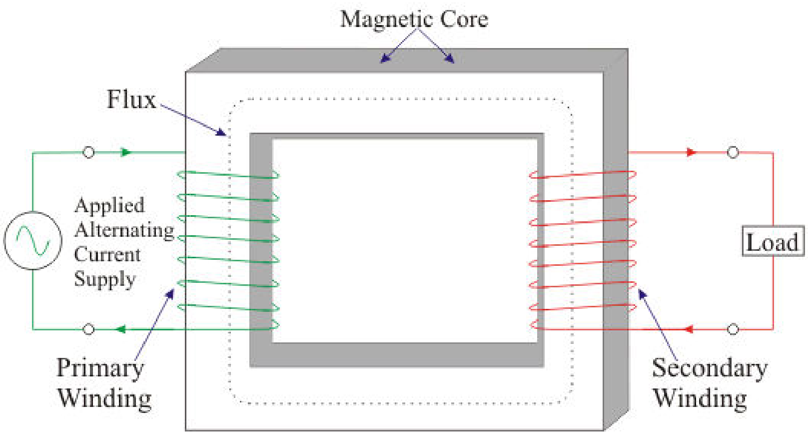
**Unit – 2 (BEE) R19&R20 Regulations – I ECE II Semester**

Transformers: Principle of operation of single phase transformer constructional features – EMF equation – Losses and efficiency of transformer- regulation of transformer – OC & SC tests predetermination of efficiency and regulations – Sumpner's test-Numerical Problems.

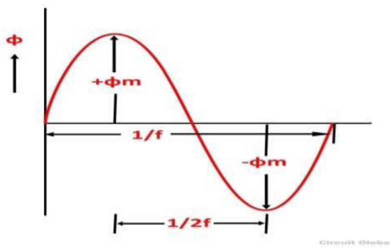
**1. Explain the *Working principle* of transformer**



Single Phase Transformer

1. The basic working principle of a transformer is mutual induction between two windings linked by common magnetic flux.
2. The primary and secondary coils are electrically separated but magnetically linked to each other.
3. When, primary winding is connected to a source of alternating voltage, alternating magnetic flux is produced around the winding.
4. The core provides magnetic path for the flux, to get linked with the secondary winding. Most of the flux gets linked with the secondary winding which is called as 'useful flux' or main 'flux', and the flux which does not get linked with secondary winding is called as 'leakage flux'.
5. As the flux produced is alternating (the direction of it is continuously changing), EMF gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This induced emf is called 'mutually induced emf', and the frequency of mutually induced emf is same as that of supplied emf. Thus, in a transformer the frequency is same on both sides.
6. If the secondary winding is closed circuit, then mutually induced makes the current flow through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit (secondary).

**2. Derive the *EMF Equation* of a Transformer**




Let

$\phi_m$ = Maximum value of flux in Weber

f = Supply frequency in Hz

$N_1$ = Number of turns in the primary winding

$N_2$ = Number of turns in the secondary winding

Φ = flux per turn in Weber

As per the faradays laws,

**The average value of the emf induced is directly proportional to the rate of change of flux.**

- The flux changes from + $\phi_m$ to – $\phi_m$ in half a cycle of 1/2f seconds.
- Flux increases from its zero value to maximum value $\phi_m$ in one quarter of the cycle i.e. in ¼ of the timeperiod.
- Average rate of change of flux is $\frac{d\phi}{dt} = \frac{\phi_m - 0}{\frac{1}{4f}} = 4\phi_m f$ volts

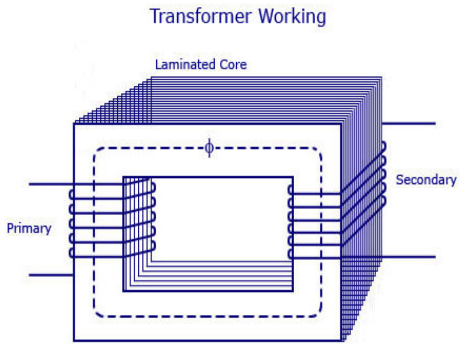


- Therefore the average e.m.f per turn is $4\phi_m f$
- As $\frac{Rmsvalue}{Averagevalue} = Formfactor = 1.11$ for sinusoidal varying quatities
- Hence, RMS value of e.m.f/turn is $1.11 * 4\phi_m f = 4.44\phi_m f$
- RMS value of e.m.f in the primary & secondary winding. =( e.m.f/turn) * No:of turns
- Therefore Emf induced in primary winding having $N_1$ turns is $E_1 = 4.44\phi_m fN_1$
- Emf induced in secondary winding having $N_2$ turns is $E_2 = 4.44\phi_m fN_2$

**3. Explain the *Construction of Transformer***

1. The simple construction of a transformer, need two coils having mutual inductance and a laminated steel core.




2. The two coils are insulated from each other and from the steel core.
3. The device will also need some suitable container for the assembled core and windings, a medium with which the core and its windings from its container can be insulated.
4. In order to insulate and to bring out the terminals of the winding from the tank, bushings made of porcelain are used.
5. In all transformers, the core is made of transformer sheet steel laminations assembled to provide a continuous magnetic path with minimum of air-gap included.
6. The steel should have high permeability and low hysteresis loss. For this to happen, the steel should be made of high silicon content and must also be heat treated.
7. By effectively laminating the core, the eddy-current losses can be reduced. The lamination can be done with the help of a light coat of core plate varnish or lay an oxide layer on the surface. For a frequency of 50 Hertz, the thickness of the lamination varies from 0.35mm to 0.5mm for a frequency of 25 Hertz.
8. To reduce the leakage fluxes in the transformer the windings of the primary and secondary coils are interleaved in the core type and sandwiched coils in the shell type.
9. To reduce the volume of the cu wire the core used must be the stepped core or cruciform core.

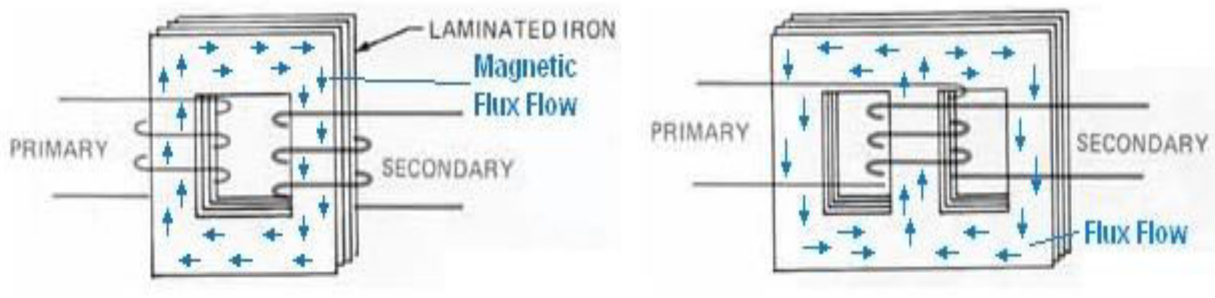
**4. Compare and distinguish *the types of transformers***

There are two major types of transformers based on construction. 1. Core type 2. Shell type

| S.No | Core type Transformer | Shell type transformer |
|---|---|---|
| 1 | The winding encircles the core | The core encircles the winding |
| 2 | The cylindrical type of coils are used | Generally multilayer disc type or sandwiched coils coils are used |
| 3 | As windings are distributed, the natural cooling is more effective | As windings are surrounded by the core, the natural cooling does not exists. |
| 4 | The coils can be easily removed from the maintenance point of view | For removing any winding for maintenance, a large number of laminations are to be removed. This is difficult. |
| 5 | The construction is preferred for low voltage transformers | The construction is used for very high voltage transformers |
| 6 | It has a single magnetic core | It has a double magnetic core |
| 7 | In a single phase type there are two limbs | In a single phase type the core has three limbs |



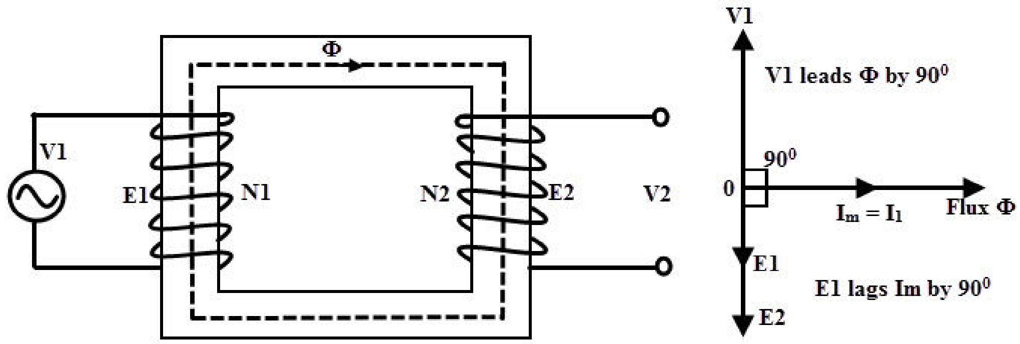
 




**5. Explain the operation of *Transformer on No Load.***

**<u>Ideal transformer at No-Load:</u>**

1. The transformer operating at no load, is equivalent to the secondary winding kept open circuited, which means current in the secondary is zero.
2. When primary winding is excited at its rated voltage it draws a current $I_m$ called magnetizing current which is 2 to 10% of the rated current. This generates the magnetic flux in the core by primary mmf $N_1I_m$
3. As the transformer is ideal, the core loss and cu loss are zero. And the net current taken is to create the mmf or flux of alternating nature.
4. This alternating flux induces the emf's $E_1$ and $E_2$ in the coils which lags the flux by $90^0$
5. The $I_m$ is inphase to the flux and the applied voltage leads to the $I_m$ by $90^0$ being the coil with pure inductive type.
6. Hence, emf's $E_1$ and $E_2$ in the coils are inphase to each other and lags the flux by $90^0$



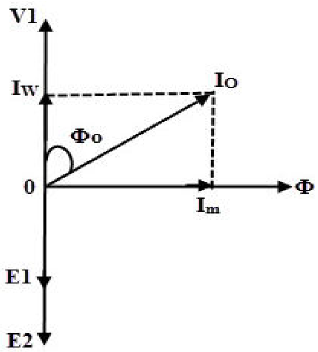

**Ideal Transformer at No-Load**

**<u>Transformer at No-Load:</u>**

1. The transformer in the practical case draws an additional current $I_w$ to the magnetizing current $I_m$ and total current from the supply mains is $I_0$ which lags to the applied voltage by an angle $\Phi_0$
2. There are two components of the current in $I_0$ namely
   i. Active (or) power (or) Watt full component of the current $I_w$ which is in phase to the voltage, and generates the core loss in the transformer
   ii. Reactive (or) Watt less (or) magnetizing component of the current $I_m$ which lags to the voltage by $90^0$, and magnetizes the core in the transformer
3. Also, the no-load input power of the transformer is the iron loss (since the cu loss are small at no-load)
4. The no load angle ($\Phi_0$) depends upon the losses in the transformer and is nearly equal to $90^0$. So that the power factor is very low and varies from 0.1 to 0.15 lagging.






**6.**

Working component $I_w = I_0 \cos\varphi_0$

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

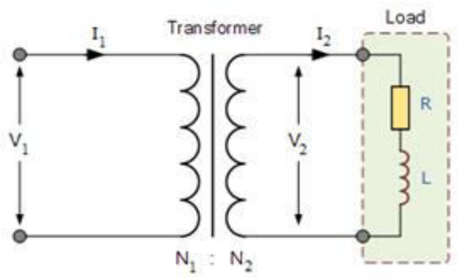
Magnetizing component $I_m = I_0 \sin\varphi_0$

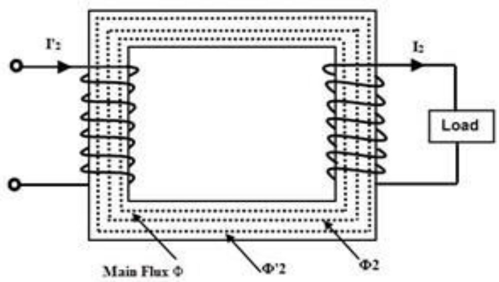
Power factor $\cos\varphi_0 = \frac{I_w}{I_0}$

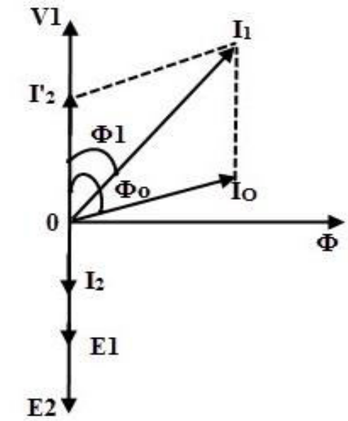
No load power input $P_0 = V_1 I_0 \cos\varphi_0$

**6. Explain the operation of Transformer on Load *without leakage impedances* of the coils.**

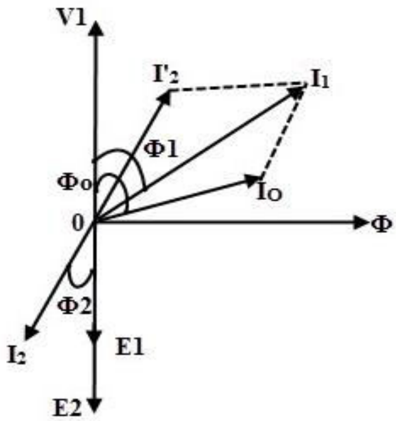
1. When an electrical load is connected to the secondary winding of a transformer a current flows in the secondary winding.
2. This secondary current is due to the induced secondary voltage, set up by the magnetic flux Φ in the core from the primary current($I_0$) and the main flux direction is from primary coil to secondary coil (clockwise)



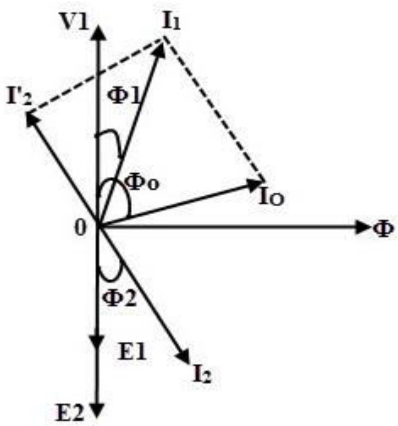




Resistive Load




Inductive Load




Capacitive Load

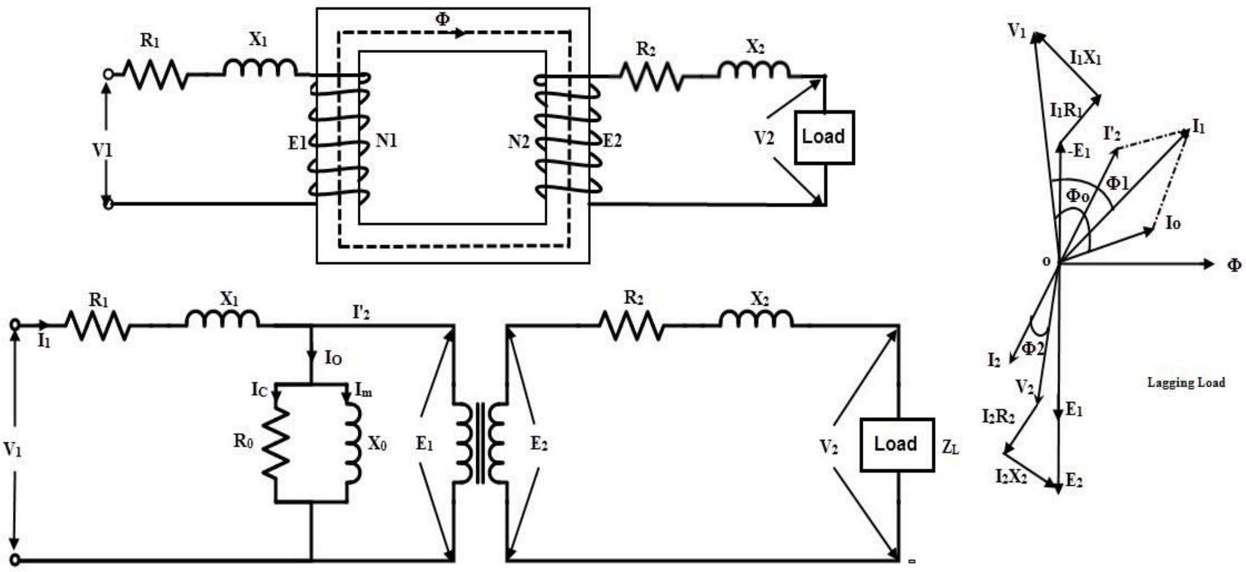
3. The secondary current, $I_2$ which is determined by the characteristics of the load, creates an secondary or load mmf ($N_2I_2$) and a secondary magnetic field, $\Phi_2$ is established in the transformer core which flows in the exact opposite direction to the main primary field, $\Phi_1$. i.e $\Phi_2$ is in anti clock wise.
4. These two magnetic fields oppose each other resulting in a combined magnetic field of less magnetic strength than the single field produced by the primary winding alone when the secondary circuit was open circuited.

5. This in turn decreases the primary induced emf and leads to the increase in primary current $I_1=I_0+I_2^1$.
6. This additional $I_2^1$ current is called load component current in the primary and will be in such a way to balance the load mmf by this mmf on the primary

   i.e $N_2I_2=N_1I_2^1$ therefore $I_2^1= I_2K$ where, $K = N_2/N_1$
7. This $N_1I_2^1$ will produce a flux $\Phi_2^1$ equal and opposite to $\Phi_2$. These fluxes will now be cancelled and the net flux in the core will be $\Phi_1$ even under the loading conditions.
8. For lagging load: $I_1^2 = I_0^2 + (I_2^1)^2 + 2I_0I_2^1\cos(\Phi_0\sim \Phi_2)$
9. As the flux remains constant from no-load to load, the iron loss will be same from no-load to load.

**7. Explain the operation of transformer on load with *leakage impedances* of the coils**

1. Below figure shows the schematic diagram, equivalent circuit and phasor diagram of the transformer with the leakage impedances of the coils.




Let,

*$R_1$=Resistance of primary coil in Ω* *$R_2$=Resistance of secondary coil in Ω*

*$X_1$=Reactance of primary coil in Ω* *$X_2$=Reactance of secondary coil in Ω*

*$Z_1$=impedance of primary coil in Ω* *$Z_2$=impedance of secondary coil in Ω*

*$E_1$=emf induced in primary coil* *$E_2$=emf induced in secondary coil*

*$V_1$=applied voltage to primary coil* *$V_2$= Load or terminal voltage of transformer*

*$I_1Z_1 = I_1(R_1+jX_1)$ = Primary leakage impedance drop*

*$I_2Z_2 = I_2(R_2+jX_2)$ = Secondary leakage impedance drop*

The magnetic core of the transformer is electrically represented with the parallel combination of $R_0$ and $X_0$ carrying the currents of $I_w$ and $I_m$ respectively and is placed across the primary coil.

**Currents Analysis of the transformer in equivalent circuit**

*Currents in the transformer at No-load:*

$I_w = \frac{V_1}{R_0}$ $\quad I_m = \frac{V_1}{X_0}$ $\quad I_0^2 = I_w^2 + I_m^2$ $\quad I_0 = \sqrt{I_w^2 + I_m^2}$ $\quad \phi_0 = \tan^{-1}\left(\frac{I_m}{I_w}\right)$

*Currents in the transformer with load*

$I_1 = (I_0\angle -\phi_0) + (I_2^1\angle \pm\phi_2)$ *Where* $I_2^1 = I_2 \times K$ *and* $K = \frac{N_2}{N_1}$

$I_1 = (I_0 \cos\phi_0 + I_2^1 \cos\phi_2) + j(I_0 \sin(-\phi_0) + I_2^1 \sin(\pm\phi_2))$ - for lag and + for lead

*Primary phase angle ($\Phi_1$)*

$\phi_1 = \tan^{-1}\left(\frac{I_0 \sin(-\phi_0) + I_2^1 \sin(\pm\phi_2)}{I_0 \cos\phi_0 + I_2^1 \cos\phi_2}\right)$ *and primary power factor is* $\cos\Phi_1$

**Voltages Analysis of the transformer in equivalent circuit**

*Primary induced emf*

$$E_1 = (V_1\angle 0) - (I_1\angle\phi_1 * Z_1)$$

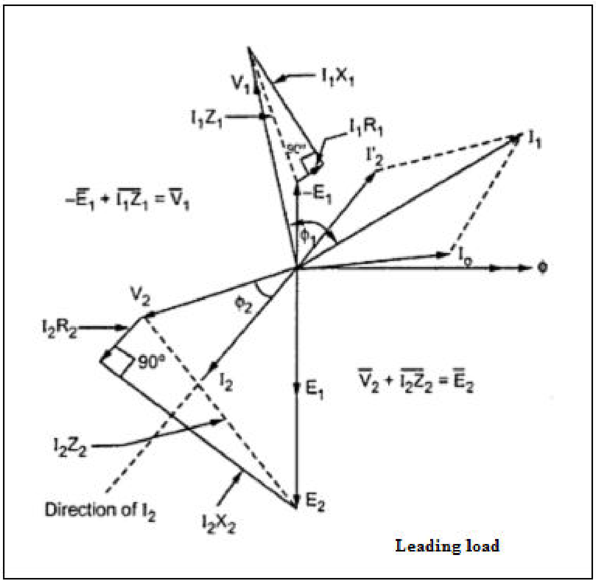
$E_1 = (V_1 + j0) - \{(I_1\cos\phi_1 + jI_1\sin\phi_1)\times(R_1 + jX_1)\}$

Using transformation ratio $E_2 = E_1 * K$

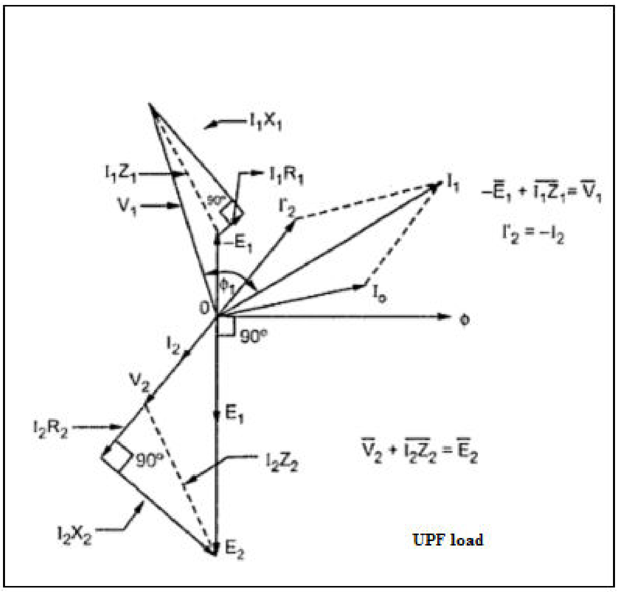
Knowing the $E_2$ and applying KVL to the secondary loop the load voltage is

$$V_2 = E_2 - I_2 Z_2$$

$V_2 = E_2\angle\phi' - (I_2\angle\pm\phi_2)Z_2$ $\quad V_2 = E_2\angle\phi' - (I_2\angle\pm\phi_2)(R_2 + jX_2)$



Leading load



UPF load

**8. Explain the *equivalent circuits* referred to both primary and secondary of the transformer**

The equivalent circuit of the transformer referred to primary is shown in the below figure in which the winding parameters of the secondary are transformed and was referred to primary based on the voltage balancing principle before and after the transformation.

Secondary Resistance referred to primary:

$$R_2^1 = \frac{V_1}{I_1} = \frac{V_1}{I_1} \times \frac{V_2 I_2}{V_2 I_2} = \times \frac{V_1 I_2}{V_2 I_1} \times \frac{V_2}{I_2} = \frac{R_2}{K^2} \qquad \left( \because \frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{1}{K} \right) also \frac{V_2}{I_2} = R_2$$

$\therefore R_2^1 = \frac{R_2}{K^2}$ Thus, it is the secondary resistance referred to primary

Secondary Reactance referred to primary:

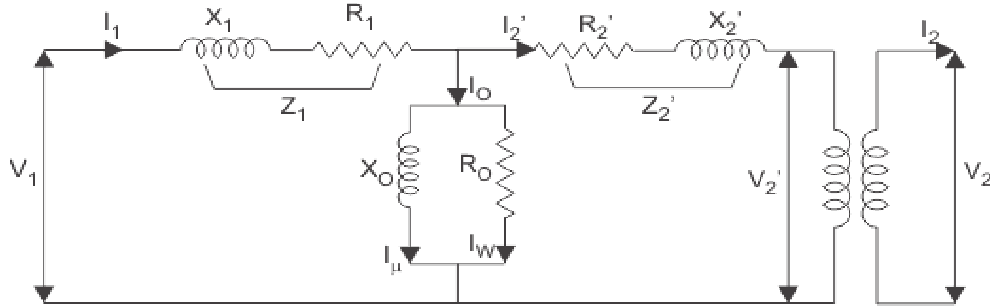
$$X_2^1 = \frac{V_1}{I_1} = \frac{V_1}{I_1} \times \frac{V_2 I_2}{V_2 I_2} = \times \frac{V_1 I_2}{V_2 I_1} \times \frac{V_2}{I_2} = \frac{X_2}{K^2} \qquad \left( \because \frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{1}{K} \right) also \frac{V_2}{I_2} = X_2$$

$\therefore X_2^1 = \frac{X_2}{K^2}$ Thus, it is the secondary reactance referred to primary

Secondary Impedance referred to primary:

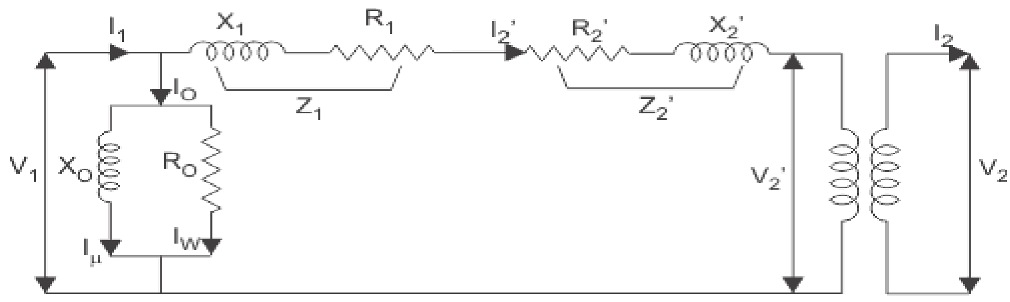
$$Z_2^1 = \frac{V_1}{I_1} = \frac{V_1}{I_1} \times \frac{V_2 I_2}{V_2 I_2} = \times \frac{V_1 I_2}{V_2 I_1} \times \frac{V_2}{I_2} = \frac{Z_2}{K^2} \qquad \left( \because \frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{1}{K} \right) also \frac{V_2}{I_2} = Z_2$$

$\therefore Z_2^1 = \frac{Z_2}{K^2}$ Thus, it is the secondary impedance referred to primary




Equivalent Circuit of Transformer referred to Primary

To have simplified calculations the equivalent circuit is modified as bringing the core branch towards the supply voltage instead of having in between the primary and secondary parameters




**simplified equivalent circuit of transformer reffered to primary**

In this simplified circuit the total resistance, reactance and impedances referred to primary are

$$\therefore R_{eq1} = R_1 + R_2^1 = R_1 + \frac{R_2}{K^2} \qquad \therefore X_{eq1} = X_1 + X_2^1 = X_1 + \frac{X_2}{K^2}$$

$$\therefore Z_{eq1} = Z_1 + Z_2^1 = Z_1 + \frac{Z_2}{K^2}$$

Similarly, the equivalent circuit referred to secondary of the transformer is shown below with their formulas

Primary Resistance referred to secondary:

$$R_1^1 = \frac{V_2}{I_2} = \frac{V_2}{I_2} \times \frac{V_1 I_1}{V_1 I_1} = \times \frac{V_2 I_1}{V_1 I_2} \times \frac{V_1}{I_1} = K^2 R_1 \qquad \left(\because \frac{V_2}{V_1} = \frac{I_1}{I_2} = K\right) also \frac{V_1}{I_1} = R_1$$

$\therefore R_1^1 = R_1 K^2$ Thus, it is the primary resistance referred to secondary

Primary Reactance referred to secondary:

$$X_1^1 = \frac{V_2}{I_2} = \frac{V_2}{I_2} \times \frac{V_1 I_1}{V_1 I_1} = \times \frac{V_2 I_1}{V_1 I_2} \times \frac{V_1}{I_1} = K^2 X_1 \qquad \left(\because \frac{V_2}{V_1} = \frac{I_1}{I_2} = K\right) also \frac{V_1}{I_1} = X_1$$

$\therefore X_1^1 = X_1 K^2$ Thus, it is the primary reactance referred to secondary

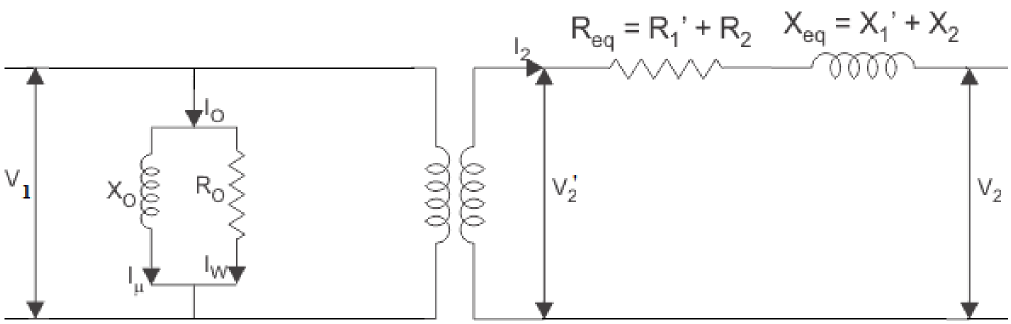
Primary Impedance referred to secondary:

$$Z_1^1 = \frac{V_2}{I_2} = \frac{V_2}{I_2} \times \frac{V_1 I_1}{V_1 I_1} = \times \frac{V_2 I_1}{V_1 I_2} \times \frac{V_1}{I_1} = K^2 Z_1 \qquad \left(\because \frac{V_2}{V_1} = \frac{I_1}{I_2} = K\right) also \frac{V_1}{I_1} = Z_1$$

$\therefore Z_1^1 = Z_1 K^2$ Thus, it is the primary impedance referred to secondary

$$\therefore R_{eq2} = R_2 + R_1^1 = R_2 + R_1 K^2 \qquad \therefore X_{eq2} = X_2 + X_1^1 = X_2 + X_1 K^2$$

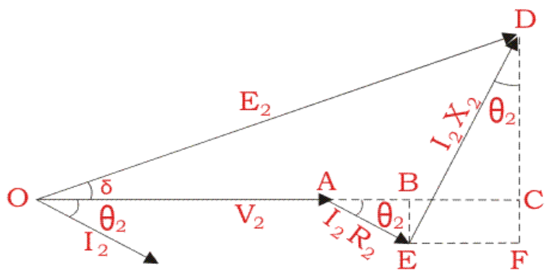
$$\therefore Z_{eq2} = Z_2 + Z_1^1 = Z_2 + Z_1 K^2$$




Approximate Equivalent Circuit of Transformer referred to Secondary

**9. Derive the expression for *voltage regulation and efficiency* of the transformer**

**Definition of voltage regulation :** Voltage regulation is defined as the percentage change in the output voltage from no-load to full-load expressed in full load voltage.




$OC = OA + AB + BC$

$Here,\ OA = V_2$

$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$

$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$

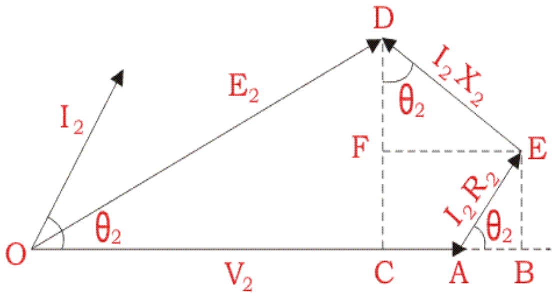
***Derivation of voltage regulation for the lagging power factor load,***
assuming the angle between OC and OD as very small, and neglected it, OD is nearly equal to OC ($E_2$ > $V_2$)

$$E_2 = OC = OA + AB + BC, \quad E_2 = OC = V_2 + I_2 R_{eq2} \cos\phi + I_2 X_{eq2} \sin\phi$$

Thus, the % voltage regulation is

$$\frac{E_2 - V_2}{V_2} * 100 = \frac{V_2 + I_2 R_{eq2} \cos\phi + I_2 X_{eq2} \sin\phi - V_2}{V_2} \times 100 = \frac{I_2 R_{eq2} \cos\phi + I_2 X_{eq2} \sin\phi}{V_2} \times 100$$

***Derivation of voltage regulation for the leading power factor load,***
Similarly, from the phasor diagram of the leading pf load , ($E_2$ < $V_2$)




Here

EF = DE sinθ = $I_2X_2$ sinθ

AB = AE cosθ = $I_2R_2$ cosθ

OA = $V_2$ and OD = $E_2$

assuming the angle between OA and OD as very small, and neglected it, OD is nearly equal to OC ($E_2$ < $V_2$)

$V_2$ - $E_2$ = OA – OC = CA = CB – AB, thus $V_2$ = $E_2$+CB - AB

Thus, the % voltage regulation is

$$\frac{E_2 - V_2}{V_2} * 100 = \frac{E_2 - E_2 - CB + AB}{V_2} \times 100 = \frac{I_2 R_{eq2} \cos\phi - I_2 X_{eq2} \sin\phi}{V_2} \times 100$$

Therefore,

$$\% regulation = \frac{I_2 R_{eq2} \cos\phi \pm I_2 X_{eq2} \sin\phi}{V_2} \times 100$$ (+ ) for lagging pf and (-) for leading pf

***10. Discuss the losses and efficiency in the transformer***

Transformer is a static device, i.e. it doesn't have any parts, so no mechanical losses exist in the transformer and only electrical losses are observed.

So there are two primary types of losses in the transformer:

1. Copper losses
2. Iron losses

Other than these, some small amount of power losses in the form of 'stray losses' are also observed, which are produced due to the leakage of magnetic flux.

***Copper losses***

1. These losses occur in the windings of the transformer when heat is dissipated due to the current passing through the windings and the internal resistance offered by the windings.
2. So these are also known as ohmic losses or $I^2R$ losses, where 'I' is the current passing through the windings and R is the internal resistance of the windings.
3. These losses are present both in the primary and secondary windings of the transformer and depend upon the load attached across the secondary windings since the current varies with the variation in the load, so these are *variable losses.*

***Iron losses or Core Losses***

1. These losses occur in the core of the transformer and are generated due to the variations in the flux.
2. These losses depend upon the magnetic properties of the materials which are present in the core, so they are also known as iron losses, as the core of the Transformer is made up of iron. And since they do not change like the load, so these losses are also *constant losses.*

There are two types of Iron losses in the transformer:

1. Eddy Current losses
2. Hysteresis Loss

***Eddy Current Losses***

1. When an alternating current is supplied to the primary windings of the transformer, it generates an alternating magnetic flux in the winding which is then induced in the secondary winding also through Faraday's law of electromagnetic induction, and is then transferred to the externally connected load.
2. During this process, the other conduction materials of which the core is composed of; also gets linked with this flux and an emf is induced.
3. But this magnetic flux does not contribute anything towards the externally connected load or the output power and is dissipated in the form of heat energy.
4. So such losses are called Eddy Current losses and are mathematically expressed as:

$$P_e = K_e f^2 K_f^2 B_m^2$$

Where;

$K_e$ = Constant of Eddy Current

$K_f^2$ = Form Constant

$B_m$ = Strength of Magnetic Field

***Hysteresis Loss***

1. Hysteresis loss is defined as the electrical energy which is required to realign the domains of the ferromagnetic material which is present in the core of the transformer.
2. These domains loose their alignment when an alternating current is supplied to the primary windings of the transformer and the emf is induced in the ferromagnetic material of the core which disturbs the alignment of the domains and afterwards they do not realign properly.
3. For their proper realignment, some external energy supply, usually in the form of current is required. This extra energy is known as Hysteresis loss.

   Mathematically, they can be defined as;

$$P_h = K_h B_m^{1.6} f V$$

- The **Efficiency** of the transformer is defined as the ratio of power output to the input power.

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

$$\eta = \frac{\text{output power}}{\text{output power + iron losses + copper losses}}$$

$$\eta = \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + P_i + P_c}$$

Where,
$V_2$ = Secondary terminal voltage
$I_2$ = Full load secondary current in A
$\cos\phi_2$ = power factor of the load
$P_i$ = Iron losses = hysteresis losses + eddy current loss
Pc = Full load copper losses = $I_2^2 R_{eq}$

Also, the efficiency at any amount of load($x$) is given by

$$\eta = \frac{outputinwatts}{inputinwatts} = \frac{xVA\cos\phi}{xVA\cos\phi + W_i + x^2 W_{FLCu}} \times 100$$

***<u>Condition for maximum efficiency in the transformer:</u>***

$$\eta = \frac{outputinwatts}{inputinwatts} = \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + W_i + I_2^2 r_{e2}} = \frac{1}{1 + \frac{W_i}{V_2 I_2 \cos\phi} + \frac{I_2^2 r_{e2}}{V_2 I_2 \cos\phi}} = \frac{1}{1 + \frac{W_i}{V_2 I_2 \cos\phi} + \frac{I_2 r_{e2}}{V_2 \cos\phi}}$$

To get the maximum efficiency the denominator must be small, therefore condition to be the denominator minimum is

$$\frac{d\left(1 + \frac{W_i}{V_2 I_2 \cos\phi} + \frac{I_2 r_{e2}}{V_2 \cos\phi}\right)}{dI_2} = 0$$

$$\frac{d\left(1 + \frac{W_i}{V_2 I_2 \cos\phi} + \frac{I_2 r_{e2}}{V_2 \cos\phi}\right)}{dI_2} = 0 + \left((-)\frac{W_i}{V_2 I_2^2 \cos\phi}\right) + \left(\frac{r_{e2}}{V_2 \cos\phi}\right) = 0$$

$$\frac{r_{e2}}{V_2 \cos\phi} = \frac{W_i}{V_2 I_2^2 \cos\phi} \qquad r_{e2} = \frac{W_i}{I_2^2} \qquad I_2^2 r_{e2} = W_i$$

Therefore the condition for obtaining the maximum efficiency is the variable loss $\left(I_2^2 r_{e2}\right)$ must be equal to the constant loss $W_i$ .

Also, the load current at which the maximum efficiency occurs is $I_{2\max} = \sqrt{\left(\frac{W_i}{r_{e2}}\right)}$

Multiplying both sides with 1000 *V$_2$

$$1000 * V_2 * I_{2\max} = 1000 * V_2 * \sqrt{\left(\frac{W_i}{r_{e2}}\right)} \qquad \text{Load KVA}_{\max} = 1000 * V_2 * \sqrt{\left(\frac{W_i}{r_{e2}}\right)}$$

$$\text{Load KVA}_{\max} = 1000 * V_2 * \frac{I_{2\text{Fullload}}}{I_{2\text{Fullload}}} \sqrt{\left(\frac{W_i}{r_{e2}}\right)}$$

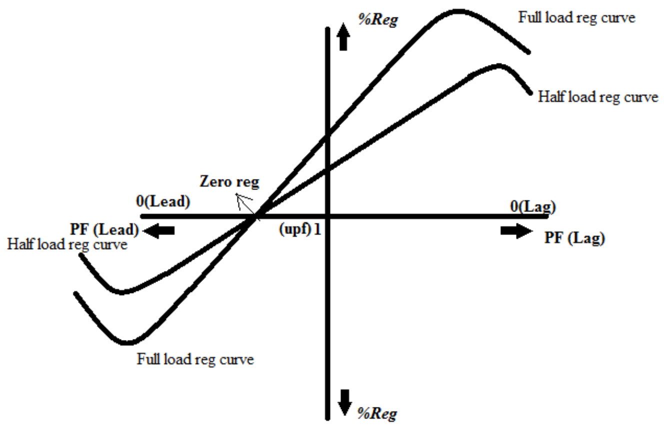
$$\text{Load KVA}_{\max} = 1000 * V_2 * I_{2\text{Fullload}} \sqrt{\left(\frac{W_i}{I_{2\text{Fullload}}^2 r_{e2}}\right)}$$

$$\text{Load KVA}_{\max} = \text{Full load KVA} \sqrt{\left(\frac{W_i}{I_{2\text{Fullload}}^2 r_{e2}}\right)}$$

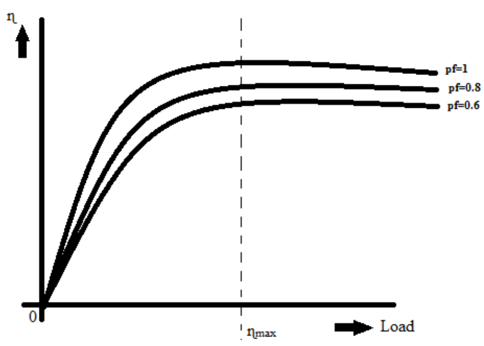
$$\text{The Load KVA at which maximum efficiency} = \text{Full load KVA} \sqrt{\left(\frac{W_i}{W_{\text{cuFullload}}}\right)}$$

$$\boxed{\text{The Load KVA at which maximum efficiency} = \text{Full load KVA} \sqrt{\frac{W_i}{W_{\text{cuFullload}}}}}$$

***<u>Variation of voltage regulation and efficiency with respect to load and load powerfactors</u>***




Regulation curves w.r.t load pf and amount of loads




Varaiation of efficiency with respect to load and load power factor





12

**11. Explain OC and SC tests on a single phase transformer**

**Ans: Purpose of conducting OC and SC tests is to find**

i) Equivalent circuit parameters ii) Efficiency iii) Regulation

**<u>Open Circuit Test:</u>**

1. The OC test is performed on LV side at rated voltage and HV side is kept opened.
2. As the test is conducted on LV side the meters selected will be at low range values like smaller voltmeter, smaller ammeter and low pf wattmeter
3. As the no-load current is quite small about 2 to 5% of the rated current, the ammeter required here will be smaller range even after on LV side which are designed for higher current values.
4. The voltmeter, ammeter and the wattmeter readings $V_0$, $I_0$ and $W_0$ respectively are noted by applying rated voltage on LV side.
5. The wattmeter will record the core loss because of noload input power.

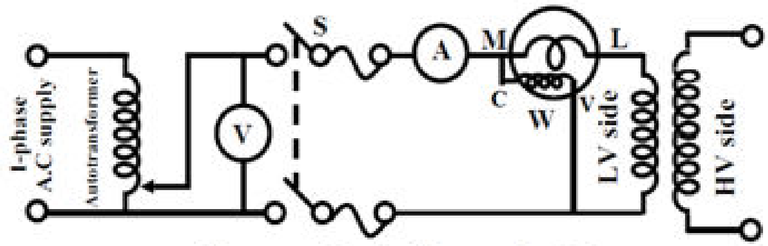



Figure : Circuit diagram for O.C test

**<u>Calculations from OC test readings:</u>**

$R_0$, $X_0$ and Iron loss are calculated from the OC test results as

Core resistance $R_0 = \frac{V_0}{I_w} = \frac{V_0}{I_0 \cos\phi_0}$

Magnetizing reactance $X_0 = \frac{V_0}{I_m} = \frac{V_0}{I_0 \sin\phi_0}$

Where $\cos\phi_0 = \frac{P_0}{V_0 I_0}$

and iron loss $W_i = P_0$ (No load input power)

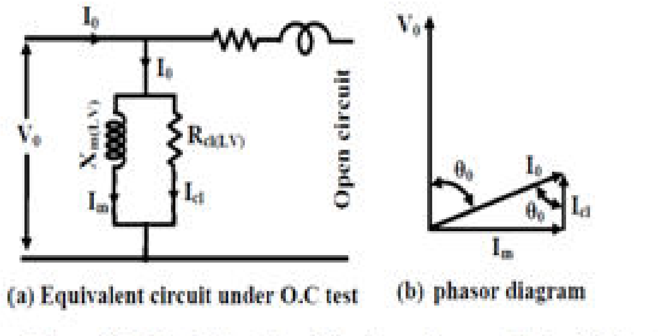



Figure 2.2: Equivalent circuit & phasor diagram during O.C test

**<u>Short Circuit Test:</u>**

1. The SC test is performed on HV side at rated current and LV side is kept Shorted.

2. As the test is conducted on HV side the meters selected will be at low range values like smaller voltmeter, smaller ammeter and unity pf wattmeter
3. As the voltage required to circulate the short circuit rated current is very small about 10 to 15% of the rated HV voltage, so the voltmeter required here will be smaller range even the test is conducted on HV side.
4. The voltmeter, ammeter and the wattmeter readings $V_{sc}$, $I_{sc}$ and $W_{sc}$ respectively are noted by passing rated current on HV side.
5. The wattmeter will record thecopper loss corresponding to the $I_{sc}$.

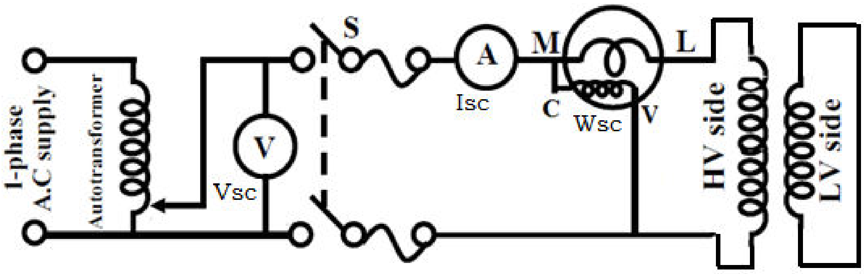
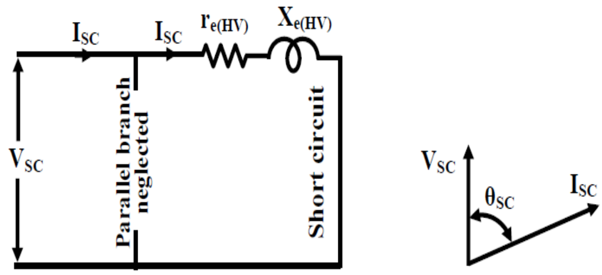



**Figure 2.3: Circuit diagram for S.C test**

**Calculations from SC test readings:**

$r_{e(HV)}$, $x_{e(HV)}$ and cu loss are calculated from the SC test results as




(a) Equivalent circuit under S.C test (b) phasor diagram

Figure 2.4: Equivalent circuit & phasor diagram during S.C test

Equivalent resistance referred to HV side is

$$R_{sc} = \frac{P_{sc}}{I_{sc}^2} = r_{e(HV)}$$

Equivalent impedance referred to HV side is

$$Z_{sc} = \frac{V_{sc}}{I_{sc}} = z_{e(HV)}$$

Equivalent reactance referred to HV side is $X_{sc} = \sqrt{Z_{sc}^2 - R_{sc}^2} = x_{e(HV)}$

The culoss is equal to the wattmeter reading $W_{sc}$

- Thus, the approximate equivalent circuit of the transformer can be drawn by the calculated values of $R_0$ and $X_0$ on LV side and $r_{e(HV)}$ and $x_{e(HV)}$ *on* HV side.
- The efficiency at any load is calculated from the losses $W_i$ and $W_{cufl}$ as

$$\eta_x = \frac{xVA\cos\phi}{xVA\cos\phi + W_i + x^2 W_{FLCu}} \times 100$$

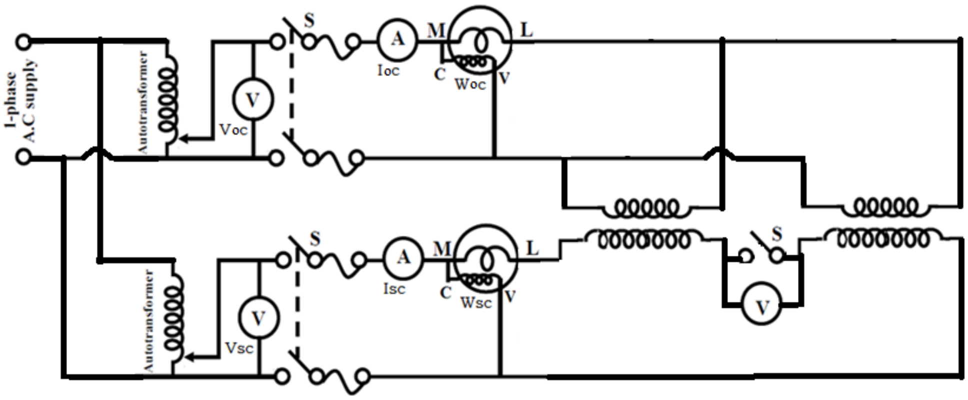
The regulation of the transformer is calculated from the $r_{e(HV)}$ and $x_{e(HV)}$ as

$$\%reg = \frac{I_{HV} r_{eHV} \cos\phi \pm I_{HV} x_{eHV} \sin\phi}{V_{HV}} \times 100 \text{ where } + \text{is for lagging pf and} - \text{is for leading pf}$$

**12. Explain Sumpner's test or back to back test**

**Ans:** Purpose of Sumpner's test or back to back test on transformer is to determine efficiency, voltage regulation considering the **heating under loaded** conditions.

1. Two identical transformers are required to conduct the Sumpner's test
2. Both transformers are connected to supply such that one transformer is loaded on another.
3. Both Primaries are connected in parallel and both secondaries are connected in series opposition which is checked by the voltmeter showing zero volts when the switch S is closed.




**<u>Procedure for sumpner's test:</u>**

1. Both the emf's cancel each other, as transformers are identical. In this case, as per superposition theorem, no current flows through secondary. And thus the no load test is simulated.
2. The current drawn from $V_{oc}$ is $2I_0=I_{oc}$ and the input power measured by wattmeter $W_{oc}$ is equal to iron losses of both transformers. i.e. iron loss per transformer $P_i = W_{oc}/2$.
3. Now, a small voltage $V_{sc}$ is injected into secondary with the help of a low voltage transformer.
4. The voltage $V_{sc}$ is adjusted so that, the rated current $I_{sc}$ flows through the secondary. In this case, both primaries and secondary's carry rated current.
5. Thus short circuit test is simulated and wattmeter $W_{sc}$ shows total full load copper losses of both transformers. i.e. copper loss per transformer $P_{Cu} = W_{sc}/2$.
6. From above test results, the full load efficiency of each transformer is calculated and is given as

$$\%\eta = \frac{xVA\cos\phi}{xVA\cos\phi + \frac{W_{oc}}{2} + x^2\frac{W_{sc}}{2}} \times 100$$

