# UNIT - III

# TRANSFORMERS

## * Necessity of Transformer :-

The generation, transmission and distribution of AC Electric power take place at different voltage levels. These changes in the voltage levels in the power system are provided by using stationary machines, known as transformers.

## * Definition of Transformer:

A Transformer is defined as a static Electromagnetic device which transforms an AC Electrical power from one Electrical circuit to another with a desired change in the voltage level with out change in the supply frequency with out any Electrical connection between the two circuits.

## * Highly Efficient Device :-

Due to the absence of moving parts in the transformer, it has no frictional losses and hence it has a very high Efficiency of the order of 97% to 98%. So the transformer is supposed to be the highly Efficient device.

## * Applications of Transformers :

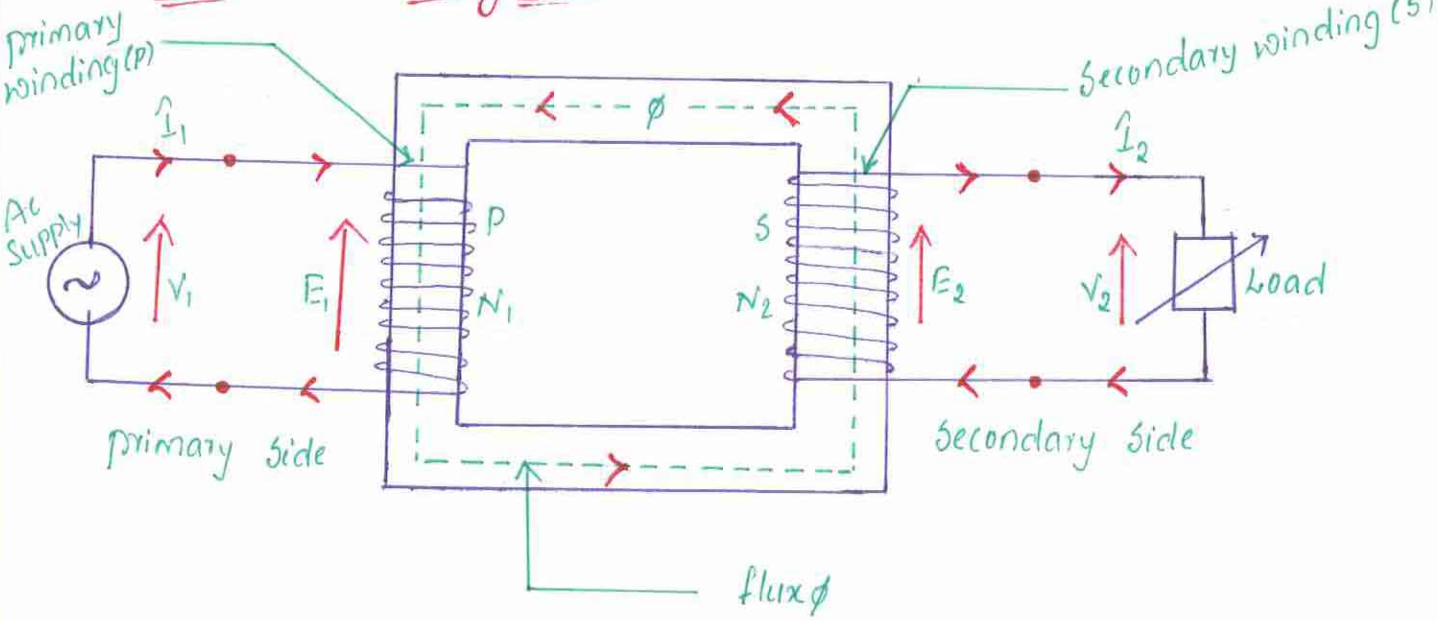
- * Basically transformers are used in A.C power systems to change the voltage levels between the two circuits.
- * The Transformer can be used for phase shift, change in number of phases e.t.c.

## * Classification Of Transformer:

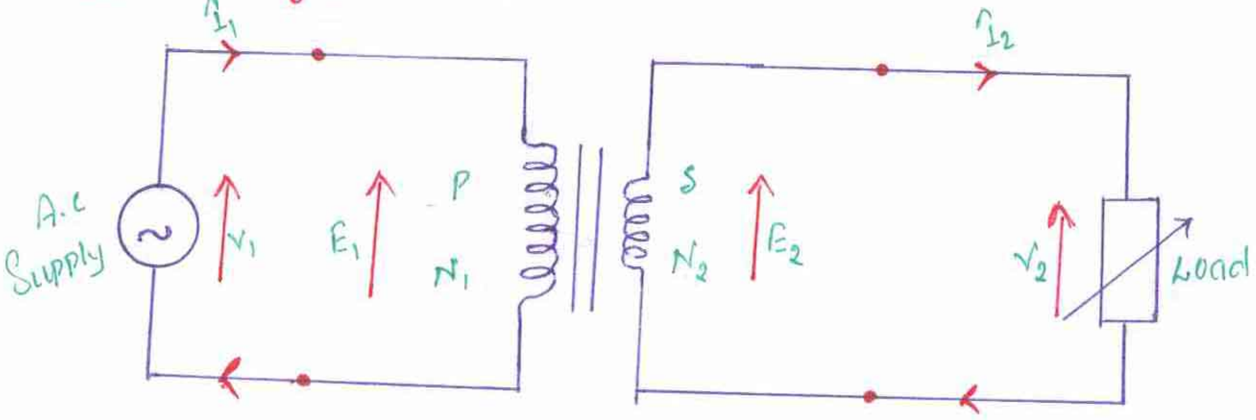
- * Depending upon the change in voltage levels transformers are classified into two types
  - * Setp-up transformer
  - * Step-down transformer.
- * Depending upon the construction
  - * Core type transformer
  - * Shell type transformer
- * Depending upon the Number Of phases.
  - * 1ø Transformer
  - * 3ø Transformer.

## * principle Of operation Of Transformer:-

### * Schematic Arrangement:-



### * Circuit Diagram:-



## * Construction of Transformer:-

* the Schematic Arrangement of a Single-phase transformer is shown in the fig:-

* it Essentially consists of a laminated rectangular Magnetic core & two windings wound on it.

* one winding is connected to A.c supply known as the primary winding. the other winding is connected to load known as secondary winding.

* there is no Electrical connection between primary and secondary.

* the Number of primary & Secondary windings are denoted by "$N_1$" & "$N_2$" respectively.

## * Working principle :-

* The transformer works on the principle of Electromagnetic induction [Mutual induction]. it is according to faraday's law of Electromagnetic induction.

* The two windings of Transformer are Electrically Seperated but they are linked by a common Mutual flux because they are wound on the same magnetic core of very low reluctance.

* when an AC supply of alternating voltage "$V_1$" is given to the primary winding, alternating current "$I_2$" is produced in it. ~~thus the Electrical power~~ This current set up an alternating flux "f" in the core.

- This flux is linked with the secondary winding to produce mutually induced Emf in it according to the faraday's law of Electromagnetic induction.

- When a load is connected across the secondary, the secondary induced E.m.f "$E_2$" circulates current "$I_2$" through it.

- Thus the Electrical power is transferred Magnetically or inductively from primary circuit to secondary circuit with out any Electrical connection between them.

* Primary and Secondary Emf's :

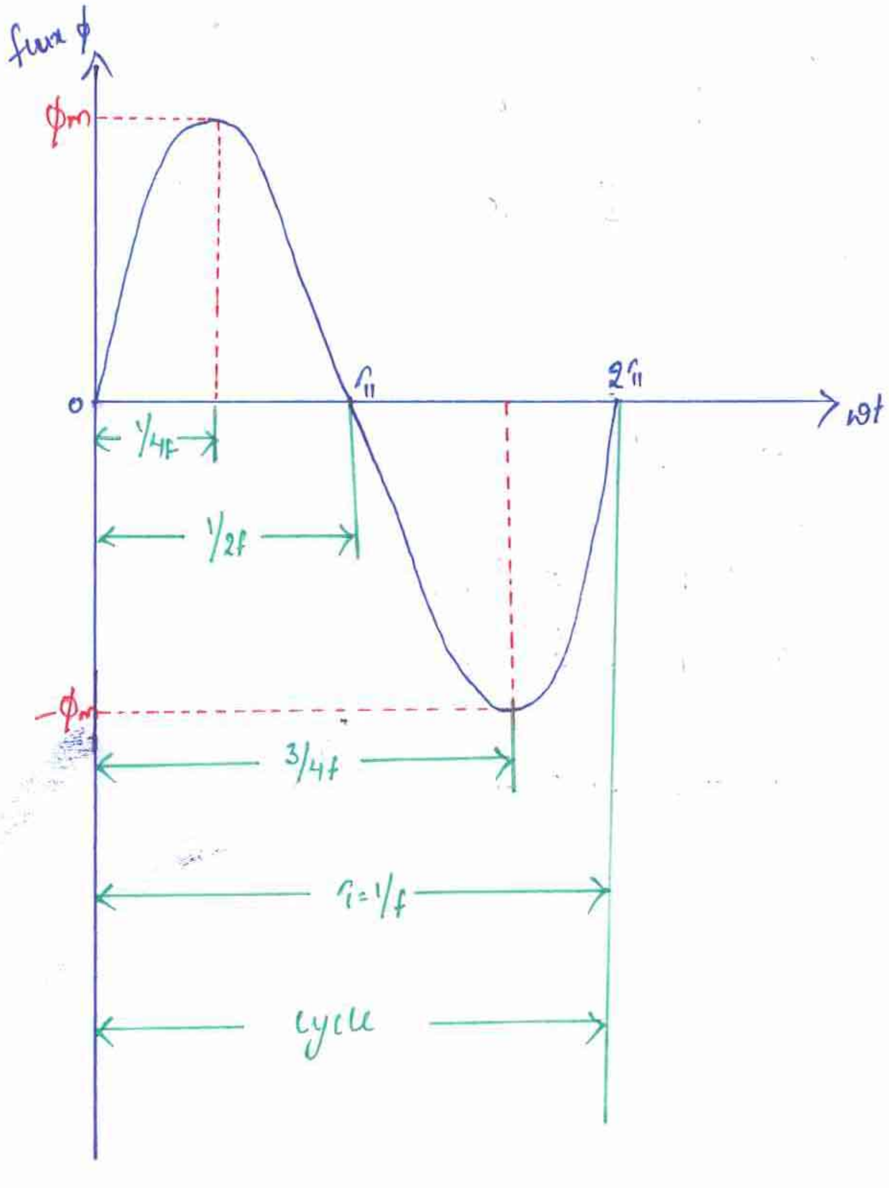
- The common alternating flux is linked with both the windings & hence the Emf's "$E_1$" & "$E_2$" are statically induced in primary & Secondary windings respectively According to the faraday's law of Electro magnetic induction.
- "$E_1$" is the Slef - induced EMF which opposes primary supply voltage "$V_1$" according to the Lenz's law. "$E_2$" is the Mutually induced Emf. The frequency of "$E_1$" & "$E_2$" is same as that of Mutual flux. i.e, Supply frequency "f".

## * E.M.F Equation of Transformer :-

It is seen in fundamental principle of transformer that the alternating sinusoidal supply voltage "V" circulates sinusoidal alternating current "$I_1$" & set up sinusoidally varying flux "f" in the core.

this alternating flux links primary & secondary windings to induce sinusoidal self-induced emf "$E_1$" in primary & Mutually - induced emf "$E_2$" in secondary.

### Derivation of E.M.F Equation :-



the above fig: shows the sinusoidally varying flux produced by the sinusoidal primary current.

Let

$\phi = \phi_m \sin \omega t$ = instantaneous value of flux in webers

$\phi_m$ : maximum value of flux in webers.

$f$ : Supply frequency in Hz

$N_1$ : Number of primary turns

$N_2$ : Number of Secondary turns.

$E_1$ : Rms value of primary induced E.M.F

$E_2$ : Rms value of secondary induced E.M.F

$E_t$ : Rms value of Emf per turn.

The average Emf induced in Each turn of the winding is Equal to the average rate of change of flux linking the winding, according to faraday's law of Electromagnetic induction.

$\therefore$ Average Emf / turn = Average rate of change of flux $= \frac{d\phi}{dt}$

$$\therefore \frac{d\phi}{dt} = \frac{\text{Change in flux}}{\text{Time for Change in flux.}}$$

from the fig, the change in flux from 0 to $\phi_m$, the time required is $1/4f$ seconds

$$\therefore \text{Average Emf/turn} = \frac{d\phi}{dt} = \frac{\phi_m - 0}{1/4f} = 4f\phi_m \text{ wb/sec (or) Volts}$$

As the flux & Emf, both are sinusoidal

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

R.M.S Value = 1.11 x Average Value.

$\therefore$ R.M.S Emf / turn = 1.11 x Average Emf / turn

$= 1.11 \times 4 f \phi_m$

$E_t = 4.44 f \phi_m$

$\therefore$ As primary winding consists of "$N_1$" turns

primary emf : $E_1 = E_t \times N_1$

$= 4.44 \phi_m f N_1$

secondary Emf : $E_2 = E_t \times N_2$

$= 4.44 \phi_m f N_2$

$\therefore$ Emf Equation of transformer is given by

$$E_1 = 4.44 \phi_m f N_1$$

$$E_2 = 4.44 \phi_m f N_2$$

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## * Voltage transformation Ratio:

* **Turns Ratio :** the ratio of number of secondary turns "$N_2$" to the number of primary turns "$N_1$" is known as the turns ratio & it is denoted by "K"

$$\therefore \quad K = \frac{N_2}{N_1}$$

* **EMF ratio:** it is defined as the ratio of Secondary induced emf "$E_2$" to the primary induced emf "$E_1$".

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

* **Voltage Ratio:** the ratio of secondary load voltage "$V_2$" to the primary supply voltage "$V_1$" is known as the voltage ratio.

generally the primary and secondary windings have resistances "$R_1$" & "$R_2$" & leakage reactances "$x_1$" & "$x_2$" respectively. therefore they have respective impedance "$Z_1$" and "$Z_2$". when the transformer is supplied at the primary & loaded on the secondary side, the primary & secondary windings carry currents "$I_1$" & "$I_2$" respectively & produce respective voltage drops "$I_1 Z_1$" & "$I_2 Z_2$" in their impedances.

Therefore, the primary induced emf "$E_1$" differs from primary voltages "$V_1$" by "$I_1 Z_1$" drop. similarly the secondary induced emf "$E_2$" differs from secondary voltage "$V_2$" by "$I_2 Z_2$" drop.

The impedances "$Z_1$" & "$Z_2$" being small, the voltage drops "$I_1 Z_1$" & "$I_2 Z_2$" may be neglected.

Then $E_1 = V_1$ and $E_2 = V_2$

$$\therefore \text{Voltage ratio} : \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

* **Current ratio:** The ratio of Secondary Current "$I_2$" to the primary Current "$I_1$" is known as the Current ratio.

In case of an ideal transformer, the power loss in the transformer is zero. Hence the i/p primary power is Equal to the o/p Secondary power.

$$\therefore V_1 I_1 \cos\phi_1 = V_2 I_2 \cos\phi_2$$

under ideal Condition, the primary & Secondary powerfactors are Equal.

$$\cos\phi_1 = \cos\phi_2$$

$\therefore V_1 I_1 = V_2 I_2$ i.e, primary VA = Secondary VA

$$\therefore \text{Current ratio} : \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$$

Current ratio is inverse of voltage ratio

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

* **Voltage transformation Ratio:**

In general, the Emf ratio or voltage ratio is known as the voltage transformation ratio. and is denoted by "K".

It is Equal to turns ratio or inverse Current ratio.

## * Voltage regulation of Transformer :

### * Introduction to Regulation :-

* when a transformer is loaded on secondary side, keeping the primary voltage strictly constant, the voltage drop takes place in the primary & secondary impedances.

* ∴ The secondary voltage changes from no load to full load even though the primary voltage is held constant.

* The secondary voltage decreases from no load to full load for lagging and unity power factor but it may increases in case of leading power factor. as shown by $V_2 - I_2$ characteristics in fig: ⓐ.

* Regulation is a term which considers the changes in the secondary terminal voltage due to load.

* it considers the numerical difference between the secondary voltages at no load & full load.

* ideally the secondary voltage should not changes with load. it should remain constant. In practice, the change in secondary voltage with load should be small.

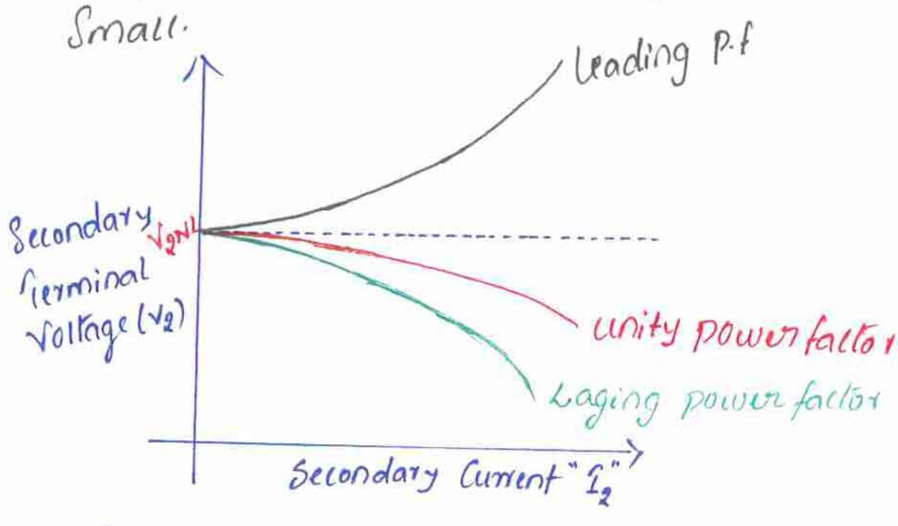


fig: ⓐ $V_2 - I_2$ characteristics

*** Definition Of Regulation :-**

A regulation is defined as the Change in the Secondary voltage from no load to full load, Expressed as a fraction of Either a no load secondary voltage or a full load secondary voltage, when the primary voltage is held constant.

The primary supply voltage "$V_1$" is necessarily mained constant because all the loading devices, Equipment & Electrical machines including transformer are designed to operate at the constant rated voltage.

*** per unit regulation:-** if the Change in Secondary voltage is Expressed as a fraction of the rated secondary voltage the corresponding regulation is Called per unit regulation.

*** percentage Regulation:-** if the Change in Secondary voltage is expressed as a percentange of the rated Secondary voltage, the Corresponding regulation is Called percentage regulation.

$$\% \text{ Regn} = \text{p.u. Regn} \times 100$$

*** Down Regulation :-** for a constant primary voltage "$V_1$", if the change in the Secondary voltage is Expressed as a fraction or percentage of the no load Secondary voltage, then the regulation is known as down Regulation.

$$\therefore \text{per unit regulation (down)} = \frac{\text{No load Secondary voltage} - \text{full load Secondary voltage}}{\text{No load Secondary voltage}}$$

$$\therefore \text{per unit regulation (down)} = \frac{V_{2(NL)} - V_{2(FL)}}{V_{2(NL)}}$$

$$\text{percentage regulation (down)} = \frac{V_{2(NL)} - V_{2(FL)}}{V_{2(NL)}} \times 100$$

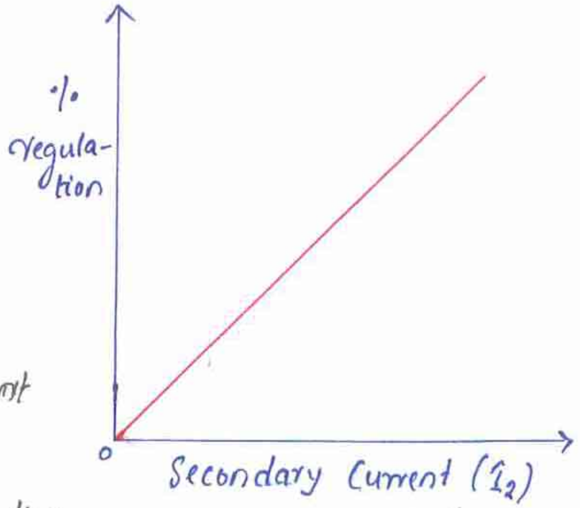
* **up regulation :-** for the constant primary voltage "$V_1$", if the change in the secondary voltage is expressed as a fraction or percentage of the full load secondary voltage, then the regulation is known as up regulation.

$$\text{per unit regulation}_{(up)} = \frac{V_{2(NL)} - V_{2(FL)}}{V_{2(FL)}}$$

$$\text{\% of regulation}_{(up)} = \frac{V_{2(NL)} - V_{2(FL)}}{V_{2(FL)}} \times 100$$

* for inductive & resistive loads i.e, for lagging & unity power factor, regulation is "+ve" due to decrease in "$V_2$" with load and for capacitive load i.e, for leading powerfactor regulation may be negative due to increase in "$V_2$" & load.

## * Characteristics of Regulation:



* the Characteristics Shown in the fig: are the regulation Char:
* it is a Curve of regulation Versus load Current "$I_2$".
* thuse the Magnitude of load Current regulation increases with the load.
* generally the full load Current is the important Quantity in the performance of the transformer.
* from the above discussion, it is Seen that the Change in the Secondary voltage depends on two important factors.
  * Load i.e, Secondary load Current "$I_2$"
  * Load P.f i.e, " power factor $\cos\phi_2$

## * Zero regulation:

* At a Certain capacitive load i.e, at Certain leading power factor, the regulation on the transformer can be zero.
* That means the transformer can produce the Same no load secondary voltage at the load Condition with a praticular leading power factor.

## * Approximate voltage regulation:

### * Voltage regulation for inductive Load [ lagging p.f $\cos\phi$ ]:

$$\% \text{ regulation} = \frac{V_1 - V_2'}{V_1} \times 100 = \frac{I_1 R_{01} \cos\phi + I_1 X_{01} \sin\phi}{V_1} \times 100$$

$$= \left[\frac{I_1 R_{01}}{V_1} \times 100\right] \cdot \cos\phi + \left[\frac{I_1 X_{01}}{V_1} \times 100\right] \cdot \sin\phi$$

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

$$\% \text{ regulation} = \frac{V_1' - V_2}{V_1'} \times 100 = \frac{I_2 R_{02} \cos\phi + I_2 X_{02} \sin\phi}{V_1'} \times 100$$

$$= \left[\frac{I_2 R_{02}}{V_1'} \times 100\right] \cdot \cos\phi + \left[\frac{I_2 X_{02}}{V_1'} \times 100\right] \cdot \sin\phi$$

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

## * Voltage regulation for purely Resistive Load [unity p.f $\cos\phi = 1$] :-

$$\% \text{ regulation} = \frac{I_1 R_{01}}{V_1} \times 100 = \frac{I_2 R_{02}}{V_1'} \times 100 = V_r$$

$[\because \cos\phi = 1 \ \& \ \sin\phi = 0]$

## * Voltage regulation for Capacitive load [Leading p.f $\cos\phi$] :-

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

$$= \frac{I_2 R_{02} \cos\phi - I_2 X_{02} \sin\phi}{V_1'} \times 100$$

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

* In general

$$\% \text{ regulation} = \frac{V_1 - V_2'}{V_1} \times 100 = \frac{V_1' - V_2}{V_1'} \times 100$$

$$= \frac{I_1 R_{01} \cos\phi \pm I_1 X_{01} \sin\phi}{V_1} \times 100 \ ; \ = \frac{I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi}{V_1'} \times 100$$

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

* where "+" sign for lagging p.f * "−" for leading p.f

## * Zero voltage regulation :-

* it is seen the regulation is "+ve" for lagging and unity p.f & regulation can be "-ve" for leading p.f.

* so there can be a certain leading p.f for the given full load condition at which the regulation is zero.

for zero voltage regulation

$$\% \text{ regulation} = 0 = V_r \cos\phi - V_x \sin\phi$$

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

$$\frac{\sin\phi}{\cos\phi} = \frac{V_r}{V_x} = \frac{I_1 R_{01}}{I_1 X_{01}} = \frac{I_2 R_{02}}{I_2 X_{02}} = \frac{R_{01}}{X_{01}} = \frac{R_{02}}{X_{02}}$$

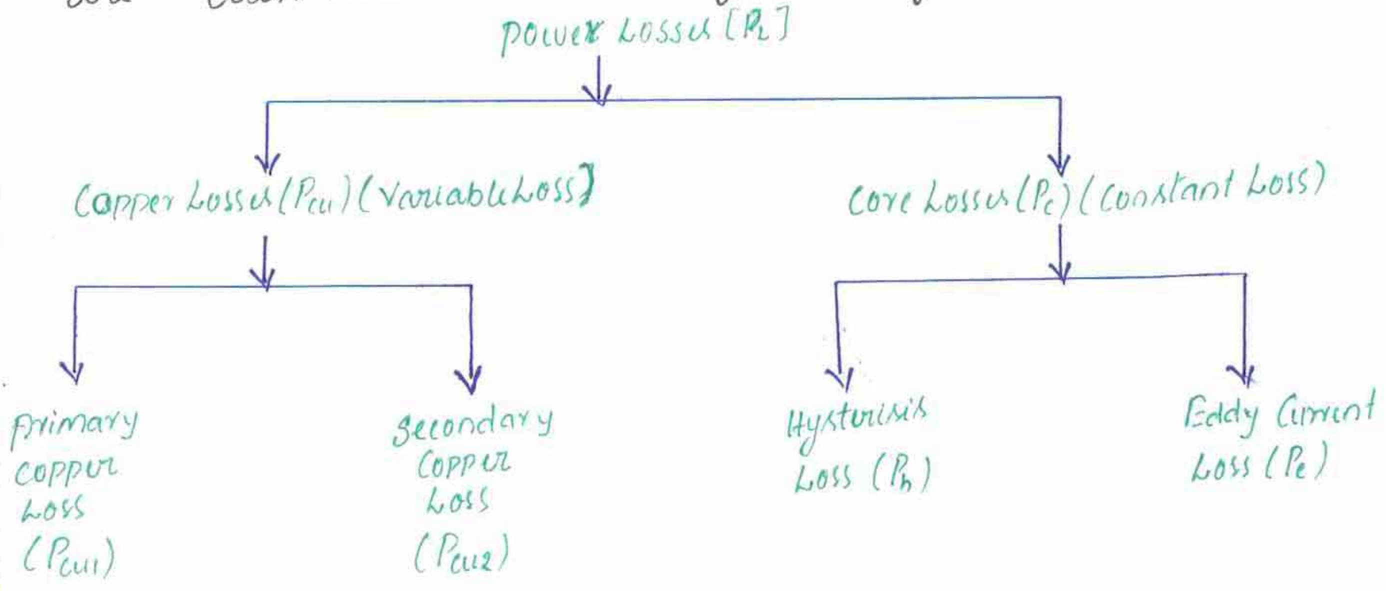
$$\therefore \tan\phi = \frac{V_r}{V_x} = \frac{R_{01}}{X_{01}} = \frac{R_{02}}{X_{02}}$$

Then the leading p.f for zero regulation is given by

$$\cos\phi = \cos\left[\tan^{-1}\left(\frac{V_r}{V_{x_0}}\right)\right] = \frac{X_{01}}{Z_{01}} = \frac{X_{02}}{Z_{02}}$$

## * Losses in a transformer :-

A practical transformer has very small power losses due to absence of moving parts & frictional loss. So it is highly efficient device. The total power losses of the transformer are classified into two groups given below.



* Copper Loss ($P_{cu}$) :- This power loss is Variously Known as resistive loss, Electrical loss, $I^2R$ loss or Variable loss it is further Sub-divided into two parts.

* primary Copper loss ($P_{cu1}$) :- it is produced due to the primary winding resistance "$R_1$" while Carrying Current "$I_1$". it is given by

$$P_{cu1} : I_1^2 R_1 \text{ watts.}$$

* Secondary Copper Loss ($P_{cu2}$) :- it is produced due to the 2ndary winding resistance "$R_2$" while Carrying Current "$I_2$". it is given by

$$P_{cu2} : I_2^2 R_2 \text{ watts.}$$

Referring all the winding resistance to primary or Secondary, the total Copper loss is given by.

$$\text{Total copper loss} = P_{cu} = P_{cu1} + P_{cu2} : I_1^2 R_1 + I_2^2 R_2$$
$$: I_1^2 (R_1 + R_2') = I_2^2 (R_2 + R_1')$$
$$: I_1^2 R_{01} = I_2^2 R_{02}$$

From the above Equations, the copper loss is proportional to the Square of the Current or load.

$$\therefore P_{cu} \propto I^2 \propto KVA^2$$

Hence the copper losses are called the Variable losses.

* Core Loss ($P_c$) :-

This loss is produced in Magnetic Core of the transformer due to the alternating flux. it is Variously known as the iron loss, magnetic loss or constant loss. it is further Sub divided into two parts.

* hysteresis Loss ($P_h$) :- this loss takes place in the Magnetic core of the transformer due to the cycles of Magnetisation of the alternating flux. it is given by.

$$P_h : K_h . v. f . B_M^{1.6} \text{ watt's}$$

where $K_h$ : Steinmetz Constant of hysteresis
$v$ : Volume of Core in $m^3$
$f$ : frequency of Current or magnetisation in Hz
$B_m$ : maximum flux density "$B_m$" in tesla

this loss is constant because, for a particular i/f Core, constant $K_h$, volume of core $v$, Frequency "f" & maximum flux density "$B_m$" are constant.

## * Eddy Current Loss ($P_e$) :-

this loss takes place in the magnetic core of the transformer due to the eddy Currents induced in the core by linking the alternating flux. it is given by

$$P_e = K_e \cdot f^2 . B_m^2 t^2 v \quad \text{watts.}$$

where, $K_e$ : Constant which depends on core material
$f$ : Supply frequency
$B_m$ : maximum flux density
$t$ : thickness of the core
$v$ : volume of the core.

∴ Total core losses are given by

$$P_c : P_h + P_e$$

## * Total losses :- ($P_L$)

Total losses $P_L : P_{cu} + P_c$

Hence the KVA Rating of Transformer depends on the losses and temperature rise.

## * Efficiency of a Transformer :-

**Definition:** Just Similar to the Efficiency of other Electrical machines, the Efficiency of the transformer is defined as the ratio of Output power to the input power at a Specific load its power factor.

the input power is the primary power taken from Supply and the Output power is the Secondary power delivered to the load. Due to the power losses in the transformer, Output power < input power.

$\therefore$ Efficiency is less than unity i.e, $\% \eta < 100\%$.

Output power $P_0$ : Secondary power $P_2$
: input power $P_i$ - Losses $P_L$
: primary power $P_1$ - Losses $P_L$

Input power $P_i$ : primary power $P_1$
: Output power $P_0$ + Losses $P_L$
: Secondary power $P_2$ + Losses $P_L$

## * Output power :

it is the Secondary power "$P_2$" delivered to the load. it is measured in watts or kw.

$$\therefore \quad P_0 : P_2 : V_2 I_2 \cos\phi_2$$

As the voltage "$V_2$" & load p.f $\cos\phi_2$ are constant for a particular load.

$P_0$ or $P_2 \propto I_2 \propto V_2 I_2 \propto VA \propto$ Load.

* **Input power ($P_i$):**

it is the primary power "$P_1$" received from the Supply. it is also measured in watts or kw.

$$P_i = P_1 = V_1 I_1 \cos\phi_1$$

In this case also, $V_1$ and $\cos\phi_1$ being constant

$$P_i \text{ or } P_1 \propto V_1 I_1 \propto I_1 \propto \text{Load} \propto VA.$$

* **Total losses [$P_L$]:**

Total losses are given by

$$\begin{aligned} P_L &= P_i - P_0 = P_1 - P_2 = P_{cu} + P_c \\ &= [P_{cu1} + P_{cu2}] + [P_h + P_e] \\ &= [I_1^2 R_1 + I_2^2 R_2] + P_c \\ &= I_1^2 R_{01} + P_c \\ &= I_2^2 R_{02} + P_c \\ &= \text{Variable loss} + \text{constant loss} \end{aligned}$$

* **Efficiency:** Effiency of the transformer may be difined as the secondary power divided by primary power at particular load & power factor.

$$\% \text{ Effiency} = \frac{\text{Secondary power } (P_2)}{\text{primary power } (P_1)} \times 100$$

But $P_2 = P_1 - P_L$

$$\% \eta = \frac{P_1 - P_L}{P_1} \times 100 = \frac{P_1 - [P_{cu} + P_c]}{P_1} \times 100$$

$$\therefore \% \eta = \frac{V_1 I_1 \cos\phi_1 - P_{cu} - P_c}{V_1 I_1 \cos\phi_1} \times 100$$

$$P_1 = P_2 + P_L$$

$$\therefore \% \eta = \frac{P_2}{P_2 + P_L} \times 100 = \frac{P_2}{P_2 + (P_{cu} + P_c)} \times 100$$

$$\therefore \% \eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_{cu} + P_c} \times 100$$