Jaipur Engineering College & Research Centre, Jaipur

Session 2020-21

Subject Notes

Unit-III

Basic Electrical Engineering (2FY3-08)

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Page No.
Date

Unit -3

Single Phase transformer

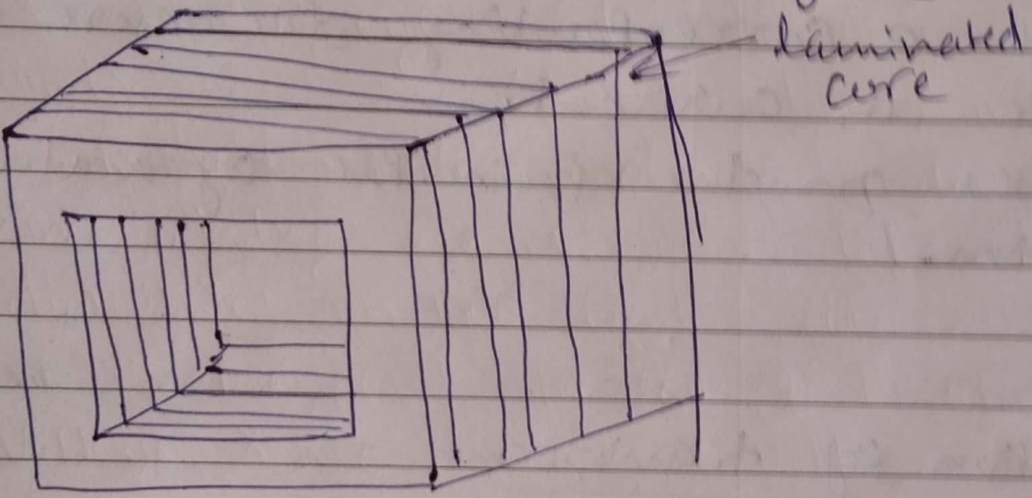
A Transformer is a static device which can transfer electrical energy from one circuit to another circuit without change of frequency.
It can increase or decrease the voltage but with a corresponding decrease or increase in current.
It works on the principle of mutual induction.

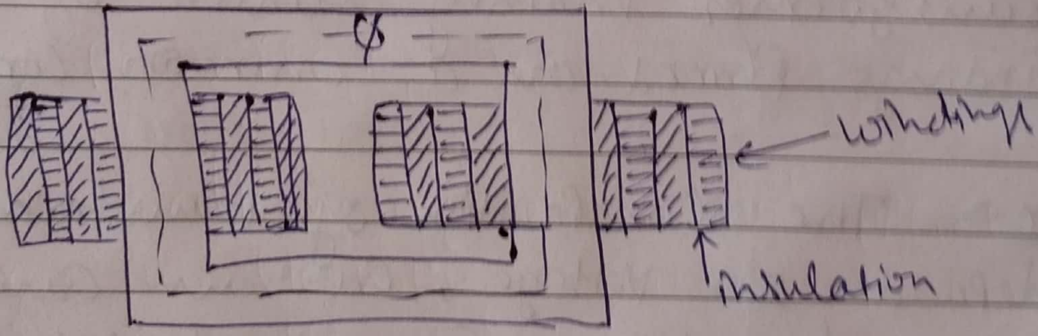
Construction of transformer ⇒

Transformer mainly consist of two coils or windings placed on a common core.

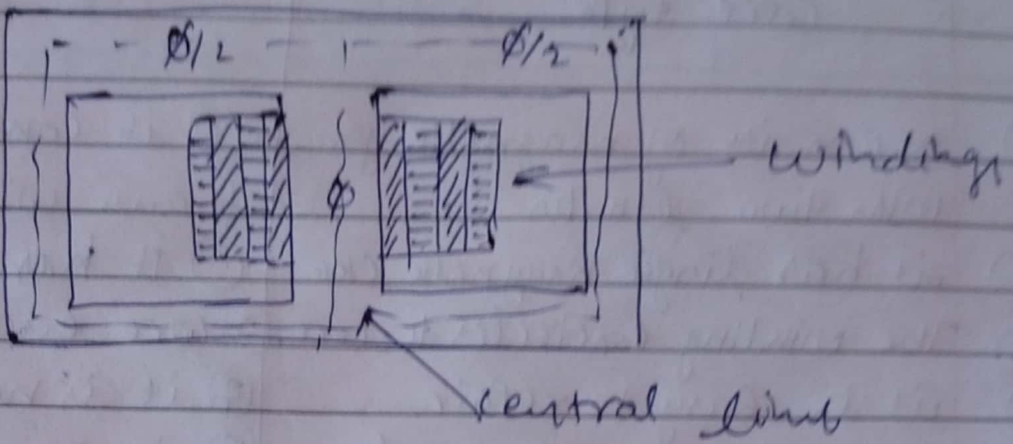
Core ⇒ The composition of transformer core depends on voltage, current and frequency. Commonly used core materials are soft-iron and steel. In most transformer the core is constructed of laminated steel to provide a continuous magnetic path. The steel used for constructing the core is high-graded silicon steel where hysteresis loss is very low. Such steel is called soft steel. Due to alternating flux, certain currents are induced in core, called as eddy currents. These currents cause considerable loss in the core, called eddy current loss. Silicon content in the steel increases it's resistivity to eddy-current loss. There by reducing eddy-current losses. To reduce eddy current losses further, the core is laminated by a light coat of varnish or by an oxide layer on the surface.

There are two main shapes of cores used in X-mer are shown in fig ⓐ and ⓑ.





construction of core in core type x-mer
fig ⓐ



Transformer winding => Transfomer consist of two coils, called windings. which are wrapped around core. The winding in which electrical energ is fed is called Primary winding. The winding which is connected to the load is called the sec. winding. windings are made up of an insulated copper conductor in the form of a round wire or strip. These windings are then placed arround the limbs of the ~~toc~~ core. windings are insulated forum each other and the core. using the cylinders of insulating material such as a Press board or Bakelite.

For simplicity, the Primary and secondary windings are shown on seperate limbs of the core. if such arrangement is used in actual Peractice, there will be some leakage flux. To reduce the leakage flux, the windinge are placed together on the same limb in actual transformer.

Comparision of Core type and Shell type X-mer

	Core type	Shell type
①	It consist of magnetic frame with two limbs	① it consist of magnetic frame with 3 limbs.
②	it has single magnetic ckt	② it has two magnetic circuits
③	The winding encircles the core	③ core encircles the winding
④	it is easy to repair	④ it is not easy to repair
⑤	it consist of cylindrical windings	⑤ it consists of sandwich type windings.
⑥	it provides better cooling since windings are uniformly distributed on two limbs	⑥ it does not provide effective cooling as the winding are surrounded by core.
⑦	it is preffered for low voltage X-mer	⑧ Preferred for high voltage X-mer.

Working Principle of transformer ⇒

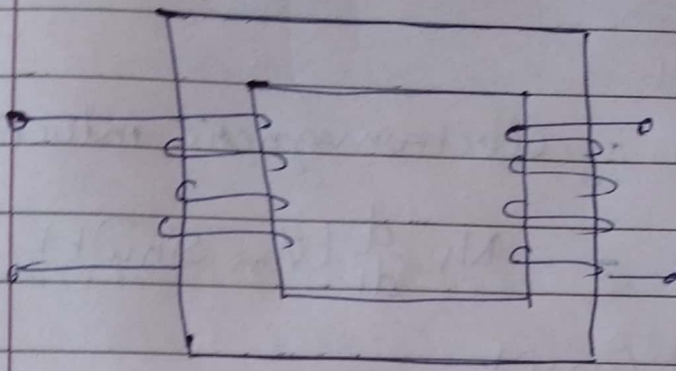
When an alternating voltage V_1 is applied to a Pri winding, an alternating current I_1 flows in it producing an alternating flux in the core. As per faraday's law of electromagnetic induction, an emf e_1 is induced in the primary winding.

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

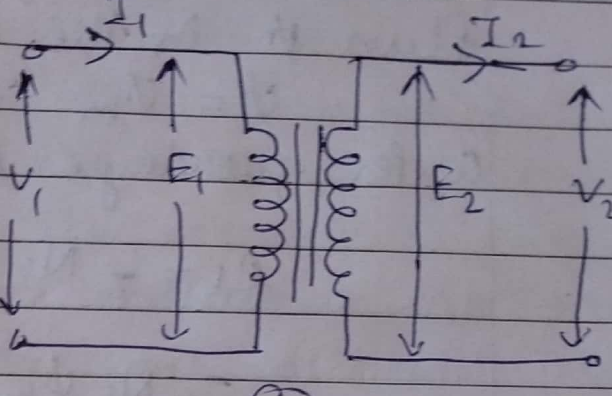
where N_1 is the no. of turns in the primary winding. The induced emf in primary winding is nearly equal and opposite to the applied voltage V_1. Flux produced in primary winding is also links with sec winding. Hence an emf is induced in sec. winding

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

where N_2 = no. of turns in sec. winding.



(a)



(b)

if the sec. circuit is closed through the load, a current I_2 flows in the sec. winding. Thus energy is transfered from Primary winding to secondary winding. The symbol for transformer is shown in fig (b).

if $N_2 > N_1$ → step up transformer

if $N_1 > N_2$ → step down transformer

Page No. ______
Date

Emf equation of X-mer -

As the Primary winding is excited by sinusoidal alternating voltage, an alternating current flows in the winding producing a sinusoidally varying flux ϕ in the core.

$$\phi = \phi_m \sin\omega t$$

as per faraday's law of electromagnetic induction

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

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

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

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

max. value of induced emf

$$E_{1max} = 2\pi f \phi_m N_1$$

Hence, rms value of induced emf in Primary winding

$$E_1 = \frac{E_{1max}}{\sqrt{2}} = \frac{2\pi f \phi_m \cancel{\phi} N_1}{\sqrt{2}}$$

$$E_1 = 4.44 f \phi_m N_1$$

Similarly $E_2 = 4.44 f \phi_m N_2$

Also, $\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 f \phi_m$

Thus, emf per turn is same in Primary and secondary winding and an equal emf is induced in each turn of the Primary and secondary winding.

Date

Transformer on DC -

A X-mer can not operate on dc supply and never be connected to a dc source. If a rated dc voltage is applied to the Primary of a X-mer, the flux Produced in the X-mer core will not vary but remain constant in magnitude and therefore, no emf will be induced in sec. winding except at the moment of switching on.

Thus the X-mer is not capable of raising or lowering the dc voltage. Also there will be no self induced emf in the Primary winding, which is only Possible with varying flux linkage, to oppose the applied voltage and since the resistance of Primary winding is quite low, a heavy current will flow through the Primary winding which may result in the burning out of the Primary winding

Ideal Transformer =>

For a better understanding and a easier explanation of a Practicle transformer, certain idealizing assumptions are made -

(1) No winding resistance.
(2) No magnetic leakage.
(3) No Core losses
(4) Zero magnetizing current

Date

From the above assumptions an ideal transformer is supposed to consists of two Purely inductive coils wound on a loss-free core.

Transformer on No load ⇒

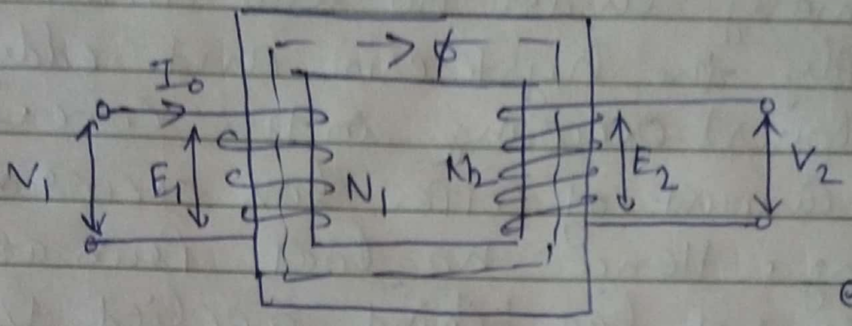
when the Primary of a transformer is connected to the source of ac supply and the secondary is open, the transformer is said to be at No-load.

Consider an ideal X-mer whose sec. side is open and the Pri winding is connected to a sinusoidal alternating voltage V_1. The alternating voltage applied to the Pri. winding will cause flow of alternating current in Pri winding. Since the Primary coil is Purely inductive and there is no O/P (sec. being open) the Pri draws the magnetising current I_m only. The function of this current is merely to magnetize the core. if the X-mer is truely ideal, I_m should be zero. Since the reluctance of magnetic circuit is never zero, I_m has definite magnitude. The I_m is small in magnitude and lags behind supply voltage V_1 by 90°

This I_m Produces an alternating flux ϕ, which is Proportional to current and hence in Phase with it.

let $\phi = \phi_m \sin\omega t$ — ①

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

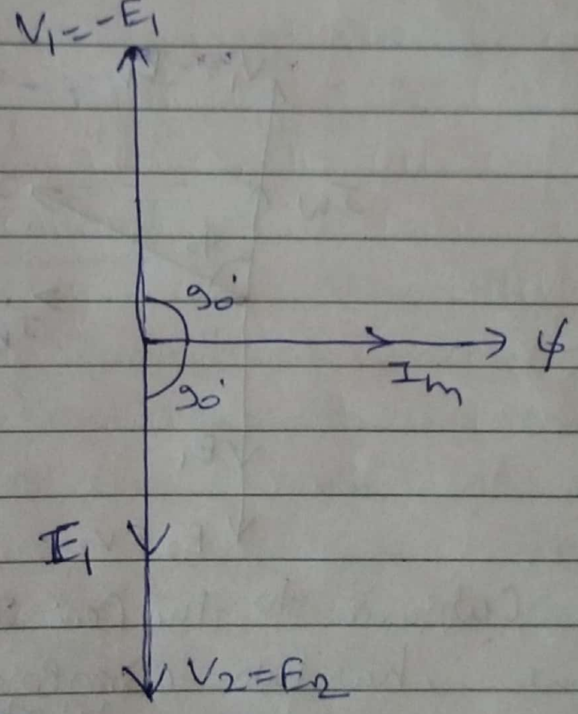


$e_1 = N_1 \omega \phi_m \sin(\omega t - \frac{\pi}{2})$ — ②

Similarly

$e_2 = N_2 \omega \phi_m \sin(\omega t - \frac{\pi}{2})$ — ③

Transformer on No load

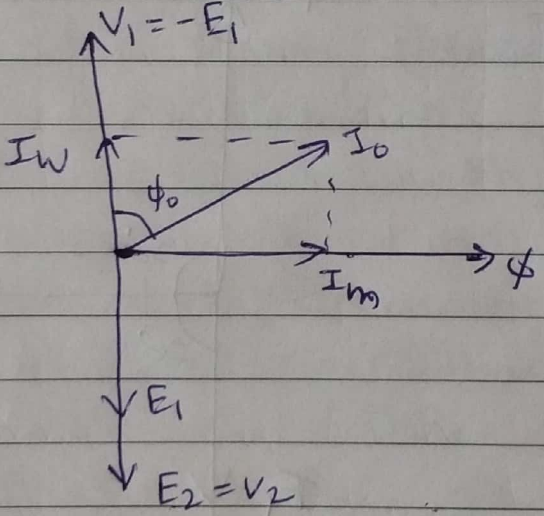


No-load Phasor dia for an ideal x-mer

for ideal X-mer $V_1 = -e_1 = -N_1 \omega \phi_m \sin(\omega t - \frac{\pi}{2})$ — ④
by comparing eq. (I), (II), (III) & (IV), it is clear that, E_1 and E_2 lags behind the ϕ by $\pi/2$. ~~and~~
$V_2 = E_2$ as no voltage drop in sec.

However, when a varying flux is set up in magnetic material, there will be power loss, called the iron or core loss. So input current to primary under no-load condition has also to supply the hysteresis and eddy currents (iron losses) occuring in the core in addition to small amount of copper loss occurring in primary winding. Hence no load primary current I_0 does not lag behind applied voltage V_1 by 90° but lags behind V_1 by angle $\phi_0 < 90°$.

i/p power on no-load, $P_0 = V_1 I_0 \cos\phi_0$



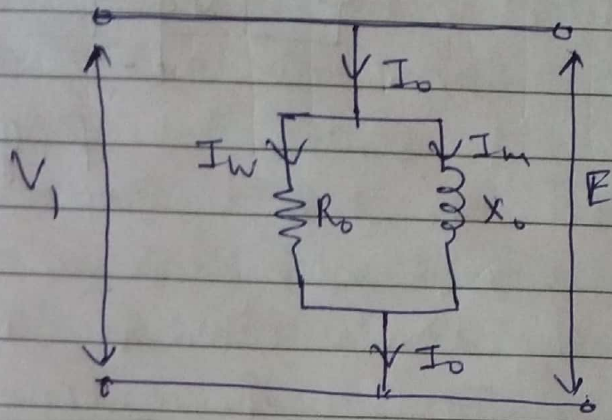
Input current to the pri I_0, called exciting current, has two components

(i) In phase, active or ~~energy~~ working component I_w used to meet iron loss in addition to small amount of copper loss occuring in primary win.

(ii) Quadrature component or wattless component or magnetizing component, I_m used to create the alternating flux in the core.

Thus $I_w = I_0 \cos\phi_0$
and $I_m = I_0 \sin\phi_0$

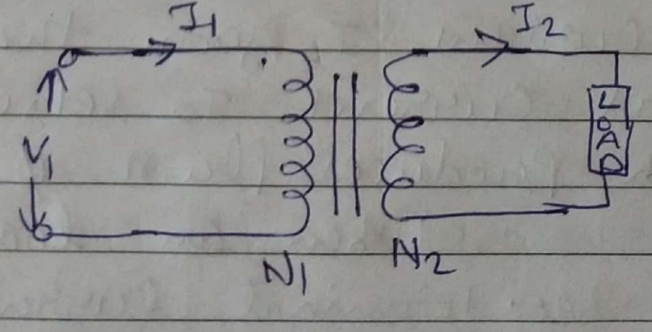
and $\sqrt{I_w^2 + I_m^2} = I_0$



equivalent circuit of X-mer at no-load.

Transformer on load ⇒

When the sec. circuit of a X-mer is completed through an impedance, or load the transformer is said to be loaded and current flows through the sec. winding and the load.



An ideal X-mer on load.

The magnitude and Phase of sec. current I_2 with respect to sec. terminal voltage V_2 will depend upon the characteristics of load.

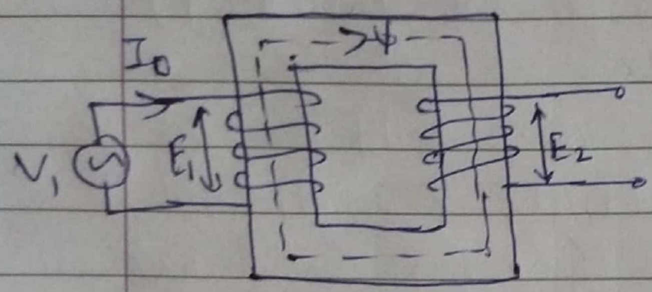


fig (a)

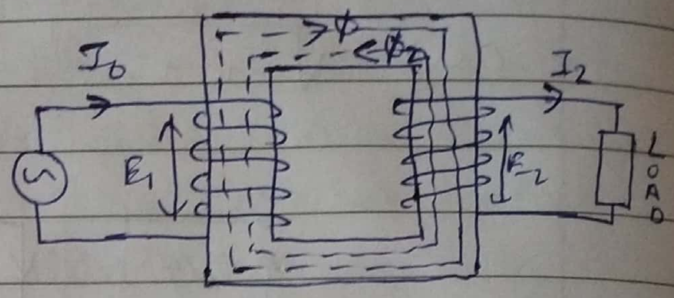


fig (b)

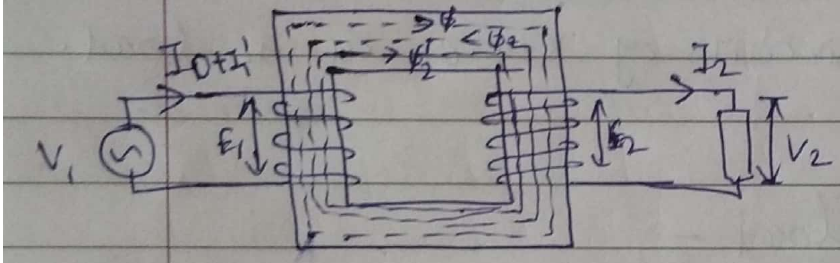


fig (c)

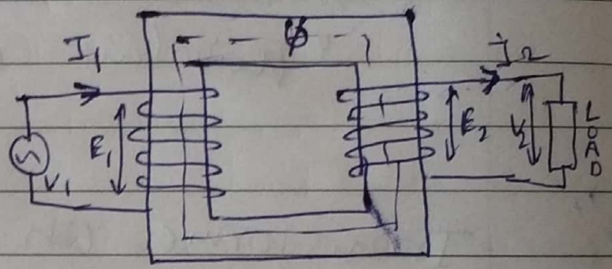


fig (d)

When the X-mer is on no load, it draws no-load current I_0 from the supply mains. The no load current I_0 sets up an MMF $N_1 I_0$ which produces flux ϕ in the core.

When an load is connected across the sec. terminal current I_2 flows through the sec. winding (fig b). The sec. current sets up it's own mmf and hence creates a sec. flux ϕ_2. The sec. flux opposes the main flux ϕ set up by the I_0 according to lenz's law. The opposing sec. flux ϕ_2 weakens the main flux ϕ momen

-tarily, so Primary back emf E_1 tends to be reduced. So difference of applied voltage V_1 and back emf E_1 increases, therefore, more current is drawn from the source of supply flowing through the Primary winding until the original value of ϕ is obtained. It again causes increase in back EMF E_1 and it adjusts itself as such that there is balance b/w applied voltage V_1 and back emf E_1.

Let the additional Primary current be I_1'. The I_1' is in Phase opposition with I_2 and is called counter balancing current. The additional current I_1' sets up an mmf $N_1 I_1'$ Producing flux ϕ_1' in the same direction as that of main flux ϕ and cancels ϕ_2 Produced by sec. mmf $N_2 I_2$ being equal in magnitude.

So:

$$N_1 I_1' = N_2 I_2$$

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

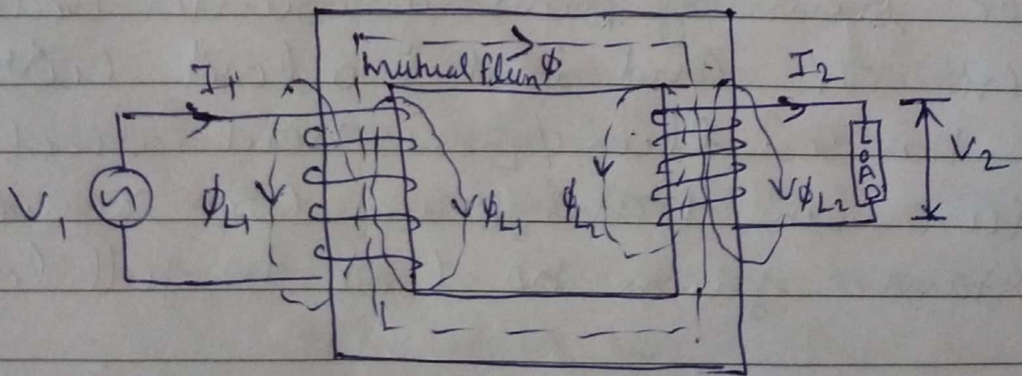
The total Primary current I_1 is therefore Phasor sum of Primary Counter balancing current I_1' and ~~load~~ no load current I_0. Since the sec. flux ϕ_2 is neutralized by ϕ_1' the flux in transformer core remains almost constant from no-load to full load.

Resistance and leakage reactance ⇒

(Practical transformer)

In an ideal X-mer it is assumed that all the flux produced by the primary winding links both the pri and sec. windings. In practice it is impossible to realize this condition. However all flux produced by pri winding does not linked with the sec. winding. Some part of primary flux ϕ_{L1} links with pri winding only. The flux ϕ_{L1} is called pri. leakage flux which links to pri winding and does not link with sec. winding. Similarly, some of the flux produced by sec winding links to sec winding and does not link with pri winding. This flux is called sec. leakage flux ϕ_{L2}.

The flux which does not pass completely through the core and links both the windings is known as the mutual flux and is represented by ϕ.



magnetic fluxes in a X-mer

The ϕ_{L1} is in Phase with I_1 and Produces self induced emf E_{L1} in Primary winding. Similarly ϕ_{L2} is in Phase ~~I_2~~ with I_2 and Produces self induced emf E_{L2} in sec. winding. E_{L1} and E_{L2} due to leakage flux ϕ_{L1} and ϕ_{L2} are different from E_1 and E_2 caused by main flux ϕ. it is therefore, equivalent to an inductive coil in series with the respective winding such the voltage drop in each series coil is equal to that Produced by leakage flux.

$$E_{L1} = I_1X_1 \quad \text{and} \quad E_{L2} = I_2X_2$$

The term X_1 and X_2 are called Primary and sec. leakage reactance respectively.

In actual Practice both the windings, Pri and sec. have finite resistances R_1 and R_2 which causes copper losses and voltage drop in them.

→ A transformer with winding resistance and magnetic leakage is equivalent to an ideal X-mer (having no resistance and leakage reactance) having winding resistances and leakage reactance connected in series with each winding as shown in fig.

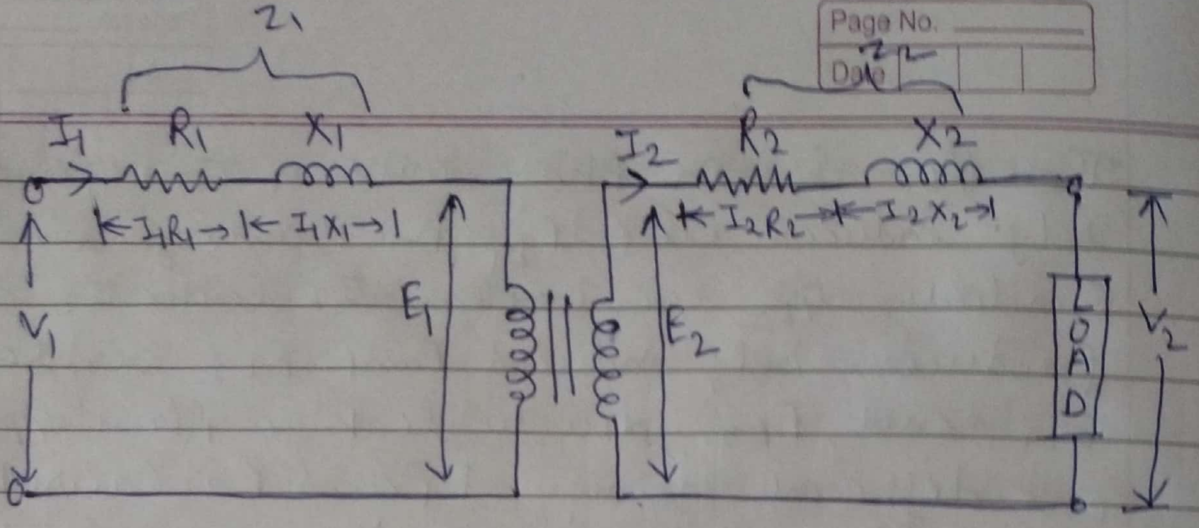
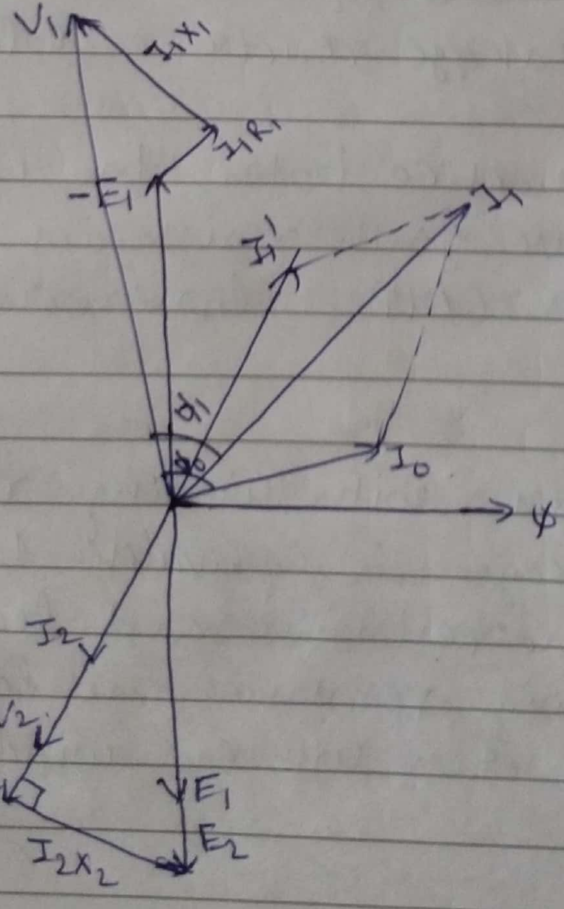


fig - winding resistence and leakage reactance of a Practical transformer.

$V_1 = I_1R_1 + I_1X_1 + E_1$

$E_2 = I_2R_2 + I_2X_2 + V_2$

Phasor diagram of actual X-mer on load ⇒



fig(a) Phasor dia of an actual X-mer on resistive load.

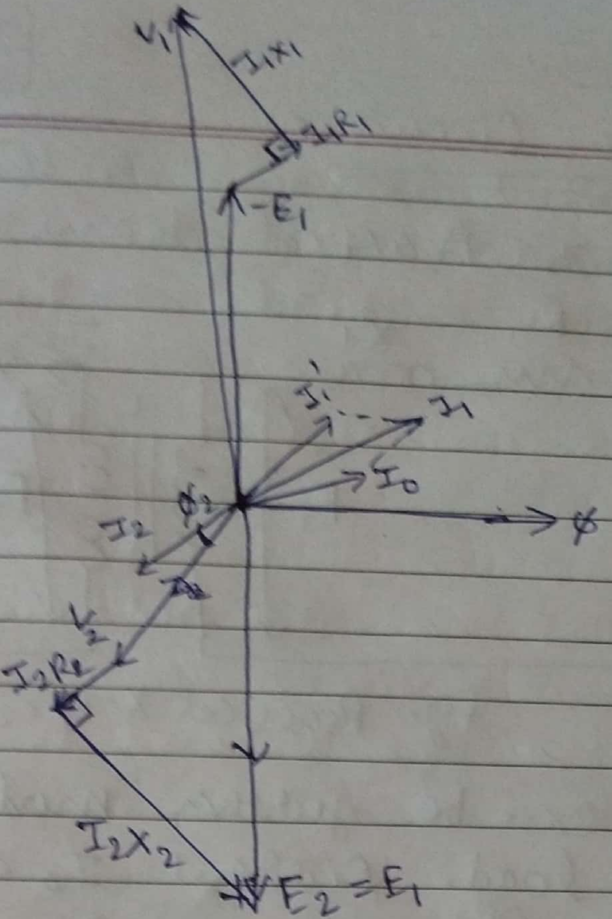
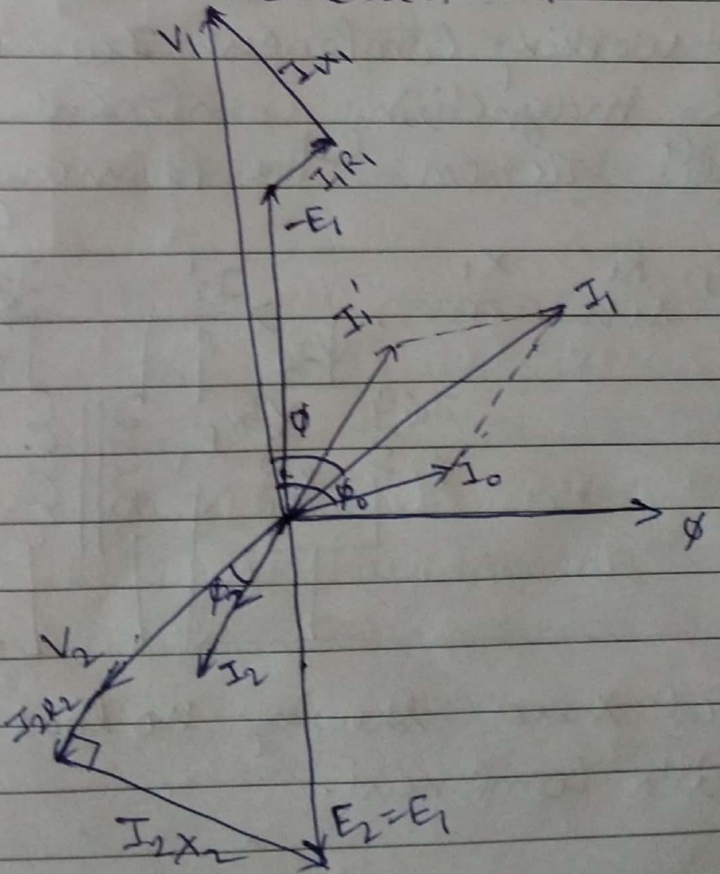


fig. (b) for inductive load.



for capacitive load

Equivalent Circuit ⇒

fig shows Practical transformer.

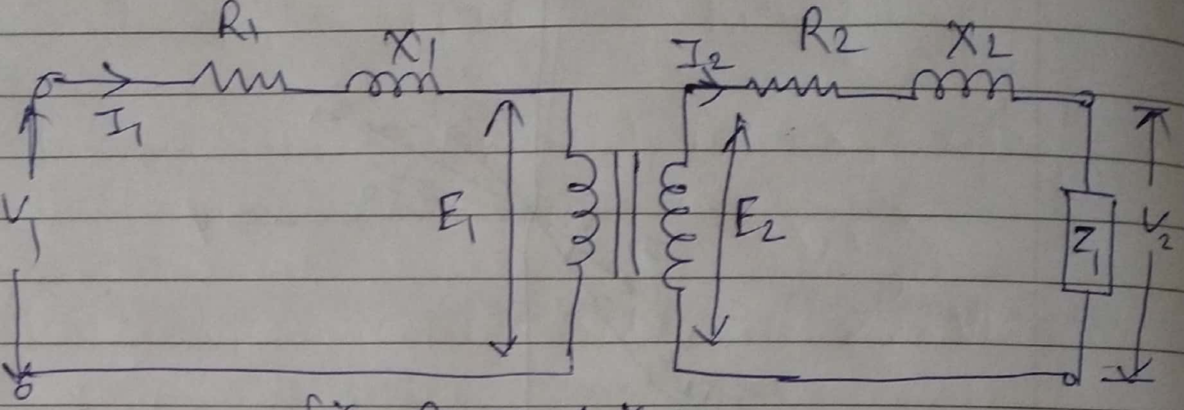


fig- Practical X-mer

This fig can be further modified to represent the no load current I_0 and it's component I_0 is the Phasor sum of I_w and I_m. Hence current I_0 is simulated by the resistance R_0 taking working component I_w and reactance X_0, taking magnetising component I_m connected in parallel across the Primary circuit

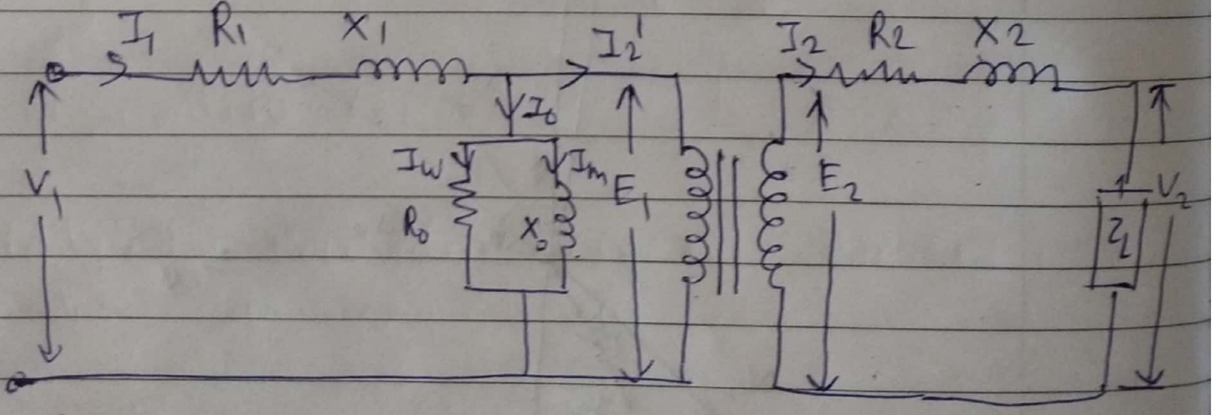


fig- Practical X-mer showing no load current I_0 and it's component.

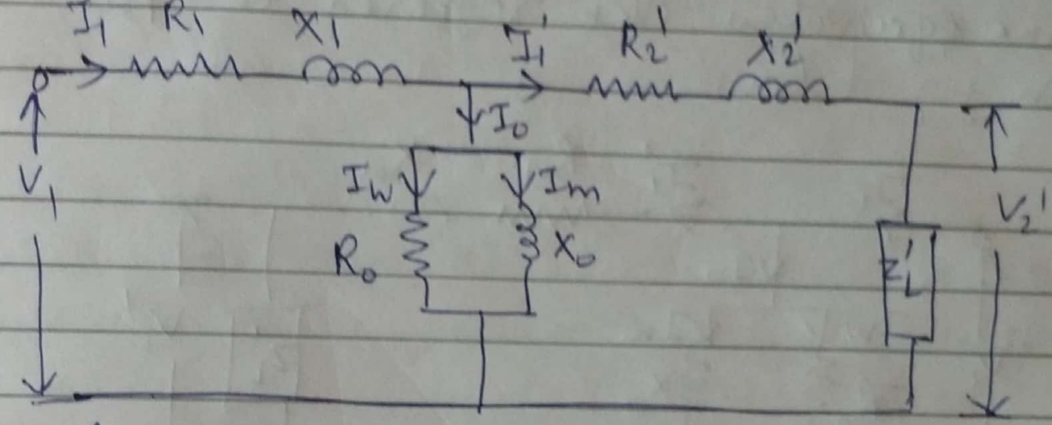
for convenience, all the quantities can be shown on only one side by transferring the quantities from one side to other without any power loss.

The Power loss in sec is $I_2^2 R_2$. if R_2' is the resistance refferred to Primary side which would have cause the same Power loss as R_2 in sec.

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

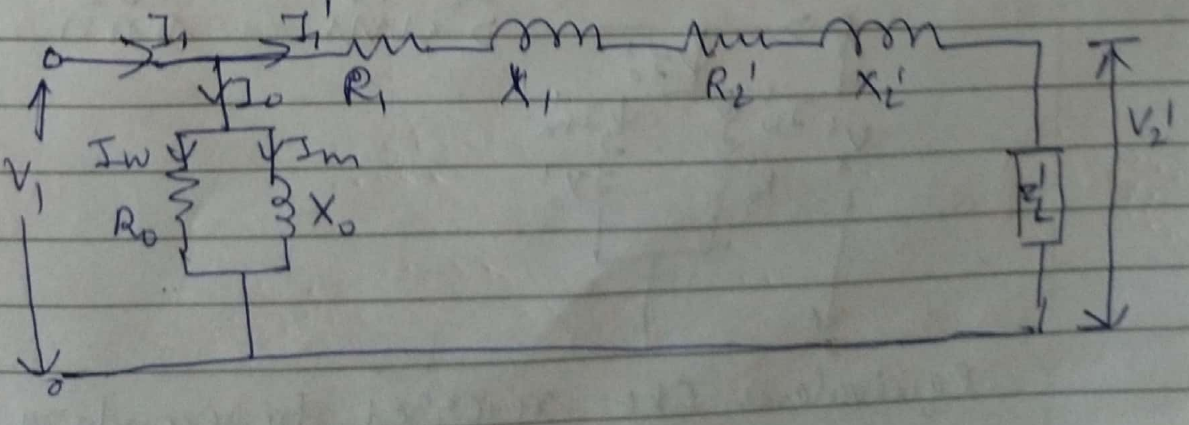
$$R_2' = \left(\frac{I_2}{I_1}\right)^2 R_2 = \frac{R_2}{k^2}$$

similarly, $X_2' = \dfrac{X_2}{k^2}$



equivalent ckt of X-mer reffered to Primary side

Since all quantities are transferred to Primary, the transformer need not be shown. The no-load current I_0 is very small compared to full-load current I_1. Hence drop across R_1 and X_1 due to I_0 can be neglected. Therefore, transferring R_0 and X_0 to the extreme left,



The equivalent resistance referred to Primary side

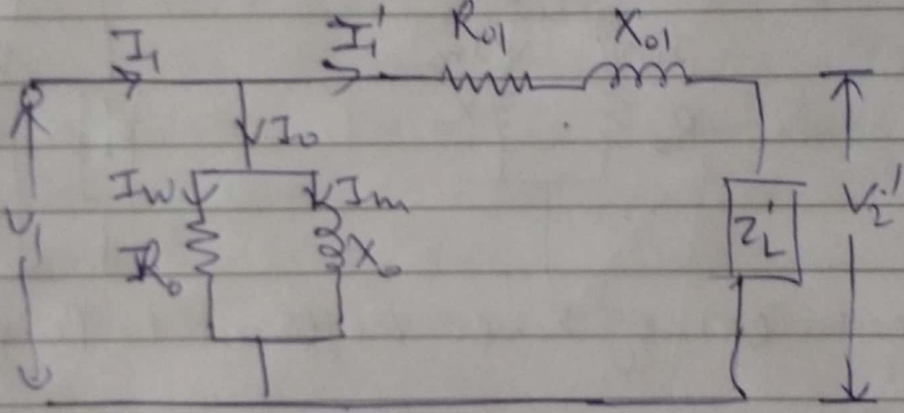
$$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{k^2}$$

equivalent reactance referred to Pri $= X_{01} = X_1 + X_2'$

$$= X_1 + \frac{X_2}{k^2}$$

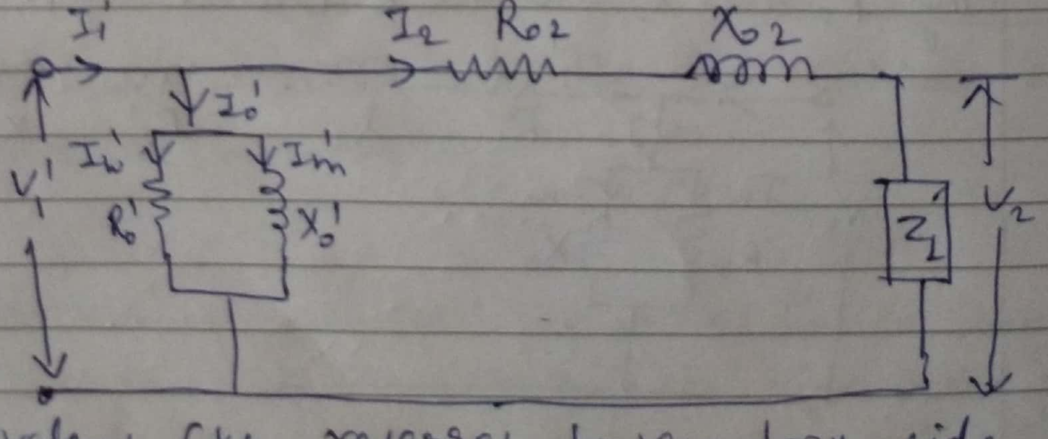
equivalent impedance referred to Pri $Z_{01} = \sqrt{R_{01}^2 + X_{01}^2}$

The equivalent ckt referred to Pri is shown in fig below.



Equivalent ckt referred to Primary

similarly, the equivalent circuit referred to secondary is show below



equivalent ckt referred to secondary side.

Page No.
Date

Equivalent resistance referred to sec. $R_{02} = R_2 + R_1'$

$$= R_2 + k^2 R_1$$
$$= k^2 R_{01}$$

Equivalent reactance referred to sec. $X_{02} = X_2 + X_1'$

$$= X_2 + k^2 X_1$$
$$= k^2 X_{01}$$

Equivalent impedance referred to sec.

$$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2} = k^2 Z_{01}$$

Note →

① While shifting any Pri resistance or reactance to sec., multiply it by k^2

② While shifting any secondary resistance or reactance to Primary, divide it by k^2.

Losses in a transformer ⇒

There are two types of losses in transformer

① Iron loss or core loss
② Copper loss

① Iron loss - This loss is due to the reversal of flux in the core. The flux set-up in the core is nearly constant. Hence iron loss is Practically constant at all the loads, from no load to full load. Iron losses can be subdivided into two losses

(i) Hysteresis loss
(ii) Eddy-current loss.

(i) Hysteresis loss ⇒ This loss occurs due to setting of an alternating flux in the core. it depeds on following factors.

ⓐ area of hysteresis loop of magnetic material which again depends upon the flux density.
ⓑ Volume of the core
ⓒ Frequency of magnetic flux reversal.

(ii) Eddy - Current loss - This loss occurs due to flow of eddy currents in the core caused by induced emf in core. it depends upon the following factors

ⓐ Thickness of lamination of core
ⓑ Frequency of magnetic flux reversal
ⓒ max. value of flux density in the core.
(d) Volume of the core.
(e) quality of magnetic material used.

Eddy current losses are reduced by decreasing the thickness of lamination and by adding silicon to steel.

② Copper losses ⇒ This loss is due to the resistance of primary and secondary windings.

$$P_C = I_1^2 R_1 + I_2^2 R_2$$

Copper loss depends upon the load on the transformer and is proportional to square of load current of KVA rating of the x-mer

Transformer efficiency =>

Efficiency is defined as the ratio of output power to input power

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

$$= \frac{\text{out put Power}}{\text{output Power + losses}}$$

$$= \frac{\text{output}}{\text{output + Copper losses + Iron losses}}$$

$$\text{Also, } \eta = \frac{\text{input} - \text{losses}}{\text{input}} = \frac{\text{input} - \text{Copper losses} - \text{Iron losses}}{\text{input}}$$

Condition for maximum efficiency =>

we know that,

$$\eta = \frac{O/P}{O/P + \text{losses}}$$

Considering sec. side of X-mer

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

differentiating both side w.r.t I_2,

$$\frac{d\eta}{dI_2} = \frac{(V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{02}) V_2 \cos\phi_2 - V_2 I_2 \cos\phi_2 (V_2 \cos\phi_2 + 2 I_2 R_{02})}{(V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{02})^2}$$

for max. efficiency $\frac{d\eta}{dI_2} = 0$

$$(V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{02}) V_2 \cos\phi_2 = V_2 I_2 \cos\phi_2 (V_2 \cos\phi_2 + 2 I_2 R_{02})$$

$$V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{02} = V_2 I_2 \cos\phi_2 + 2 I_2^2 R_{02}$$

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

Similarly on Primary side

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

Thus when copper loss = iron loss, efficiency of transformer is maximum.

Load corresponding to max. efficiency →

for max. efficiency,

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

$$I_{2\,(\text{max effi.})} = \sqrt{\frac{P_i}{R_{02}}}$$

multiplying both side by V_2,

$V_2 I_2$ (man. effi) $= V_2 \sqrt{\dfrac{P_i}{R_{02}}}$

load VA (man. effi) $= V_2 I_2 \sqrt{\dfrac{P_i}{I_2^2 R_{02}}} = V_2 I_2 \sqrt{\dfrac{P_i}{P_c}}$

load KVA (man. effi) $=$ full-load KVA $\sqrt{\dfrac{P_i}{P_c}}$

where P_i = iron loss (KW)

P_c = copper loss (full load) (KW)

<u>Note</u>- The efficiency at any load is given by

$$\% \eta = \frac{x \times \text{full-load KVA} \times \text{P.f}}{x \times \text{full load KVA} \times \text{P.f.} + P_i + x^2 P_c} \times 100$$

where x = ratio of actual to full load KVA