

## Chapter - 07 Transformer

### Introduction

Transformer is an a/c machine

that is

- i) transfers electrical energy from one electric circuit to another
- ii) does so without a change of frequency
- iii) does so by the principle of electromagnetic induction and
- iv) has electric circuits that are linked by a common magnetic circuit

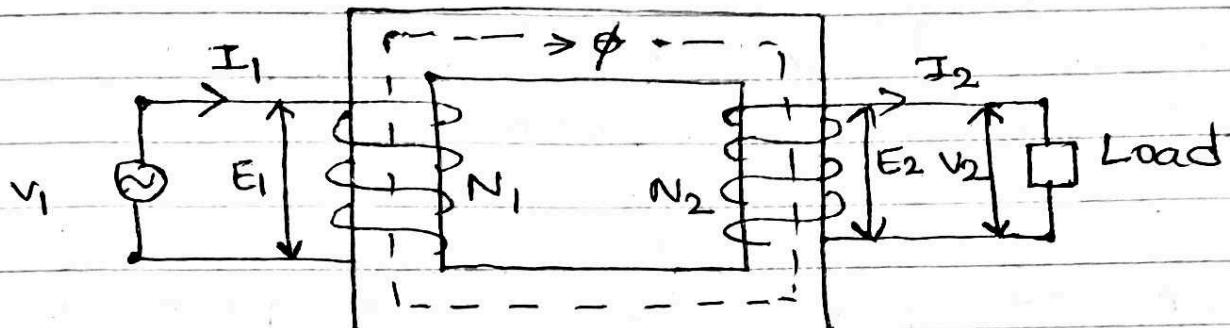


Fig. transformer

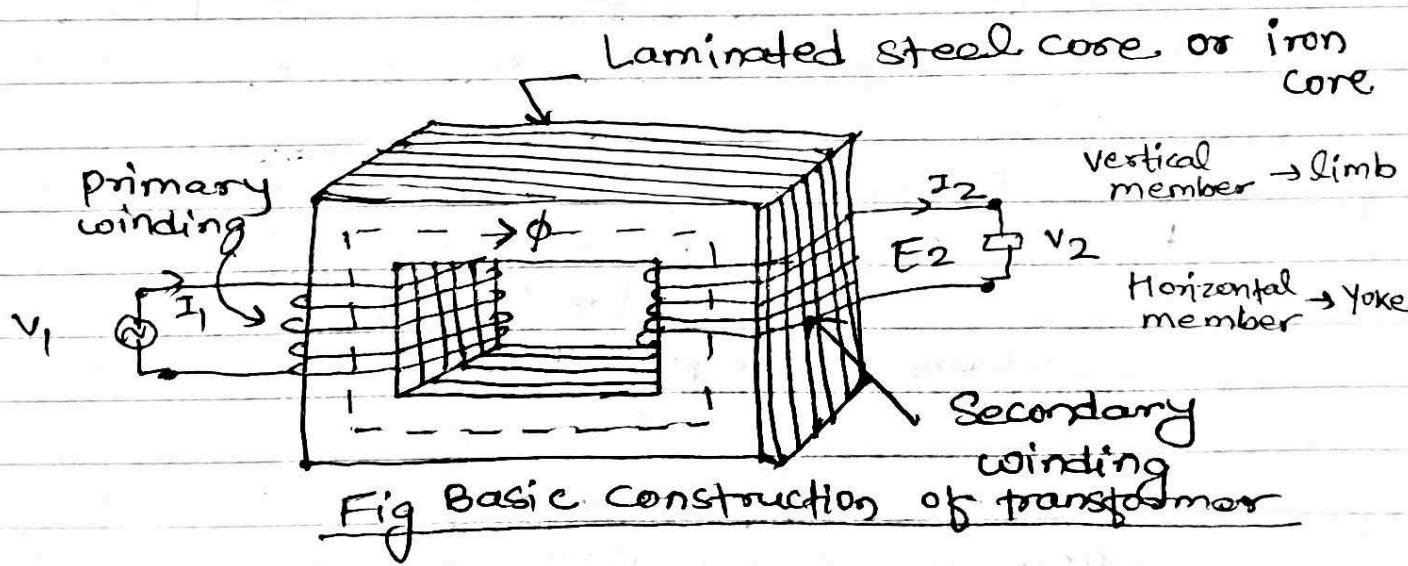


Fig Basic construction of transformer

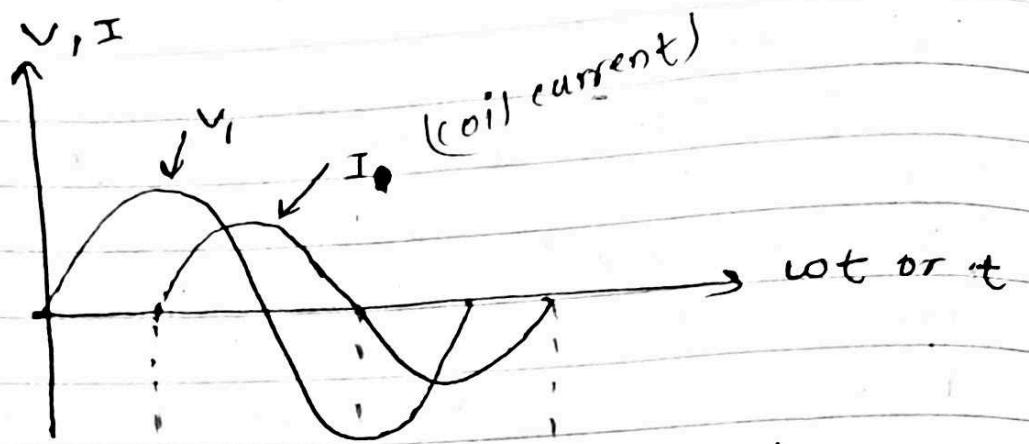


Fig. waveform of  $V_1$  and  $I_1$

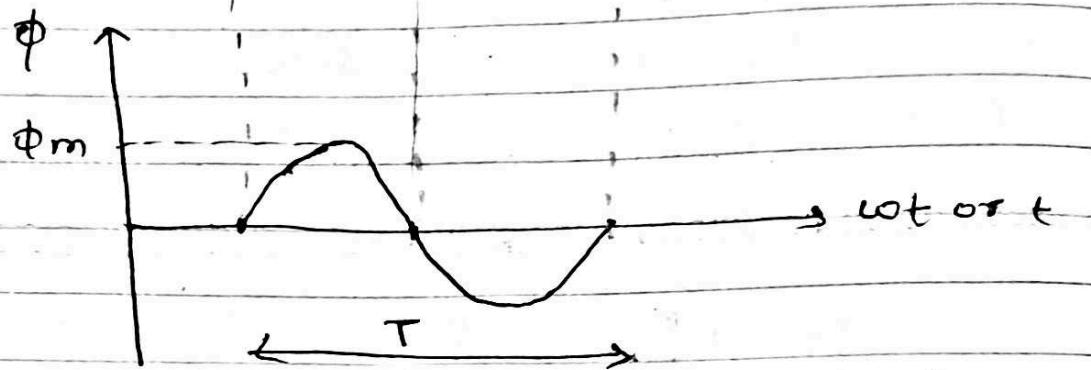


Fig. waveform of flux

- A transformer is a static piece of equipment used either for raising or lowering the voltage of ac supply with corresponding increase or decrease in current.
- It essentially consists of two windings, the primary and secondary windings, wound on a common laminated magnetic core as shown in fig. above.
- The winding connected to ac supply is called primary winding and the winding connected to load is called secondary winding.

- The alternating voltage  $v_1$  whose magnitude is to be changed is applied on primary.
- Depending upon number of turns of the primary ( $N_1$ ) and secondary ( $N_2$ ), an alternating Emf  $E_2$  is induced in the Secondary. The induced emf  $E_2$  in secondary causes  $I_2$  current and consequently terminal voltage  $v_2$  will appear across load.
- If  $N_2 > N_1$ , then  $v_2 > v_1$  ( $E_2 > E_1$ ), it is called step-up transformer.
- If  $N_2 < N_1$ , then  $v_2 < v_1$ , it is called step-down transformer

### Working principle of transformer

When the primary winding is connected to an ac supply mains, a current flows through it. Since this winding links with an iron core, current flows through this winding produces an alternating flux  $\phi$  in the core. Since this flux is alternating and links with secondary winding also, induces an emf in the secondary winding. The frequency of induced emf in the secondary winding is same as that of the flux or that of supply voltage. The ~~induced emf~~ in the secondary winding enables it to deliver current to an external load connected across it.

Thus the energy is transferred from primary winding to the secondary winding by means of electromagnetic induction without any change in frequency. The flux  $\phi$  of the iron core links not only secondary winding but also the primary winding so produces self induced emf in the primary winding. This induced emf in the primary winding opposes the applied voltage and therefore it is known as back emf of the primary.

### Emf equation of a transformer

When an alternating voltage (sinusoidal) is applied to the primary winding of a transformer, an ac flux (sinusoidal), as shown in the fig below is set up in the iron core which links both windings (primary and secondary).

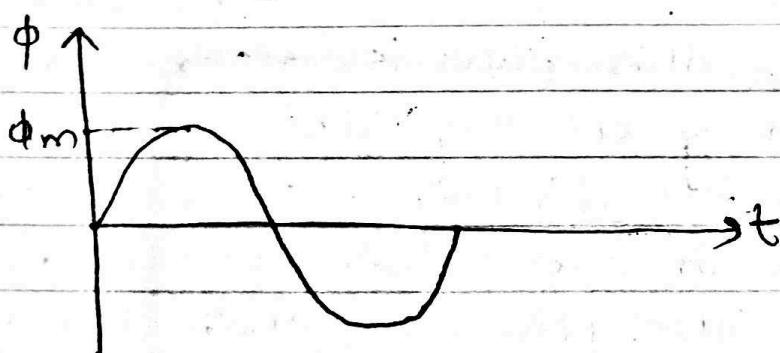


Fig. Sinusoidal variation of flux with time

The instantaneous value of sinusoidally varying flux may be given as,

$$\phi = \phi_m \sin \omega t \quad \dots \text{①}$$

The instantaneous value of emf induced in the primary is,

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

$$e_1 = \underbrace{2\pi f N_1 \phi_m}_{e_{1m}} \sin(\omega t - 90^\circ) \quad \dots \text{②}$$

From eqn ① and eqn ②, it is clear that  $e_1$  lags behind  $\phi$  by  $90^\circ$ .

$$\overbrace{e_1}^{e_{1m}} = 2\pi f N_1 \phi_m \quad \dots \text{③} \quad [\text{From eqn ②}]$$

The rms value of primary induced emf

$$E_1 = \frac{e_{1m}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}} = 4.44 f N_1 \phi_m$$

$$E_1 = 4.44 f N_1 \phi_m$$

Similarly,

$$E_2 = 4.44 f N_2 \phi_m$$

$$e_2 = -N_2 \frac{d\phi}{dt}$$

Voltage transformation ratio ( $k$ )  
we have,

$$E_1 = 4.44 f N_1 \Phi m$$

$$E_2 = 4.44 f N_2 \Phi m$$

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

$k$  = transformation ratio

For ideal transformer,

i)  $E_1 = V_1$ , and  $E_2 = V_2$

$$\frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = k = \frac{\text{Secondary voltage}}{\text{Primary voltage.}}$$

ii) no losses in ideal transformer,

$$V_1 I_1 = V_2 I_2$$

$$\frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{k}$$

→ currents are in inverse ratio of voltage transformation ratio.

→ so if raise voltage then there will be decrease in current.

### Voltage transformation Ratio (Turn Ratio)

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

Where,  $K$  is called transformation ratio.

## Ideal transformer

(Imaginary transformer)

An ideal transformer is one that has

- i) no winding resistance (pure inductive)
- ii) no leakage flux i.e. the same flux links both windings.  
(100% flux passes through core and links both windings)
- iii) no iron losses (i.e. eddy current and hysteresis losses) in the core.
- iv) zero magnetising current i.e. core has infinite permeability and zero reluctance.

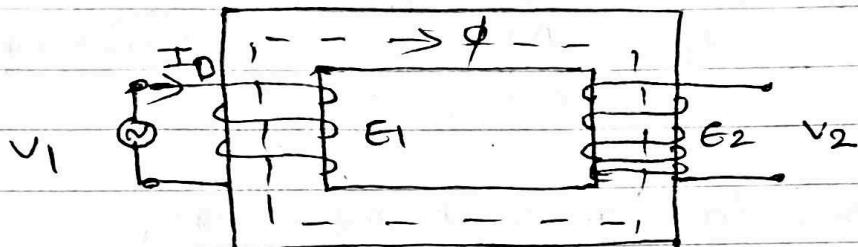
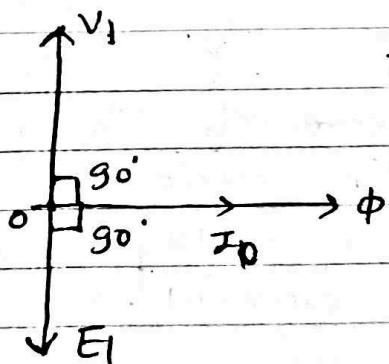


Fig Ideal transformer on no load



$I_0 \rightarrow$  used for magnetising  
↳ very very less current

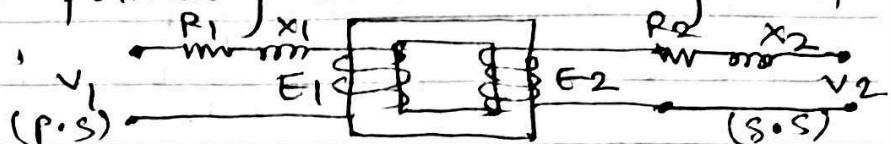
- $E_1$  and  $V_1$  are  $180^\circ$  out of phase
- current lags  $90^\circ$  behind supply voltage  $V_1$  as it is purely inductive.

## Practical transformer

The practical transformer has

- i) winding resistance.
- ii) iron losses and copper losses
- iii) leakage reactance.

i) winding resistance — Since the windings consists of copper conductors, it immediately follows that both primary and secondary will have winding resistance.

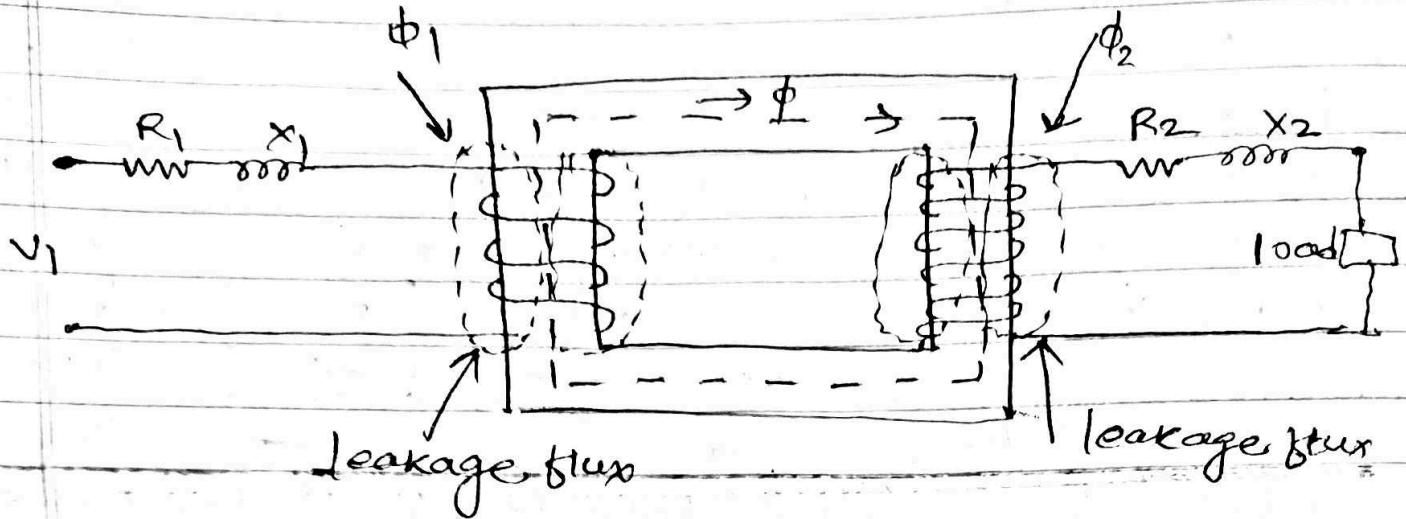


ii) iron losses and copper losses — Since iron core is subjected to alternating flux, there occurs eddy current and hysteresis losses in it. These two losses together are known as iron losses or core losses. These two losses depend upon supply frequency and maximum flux density in core.

$I^2 R$  loss in the winding called copper loss.

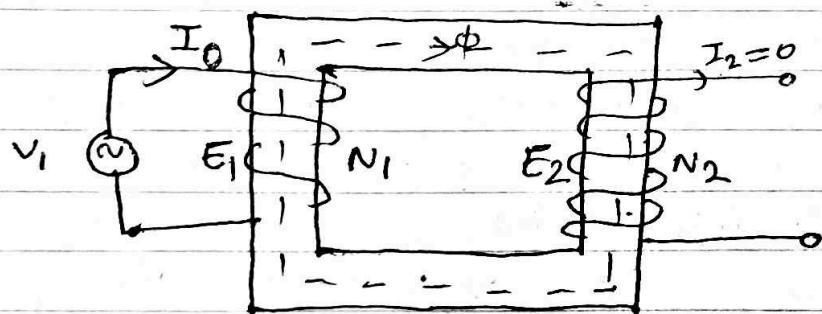
iii) leakage reactance — Both primary and secondary currents produce flux. The flux of which links both the windings is useful flux and is called the mutual flux. However primary winding will produce some flux  $\phi_1$ , which will not link with secondary winding. Similarly secondary will produce some flux  $\phi_2$ , which will not link with primary winding. Such flux  $\phi_1$  or  $\phi_2$  which link only one winding is called leakage flux.

The effect of leakage flux is that it will introduce inductive reactance  $x_1$  in primary  $x_2$  in secondary.



### Practical transformer on No load

Consider a practical transformer on no load i.e Secondary on open-circuited as shown below in fig -



The current drawn by transformer during the no-load conditions

is known as exciting current.

Fig practical transformer on No load

- The primary will draw a small current  $I_0$  to supply i) iron loss ii) a very small copper loss in the primary.

$(I_0^2 R$  is neglected due to very small value of  $I_0$ )

→ Hence the primary no load current is not  $90'$  behind the applied voltage  $v_1$  (lags by an angle  $(\phi_0 < 90')$

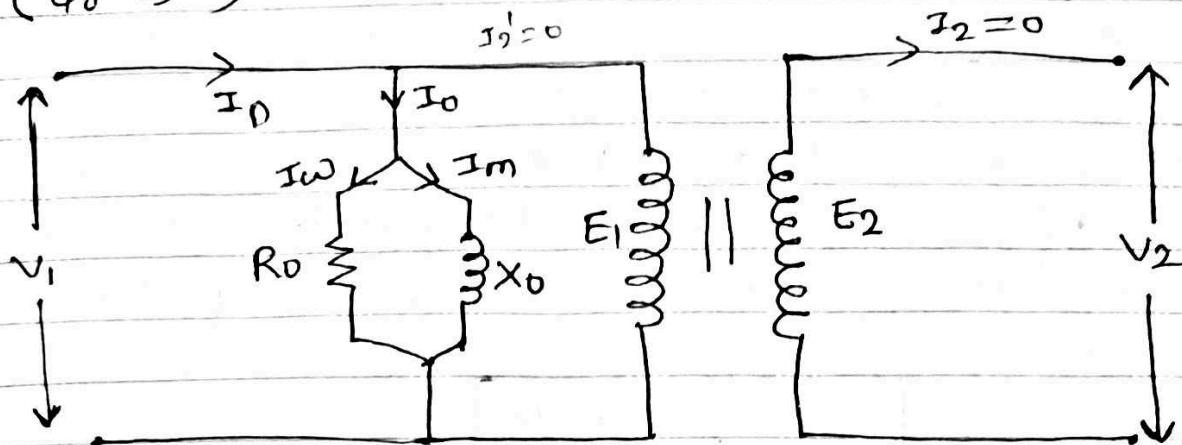


Fig. No load equivalent circuit of practical transformer

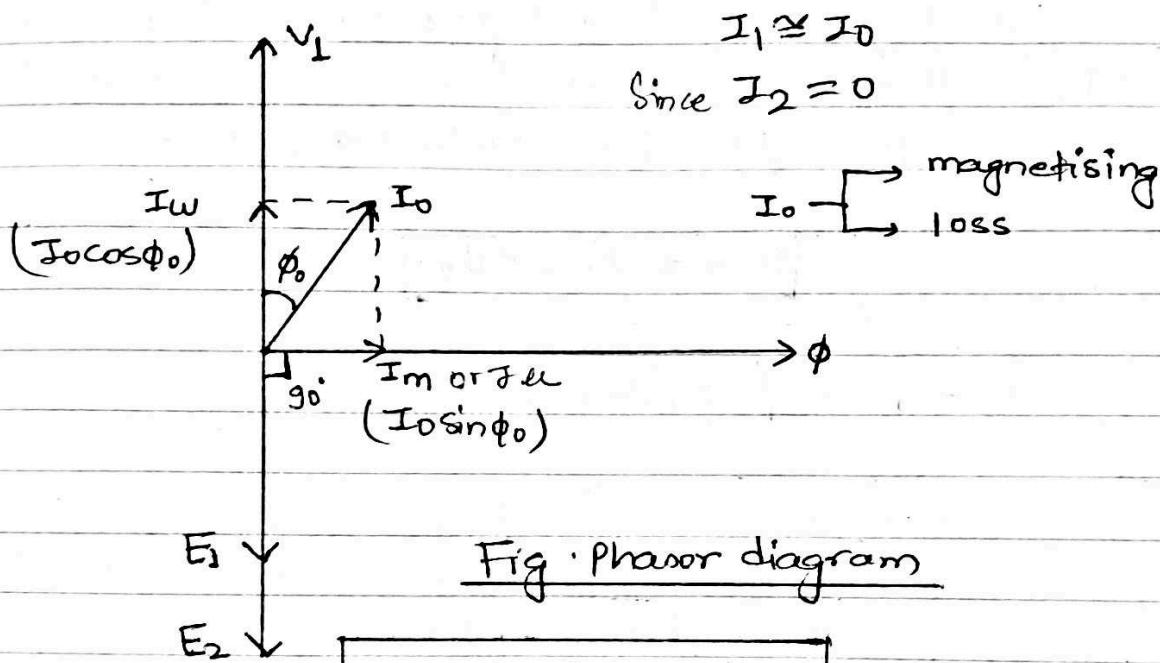


Fig. Phasor diagram

$$\phi_0 = \tan^{-1} \left( \frac{I_m}{I_w} \right)$$

$I_m$  = magnetising component

$I_w$  = active or working or iron loss or core loss component

$$I_m = \frac{V_1}{X_0}, \quad I_w = \frac{V_1}{R_0}$$

$$\text{input power} = \text{core or iron loss} = \frac{V_1^2}{R_0} = V_1 I_0 \cos\phi$$

No load current is resolved into two components -

- a) The component  $I_{00}$  in phase with applied voltage  $V_1$ . This is known as active or working or iron loss component and supplies iron loss and very small primary copper loss.

$$I_{00} = I_0 \cos\phi_0$$

- b) The component  $I_m$  lagging behind  $V_1$  by  $90^\circ$  and is known as magnetising component. It is this component which produces the alternating flux (mutual flux) in the core.

$$I_m = I_0 \sin\phi_0$$

$$I_0 = \sqrt{I_{00}^2 + I_m^2}$$

$$\cos\phi_0 = \frac{I_{00}}{I_0} \quad (\text{From above})$$

$\uparrow$   
No load power factor

$$\text{No load input power} - (W_0) = \text{iron losses} \\ = I_{00}^2 R_0$$

$$= \frac{V_1^2}{R_0}$$

Q.1) A 11kV/400V distribution transformer takes a no load primary current of 1amp at a power factor of 0.24 lagging.  
 Find i) The coreloss current ii) magnetising current  
 iii) The iron loss

⇒ Soln

we have given,

$$\text{No load current } (I_0) = 1 \text{ A}$$

$$\text{power factor } (\cos\phi) = 0.24 \text{ lagging}$$

$$\text{primary voltage } (V_1) = 11 \text{ kV}$$

i) coreloss current

$$\rightarrow \text{coreloss current } (I_w) = I_0 \cos\phi = 1 \times 0.24 \\ = 0.24 \text{ A}$$

$$\text{i) magnetising current } (I_m) = I_0 \sin\phi = I_0 \sqrt{1 - \cos^2\phi} \\ = 1 \times \sqrt{1 - 0.24^2} \\ = 0.971 \text{ A}$$

iii) Iron loss

$$\rightarrow \text{Iron loss} = V_1 I_0 \cos\phi = 11000 \times 1 \times 0.24 \\ = 2640 \text{ W} \\ = 2.64 \text{ kW}$$

$$\text{Iron loss} = 2.64 \text{ kW}.$$

Q.2) A single phase transformer of 3300/220V, 50Hz takes a no load current of 0.8A and 500W. Calculate i) active and magnetising current ii) its pf

→ Soln -

we have given,

$$\text{No load current } (I_0) = 0.8 \text{ A}$$

$$\text{No load power} = 500 \text{ W}$$

$$\text{Primary voltage} = 3300 \text{ V}$$

i) active and magnetising current

$\rightarrow \text{active current } (I_{\text{ac}}) = I_0 \cos \phi_0 = \frac{\text{No load power}}{\text{primary voltage}}$

$[\text{No load power } (P_0) = I_0 \times V_1]$   $= \frac{500}{3300} = 0.152 \text{ A}$

$$\begin{aligned}\text{magnetising current } (I_m) &= \sqrt{I_0^2 - I_{\text{ac}}^2} \\ &= \sqrt{0.8^2 - 0.152^2} \\ &= 0.785 \text{ A}\end{aligned}$$

ii)  $\cos \phi_0 = \frac{I_{\text{ac}}}{I_0} = \frac{0.152}{0.8} = 0.19$  lagging

## Ideal transformer on Load

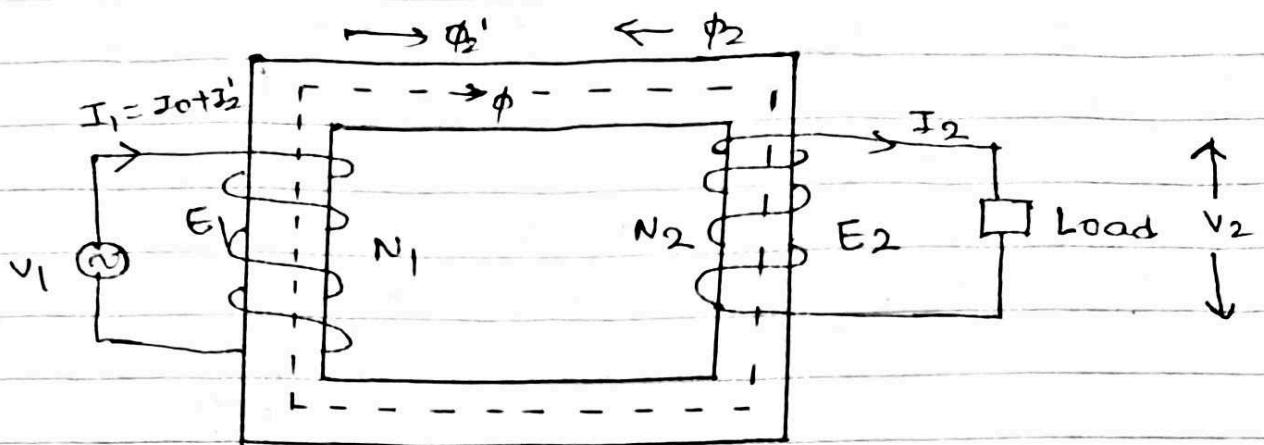


Fig. An ideal transformer on load

The no load current  $I_0$  sets up mmf  $N_1 I_0$  producing flux  $\phi$  in the core. When load is connected, current  $I_2$  flows in the secondary winding which also set up a mmf  $N_2 I_2$  producing secondary flux  $\phi_2$  which opposes main flux  $\phi$  according to Lenz law. This weakens the main flux momentarily i.e. the back emf  $E_1$  also tends to reduce the difference between  $V_1$  and  $E_1$ . This will cause more current to be drawn from the source until the back emf  $E_1$  balances the voltage  $V_1$ . Let  $I_2'$  be the additional primary current. The current  $I_2'$  is called counter-balancing current because it is in phase opposition with the secondary current  $I_2$ . Such that the  $I_2'$  set some extra mmf  $N_1 I_2'$  producing flux  $\phi_1'$  which will be in the same direction of main flux  $\phi$  and can cancel the flux  $\phi_2$  produced by mmf  $N_2 I_2$  and tries to maintain the original value of main flux.

we can show that the flux  $\phi_2$  and  $\phi_2'$  are equal in magnitude as follows -  
we have,

$$\text{Output VA} = V_2 I_2$$

and additional power input  $= V_1 I_2'$

$$[I_1 = I_0 + I_2' \quad I_0 \approx 0]$$

$$I_1 \approx I_2'$$

For power balance,

$$V_2 I_2 = V_1 I_2'$$

$$\frac{V_2}{V_1} = \frac{I_2'}{I_2} = \frac{N_2}{N_1}$$

$$N_1 I_2' = N_2 I_2 \quad \text{--- (i)}$$

$$\phi_2 = \frac{N_2 I_2}{R} \quad \text{--- (ii)} \quad \phi_2' = \frac{N_1 I_2'}{R} \quad \text{--- (iii)}$$

From eqn (i), eqn (ii) and eqn (iii)

$$\boxed{\phi_2 = \phi_2'}$$

It is evident from this discussion that  $\phi_2$  and  $\phi_2'$  are of equal magnitude and always oppose each other (Lenz law) and cancel out completely. Hence the net magnetic flux in the core of a transformer is always irrespective of the load. (constant flux)

From above

$$\frac{I_2'}{I_2} = \frac{N_2}{N_1} = \frac{I_1}{I_2} \quad [I_1 = I_0 + I_2' \quad I_0 \approx 0]$$

$$\boxed{I_2' = k I_2}$$

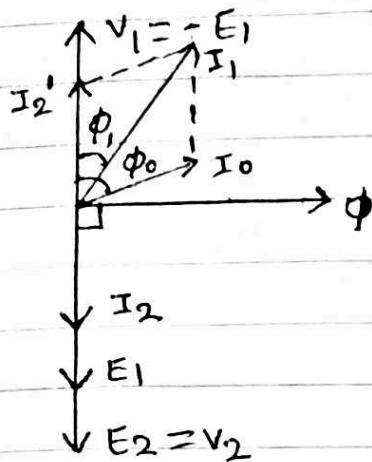
$$k = N_2 / N_1$$

$$\boxed{\frac{I_1}{I_2} = \frac{N_2}{N_1} = k}$$

The phasor diagrams of ideal transformer on load

- a) resistive load
- b) Inductive load
- c) capacitive load

$\Rightarrow V_1 = -E_1$  and  $V_2 = E_2$  as voltage drops in both windings are negligible.



$$\boxed{I_2' = k I_2}$$

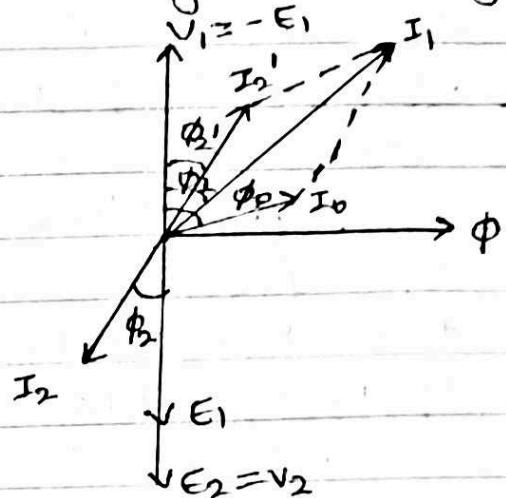


Fig (a) resistive load

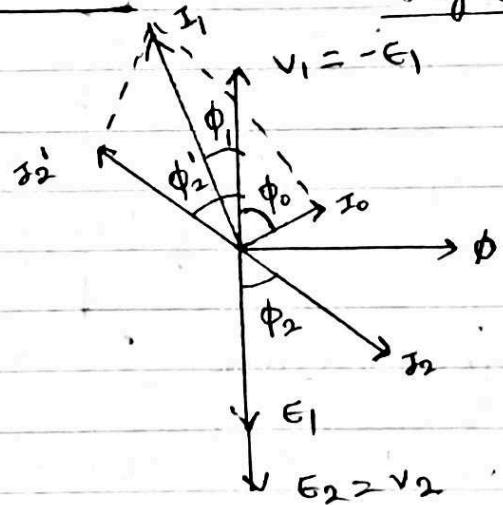


Fig (b) inductive load

Fig (c) capacitive load

## Practical transformer on Load.

### Resistance and leakage reactance.

In actual transformer both the windings, primary and secondary windings have finite resistance  $R_1$  and  $R_2$  which cause copper losses and voltage drop in them.

It was assumed that entire flux  $\phi$ , developed by the primary coincides with the secondary winding but it is impossible to realize this condition. However, part of the flux set up by the primary winding links only primary turns named  $\phi_{l1}$  and also some of flux set up by the secondary winding links only secondary turns named as  $\phi_{l2}$  as shown in fig below: These two fluxes  $\phi_{l1}$  and  $\phi_{l2}$  are known as leakage flux.

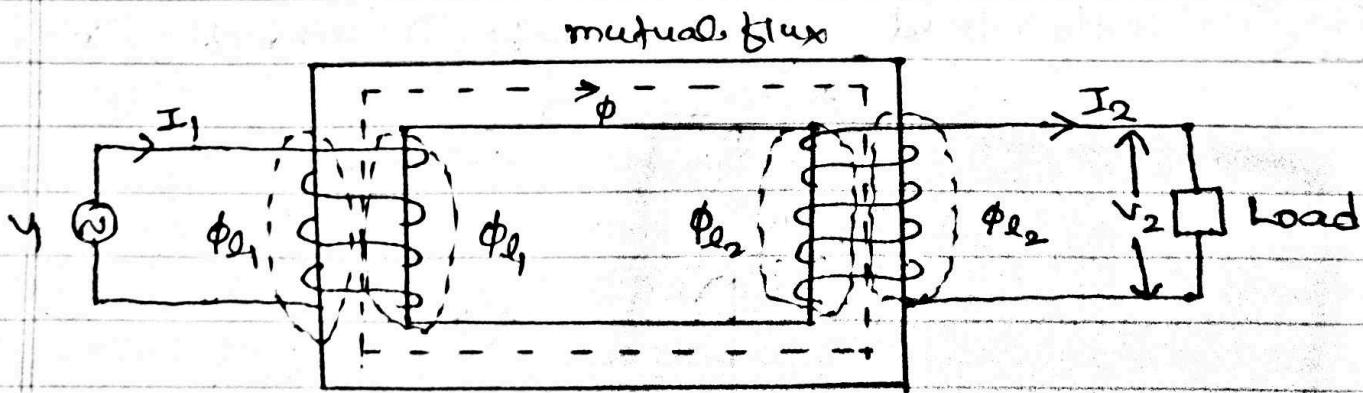


Fig. magnetic fluxes in a transformer

To represent the effect of leakage flux, we add an reactance in the equivalent circuit as follow:

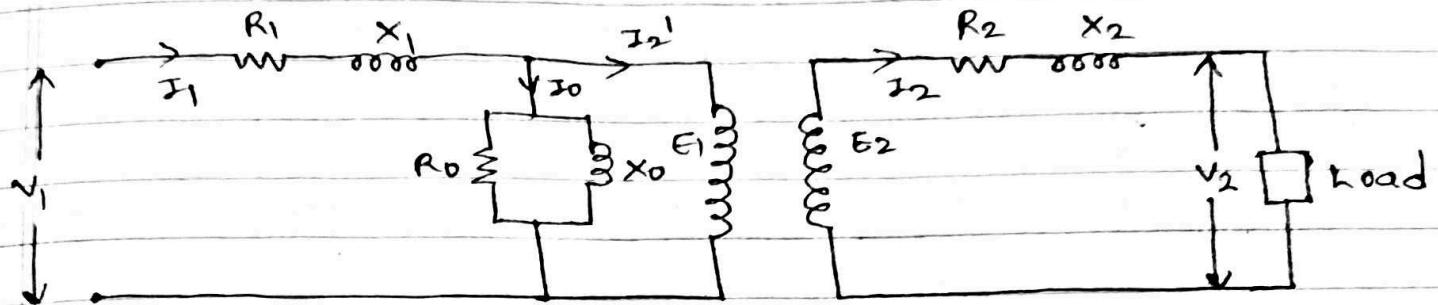
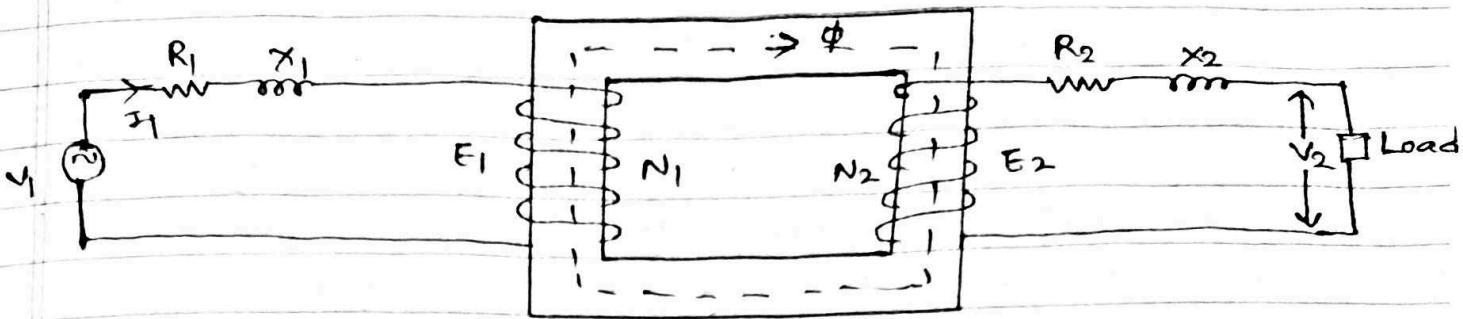


Fig. equivalent circuit diagram of practical transformer

$R_1$  = internal resistance of pw

$X_1$  = leakage reactance of pw

$R_2$  = internal resistance of sw

$X_2$  = leakage reactance of sw

$Z_1 = R_1 + jX_1$  = impedance of pw

$Z_2 = R_2 + jX_2$  = impedance of sw

Since  $E_1$  is the voltage induced in the primary winding, it is equal and opposite to the component of the applied voltage at the ideal transformer winding. Let  $v'_1$  be the voltage applied to the primary of the ideal transformer to neutralize the effect of induced voltage  $E_1$ . Thus  $v'_1$  is equal and opposite to  $E_1$ . The phasor sum  $v'_1 R_1$ ,  $v'_1 X_1$  and  $v'_1$  is equal to the supply voltage  $V_1$ .

$$V_1 = V_1' + jI_1 R_1 + jI_1 X_1$$

$$V_1 = -E_1 + jI_1 R_1 + jI_1 X_1$$

$$V_1 = -E_1 + j_1 (R_1 + jX_1) \quad - \textcircled{1}$$

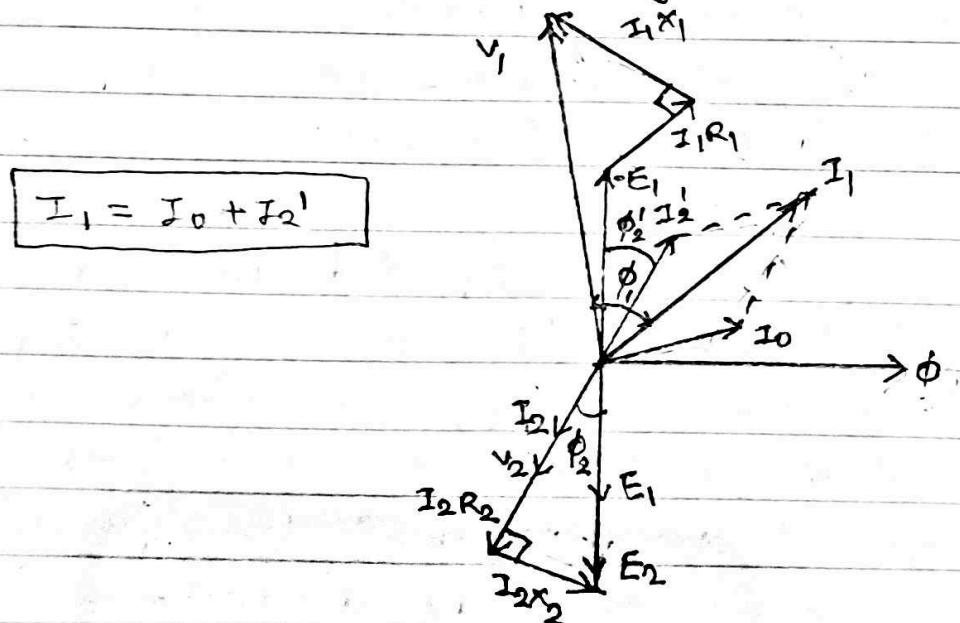
Similarly Secondary induced voltage  $E_2$  is the phasor sum of  $V_2$ ,  $j_2 R_2$  and  $j_2 X_2$

$$E_2 = V_2 + j_2 R_2 + j_2 X_2$$

$$E_2 = V_2 + j_2 (R_2 + jX_2) \quad - \textcircled{2}$$

### Phasor diagram of actual transformer on load

The phasor diagrams of actual (practical) transformer on load (i) pure resistive  
(ii) resistive-inductive and (iii) resistive-capacitive loads are shown below in fig (a), fig (b)  
and fig (c) respectively.



Fig(a) Phasor diagram of actual transformer on pure resistive load

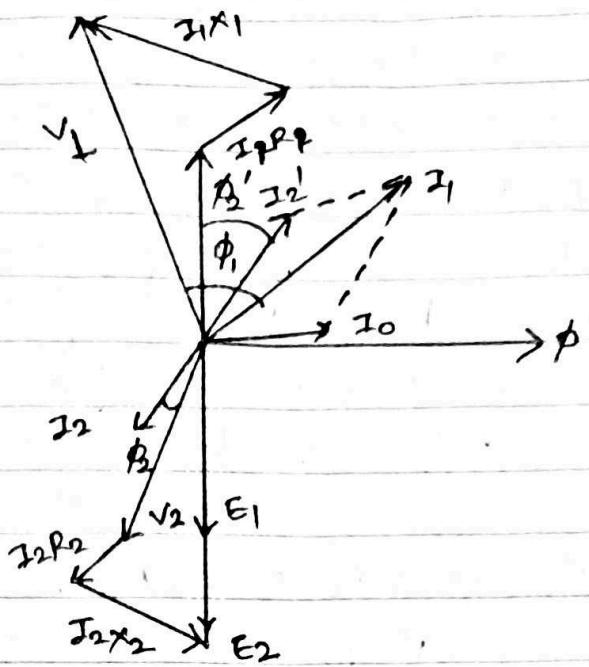


Fig (b) resistive - inductive load

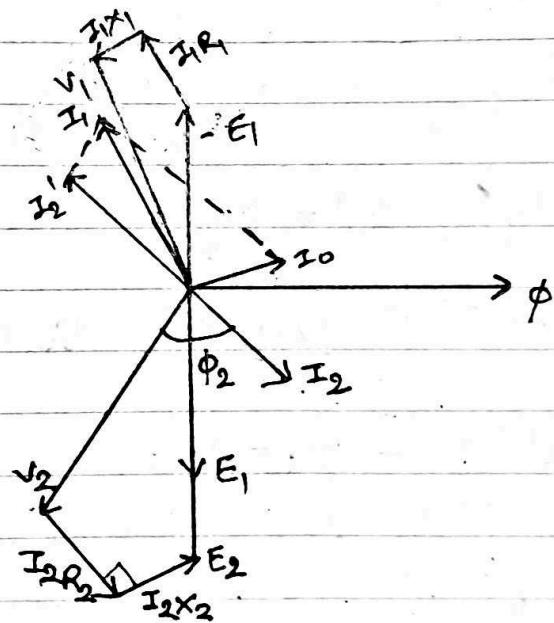


Fig (c) resistive capacitive load

## Transformation of Impedance

The transformation of Impedance is done for the simplicity of mathematical analysis. The resistance and leakage reactance in secondary winding can be transferred to primary side so that effect of  $(R_2')$  in primary side is equivalent to effect of  $R_2$  in Secondary side.

The  $R_2$  produces heat loss of  $I_2^2 R_2$  when  $R_2$  is transferred to primary side, it should produce same amount of heat loss i.e.

$$I_2^2 R_2 = I_1^2 R_2' \approx I_2'^2 R_2'$$

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

We know,

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1} = k$$

$$R_2' = \left(\frac{1}{k}\right)^2 R_2$$

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

$$\text{Similarly, } X_2' = \frac{X_2}{k^2} \quad \text{and } Z_L' = \frac{Z_L}{k^2}$$

Secondary terminal voltage referred to primary side,

$$V_2' = I_2' Z_L' = I_1 Z_L' = (k I_2) \left(\frac{Z_L}{k^2}\right) = \frac{I_2 Z_L}{k}$$

$$V_2' = (V_2/k)$$

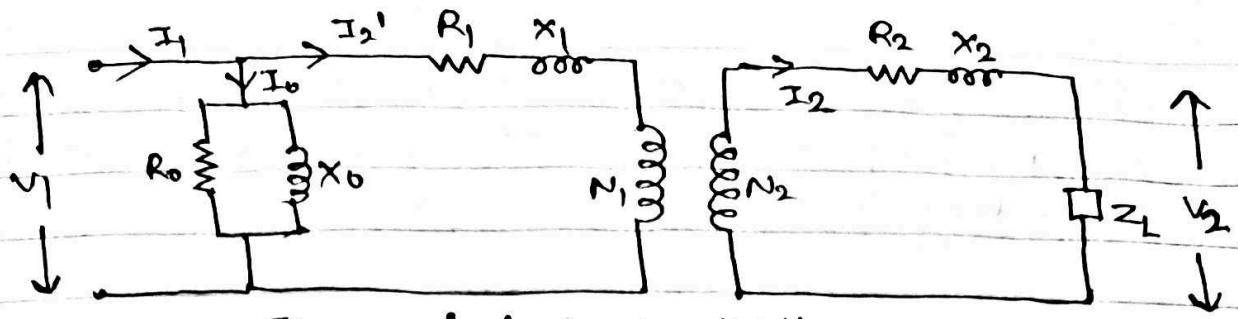


Fig. equivalent circuit diagram of tr-er

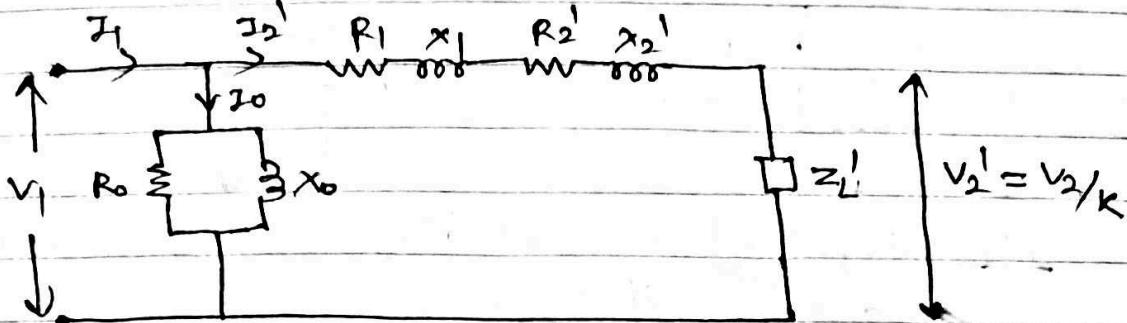


Fig. equivalent circuit diagram referred to primary side

Also,

$$R_{01} = (R_1 + R_2') = R_1 + \frac{R_2}{k^2} = \text{equivalent resistance referred to primary side}$$

$$x_{01} = x_1 + x_2' = x_1 + \frac{x_2}{k^2} = \text{equivalent leakage reactance referred to primary side.}$$

$$z_{01} = \sqrt{R_{01}^2 + x_{01}^2} = \text{equivalent impedance referred to primary side}$$

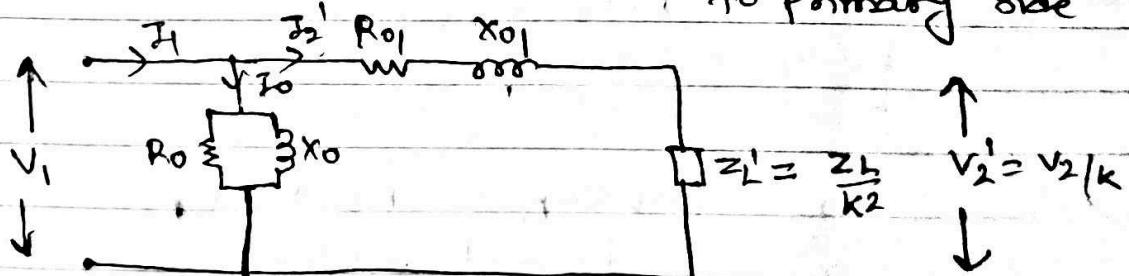


Fig. Simplified eq. ckt of tr-er referred to P.S

Similarly, resistance and leakage reactance of primary winding can be transferred to Secondary side.

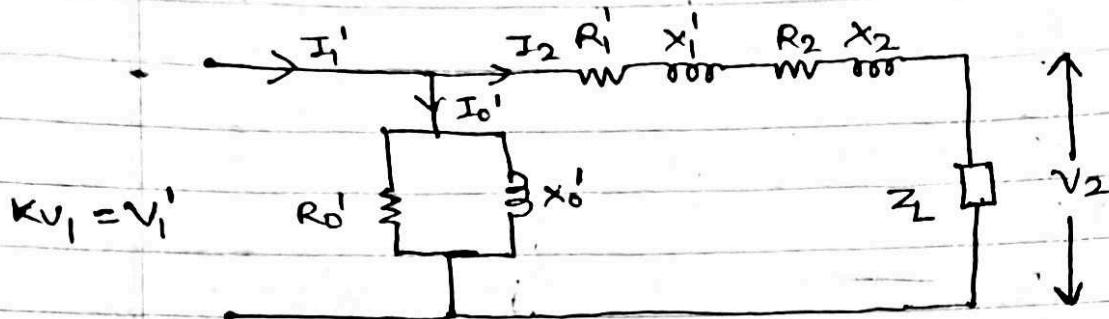


Fig Simplified eq. ckt diagram referred to Secondary side.

For heat loss to be same;

$$(I_2')^2 R_1 = I_2^2 R_1'$$

$$\left(\frac{I_2'}{I_2}\right)^2 = \left(\frac{R_1'}{R_1}\right)$$

$$\left(\frac{I_2}{I_2}\right)^2 = \left(\frac{R_1'}{R_1}\right) = k^2$$

$$R_1' = k^2 R_1$$

Similarly,

$$\boxed{\begin{aligned} x_1' &= k^2 x_1 \\ R_0' &= k^2 R_0 \\ x_0' &= k^2 x_0 \end{aligned}}$$

$$\text{Also, } R_{02} = R_0 + R' = R_2 + k^2 R$$

= equivalent resistance of torer  
referred to Secondary side

$$x_{02} = x_2 + x'_1 = x_2 + k^2 x_1$$

= equivalent leakage reactance of transformer referred to secondary side.

$$z_{02} = \sqrt{R_{02}^2 + x_{02}^2} = \text{eq. impedance}$$

$$\frac{(v'_1)^2}{R_0'} = \frac{(v_1)^2}{R_0}$$

$$\frac{v'^2}{k^2 R_0} = \frac{v_1^2}{R_0} \Rightarrow v'^2 = k^2 v_1^2$$

$$v'_1 = k v_1$$

Primary voltage referred to secondary side.

$$I_0' = \frac{v'_1}{z_0'} = \frac{v'_1}{R_d + j X_d} = \frac{k v_1}{k^2 (R_0 + j X_0)} = \frac{I_0}{k}$$

$$I_0' = I_0/k$$

Primary no load current referred to secondary side.

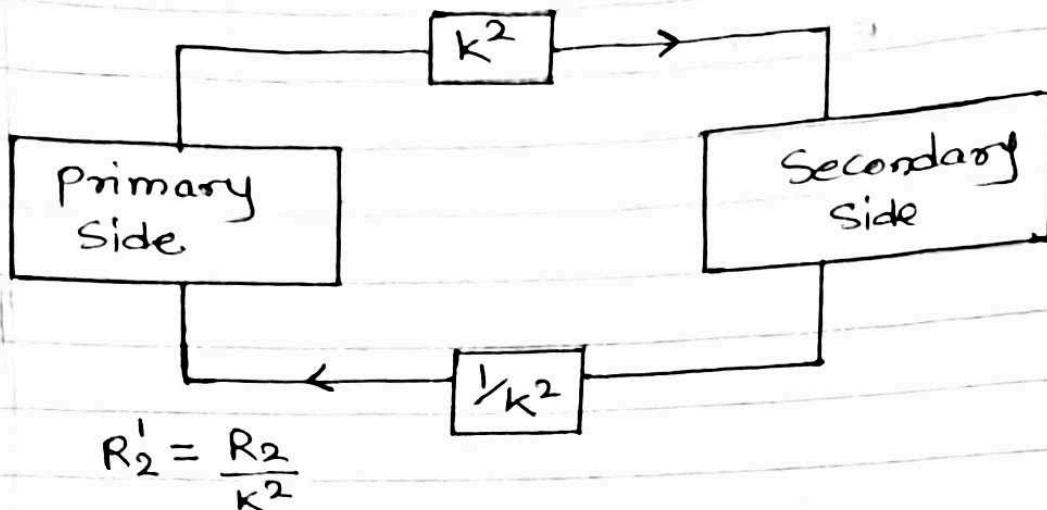
$$I_1' = I_0' + I_2 = \left( \frac{I_0}{k} + \frac{I_2'}{k} \right) = \frac{I_0 + I_2'}{k} = \frac{I_1}{k}$$

$$I_1' = \frac{I_1}{k} \quad \text{primary current referred to secondary side.}$$

Summary

For impedance ( $Z$ ),  $R$  and  $X$

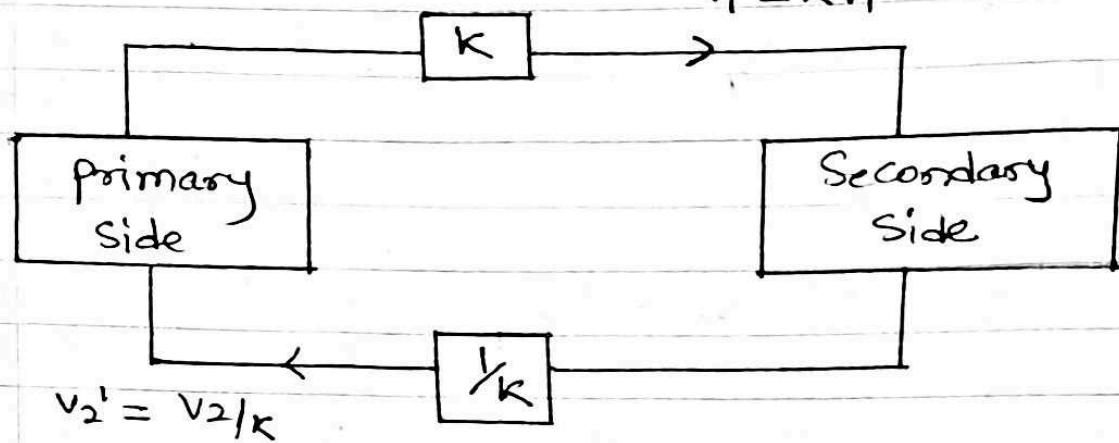
$$R'_1 = k^2 R_1$$



2)

For voltage

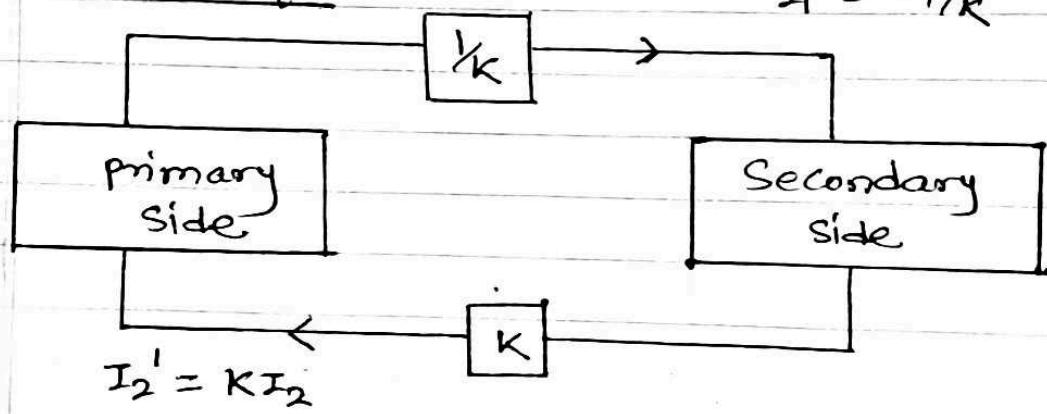
$$V'_1 = k V_1$$



3)

current

$$I'_1 = I_1 / k$$



Q) 1) A 25kVA, 2200/220V, 50Hz, 1-phase transformer has following parameters :

$R_1 = 1.75 \Omega$ ,  $R_2 = 0.0045 \Omega$ ,  $x_1 = 2.6 \Omega$ ,  $x_2 = 0.0075 \Omega$   
 calculate : i) Equivalent resistance referred to primary and secondary ii) Equivalent reactance referred to primary and secondary

⇒ Soln -

$$\text{Transformation ratio (K)} = \frac{V_2}{V_1} = \frac{220}{2200} = 0.1$$

i) Equivalent resistance referred to primary

$$R_{01} = R_1 + \frac{R_2}{K^2} = 1.75 + \frac{0.0045}{0.1} = 2.2 \Omega$$

Equivalent resistance referred to secondary

$$R_{02} = K^2 R_1 + R_2 = (0.1)^2 * 1.75 + 0.0045 \\ = 0.022 \Omega$$

ii) Equivalent reactance referred to primary

$$X_{01} = x_1 + \frac{x_2}{K^2} = 2.6 + \frac{0.0075}{(0.1)^2} = 3.35 \Omega$$

Equivalent reactance, referred to secondary

$$X_{02} = K^2 x_1 + x_2 = (0.1)^2 * 2.6 + 0.0075 \\ = 0.0335 \Omega$$

Q.2) A 30kVA, 2000/200V, Single-phase, 50Hz transformer has primary resistance of  $3\text{ }\Omega$  and reactance of  $4\text{ }\Omega$ . The secondary resistance and reactance are  $0.015\Omega$  and  $0.02\Omega$  respectively. Find i) equivalent resistance, reactance and impedance referred to the primary side ii) total copper loss in the transformer.

$\Rightarrow$  Soln -

$$\text{Transformation ratio } (K) = \frac{v_2}{v_1} = \frac{200}{2000} = 0.1$$

$$\text{Full load primary current } (I_1) = \frac{30 \times 1000}{2000}$$

$$= 15 \text{ A}$$

Equivalent resistance referred to primary

$$R_{01} = R_1 + \frac{R_2}{K^2} = 3.5 + \frac{0.015}{(0.1)^2} = 5\Omega$$

Equivalent reactance referred to primary

$$X_{01} = X_1 + \frac{X_2}{K^2} = 4.5 + \frac{0.02}{(0.1)^2} = 6.5\Omega$$

Equivalent impedance referred to primary

$$Z_{01} = \sqrt{(R_{01})^2 + (X_{01})^2}$$

$$= \sqrt{5^2 + 6.5^2}$$

$$= 8.2\Omega$$

$$\text{Total copper loss in tower} = I_1^2 R_{01}$$

$$= 15^2 * 5 = 1125 \text{ W}$$

## Testing of transformer

### 1) Polarity testing -

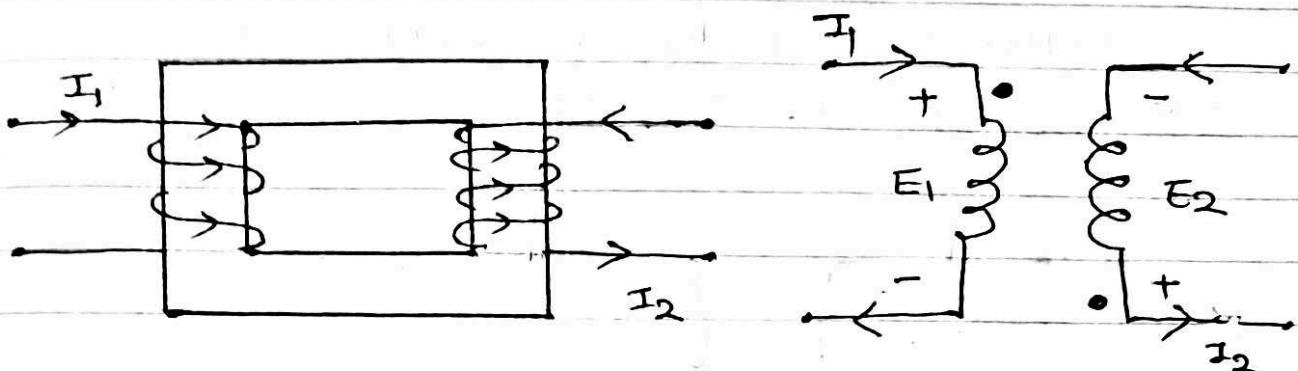
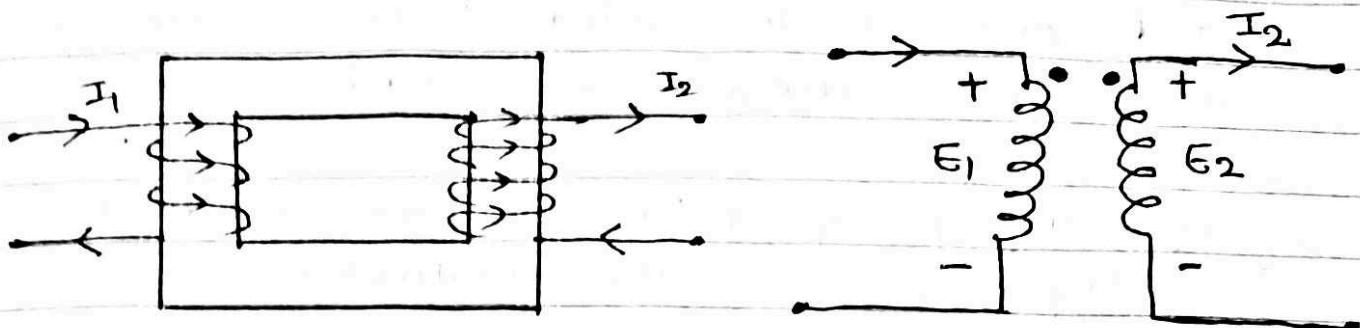


Fig. Polarity of transformer windings

### Dot convention

positive terminal  $\rightarrow$  dot ( $\bullet$ )

p.s  $\rightarrow$  current enters at dot ( $\bullet$ )

s.s  $\rightarrow$  current leaves from dot ( $\bullet$ )

$\Rightarrow$  Polarity test are performed to determine the terminals having same instantaneous polarity.

usually polarity is indicated by the dot convention as shown in fig above. Similar polarity ends of a two winding transformer are those ends that acquire simultaneously positive or negative polarity because of emf induced in them.

In polarity test, the two windings are connected in series across the voltmeter and one of the winding is excited by a suitable voltage source and

- If polarity of primary and Secondary winding is same then voltmeter reading will be  $V = E_1 - E_2$
- If voltmeter reads  $V = E_1 + E_2$  then windings are of opposite polarity.

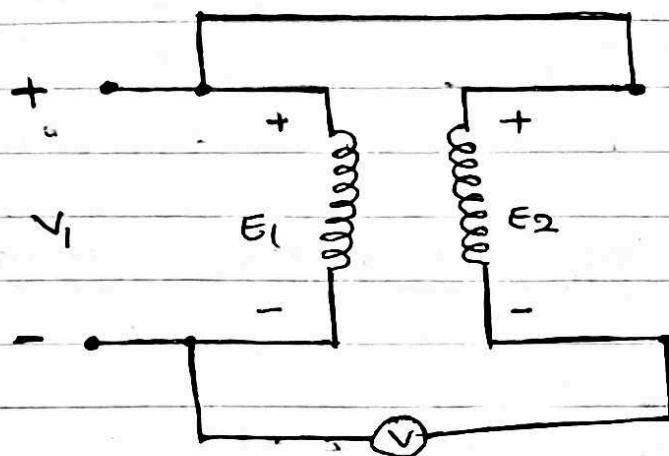


Fig. polarity test

- open circuit and short-circuit tests -  
open circuit and short circuit tests are performed to determine the circuit constants, efficiency and regulation without actually loading transformer. These tests give more accurate results than those obtained by taking measurements on fully loaded transformer. Also, the power consumption in these tests is very small compared with

the full-load output of the transformer.

a) open-circuit test (No load test) -

- This test is performed on L.V side
- It is done at rated voltage and frequency.

L.V	H.V
$V \downarrow$	$V \uparrow$
$I \uparrow$	$I \downarrow$

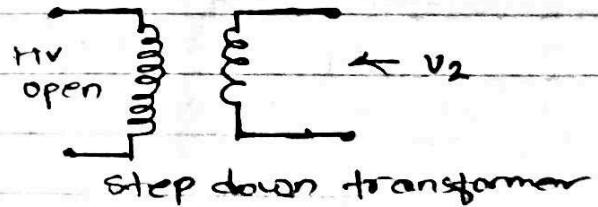
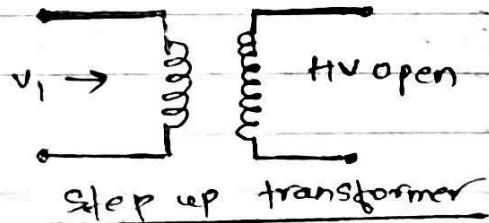
No load current is (2-5)% of full load current

→ The main purpose of this test is to obtain:

- i) Shunt branch parameters of the eq. ckt
- ii) No load power loss
- iii) No load current
- iv) No load power factor

Procedure :

- i) The high voltage winding is kept open and low voltage winding is supplied by rated voltage.
- ii) Ammeter, voltmeter and wattmeter are connected as shown in figure.



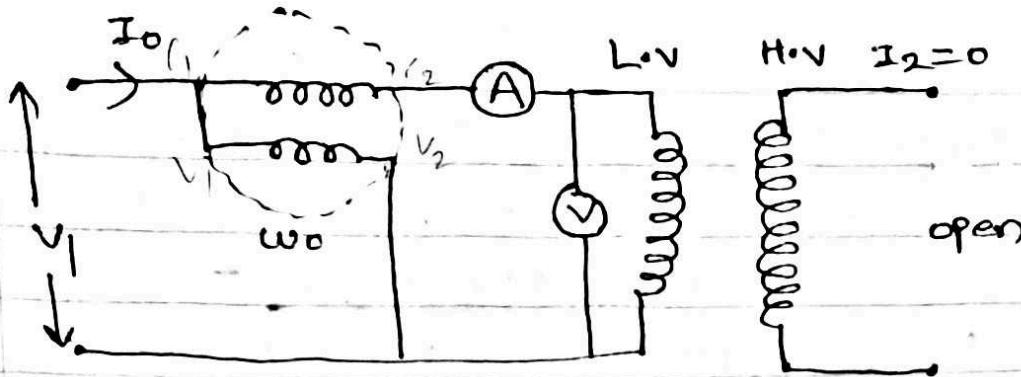


Fig open circuit test on transformer

Let  $V_1$  = voltmeter reading (rated voltage)  
 $I_0$  = Ammeter reading (no load current)  
 $W_0$  = wattmeter reading (no load power loss)  
 ↓  
 iron loss

As the no load current is very small with compare to full load current and the series resistance and reactance  $R_1$  and  $x_1$  are also small. copper loss at no load can be neglected and the wattmeter reading can be considered as no load power loss or iron loss of the transformer. The equivalent ckt at no load condition can be realised as shown in fig below:

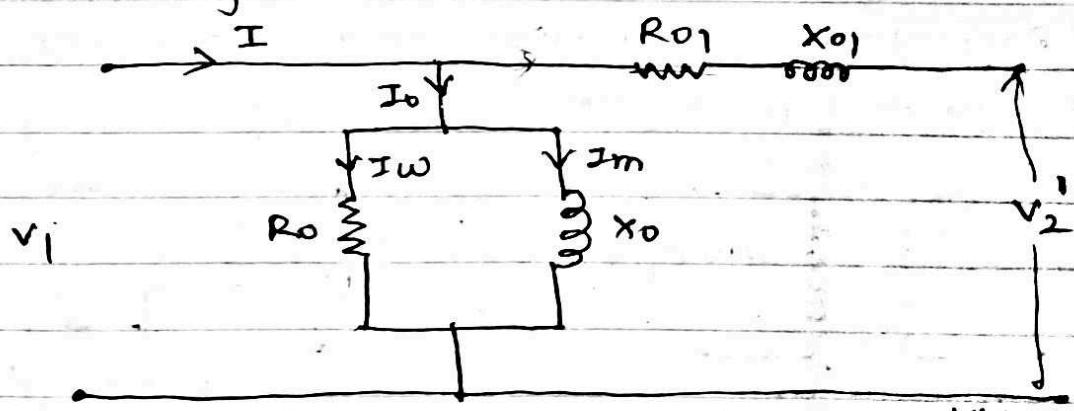


Fig Eq. ckt for no load condition

$$w_0 = V_1 I_0 \cos \phi_0$$

$\cos \phi_0$  = No load power factor

$$I_w = I_0 \cos \phi_0$$

$$I_m = I_0 \sin \phi_0$$

$$R_o = \frac{V_1}{I_w} = \frac{V_1}{I_0 \cos \phi_0}$$

$$X_o = \frac{V_1}{I_m} = \frac{V_1}{I_0 \sin \phi_0}$$

Hence  $R_o$  and  $X_o$  are obtained in above analysis

### b) Short circuit test (Impedance test) -

→ This test is performed on H.V side.

→ The main purpose of this test is to obtain the series resistance and leakage reactance and copper loss of transformer at full load.

→ This test is done at rated current.

Procedure:

i) In this test, (L.V) winding is shorted (short circuited) by a thick wire and variable voltage is applied to H.V winding. The low input voltage is gradually increased till at voltage ( $V_{sc}$ ), full load current  $I_1$ , flows in the primary. Then  $I_2$  in the secondary also has full load value since ( $Z_{sc} = \frac{V_2}{I_2}$ )

There is no output from transformer under short circuit conditions, and therefore input power is all loss and this loss is entirely

Copper loss and iron loss is negligible in this case because  $V_{SC}$  is very small.

ii)

Ammeter, voltmeter and wattmeter are connected as shown.

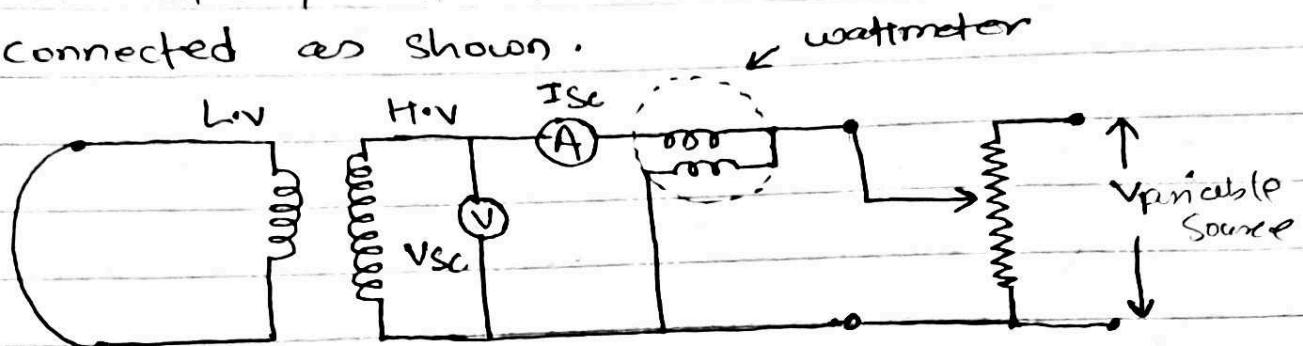


Fig. short circuit test

The equivalent circuit of the transformer for short circuit test is shown below:

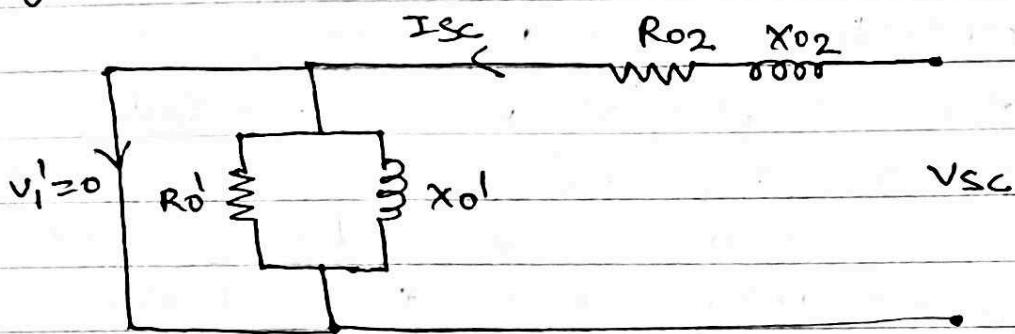


Fig. Eq. ckt for short circuit test

Now we take readings of ammeter, voltmeter and wattmeter as,

$I_{SC}$  = ammeter reading

$V_{SC}$  = voltmeter reading

$W_{SC}$  = wattmeter reading

Here, shunt branch is shorted and no current flows through shunt branch

$$V_{SC} = I_{SC}^2 R_{02}$$

$$R_{02} = \frac{V_{SC}}{I_{SC}^2}$$

also,

$$Z_{02} = \frac{V_{SC}}{I_{SC}}$$

$$X_{02} = \sqrt{(Z_{02})^2 - (R_{02})^2}$$

Hence, parameters of equivalent circuit can be calculated.

Q) Why short circuit test is performed on hv side?

⇒ The reasons for shorting Lv side and taking measurements on the hv side are as follows:

i) The rated current on hv side is lower than that on Lv side. This current can be safely measured with the available laboratory ammeters.

ii) Since the applied voltage is less than 5% of the rated voltage of the winding, greater accuracy in the reading of the voltmeter is possible when the hv side is used as the primary.

Q.1) A 50kVA, 2200/110 transformer when tested gave the following results :

OC test : 400W 10A 110V

SC test : 808W 20.5A 90V

Compute all the parameters of the equivalent circuit referred to H.V side and L.V side of the transformer.

⇒ Sol'n -

Here,

$$S = 50 \text{ kVA}$$

$$V_1 = 2200 \text{ V} \quad V_2 = 110 \text{ V}$$

H.V → primary      L.V → Secondary

Now, OC test

$$w_d = 400 \text{ W} \quad I_o' = 10 \text{ A} \quad V_1' = 110 \text{ V} = V_2$$

SC test

$$w_{sc} = 808 \text{ W} \quad I_{sc} = 20.5 \text{ A} \quad V_{sc} = 90 \text{ V}$$

From O.C test :-

Referred to L.V side

$$\cos \phi_0 = \frac{w_d}{V_1' I_o} = \frac{400}{110 \times 10} = 0.36$$

$$R_o' = \frac{V_1'}{I_o \cos \phi_0} = \frac{110}{10 \times 0.36} = 30.55 \Omega$$

$$X_o' = \frac{V_1'}{I_o \sin \phi_0} = \frac{110}{10 \times \sqrt{1-0.36^2}} = 11.79$$

Referred to H.V side

$$R_o = \frac{R_o'}{K^2} = \frac{30.55}{0.05^2} = 1222 \Omega$$

$$X_o = \frac{X_o'}{K^2} = \frac{11.79}{0.05^2} = 4720 \Omega$$

From S.C test, (P.S)

Referred to H.V side,

$$R_{01} = \frac{V_{SC}}{I_{SC}} = \frac{808}{(20.5)^2} = 1.922 \Omega$$

$$Z_{01} = \frac{V_{SC}}{I_{SC}} = \frac{90}{20.5} = 4.39 \Omega$$

$$x_{01} = \sqrt{z_{01}^2 - R_{01}^2} = \sqrt{4.39^2 - 1.922^2}$$

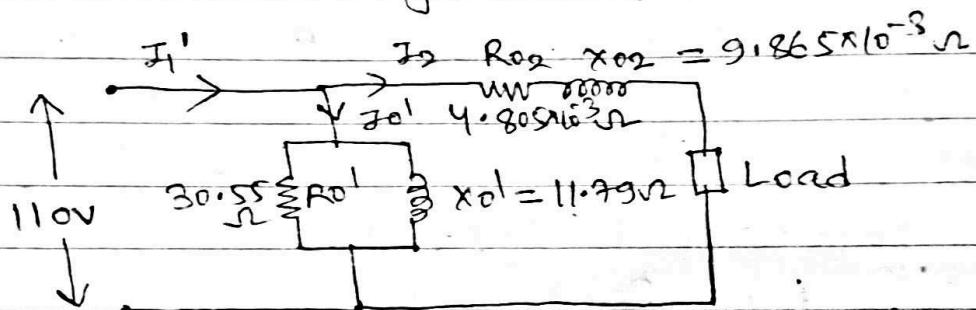
$$x_{01} = 3.946 \Omega$$

Referred to L.V side,

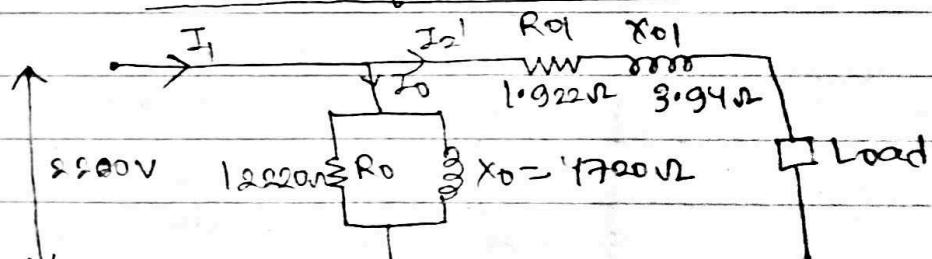
$$R_{02} = 1.922 * (0.05)^2 = 4.805 * 10^{-3} \Omega$$

$$x_{02} = 3.946 * (0.05)^2 = 9.865 * 10^{-3} \Omega$$

Equivalent C.R.T diagram referred to L.V side,



Eq. C.R.T referred to L.V side (S.S.)



Q.2) A 20kVA, 250/2500V, 50Hz, 1- $\phi$  transformer gave the following test results:

OC (L.V side)	250V	1.4A	105W
SC (H.V side)	120V	8A	320W

Find the parameters and draw the equivalent circuit of 1- $\phi$  transformer as referred to:

i) Low voltage side. ii) High voltage side.

$\Rightarrow$  Sol'n -

we have given,

$$S = 20\text{kVA}$$

$$V_1 = 250\text{V} \quad V_2 = 2500\text{V}$$

OC (L.V side) test

$$V_1 = 250\text{V} \quad I_0 = 1.4\text{A} \quad W_0 = 105\text{W}$$

$$P_0 = V_1 I_0 \cos \phi_0$$

SC (H.V side) test

$$V_{SC} = 120\text{V} \quad I_{SC} = 8\text{A} \quad W_{SC} = 320\text{W}$$

From OC test

referred to L.V side,

$$\cos \phi_0 = \frac{W_0}{V_1 I_0} = \frac{105}{250 \times 1.4} = 0.3$$

$$R_0 = \frac{V_1}{I_0 \cos \phi_0} = \frac{250}{1.4 \times 0.3} = 595.23\Omega$$

$$X_0 = \frac{V_1}{I_0 \sin \phi_0} = \frac{250}{1.4 \sqrt{1-0.3^2}} = 187.19\Omega$$

No load resistance ( $R_0$ ) and reactance ( $X_0$ ) referred to hv side

$$R'_0 = K^2 R_0 = \left(\frac{2500}{250}\right)^2 \times 595.23 = 59523\Omega$$

$$X'_0 = K^2 X_0 = (10)^2 \times 187.19 = 18719\Omega$$

From S.C test,  
Equivalent impedance referred to hv side,

$$z_{02} = \frac{V_{SC}}{I_{SC}} = \frac{120}{8} = 15 \Omega$$

Equivalent resistance referred to hv side,

$$R_{02} = \frac{V_{SC}}{I_{SC}^2} = \frac{320}{8^2} = 5 \Omega$$

Equivalent reactance referred to hv side,

$$x_{02} = \sqrt{z_{02}^2 - R_{02}^2} = \sqrt{15^2 - 5^2} = 14.14 \Omega$$

Equivalent resistance and reactance referred to L.V side,

$$R_{01}' = R_{01} = \frac{R_{02}}{K^2} = \frac{5}{10^2} = 0.05 \Omega$$

$$x_{01}' = \frac{x_{02}}{K^2} = \frac{14.14}{10^2} = 0.1414 \Omega$$

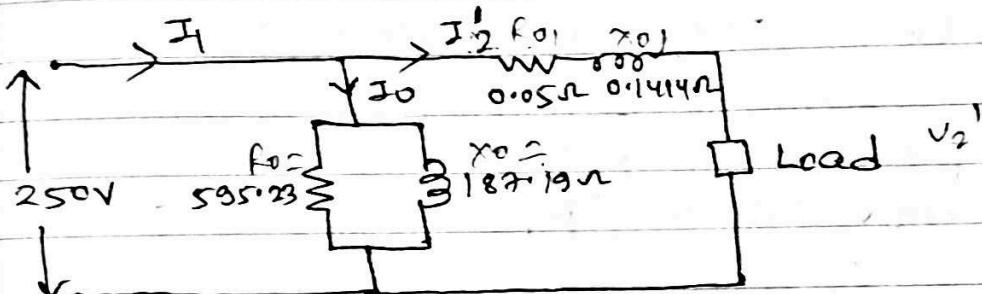


Fig. 59. ckt referred to L.V side. (primary side)

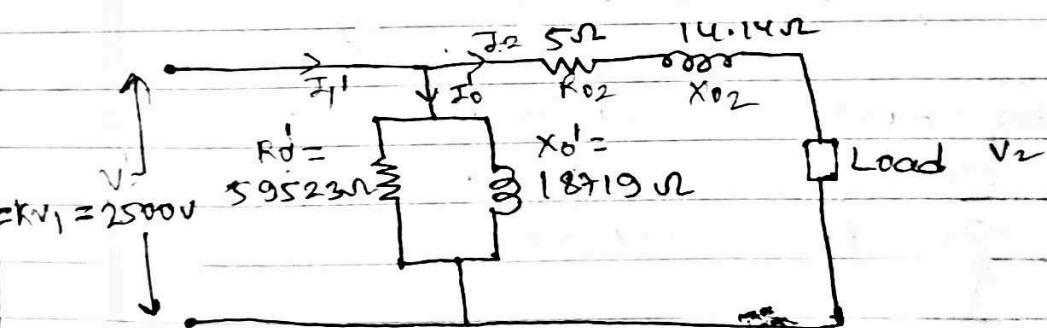


Fig. 59. ckt referred to H.V side (secondary side)

## Losses and Efficiency of transformer

The transformer has no moving parts so that its efficiency is much higher than rotating machines.

usually there are no such devices, which are 100% efficient. Similarly power loss takes place within the transformer, while it transfers power from one circuit to another circuit.

The various power losses occurring in a transformer are -

- 1) Iron or core loss - Iron loss is caused by the alternating flux in the core and consists of hysteresis and eddy current losses.  
a) Hysteresis loss - The core of a transformer is subjected to an alternating magnetising force, and for each cycle of emf, a hysteresis loop is traced out. The hysteresis loss per second is given by -

$$\text{Hysteresis loss } (P_h) = \eta (B_{\max})^x f v \text{ joules per sec}$$

or watt

where,  $f$  is supply frequency

$v$  is the volume of core in cubic metres.

$\eta$  is the hysteresis coefficient

$B_{\max}$  is peak value of flux density in the core and  $x$  lies between 1.5 and 2.5 depending upon material and is often taken as 1.6.

b)

Eddy current loss - If the magnetic circuit is made up of iron and if the flux in the circuit is variable, current will be induced by induction in the iron circuit itself. All such currents are known as eddy currents.

$$P_e = K_e (B_{max})^2 \delta^2 t^2 v \text{ watts or Joules/sec}$$

$t$  = thickness

Hysteresis and eddy current loss depend upon the maximum flux density in the core and supply frequency. Since it has determined that the mutual flux varies somewhat with load i.e. (1 to 3.1) from no load to full load, the core losses will vary somewhat with load and its power factor. This loss is assumed to be constant from no load to full load being very small and negligible.

$$\begin{aligned} \text{Iron loss } (P_i) &= \text{Hysteresis loss + Eddy current loss} \\ &\text{or} \\ &\text{core loss} \end{aligned}$$

= Constant losses

Note -

- i) Hysteresis loss can be minimised by using steel of silicon content for core.

whereas eddy current loss are minimised by using thin lamination (0.3 to 0.5 mm) (iron laminated).

- 2) Copper loss - These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test.

$$\begin{aligned}\text{Total losses } (P_C) &= I_1^2 R_1 + I_2^2 R_2 \\ &= I_1^2 R_{01} \text{ or } I_2^2 R_{02}\end{aligned}$$

$$\begin{aligned}\text{Total losses in a transformer} &= P_i + P_C \\ &= \text{constant losses} + \\ &\quad \text{variable losses}\end{aligned}$$

- 3) Stray load loss - leakage fields presents in the transformers include eddy currents in the conductors, tank wall, bolts etc. These eddy current loss gives rise to stray load loss

- 4) Dielectric loss - This loss occur in the insulating materials particularly in oil and solid materials

⇒ These stray load loss and dielectric loss are very small and are neglected. Thus major losses

are by far the first two losses i.e. iron loss or core loss (constant loss) and copper loss (variable loss).

### Efficiency of transformer

The efficiency ( $\eta$ ) of a transformer is defined as the ratio of output power to the input power, the two measured in same units.

$$\eta = \frac{\text{output power (Pout)}}{\text{input power (Pin)}} * 100\%.$$

$$\eta = \frac{P_{out}}{P_{out} + \text{losses}} * 100\%.$$

$$\text{or, } \eta = \frac{P_{in} - \text{losses}}{P_{in}} * 100\%.$$

$$\text{output power (Pout)} = V_2 I_2 \cos \phi_2 \text{ watts}$$

$\phi_2 \rightarrow$  phase angle between  $V_2$  and  $I_2$

$$\text{Input power (Pin)} = V_1 I_1 \cos \phi_1 \text{ watts}$$

$\phi_1 \rightarrow$  phase angle between  $V_1$  and  $I_1$ .

$$P_{out} = P_{in} - \text{losses}$$

$$= P_{in} - \text{iron loss} - \text{copper loss}$$

$$P_{out} = P_{in} - w_i - I_1^2 R_{01}$$

$$\eta = \frac{V_1 I_1 \cos \phi_1 - w_i - I_1^2 R_{01}}{V_1 I_1 \cos \phi_1} * 100\%.$$

$$\eta = \frac{V_1 I_1 \cos \phi_i - w_i - I_1^2 R_{01}}{V_1 I_1 \cos \phi_i} \quad \text{--- (1)}$$

From eqn (1), it is clear that the efficiency depends upon the load current. If we plot a curve showing the efficiency of transformer at different values of load current, the curve will be as shown below :-

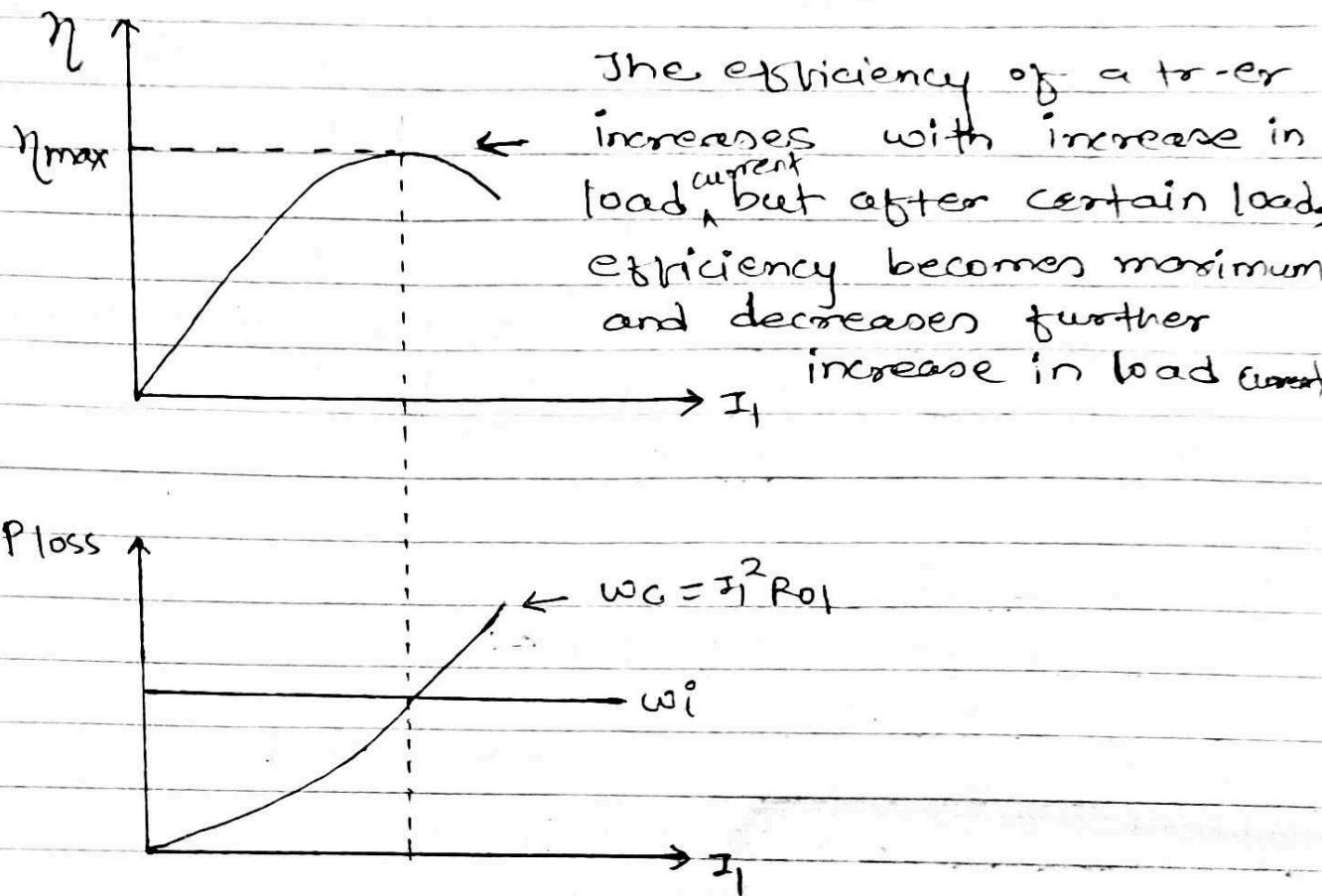


Fig. Efficiency and power loss curve of transformer

Eqn (1) can be written as,

$$\eta = 1 - \frac{w_i}{V_1 I_1 \cos \phi_i} - \frac{I_1^2 R_{01}}{V_1 I_1 \cos \phi_i}$$

Differentiating w.r.t to  $I_1$ ,

$$\frac{d\eta}{dI_1} = 0 + \frac{wi}{V_1 I_1^2 \cos \phi_1} - \frac{R_{01}}{V_1 \cos \phi_1}$$

The efficiency ( $\eta$ ) will be maximum when

$$\frac{d\eta}{dI_1} = 0$$

$$\text{i.e. } \frac{wi}{V_1 I_1^2 \cos \phi_1} - \frac{R_{01}}{V_1 \cos \phi_1} = 0$$

$$\text{or, } wi = I_1^2 R_{01} \quad \text{--- (ii)}$$

$\therefore$  Iron loss = Copper loss

$$\therefore I_1 = \sqrt{\frac{wi}{R_{01}}}$$

Hence, maximum efficiency will occur when  
iron loss = copper loss.

Note :-

1) copper at any load

$$w_{cu}(x) = x^2 w_{cu}(f) \quad \xrightarrow{\text{full load}}$$

where,

$$x = \frac{\text{actual load}}{\text{full load}}$$

2) Above eqn(ii) can be written as

$$wi = x^2 w_c$$

$$x = \sqrt{\frac{wi}{w_c}} = \sqrt{\frac{P_i}{P_c}}$$

$\rightarrow x$  is fraction of full load kVA at which efficiency is maximum.

Q.1) calculate the efficiency at half-full load of a 100 kVA transformer for pf of unity and 0.8. The copper loss is 1000 W at full load and iron loss is 1000 W.

⇒ sol'n -

we have given,

$$\text{Iron loss at full load } (P_i) = 1000 \text{ W}$$

$$\text{copper loss at full load} = 1000 \text{ W}$$

$$\text{copper loss at half load} = \frac{1}{2}^2 \times 1000 \text{ W}$$

$$= \left(\frac{1}{2}\right)^2 \times 1000$$

$$P_{Cu(h)} = \frac{1}{4} \times 1000 = 250 \text{ W}$$

Transformer output on half-full load and unity pf

$$P_{out_1} = \frac{1}{2} \times 100 \times 1 = 50 \text{ kW}$$

Transformer output on half-full load and 0.8 pf

$$P_{out_2} = \frac{1}{2} \times 100 \times 0.8 = 40 \text{ kW}$$

$$\text{Transformer efficiency } (\eta_1) = \frac{P_{out_1}}{P_{out_1} + P_C + P_i} \times 100 \%$$

$$= \frac{50}{50 + 250 + \frac{1000}{1000}} \times 100 \%$$

$$= \frac{50}{50 + 0.25 + 1} \times 100 \%$$

$$\eta_1 = 0.9756 \times 100 \%$$

$$\eta_1 = 97.56 \%$$

$$\eta_2 = \frac{P_{out2}}{P_{out2} + P_C + P_I} * 100\%$$

$$= \frac{40}{40 + 0.25 + 1} * 100\%$$

$$\eta_2 = 0.969\%$$

Q.2) A 30 kVA, single phase transformer has an iron loss of 457 and copper loss of 125 W when delivering half - full load. At what percent of the full load will the transformer have maximum efficiency?

$\Rightarrow$  Soln - we have given,

$$\text{Iron loss} = 457 \text{ W}$$

$$\text{copper loss at half-full load} = 125 \text{ W}$$

Copper loss at full load,  
we have,

$$w_{Cu}(x) = x^2 w_{Cu}(f)$$

$$w_{Cu}(f) = \frac{w_{Cu}(x)}{x^2}$$

$$= \frac{w_{Cu}(\frac{1}{2})}{(\frac{1}{2})^2} = \frac{125}{(\frac{1}{2})^2}$$

$$w_{Cu}(f) = 500 \text{ W}$$

Let the transformer maximum efficiency occur at  $x\%$  of full load,

$$\frac{x}{100} = \sqrt{\frac{P_I}{P_C}}$$

$$x = \sqrt{\frac{P_I}{P_C}} * 100\%$$

$$\therefore x = \sqrt{\frac{457}{500}} * 100\%$$

$$\therefore x = 35.6\%$$

- Q.3) A single-phase transformer working at unity PF has an efficiency of 90% on both half load and at full load of 500 kW. Determine i) iron loss ii) full-load copper loss iii) efficiency at 75% of full load iv) maximum efficiency.

$\Rightarrow$  Soln -

We have given,

At full load and unity PF.

$$\text{Power output (P}_{\text{out}}) = 500 \text{ kW}$$

$$\text{Efficiency } (\eta) = 90\% = 0.9$$

$$\text{Power input (P}_{\text{in}}) = \frac{\text{P}_{\text{out}}}{\eta} = \frac{500}{0.9} = 555.5 \text{ kW}$$

$$\text{Total loss} = \text{P}_{\text{it}} + \text{P}_{\text{C}} = \text{P}_{\text{in}} - \text{P}_{\text{out}} = 555.5 - 500$$

$$\text{P}_{\text{it}} + \text{P}_{\text{C}} = 55.5 \text{ kW} \quad \text{--- (1)}$$

At half full load and unity PF

$$\text{Power output (P}_{\text{out}}) = \frac{1}{2} * 500 = 250 \text{ kW}$$

$$\text{Power input (P}_{\text{in}}) = \frac{\text{P}_{\text{out}}}{\eta} = \frac{250}{0.9} = 277.8 \text{ kW}$$

$$\text{Total loss} = \text{P}_{\text{it}} + \left(\frac{1}{2}\right)^2 \text{P}_{\text{C}} = \text{P}_{\text{in}} - \text{P}_{\text{out}} = 277.8 - 250$$

$$\text{P}_{\text{it}} + \frac{1}{4} \text{P}_{\text{C}} = 27.8 \text{ kW} \quad \text{--- (2)}$$

Solving eqn① and eqn② we get

$$P_i = 18.6 \text{ kW}$$

$$P_C = 36.9 \text{ kW}$$

i) iron loss = 18.6 kW

ii) full load copper loss = 36.9 kW.

iii) Efficiency at 75% of full load

$$\Rightarrow P_{out} = \frac{3}{4} * 500 = 375 \text{ kW.}$$

$$\text{total. losses} = P_i + (\frac{3}{4})^2 P_C$$

$$= 18.6 + (\frac{3}{4})^2 * 36.9$$

$$= 39.36 \text{ kW.}$$

$$\eta = \frac{P_{out}}{P_{out} + P_i + P_C} = \frac{375}{375 + 39.36}.$$

$$\eta = 90.5 \%$$

iv) maximum efficiency.

$$\Rightarrow x = \sqrt{\frac{P_i}{P_C}} = \sqrt{\frac{18.6}{36.9}} = 0.7$$

output power at maximum efficiency

$$(P_{out})_{\eta_{max}} = 0.7 * 500 = 354.98 \\ = 355 \text{ kW.}$$

$$\text{Efficiency } (\eta)_{\max} = \frac{(P_{out})_{\eta_{\max}}}{(P_{out})_{\eta_{\max}} + 2 * \text{ironloss}}$$

[iron loss = copper loss]

$$\eta_{\max} = \frac{355}{355 + 2 * 18.6} * 100\%$$

$$\eta_{\max} = 30.515 \%$$

## Voltage Regulation

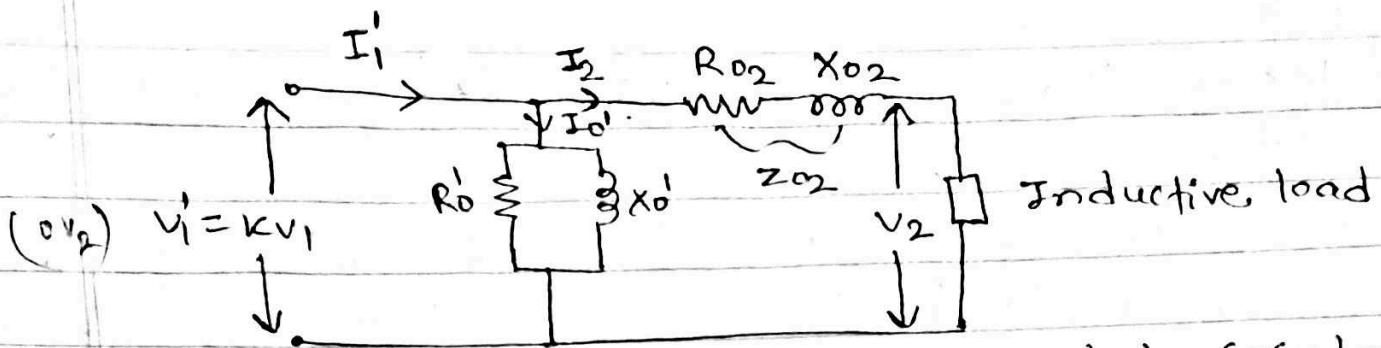
When a transformer is loaded with a constant primary voltage, secondary voltage varies because of voltage drop in its internal resistance and leakage reactance. The quality of a transformer from the point of view of voltage drop is expressed in terms of a quantity known as the voltage regulation. The voltage regulation of a transformer is thus defined as the change in the magnitude of the output voltage from full load to no load expressed usually as the % of full load voltage or no-load voltage.

$$V_{reg} = \frac{OV_2 - fV_2}{fV_2} * 100\% \Rightarrow \text{reg. up}$$

$$V_{reg} = \frac{OV_2 - fV_2}{OV_2} * 100\% \Rightarrow \text{reg. down}$$

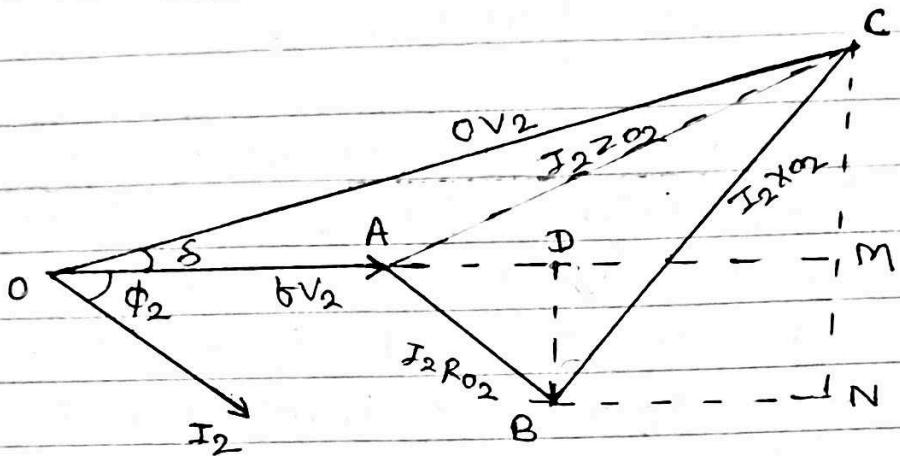
$OV_2$  = No-load terminal voltage (secondary)

$fV_2$  = full load



Fig(i) Equivalent ckt referred to secondary side

$$I_1' \approx I_2 \quad I_0 \approx 0$$



Fig(ii) phasor diagram of equivalent ckt referred to secondary side.

Here, the total voltage drop  $= I_2 Z_{02} = AC$   
Assume that the angle  $s$  is very small then

$$AC \approx AM$$

$$\text{or } AC = AD + DM$$

$$\text{or } AC = AD + BN = I_2 R_{02} \cos \phi_2 + I_2 X_{02} \sin \phi_2$$

$$\therefore AC = I_2 R_{02} \cos \phi_2 + I_2 X_{02} \sin \phi_2$$

From the phasor diagram it is clear that,

$$OV_2 - bV_2 = AC$$

$$\text{Voltage regulation} = \frac{OV_2 - bV_2}{bV_2}$$

$\delta v_2 \rightarrow$  rated voltage  
of secondary side

$$V_{reg} = \frac{I_2 R_{02} \cos \phi_2 + I_2 X_{02} \sin \phi_2}{\delta v_2}$$

$$= \frac{I_2 R_{02} \cos \phi_2}{\delta v_2} + \frac{I_2 X_{02} \sin \phi_2}{\delta v_2}$$

$V_{reg} = R(pu) \cos \phi_2 + X(pu) \sin \phi_2$  for lagging load

where,

$$R(pu) = \frac{I_2 R_{02}}{\delta v_2} = \begin{aligned} &\text{drop in resistance expressed} \\ &= \text{as \% full load voltage} \\ &= \text{percentage resistance} \end{aligned}$$

$$X(pu) = \frac{I_2 X_{02}}{\delta v_2} = \begin{aligned} &\text{percentage reactance} \\ &= \text{of the transformer} \\ &= \text{drop in reactance expressed} \\ &= \text{as \% full load voltage} \end{aligned}$$

$$Z_{pu} = \sqrt{R(pu)^2 + X_{pu}^2}$$

is known as percentage impedance.

when the load is capacitive ( $P_f$  is leading),

$V_{reg} = R(pu) \cos \phi_2 - X(pu) \sin \phi_2$  for leading load.

Condition for zero voltage regulation

$$V_{reg} = \frac{\delta v_2 - \delta v_2}{\delta v_2}$$

$\rightarrow V_{reg}$  can be zero when  $\delta v_2 - \delta v_2 = 0$  and this can be possible only when load is leading

$$V_{reg} = 0$$

$$R(pu) \cos \phi_2 - X(pu) \sin \phi_2 = 0$$

$$\tan \phi_2 = \frac{R_{pu}}{X_{pu}} = \frac{R_{02}}{X_{02}}$$

Condition for maximum voltage regulation

$$V_{reg} = \frac{OV_2 - \delta V_2}{kV_2}$$

$\Rightarrow$   $V_{reg}$  can be maxm when  $OV_2 - \delta V_2 = \text{maxm}$  and this can be possible, only when load is lagging.

$$\frac{d}{d\phi_2} (R_{pu} \cos \phi_2 + X_{pu} \sin \phi_2) = 0$$
$$- R_{pu} \sin \phi_2 + X_{pu} \cos \phi_2 = 0$$

$$\tan \phi_2 = \frac{X_{pu}}{R_{pu}} = \frac{X_{02}}{R_{02}}$$

Q1 In a 500kVA, 3300/500V, 50Hz single-phase transformer, the maximum efficiency of 98.1% occurs at 75% of load at a pf of unity. Calculate the voltage regulation at full load and 0.8 pf lagging if the impedance is 0.1.

=) Soln =

At  $3/4$  full load and pf of unity.

$$\text{Power output (P}_{out}\text{)} = 3/4 * 500 * 1 = 375 \text{ kW}$$

$$\text{maximum efficiency } (\eta_{max}) = 98.1\% = 0.98$$

$$\text{power input (P}_{in}\text{)} = \frac{\text{P}_{out}}{\eta} = \frac{375}{0.98} = 382.65 \text{ kW}$$

$$\text{Total loss} = \text{P}_{input} - \text{P}_{output}$$

$$\text{Total loss} = 382.65 - 375 = 7.65 \text{ kW}$$

This loss is equally divided between iron and copper loss so

$$(3\%)^2 P_C = P_i = \frac{7.65}{2} = 3.82 \text{ kW}$$

$$P_C = (4\%)^2 * 3.825 = 6.8 \text{ kW}$$

$$\text{Percentage resistance} = \frac{I_2 R_{02}}{V_2} * 100$$

$$= \frac{I_2^2 R_{02}}{I_2 V_2} * 100$$

$$= \frac{6.8}{500} * 100 = 1.36 \%$$

$$\text{Percentage impedance} = 100 * 0.1 = 10 \%$$

$$\text{Percentage reactance} = \sqrt{10^2 - 1.36^2} = 9.907 \%$$

$$\text{Percentage Regulation} = \frac{I_2 R_{02} \cos \phi_2 + I_2 X_{02} \sin \phi_2}{V_2} * 100$$

$$= \left[ \frac{I_2 R_{02} \cos \phi_2}{V_2} + \frac{I_2 X_{02} \sin \phi_2}{V_2} \right] * 100$$

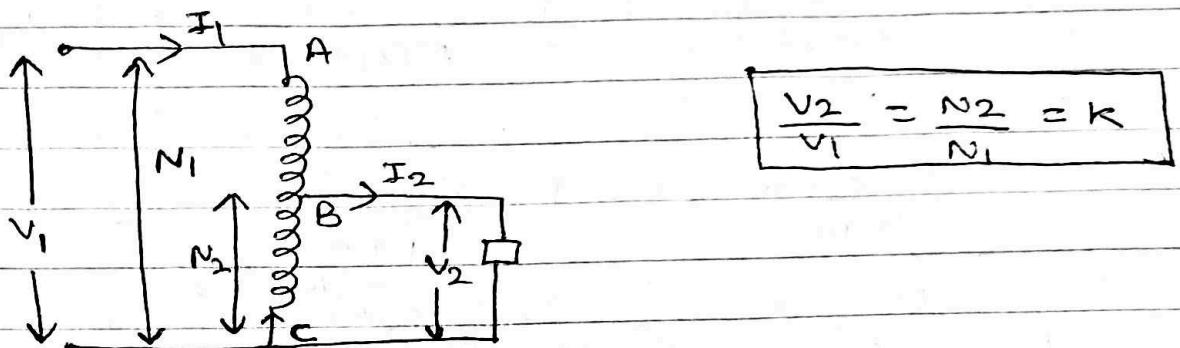
$$= [1.36 * 0.8 + 9.907 * 0.6] * 100$$

$$= 7.0322 \%$$

## Auto Transformer

An auto transformer is a special type of transformer with only one winding. A part of the winding is common to both primary and secondary sides. In Auto transformer, Primary and Secondary windings are connected electrically as well as magnetically.

The figure shows a single phase auto transformer having  $N_1$  turns in the primary and  $N_2$  turns tapped for lower secondary voltage. The winding section BC with  $N_2$  turns is common to both primary and Secondary side.



## Fig Step down auto transformer

If  $I_2$  = current drawn by the load  
 $I_1$  = current drawn from supply

$$\text{Current in section BC} = I_2 - I_1$$

Cu Saving  $\Rightarrow$  weight of Cu & N.I  
 weight of Copper in section AB  $\Delta(N_1 - N_2)I_1$ ,  
 " " " " " " BC  $\Delta(N_2)(J_2 - J_1)$

Total weight of copper used in auto transformer

$$(w_{\text{auto}}) \propto (N_1 - N_2) I_1 + N_2 (I_2 - I_1)$$

If a two winding transformer were to perform the same duty, then weight of copper in two winding transformer  $(w_{\text{two}}) = N_1 I_1 + N_2 I_2$

Now,

$$\frac{w_{\text{auto}}}{w_{\text{two}}} = \frac{N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$\frac{w_{\text{auto}}}{w_{\text{two}}} = 1 - 2 \frac{N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$\frac{w_{\text{auto}}}{w_{\text{two}}} = 1 - \frac{2 N_2 I_1}{N_1 I_1 + N_2 I_2} \times \frac{N_1 I_1}{N_1 I_1}$$

$$\frac{w_{\text{auto}}}{w_{\text{two}}} = 1 - \frac{2 N_2 / N_1}{1 + N_2 / N_1} \times \frac{I_1}{I_2}$$

$$\frac{w_{\text{auto}}}{w_{\text{two}}} = 1 - \frac{2 k}{1 + k} = 1 - k$$

$$w_{\text{auto}} = (1 - k) w_{\text{two}}$$

Case I - if  $V_1 = 220V$  and  $V_2 = 200V$  then,

$$k = \frac{200}{220} = 0.909 \approx 1$$

$$w_{\text{auto}} = (1 - 0.909) w_{\text{two}} = 0.091 w_{\text{two}}$$

$\Rightarrow$  So the weight of cu required in auto transformer is 9.1% of the normal two winding transformer.

Case-II - If  $v_1 = 220\text{V}$  and  $v_2 = 6\text{V}$  then  $K = \frac{6}{220} = 0.0272$   
(very less than 1)

$$w_{\text{auto}} = 0.9728 w_{\text{two}}$$

$\Rightarrow$  The weight of the copper required is 97.2% of the normal two winding transformer. Hence, the saving in copper in an auto transformer is only significant when  $K$  approaches unity.

## Isolation Transformer

→ Equal number of windings on both sides i.e. turns ratio is 1:1 ( $V_1 = V_2$ ,  $N_1 = N_2$ )

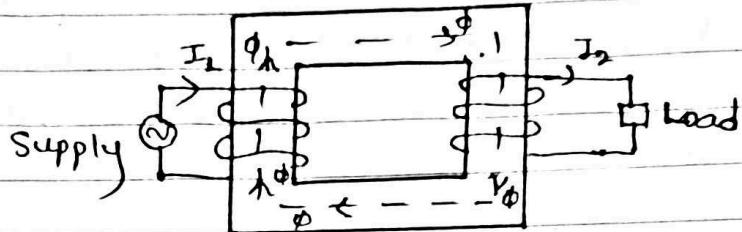
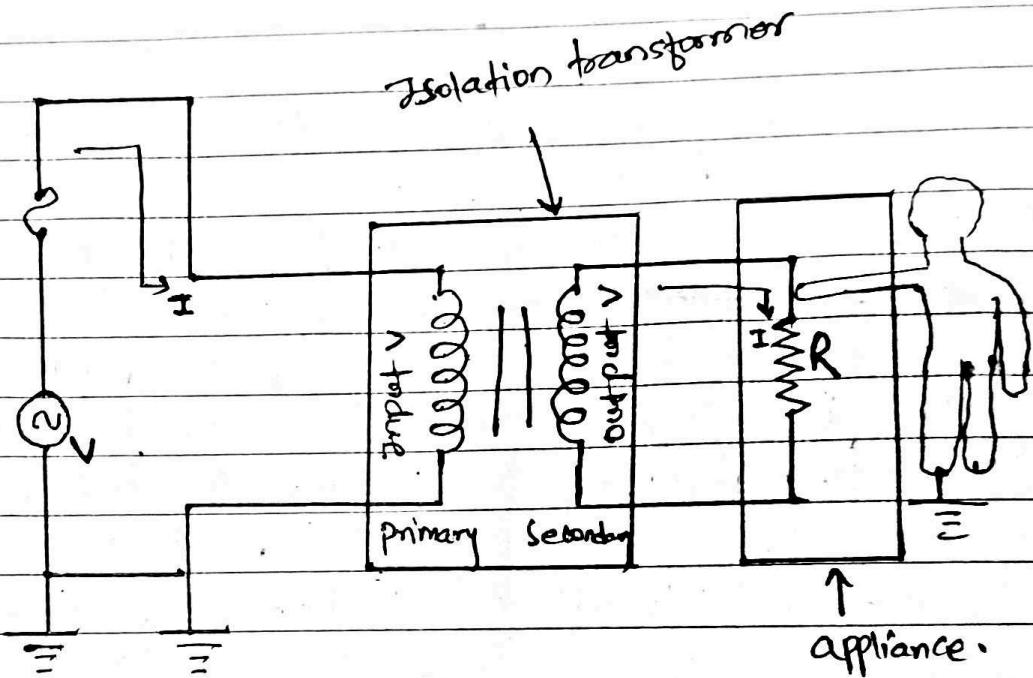


Fig. Isolation transformer

→ An Isolation transformer is a stationary device with isolated primary and secondary windings that keeps two circuits separated physically and electrically. It transmits electrical energy between circuits by incorporating a magnetic induction mechanism that uses a magnetic field to generate Emf in another circuit without affecting the frequency.

→ An Isolation transformer's main purpose is to reduce voltage spikes in the supply lines; illumination, static electricity, or a quick voltage change can cause voltage spikes, transients, and surges in electrical power supply lines. A voltage spike is a rapid increase in voltage levels that lasts for a short time (3 nanoseconds or more).

→ Another essential feature of an isolation transformer is that it prevents load equipments or due secondary side from being grounded. As a result an isolation transformer eliminates ground loop interference and noise effect on the load. An isolation transformer protect sensitive equipments, and other application from voltage spikes, ground loops and other power line distortion.



## Advantages

- 1) Reliable and safe equipment
- 2) Reduced presence of power surges
- 3) Reduced noise disruption.
- 4) Harmonics correction
- 5) Prevention of starting failures
- 6) Improved power quality.

## Disadvantages:

- 1) When the isolation transformer is used as pulse transformer and operated at a low frequency, the secondary or output waveform produces distortion.
- 2) The saturation property of the core is lessened when an isolation transformer is running at a DC pulse signal.
- 3) Due to their unique construction, isolation transformer cost more than standard transformers.

(Q2) A 25 kVA, single phase, 11 kV / 400 V transformer has impedance of primary and secondary  $0.4 + j2\Omega$  and  $0.02 + j1\Omega$  respectively. Determine the load terminal voltage and primary current at half load.



Soln -

we have given,

$$V_1 = 11 \text{ kV} \quad R_1 = 0.4 \Omega, X_1 = 2 \Omega$$

$$V_2 = 400 \text{ V} \quad R_2 = 0.02 \Omega, X_2 = 1 \Omega$$

$$S = 25 \text{ kVA}$$

$$\text{Let } P_F = 1 \quad I_1 = \frac{25 \times 10^3}{11 \times 10^3} = 2.272 \text{ A}$$

$$V_2 = ?$$

primary induced emf,

$$\begin{aligned} E_1 &= V_1 - I_1 R_1 = 11 \times 10^3 - 2.272 \times 0.4 \\ &= 11 \times 10^3 - 0.909 \\ &= 10.09 \times 10^3 \text{ V} \end{aligned}$$

$$E_1 = 10.09 \times 10^3 \text{ V}$$

$$K = \frac{V_2}{V_1} = \frac{400}{11 \times 10^3} = 0.0363$$

$$I_2 = \frac{25 \times 10^3}{400} = 62.5 \text{ A}$$

$$E_2 = K E_1 = 10.09 \times 10^3 \times 0.0363 = 366.909 \text{ V}$$

$$\text{Load terminal voltage } (V_2) = E_2 - I_2 R_2$$

$$= 366.909 - 62.5 \times 0.02$$

$$= 366.909 - 1.25$$

$$V_2 = 365.659 \text{ V}$$

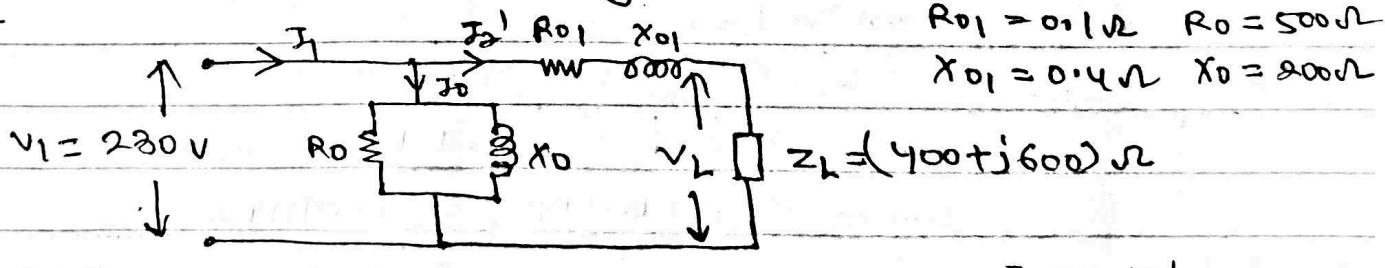
$$\text{Primary current at half load } I_{(k)} = \frac{k \times 25 \times 10^3}{11 \times 10^3}$$

$$I_{(k)} = 1.136 \text{ A}$$

2070 Bhadra

- Q.3) A 230V/2300V Single-phase transformer is excited by 230V ac voltage. The equivalent resistance and reactance referred to primary side are  $0.1\Omega$  and  $0.4\Omega$  respectively. Given that  $R_o = 500\Omega$  and  $X_o = 200\Omega$ . The load impedance is  $(400+j600)\Omega$ . Calculate i) Primary current and input power factor ii) Secondary terminal voltage.

$\Rightarrow$  Soln-



$$V_1 = I_1 R_{01} + j I_1 X_{01} + I_1 Z_L$$

$$I_1 = I_2 + I_2'$$

$$I_1 \approx I_2'$$

$$V_1 = I_1 (R_0 + jX_0) + Z_L$$

$$230 = I_1 (0.1 + j0.4 + 400 + j600)$$

$$I_1 = \frac{230}{0.1 + j0.4 + 400 + j600}$$

$$I_1 = 0.1767 - j0.2652$$

$$I_1 = 0.31878 \angle -56.32^\circ$$

(Inductive load)

i) primary current ( $I_1$ ) = 0.31878 A

Input power factor =  $\cos\phi = \cos(56.32) = 0.5545$   
(lagging)

ii) terminal secondary voltage

$$\Rightarrow V_L = I_1 Z_L = 0.31878 * \sqrt{(400)^2 + (600)^2}$$

$$= 0.31878 * 721.11$$

$$V_L = 229.87 \text{ V}$$

2066 mag

Q.3) A 4.2 kV / 120 V, 50 Hz, 1-phase transformer has the following series parameters:

$R_1 = 1.4 \Omega$ ,  $X_1 = 3.5 \Omega$ ,  $R_2 = 0.04 \Omega$ ,  $X_2 = 0.1 \Omega$ . If the transformer draws 500 A current on the secondary at rated terminal voltage, calculate voltage regulation at unity power factor.

$$\Rightarrow \text{Soln- } K = \frac{120}{4.2 \times 10^3} = 0.0285$$

$$R_{02} = R_2 + R_1 = 0.04 + 0.0285^2 \times 1.4$$

$$R_{02} = 0.04 + 0.01428 = 0.04114 \Omega$$

$$X_{02} = X_2 + K^2 X_1 = 0.1 + (0.0285^2 \times 3.5) = 0.1027 \Omega$$

$$I_2 = 500 \text{ A}$$

$$P_f = 1 \quad \cos\phi_2 = 1 \quad \sin\phi_2 = 0$$

$$\text{Voltage regulation} = \frac{j_2 R_02 \cos \phi_2 + j_2 X_02 \sin \phi_2}{V_2}$$

$$= \frac{500 \times 0.0414 \times \cos(0) + 0}{120}$$

$$\% \text{ Vreg} = 0.1725 \times 100 \%$$

$$= 17.25 \%$$

