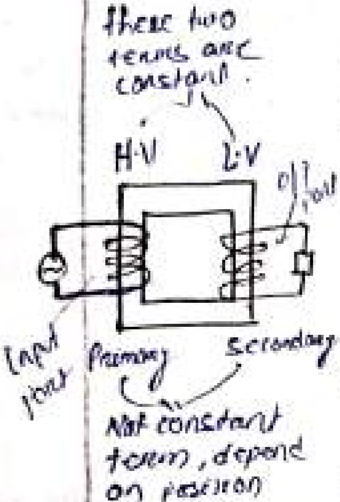
-: TRANSFORMER :-

Features :→ Which transfer power from one ckt to another ckt without changing frequency.



1. Constant Frequency device.
2. A constant power device.
3. An electromagnetic energy conversion device. (Internally collect) electrical energy convert to magnetic energy & stored in magnetic field & re convert to electrical energy.
4. Overall Transformer → Not an energy conversion dev
5. Transformer is a coupled ckt. (Electrically isolated
6. Transformer can be treated as phase shifting device same as transducer in Electronics ckt. It gives 180° phase shift to it's input signal.
7. Single Excited device.
8. Transformer is a control ckt (or) -ve feed back ckt
9. Transformer is a constant flux device.
10. Transformer is a two port N/W. O/P & i/p quantity can be related by A, B, C, D parameter.

WORKING PRINCIPLE :→

Faraday's law of electromagnetic induction :→

When a there is a relative space variation or time variation betn a magnetic field & a set of conductor, an emf is induced in set of conductor.

Basic requirement :-

1. Magnetic field
2. set of conductor
3. Relative space variation or relative time variation.

Method - 1 . Relative space variation. (Dynamically or motionally induced emf.)

Magnetic field → steady or time invariant. Ex. DC Gen

set of conductor → being moved in Mag field.

Here there is a space variation betn mag field & conductor.

Method - 2 Relative time variation (Statically induced emf) (betn & conductor is constant)

Mag field → Time varying (A.C supply)

conductors → stationary.

Ex → Transformer.

Dynamically induced emf :-

① This is emf induced in set of conductors which are being moved inside a time invariant mag field. ~~The rate~~

② The nature of emf induced in DC Generator is dynamically or motionally ~~em~~ induced emf

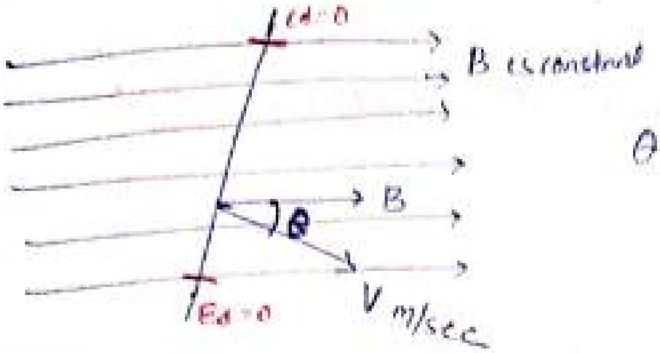
Statically induced emf :-

① This is emf induced in ~~de~~ set of stationary conductor which are placed in time varying magnetic field.

② The nature of emf in transformer is statically induced emf.

Dynamically induced emf.

Flux cutting rule.



$\theta = \angle B \& V$

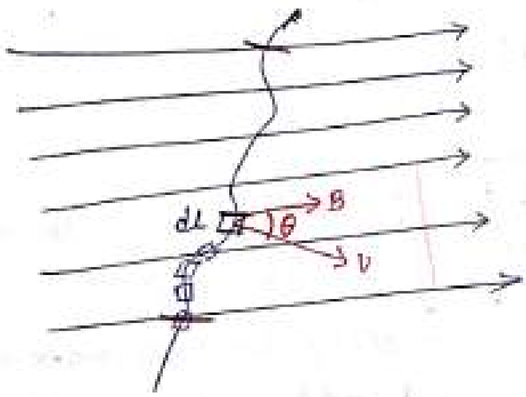
$$E_d = BLV \sin\theta$$

B - flux density in Tesla

L - effective length / active length of conductor in mt

V → velocity of moving conductor - m/s

θ → angle betn B & V. in - degree.



$dE_d = BV \sin\theta \, dL$

$$E_d = \int_{line} B \cdot V \sin\theta \, dL$$

Limit is active length.

$$E_d = \int_{line} (\vec{V} \times \vec{B}) \, dL$$

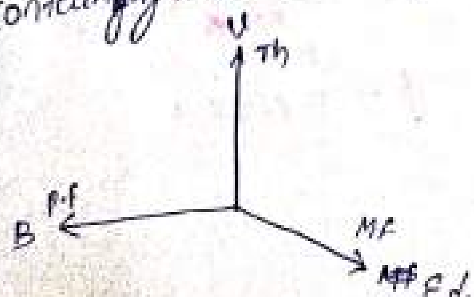
↓ Gives right direction

Not $\int_{line} (B \times V) dL$

↓ This will give wrong direction of induced emf.

* Direction of dynamically induced can be find out by applying Flemings right hand rule.

Induced emf is perpendicular to the plane containing the velocity & flux density vector.

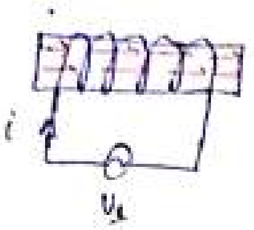


According to Fleming's R.H.L the induced emf direction is always ⊥ to the plane containing velocity & flux density vector.

Magnitude of statically induced emf.

1. Faradays second law.

$\mathcal{E}_s$ = Rate of change flux linkage.



$i = I_m \sin\omega t$

$MMF = Ni$

$= N I_m \sin\omega t$ (alternating in nature)

$\text{Flux} = \frac{\text{mmf}}{\text{Reluctance}}$ (A flux produced in core due to alternating mmf)

$\phi = \frac{N I_m \sin\omega t}{R}$

(The flux is also alternating)

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

Flux linkage $= N\phi$

" $= N\phi_m \sin\omega t$

$$\mathcal{E}_s = \frac{d(N\phi)}{dt}$$

$$\boxed{\mathcal{E}_s = -N\frac{d\phi}{dt}}$$

[To satisfy lenz's law the -ve sign is given.]

→ Here two laws are involved.

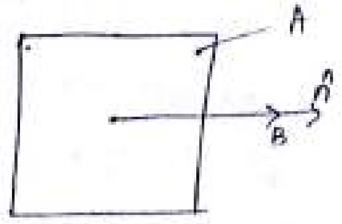
1. $N\frac{d\phi}{dt}$ → Faradays 2^{nd} Law

2. $(-)$ → lenz's law.

Generalised representation of statically induced emf.

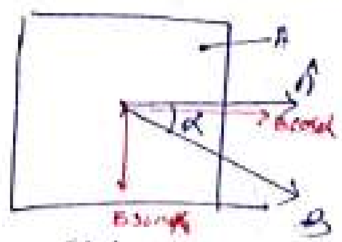
Flux line ⊥ surface & inclined normal.

Flux inclined to surface



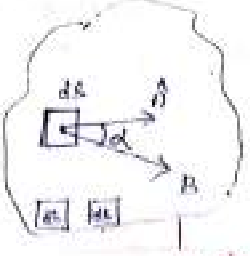
(i)

$\phi = BA$



(ii)

$\phi = B\cos\alpha\, A$



$$d\phi = B\cos\alpha\, ds$$

$$\phi = \iint B\cos\alpha\, ds$$

(fig) Any shaped magnetic ckt (core)

so $$\mathcal{E}_s = -N\frac{d}{dt}\iint B\cos\alpha\, ds$$

$$= -N\iint \frac{\partial B}{\partial t}\cos\alpha\, ds$$

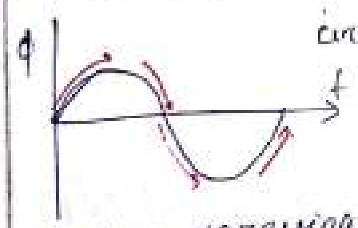
Flux not only depends on time also depends on other factor. so it is taken partial differentiation, derivative of other factor w.r.t time is zero.

$$\vec{ds} = ds\cdot\hat{n}$$

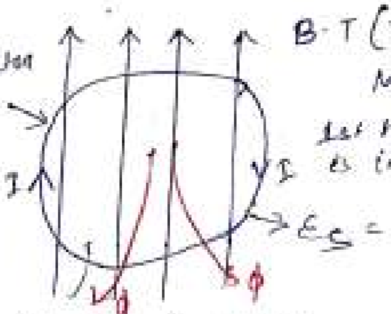
so
$$E_s = -N\iint \frac{\partial \vec{B}}{\partial t}\cdot\vec{ds}$$

⑤ Direction of statically induced emf can be found out by lenz's law.

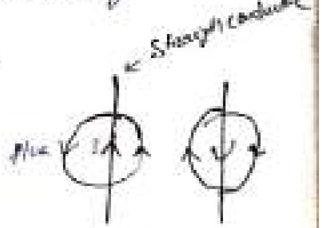
Lenz's law:-

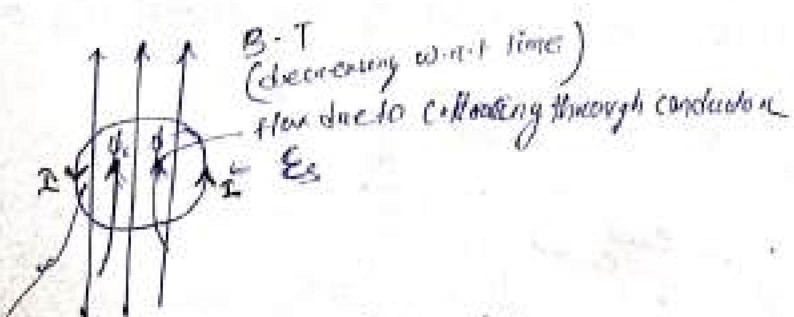


any time varrying quantity having atleast two change. (increasing & decreasing)



Flux due to current flow through conductor.



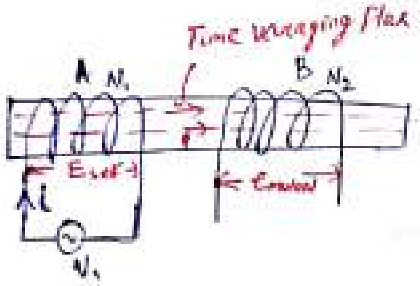


flux due to current carrying conducto

According to lenz's law the direction of statically induced emf such that is such that the current due this emf will flow through a conductor in such a direction which in turn produce some flux according to electromagnetic theory and this flux must oppose the change in main field flux, which is the cause of production of emf and current.

Types of statically induced emf :

1. Self induced emf
2. Mutually induced emf



Self induced emf known as statically induced in a coil due to time varying nature of current through it's own coil.

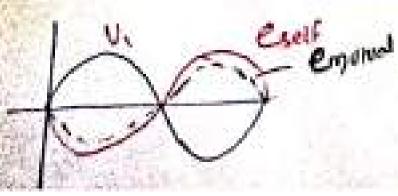
$$e_{self} = -N \frac{d\phi}{dt}$$

$$= -\left(N_1 \frac{d\phi}{di}\right) \frac{di}{dt}$$

Self inductance of coil : $L_{self} = \frac{d}{di}(N\phi)$

The self inductance of a coil may be defined as rate of change of flux linkage w.r.t the time varying nature of current flowing through it's own coil.

$$e_{self} = -L_{self} \times \frac{di}{dt}$$



$V_1 = -e_{self}$

According to lenz's law the self induced emf always opposes the change in applied voltage. so that there 180° out of phase with each other in a coupled circuit.

Mutual induced emf is the statically induced emf induced in a coil due to time varying nature of current through another coil which is magnetically coupled to it.

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

$$= -N_2 \frac{d\phi}{di} \cdot \frac{di}{dt}$$

$$\therefore \boxed{M = \frac{d}{di}(N_2 \phi)}$$

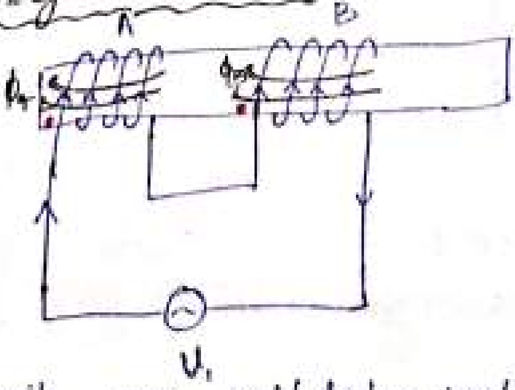
Mutually inductance bet two coil may be defined as the rate of change of flux linkages of a coil with respect to the time varying nature of current through another coil which is magnetically coupled to first one.

$$\boxed{e_m = -M \frac{di}{dt}}$$

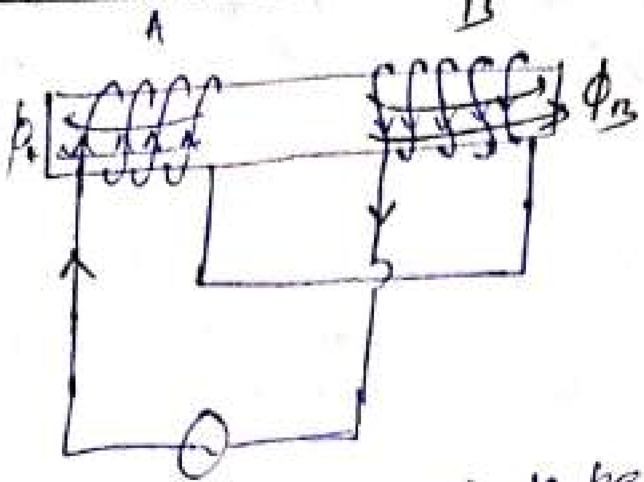
Mutual induced emf also opposes the changes in applied voltage source to satisfy the lenz's law, so that the mutual induced emf and applied voltage 180° out of phase with one another.

That means in coupled ckt self & mutual induced emf are always in phase with one another.

Types of magnetic coupling :-



If the two coils are said to be truly coupled if the flux produced by them aids one another in common magnetic ckt



The two coils are said to be -vely coupled if the flux produced by them opposes one another in the comon magnetic ckt.

Dot notation :→

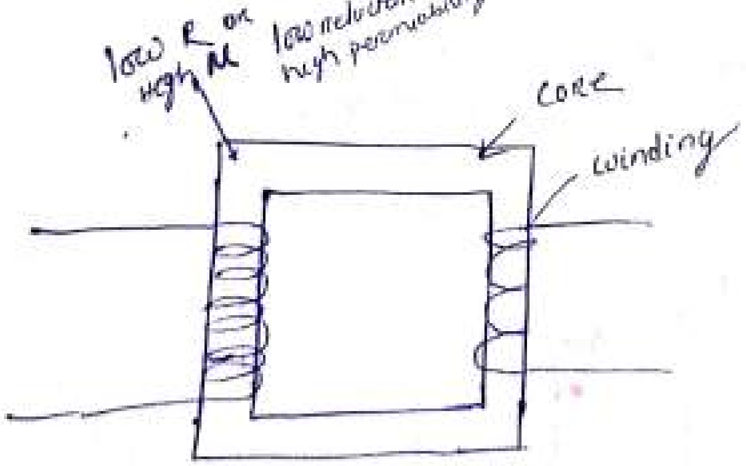
If the current enters or leaves the dots at both the coils then the two coils are said to be +vely coupled and the polarity of mutual inductance betn two coils is +ve.

If the current enter (leaves) dot at one coil leaves (enter) at anothe coil then the two coils are said to be -vely coupled and the polarity of mutual induced betn them is '-ve'.

The transformer operates on mutual induction principle. This is the main principle of transformer.

... details of Transformer :-

-: Constructional details of Transformer :-



Transformer core :-

Material construction :- → Silicon steel (electrical steel)

Feature of silicon steel :-

1. Ferro magnetic material.
2. Low reluctance & high permeability to the flow of magnetic flux
3. Has low hysteresis co-efficient.

$W_h = \eta B_{max}^{x} f V$

x → hysteresis coefficient.
- 1.6 for silicon steel
- This is the least value compared to other metals

4. Hysteresis loss is low.

[Conductivity of steel is reduced by adding silica contained so eddy current reduces & eddy current loss will be reduced. [but magnetic property does not changes.]

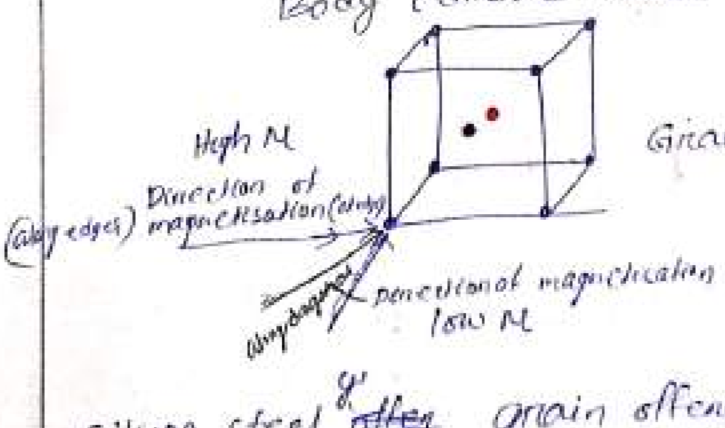
If more silicon is added to core, mechanical strength brittleness will increase for which mechanical strength will reduce.

silicon → σ↓ We↓ brittleness↑ mech strength↓

5. 4% to 5% silica added to steel.

Eddy current loss can be reduced by decreasing conductivity.
① by adding silica to steel
② by laminating it's core

6. Crystaline structure.
Shape of crystaline structure → Body centered cubic.

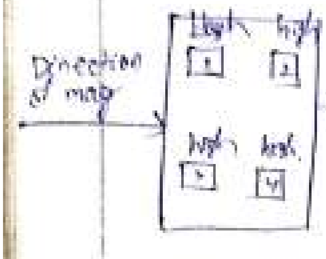


Silicon steel grain offers high permeability along cube edges when compared along diagonal.

$\text{Permiability} \propto \frac{1}{\text{length}}$.

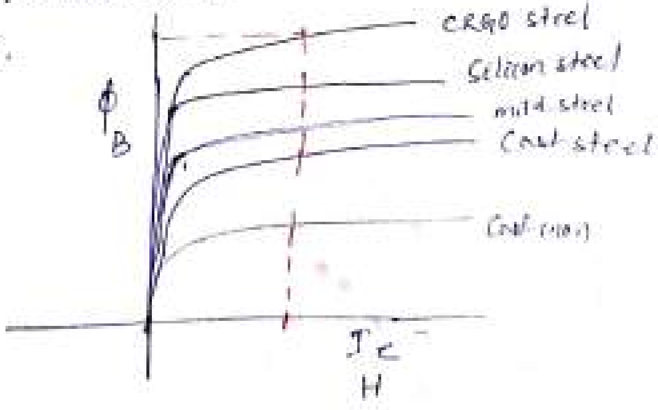
Normal Silicon steel slab

If the direction of magnetisation is in one direction all cubes are not gives high μ. so overal μ is low.
As all the grain are in arbitrary position in Normal silicon steel so we prefer CRGO steel.



Cold rolling grain orientation process
after the process all cube are align in one direction. so μ is increase
This steel is called C.R.G.O steel.

If silicon steel grain offer higher permiability along the cube at edge rather than diagonal. If the cubes are given orientation such that cube edges are parallel to direction of magnetisation. the μ of silicon steel further increases. This can be practically achived by using cold rolling grain orientation process & the resulting steel is called CRGO steel. which is used as core material in morden transformer.



$B = \mu H$

$\uparrow B = \uparrow \mu H$ → for H constant

B (silicon steel) → 1 to 1.2 Tesla

B (CRGO steel) → 1.2 to 1.6 Tesla.

$\phi = \uparrow B \times A \downarrow$

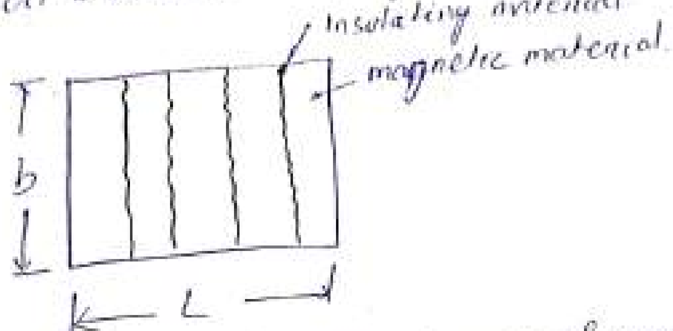
If ϕ is constant A will decrease As B is high.

B in CRGO steel B is more for same H than silicon steel. So for same flux area of core reduces in CRGO steel.

the core having less cross sectional area with CRGO steel.

INSULATING MATERIALS BETWEEN LAMINATION:-

1. Oxide paint (Red oxide)
2. China clay
3. Japan varnish
4. Thin impregnated paper (i.e when normal paper immersed in transformer oil it absorbs the insulating oil & become impregnated paper)



1. (A_g) Gross x sectional area of core (i.e Area occupied by magnetic material + Area occupied by insulating material) A_g

2. Net x sectional area of core (i.e Area occupied by the magnetic material) A_n

so
$$A_g = L \times b$$

Stacking factor or Iron factor (K_s).

$$= \frac{\text{Net cross sectional area}}{\text{Gross cross sectional area}}$$

$$K_s = \frac{A_n}{A_g} \Rightarrow \boxed{A_n = A_g \times K_s}$$

$k_s \simeq 0.9$ for practical transformer

Core staggering :-

The process of bunching the core is called core staggering

undesirable consequences due to poor core staggering :-

$$\text{Flux} = \frac{MMF}{S} = \frac{NI_e \uparrow}{S \uparrow}$$

a) If the core laminations are not properly staggered there is a possibility of thin airgap lines between the lamination which increase the reluctance of magnetic path there by demand high excitation current from source.

b) If the laminations are not properly staggered there is possibility of some sound from transformer which is known as magnetic hum.

The main reason for production of magnetic hum in transformer is magnetostriction phenomena.

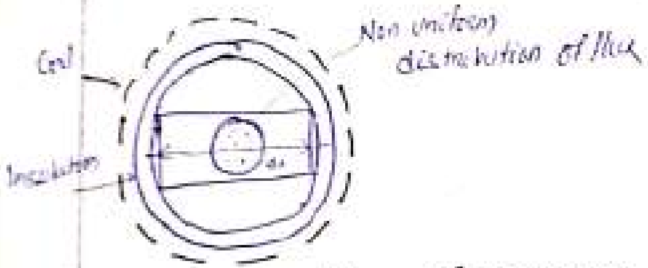
Magnetostriction:-

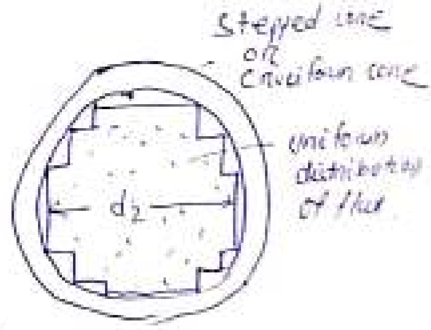
This is the tendency of any magnetic material due to which slight change in dimension of lamination takes place because of alternating nature of flux flowing through it.

In order to reduce noise level in transformer all lamination must be properly staggered.

In steady state flux magnetostriction force is zero.

Alternating flux → causes magnetostriction → due to which change in dimension of core occur → that produces mechanical stress on core → which causes vibration of core → that finally produces noise. if it is audible range then we can hear noise.





Advantage of cruciform core:-

For same cross sectional area. i.e $d_1 > d_2$ of circumcircle so it

- Cruciform core has less diameter of insulating material requires less amount of insulating material.

It requires less amount of insulating material.

* As dia of circum circle is less the length portion in cruciform is less therefore this construction reduces amount of copper required for winding.

* Due to above reason size, weight & cost of transformer is reduces

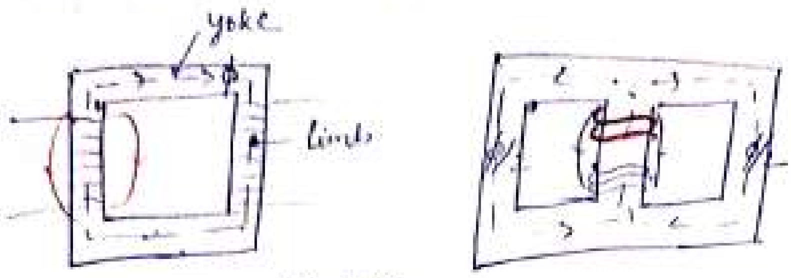
Utilisation factor of transformer = $\frac{\text{effective cs area through which flux passing}}{\text{total c.s area}}$

* As flux distribution in cruciform core is uniform it's utilization factor is more than square core of same c.s area.

Types of magnetic ckt

1-ϕ Transformer:-

① Core type Mag ckt
② Shell type mag ckt



horizontal component → yoke
Vertical component → limb.

Core type	Shell type
1. Core is ~~short~~ surrounded by winding	① winding are being surrounded by core
2. Mechanical supports to windings is not good	② Good mechanical support.
3 No flux division. series ~~ckt~~ ~~winding~~ magnetic ckt	③ parallel magnetic ckt. flux division.
4. Both limbs having same cross sectional area (bcoz same flux passing though each limb)	④ Here outer limb having 50% of cross sectional area compared to central limb.
5. Magnetic ~~of~~ leakage flux is more coefficient of coupling is less.	⑤ Magnetic leakage flux is less, all flux pass through the core instead of surrounding air, because core having less reluctance. OR coefficient of coupling is high.
⑥ More copper material ~~less~~ ~~insulation~~. bcoz concentric cylindrical nature of winding.	⑥ less copper, ~~more~~ ~~insulation~~
⑦ less insulation.	⑦ more insulation
⑧ Economical for high voltage application	⑧ ~~A~~ Economical for low voltage application
⑨ ~~D~~ Low current application	⑨ High current application.
⑩ High voltage & ~~large~~ low KVA Rating	⑩ low voltage high KVA Rating transformer.

As core type requires less insulation it is suitable for high voltage application.
As core type requires more conductor copper material it it is used for high ct application cu loss will be more soil is used for low ct application

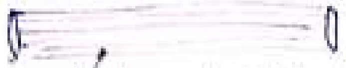
Constructional feature of Transformer winding

Cu or Al material required.

A part of load current complete its path within conductor, it is a part of load current. local current / stray current, it is a part of load current

so some loss is there called stray load loss.

Instead of solid conductor stranded conductor is used.



all strands are electrically isolated by enamel paint because stray current will not pass to other strand. (This is same process as lamination of core to reduce eddy current)

circulating current is less (as x area of ... decreased), but load current remain same.

In actual practice Tr windings are made of stranded conductor instead of solid conductors to reduce stray load loss in winding.

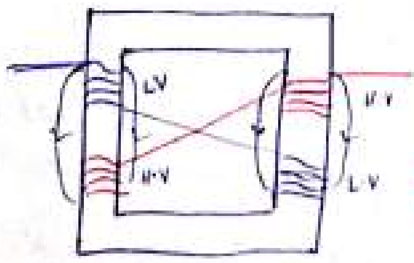
$R_{ac} = 1.6 R_{dc}$. This .6 is due to skin effect only.

skin effect $\propto d^2$, in stranded conductor x-sectional area is less of each conductors

The additional advantage of using stranded conductor instead of solid conductor, it reduces the skin effect of winding.

Placement of wdg in core :-

Core type transformer :-



~~Inter~~

The process of keeping half of one winding in one core & another half in other core is called interleaving of winding.

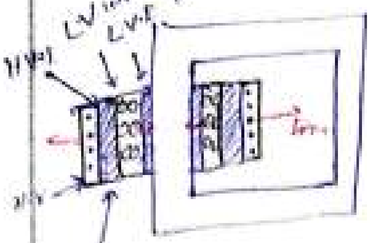
When flux of one winding trying to pass through air it links with other winding, so now it not a leakage flux it is a ~~common~~ be come a common flux.

Interleaving winding :-

The main purpose of using interleaving nature of winding in core type core is to reduce magnetic leakage flux & hence to improve coefficient of coupling both winding.

Adv of placing L.V winding nearer to the core.

11 kV / 3.3 kV



L.V insulation is corresponding to 3.3 kV.

* If H.V placed near to core, the insulation required ∝ 11 kV, interwinding 7.7 kV, so total is 18.7 kV whereas in L.V nearer to core is only 11 kV (3.3 + 7.7) insulation.

H.V.I ∝ 11 kV − 3.3 kV = 7.7 kV
it is called interwinding insulation, ∝ to difference betn H.V & L.V.

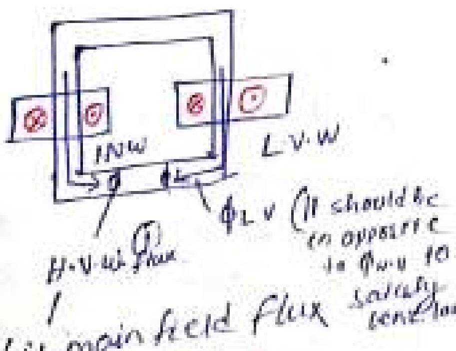
By placing L.V winding nearer to the core the amount of insulation required for transformer can be reduce.

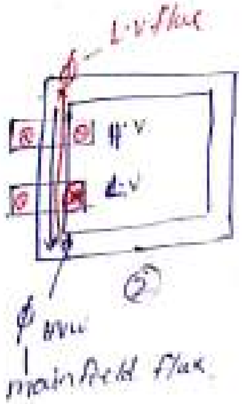
It is also reduces the amount of copper for the winding. [As L.V winding having larger × section area if it placed over H.V winding ~~which having more cross section & its cylindrical etc~~ a long length of L.V winding wire is required. that means more copper wire.

Due to above reason the size, weight & cost of transformer will reduce.

If H.V wdg outside the L.V wdg then there is easy access to H.V to provide tapping for voltage control purpose. tapping is used in H.V to get smooth variation & less spark (as current in H.V are less).

Nature of current in wdg w.r.t. position of winding.





For ckt-1

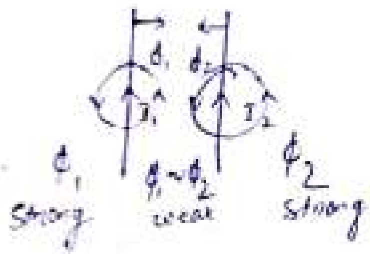
If H.V carry current in clockwise direction, it's flux is downward & the flux of secondary should downward to obey lenz's law so it's current direction should be clockwise.

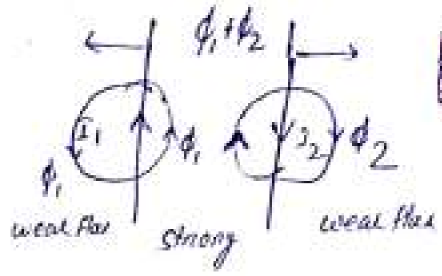
If the two windings are placed on separate limb then they should carry current in same direction to satisfy lenz's law.

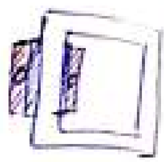
If the two windings are placed on same limb then they should carry ~~in~~ current in opposite direction to satisfy lenz's ~~ty~~ law.

Nature of mechanical force betn LV & H.V winding.

Lorentz's principle.







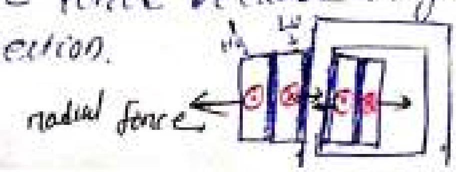
If the two parallel conductor carry ct in same direction then the nature of force betn them is attractive.

If the two parallel conductor carrying current in opposite direction · the nature of force betn them is repulsive

If the windings are placed on same limb they should carry current in opposite direction to ~~s~~ satisfy lenz's law so that nature of force bet the two winding is repulsive.

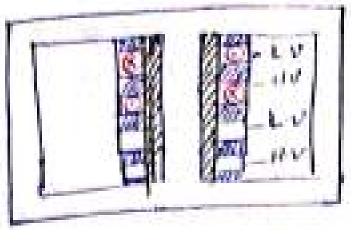
As amp turns on both side of transformer under normal condition are same the repulsive forces are equal & opposite so that resultant force act on transformer wdg is zero, therefore there is no possibility of dislocation of winding in normal condition.

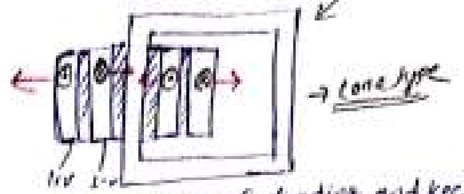
The conductors within a same winding always experience attractive force because they carry current in same direction.



Radial force are present in core type core.

Procedure to place winding in shell type core.





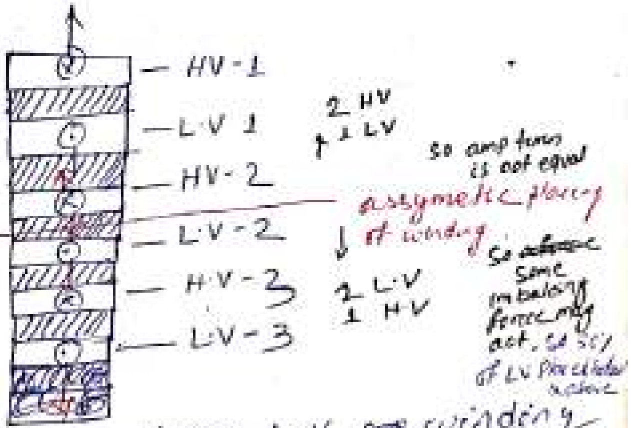
The process of dividing and keeping side by side ~~one after another~~ [alternatively] HV & L.V is called sandwich winding

Sandwitching nature of winding.

The main purpose of using sandwitching nature of winding in shell type core is to reduce magnetic leakage flux & hence to improve co-efficient of coupling betn winding.

Let HV.W = 3
LVW = 3

Here forces are axial.



In shell type construction the extrem L.V winding section should have 50% turns in compare to inner L.V wdg to get symetry in order to get the good mechanical balance betn repulsive forces.

In shell extreme winding section **should be L.V** only to save amount of insulation.

As in core type transformer winding are concentric.
so more length of winding required. so cu require is more
core type insulation required is less.
But in shell type many insulations are required like base insulation (core & winding) & many no of insulation (inter insulation) and one in upper side and lower side of lower & upper L.V winding.

~~In winding~~ there is a force developed in the winding due to the current carrying conductor of (interaction) of the winding between the conductors of winding.

-: Ideal transformer :-

Assumption :-

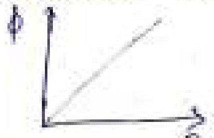
1. permeability of transformer core is = ∞
   so no mmf required to produce flux ~~or zero~~
   so excitation current is zero. ($I_c = 0$)

2. Iron losses in core is zero.

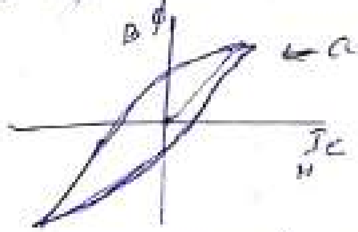
3. Resistance of transformer winding is zero
   i.e winding made of ~~non~~ nonresistive material
   IR drop is zero
   I^2R loss is zero

4. There is no magnetic leakage flux
   i.e coefficient of coupling is 1

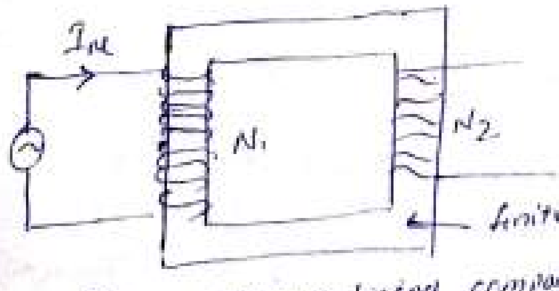
5. Magnetisation curve of transformer core
   is ~~linear~~ linear



Non linearity ~~for~~ In practical core
① saturation non linearity
② Hysteresis non linearity.



Operation of transformer with finite permeability core



As the core having some finite permeability, it require some amount of current to produce flux in the core. That current is I_M (Magnetising current)

I_M = Magnetising component current.

$I_M = I_m \sin \omega t$ (As supply is AC)

Primary mmf

$= N_1 I_m$

$= N_1 I_m \sin \omega t$

$$\text{flux} = \frac{MMF}{R} = \frac{N_1 I_m \sin\omega t}{R} = \phi = \phi_m \sin\omega t.$$

So the flux is a time varying flux. So some self & mutual induced emf ~~present~~ induced in primary & secondary winding respectively, according to Faraday law of electromagnetic induction

Magnitude of self induced emf.

$\phi = \phi_m \sin \omega t \rightarrow$ ~~Taken~~ as Reference

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

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

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

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

Self induced emf in primary always lag behind the flux quantity exactly by 90°. i.e after 90° delay emf is produced than flux produced.

when $\omega t = \pi$

$$E_{1max} = N_1 \phi_m \omega$$

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

$$\boxed{E_1 = 4.44 N_1 \phi_m f}$$

$$E_1 = 4.44 N_1 B_m A f$$

$$E_1 = 4.44 N_1 B_m A_n f \qquad \boxed{A_n = K_c \cdot A_g}$$

Magnitude of mutual induced emf.

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

$$= -N_2 \frac{d}{dt}(\phi_m \sin\omega t)$$

$$= -N_2 \phi_m \omega \cos\omega t$$

$$e_2 = N_2 \phi_m \omega \sin(\omega t - \pi/2)$$

Mutual induced emf in secondary also lagging behind the flux by 90° and this inphase with the self induced emf in primary.

At $\omega t = \pi$

$$E_{2max} = N_2 \phi_m \omega$$

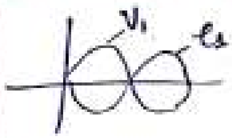
$$E_2 = \frac{E_{2max}}{\sqrt{2}} = \frac{N_2 \phi_m 2\pi f}{\sqrt{2}}$$

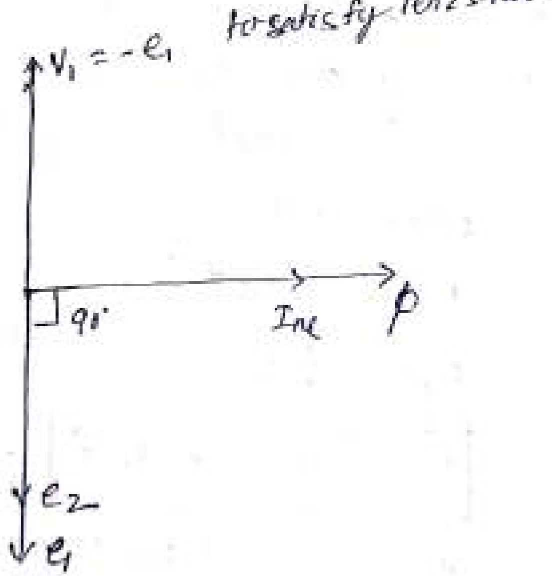
$$E_2 = 4.44 N_2 \phi_m f$$

$$\boxed{E_2 = 4.44 N_2 B_m A_n f}$$

These are emf eq^n of transformer.

Vector diagram:-





ϕ as reference.
e_1 & e_2 lags by 90°
As e_1 produced due to V_1 to e_1 & V_1 should obey lenz's law
in order to obey lenz's law V_1 should 180° phase difference to e_1 as shown in fig vector diagram.

Observation's of emf eq^n:-

$E_1 = 4.44 B_m A_n N_1 f$

$\frac{E_1}{N_1} = 4.44 B_m A_n f$ [emf/turn in primary]

$\frac{E_2}{N_2} = 4.44 B_m A_n f$ [same emf/turn in sec.]

* Emf per turn on both side of transformer is same

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

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$ [transformation ratio of transformer]

Voltage rating of transformer [written in transformer name plate] are induced voltage (i.e E_1 & E_2)

Turn ratio:- $\frac{N_1}{N_2} = \frac{E_1}{E_2} = \frac{1}{K}$

During operation of tran:- As during operation we can't change A_n & N

$$B_m \propto \frac{E_1}{f} \propto \frac{V_1}{f} \text{ as } E_1 \propto V_1$$

If we want to maintain B_m as constant

So we have to keep $\frac{V_1}{f}$ constant.

$$\Rightarrow \frac{V_{11}}{f_1} = \frac{V_{12}}{f_2} \text{ so } B_m \text{ is constant.}$$

200V, 50 hz

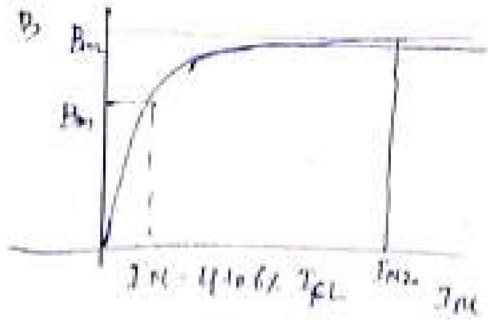
160 V, f = ? so that B_m is constant.

so $\frac{V_{11}}{f_1} = \frac{V_{12}}{f_2}$

$\Rightarrow \frac{200}{50} = \frac{160}{f_2}$ so $f_2 = 40$ hz

As in tran flux is constant i.e $\frac{V}{f}$ is constant.

* Supply Voltage to frequency ratio should be constant.



V is constant &
If f is reduced B_m is increased, so for this high B_m, a high value of magnetising current is required.

If it is required to reduce the frequency for any application so same time reduce the supply voltage.

* By keeping applied voltage constant if the frequency of operation of transformer decreases then B_m of iron increases which drives the transformer into deep saturation there by demands very high magnetising component of current from source.

That's why never reduce only frequency by keeping supply voltage constant.

If it is necessary to operate the transformer at reduced ~~voltage~~ frequency, applied voltage should be reduced simultaneously to maintain $\frac{V}{f}$ constant.

Rating of Transformer :-

$\downarrow E_1 \propto f \downarrow$ $E_1 I_1$ - Apparent power

The KVA rating of transformer changes proportionality with change in frequency.

100 KVA, US made 60 hz

$100 \times \left(\frac{50}{60}\right)$ India, 50 hz

Same trans will be having 83 KVA in India operating frequency.

During design of transformer:-

which having Less in size, weight, cost.

(a) 100 KVA, 25 hz
(b) 100 KVA, 50 hz
(c) 100 KVA, 75 hz
(d) 100 KVA, 100 hz

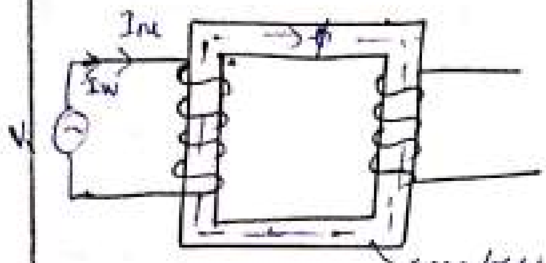
KVA is fixed $= E_1 I_1$

As I_1 depends on size of conductor & $E_1 = 4.44 B_m A_i f N_1$

In design we can change A & N

2nd assumption :- i.e iron loss is absent but in Practically two iron losses are there, so now will consider,

Operation of transformer with iron loss :→



As iron loss present in core so supply has to give a current for this loss (i.e I_w)

I_W - iron loss component of current.
∴ it's function is to supply iron losses present in core.

$\vec{I_0} = \vec{I_\mu} + \vec{I_W}$ - In No load condition.

I_μ	I_W
Reactive component current	Active comp of current
watt less current	Wattful component of current
It is quadrature with V_1	Active component inphase with V_1

$I_\mu \gg I_W$

I_μ: 4 to 6% of full load current; I_W: 1 to 2% of full load current.

Normally
$I_0 \Rightarrow$ 5 to 8% of full load current

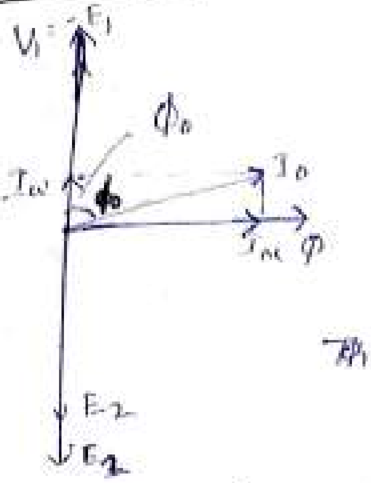
To represent the behaviour of I_μ we use —ꝏꝏ— X_0
it is fictitious inductor

As I_w & V are same phase like resistor so I_w behaviour represent by a resistive parameter. —ʌʌʌʌ— R_0

As this is only to produce flux in core, not related to the active power (watt) it is called Reactive component or wattless component. And we know reactive component lag voltage by 90° this is the property of inductor

We know active component is in phase with voltage this is the property of Resistance we represent I_w as a resistor.

Vector diagram:-



$\phi_0 \to 70.1075'$

$\cos\phi_0$ = NL p.f of transformer
$\simeq .2$ lag

The transformer has poor no load p.f order of 0.2 laging becaus it's $I_M \gg I_w$ current because of this relation p.f is poor.

By keeping applied voltage constant if the frequency of operation reduce consequences are

1. Magnetising component drawn by primary winding increases. (As B_m increases)
2. As I_M increases no load p.f of tran decreases further.

$I_0 \angle -\phi$

$I_M = I_0 \sin\phi_0$

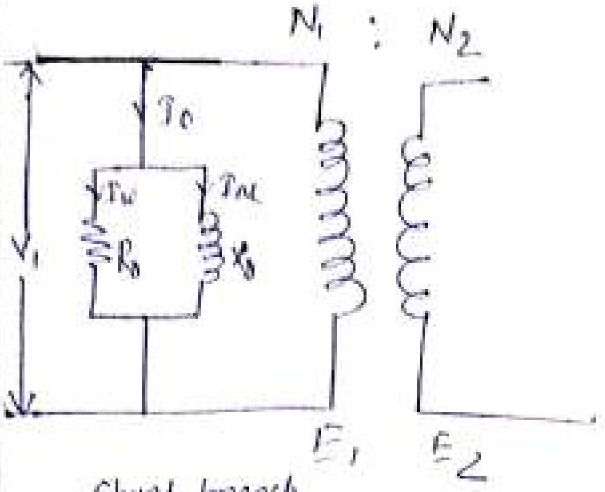
$I_w = I_0 \cos\phi_0$

No load power = $V_1 I_0 \cos\phi_0$
$= V_1 I_w$
= Iron losses
(It is approximate only)

~~So total power loss in no load~~
So total power in no load condition is the only Iron loss.

The power consumed by tran under no load condition is approximately equal to iron loss-es in transformer only (if the primary winding resistance is consider small amount of NL cu loss in primary take place in addition to iron loss under no load condition.

Equivalent ckt of transformer under no load.

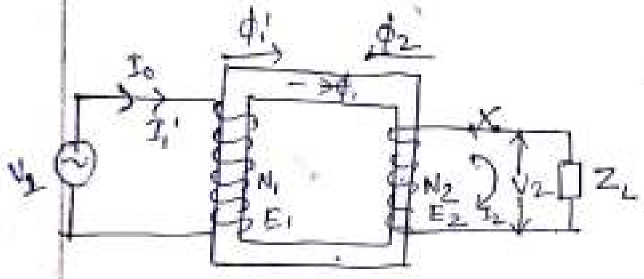


Shunt branch or N.L branch of equivalent ckt of transformer.

As I0 is only flow through the primary winding, not reflected on secondary side. It's component Iw & Iμ 's behaviours should be connected to primary only. so R0 & X0 are connected as in parallel to primary winding.

As R0, X0 it bypass some current of primary winding (I1) so they are connected in parallel.

operation of transformer under load condition:-



$N_1 . I_\mu$ = primary m.m.f

↓

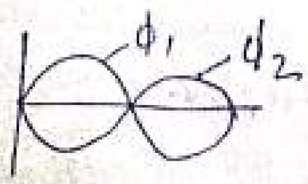
ϕ = primary flux or Mainfield flux or working load.

V_2 = secondary terminal voltage.

I_2 = secondary load current.

direction of I_2 can be found out by lenz's law.

So this I_2 will produce $N_2 I_2$ mmf



$N_2 I_2$ mmf secondary mmf

↓

ϕ_2 = secondary flux

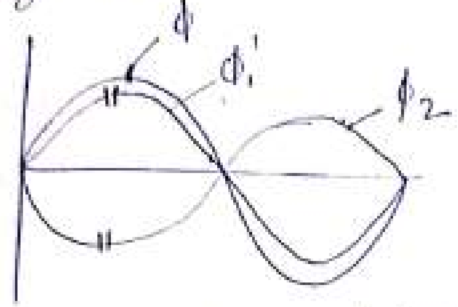
So this flux should oppose the main field flux. to satisfy the lenz' law of production of effect i.e I_2 & angle betn ϕ_1 & ϕ_2 is 180°.

I_1' = load component of ~~load current~~ primary current.

If $V_1 = 220$ $e_1 = 210$

As 10 v drive no load current in transformer.

due to this additional current I_1' in primary, it produces some mmf = $N_1 I_1'$ which in turn produce ϕ_1' which is known as load component of primary flux.



For power transformer ϕ_1' should nullify the effect of ϕ_2 so flux in core is always ϕ. so net flux component of load it is zero.

The flux in core is always maintain constant irrespect of magnitude of load across it's secondary terminals. That's why the transformer can be treated as constant flux device.

Under steady state condition: $\phi_1' = \phi_2$

If the load increase the ϕ_2 increase so I_1' in primary increases so that ϕ_1' increases so ϕ_1' will be again equal to ϕ_2. so again steady state condition will be achive. As automatically these process takes place it is called a control device.

$$\phi_1' = \phi_2$$

$$N_1 I_1' = N_2 I_2$$

load component of primary amp turn = sec A.T

as I_0 not transfer from primary to secondary. As $I_1 = I_0 + I_1'$

so we can say primary mmf = sec mmf.

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1'}{I_2} = K$$ - transformation ratio, as I_0 not transform. so exact value of $K = \frac{I_1'}{I_2}$

$$\boxed{I_1' = K I_2}$$

$$E_1 I_1' = E_2 I_2$$

~~load current of~~

i.e. load component of primary kVA = sec kVA

If I_0 neglected :→

These are approximate value:

$$I_1 \simeq I_1'$$

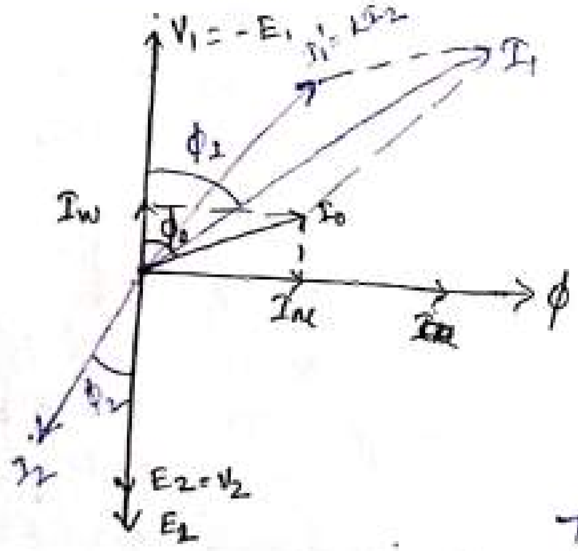
$$N_1 I_1 \simeq N_2 I_2$$

$$K \simeq \frac{I_1}{I_2}$$

$$E_1 I_1 \simeq E_2 I_2$$

} exact eq is $N_1 I_1' = N_2 I_2$ like that

Vector diagram :-



lagging load p.f

The phase of I_2 w.r.t V_2 depends on the nature of load

ϕ_2 = is called load p.f angle.
• Secondary p.f.

$$\phi_0 = \angle V_1 \, \& \, I_0$$

$$\phi_2 = \angle V_2 \, \& \, I_2$$

$$\phi_1 = \angle V_1 \, \& \, I_1$$

$\cos\phi_0$ = N.L p.f
$\cos\phi_2$ = sec p.f = load p.f
$\cos\phi_1$ = primary p.f

sec p.f is given on this is known power factor.

$\cos\phi_1 \neq \cos\phi_2$
But if I_0 is neglected.

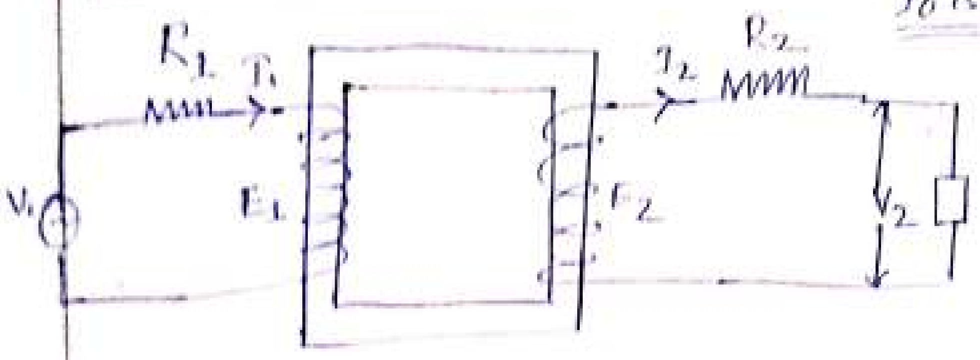
$I_1' = KI_2$ then only $\phi_1 \simeq \phi_2$ then $\cos\phi_1 = \cos\phi_2$

$\boxed{\cos\phi_1 \simeq \cos\phi_2 \simeq \text{load p.f}}$

3rd assumption :-

Effect of winding resistance on the operation of transformer.

I_0 is neglected.



two undesirable consequence.

① IR drop

② I^2R loss.

when R is consider V_1 should have two component i.e E_1 & drop.

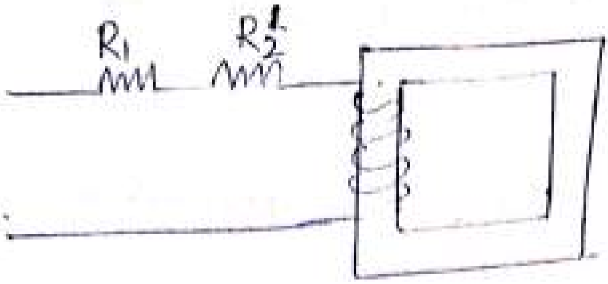
$$\vec{V_1} = -E_1 + I_1 R_1 \qquad \vec{E_2} = \vec{V_2} + \vec{I_2 R_2}$$

Total copper loss in transformer = $I_1^2 R_1 + I_2^2 R_2$

It is always convinient to consider all resistance in one side for easy analysis.
we can not transfer as our wish. so condition is copper loss in that resistance

Condition that must satisfied when transfering the winding resistance from one side to other side copper loss in that resistance should maintain constant

Cu loss in R before Tr = Cu loss in same R after Tr



Sec to primary transfer

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

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

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

R_2' = equivalent resistance of secondary refer to primary side.

Primary to secondary side :-

$$I_1^2 R_1 = I_2^2 \cdot R_1'$$

$$\boxed{R_1' = k^2 R_1}$$

R_1' = equivalent resistance of primary refer to sec side

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

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

So total cu loss $= I_1^2 R_{01}$

$= I_2^2 R_{02}$

→ equivalent resistance of transformer referred to secondary side.

drop in resistance expresses in % of ~~supply~~ base voltage is known as per unit resistance.

p.u primary ~~resitive~~ resistive drop = $\frac{I_1 R_1}{E_1}$

per unit sec ~~restive~~ resistive drop = $\frac{I_2 R_2}{E_2}$

Total per unit resistive drop w.r.t primary = $\frac{I_1 R_{01}}{E_1}$

" " " " " " sec side = $\frac{I_2 R_{02}}{E_2}$

Per unit value of resistive drop on both side of transformer is same

percentage ~~drop~~ value of resistive drop on both side of tran is same. percentage = per unit × 100

percentage drop = .

In p.u system the p.u resistive drop is also simply known as p.u resistance of transformer.

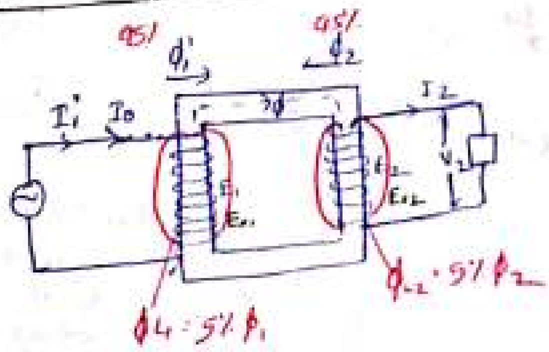
ϕ R

As p.u resistance on both side of transfer is same

As p.u resistance on both side of transfer p.u value of resistance it is easy to transfer from one side to another side when compared to resistance in ohmic value where xk^2 or $\frac{1}{k^2}$ is required.

4th assumption:-

Operation of transformer with magnetic leakage flux:-



leakage flux is due to load component of flux

leakage flux depends on load it is not a constant. But flux in core always ϕ i.e due to no load current.

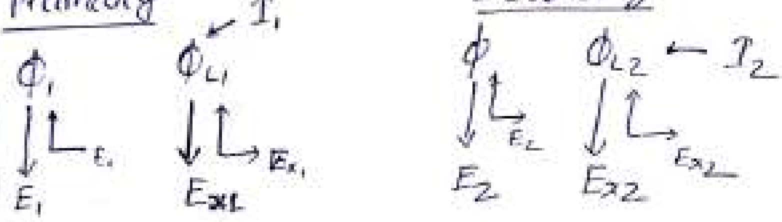
ϕ_{L1} is in phase with I_1

ϕ_{L2} is in phase with I_2

Magnetic leakage flux is the part of the load component of flux which links either HV or LV winding but not both and it is not having any role in transferring power from one ckt to another. If the leakage flux in transformer is more the magnitude of power transfer from one ckt to other ckt decreases, that's why the leakage flux should be as minimum as possible during operation of transformer.

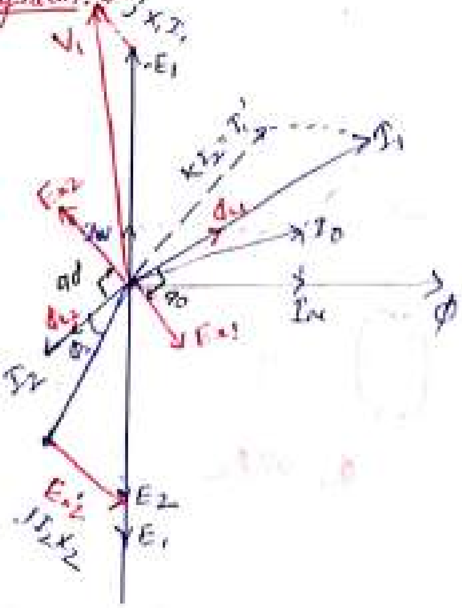
Magnetic flux in transformer depends on magnitude of load current in the windings. That's why mag leakage flux is not constant in transformer core it is treated as variable flux. Magnetic leakage flux available in primary and secondary winding are inphase with respective load current.

Primary　　　　　　　　Secondary



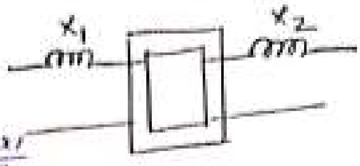
When ever magnetic flux (leakage) are available at primary and secondary some additional emf will be induced in both primary and secondary due to leakage flux and these emfs are lagging behind the respective load current exactly by 90°.

Phasor diagram:



Here E_{x1} leads I_1 by 90° that is the behaviour of inductor so this drop is represented as drop in an inductor.

E'_{x2} is 180° phase shift to I_{x2} bcoz E'_{x2} is the extra component of supply voltage to compensate supply the voltage drop due to leakage flux. Which lead I_2 by 90°. so which is a property of inductor, so this voltage drop is represented by an inductor.



$$X_2 = \frac{E'_{x2}}{I_2} \qquad X_1 = \frac{E_{x1}}{I_1}$$

To take the account of emf due to magnetic leakage flux some ficticious on imaginary reactance assumed in series with primary and secondary winding such that the magnitude of voltage drop across the reactance is used to represent emf in the windings due to magnetic leakage flux. These imaginary reactances in transformer are called leakage reactance.

$$\bar{V}_1 = -\bar{E}_1 + jI_1X_1$$

$$V_1 = -\bar{E}_1 + I_1R_1 + jI_1X_1$$
$$= -\bar{E}_1 + I_1(R_1 + jX_1)$$

$$V_1 = -E_1 + I_1 Z_1$$

Z_1 = is primary leakage impedance, as it is a function of leakage reactance

$$E_2 = V_2 + jI_2X_2$$
$$E_2 = V_2 + I_2R_2 + jI_2X_2$$
$$= V_2 + I_2(R_2 + jX_2)$$

$$\boxed{E_2 = V_2 + I_2 Z_2}$$

Z_2 = secondary leakage ~~reactance~~ impedance

→ Exact voltage equation of transformer.

* The condition that must be satisfied while transfering leakage reactance is per unit value of reactance drop should be maintain constant.

$$\text{p.u primary reactance drop} = \frac{I_1X_1}{E_1}$$

$$\text{p.u secondary ~~primary~~ reactance drop} = \frac{I_2X_2}{E_2}$$

p.u reactance drop before transfer = pu reactance drop after transfer.

R

Transfer of reactance from sec to primary:-

$$\frac{I_2 X_2}{E_2} = \frac{I_1 X_2'}{E_1}$$

$$\Rightarrow X_2' = X_2 \times \frac{E_1}{E_2} \times \frac{I_2}{I_1} \Rightarrow \boxed{\frac{X_2}{K^2} = X_2'}$$

Primary to secondary:-

$$\frac{I_1 X_1}{E_1} = \frac{I_2 X_1'}{E_2} \quad \therefore \boxed{X_1' = K^2 X_1}$$

Total Reactance when refer to primary side

$$= X_1 + X_2' = \boxed{X_1 + X_2/K^2}$$

when refer to (X_{02}) secondary i.e $X_{02} = X_2 + X_1' = \boxed{X_2 + X_1 K^2}$

Total p.u reactance drop w.r.t primary-

$$= \boxed{\frac{I_1 X_{01}}{E_1} = \text{p.u reactance w.r.t primary.}}$$

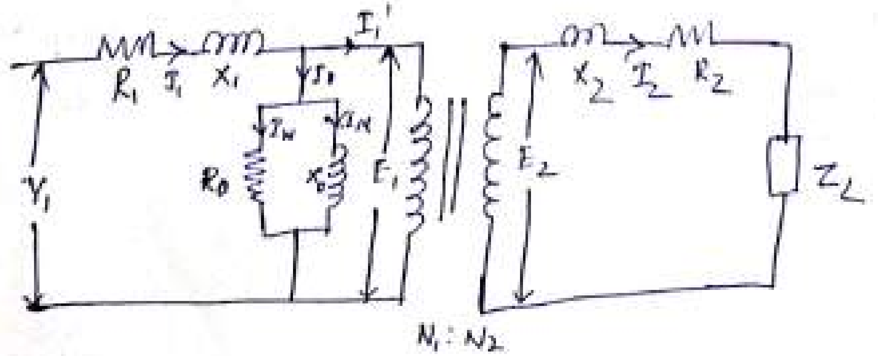
total p.u reactance drop w.r.t secondary.

$$= \boxed{\frac{I_2 X_{02}}{E_2} = \text{p.u reactance w.r.t secondary}}$$

The p.u reactance drop on both side of transformer is same

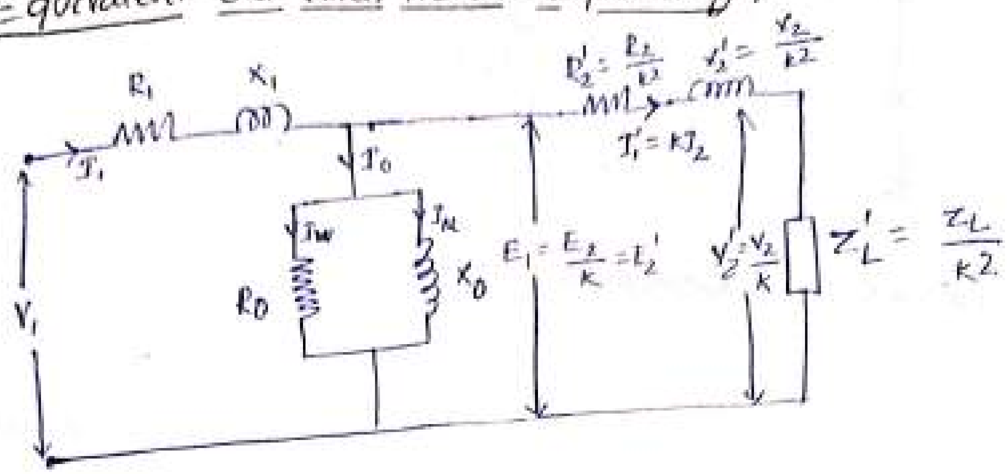
As pu reactance on both side of transformer is same its easy to transfer the pu value of reactance from one side to another side when compared to reactance in ohmic value.

Exact equivalent ckt diagram of transformer:-

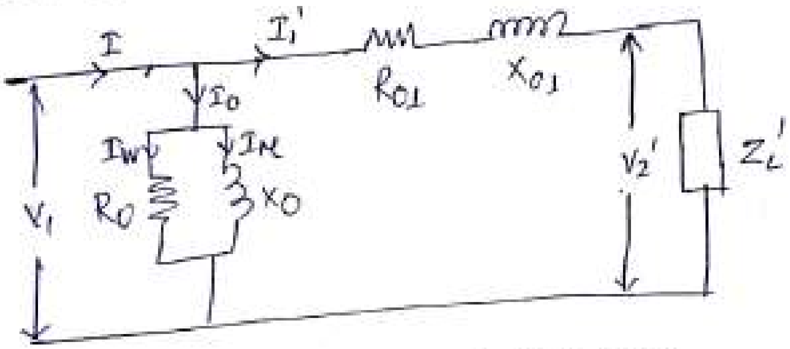


No load current will flow only in primary it will not reflect on secondary side. or not transfer to sec. so it is connected in parallel with primary winding.

Equivalent ckt when refer to primary :-



1st approximation to equivalent ckt



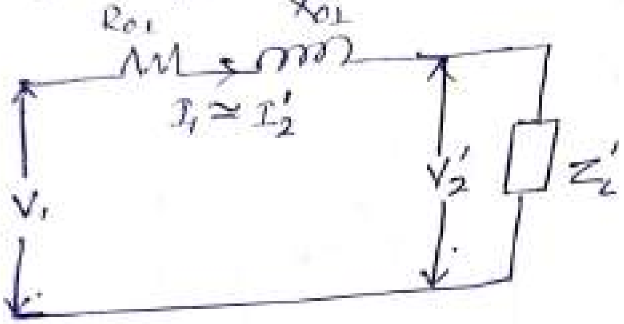
Deviation in above equivalent ckt :-

1. No load primary impedance drop is neglected i.e. $I_0 Z_1$
2. No load primary cu loss is also neglected $= I_0 R_1^2$, or under estimated.
3. As $|V_1| > |E_1|$
   No load current & it's components are over estimated as connected across high voltage $|V_1|$
   so No load current I_0 increases, hence I_w & I_M are also increases
4. so Iron loss over ~~compare~~ estimated

∴ Under estimated no load cu loss = over estimated iron loss.

2nd approximation to Equivalent ckt of transformer:

By neglecting no load current as it's very less.



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