

EC - 1

Part - 2

Transformer

A transformer is a static (or stationary) piece of device by means of which electrical power is transferred from one ckt to another ckt at const. frequency.

It can raise (step up) or lower (step down) the voltage in a ckt but with a corresponding decrease or increase in current.

Physically, a transformer is mutual induction between two ckt's linked by a common magnetic flux.

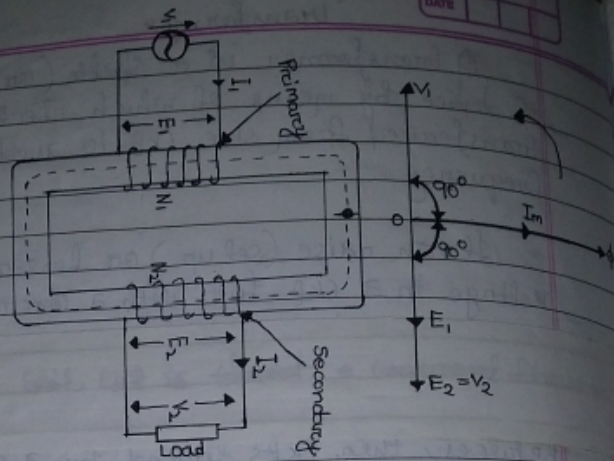
It consists of two conductive coils which are electrically separated but magnetically linked through a path of low reluctance.

Two coils possess high mutual inductance. If one coil is connected to a source of AC voltage an AC flux is set up in the laminated core. Most of which is linked with the other coil in which it produces mutually induced emf.

According to Faraday's law of electromagnetic induction

$$e = M \frac{di}{dt}$$

If the second coil ckt is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first coil to the second coil.



The first coil, in which electrical energy is fed from the AC Supply main is called primary winding and other ckt from which energy is drawn out, is called secondary winding.

N_1 = No. of turns of primary

N_2 = No. of turns of secondary

V_1 = Alternating voltage applied to primary

E_1 = primary induced emf

E_2 = Secondary induced emf

$$E_1 = -N_1 \frac{d\phi}{dt}$$

$$E_2 = -N_2 \frac{d\phi}{dt} \quad \text{--- (1)}$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} \quad \text{--- (2)}$$

V_2 = Voltage across the load.

If $N_2 > N_1$ $E_2 > E_1$ or $V_2 > V_1$
Step up transformer

If $N_1 > N_2$ $E_1 > E_2$ $V_1 > V_2$
Step down transformer

Losses in a transformer :-

Core losses :- eddy current and hysteresis losses.

Copper losses :- in the resistance of windings.

Practically these losses are very small output power = Input power.

Ideal transformer :-

An ideal transformer

(i) No winding resistance

(ii) No leakage flux

Same flux links both the winding.

(iii) No iron losses (i.e. eddy current and hysteresis losses)

Ideal transformer can't be physically realised.

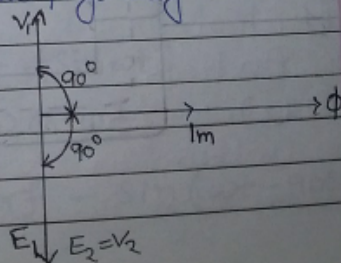
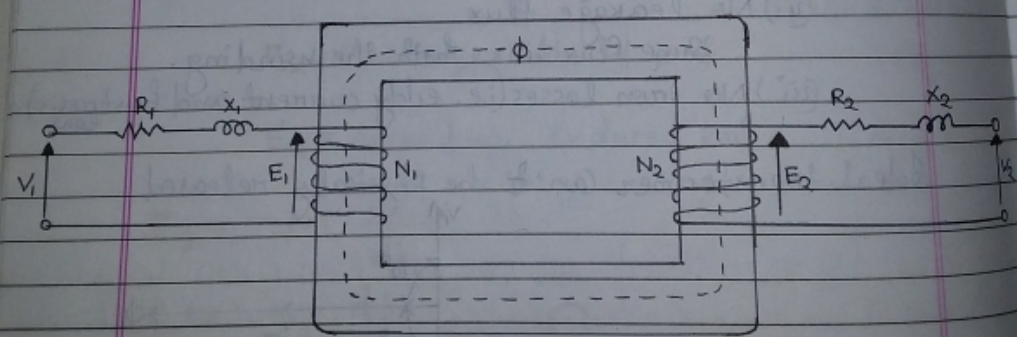
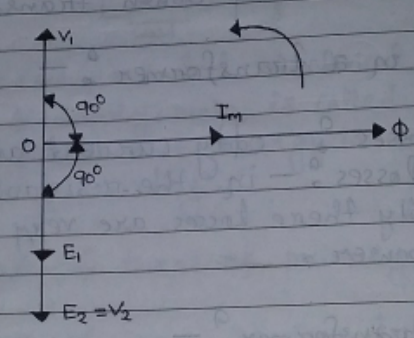
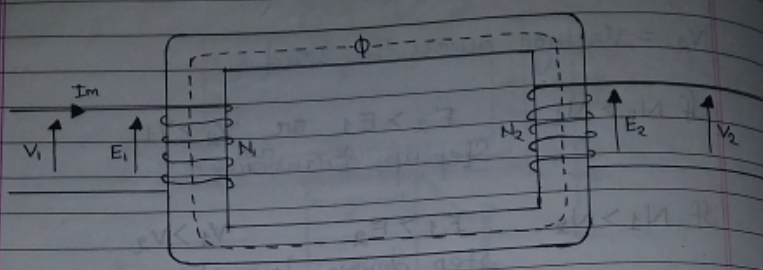


Fig.



Voltage transformation ratio (K) :-

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

K = voltage transformation ratio

For ideal T.F

$$E_1 = V_1$$

$$E_2 = V_2$$

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

No losses

$$\text{o/p power} = \text{i/p power}$$

$$V_1 I_1 = V_2 I_2$$

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = K \quad \text{--- (3)}$$

Fig. 2

EMF equation of a transformer :-

Consider an alternating voltage V_1 of frequency f is applied to primary as shown in fig. ideal transformer

Sinusoidal flux

$$\phi = \phi_m \sin \omega t \quad \text{--- (4)}$$

e_1 = induced emf in the primary

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

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

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

$$= -N_1 \phi_m \omega \cos \omega t$$

$$= -N_1 \phi_m 2\pi f - \sin(\omega t - 90^\circ)$$

$$e_1 = 2\pi f N_1 \phi_m \sin(\omega t - 90^\circ)$$

E_{m1} = maximum induced emf

$$= 2\pi f N_1 \phi_m$$

E_1 = r.m.s value of E_1

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}}$$

$$E_1 = \sqrt{2} \pi f N_1 \phi_m$$

$$E_1 = 4.44 f N_1 \phi_m \quad \text{--- (5)}$$

$$\text{Similarly } E_2 = 4.44 f N_2 \phi_m \quad \text{--- (6)}$$

For ideal transformer $E_1 = V_1$, $E_2 = V_2$

Example ①

A sinusoidal flux 0.02 wb (max) links with 55 turns of a transformer secondary. Calculate the rms value of the induced emf in the secondary. $f = 50$ Hz.

Solⁿ

$\phi_m = 0.02$ wb, $N_2 = 55$ turns, $f = 50$ Hz

R.M.S value of induced emf in the secondary is

$$E_2 = 4.44 f \phi_m N_2$$

$$= 4.44 \times 50 \times 0.02 \times 55 = 244.2 \text{ V}$$

Practical Transformer ② —

Practical transformer has following losses.

(i) iron loss

(ii) winding resistance

(iii) Magnetic leakage, giving rise to leakage reactance

Iron losses :-

Since iron core is subjected to alternating flux, hence eddy current and hysteresis loss occurs. Thus two losses are known as iron losses or core losses.

Iron loss depends upon

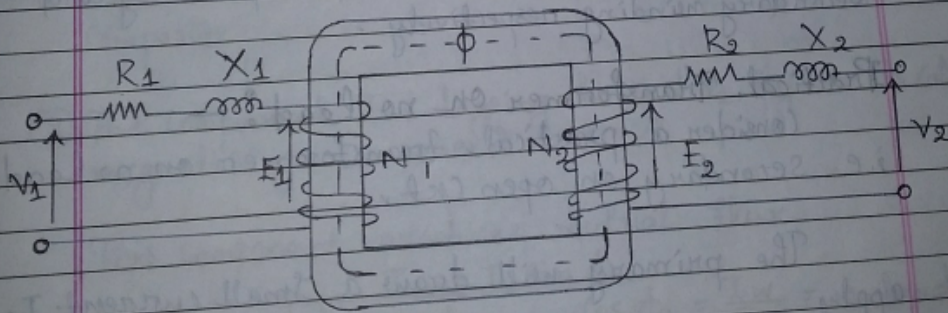
- (i) Supply frequency
- (ii) maximum flux density
- (iii) volume of the core.

Winding resistance :-

Winding of transformer consists of copper conducts. Hence it is having with resistance both in primary and secondary.

The resistance R_1 is in series with primary windings. The resistance R_2 is in series with secondary winding.

Fig. -



Leakage Reactance -

Both primary and secondary current produce flux. The flux ϕ which links both the winding is the useful flux and it is called mutual flux.

But the primary current I_1 produces flux ϕ_1 which would not link secondary.

Similarly,

The secondary current I_2 produces flux ϕ_2 which would not link primary.

The flux ϕ_1 and ϕ_2 which only link one winding is called leakage flux.

The leakage flux path through the air.

Due to leakage flux ϕ_1 and ϕ_2 , there is a leakage reactance X_1 and X_2 connected to primary and secondary winding respectively.

Practical Transformer on no load -

Consider a practical transformer on no load, i.e. secondary on open ckt.

The primary will draw a small current I_0 to supply

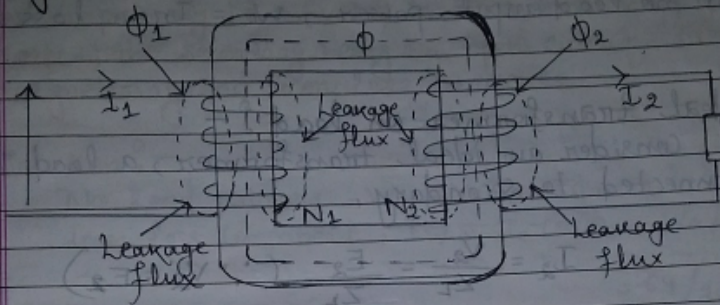
(i) Iron losses

(ii) Very small amount of copper loss.

Hence I_0 is not exactly 90° lag to V_1 but I_0 lags

phase angle $\phi < 90^\circ$.

Fig. -



I_0 (no load primary current) is resolved into two rectangular components.

- ① The component I_w in phase with the supply voltage V_1

$$I_w = I_0 \cos \phi_0$$

This is called core loss component or active or working component.

- ② The component I_m lagging behind V_1 by 90° is called magnetising component.

This component produces mutual flux.

$$I_m = I_0 \sin \phi_0$$

$$I_0 = \sqrt{I_m^2 + I_w^2}, \quad \cos \phi_0 = \frac{I_w}{I_0} = \text{No load pf.}$$

As no-load primary copper loss ($I_0^2 R_1$) is very small it may be neglected.

At no-load primary copper loss ($I_0^2 R_1$) is very

Small it may be neglected.

At no load input power, $w_0 = \text{Iron loss}$.

Ideal transformer on load :-

Consider an ideal transformer, a load Z_L is connected to secondary.

$$I_2 = \frac{V_2}{Z_L} = \frac{E_2}{Z_L} \quad (\because V_2 = E_2)$$

The secondary current I_2 sets up an mmf $N_2 I_2$.

MMF $N_2 I_2$ produces a flux in opposite direction to the mutual flux in primary.

This will change the flux in the core.

The flux in the core remains practically constant. To counter flux produce by secondary mmf $N_2 I_2$, primary will produce a flux due to mmf $N_1 I_1$.

$$N_1 I_1 = N_2 I_2$$

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

$$I_1 = K I_2$$

Example - 1

A transformer takes a current of 0.6 A and absorbs 64 W when primary is connected to its normal supply of 200 V, 50 Hz; the secondary being an open circuit. Find the magnetising and iron loss currents.

Solution: -

$$\text{No load primary, } W_0 = V_1 I_0 \cos \phi_0$$

$$\text{Iron loss component, } I_w = I_0 \cos \phi_0 = W_0 / V_1$$

$$= 64 / 200 = 0.32 \text{ A}$$

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

$$\therefore \text{Magnetising current, } I_m = \sqrt{I_0^2 - I_w^2}$$

$$= \sqrt{(0.6)^2 - (0.32)^2}$$

$$= 0.507 \text{ A}$$

Example - 2

A 230/2300 V transformer takes no load current of 5 A at 0.25 power factor lagging. Find (i) the core loss and (ii) magnetising current.

Solution: -

$$(i) \text{ core loss, } W_0 = V_1 I_0 \cos \phi_0 = 230 \times 5 \times 0.25 = 287.5 \text{ W}$$

$$(ii) \text{ Magnetising current, } I_m = \sqrt{I_0^2 - I_w^2}$$

$$I_0 = 5 \text{ A}$$

$$I_w = \frac{W_0}{V_1} = \frac{287.5}{230} = 1.25 \text{ A}$$

$$I_m = \sqrt{(5)^2 - (1.25)^2} = 4.84 \text{ A}$$

Example - 3

A 230/2300V transformer takes a no load current of 6.5A and absorbs 187W. If the resistance of primary is 0.06Ω , find (i) the core loss (ii) no load p.f. (iii) active component of current and (iv) magnetising current.

Solution -

No-load loss, $W_0 = 187W$
primary Cu loss due to no-load current $= I_0^2 R_1 = (6.5)^2 \times 0.06 = 2.5W$

(i) Iron loss $= 187 - 2.5 = 184.5W$

(ii) No load p.f., $\cos \phi_0 = \frac{W_0}{V_1 I_0} = \frac{187}{230 \times 6.5} = 0.125 \text{ lag}$

(iii) Active component, $I_w = \frac{W_0}{V_1} = \frac{187}{230} = 0.81A$

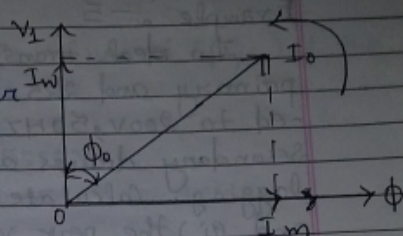
(iv) Magnetising current, $I_m = \sqrt{I_0^2 - I_w^2}$
 $= \sqrt{(6.5)^2 - (0.81)^2} = 6.4A$

Example - 4

A single-phase transformer on no-load takes 4.5A at a power factor of 0.25 lagging when connected to a 230V, 50Hz supply. The number of turns of the primary winding is 250. Calculate (i) the magnetising current (ii) the core loss and (iii) the maximum value of flux in the core.

Solution -

Fig(1) Shows the phasor diagram of the transformer on no load.



(i) Magnetising current,

$$I_m = I_0 \sin \phi_0 \\ = 4.5 \times 0.968 = 4.35 \text{ A}$$

(Fig. 1)

(ii) Core loss, $W_0 = V_1 I_0 \cos \phi_0$

$$= 230 \times 4.5 \times 0.25 = 259 \text{ W}$$

(iii) Since no-load current I_0 is small, $E_1 \approx V_1$.

$$V_1 = 4.44 \phi_m f N_1$$

or

$$230 = 4.44 \times \phi_m \times 50 \times 250$$

$$\phi_m = 4.14 \times 10^{-3} \text{ Wb}$$

Practical transformer on load -

when practical transformer loaded two cases arises.

- ① No winding resistance and leakage flux.
- ② Transformer has winding resistance and leakage flux.

① No-winding resistance and leakage flux? -

Practical Transformer has no winding resistance and leakage reactance

$$V_2 = E_2, V_1 = E_1 \quad I_0 \text{ current flows}$$

Take inductive load

I_2 lag ϕ_2 to Secondary voltage V_2

I_1 = primary current, I_2 = Secondary current

Example :- 5

An ideal transformer having 90 turns on the primary and 2250 turns on the secondary is connected to 200V, 50Hz supply. The load across the secondary draws a current of 2A at a p.f. of 0.8 lagging. Calculate (i) the value of primary current and (ii) the peak value of flux linked with the secondary. Draw the phasor diagram.

Soln: The condition of the problem are represented fig (1).

$$K = N_2 / N_1 = 2250 / 90 = 25$$

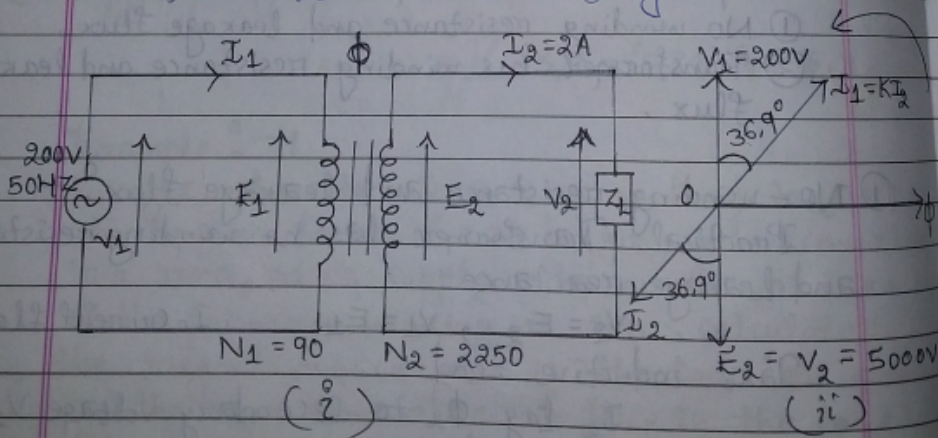
(i) $I_1 = KI_2 = 25 \times 2 = 50A$

(ii) $E_1 = 4.44 f N_1 \phi_m$

or $200 = 4.44 \times 50 \times 90 \times \phi_m$

$$\phi_m = \frac{200}{4.44 \times 50 \times 90} = 0.01 \text{ wb}$$

This flux links both the windings.



Phasor diagram -

(ii) shows the phasor diagram (not to scale) of the transformer.

$$E_2 = KE_1 = 25 \times 200 = 5000 \text{ V}$$

ϕ_2 = phase angle between V_2 and V_1

$$= \cos^{-1} 0.8 = 36.9^\circ$$

The phase angle between V_1 and I_1 is also 36.9° .

Example - 6

An ideal transformer has 1000 turns on its primary and 500 turns on its secondary. The driving voltage on the primary side is 100V and the load resistance is 5Ω . Calculate V_2 , I_1 and I_2 .

$$K = N_2/N_1 = 500/1000 = 1/2$$

$$V_2 = KV_1 = (1/2) \times 100 = 50 \text{ V}$$

$$I_2 = V_2/R_2 = 50/5 = 10 \text{ A}$$

$$I_1 = KI_2 = (1/2) \times 10 = 5 \text{ A}$$

I_1 must have two component $I_1 = I_0 + I_2'$

(a) I_0 = No-load current to meet iron losses in the transformer and provide flux in the core.

(b) I_2' to counteract the demagnetizing effect of secondary current I_2 .

$$N_1 I_2' = N_2 I_2$$

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

$$I_2' = K I_2$$

E_1 & E_2 lag behind the mutual flux ϕ by 90°

$$I_2' = KI_2 \text{ antiphase.}$$

I_0 makes ϕ_0 with V_1

I_1 makes ϕ_1 with V_1

I_2 makes ϕ_2 with V_2

Practical Transformer on load? —

(11) with winding resistance and leakage reactance.

Fig below shows a practical transformer having winding resistance and leakage reactance.

This is the actual conditions of a practical transformer.

$E_1 < V_1$ As voltage drop across R_1 & X_1 .

$V_2 < E_2$ As voltage drop across R_2 & X_2 .

Consider an inductive load.

I_2 lags behind V_2 and ϕ_2 .

Total primary current

$$I_1 = I_0 + KI_2 = I_0 + I_2'$$

(a) I_0 is the no-load current to must the iron losses in the transformer and provide the flux in the core.

(b) I_2' is the part of primary current to counteract the demagnetising effect of secondary

Current I_2 ,

$$N_1 I_2' = N_2 I_2$$

$$I_2' = \frac{N_2}{N_1} I_2 = K I_2$$

$$I_2' = K I_2$$

I_1 = phasor, sum of I_0 and I_2'

$$I_1 = I_2' + I_0$$

$$I_2' = -K I_2$$

$$V_1 = -E_1 + I_1 (R_1 + jX_1)$$

$$V_1 = -E_1 + I_1 Z_1$$

$$V_2 = E_2 - I_2 (R_2 + jX_2)$$

$$V_2 = E_2 - I_2 Z_2$$

Phasor diagram (Lagging P.f.) :-

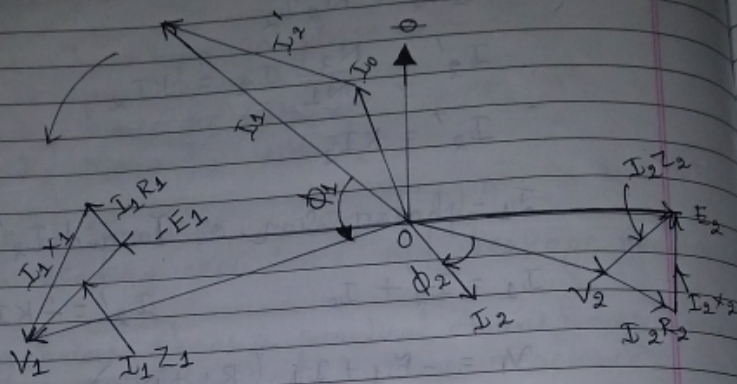
Load power factor = $\cos \phi_2$

primary power factor = $\cos \phi_1$

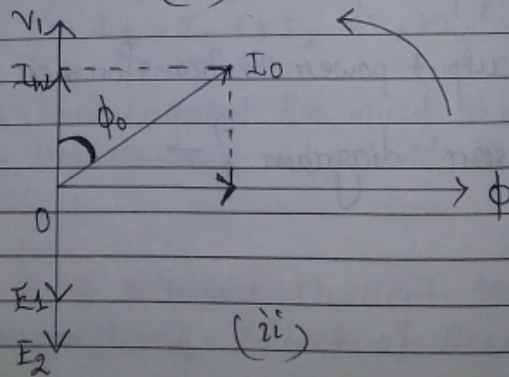
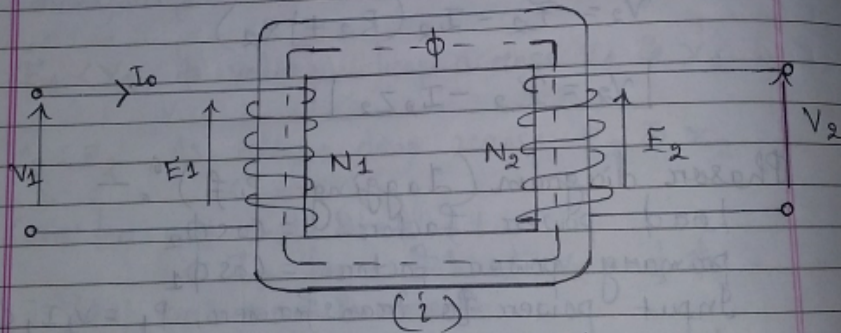
Input power to transformer, $P_1 = V_1 I_1 \cos \phi_1$

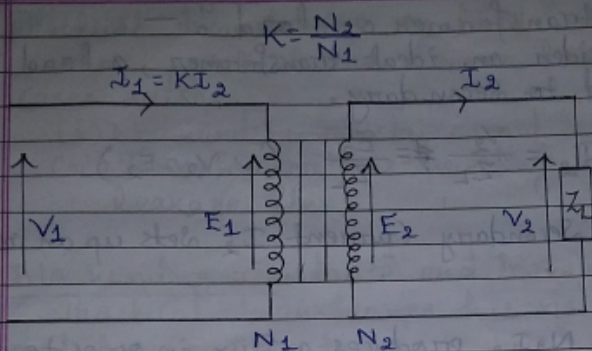
output power to transformer $P_2 = V_2 I_2 \cos \phi_2$

Phasor diagram :-

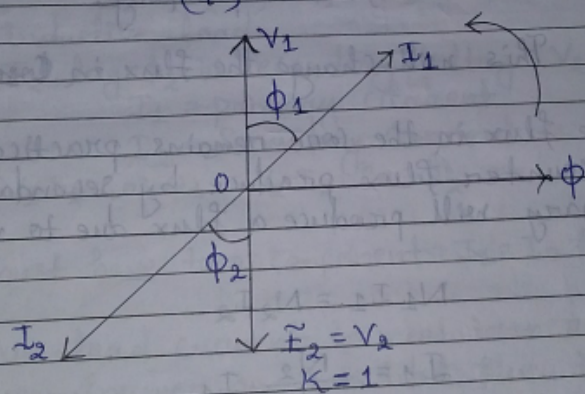


No load input power, $W_0 = V_1 I_0 \cos \phi_0$





(i)



(ii)

As no-load primary copper loss ($I_0^2 R_1$) is very small it may be neglected.

At no load input power, $W_0 = \text{Iron loss.}$

IDEAL TRANSFORMER ON LOAD :-

Consider an ideal transformer, a load Z_L is connected to secondary.

$$I_2 = \frac{V_2}{Z_L} = \frac{E_2}{Z_L} \quad (\because V_2 = E_2)$$

This Secondary Current I_2 sets up an mmf $N_2 I_2$.

MMF $N_2 I_2$ produces a flux in opposite direction to the mutual flux is primary.

This will change the flux in core.

The flux in the core remains practically constant to counter flux produce by secondary mmf $N_2 I_2$. primary will produce a flux due to mmf $N_1 I_1$.

$$N_1 I_1 = N_2 I_2$$

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

$$I_1 = K I_2$$

$$N_1 I_1 = N_2 I_2$$

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

$$I_1 = K I_2$$

Practical transformer on load :-
when practical transformer loaded, two cases arises.

- (i) No winding resistance and leakage flux.
- (ii) Transformer has winding resistance and leakage flux.

- ① No winding resistance and leakage flux :-
Practical transformer has no winding resistance and leakage reactance.

$$V_2 = E_2, \quad V_1 = E_1$$

Take inductive load

I_2 lag ϕ_2 to secondary voltage V_2 .

I_1 = primary current

I_2 = Secondary current

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

I_1 must have two components $I_1 = I_0 + I_1'$

- (a) I_0 = No-load current to meet iron losses in the transformer and provided flux in the core.

- (b) I_1' to counteract the demagnetising effect of Secondary current I_2 .

$$N_1 I_1' = N_2 I_2$$

$$I_1' = \frac{N_2}{N_1} I_2$$

$$I_1' = K I_2$$

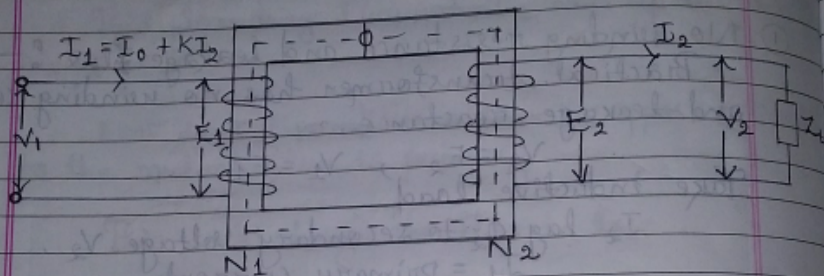
E_1 and E_2 lag behind the mutual flux ϕ by 90° .

$$I_2' = KI_2 \text{ antiphase,}$$

I_0 makes ϕ_0 with V_1

I_1 makes ϕ_1 with V_1

I_2 makes ϕ_2 with V_2 .



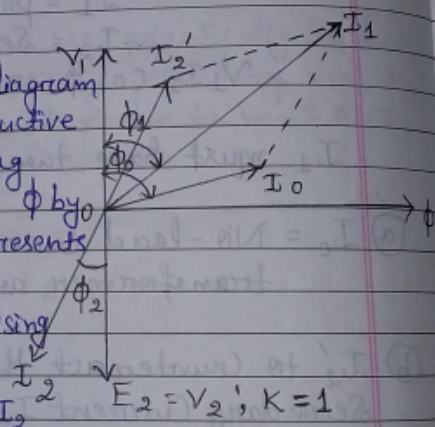
Phasor diagram

(1) shows the phasor diagram for the usual case of inductive load. Both E_1 and E_2 lag behind the mutual flux ϕ by 90° . The current I_2' represents the primary current to neutralise the demagnetising effect of secondary

current I_2 . Now $I_2' = KI_2$ and is antiphase with I_2 .

Fig. (1)

I_0 is the no-load current of the transformer. The phasor sum of I_2' and I_0 gives the total primary current I_1 . Note that in drawing the phasor diagram, the value of K is assumed to be unity so that primary phasors are equal to secondary phasors.



$$\text{Primary p.f.} = \cos \phi_1$$

$$\text{Secondary p.f.} = \cos \phi_2$$

$$\text{Primary input power} = V_1 I_1 \cos \phi_1$$

$$\text{Secondary output power} = V_2 I_2 \cos \phi_2$$

* However, V_1 and E_1 are 180° out of phase.

Practical transformer on load? —

(ii) with winding resistance and leakage reactance? —

Fig below shows a practical transformer having winding resistance and leakage reactance.

This is the actual conditions of a practical transformer.

$$E_1 < V_1 \text{ as voltage drop across } R_1 \text{ and } X_1.$$

$$V_2 < E_2 \text{ as voltage drop across } R_2 \text{ and } X_2.$$

Consider an inductive load.

I_2 lags behind V_2 by ϕ_2 .

$$\text{Total primary current } I_1 = I_0 + KI_2$$

$$= I_0 + I_2'$$

(a) I_0 is the no-load current to meet the iron losses in the transformer and provide the flux in the core.

(b) I_2' is the part of primary current to counteract the demagnetising effect of secondary current I_2 .

$$N_1 I_2' = N_2 I_2$$

$$I_2' = \frac{N_2}{N_1} I_2 = KI_2$$

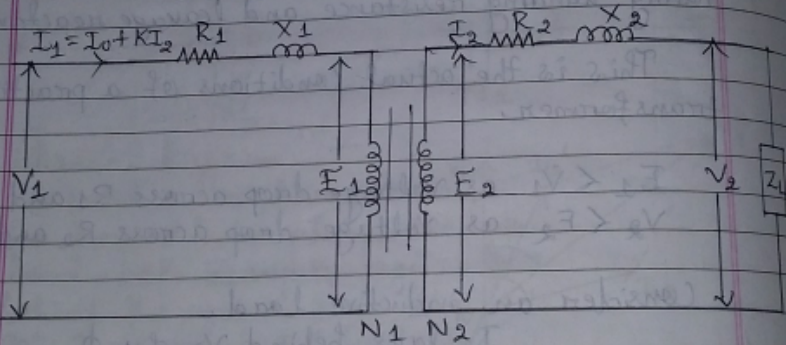
$$I_2' = KI_2$$

$$\text{or } N_1 I_2' = N_2 I_2$$

$$I_2' = \frac{N_2}{N_1} I_2 = KI_2$$

The total primary current I_1 will be the phasor sum of I_2' and I_0 i.e.,

$$I_1 = I_2' + I_0 \quad \text{where } I_2' = -KI_2$$



$$V_1 = -E_1 + I_1(R_1 + jX_1) \quad \text{where } I_1 = I_0 + (-KI_2)$$

phasor

$$= -E_1 + I_1 Z_1$$

$$V_2 = E_2 - I_2(R_2 + jX_2)$$

$$= E_2 - I_2 Z_2$$

$$I_1 = \text{Phasor sum } I_0 \text{ and } I_2'$$

$$I_1 = I_2' + I_0$$

$$I_2' = -KI_2$$

$$V_1 = -E_1 + I_1(R_1 + jX_1)$$

$$V_1 = -E_1 + I_1 Z_1$$

$$V_2 = E_2 - I_2(R_2 + jX_2)$$

$$V_2 = E_2 - I_2 Z_2$$

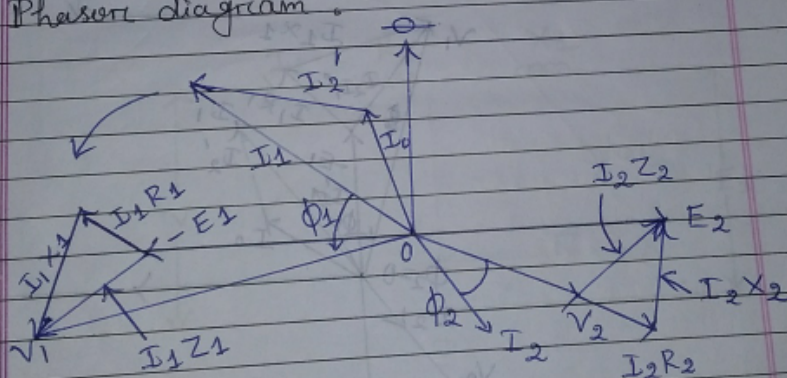
Phasor diagram (Lagging P.f.) :-

Load power factor = $\cos \phi_2$

primary power factor = $\cos \phi_1$

Input power to transformer, $P_1 = V_1 I_1 \cos \phi_1$
 Output power of transformer, $P_2 = V_2 I_2 \cos \phi_2$

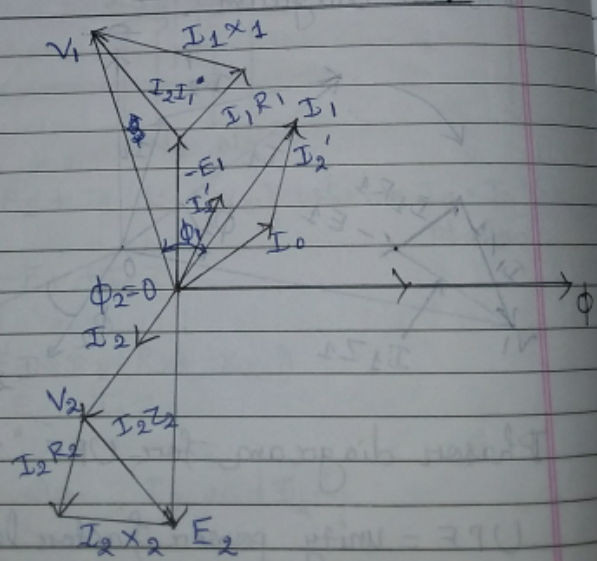
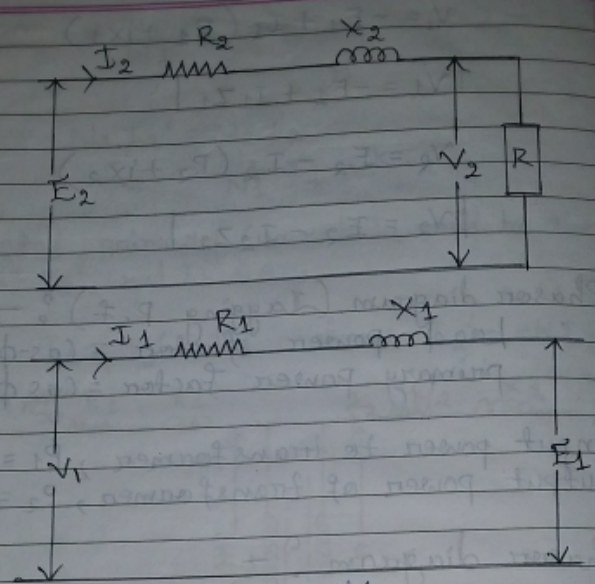
Phasor diagram :-



Phasor diagram for U.P.F. :-

U.P.F. = unity power factor load.

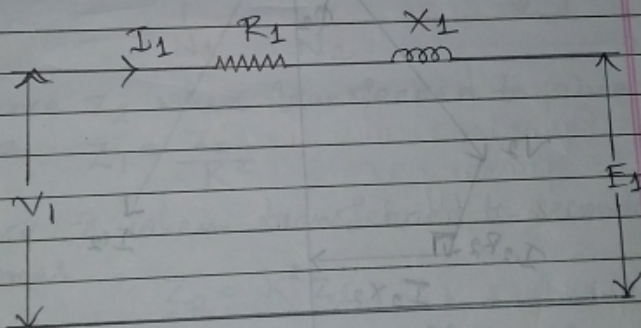
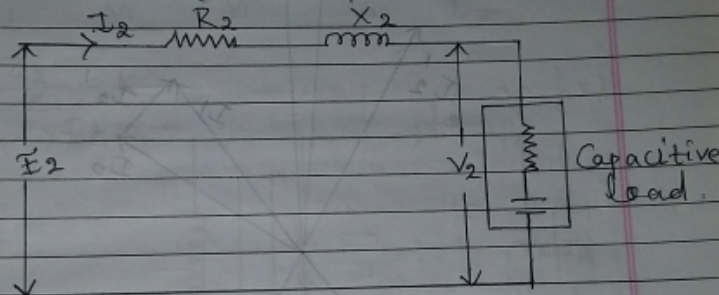
U.P.F. load means resistive load.



Load P.f = $\cos \phi_2 = \cos 0 = 1$
primary p.f = $\cos \phi_1 =$

Phasor diagram of LPF :-

LPF $\rightarrow$ leading power factor load,
LPF $\rightarrow$ means capacitive load.





Phasor diagram for LPF load.

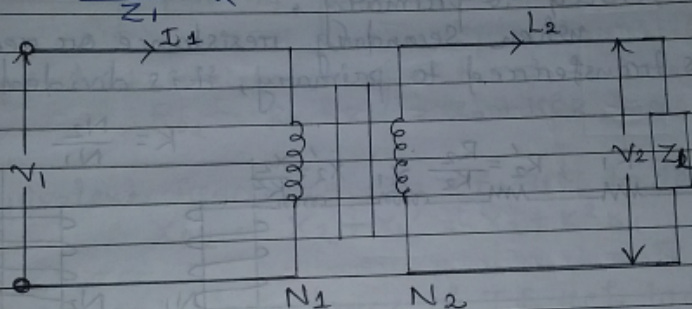
Impedance ratio :-

Consider a transformer Z_1 in primary and Z_2 in secondary.

$$Z_2 = \frac{V_2}{I_2}, \quad Z_1 = \frac{V_1}{I_1}$$

$$\frac{Z_2}{Z_1} = \frac{V_2}{V_1} \times \frac{I_1}{I_2} = \frac{V_2}{V_1} \times \frac{I_1}{I_2} = K \times K$$

$$\frac{Z_2}{Z_1} = K^2$$



Impedance Z_2 when transferred to primary becomes $Z_1 = \frac{Z_2}{K^2}$

Impedance Z_1 when transferred to secondary becomes $Z_2 = K^2 Z_1$

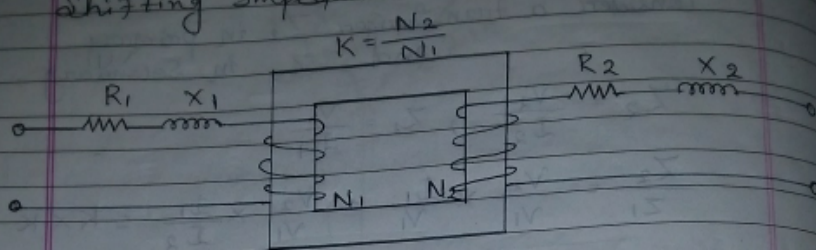
Similarly $\frac{R_2}{R_1} = K^2$ $\frac{X_2}{X_1} = K^2$

Resistance R_1 is primary becomes $K^2 R_1$ when transferred to secondary.

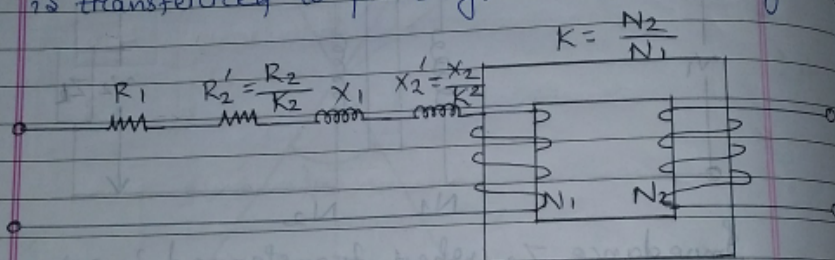
Resistance R_2 is secondary becomes $\frac{R_2}{K^2}$ when transferred to secondary primary.

Similarly X_1 and X_2 .

Shifting Impedance In a T.F. -



Referred to primary -
when secondary resistance or reactance is transferred to primary, it is divided by K^2 .



Equivalent resistance of transformer referred to primary is

$$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}$$

Equivalent reactance of transformer ref to primary

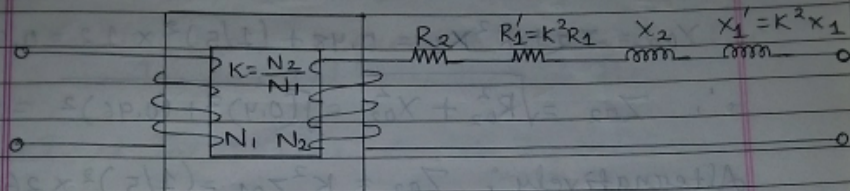
$$X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

Equivalent impedance of T.F. ref to primary

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

Referred to Secondary :-

When primary resistance or reactance is transferred to secondary, it is multiplied by K^2 .



Equivalent resistance of T.F ref. to secondary is

$$R_{02} = R_2 + R_1' = R_2 + K^2 R_1$$

Equivalent reactance of T.F ref. to secondary is

$$X_{02} = X_2 + X_1' = X_2 + K^2 X_1$$

Equivalent impedance of T.F ref. to secondary is

$$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$$

Example :-

A 10 kVA, 2000/400 V Single-phase transformer has $R_1 = 5 \Omega$; $X_1 = 12 \Omega$; $R_2 = 0.2 \Omega$ and $X_2 = 0.48 \Omega$. Determine the equivalent impedance of the transformer referred to (i) primary side

(ii) Secondary side,

Solution :- step down transformer

$$K = \frac{400}{2000} = \frac{1}{5}$$

$$(i) \quad R_{01} = R_1 + \frac{R_2}{K^2} = 5 + \frac{0.2}{(1/5)^2} = 10 \Omega$$

$$X_{01} = X_1 + \frac{X_2}{K^2} = 12 + \frac{0.48}{(1/5)^2} = 24 \Omega$$

$$\therefore Z_{01} = \sqrt{R_{01}^2 + X_{01}^2} = \sqrt{10^2 + 24^2} = 26 \Omega$$

$$(ii) R_{02} = R_2 + K^2 R_1 = 0.2 + (1/5)^2 \times 5 = 0.4 \Omega$$

$$X_{02} = X_2 + K^2 X_1 = 0.48 + (1/5)^2 \times 12 = 0.96 \Omega$$

$$\therefore Z_{02} = \sqrt{R_{02}^2 + X_{02}^2} = \sqrt{(0.4)^2 + (0.96)^2} = 1.04 \Omega$$

$$\text{Alternatively: } Z_{02} = K^2 Z_{01} = (1/5)^2 \times 26 = 1.04 \Omega$$

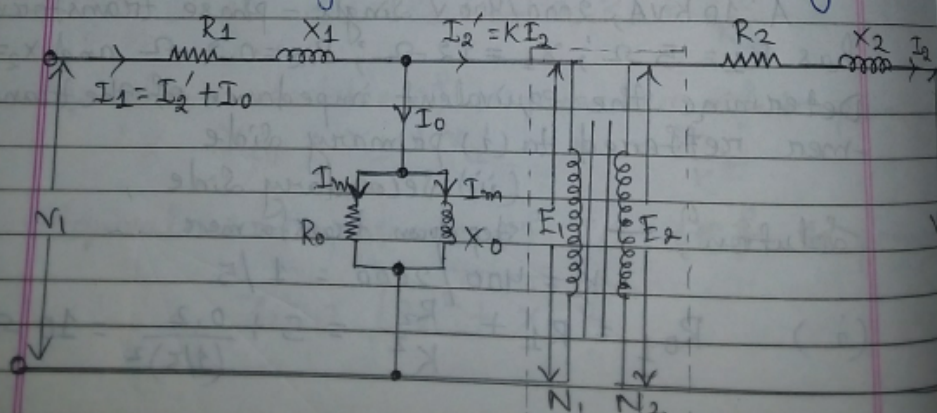
Exact equivalent ckt of a loaded T.F.:-

R_1 = primary winding resistance

R_2 = secondary winding resistance

X_1 = Leakage reactance of primary

X_2 = Leakage reactance of secondary



Ideal transformer

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The parallel ckt $R_0 - X_0$ is the no-load equivalent ckt of the transformer.

R_0 , resistance represent core loss. So I_w current pass through it.

X_0 , reactance represent loss free coil, So I_m current pass through it.

I_0 is the phasor sum of I_w and I_m .

Simplified equivalent ckt of a loaded T.F. —
No-load current I_0 of T.F. is small compared to rated primary current.
Voltage drop in R_1 and X_1 due to I_0 are neglected.

(a) Equivalent ckt ref. to primary —
All secondary quantities are referred to primary.

$$R_2' = \frac{R_2}{K^2}, \quad X_2' = \frac{X_2}{K^2}, \quad Z_1' = \frac{Z_1}{K^2}$$

$$V_2' = \frac{V_2}{K}, \quad I_2' = KI_2$$

$$R_{01} = R_1 + R_2'$$

$$X_{01} = X_1 + X_2$$

Equivalent resistance of the transformer ref. to primary side.

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

$$Z_{01} = R_{01} + jX_{01}$$

Equivalent impedance

Z_L = Impedance of the referred to primary

It's side.

I_0 = no load current

(b) Equivalent ckt referred to Secondary. —

All primary quantities are referred to Secondary.

$$R_1' = K^2 R_1 \quad X_1' = K^2 X_1, \quad V_1' = K V_1, \quad I_1' = I_1 / K$$

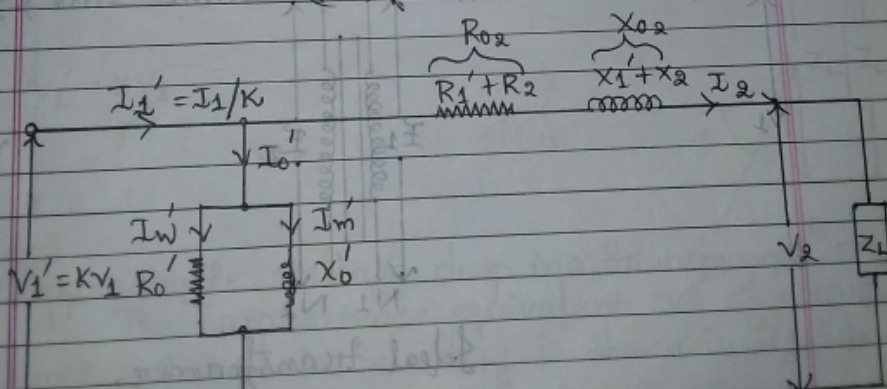
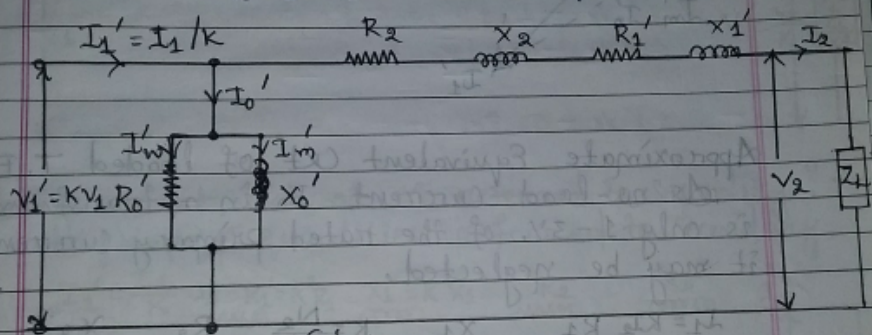
$$R_{02} = R_2 + R_1'$$

$$X_{02} = X_2 + X_1'$$

Equivalent resistance of the transformer ref. to secondary side

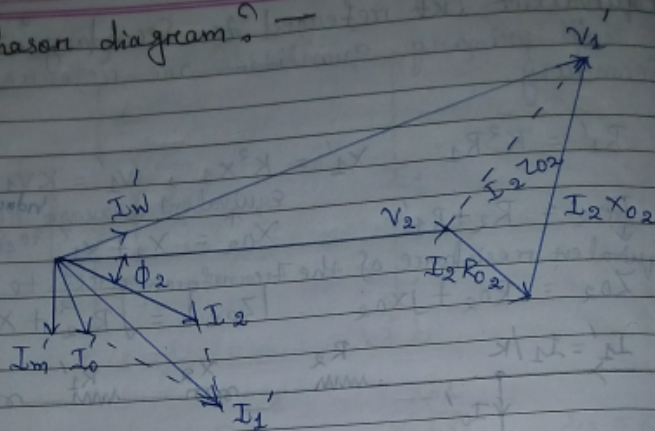
$$Z_{02} = R_{02} + jX_{02}$$

$$|Z_{02}| = \sqrt{R_{02}^2 + X_{02}^2}$$



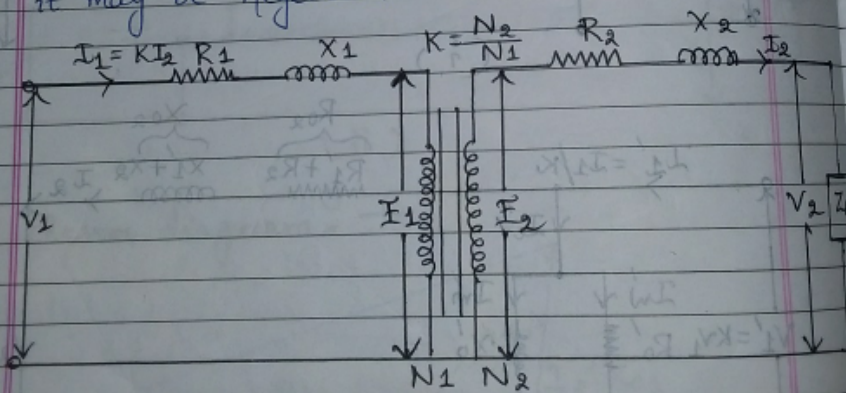
(ii)
 $I_0 = \text{No-load current}$

Phasor diagram? —



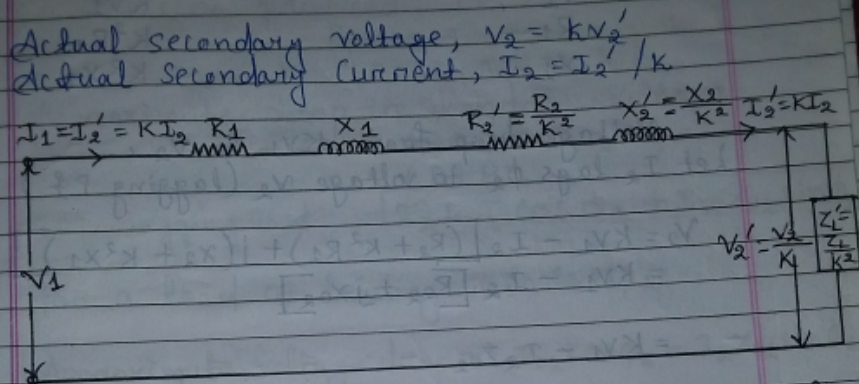
Approximate Equivalent Ckt of loaded T.F. —

As no-load current I_0 in a transformer is only 1-3% of the rated primary current it may be neglected.

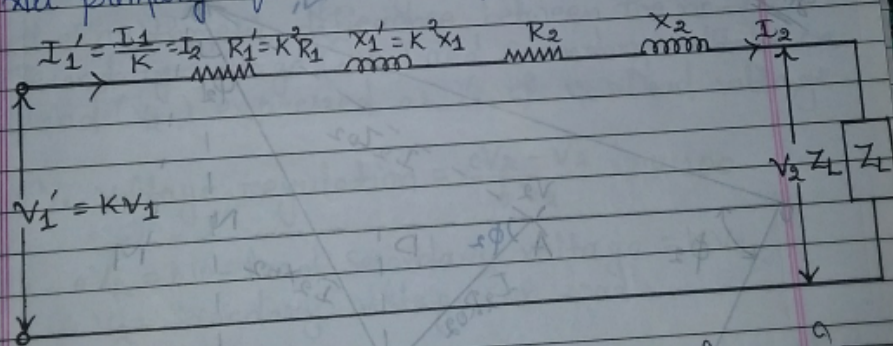


Ideal transformer.

(a) Equivalent ckt of T.F. referred to primary. —
All secondary quantities referred to primary.



(b) Equivalent ckt of T.F. referred to secondary. —
All primary quantities referred to secondary.



Approx Approximate voltage drop in a transformer. —
The approximate equivalent ckt of a transformer referred to secondary is shown in fig below.

Primary quantity

becomes in Secondary

$$V_1$$

$$KV_1$$

$$R_1$$

$$K^2 R_1$$

$$X_1$$

$$K^2 X_1$$

Voltage drop from KV_1 to V_2 .
Let I_2 lags ϕ_2 to voltage V_2 (lagging P.f.)

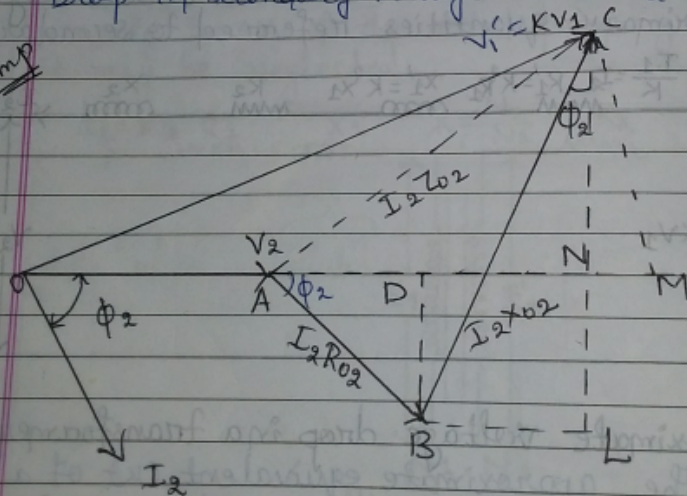
$$V_2 = KV_1 - I_2 [(R_2 + K^2 R_1) + j(X_2 + K^2 X_1)]$$

$$= KV_1 - I_2 [R_{02} + jX_{02}]$$

$$= KV_1 - I_2 Z_{02}$$

$$\text{Drop in Secondary voltage} = KV_1 - V_2 = I_2 Z_{02}$$

Imp



From phasor diagram, it is clear that $AC = I_2 Z_{02}$. It is found that O is centre, $\therefore$ as radius, draw an arc cutting OA produced

at M.

So $AC = AM \approx AN$

$BD \perp OA$ produced, $CN \perp OM$
 $BL \parallel OM$

Approximate drop in secondary voltage
 $= AN = AD + DN$
 $= AD + BL$

lagging load $= I_2 R_{02} \cos \phi_2 + I_2 X_{02} \sin \phi_2$

for a load of leading p.f. $\cos \phi_2$

Approximate voltage drop $= I_2 R_{02} \cos \phi_2 - I_2 X_{02} \sin \phi_2$

Voltage regulation :-

The voltage regulation of a transformer is the arithmetic difference between the no-load secondary voltage ($0V_2$) and secondary voltage on load (V_2) expressed as % of no-load voltage.

$$\% \text{ voltage regulation} = \frac{0V_2 - V_2}{0V_2} \times 100$$

$0V_2 = \text{No-load secondary voltage} = KV_1$
 $V_2 = \text{Secondary voltage on load}$

$$0V_2 - V_2 = I_2 R_{02} \cos \phi_2 \pm I_2 X_{02} \sin \phi_2$$

+ve sign for lagging p.f.
 -ve sign for leading p.f.

$$V_R = \frac{100 \times I_2 R_{02}}{0V_2} = \text{percentage resistive drop.}$$

$$V_x = \frac{100 \times I_2 \times X_{02}}{0 V_2} = \text{percentage reactive drop}$$

Example :-

A 10 KVA, 2000/400 V single-phase transformer has the following data.
 $R_1 = 5 \Omega$; $X_1 = 12 \Omega$; $R_2 = 0.2 \Omega$; $X_2 = 0.4 \Omega$

Determine the secondary terminal voltage at full-load, 0.8 p.f. lagging when the primary supply voltage is 2000 V.

Solution :- $K = 400/2000 = 1/5$

$$R_{02} = R_2 + K^2 R_1 = 0.2 + (1/5)^2 \times 5 = 0.4 \Omega$$

$$X_{02} = X_2 + K^2 X_1 = 0.48 + (1/5)^2 \times 12 = 0.96 \Omega$$

F.L. secondary current, $I_2 = \frac{10 \times 1000}{400} = 25 \text{ A}$
 $\cos \phi_2 = 0.8$ $\therefore \sin \phi_2 = 0.6$

$$\begin{aligned} \text{Voltage drop} &= I_2 (R_{02} \cos \phi_2 + X_{02} \sin \phi_2) \\ &= 25 (0.4 \times 0.8 + 0.96 \times 0.6) \\ &= 25 (0.32 + 0.576) = 22.4 \text{ V} \end{aligned}$$

$\therefore$ secondary terminal voltage at full-load is

$$V_0 = 400 - 22.4 = 377.6 \text{ V}$$

Example :-

Calculate the % voltage regulation of a transformer in which the percentage resistance drop is 1% and percentage reactance drop is

5% when the power factor is (i) 0.8 lagging
(ii) unity and (iii) 0.8 leading.

Solutionⁿ -

$$\% \text{ voltage regulation} = \frac{I_2 R_{02} \cos \phi_2 \pm I_2 X_{02} \sin \phi_2}{0V_2} \times 100$$

$$= \frac{100 \times I_2 R_{02}}{0V_2} \cos \phi_2 \pm \frac{100 \times I_2 X_{02}}{0V_2} \sin \phi_2$$

$$= V_R \cos \phi_2 \pm V_X \sin \phi_2$$

where

$$V_R = \frac{100 \times I_2 R_{02}}{0V_2} = \text{percentage resistive drop}$$

$$V_X = \frac{100 \times I_2 X_{02}}{0V_2} = \text{percentage reactive drop}$$

$$(i) \text{ when } \cos \phi_2 = 0.8 \text{ lag, regulation} = V_R \cos \phi_2 + V_X \sin \phi_2$$

$$= 1 \times 0.8 + 5 \times 0.6 = 3.8\%$$

$$(ii) \text{ when } \cos \phi_2 = 1, \text{ regulation} = 1 \times 1 + 5 \times 0 = 1\%$$

$$(iii) \text{ when } \cos \phi_2 = 0.8 \text{ lead, regulation} = 1 \times 0.8 - 5 \times 0.6 = -2.2\%$$

Exampleⁿ -

A 80 KVA, 2000/200 V, 50 Hz single-phase transformer has impedance drop of 8% and resistance drop of 4%. Calculate the % voltage regulation of the transformer at full-load 0.8 p.f. lagging.

Solutionⁿ -

$$\% \text{ Impedance drop} = \frac{I_2 Z_{02}}{0V_2} \times 100$$

or

$$8 = \frac{I_2 Z_{02}}{200} \times 100$$

$$\therefore I_2 Z_{02} = \frac{8 \times 200}{100} = 16 \text{ V}$$

$$\% \text{ resistance drop} = \frac{I_2 \times R_{02}}{0V_2} \times 100$$

or

$$4 = \frac{I_2 R_{02}}{200} \times 100$$

$$\therefore I_2 R_{02} = 8 \text{ V}$$

$$\therefore I_2 X_{02} = \sqrt{(I_2 Z_{02})^2 - (I_2 R_{02})^2}$$

$$= \sqrt{(16)^2 - (8)^2} = 13.86 \text{ V}$$

$\therefore \% \text{ voltage regulation} =$

$$\frac{I_2 R_{02} \cos \phi_2 + I_2 X_{02} \sin \phi_2}{0V_2} \times 100$$

$$= \frac{8 \times 0.8 + 13.86 \times 0.6}{200} \times 100 = 7.35\%$$

Transformer test

Transformer tests are required to determine.

- (1) Ckt const
- (2) Efficiency & voltage regulation

There are two types of transformer test.

- (a) open ckt or no-load test
- (b) short ckt or impedance test.

These tests consists of measuring the input voltage current and power to the primary first with Secondary open ckted. and then Secondary short ckted.

(a) Open ckt or no-load test :-

This test is conducted to determine.

- (i) Iron losses (core losses)
- (ii) Parameter of R_0 and X_0 .

In this test rated voltage is applied to primary (L.V. winding) and secondary is open ckted.

Applied rated voltage V_1 is measured by voltmeter.

No-load current I_0 by ammeter.

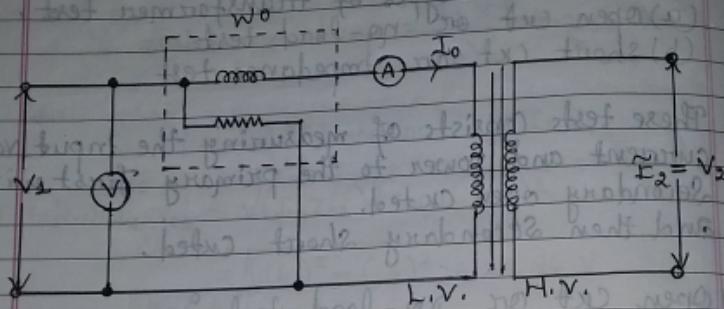
No-load input power W_0 by wattmeter.

As normal rated voltage is applied to primary normal iron losses will occur.

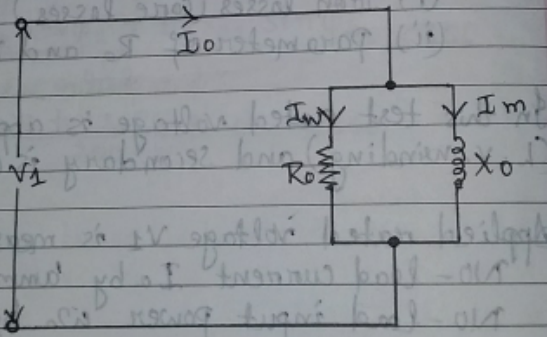
As no-load current I_0 is 2-10% of rated current, Cu-losses in primary under no-load condition are neglected.

Wattmeter reading practically gives the iron loss in the transformer.

Iron losses are same at all loads.



(i)



(ii)

Iron losses, $P_i = \text{Wattmeter reading} = W_0$

No load current = Ammeter reading = I_0

Applied voltage = Voltmeter reading = V_1

Input power, $W_0 = V_1 I_0 \cos \phi_0$

$\therefore$ No-load P.f., $\cos \phi_0 = W_0 / V_1 I_0$

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

$$R_0 = V_1 / I_w, \quad X_0 = V_1 / I_m$$

The open circuit test enable us to determine iron losses and parameters R_0 and X_0 of the transformer.

Short - Circuit or impedance test :-

This test is conducted to determine

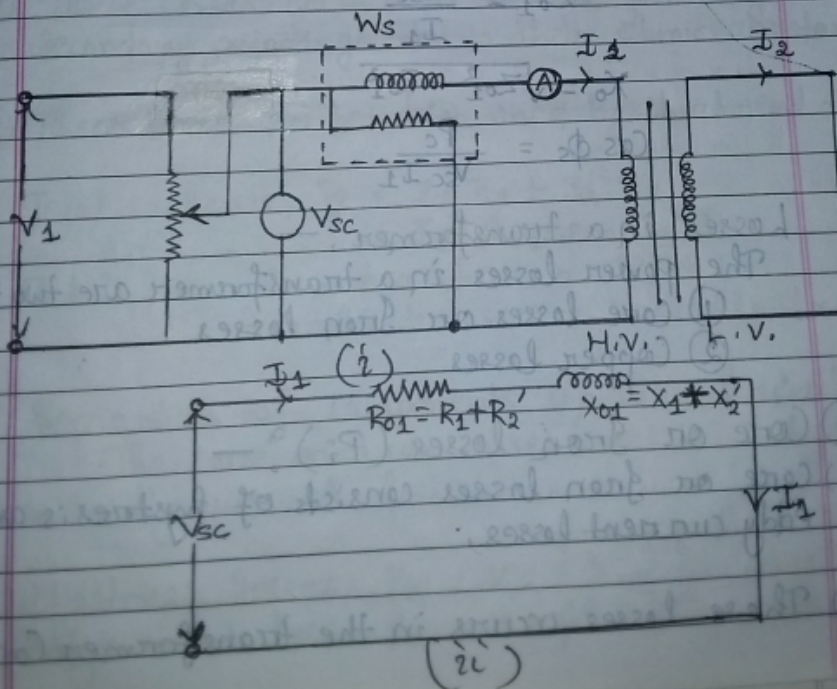
(i) R_{01} (or R_{02}), X_{01} (or X_{02})

(ii) Full-load copper losses.

L.V. side is short circuited.

A voltage is applied to primary gradually till full load current to short cut side.

The input power loss is entirely copper losses because iron loss is negligible.



wattmeter reading will give the Full load
Copper loss.

Full load copper losses, $P_c = \text{wattmeter reading}$

Applied voltage = Voltmeter reading = V_{sc}

F.L. primary current = Ammeter reading = I_1

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

$$P_c = I_1^2 R_{01}$$

$$R_{01} = \frac{P_c}{I_1^2}$$

$$Z_{01} = \frac{V_{sc}}{I_1}$$

$$X_0 = \sqrt{Z_{01}^2 - R_{01}^2}$$

$$\cos \phi_s = \frac{P_c}{V_{sc} I_1}$$

Losses in a transformer, —

The power losses in a transformer are two types.

① Core losses or Iron losses

② Copper losses

① Core or Iron losses (P_i) —

(i) Core or Iron losses consists of hysteresis and eddy current losses.

(ii) These losses occurs in the transformer Core.

to alternating flux.

(iii) These losses can be determined by open-circuit test.

$$\text{Hysteresis losses} = K_h f B_m^{1.6} \text{ watts/m}^3$$

$$\text{Eddy current loss} = K_e f^2 B_m^2 \text{ watts/m}^3$$

Since transformer operated at const frequency and const. supply voltage, f , B_m are const.

This core or iron losses is called const losses.

② Copper losses (P_c). —

① These losses occurs in both the primary and secondary windings due to their ohmic resistance.

② These losses can be determined by short-circuit test.

$$\text{Total cu losses, } P_c = I_1^2 R_1 + I_2^2 R_2$$

$$= I_1^2 R_{01} \text{ or } I_2^2 R_{02}$$

$$\text{Total losses in a transformer} = P_i + P_c$$

$$= \text{Constant losses} + \text{variable losses}$$

Separation of components of core losses: —

The core or iron losses consists of hysteresis and eddy current losses.

$$\text{Hysteresis losses, } P_h = K_h f B_m^{1.6} \text{ watts/m}^3$$

$$\text{Eddy current loss } P_e = K_e f^2 B_m^2 \text{ watts/m}^3$$

B_m = max. flux density

f = frequency

Kn, K_e = Const.

$$P_n \propto f$$
$$P_n = af$$

and $P_e \propto f^2$

$$P_e = bf^2$$

The total losses, $P_i = af + bf^2$

$$\frac{P_i}{f} = a + bf$$

Plotting a graph $\frac{P_i}{f}$ vs f , we can calculate a and b .

By knowing a & b we can find out P_n, P_e .

Example: -

The iron loss in a certain transformer is 80 W at 25 Hz and 204 W at 60 Hz, the maximum flux density being the same. Calculate the total iron losses at 100 Hz at the same maximum flux density.

Solution: -

Total iron losses, $P_i = af + bf^2$ (i)

$$\frac{P_i}{f} = a + bf$$

At 25 Hz: $\frac{80}{25} = a + 25b$; At 60 Hz: $\frac{204}{60} = a + 60b$

On solving these two equations, we have $a = 107/5$, $b = 1/175$.

Total iron loss at 100 Hz can be obtained by putting the values of a, b and $f (= 100 \text{ Hz})$ in

eq. (i)

$$\therefore \text{Total iron loss, } P_i = \frac{107}{35} \times 100 + \frac{1}{175} \times (100)^2 \\ = 362.85 \text{ W}$$

Why transformer rating in KVA. —
We know that copper loss in a transformer depends upon current and iron loss depends upon voltage.

Total loss depends upon the volt-ampere product not the phase angle between voltage and current i.e. it is independent of load p.f.

For this reason, the rating of a transformer is in KVA and not KW.

Efficiency of a transformer. —

Efficiency of a transformer is defined as the ratio of output power (watts or KW) to input power (watt or KW).

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}}$$

$$= \frac{\text{Output p}}{\text{Output} + \text{losses}}$$

direct loading method to determine efficiency has drawback.

So direct loading method is seldom used in practice, open ckt and short-ckt tests are carried out.

Efficiency from transformer tests: —

From open ckt test,

$$\text{full load iron loss} = P_i$$

From short ckt test

$$\text{full load cu. loss} = P_c$$

$$\text{Total full load losses} = P_i + P_c$$

Full-load efficiency of T.F. at any P.f. without loading

F.L efficiency =

$$\eta_{F.L} = \frac{\text{full load VA} \times P.f.}{(\text{full load VA} \times P.f.) + P_i + P_c}$$

Let $x = \frac{\text{Any load}}{\text{full load}}$

$$\text{Any load} = x \times \text{full load}$$

$$\eta_x = \frac{(x \times \text{full load VA}) \times P.f.}{(x \times \text{full load VA} \times P.f.) + P_i + x^2 P_c}$$

$$\text{where total losses} = P_i + x^2 P_c.$$

Condition for maximum Efficiency: —

$$\text{Output power} = V_2 I_2 \cos \phi_2$$

R_{e2} = Total resistance of T.F. referred to Secondary

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$$\text{Total Cu loss, } P_c = I_2^2 R_{02}$$

$$\text{Total losses} = P_i + P_c$$

$$\text{Efficiency } \eta = \frac{V_2 I_2 \cos \phi_2}{V_2 I_2 \cos \phi_2 + P_i + I_2^2 R_{02}}$$

Dividing I_2 on both numerator and denominator,

$$\eta = \frac{V_2 \cos \phi_2}{V_2 \cos \phi_2 + \frac{P_i}{I_2} + I_2 R_{02}}$$

V_2 is approximately const.

$\cos \phi_2$ is const.

Numerator is const.

η is max if denominator

$V_2 \cos \phi_2 + \frac{P_i}{I_2} + I_2 R_{02}$ is minimum.

$$\text{So, } \frac{d}{dI_2} \left(V_2 \cos \phi_2 + \frac{P_i}{I_2} + I_2 R_{02} \right) = 0$$

$$\frac{d}{dI_2} (V_2 \cos \phi_2) + \frac{d}{dI_2} \left(\frac{P_i}{I_2} \right) + \frac{d}{dI_2} I_2 R_{02} = 0$$

$$\Rightarrow 0 - \frac{P_i}{I_2^2} + R_{02} = 0$$

$$\Rightarrow -P_i + I_2^2 R_{02} = 0$$

$$\Rightarrow P_i = I_2^2 R_{02}$$

$$\boxed{P_i = P_c}$$

For max, efficiency Iron losses = Copper losses

Hence efficiency of a transformer will be max when copper losses are equal to const or Iron loss.

$$I_2^2 R_{02} = P_i$$

$$I_2 = \sqrt{\frac{P_i}{R_{02}}}$$

Output KVA corresponding to max. η ? —

Let P_i = Iron losses

P_c = Copper losses at full load KVA

x = fraction of full load KVA at which efficiency is max.

$$x^2 P_c = P_i$$

for max. efficiency

$$x = \sqrt{\frac{P_i}{P_c}} = \sqrt{\frac{\text{Iron loss}}{\text{Full load cu loss}}}$$

output KVA corresponding to max. efficiency

$$= x \times \text{full load KVA}$$

$$= \text{full load KVA} \times \sqrt{\frac{\text{Iron loss}}{\text{F.L. Cu loss}}}$$

Example:-

The low voltage winding of a 300 kVA, 11000/2200V, 50 Hz transformer has 190 turns and a resistance of 0.06Ω . The high voltage side has 910 turns and a resistance of 1.6Ω . When the low-voltage winding is short-circuited, the full-load current is obtained with 550V applied to h.v. side. Calculate the equivalent resistance and leakage reactance referred to high-voltage side. Assume full-load efficiency of 98.5%.

Solution:-

$$V_{sc} = 550 \text{ V}, K = 190/910 = 19/91, \eta = 98.5\%$$

$$\text{T.I. primary current, } I_1 = \frac{300 \times 10^3}{11000 \times 0.985} = 27.7 \text{ A}$$

$$Z_{01} = V_{sc} / I_1 = 550 / 27.7 = 19.8 \Omega$$

$$R'_2 = R_2 / K^2 = 0.06 / (19/91)^2 = 1.38 \Omega$$

$$R_{01} = R_1 + R'_2 = 1.6 + 1.38 = 2.98 \Omega$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{(19.8)^2 - (2.98)^2} = 19.5 \Omega$$

Q. In a no-load test of a single-phase transformer, the following test data were obtained:-
 primary voltage: 220 V; secondary voltage: 110V;
 primary current: 0.5A; power input: 30W
 find (i) the turns ratio (ii) the magnetising component of no-load current (iii) the iron-loss component of no-load current (iv) iron loss. The resistance of primary winding is 0.6Ω .

Solⁿ (i) Turns ratio $= \frac{N_1}{N_2} = \frac{E_1}{E_2} = \frac{V_1}{V_2} = \frac{220}{110}$

(ii) $W_0 = V_1 I_0 \cos \phi_0$
 $\therefore$ No load p.f., $\cos \phi_0 = \frac{W_0}{V_1 I_0} = \frac{30}{220 \times 0.5} = 0.273$

$\sin \phi_0 = 0.962$
 Magnetising current $I_m = I_0 \sin \phi_0 = 0.5 \times 0.962 = 0.48 \text{ A}$

(iii) Component of no-load current corresponding to core loss is
 $I_w = I_0 \cos \phi_0 = 0.5 \times 0.273 = 0.1365 \text{ A}$

(iv) primary Cu loss $= I_0^2 R_1 = (0.5)^2 \times 0.6 = 0.15 \text{ W}$
 Iron loss $= 30 - 0.15 = 29.85 \text{ W}$

Q. A 10 KVA, 200/400 V, 50 Hz single-phase transformer gave the following test results:-

O.C. test: 200 V, 1.3 A, 120 W ... on L.V. side

S.C. test: 22 V, 30 A, 200 W ... on H.V. side

Calculate (i) the magnetising current and the component corresponding to core loss at normal frequency and voltage (ii) the magnetising-branch impedances and (iii) percentage voltage regulation when supplying full-load at 0.8 p.f. leading,

Ans (i) No-load p.f., $\cos \phi_0 = \frac{W_0}{V_1 I_0} = \frac{120}{200 \times 1.3} = 0.462$

Magnetising current, $I_m = I_0 \sin \phi_0 = 1.3 \times 0.886 = 1.15 \text{ A}$
 Component of no-load current corresponding to core loss is

$$I_w = I_0 \cos \phi_0 = 1.3 \times 0.462 = 0.6 \text{ A}$$

(ii)

$$R_0 = \frac{V_1}{I_0 \cos \phi_0} = \frac{200}{0.6} = 333 \Omega$$

$$X_0 = \frac{V_1}{I_0 \sin \phi_0} = \frac{200}{1.15} = 174 \Omega$$

(iii) Total impedance referred to H.V. side (secondary) is

$$Z_{02} = \frac{V_{sc}}{\text{sec. current}} = \frac{22}{30} = 0.733 \Omega$$

Total resistance referred to H.V. side (secondary) is

$$R_{02} = \frac{W_s}{(\text{sec. current})^2} = \frac{200}{(30)^2} = 0.222 \Omega$$

Total leakage reactance referred to H.V. side (secondary) is

$$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = \sqrt{(0.733)^2 - (0.222)^2} = 0.698 \Omega$$

F.L. Current on H.V. side, $I_2 = \frac{10 \times 10^3}{400} = 25 \text{ A}$

$$\begin{aligned} \text{Approximately voltage drop} &= I_2 (R_{02} \cos \phi_2 - X_{02} \sin \phi_2) \\ &= 25 (0.222 \times 0.8 - 0.698 \times 0.6) \\ &= -6 \text{ V} \end{aligned}$$

Note that there is a voltage rise due to leading

power factor.

$$\% \text{ age voltage regulation} = \frac{(-6/400) \times 100}{-1.5\%}$$

Q. A 200 KVA, 2000/440 V, 50Hz Single-phase transformer gave the following test results:-

O.C. test: 2000V, 1.8A, 1.75KW. On H.V. Side

S.C. test: 13V, 300A, 1KW. On L.V. Side

Obtain the equivalent circuit as referred to H.V. Side.

Solution:

Component of no-load current corresponding to core loss is

$$I_w = \frac{W_0}{V_1} = \frac{1.75 \times 10^3}{2000} = 0.875 \text{ A}$$

Magnetising current,

$$I_m = \sqrt{I_0^2 - I_w^2} = \sqrt{(1.8)^2 - (0.875)^2} = 1.57 \text{ A}$$

$$\therefore R_0 = \frac{V_1}{I_w} = \frac{2000}{0.875} = 2286 \Omega$$

$$X_0 = \frac{V_1}{I_m} = \frac{2000}{1.57} = 1274 \Omega$$

Total impedance referred to L.V. side (secondary) is

$$Z_{02} = V_{sc} / I_2 = 13 / 300 = 0.0433 \Omega$$

Total resistance referred to L.V. side (secondary) is

$$R_{02} = \frac{W_s}{I_2^2} = \frac{1 \times 10^3}{(300)^2} = 0.011 \Omega$$

$$\therefore X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = \sqrt{(0.0433)^2 - (0.011)^2} = 0.042 \Omega$$

Total resistance and reactance referred to H.V. side (primary) are.

Q. The primary and secondary windings of a 50kVA, 6600/220V transformer have resistance of 7.8Ω and 0.0085Ω respectively. The transformer draws no-load current of 0.328 A at p.f. of 0.3 lagging. Calculate the efficiency at full-load if the p.f. of the load is 0.8 lagging.

Solution

$$K = 220/6600 = 1/30$$

$$\text{F.L. iron losses} = 6600 \times 0.328 \times 0.3 = 650 \text{ W}$$

$$R_{01} = R_1 + R_2/K^2$$

$$= 7.8 + (0.0085) \times (30)^2 = 15.45 \Omega$$

$$\text{F.L. primary current, } I_1 = 50 \times 10^3 / 6600 = 7.57 \text{ A}$$

$$\text{F.L. Cu losses} = I_1^2 R_{01} = (7.57)^2 \times 15.45 = 885.4 \text{ W}$$

$$\text{Total F.L. losses} = 650 + 885.4 = 1535.4 \text{ W}$$

$$\text{F.L. output} = 50 \times 10^3 \times 0.8 = 40,000 \text{ W}$$

$$\text{F.L. input} = 40,000 + 1535.4 = 41535.4 \text{ W}$$

$$\text{F.L. efficiency} = \frac{40,000}{41535.4} \times 100 = 96.3\%$$