Unit - II . TRANSFORMER

→ Transformer is a static device having coils coupled through a magnetic medium connecting two ports at different voltage level.

→ It is used for

i) changing voltage and current levels

ii) matching source and load impedance for maximum power transfer.

iii) Providing electrical isolation

Construction :-

→ It essentially consist of two insulated windings interlinked by a common (or) mutual magnetic field established in a core of magnetic material.

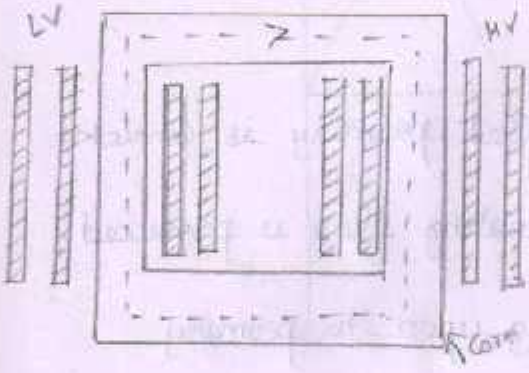
→ The main part is magnetic core which is made up of stack of thin lamination of cold rolled grain oriented silicon steel which allows the use of high flux densities and it has low loss properties.

→ The primary and secondary winding are wound on the core and are insulated from each other

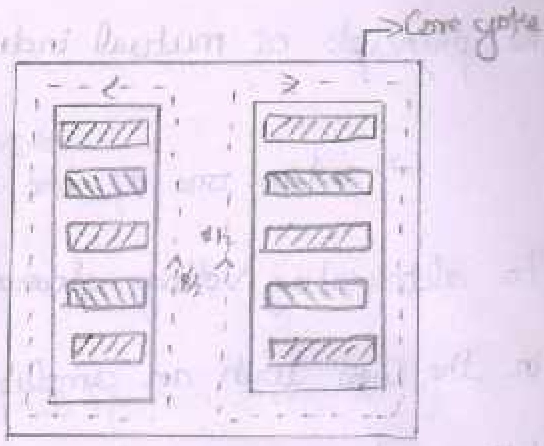
→ Two types of cores are there namely core type and shell type.

→ In core type, the windings are wound on the two legs of the rectangular magnetic core

-> In Shell type, the windings wound on the Central leg of a three legged Core



(Core type)



(Shell type)

-> The Core type Construction has longer mean length of core and shorter mean length of coil turn and it is suited for EHV lines

-> The Core type permits Visual inspection of coils and hence it Can be easily repaired in Case of faults

-> The Shell type has better mechanical support and good provision for bracing the windings but it requires more specialized fabrication facilities

-> Transformer windings are made of Solid (or) stranded Copper (or) aluminium strip Conductors

-> The Construction must be such that it Should have efficient removal of heat which is produced by Core and winding.

Principle of operation:

→ As the transformer has two interlinked windings which is interlinked by Common (or) magnetic field, it works based on the principle of mutual induction.

→ When one of the windings called primary is connected to alternating Voltage source, an alternating flux is produced in the Core with an amplitude depending upon the primary Voltage, frequency and number of turns.

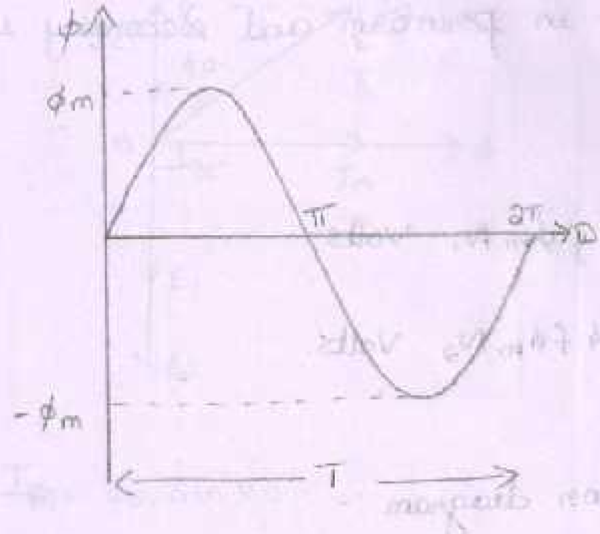
→ This mutual flux links the other winding called Secondary winding. Therefore a Voltage will be induced in the Secondary of the same frequency as the primary Voltage but their magnitude will depend upon the secondary turns.

→ When the number of primary and secondary turns are properly designed, any desired Voltage ratio can be achieved.

→ If the Secondary Voltage is greater than the primary Value, it is called step up transformer.

→ If the Secondary Voltage is less than the primary Value it is called Step down transformer.

EMF equation of transformer:



⇒ From Faraday's law of electromagnetic induction, the average e.m.f induced in each turn is proportional to the average rate of change of flux

$$\frac{d\phi}{dt} = \frac{\text{Change in flux}}{\text{Time required for change in flux}}$$

$$\frac{d\phi}{dt} = \frac{\phi_m - 0}{\left(\frac{1}{4f}\right)} = 4f\phi_m$$

Avg. emf per turn = $4f\phi_m$.

→ For sinusoidal quantity,

$$\text{Form factor} = \frac{\text{R.M.S Value}}{\text{Average Value}} = 1.11$$

R.M.S Value = 1.11 × Average Value.

∴ R.M.S value of induced e.m.f per turn = $1.11 \times 4f\phi_m$

$= 4.44 f\phi_m$

→ If there are N_1 primary turns and N_2 secondary turns, the induced e.m.f in primary and secondary is given by,

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

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

Transformer no load phasor diagram :-

⇒ Normally in transformer there will be iron core and hence it results in hysteresis and eddy current losses and so also there will be iron losses in transformer.

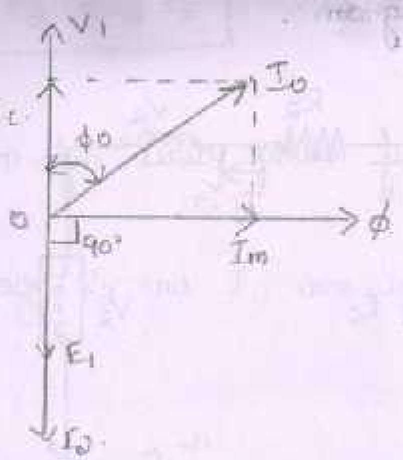
→ Therefore the primary current under no load condition must supply the iron loss and copper loss and the current is denoted by I_0.

$$\vec{I_0} = \vec{I_m} + \vec{I_c}$$

→ I_0 has two components namely magnetising component and core loss component.

→ Due to the presence of winding resistance, I_0 is no longer at 90° with respect to V_1 and it lags V_1 by a angle ϕ_0 which is less than 90°.

→ $\cos\phi_0$ is called no load power factor.



$I_m = I_0 \sin\phi_0$

$I_c = I_0 \cos\phi_0$

→ The magnitude of no load current is given by,

$$I_0 = \sqrt{I_m^2 + I_c^2}$$

→ The total power input is given by,

$$W_0 = V_1 I_0 \cos\phi_0$$

$$W_0 = V_1 I_c$$

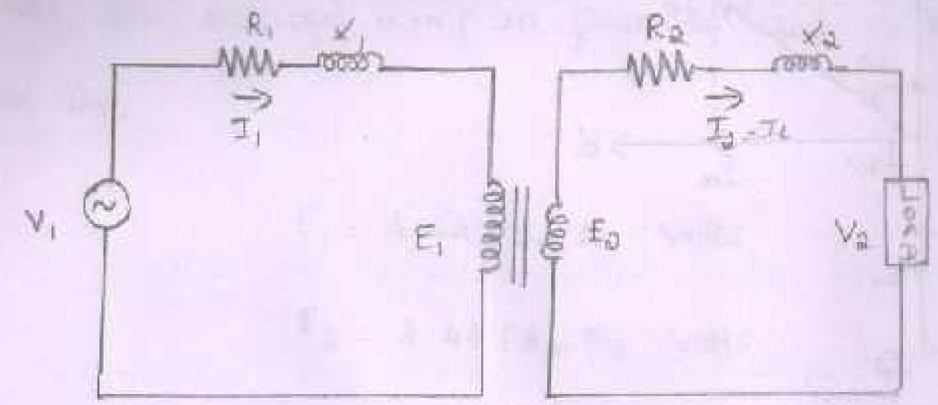
→ From the equations, it is cleared that, the current I_0 is very small for 3 to 5% of full load rated current which shows that, the W_0 on no load always represents iron loss and copper loss is very less.

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

$$= P_i$$

W_0 = iron loss

Transformer On load phasor diagram :-



→ $\overline{I_1} = \overline{I_0} + \overline{I_2'}$

where, I_0 = No load current.

$I_2' = KI_2$

→ The primary voltage V_1 has three components.

* $-E_1$ → induced emf which opposes V_1
* $I_1 R_1$ → drop across resistance
* $I_1 x_1$ → drop across reactance.

$$\overline{V_1} = -\overline{E_1} + \overline{I_1 R_1} + \overline{I_1 x_1}$$

$$= -\overline{E_1} + \overline{I_1}\,[R_1 + jx_1)$$

$$\boxed{\overline{V_1} = -\overline{E_1} + \overline{I_1 Z_1}}$$

→ The secondary voltage has three components.

* V_2 → terminal voltage
* $I_2 R_2$ → drop across resistance
* $I_2 x_2$ → drop across reactance

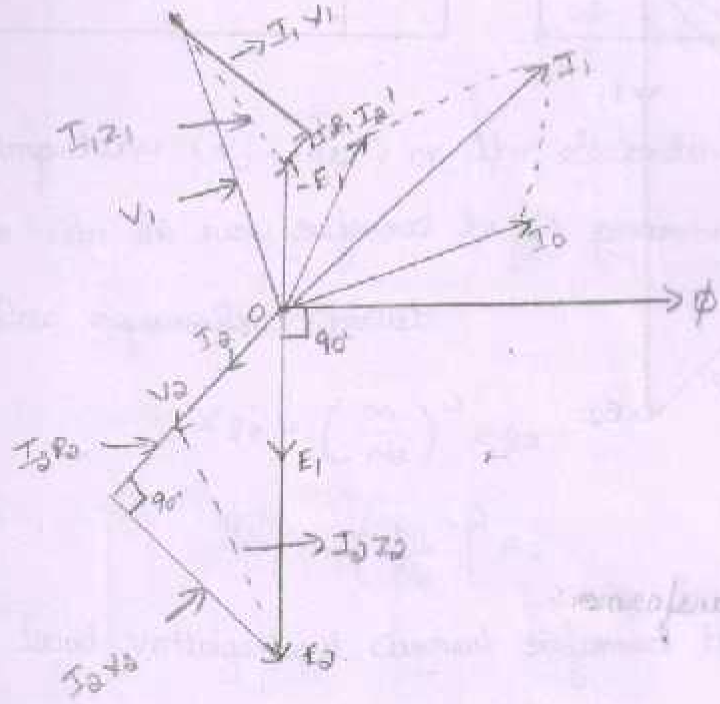
$$\overline{E_2} = \overline{V_2} + \overline{I_2 R_2} + \overline{I_2 x_2}$$

$$\overline{V_2} = \overline{E_2} - \overline{I_2}\,(R_2 + j x_2)$$

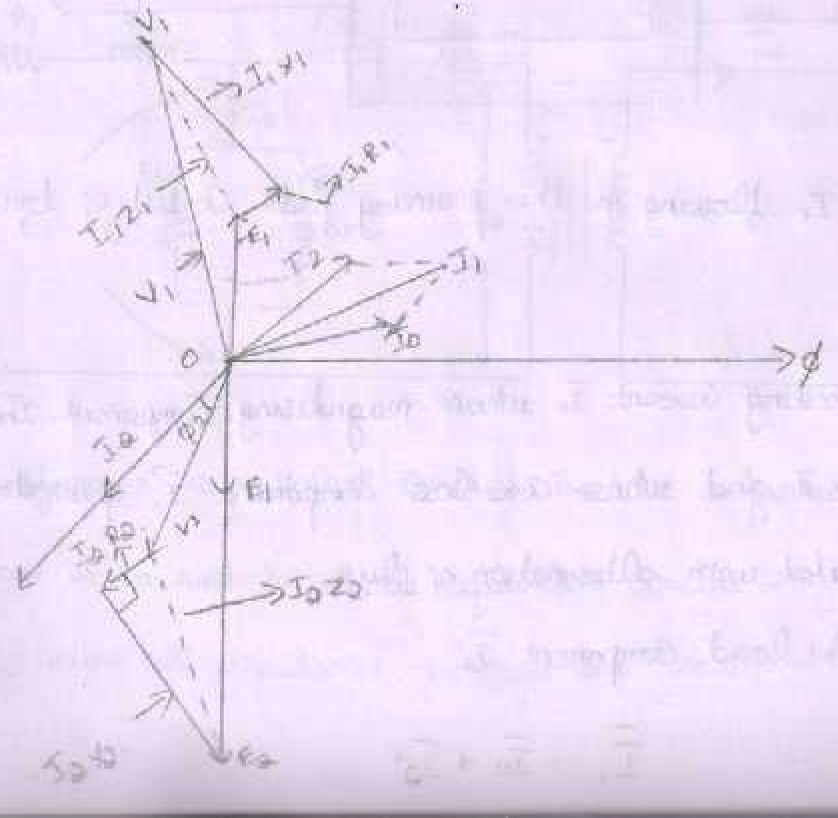
$$\overline{V_2} = \overline{E_2} - \overline{I_2 Z_2}$$

i) Phasor diagram for unity power factor load:

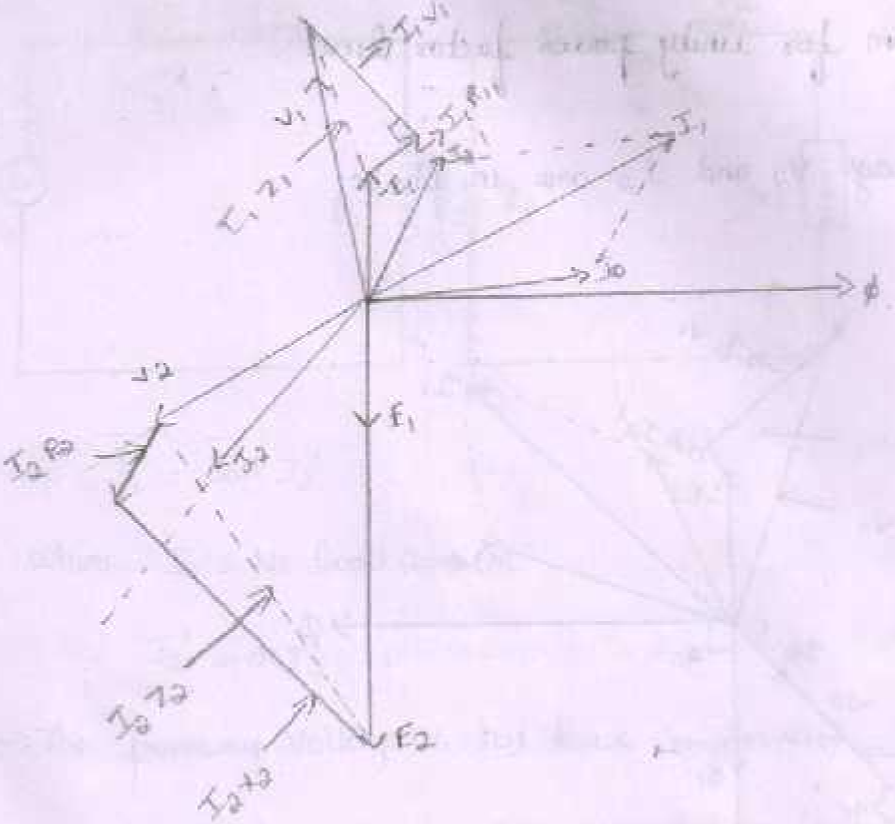
→ Voltage V_2 and I_2 are in phase



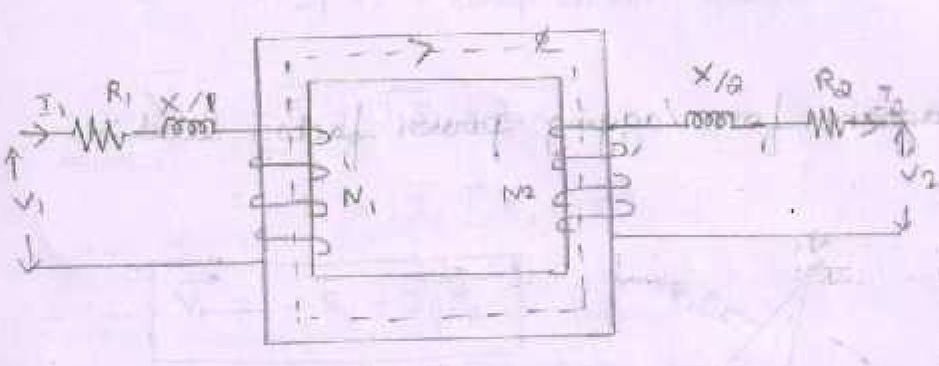
ii) Phasor diagram for Lagging power factor load:



Phasor diagram for leading power factor load:



Equivalent Circuit of Transformer:



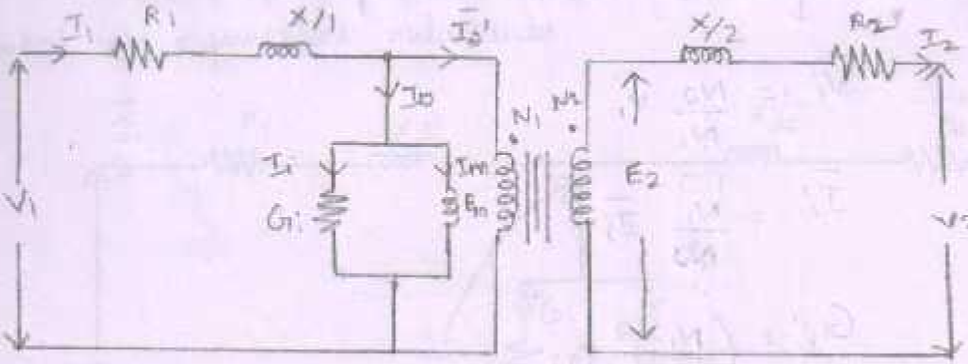
→ The I_1 flowing in the primary side consist of two components.

* Exciting current I_0 whose magnetising component I_m creates mutual flux $\bar{\phi}$ and whose core loss component $\vec{I_i}$ provide the loss associated with alternation of flux

* A load component $\bar{I_2'}$

$$\bar{I_1} = \bar{I_0} + \bar{I_2'}$$

$$\frac{\bar{I}_2'}{\bar{I}_2} = \frac{N_2}{N_1}$$



→ The impedance $(R_2 + jX_{l2})$ on the secondary side of the ideal transformer can be now referred to its primary side which results in the below equivalent circuit

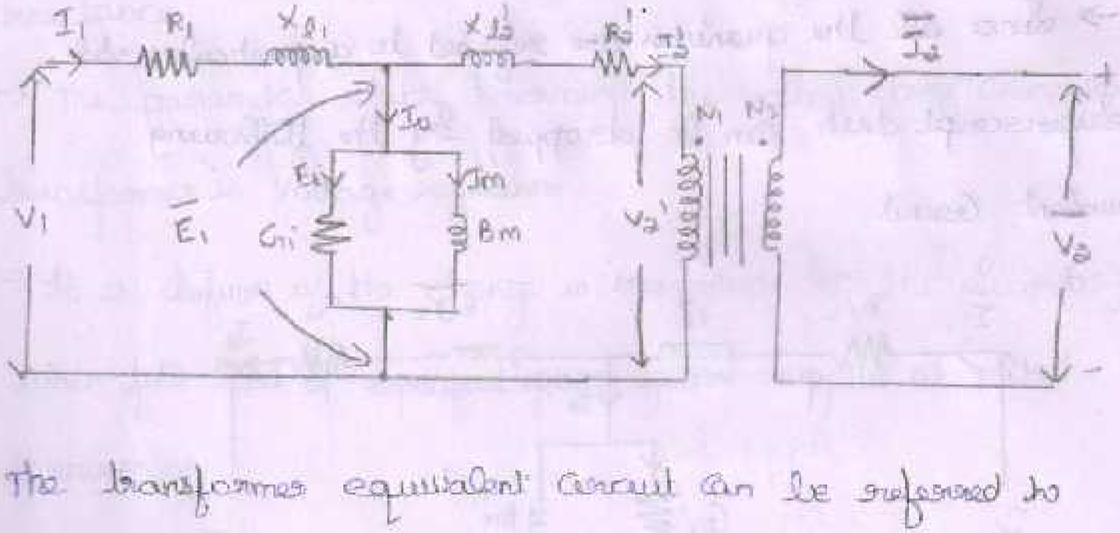
$$X_{l2}' = \left(\frac{N_1}{N_2}\right)^2 X_{l2}$$

$$R_2' = \left(\frac{N_1}{N_2}\right)^2 R_2$$

→ The load voltage and current referred to primary side are

$$\bar{V}_2' = \left(\frac{N_1}{N_2}\right)\bar{V}_2$$

$$\bar{I}_2' = \left(\frac{N_2}{N_1}\right)\bar{I}_2$$



→ The transformer equivalent circuit can be referred to side 2 since there is no need to show equivalent circuit referred to side 1 by transforming all impedances, voltages and currents to side 2.

→ It is noted that the admittances are transformed in the inverse ratio squared in contrast to impedances.

$$\bar{V_1}' = \frac{N_2}{N_1} \bar{V_1}$$

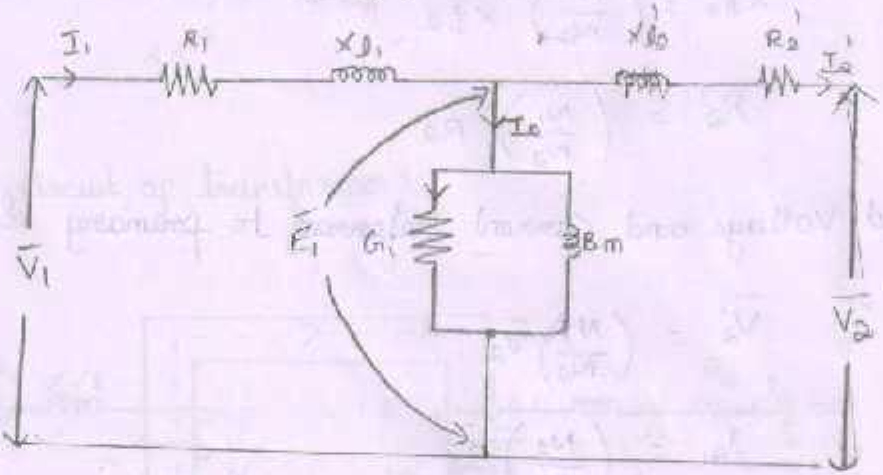
$$\bar{I_1}' = \frac{N_1}{N_2} \bar{I_1}$$

$$G_i' = \left(\frac{N_1}{N_2}\right)^2 . G_i$$

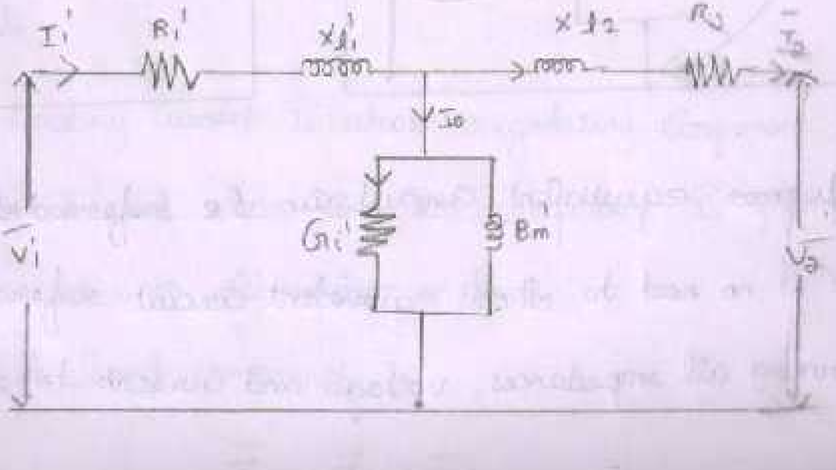
$$B_m' = \left(\frac{N_1}{N_2}\right)^2 B_m$$

$$R_2' = \left(\frac{N_2}{N_1}\right)^2 R_2'$$

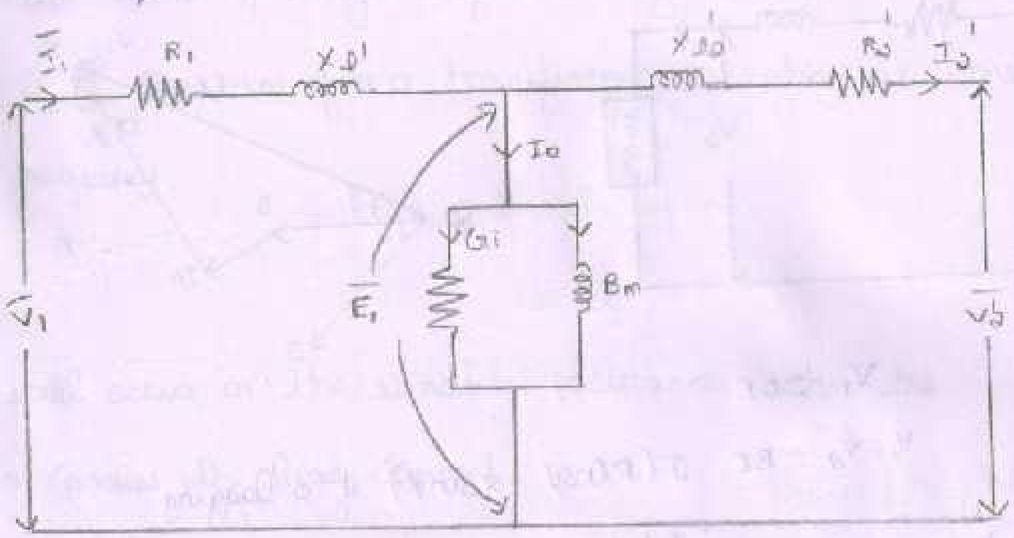
$$X_{l_1}' = \left(\frac{N_2}{N_1}\right)^2 X_{l_1}$$



→ Since all the quantities are referred to a particular side, a superscript dash can be dropped by the following equivalent circuit



→ The equivalent Circuit given below is Valid for Sinusoidal steady state analysis and for transient analysis, all reactance must be converted into equivalent inductance



Regulation of transformer:

→ For all the types of loads, it is necessary requirement of having Constant loads.

→ Therefore, the output Voltage of transformer must be within narrow limits when the load and the power factor Varies.

→ The Voltage drop in a transformer is determined by the leakage reactance.

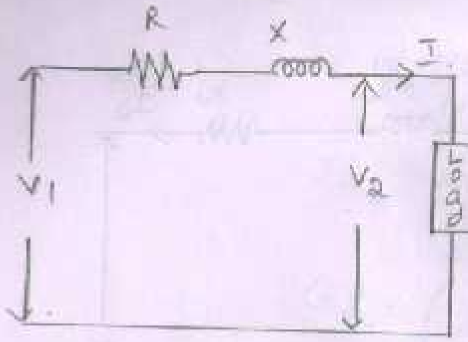
→ The parameter which determines the Voltage drop Characteristics of the transformer is Voltage regulation.

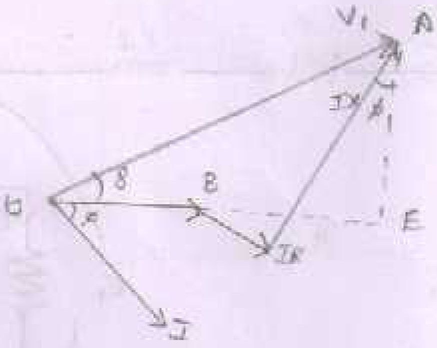
→ It is defined as the change in magnitude of the Secondary voltage, when full load of specified power factor supplied at rated voltage thrown off.

$$\% \text{ Voltage regulation} = \frac{V_{20} - V_{2fl}}{V_{2fl}} \times 100$$

→ $V_{2,fl}$ → rated Secondary Voltage

V_{20} : Secondary Voltage when load is thrown off.





$V_1 \simeq OE$

$V_1 - V_2 = BE = I(R\cos\phi + X\sin\phi)$ if ϕ lagging

$= I(R\cos\phi - X\sin\phi)$ if ϕ leading

→ when load is thrown off,

$V_{20} = V_1$

$V_{20} - V_2 = I(R\cos\phi \pm \sin\phi)$

$\%\ Vge\ Reg = \frac{V_{20} - V_2}{V_2} \times 100$

$= \frac{I(R\cos\phi \pm X\sin\phi)}{V_2} \times 100$

$\frac{IR}{V_2} = R(pu)$ & $\frac{IX}{V_2} = X(pu)$

∴ per unit Voltage regulation $= R(pu)\cos\phi \pm X(pu\ \cos\phi)$

Transformer losses :-

→ Core loss

→ Copper loss

→ Stray loss

→ Dielectric loss

Core loss:-

-> It Comprises of hysteresis and eddy Current loss which results from alternation of magnetic flux in the Core.

-> It is a Constant for a transformer operating at Constant voltage and frequency.

Copper loss:-

-> It will occur in the winding resistances when the transformer Carries the load Current.

-> This loss Varies as the square of the loading expressed as a ratio of full load.

Stray loss:-

-> It is the result from leakage fields which will induce the eddy Currents in the Conductors.

Dielectric loss:-

-> It is the due to the insulating materials.

-> The major losses in the transformer are the Core and Copper loss.

Efficiency:-

-> Since the transformer has no moving parts, their efficiency is higher than the rotating machines.

-> It is defined as the ratio of useful power output to the input power.

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

→ It is in the range of 96 - 99 %

→ The efficiency can be calculated by finding the losses by oc and sc tests.

$$\eta = \frac{\text{output}}{\text{output} + \text{losses}}$$

$$\eta = 1 - \frac{\text{losses}}{\text{output} + \text{losses}}$$

All day efficiency :-

→ It is the ratio of the total energy output (kwh) in a 24-h day to the total energy input in the same time.

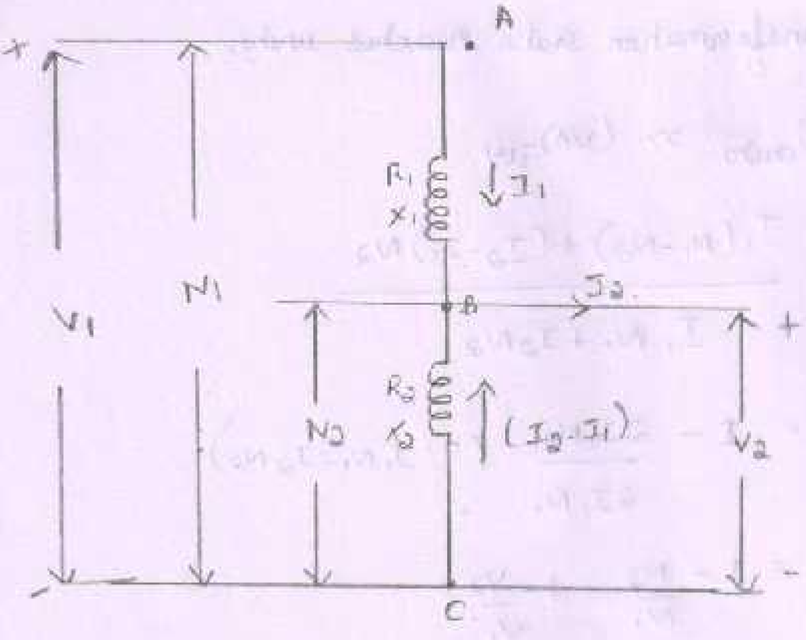
→ It is dependable upon the load cycle and it can't be predicted by the load factor.

→ It is an important parameter for distribution transformers which feed daily load cycle.

→ High efficiency is achieved by designing the transformer to give maximum power efficiency at less than the full load by decreasing the core flux density by increasing the core cross section

Auto transformer :-

→ when the primary and secondary winding are electrically connected so that a part of the winding is common to two is called auto transformer.



→ Its voltage ratio is less than 2.

→ It has N_1 turns primary with N_2 turns tapped for a lower voltage secondary.

→ The section BC of N_2 turns is common to both primary and secondary circuits.

→ Voltage and turns ratio is given by,

$$a' = \frac{V_1}{V_2} = \frac{N_1}{N_2} > 1.$$

$$a' = 1 + a \quad \left[a = \frac{V_1 - V_2}{V_2} = \frac{N_1 - N_2}{N_2} ;\ N_1 > N_2 \right)$$

$$(VA)_{TW} = (V_1 - V_2) I_1 = (I_2 - I_1) V_2 .$$

$$(VA)_{Auto} = V_1 I_1 - V_2 I_2$$

$$\therefore (VA)_{TW} = \left(1 - \frac{N_2}{V_1}\right) V_1 I_1$$

$$= \left(1 - \frac{N_2}{N_1}\right) (VA)_{auto}$$

$$\therefore (VA)_{auto} > (VA)_{TW}$$

→ when the transformation ratio reaches unity,

$$(VA)_{auto} \gg (VA)_{TW}$$

→ $$\frac{G_{auto}}{G_{TW}} = \frac{I_1(N_1 - N_2) + (I_2 - I_1)N_2}{I_1 N_1 + I_2 N_2}$$

$$= 1 - \frac{2 I_1 N_2}{2 I_1 N_1} \quad (\because I_1 N_1 = I_2 N_2)$$

$$= 1 - \frac{N_2}{N_1} = 1 - \frac{V_2}{V_1}$$

$$G_{TW} - G_{auto} = \frac{1}{a'} \times G_{TW}$$

→ If $a' = 1.1$, we can save upto 90% and hence the ratio must be close to unity.

Advantage:

→ Lower reactance

→ Lower losses

→ Smaller exciting current

→ Better voltage regulation.

Application:

→ Induction motor starters

→ Interconnection of HV systems.

Cont-2 Completed 30/6/16.