UNIT-III

TRANSFORMERS

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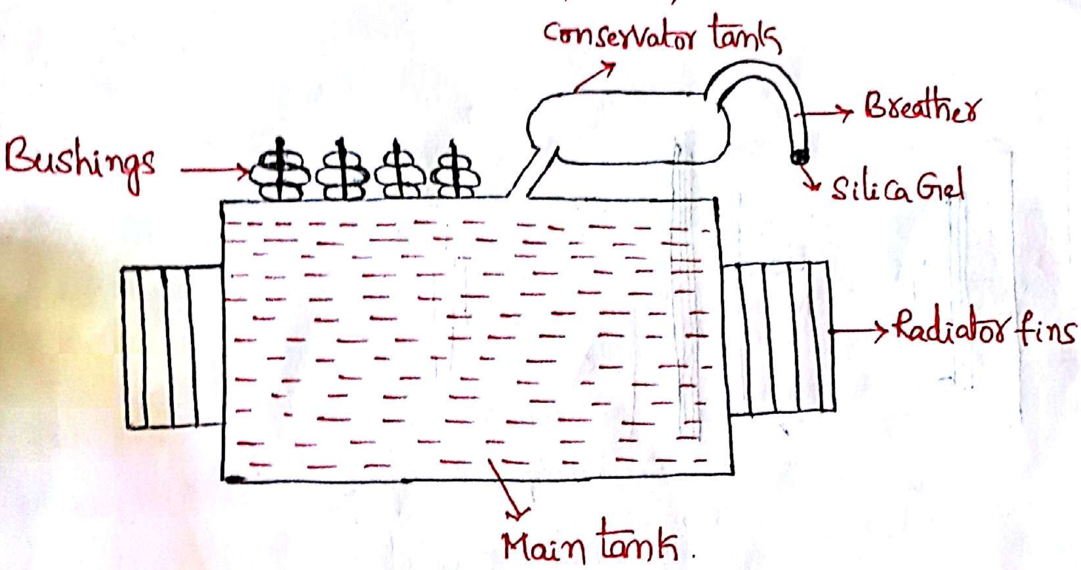
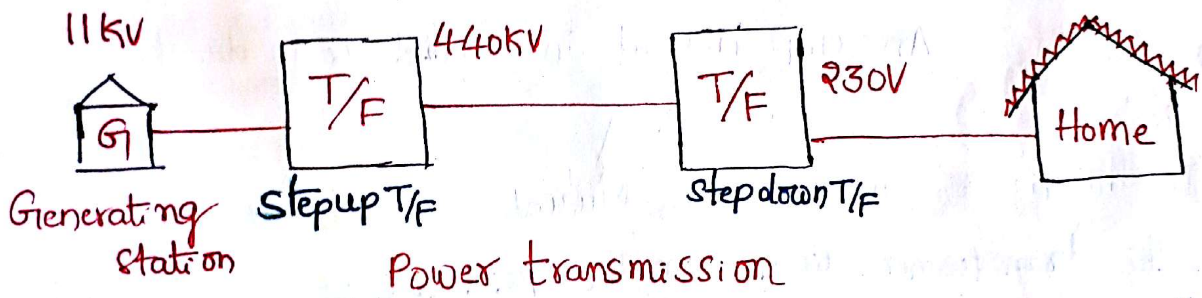


TRASFORMER



Power transmission

★ Transformer is a static device which can transfers the power from one circuit to another circuit by without change in magnitude of power and frequency.

The transfer of power takes place by changing voltage and current.

Working Principle :-

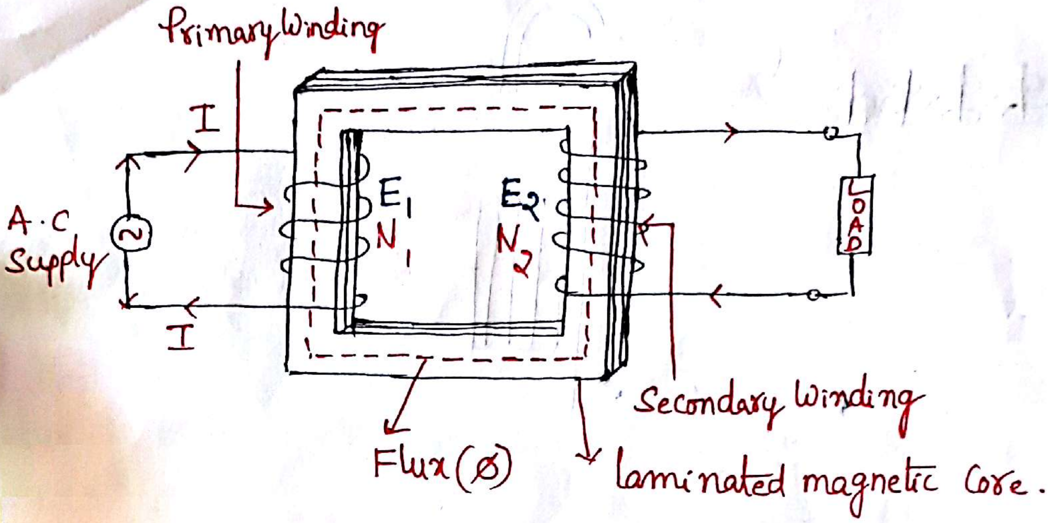
The transformer works based on "Faraday's law of electromagnetic Induction"

Faraday's 1st law :- When a conductor cuts the flux an emf will be induced in that conductor.

Faraday's 2nd law :- The magnitude of induced emf is given by

$$E = \frac{d\psi}{dt} = \text{rate of change of flux linkage}$$

Self Induced emf :- An emf induced in a coil due to excitation of same coil is known as self induced emf



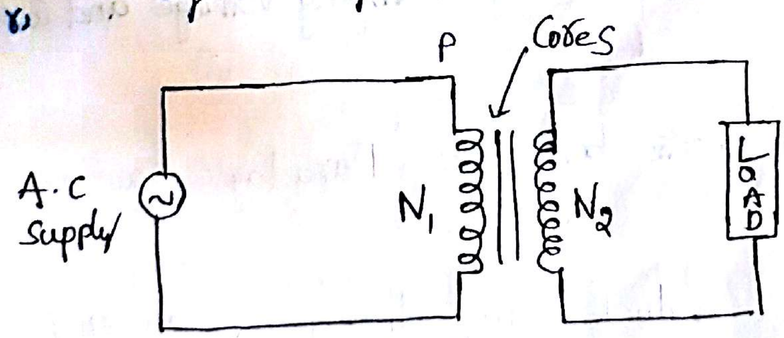
In the fig E_1 is known as self induced emf.

Mutual Induced emf :- An emf induced in second coil due to excitation of first coil.

In the fig E_2 is known as Mutual induced emf

* So the transformer works on the principle of "Mutual induction". which states that when two coils are inductively coupled and if current in one coil is changed uniformly then an e.m.f gets induced in the other coil.

Symbolically the transformer is indicated as shown below.



Two lines represents the core.

P – Primary winding (which is connected with source)
S – Secondary winding (which is connected with load)

Primary winding having N_1 number of turns and secondary winding having N_2 number of turns.

Thus there is no electrical connection between the two windings, ②
i.e electrically seperated but magnetically coupled.

Parts of a trans-former

1. **Core :** It is made up of CRGO (Cold rolled Grain oriented) Silicon steel laminations as its function is to carry the flux produced by the winding.

2. **Limb :-** It is vertical portion of the core and its function is to carry the windings.

3. **Yoke :-** The top and bottom horizontal portion of the core is called Yoke. Its function is to carry the flux produced by one winding to reach to the other winding and provide the low reluctance path to the flux.

4. **Conservator :-** The oil in the trans-former expands when temparature inside the trans-former increases due to heat while it contracts when the temparature decreases. The function of the conservator is to take up the expansion and contraction of the oil without allowing it to come in contact with the ambient air.

5. **Windings :-** The coils used are wound on the limbs and are insulated from each other. The function of the windings is to carry the current and produce the fluxnecessary for the functioning of the transformer.

6. **Radiator fins :-** These are used to provide natural cooling

7. **Bushings :-** The function of bushings are to make the connection.

Types of Single phase Transformers

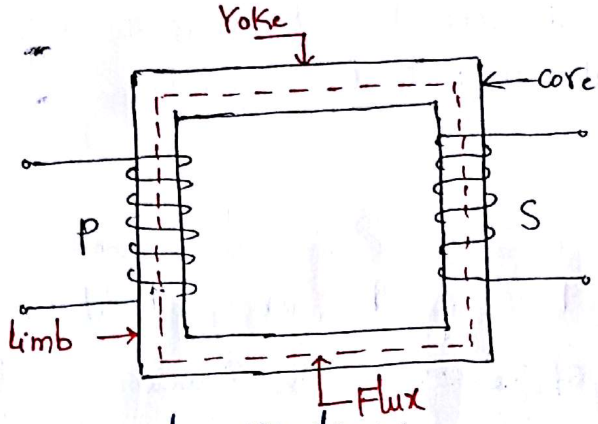
Based on construction the single phase transformers are classified as

1. Core type 2. Shell type

1. Core type Transformer :-

→ It has two limbs and two Yokes

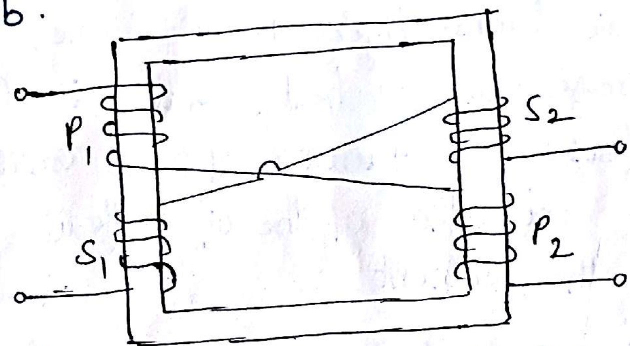
→ Both the limbs are provided with winding



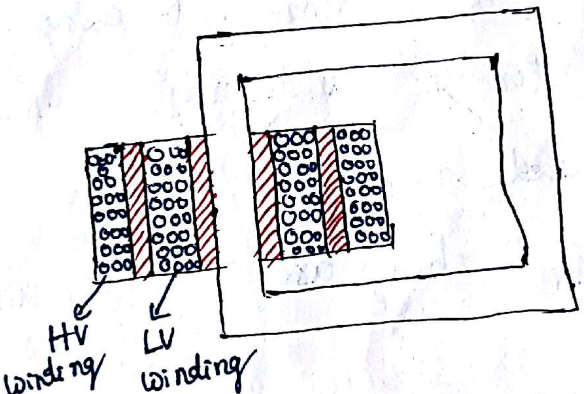
→ Core is covered by winding

→ In core type interleaved, concentric winding proceduced is adopted.

Interleaving winding: To reduce magnetic leakage flux each winding divided in to two parts one winding on one limb and another winding on other limb.



Concentric winding:- To reduce insulation requrement.



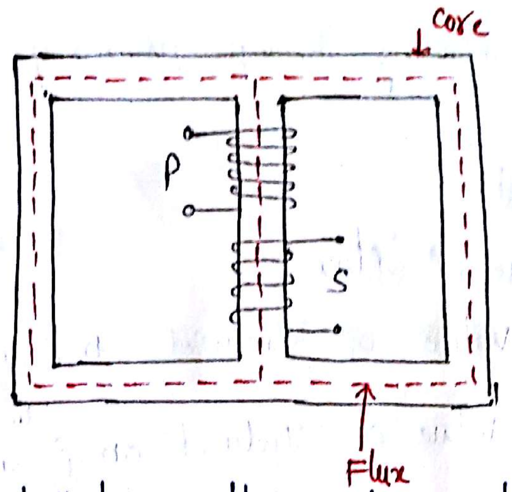
→ Core type used for high Voltage transformer.

2. Shell type Transformer :-

→ It has 3 limbs and 2 Yokes

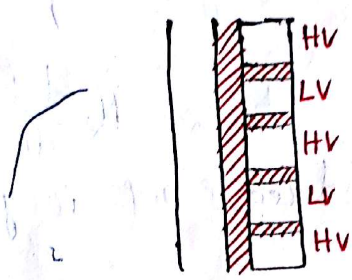
→ windings are placed only on Central limb.

→ windings covered by core



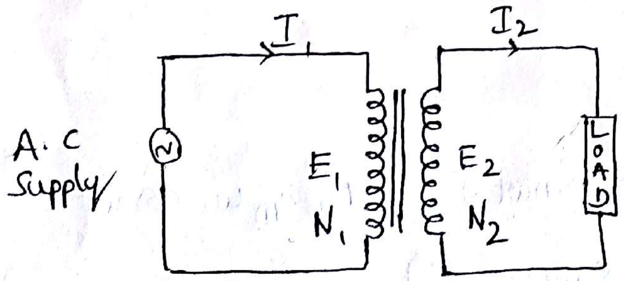
→ In shell type HV winding and LV winding placed on Central limb

→ In shell type Sandwitched winding procedure is adopted.



→ shell type is used for Low voltage transformer

E.M.F Equation of a Transformer :-



E_1 = R.M.S Value of the primary induced e.m.f

E_2 = R.M.S Value of the Secondary induced e.m.f.

N_1 = Number of primary winding turns

N_2 = Number of Secondary winding turns.

The primary winding is excited by purely Sinusoidal alternating voltage. Hence the flux produced is also Sinusoidal in nature.

The nature of flux depends on the nature of current.

Let $i = I_m \sin\omega t$ is flowing through primary winding

Then the flux produced is

$$\phi = \phi_m \sin\omega t$$

ϕ_m = Maximum Value of flux.

Let e_1 = instantaneous Value of Induced emf in primary winding

e_2 = instantaneous Value of Induced em.f in Secondary Winding.

According to Faraday's law of electromagnetic Induction The magnitude of induced e.m.f is given by

$$e_1 = \frac{d\psi}{dt} = N_1 \frac{d\phi}{dt} \quad \& \quad e_2 = N_2 \frac{d\phi}{dt}$$

But the direction of Induced e.m.f is given by Lenz's law

<u>Lenz's law</u> :- It Said that always effect opposes the Cause. i.e Induced emf oppose the flux.

$$e_1 = -N_1 \frac{d\phi}{dt}$$

$$\phi = \phi_m \sin\omega t$$

$$e_1 = -N_1 \frac{d}{dt}(\phi_m \sin\omega t) = -N_1 \phi_m \omega \cos\omega t$$

$$e_1 = N_1 \phi_m \omega \sin(\omega t - 90^\circ)$$

slly

$$e_2 = N_2 \phi_m \omega \sin(\omega t - 90^\circ)$$

$$\therefore \quad E_1 = \frac{N_1 \phi_m \omega}{\sqrt{2}} = \frac{N_1 \phi_m \times 2\pi f}{\sqrt{2}} = 4.44\, \phi_m f N_1 \text{ Volts}$$

$$E_2 = \frac{N_2 \phi_m \omega}{\sqrt{2}} = 4.44\, \phi_m f N_2 \text{ Volts.}$$

$$\boxed{\begin{aligned} E_1 &= 4.44\, \phi_m f N_1 \text{ Volts} \\ E_2 &= 4.44\, \phi_m f N_2 \text{ Volts.} \end{aligned}}$$

Ideal Transformer

A transformer is said to be ideal if it satisfies the fallowing properties:

1) It has no losses
2) Its windings have zero resistance
3) Leakage flux is zero i.e 100% flux produced by primary links with the secondary.
4) Permeability of core is so high that negligible current is required to establish the flux in it.

Ratios of a Transformer

1. Voltage ratio :-

We know from the e.m.f equations,

$$E_1 = 4.44\, \phi_m f N_1$$

$$E_2 = 4.44\, \phi_m f N_2$$

Then

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

K = Transformation ratio

It is defined as the ratio of secondary induced e.m.f to primary induced e.m.f.

1. If $N_2 > N_1$ i.e $K > 1$, Then the transformer is called Step-up T/F
2. If $N_2 < N_1$ i.e $K < 1$, Then the transformer is called Step-down transforme

2. Current ratio :-

For an ideal transformer there are no losses. Hence the produ of primary V_1 and primary current I_1, is same as the product of secondary voltage V_2 and the secondary current I_2.

So $V_1 I_1$ = Input VA and $V_2 I_2$ = output VA

For an Ideal transformer $V_1 I_1 = V_2 I_2$

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

Rating of a Transformer

The rating of any device decided based on losses. In transformer two types of losses takes place

1. Copper losses (I^2R)
2. Iron losses (or) Core losses

The copper loss in the transformer depends on the current 'I' through the winding while the iron (or) core losses depends on the voltage 'V'. None of these losses depends on the power factor ($\cos\phi$) of the load.

→ As losses depends on V and I only, the rating of the transformer is specified as a product of these two parameters i.e $V \times I$.

Hence the transformer ratings are expressed in VA rating (or) KVA (volt amperes)

1. A single phase 2200/250 V, 50 Hz transformer has a net core area of 36 sq.cm and a maximum flux density of 6 wb/m². Calculate the number of turns of primary and secondary windings?

Sol $E_1 = 2200\ V,\ E_2 = 250\ V,\ f = 50\ Hz,\ a = 36\ cm^2,$

$B_m = 6\ wb/m^2$

$\phi_m = B_m \times a = 6 \times 36 \times 10^{-4} = 0.0216\ wb.$

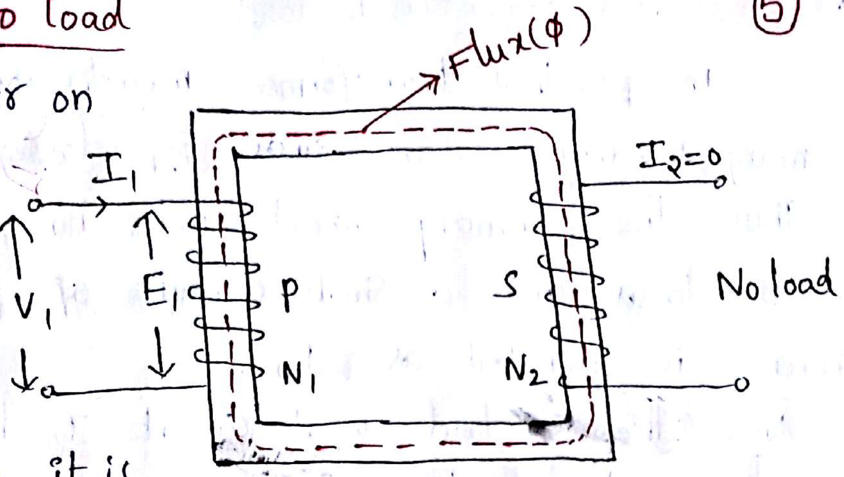
$E_1 = 4.44\, \phi_m f N_1$ i.e $N_1 = \dfrac{2200}{4.44 \times 50 \times 0.0216} = 458.79 \approx 459$

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

$\Rightarrow N_2 = \dfrac{E_2}{E_1} \times N_1 = \dfrac{250}{2200} \times 459 = 52.15 \approx 52.$

$$\boxed{\begin{array}{l} N_1 = 459 \\ N_2 = 52 \end{array}}$$

Ideal Transformer on No load



→ Consider an ideal transformer on no load. i.e $I_2=0$

→ The primary draws a current I_1 which is just necessary to produce flux in the core.

As it is magnetizing the core, it is called magnetizing current denoted as I_m.

→ As the transformer is ideal, the winding resistance is zero and it is purely inductive in nature.

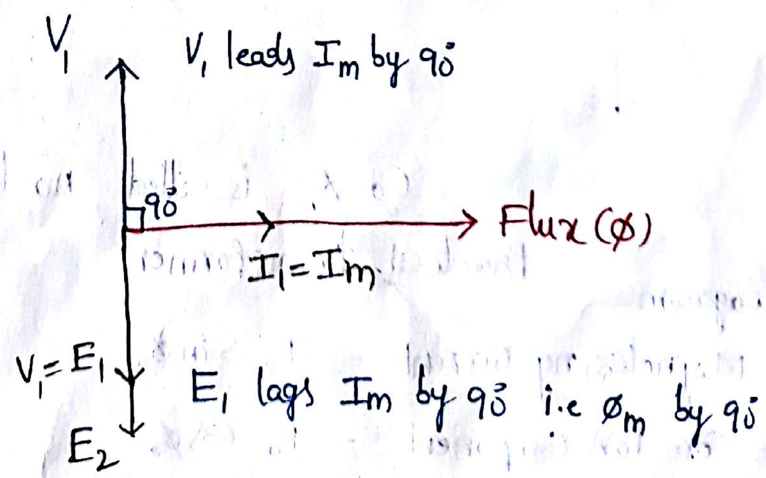
→ So magnetizing current I_m is very small and lags V_1 by $90°$ as the winding is purely inductive. This I_m produces an alternating flux ϕ which is in phase with I_m.

→ As the flux links both the windings and produces e.m.f.s E_1 and E_2

→ Acc to Lenz's law E_1 & E_2 opposes the cause i.e V_1. Hence E_1 is in antiphase with V_1 but equal in magnitude.

→ E_2 also opposes V_1 but its magnitude depends on N_2.

The phasor diagram for the ideal transformer on no load is shown below.



Practical Transformer on No load

In practical transformer magnetic core Causes Iron losses and Primary winding resistance causes Copper losses (Small amount).

Thus the primary current under no load condition has to supply the iron losses and a small amount of primary copper loss. This current is denoted as I_0.

Now the no load input current I_0 has two components

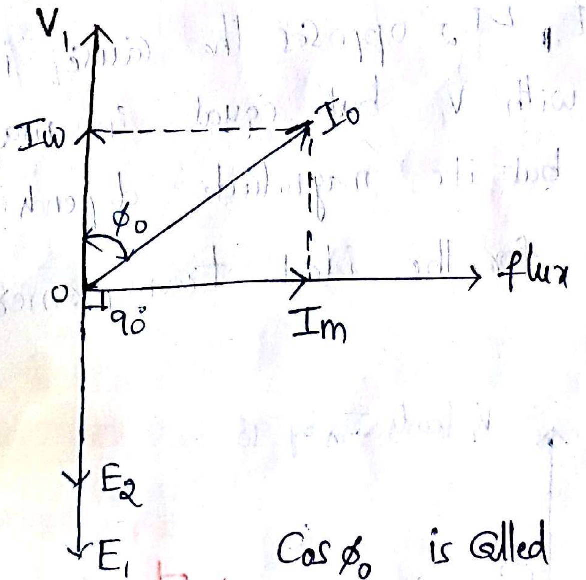
1. A purely reactive component I_m called magnetizing component of no load current required to produce flux. This is also called wattless component.

2. An active component I_w which supplies total losses under no load condition called watt-ful component.

The total no load current I_0 is the vector addition of I_m and I_w

$$\boxed{\bar{I}_0 = \bar{I}_m + \bar{I}_w}$$

The phasor diagram for the practical transformer on No load shown below.



$\cos\phi_0$ is called no load power factor of Practical transformer.

From phasor diagram

I_m = Magnetizing current = $I_0 \sin\phi_0$

I_w = Core loss component = $I_0 \cos\phi_0$

of No load current $I_0 = \sqrt{I_m^2 + I_w^2}$

ϕ_0 = No load primary power factor angle

The total power input on no load is denoted as W_0 and is given by ⑥

$$\boxed{W_0 = V_1 I_0 \cos\phi_0 = V_1 I_W}$$

The no load power is almost equals to iron losses, because the no load current I_0 is very small, about 3 to 5% of the full load rated current. Hence the primary copper loss is negligibly small.

$$\boxed{W_0 = V_1 I_0 \cos\phi_0 = P_i = \text{Iron loss}}$$

2. A 3300/220 V, 30 KVA, 1-phase transformer takes a no load current of 1.5 A when the low voltage winding is open. The iron loss component is 0.4 A. Find :
   (i) No Load input power (ii) Magnetizing Component
   (iii) Power factor of No load current

Sol

$I_0 = 1.5$ A, $I_W = 0.4$ A, 3300/220 V

$I_W = I_0 \cos\phi_0$

$\Rightarrow 0.4 = 1.5 \cos\phi_0$

$\Rightarrow \cos\phi_0 = \text{No load p.f} = \frac{0.4}{1.5} = 0.2667$ lagging

$\sin\phi_0 = \sin(\cos^{-1}(0.2667)) = 0.96378$

$I_m = I_0 \sin\phi_0 = 1.5 \times 0.96378 = 1.4456$ A

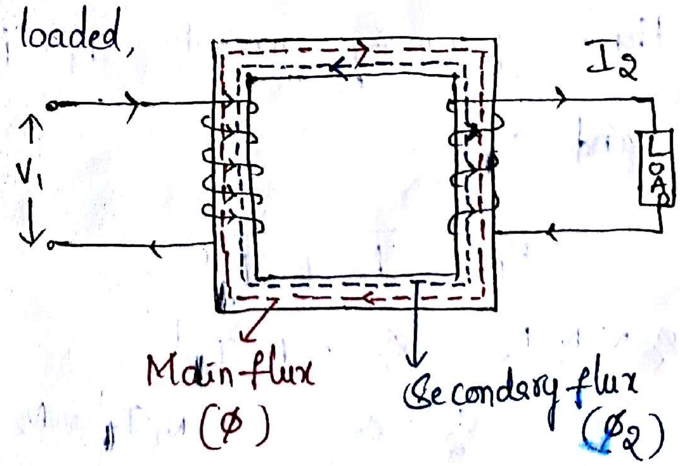
V_0 = No load primary voltage = 3300 V

$P_0 = V_0 I_0 \cos\phi_0 = 3300 \times 1.5 \times 0.2667 = 1320.165$ W

No load input power $P_0 = 1320.165$ W.

Transformer on Load :-

→ when the transformer is loaded, then current I_2 flows through the secondary winding and produces ϕ_2 (flux)



(i) ϕ_2 opposes ϕ

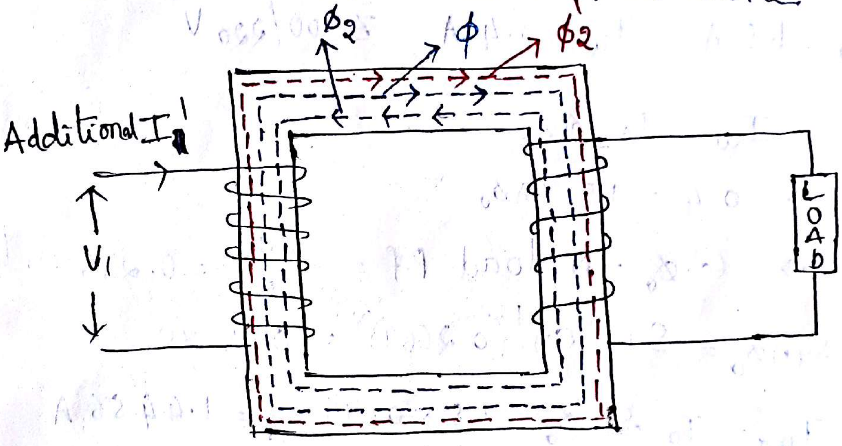
→ According to lenz's law Secondary flux ϕ_2 opposes the main flux ϕ.

→ The flux ϕ_2 momentarily reduces the main flux ϕ, due to which the primary induced e.m.f E_1 also reduces. Hence the Vector difference $\bar{V}_1 - \bar{E}_1$ increases due to which primary draws more current from the supply.

→ This additional current is known as load component of primary current denoted as I_1'

→ This current I_1' is in antiphase with I_2. This current I_1' Sets up its own flux ϕ_2' which opposes the flux ϕ_2. Hence the net flux in the core is constant.

→ So the transformer is called Constant flux device.



Thus when transformer loaded, the primary current I_1 has two components:

1. The no load current I_0 which lags V_1 by angle ϕ_0. It has two components I_m and I_w.

2. The load component I_1' which is in antiphase with I_2.

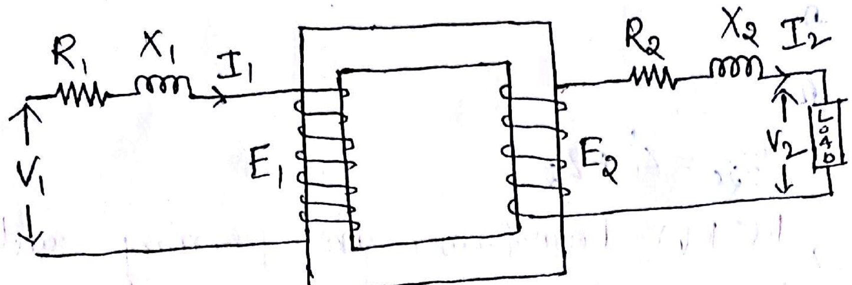
Hence primary current I_1 is Vector sum of I_0 and I_1'

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

$\phi_2 \propto N_2 I_2$ $\quad$ $\phi_2' \propto N_1 I_1'$

$$\phi_2' = \phi_2 \Rightarrow N_1 I_1' = N_2 I_2 \Rightarrow I_1' = \frac{N_2}{N_1} I_2 = K I_2$$

Equivalent Resistance & Reactance of a transformer



$$V_1 = -E_1 + I_1 R_1 + j I_1 X_1$$

$$E_2 = V_2 + I_2 R_2 + j I_2 X_2$$

R_1 = Primary winding Resistance in ohms

R_2 = Secondary winding Resistance in ohms

Total Copper losses $= I_1^2 R_1 + I_2^2 R_2$

$$= I_1^2 \left(R_1 + \left(\frac{I_2}{I_1}\right)^2 R_2\right)$$

$$= I_1^2 \left(R_1 + \frac{R_2}{K^2}\right)$$

i.e The resistance of the two windings can be transferred to any one side either primary (or) secondary without effecting the performance of the transformer.

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

$R_2' = \frac{R_2}{K^2}$ = Equivalent value of secondary resistance when referred to primary.

slly $= I_2^2 (K^2 R_1 + R_2) = I_2^2 (R_1' + R_2)$

$R_1' = K^2 R_1$ = equivalent value of primary resistance when referred to secondary

R_{1e} = Total resistance when referred to primary $= R_1 + R_2'$

$R_{2e} = R_1' + R_2$

slly

X_{1e} = Total leakage reactance when referred to primary

$$= X_1 + X_2'$$

$$X_2' = \frac{X_2}{K^2}$$

$X_{2e} = X_1' + X_2 \Rightarrow X_1' = K^2 X_1$

Equivalent Impedance

$$Z_1 = R_1 + jX_1 \ \Omega$$

$$Z_2 = R_2 + jX_2 \ \Omega$$

$$Z_{1e} = Z_1 + Z_2' \qquad Z_{2e} = Z_1' + Z_2$$

3. A 220/110 V, 50 Hz, 1.5 KVA transformer has primary and Secondary winding resistance of 1Ω and 2Ω while reactances of 3Ω and 5Ω respectively. Find the total resistance, equivalent reactance and equivalent Impedance referred to primary and Secondary ?

Sol

$$R_1 = 1\Omega, \quad R_2 = 2\Omega, \quad X_1 = 3\Omega, \quad X_2 = 5\Omega$$

$$K = \frac{E_2}{E_1} = \frac{110}{220} = 0.5$$

$$R_{1e} = R_1 + R_2' = 1 + \frac{2}{K^2} = 9\Omega$$

$$X_{1e} = X_1 + X_2' = 3 + \frac{5}{(0.5)^2} = 23\Omega$$

$$Z_{1e} = \sqrt{R_{1e}^2 + X_{1e}^2} = \sqrt{9^2 + 23^2} = 24.6981\,\Omega$$

$$R_{2e} = R_1' + R_2 = 2.25\Omega \qquad X_{2e} = X_1' + X_2 = 5.75\Omega$$

$$Z_{2e} = \sqrt{R_{2e}^2 + X_{2e}^2} = 6.1745\,\Omega$$

Equivalent Circuit of a Transformer

Equivalent Circuit of a transformer means the representation of physical transformer interms of electric circuit elements like Resistance, and Inductance.

i.e The performance of a physical transformer and equivalent circuit must be Same.

under load condition

$$I_1 = I_0 + I_1'$$

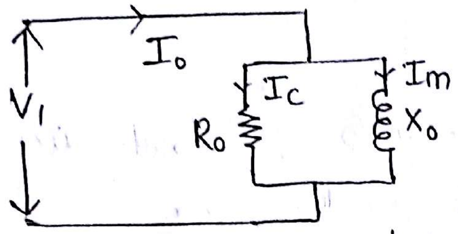
I_0 = No load current, it doesn't flows from one side to other side. So it is connected as shunt branch (8)

But $I_0 = I_w + I_m$

I_w = loss component
I_m = Magnetizing Component

No load condition

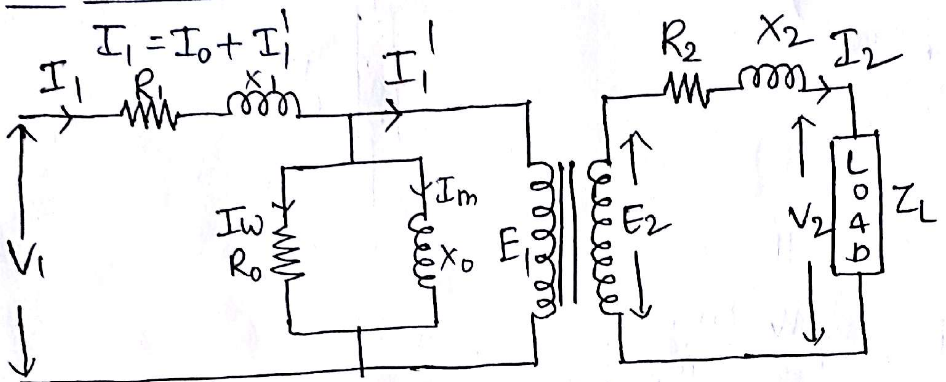
$I_1 = I_0$



No-load equivalent circuit.

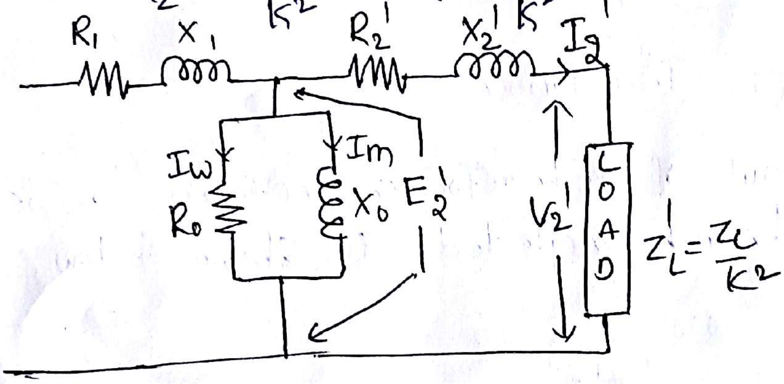
load condition

$I_1 = I_0 + I_1'$



when referred to primary side

$R_2' = \frac{R_2}{K^2}$ $X_2' = \frac{X_2}{K^2}$

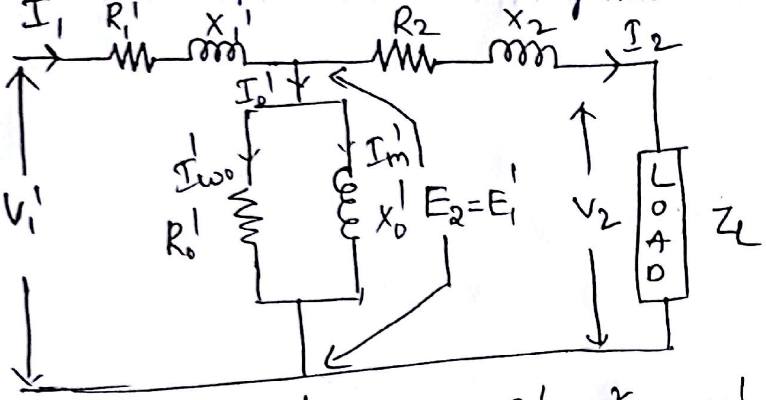


$V_2' = \frac{V_2}{K}$, $Z_L' = \frac{Z_L}{K^2}$

$R_2' = \frac{R_2}{K^2}$ $X_2' = \frac{X_2}{K^2}$

$E_2' = \frac{E_2}{K}$. $I_2' = KI_2$

When referred to Secondary side

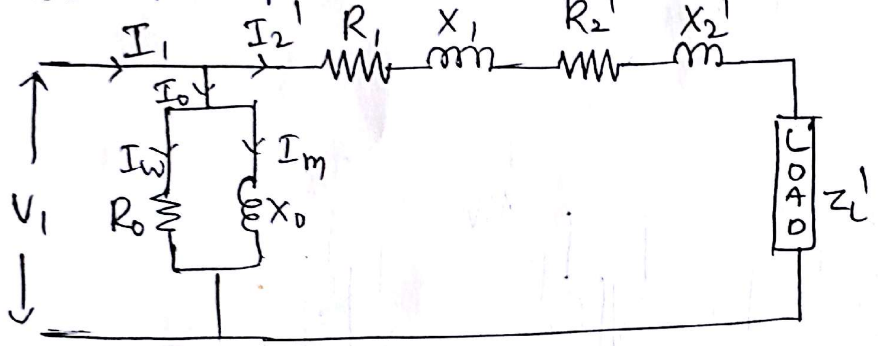


$$E_1' = KE_1 \qquad R_1' = K^2 R_1 \qquad X_1' = K^2 X_1$$

Aproximate equivalent circuit

The no load current I_0 is 3-5 % of full load current.

So we can shift the no load branch to the front.



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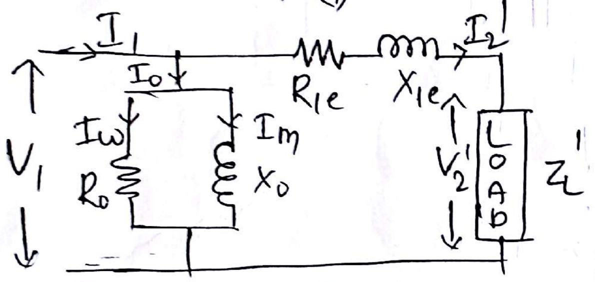
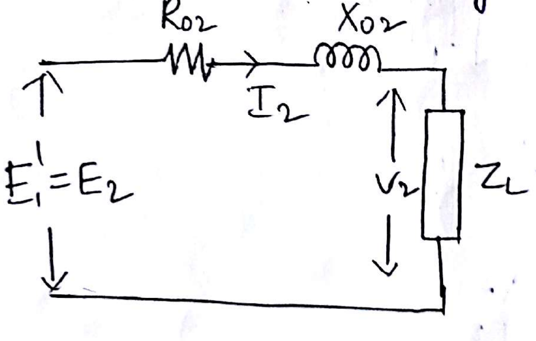


Voltage Regulation of Transformer

Equivalent circuit of a transformer referred to Secondary side when shunt branch neglected is shown below



$$E_2 = V_2 + I_2 R_{02} + jI_2 X_{2e}$$

E_2 = No load Secondary terminal voltage

V_2 = Full load Secondary terminal voltage.

Voltage regulation of a transformer can be defined as

$$V.R = \frac{E_2 - V_2}{E_2} \rightarrow \text{Regulation down}$$

$$= \frac{E_2 - V_2}{V_2} \rightarrow \text{Regulation up}.$$

Because of the voltage drop across the primary and Secondary impedences it is observed that the secondary terminal voltage drops from its no load value (E_2) to load value (V_2) as load and load current increases.

→ If dont mention consider Regulation down

→ The decrease in the secondary terminal voltage expressed as a fraction of the no load secondary terminal voltage is called Regulation of a transformer.

$$\% \; V.R = \frac{E_2 - V_2}{E_2} \times 100$$

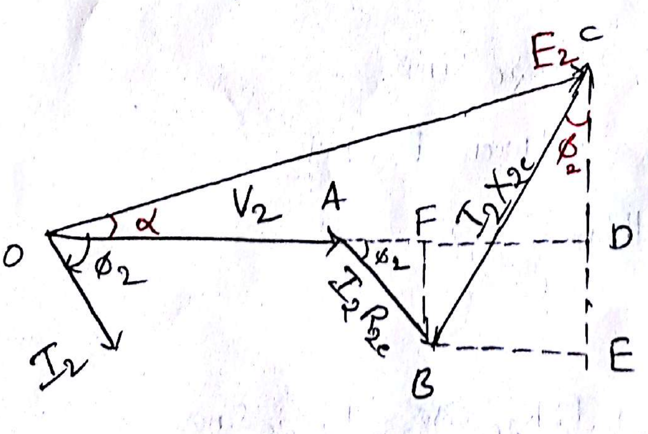
Expression for Voltage Regulation

1. lagging P.f loads:

$$E_2 = I_2 R_{2e} + j \, I_2 X_{2e} + V_2$$

Consider load current I_2 is lagging w.r.t V_2 by an angle of ϕ_2.

Phasor diagram



$OA = V_2$

$AF = AB \cos\phi_2 = I_2 R_{2e} \cos\phi_2$

$BE = FD = BC \sin\phi_2$

$= I_2 X_{2e} \sin\phi_2$

Consider 'α' is the angle between E_2 & V_2

→ If 'α' is neglected then

$$E_2 \cong OD$$

$$OD = OA + AF + FD$$

$$E_2 = V_2 + I_2 R_{2e} \cos\phi_2 + I_2 X_{2e} \sin\phi_2$$

$$E_2 - V_2 = I_2 R_{2e} \cos\phi_2 + I_2 X_{2e} \sin\phi_2$$

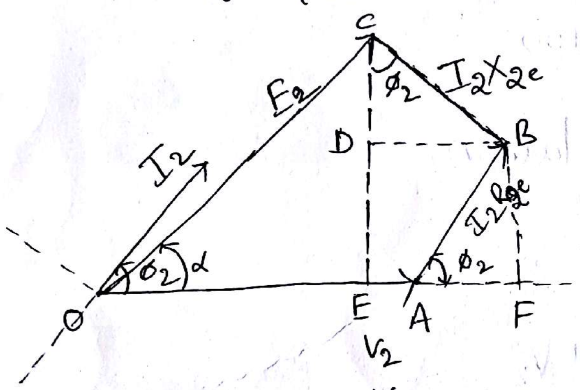
$$\% VR = \frac{E_2 - V_2}{E_2} \times 100 = \frac{I_2 R_{2e} \cos\phi_2 + I_2 X_{2e} \sin\phi_2}{E_2} \times 100$$

(ii) Leading power factor load :-

Consider load current I_2 leads V_2 by ϕ_2

Phasor diagram

$$E_2 = V_2 + I_2 R_{2e} + j I_2 X_{2e}$$



$$OA = V_2$$

$$AF = AB \cos\phi_2 = I_2 R_{2e} \cos\phi_2$$

$$BD = BC \sin\phi_2 = I_2 X_{2e} \sin\phi_2 = EF$$

$$OE = OA + AF - EF$$

$$= V_2 + I_2 R_{2e} \cos\phi_2 - I_2 X_{2e} \sin\phi_2$$

let 'α' is the angle between E_2 & V_2

If α neglected then

$$OE = E_2$$

but $OE = V_2 + I_2 R_{2e} \cos\phi_2 - I_2 X_{2e} \sin\phi_2$

Scanned by CamScanner

$$\Rightarrow E_2 = V_2 + I_2 R_{2e} \cos\phi_2 - I_2 X_{2e} \sin\phi_2$$

$$E_2 - V_2 = I_2 R_{2e} \cos\phi_2 - I_2 X_{2e} \sin\phi_2$$

$$\% VR = \frac{E_2 - V_2}{E_2} \times 100$$

$$= \frac{I_2 R_{2e} \cos\phi_2 - I_2 X_{2e} \sin\phi_2}{E_2} \times 100$$

In terms of primary quantities

$$\% VR = \frac{I_1 R_{1e} \cos\phi_2 - I_1 X_{1e} \sin\phi_2}{E_1} \times 100$$

(III) unity P.f loads

$\phi_2 = 0$, V_2 and I_2 are in inphase.

$$\% VR = \frac{I_2 R_{2e}}{E_2} \times 100$$

Condition for Zero Voltage Regulation

For lagging power factor and unity power factor condition

V.R is +Ve i.e $V_2 < E_2$

But for leading P.f V.R may be +Ve (or) -Ve (or) Zero

at a certain power factor.

So zero regulation is always possible with leading power factor

The condition for zero regulation

$$\text{i.e } E_2 = V_2$$

$$E_2 - V_2 = 0$$

$$\Rightarrow I_2 R_{2e} \cos\phi_2 - I_2 X_{2e} \sin\phi_2 = 0$$

$$\cancel{I_2} R_{2e} \cos\phi_2 = \cancel{I_2} X_{2e} \sin\phi_2$$

$$\tan\phi_2 = \frac{R_{2e}}{X_{2e}}$$

$$\therefore \cos\phi_2 = \cos\left(\tan^{-1}\left(\frac{R_{2e}}{X_{2e}}\right)\right)$$

This is the power factor at which zero regulation occurs

Condition for maximum Voltage Regulation

Max Voltage Regulation occurs only for lagging P.f load

i.e

$$\% R = \frac{I_2 R_{2e} \cos\phi_2 + I_2 X_{2e} \sin\phi_2}{E_2} \times 100$$

For max regulation

$$\frac{dR}{d\phi_2} = 0$$

$$\frac{-I_2 R_{2e}}{E_2} \sin\phi_2 + \frac{I_2 X_{2e}}{E_2} \cos\phi_2 = 0$$

$$\tan\phi_2 = \frac{X_{2e}}{R_{2e}}$$

$$\phi_2 = \tan^{-1}\left(\frac{X_{2e}}{R_{2e}}\right)$$

The p.f at which max regulation occurs is

$$\cos\phi_2 = \cos\left(\tan^{-1}\left(\frac{X_{2e}}{R_{2e}}\right)\right)$$

4) A 20 KVA, 2000/200 V Single phase transformer has the fallowing Parameters. HV winding $R_1 = 3\Omega$ $X_1 = 5.3\Omega$, L.V winding $R_2 = 0.5\Omega$ $X_2 = 0.1\Omega$ Find the voltage regulation at

(i) Power factor of 0.8 lagging (ii) U.P.F (iii) 0.707 P.f leading

Sol

$E_1 = 2000$ $E_2 = 200$

$R_1 = 3\Omega$ $R_2 = 0.05\Omega$ $X_1 = 5.3\Omega$

$X_2 = 0.1\Omega$

$$K = \frac{E_2}{E_1} = \frac{200}{2000} = 0.1$$

$$R_{1e} = R_1 + R_2' = R_1 + \frac{R_2}{K^2} = 3 + \frac{0.05}{(0.1)^2}$$

$$= 8\Omega$$

$$X_{1e} = X_1 + X_2' = X_1 + \frac{X_2}{K^2} = 5.3 + \frac{0.1}{(0.1)^2} = 15.3\Omega$$

$$(I_1)_{FL} = \frac{KVA}{E_1} = \frac{20 \times 10^3}{2000}$$

$$= 10A$$

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(i) $\cos\phi = 0.8$ lagging, $\sin\phi = 0.6$

$$\%R = \frac{I_1 (R_{1e}\cos\phi + X_{1e}\sin\phi)}{E_1} \times 100$$

$$= \frac{10 \times [8 \times 0.8 + 15.3 \times 0.6]}{2000} \times 100$$

$$= 7.79\%$$

(ii) $\cos\phi = 1$, $\sin\phi = 0$

$$\%R = \frac{I_1 R_{1e}}{E_1} = \frac{10 \times 8}{2000} \times 100$$

$$= 4\%$$

(iii) $\cos\phi = 0.707$ leading $\sin\phi = 0.707$

$$\%R = \frac{I_1 [R_{1e}\cos\phi - X_{1e}\sin\phi]}{E_1} \times 100$$

$$= -2.5805\%$$

Losses in a Transformer.

In transformer, there exists two types of losses

(i) Iron losses (or) Core losses

(ii) Copper losses (or) I^2R losses

(i) Iron losses (or) Core losses

Core losses are classified in to two types

(i) Eddy current losses

(ii) Hysteresis losses

→ Core losses are due to presence of alternating flux in the core

(i) Eddy Current losses

The induced emf in the core tries to set up currents in the cor. These currents are called eddy currents and hence responsible for the eddy current losses

The eddy current loss is given by

$$\text{Eddy current loss} = K_e B_m^2 f^2 t^2 \text{ watts/unit volume}$$

K_e = eddy current constant

t = Thickness of the core

(ii) Hysteresis losses

Due to hysteresis effect there is a loss of energy is called hysteresis losses

$$\text{Hysteresis loss} = \eta B_m^{x} f V$$

Steinmentz's formula

η = steinmentz co-efficient

$x = 1.6$ for silicon steel core.

Hysteresis loss

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

→ The flux in the core is almost constant, Hence flux density B_m in the core is constant hence both eddy current and Hysteresis losses are constant at fixed voltage and frequency So Iron losses are also called as constant losses.

2) Copper losses :-

Copper losses are due to the presence of transformer winding resistance.

Copper losses depends on magnitude of current flowing through the core.

$$\text{Total Cu losses} = I_1^2 R_1 + I_2^2 R_2$$

$$= I_1^2 R_{1e} = I_2^2 R_{2e}$$

I_2 = Full load current

$$\text{Half load Copper losses} = \left(\frac{I_2}{2}\right)^2 R_{2e} = \frac{I_2^2 R_{2e}}{4} = \frac{\text{Full load Cu lo}}{4}$$

thus Copper losses are called Variable losses.

Thus in a transformer

$$\text{Total losses} = \text{Iron losses} + \text{Copper losses}$$

Efficiency of a Transformer

Due to losses in a transformer, the o/p power is less than the input Power.

Power output = Power input - total losses

∴ Power input = Power output + $P_i + P_{cu}$

The efficiency of any device is defined as the ratio of the power output to power input. So for a transformer the efficiency can be expressed as

$$\eta = \frac{\text{Power output}}{\text{Power input}} = \frac{\text{Power o/p}}{\text{Power o/p} + P_i + P_{cu}}$$

$$\% \eta = \frac{\text{Power o/p}}{\text{Power o/p} + P_i + P_{cu}}$$

Power o/p $= V_2 I_2 \cos\phi_2$ $\quad \cos\phi_2 =$ load P.f

$$P_{cu} = I_2^2 R_{2e} = I_1^2 R_{1e}$$

$$\eta_{\text{Full load}} = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + P_{cu}} \times 100$$

$$= \frac{(\text{VA rating}) \cos\phi_2}{(\text{VA rating}) \cos\phi_2 + P_i + P_{cu}} \times 100$$

$$\eta_{\text{Half load}} = \frac{\left(\frac{VA}{2}\right) \times \cos\phi_2}{\left(\frac{VA}{2}\right) \times \cos\phi_2 + P_i + \frac{P_{cu}}{4}} \times 100$$

$$\eta_{3/4\text{th load}} = \frac{\left(3/4 \times VA\right) \times \cos\phi_2}{\left(3/4 \times VA\right) \times \cos\phi_2 + P_i + \frac{P_{cu}}{4}} \times 100$$

Condition for maximum efficiency

η is a function of load current

$\cos\phi_2, V_2 \rightarrow$ constant

For max η $\quad \frac{d\eta}{dI_2} = 0$

$$\Rightarrow \frac{d}{dI_2}\left[\frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e}}\right] = 0$$

$$\Rightarrow \left[V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e}\right]\left[V_2 \cos\phi_2\right] - \left[V_2 I_2 \cos\phi_2\right]\left[V_2 \cos\phi_2 + 2 I_2 R_{2e}\right] = 0$$

$$\Rightarrow \left[V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e}\right] \cancel{V_2} \cancel{\cos\phi_2} = \left(\cancel{V_2} I_2 \cancel{\cos\phi_2}\right)\left[V_2 \cos\phi_2 + 2 I_2 R_{2e}\right]$$

$$\Rightarrow \cancel{V_2 I_2 \cos\phi_2} + P_i + I_2^2 R_{2e} = \cancel{V_2 I_2 \cos\phi_2} + 2 I_2^2 R_{2e}$$

$$P_i = I_2^2 R_{2e}$$

$$\boxed{\therefore \; P_i = P_{cu}}$$

So the condition to achieve maximum efficiency is total Iron losses are equals to Full load Copper losses.

5) The full load copper and Iron losses of a 15 KVA, Single phase transformer are 320 W and 200 W respectively. Calculate the efficiency on (i) Full load (ii) Half load when the p.f is 0.8 lagging.

Sol. $P_i = 200\,W$ $\quad$ Full load $P_{cu} = 320\,W$, $\quad$ 15 KVA,

$$\%\,\eta = \frac{(\text{VA rating}) \times \cos\phi_2}{(\text{VA rating}) \times \cos\phi_2 + P_i + P_{cu}} \times 100 = \frac{15 \times 10^3 \times 0.8}{15 \times 10^3 \times 0.8 + 200 + 320} \times 100$$

$$= 95.84\,\%$$

For half load

$$\%\eta = \frac{\left(\frac{VA\,rating}{2}\right)\times\cos\phi_2}{\left(\frac{VA\,rating}{2}\right)\times\cos\phi_2 + P_i + \frac{P_{cu}}{4}} \times 100$$

$$= \frac{\left(\frac{15\times10^3}{2}\right)\times 0.8}{\left(\frac{15\times10^3}{2}\right)\times 0.8 + 200 + \frac{320}{4}} \times 100 = 95.54\%$$

Testing of Transformer

Transformer testing methods are used to know the performance i.e η and Voltage Regulation of a particular transformer at any load condition and at any load p.f.

→ These methods are also called indirect loading methods

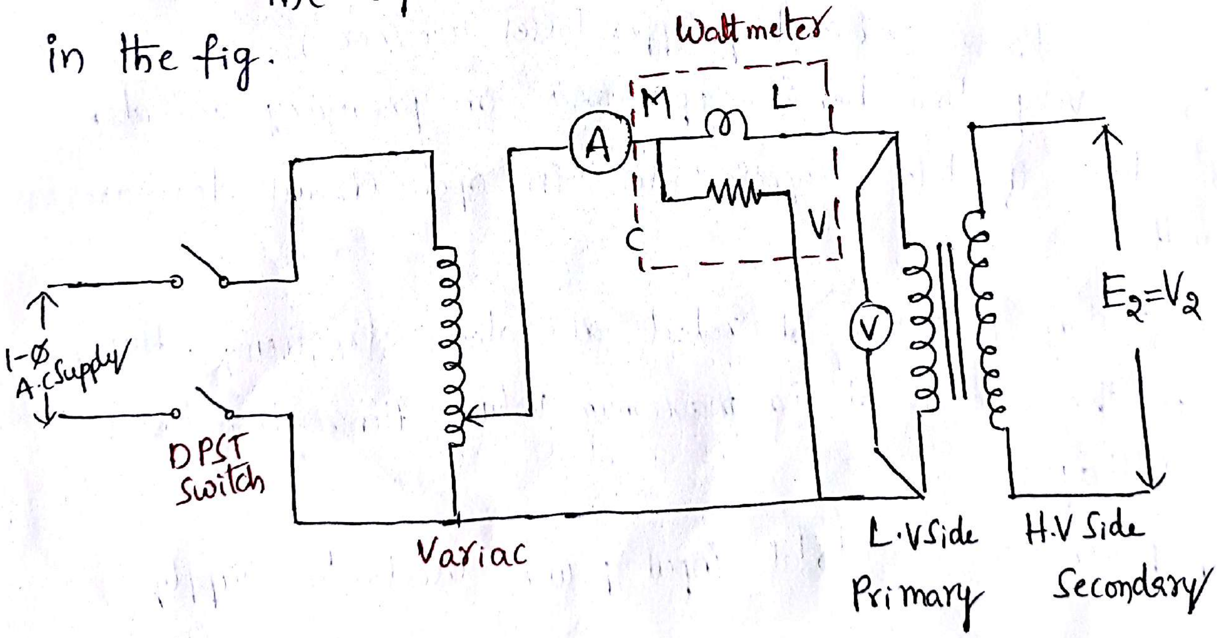
→ Indirect loading methods includes two tests on transformer which are.

(i) open circuit test (o.c test)

(ii) short circuit test (s.c test)

(i) open circuit test :- (No load Test)

The experimental circuit to conduct o.c test is shown in the fig.



The transformer primary is connected to a.c supply through Ammeter, wattmeter and Variac.

→ The secondary of transformer is kept open usually low voltage side is used as primary and high voltage side as secondary to conduct o.c test.

→ Primary is excited by rated voltage with the help of variac.

Wattmeter (W) → measure i/p power

Ammeter (A) → Measure input current

The voltmeter gives the value of rated primary voltage applied at rated frequency.

The observation table.

V_0	I_0	W_0
Rated		

V_0 = Rated voltage , W_0 = Input power

I_0 = No load current

→ The current drawn by the primary is no load current I_0

$$W_0 = V_0 I_0 \cos\phi_0$$

$$\cos\phi_0 = \text{No load P.f} = \frac{W_0}{V_0 I_0}$$

$$I_m = I_0 \sin\phi_0 \qquad I_w = I_0 \cos\phi_0$$

→ I_0 → 2 to 4% I_{FL}

$I_2 = 0$ (Secondary copper losses are zero).

and $I_1 = I_0$ is very low hence copper losses on primary are also very very low thus the total copper losses in open circuit test are negligibly small.

→ Input voltage is rated at rated at rated frequency. Hence flux density in the core is at its maximum value. Hence iron losses are at rated voltage.

→ O/p power = 0, so total input power used to supply iron losses.

Hence the wattmeter in o.c test gives iron losses

$$W_0 = P_i = \text{Iron losses}$$

Calculations:-

$$\cos\phi_0 = \frac{W_0}{V_0 I_0}$$

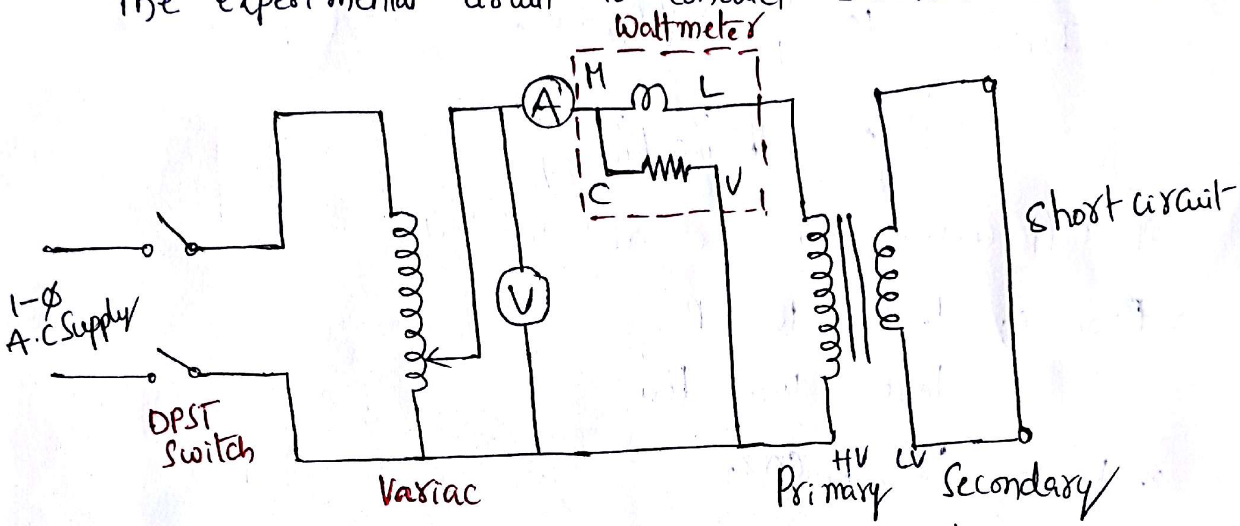
$$I_w = I_0 \cos\phi_0$$

$$I_m = I_0 \sin\phi_0$$

$$R_0 = \frac{V_0}{I_w}, \quad X_0 = \frac{V_0}{I_m}$$

short circuit test (S.C test) (or) Full load test

The experimental circuit to conduct S.C. test is shown below



The secondary is short circuited with the help of thick copper wire (or) solid link.

→ If we apply rated voltage it may draw very large current.

→ To limit this short circuit current, primary is supplied with low voltage which is just enough to cause rated current to flow through primary which can be observed on an ammeter.

→ The low voltage can be adjusted with the help of Variac. Hence this test is also called low voltage test. (or) Reduced voltage test.

observation table.

V_{sc}	I_{sc}	W_{sc}
	rated	

→ Hence full load copper losses occured

→ Small fraction of the rated voltage applied, so Iron losses are small and negligible

Hence the wattmeter in s.c test gives full load Copper losses

$$W_{sc} = P_{cu}$$

Calculations:

$$W_{sc} = V_{sc} I_{sc} \cos\phi_{sc}$$

$$\cos\phi_{sc} = \frac{W_{sc}}{V_{sc} I_{sc}}$$

$$W_{sc} = I_{sc}^2 R_{1e}$$

$$\boxed{R_{1e} = \frac{W_{sc}}{I_{sc}^2}}$$

$$Z_{1e} = \frac{V_{sc}}{I_{sc}} = \sqrt{R_{1e}^2 + X_{1e}^2}$$

$$\boxed{X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2}}$$

Calculation of Efficiency from o.c and s.c tests

From o.c test $W_o = P_i$

s.c test $W_{sc} = P_{cu}$

$$\% \eta = \frac{V_2 (I_2)_{FL} \cos\phi_2}{V_2 (I_2)_{FL} \cos\phi_2 + W_o + W_{sc}}$$

Calculation of Regulation

From s.c test we get

R_{1e} and X_{1e}

$$\% R = \frac{I_1 R_{1e} \cos\phi \pm I_1 X_{1e} \sin\phi}{E_1} \times 100$$

6) The following readings were obtained from o.c and s.c tests on 8 KVA, 400/120 V, 50 Hz transformer.

o.c test on LV Side	120V	4A	75W
s.c test on HV Side	9.5V	20A	110W

Calculate the voltage regulation and efficiency at full load, 0.8 p.f lagging?

Sol From o.c test $P_i = W_o = 75W$

s.c test $(P_{cu})_{FL} = 110W$

$V_{sc} = 9.5 \quad I_{sc} = 20\,A \quad W_{sc} = 110\,W$.

$$Z_{1e} = \frac{V_{sc}}{I_{sc}} = \frac{9.5}{20} = 0.475\,\Omega$$

$$R_{1e} = \frac{W_{sc}}{I_{sc}^2} = \frac{110}{(20)^2} = 0.275\,\Omega$$

$$X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2} = 0.3873\,\Omega$$

$$(I_1)_{FL} = \frac{VA}{V_1} = \frac{8\times10^3}{400} = 20\,A = I_{sc}$$

$\cos\phi = 0.8$, $\sin\phi = 0.6$

$$\%R = \frac{(I_1)_{FL}\left[R_{1e}\cos\phi + X_{1e}\sin\phi\right]}{V_1}\times100$$

$$= \frac{20\left[0.275\times0.8 + 0.3873\times0.6\right]}{400}\times100 = 2.2619\,\%$$

$$\%\eta = \frac{VA\cos\phi}{VA\cos\phi + P_i + P_{cu}}\times100$$

$$= \frac{8\times10^3\times0.8}{8\times10^3\times0.8 + 75 + 110}\times100 = 97.19\,\%$$

7) A 200/400 V, 50 Hz single phase transformer on test gave the fallowing readings:

O.C (LV) : 200 V , 0.7 A , 70 W

S.C (HV) : 15 V , 10 A , 80 W

Find % Regulation at 0.8 p.f lag at Full load ?

Sol

S.C test on H.V Side which is Secondary hence the parameters from S.C test will be referred to Secondary.

$V_{sc} = 15\,V$, $I_{sc} = 10\,A$

$W_{sc} = 80\,W$

$$Z_{2e} = \frac{V_{sc}}{I_{sc}} = \frac{15}{10} = 1.5\,\Omega$$

$$R_{2e} = \frac{80}{(10)^2} = 0.8\,\Omega$$

$$X_{2e} = \sqrt{Z_{2e}^2 - R_{2e}^2} = 1.2688\,\Omega$$

$(I_2)_{FL} = 10\,A$ and $V_2 = 400\,V$

$$\%R = \frac{I_{2FL}\left[R_{2e}\cos\phi + X_{2e}\sin\phi\right]}{E_2} \times 100$$

$\cos\phi = 0.8$, $\sin\phi = 0.6$ lag

$$= \frac{10 \times \left[0.8 \times 0.8 + 1.2688 \times 0.6\right]}{400} \times 100$$

$$= 3.503\,\%$$