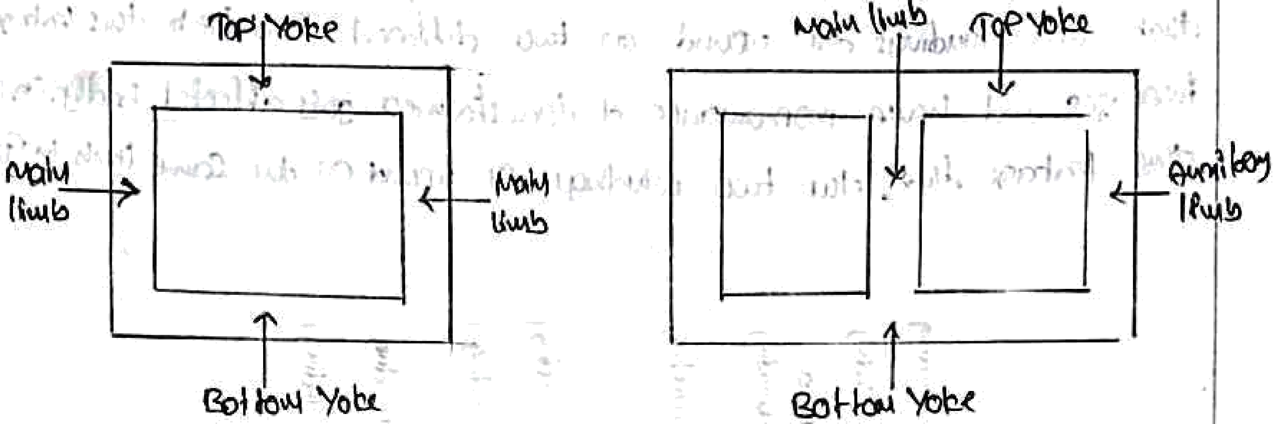
i. Magnetic core :-

The core material and it's construction should be such that the maximum flux is created with minimum magnetising current and minimum core loss.

Limbs (or) legs :- The vertical portion on which windings or coils are wound is called as limbs

Yokes: The top and bottom horizontal portions are called as Yokes of the core, which connect the legs and serve for closing the magnetic circuit.

The two-limbed & three-limbed cores are shown in fig



In two limbed core, the cross sectional area of the limbs and Yokes are identical.

In three limbed core, windings are placed around the central limb is also known as main limb.

Core is made up of laminated stampings to reduce eddy current losses. Eddy currents are induced in the core because the core is cut by alternating flux produced in the core by alternating current flowing through the winding.

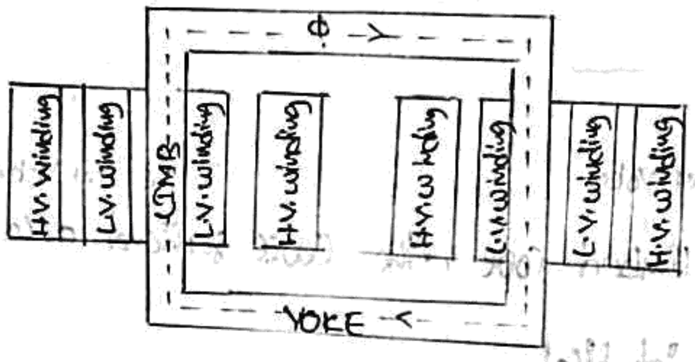
To reduce the losses further, Cold rolled grain oriented (CRGO) silicon steel laminations are used for the construction of transformer core. This reduces the amount of magnetising current taken by the primary winding needed to produce the required flux in the core

The laminated stampings are different shapes like L, E, I, U, J, C etc.

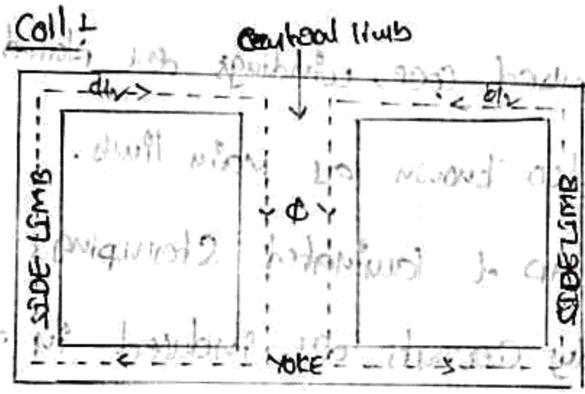
Windings (or) Coils:

The transformer has high voltage and low voltage coils for each phase. The coil may be either cylindrical concentric (or) sandwiched type.

Concentric Coils: Concentric coils are used in core type transformer. It says that two windings are wound on two different limb due to this leakage flux increases and hence performance of transformer gets affected badly. To reduce this leakage flux, the two windings are wound on the same limb in T/F.



Sand witched Coil:



Sand witched coils are commonly employed for shell type T/F. The leakage reactance of the windings can be easily controlled by employed sand-witched winding.

The nearer the high voltage and low voltage coils, the less is the leakage flux. leakage can be further reduced by subdividing the HV & LV coils. The high voltage sections lie b/w two consecutive low voltage sections. The two end sections are L.V. sections and contain half the turns of other L.V. sections. lower values of reactance can be obtained by increasing the number of sub divisions. The schematic diagram of sandwitched winding is shown in above fig.

Types of Transformers :- [Based on Construction]

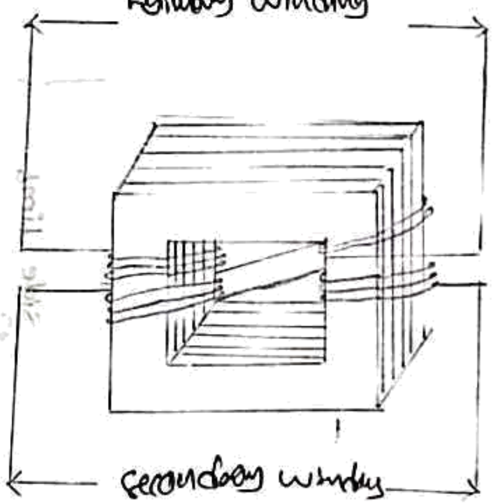
Based on construction i.e, the relative arrangement of the core and the winding transformers are classified as :

i. Core type ii. Shell type iii. Berry type

Core type transformer :-

In this type of transformer, the windings are wound around the two limbs. The flux is same in both the limbs. It has only one magnetic path or circuit. In this type, the wound windings surround a considerable part of the core.

The primary & secondary windings are split in to two parts. Half the primary & half the secondary windings are placed side by side concentrically on each limb to reduce the leakage flux as shown in fig. Coils used are of cylindrical type. Such coils are wound in helical layers with different layers insulated from each other by paper, cloth, mica etc.

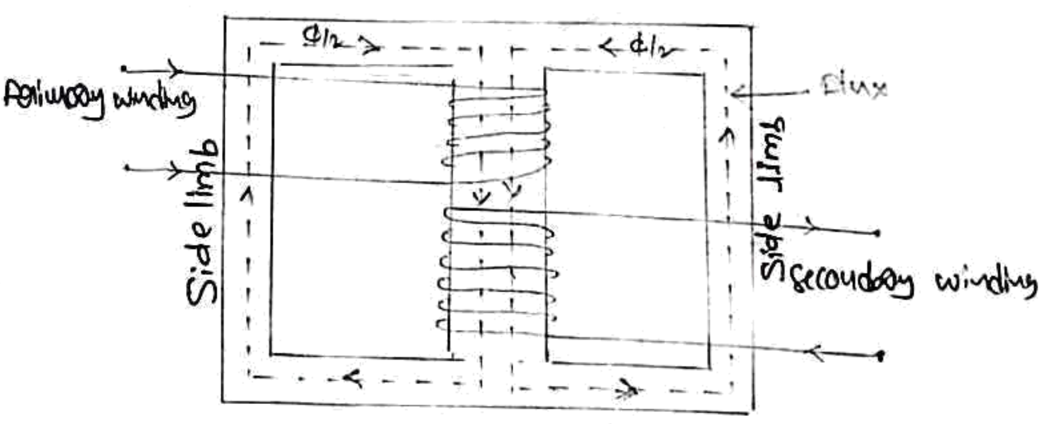


Cross sections of the limbs :-

For small core type transformers simple rectangular limbs can be used and cylindrical coils which are either circular or rectangular in form, However, for large transformer, the limbs can be square and circular cylindrical coils are used. In this arrangement, a considerable amount of useful space is unutilised. An improved arrangement is to employ cruciform limb sections. Stepping not only gives high space factor but also results in reduced mean lengths of turns and the consequent copper loss.

Shell type Transformers :-

In this type of transformer, the windings are wound on the central limb of three-limbed core. The central limbs has flux ϕ, while the other two limbs have flux $\phi/2$. It has double magnetic circuit. In this type, the core surrounds a considerable portion of the winding as shown in fig.

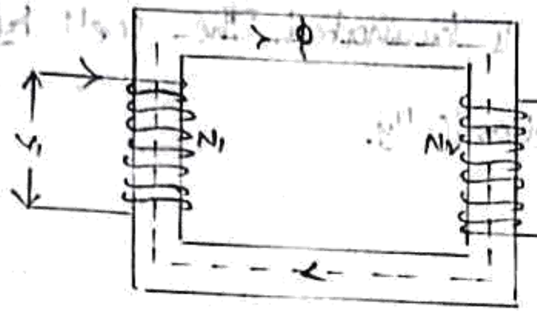
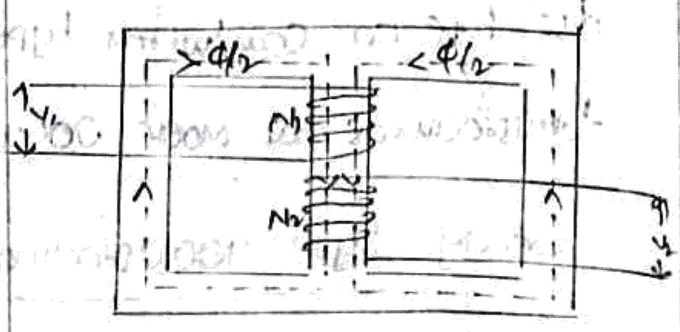


The primary winding is wound deep near the core and secondary winding is done on it. The coils are multi layer disc type or sandwich type. Core is laminated. The shell type of transformers are more robust mechanically.

Berry type Transformer :-

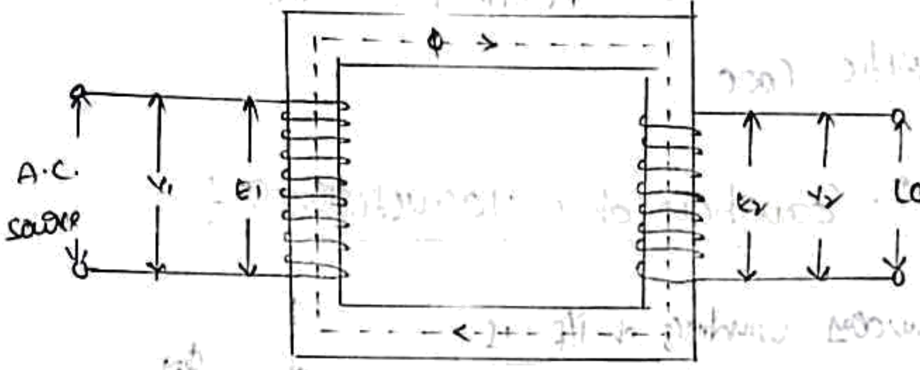
It has Distributed magnetic circuit. The number of independent magnetic circuits are more than 2.

This type of transformer has magnetic cores in the shape of rectangular frames. One limbs of all the frames passes through the centre of the core where as other limbs are kept around the coils and thus the transformer will have as many parallel paths as the number of frames in the transformer. This type of transformers having multi magnetic paths is known as Berry-type Transformer. The figure shows a simple Berry type transformer. In case there are eight parallel paths for the flux.

Core type transformer	Shell type transformer
	
1. Two limbs of 1-ϕ transformer	Three limbs of 1-ϕ transformer
2. Windings are wound around the two limbs	Winding are wound on the central limb only
3. Flux ϕ is same in both the limbs	Central limb has flux ϕ, while the other two limbs have flux $\phi/2$
4. Single magnetic circuit	Double magnetic circuit
5. Winding surround a considerable part of the core	Core surrounds a considerable portion of the windings
6. Cylindrical concentric coils are used	Sandwiched (or) multilayered disc type coils are used.
7. Construction is difficult	Easy construction
8. Rarely used	Widely used

Working principle of a Transformer :-

A ~~dc~~ transformer works on the principle of electro magnetic induction and mutual induction between the two coils. To understand this, consider the elementary transformer as shown in figure



It consists of two windings electrically seperated but linked by a common magnetic circuit of low reluctance formed by a laminated soft iron core.

The winding which is connected to the supply is known as primary winding (P) and the other winding on which the load is connected, is called secondary winding (S)

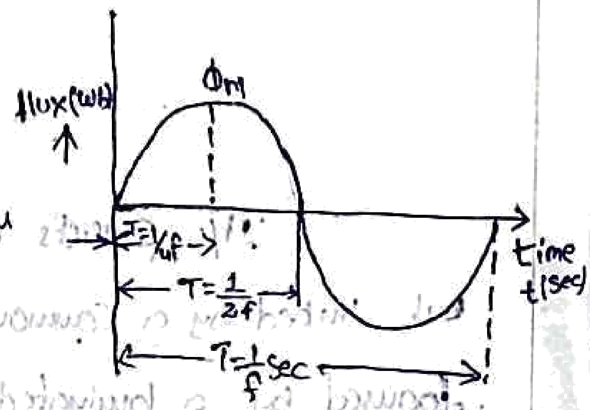
When primary winding is excited by an a.c. supply mains, a current flows through it. This current produces an alternating flux ϕ in the core shown in fig. which completes its path through the common magnetic core.

This flux links with both the windings. Because of this, it produces self induced ~~ct~~ e.m.f in the primary winding and mutual induced emf [According to Faraday's laws of Electro Magnetic Induction] in the secondary winding.

If now secondary circuit is closed through the load, the mutually induced emf in the secondary windings circulates current through the load. Thus electrical energy is transferred from primary to secondary with the help of magnetic core.

E.M.F. Equation of a Transformer :

The primary winding of T/F is excited by alternating voltage. This circulates a current & hence the alternating flux is produced.



ϕ_m = Maximum flux in wb

f = frequency in Hz

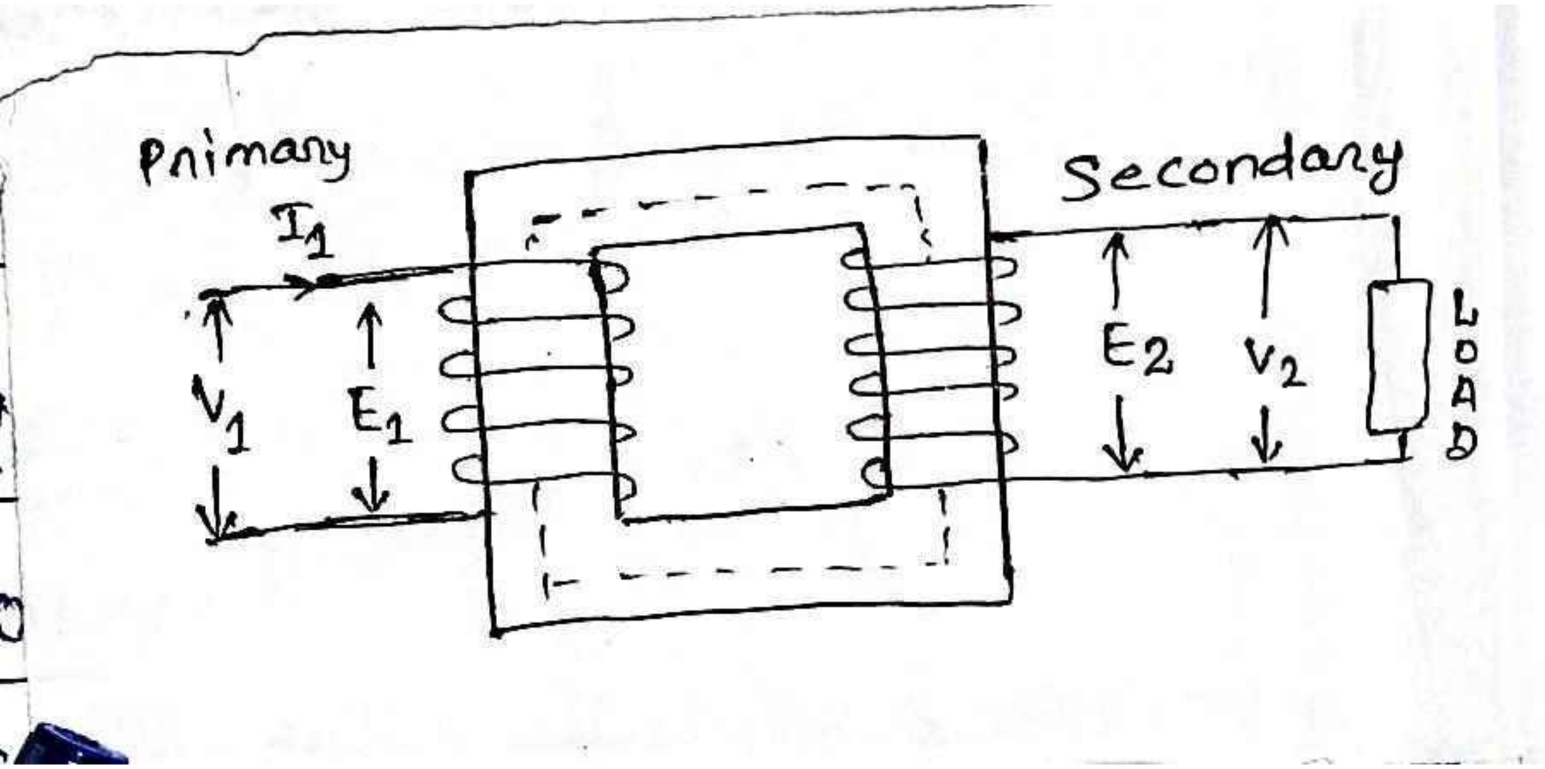
From Faraday's law of Electro magnetic Induction

Average emf induced per turn = Average rate of change of flux

$$= \frac{d\phi}{dt}$$

[To find average rate of change of flux of $\frac{1}{4}$th cycle of flux]

The magnetic flux increases from zero its maximum value ϕ_m in one-fourth of a cycle [i.e. $\frac{1}{4f}$ sec]



Primary
I_1
V_1
E_1
Secondary
E_2
V_2
LOAD

Average rate of change of flux

$$\frac{d\phi}{dt} = \frac{\phi_m}{\frac{1}{4f}} = 4f\phi_m \text{ Wb/sec (or) V.}$$

Average rate of emf induced per turn = $4f\phi_m$ Volts

Since flux "ϕ" is varying sinusoidally with time, so emf induced will be sinusoidal.

Form factor = $\frac{\text{RMS value}}{\text{Average value}} = 1.11$

RMS value of induced emf per turn = $1.11 \times 4f\phi_m = 4.44 f\phi_m$ Volts

The no. of turns primary & secondary windings are N_1 & N_2.

RMS value of induced emf in primary winding

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

RMS value of induced emf in secondary winding

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

EMF equation is

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

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

Note: If B_m is the maximum flux density in wb/m² (tesla) and A is the area of cross-section in square meters,

$$\phi_m = B_m \times A \text{ wb.}$$

Transformer on no load :-

Actually in practical transformer, core causes iron losses as it is subjected to alternating flux.

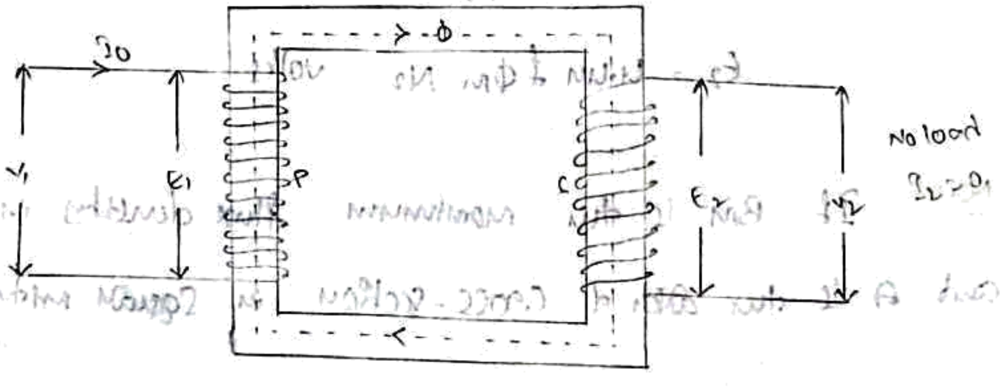
[When a.c. supply is given to the primary of the transformer and no load on secondary $I_2=0$ i.e, secondary terminals are left open, its primary winding takes very small current known as no. load current I_0 as shown in fig.

Alternating flux ϕ will induce an emf in the primary & secondary windings E_1 & E_2 are in phase with each other. The induced emf's will lags the flux by 90°.] The magnitude of induced emf's will depends upon their number of turns.

The no. load current I_0 taken by the primary consists of two components :-

1. A reactive (or) magnetizing component I_μ, producing the flux and inphase with the flux.

ii. An active (or) working component I_w, supplying the iron losses and negligible Cu. losses in the primary winding. I_w is inphase with supply voltage.



$\bar{I}_0 = \bar{I}_\mu + \bar{I}_w$ phasor addition.

No load current

$$I_0 = \sqrt{I_\mu^2 + I_w^2}$$

No. load current I_0 lags supply voltage V_1 by an angle ϕ_0

$\cos\phi_0$ = No. load power factor.

Active (or) working component

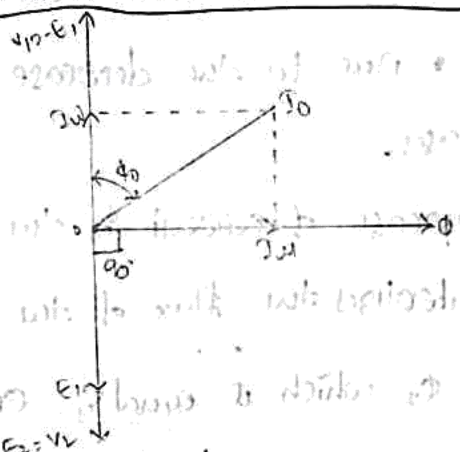
$$I_w = I_0 \cos\phi_0.$$

Reactive (or) magnetising component

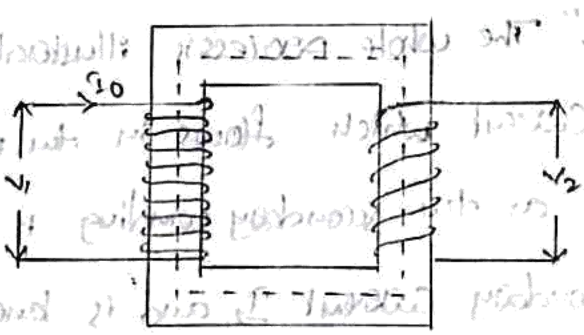
$$I_\mu = I_0 \sin\phi_0$$

No. load input power.

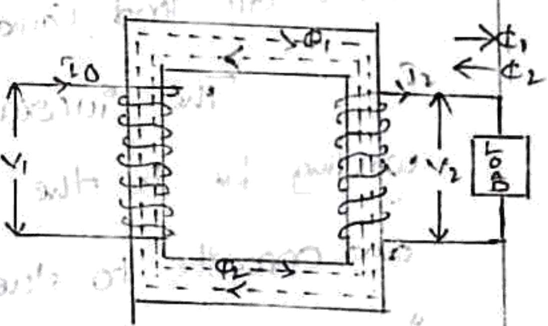
$$W_0 = V_1 I_0 \cos\phi_0 = V_1 I_w \text{ watts}$$



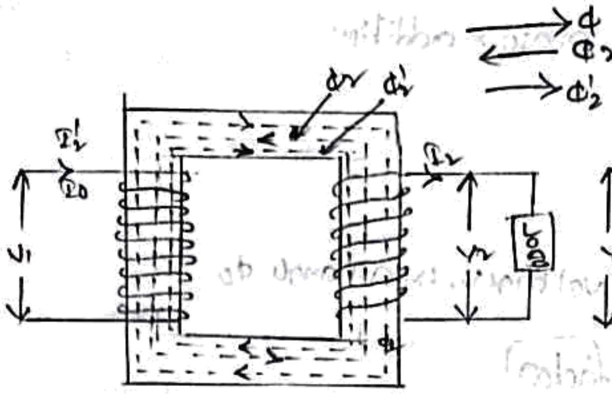
Transformer on load :-



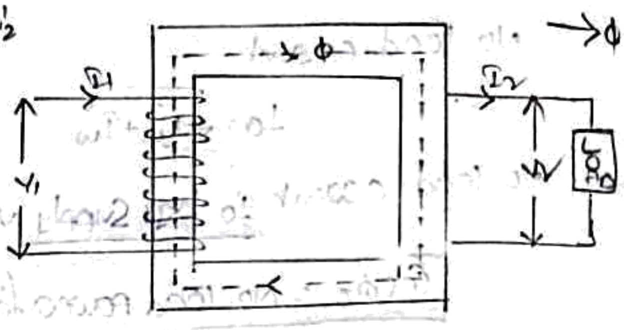
No load Condition



load condition flux ϕ_2 produced



Flux Φ_2' Neutralizes the Φ_2



Net flux Φ is same

When load is connected to the transformer, the current I_2 flows through secondary of the transformer. This current produces flux Φ_2 in the core which opposes the main flux Φ produced by the primary current. This reduces the this reduces the total flux and thereby the emf induced in the winding E_1. Due to the decrease of E_1, the current in the primary increases.

The increase of current in the primary winding is such that it neutralizes the flux of the secondary winding i.e it sets up a flux Φ_2 which is equal & opposite to Φ_2 and thus the total flux remains the same from no-load to full load. Due to this reason the "Core loss is practically the same under all load condition." The whole process is illustrated in fig.

The increased current which flows in the primary winding due to the load on the secondary winding is equal and opposite to the secondary current I_2 and is known as "Primary balancing current or load component of primary current I_2'".

$$N_2 I_2 = N_1 I_2'$$

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

where k = transmission ratio.

As ampere turns are balanced, core flux ϕ is maintained at constant value.

The total primary current I_1 has two components

i. No. load current I_0

ii. Load component of primary current I_2'

The vector sum of I_0 & I_2' is the total primary current I_1 lags behind V_1 by angle ϕ_1.

$$\bar{I}_1 = \bar{I}_2' + \bar{I}_0$$

The vector diagrams for transformer on resistive, inductive & capacitive load are shown in below fig.

Since the voltage drops in both of the windings of the transformer are assumed to be negligible.

Therefore $V_2 = E_2$ & $V_1 = -E_1$.

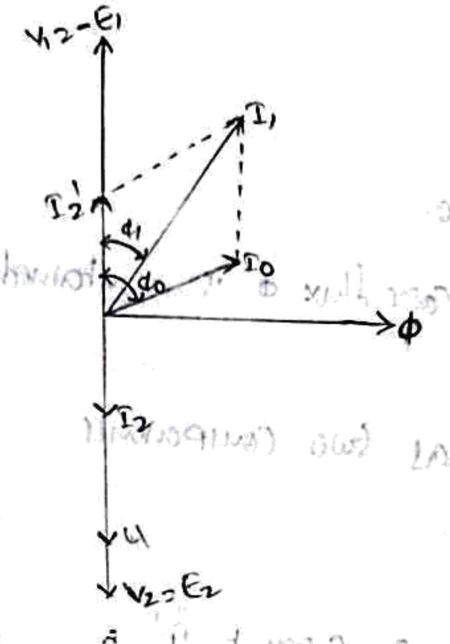
ϕ_1 = No. load power factor angle.

ϕ_2 = load power factor angle

No load current I_0 is very small & neglected.

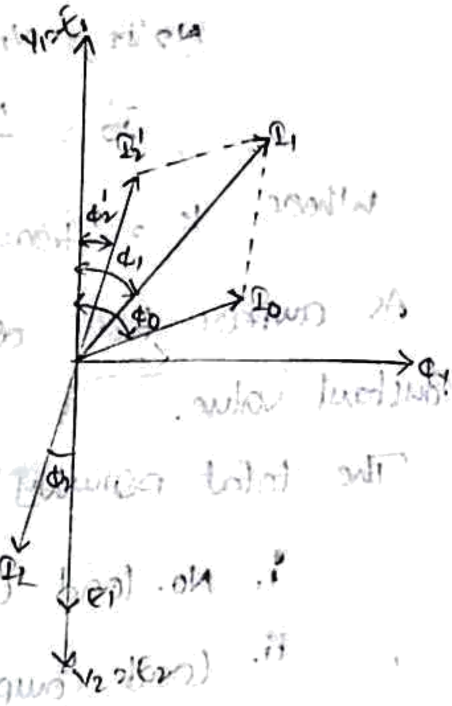
The primary current I_1 is equal to I_2' (opposite to phase I_2)

$$I_1 = I_0 + I_2' = I_2' = k I_2 \quad \text{neglecting } I_0.$$



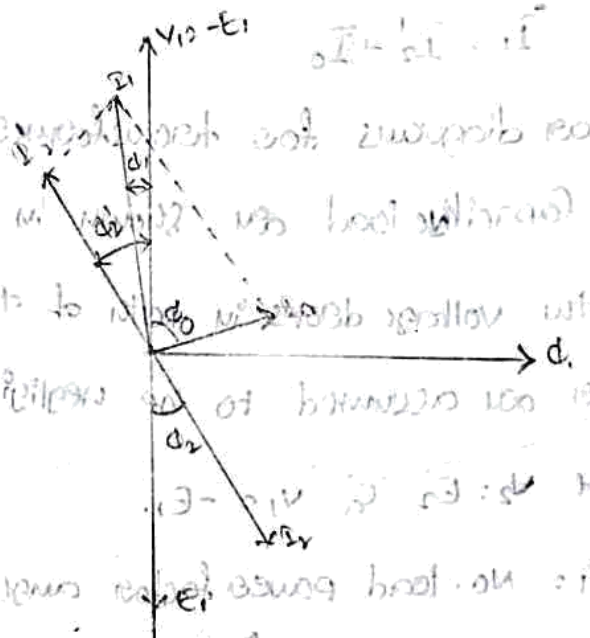
Pure Resistance load :

I_2 in phase with V_2



Inductive load

I_2 lags V_2 by ϕ_2 .

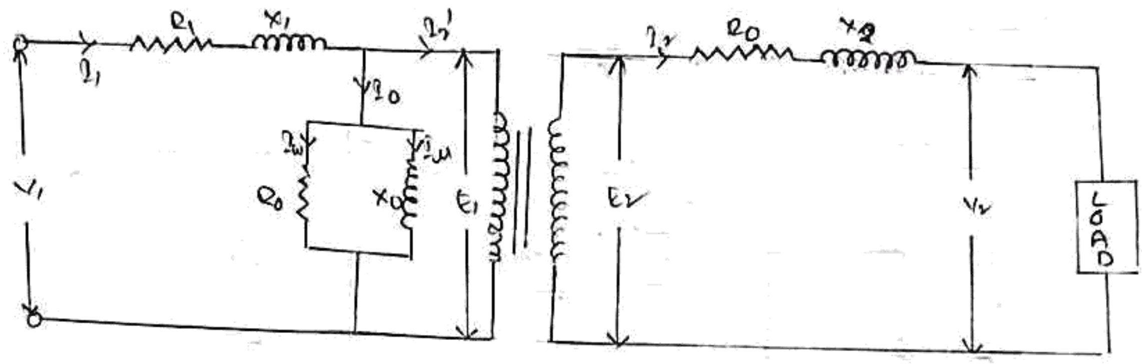


Capacitive load

I_2 leads V_2 by ϕ_2.

Equivalent circuit of a transformer :

The equivalent circuit of a transformer is quite helpful in predetermining the behaviour of the transformer under various conditions of operation.



The transformer shown in above. it can assumed equivalent to an ideal transformer along with the additional impedances inserted b/w the supply & the primary winding and b/w the secondary winding & the load as shown in above is the load impedance.

R_1 & R_2 are resistance of the primary & the secondary windings respectively of the actual transformer

X_1 & X_2 are leakage reactances of the windings due to leakage flux in the actual transformer.

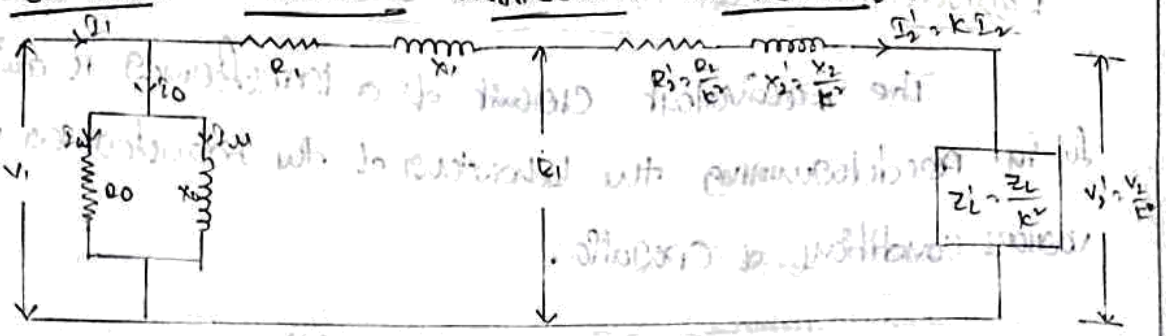
The no. load current I_0 is simulated by a pure inductance X_0 taking the magnetising current I_μ and non-inductive resistance R_0 taking the working component of the primary current I_w. R_0 & X_0 are connected in parallel across the primary circuit.

$$R_0 = \frac{E_1}{I_w}$$

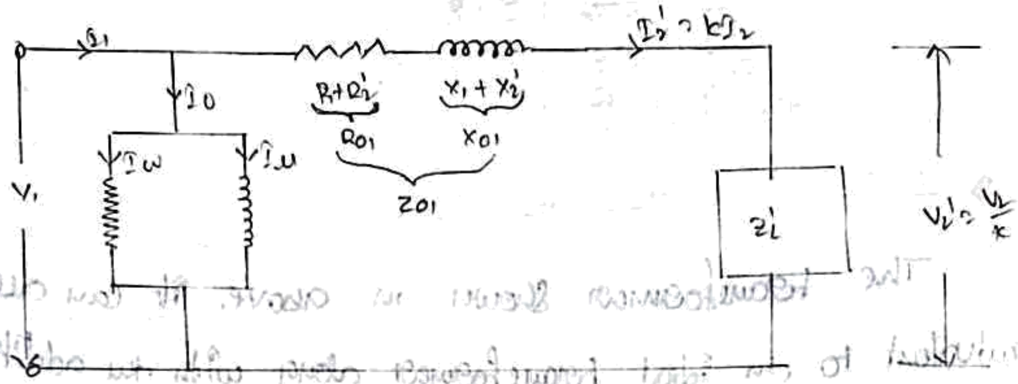
$$X_0 = \frac{E_1}{I_\mu}$$

$$\bar{I}_0 = \bar{I}_\mu + \bar{I}_w$$

Equivalent circuit Referred to primary :



(A)



(B)

If all the secondary quantities are transferred to primary side, we get the equivalent circuit of a T/F referred to the primary as shown in above fig. This circuit can further be simplified as shown in above fig.

When secondary quantities are referred to primary resistance - reactance - impedances are divided by k^2, voltages are divided by k & currents are multiplied by k

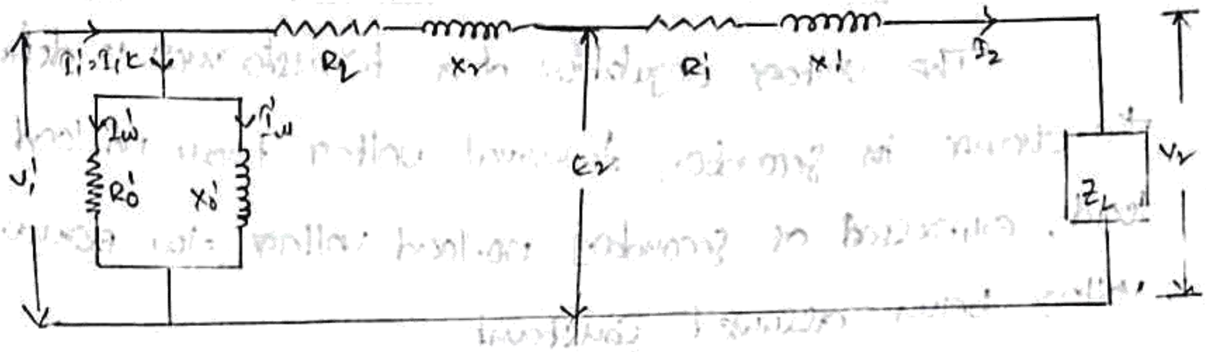
$R_2' = \frac{R_2}{k^2}$ $V_2' = \frac{V_2}{k}$

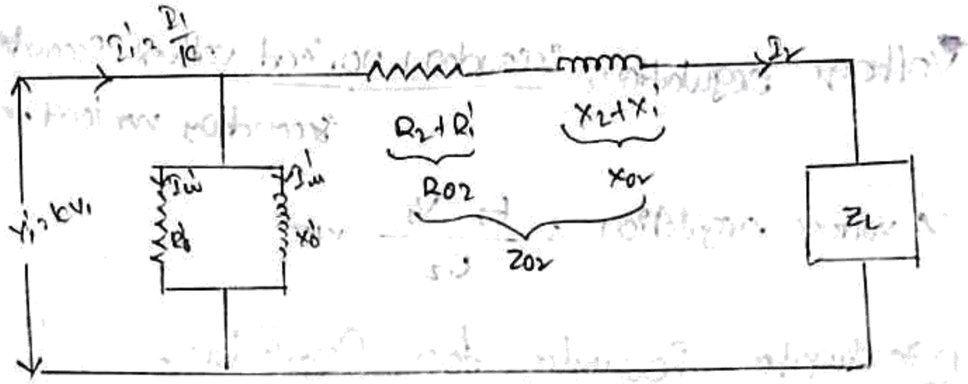
$X_2' = \frac{X_2}{k^2}$ $I_2' = kI_2$

$Z_2' = \frac{Z_2}{k^2}$

$R_{01} = R_1 + R_2'$ $X_{01} = X_1 + X_2'$ $Z_{01} = R_{01} + jX_{01}$

Equivalent circuit Referred to secondary :





If all the primary quantities are transferred to secondary side, we get the equivalent circuit of a transformer referred to secondary as shown in above fig (a). The circuit referred to secondary can be primary quantities are refferred to secondary resistance - reactance - impedances are multiplied by k^2. voltages are multiplied by k & currents are divided by k.

$$R_1' = k^2 R_1$$

$$X_1' = k^2 X_1$$

$$Z_1' = k^2 Z_1$$

$$V_1' = kV_1$$

$$I_1' = \frac{I_1}{k}.$$

$R_{02} = R_2 + R_1'$ $\quad X_{02} = X_2 + X_1'$ $\quad Z_{02} = R_{02} + jX_{02}$.

Voltage Regulation of a Transformer :-

The voltage regulation of a transformer is defined as the change in secondary terminal voltage from no-load to full load, expressed as secondary no-load voltage, the primary voltage being assumed constant

$$\text{Voltage regulation} = \frac{\text{Secondary no-load voltage} - \text{Secondary full load voltage}}{\text{Secondary no load voltage}}$$

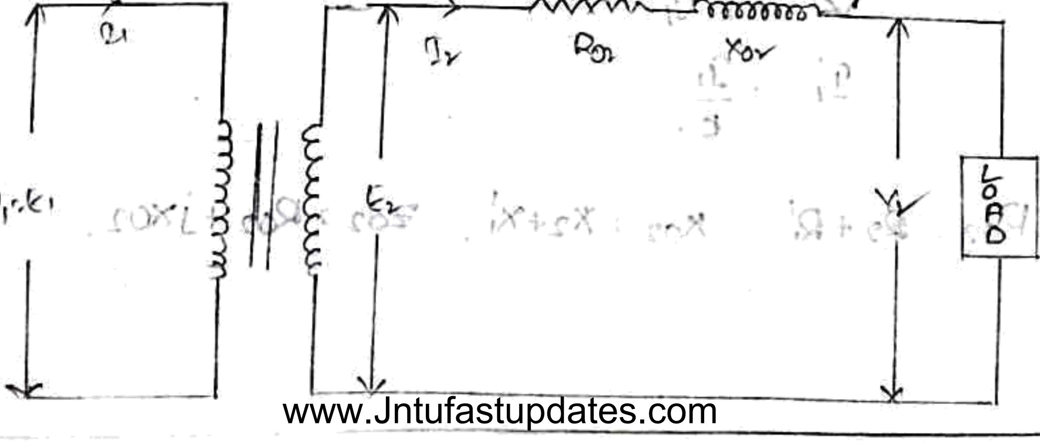
$$\%\ \text{voltage regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

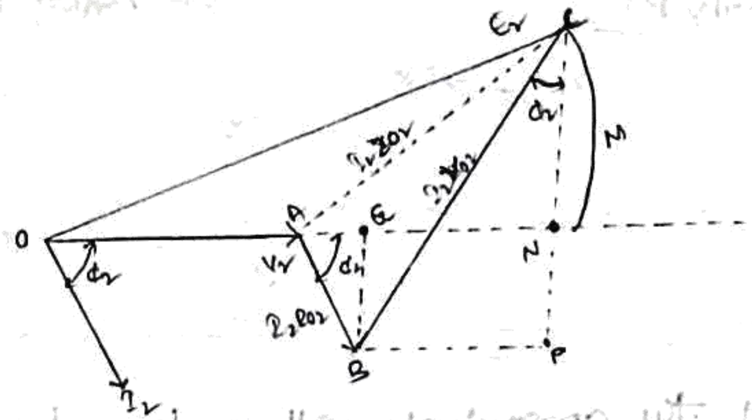
Approximate Formula for Regulation :-

The expression for voltage regulation can be derived from the approximate equivalent circuit of the transformer referred to the primary or to the secondary side and the associated phasor diagram

The approximate equivalent circuit of a transformer with resistance & Reactance reffered to the secondary side as shown in fig. for a lagging power factor load $\phi_2 = \phi$ is the power factor angle on load

$$\bar{E}_2 = \bar{V}_2 + \bar{I}_2 (R_{02} + jX_{02})$$





In order to find an approximate formula for voltage regulation.

i. Draw an arc with 'O' as the center and radius OC meeting the extension of the OA in M.

ii. From the point C draw CN perpendicular to OM.

iii. From B, draw BQ perpendicular on the line ON

iv. Draw BP parallel to OM.

It may be seen from fig. that

$E_2 (= OM)$ Approximately equal to ON

Now the voltage drop b/w No. load and full load

$= E_2 - V_2 = OM - OA$

$\approx AM$

$\approx AN$

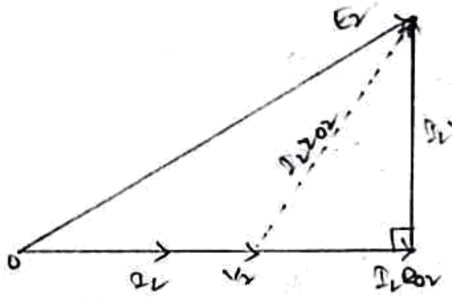
Approximate voltage drop $= AN = AQ + QN$

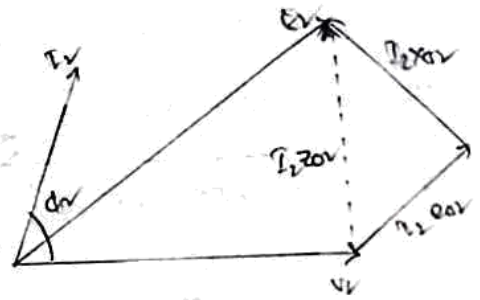
$E_2 - V_2 = AQ + BP$

$E_2 - V_2 = I_2 R_{02} \cos\phi + I_2 X_{02} \sin\phi$ (for lagging P.F)

The phasor diagram of the transformer on load at unity power factor and leading power factor as shown fig.

At Unity P.F. | At leading P.F





Similarly the approximate voltage drop for leading power factor referred to secondary

$$E_2 - V_2 = I_2 R_{02} \cos\phi - I_2 X_{02} \sin\phi$$

The approximate voltage drop for unity P.f ($\phi = 0$)

$$E_2 - V_2 = I_2 R_{02}$$

The voltage regulation of the transformer is given by

$$\% \text{ voltage regulation} = \frac{I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi}{E_2} \times 100$$

+ve sign for lagging P.F

−ve sign for leading P.F

Where R_{02} & X_{02} are equivalent parameters referred to secondary

If parameters are referred to the primary R_{01} & X_{01} then regulation can be calculated

$$\% \text{ voltage regulation} = \frac{I_1 R_{01} \cos\phi \pm I_1 X_{01} \sin\phi_1}{V_1} \times 100$$

$$= V_r \cos\phi \pm V_x \sin\phi$$

V_r = percentage resistance drop

V_x = percentage reactance drop

Condition for zero Regulation :-

$$\text{Regulation} = \frac{I_2 R_{02}\cos\phi + I_2 X_{02}\sin\phi}{E_2}$$

Regulation will be zero, if the numerator will be equal to zero.

$$I_2 R_{02}\cos\phi + I_2 X_{02}\sin\phi = 0$$

$$\tan\phi = -\frac{R_{02}}{X_{02}}$$

The "-ve" sign indicates that zero regulation occurs at a leading power factor

Condition for Maximum Regulation :-

Regulation will be maximum

If $\frac{d}{d\phi}(\text{regulation}) = 0$

$$\frac{d}{d\phi}\left[\frac{I_2 R_{02}\cos\phi + I_2 X_{02}\sin\phi}{E_2}\right] = 0$$

$$-\frac{I_2 R_{02}}{E_2}\sin\phi + \frac{I_2 X_{02}}{E_2}\cos\phi = 0$$

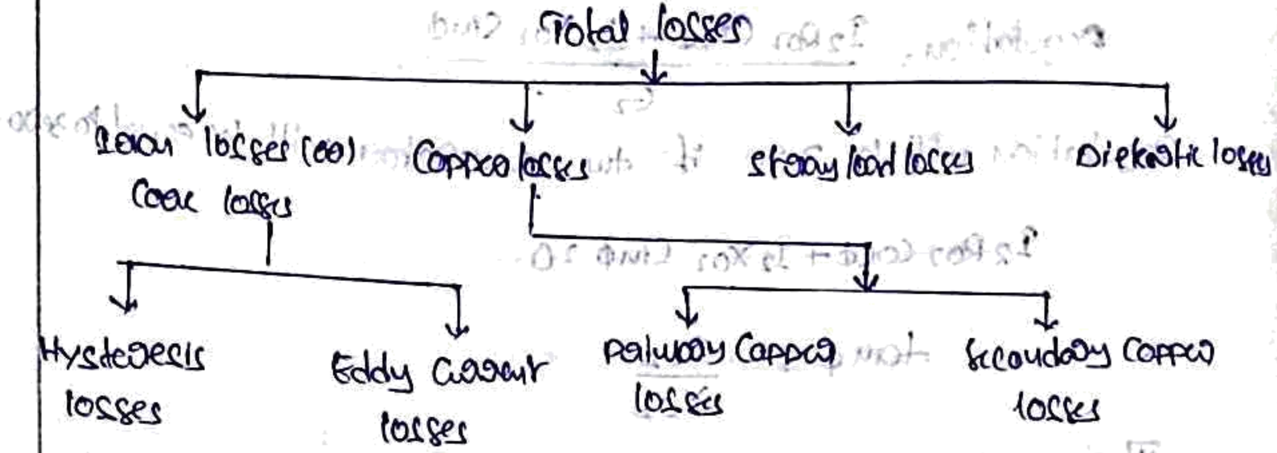
$$\tan\phi = \frac{X_{02}}{R_{02}}$$

i.e. Maximum regulation occurs at lagging P.f.

Effect of Power factor on Regulation :-

1. The regulation (or) the voltage drop is minimum at the UPF load
2. At lagging P.f. the voltage drop increases as the P.f. lags more and more.
3. In case of leading P.f load, the voltage on load is greater than the voltage on no. load and the regulation is negative. Instead of drop of volts, there is rise of voltage

Losses in a Transformer:



1. Core (or) Iron losses:

It consists of hysteresis and eddy current losses. These are caused by the alternating flux in the core.

The iron losses are constant losses, because the core flux in a transformer is remains practically constant for all loads

Hysteresis loss:

Due to alternating flux is set up in the magnetic core of the transformer, it undergoes a cycle of magnetization and demagnetization. Due to hysteresis effect there is loss of energy as heat in this process, which is called as hysteresis loss.

It is given by

Hysteresis loss $W_h = \eta (B_m)^{1.6} f V$ watts

where η = Hysteresis constant depends on material

B_m = Maximum flux density in Wb/m^2

f = Frequency in Hz

V = volume of the core in m^3

Eddy current loss :

This loss occurs in the core of the transformer as induced eddy current appear in the form of heat in the core. Iron losses are determined from the O.C test

Eddy current loss, $W_e = k_e B_m^2 f^2 t^2$ watts

where

k_e = Eddy current constant

t = Thickness of laminations in m.

2. Copper losses :

These are the losses taking place in the t/f windings due to their resistance. Primary winding copper losses are given by $I_1^2 R_1$ & the secondary by $I_2^2 R_2$.

The copper losses are variable losses. They are proportional to the square of the load current and therefore to the kVA output. Copper losses are determined from S.C. Test

Stray load loss :

It is largely results from leakage fields inducing eddy-current in the tank walls, conductors, bolts etc.

Dielectric loss :

This loss occurs in the insulating materials, particularly in oil and solid insulators.

"The stray load loss & dielectric loss are small and are therefore neglected."

Efficiency of a Transformer :

The efficiency of a transformer is defined as the ratio of output power to input power

$$\text{Efficiency } \eta = \frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{Output Power}}{\text{Output Power + losses}}$$

$$= \frac{\text{Output Power}}{\text{Output Power + Iron loss + Cu loss}}$$

Let V_2 = Secondary terminal voltage

I_2 = Secondary load current

$\cos\phi$ = P.f. of the load

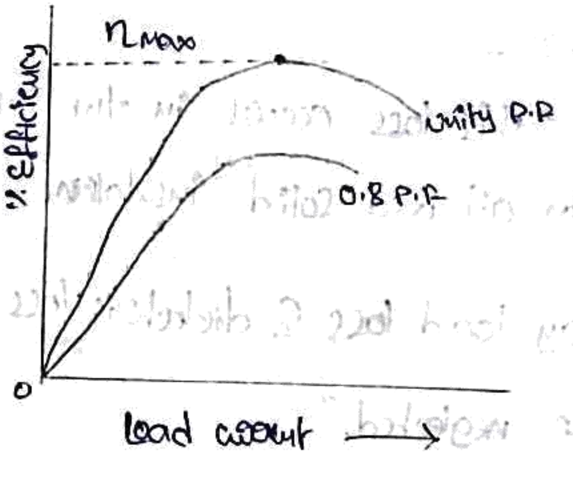
W_i = Iron loss

Total Cu losses $= I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{01} + I_2^2 R_{02}$

Where R_{01} & R_{02} are equivalent resistance referred to primary & secondary respectively

$$\text{Efficiency } \eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}}$$

The normal efficiency curve of the transformer.



Condition for maximum efficiency :

Considering Secondary side.

Secondary output = $V_2 I_2 \cos\phi_2$

Iron losses = W_i

Total Cu losses = $I_2^2 R_{02}$

efficiency of a transformer $\eta = \frac{\text{Output power}}{\text{Input power}}$

$= \frac{\text{output power}}{\text{output power} + \text{Iron loss} + \text{Cu loss}}$

$= \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}}$

Dividing the numerator and denominator by I_2

$\therefore$ Efficiency $\eta = \frac{V_2 \cos\phi_2}{V_2 \cos\phi_2 + \frac{W_i}{I_2} + I_2 R_{02}}$

The terminal voltage V_2 is approximately constant. Thus for a load of given p.f. the efficiency is maximum when denominator is minimum

$$\frac{d}{dI_2}\left(V_2 \cos\phi_2 + \frac{W_i}{I_2} + I_2 R_{02}\right) = 0$$

$$-\frac{W_i}{I_2^2} + R_{02} = 0$$

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

Copper losses = Iron losses

The efficiency will be maximum when Cu loss is equal to iron loss.

Variation of Efficiency with power factor :-

The efficiency of transformer is given by

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{losses}}{\text{Input}}$$

$$= 1 - \frac{\text{losses}}{\text{Input}} = 1 - \frac{\text{losses}}{V_2 I_2 \cos\phi + \text{losses}}$$

Let $\text{losses} / V_2 I_2 = x$

$$\eta = 1 - \frac{\text{losses} / V_2 I_2}{\cos\phi + (\text{losses} / V_2 I_2)}$$

$$\eta = 1 - \frac{x}{\cos\phi + x}$$

$$\eta = 1 - \frac{x / \cos\phi}{1 + (x / \cos\phi)}$$

Effect of frequency :-

According to the hysteresis & eddy current losses increases with increased frequency

Effect of voltage :-

When supply voltage changes the flux density in the core changes. Therefore iron losses i.e hysteresis & eddy current losses increases with increased voltage

But the flux density is constant as long as the ratio of supply voltage to frequency is constant. so the hysteresis & eddy current losses changes with frequency only

All-Day Efficiency :-

The efficiency of a transformer is given by

$$\eta = \frac{\text{output power}}{\text{Input power}}$$ ordinary (or) Commercial efficiency

All-day efficiency is considered on energy basis. It is defined as the ratio of energy (kwh) output in 24 hours to the energy input in the same period.

$$\text{All-day efficiency } \eta_{\text{all-day}} = \frac{\text{output in kwh}}{\text{Input in kwh}} \text{ (for 24 hrs)}$$

The transformers used for distribution are energized for all the 24 hours in a day. Thus "core loss will occur for the whole day the copper loss will occur only when the transformer is loaded."

∴ Distribution transformers are so designed that core-losses are as low as possible. The performance of such a transformer ~~of such a transformer~~ is judged by its all-day efficiency

For a given kVA loading, the all-day efficiency of the transformer is less than the commercial efficiency.

Distribution Transformer	Power Transformer.
1. Used to supply power to different consumers	1. used in generating stations & substations
2. Always step down (K<1) transformer	2. Step-up (or) step-down transformer
3. It's secondary is star connected which enables to provide 3-φ, 4-wire system	3. The secondary of this transformer is usually delta connected
4. kept in operation for all the 24 hours in a day	4. operates mostly when load exists
5. Iron loss takes place always	5. losses takes place when loaded
6. Designed to have max. efficiency at about 50% of full load	6. Designed to have max. efficiency at nearly full load.
7. usual rating are up to 500kva	7. Ratings will vary depending upon service
8 These have good voltage regulation	8. voltage regulation is less important

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