@ Om Sai Ram

# Transformers

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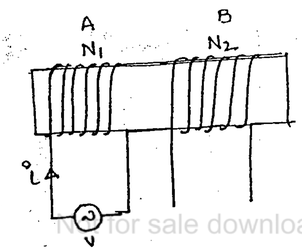
→ Induced Emf's are two types.
- ↳ Dynamically induced Emf — Space variation b/w Conductor & field
- ↳ Statically induced Emf — Time variation b/w Conductor & field.

→ Statically induced Emf again 2 types.
- ↳ Self induced Emf
- ↳ Mutually induced Emf.

Now we discuss / understand how these Emf's are generate & in which direction it produce.




$i = i_m \sin\omega t$

created time varying mmf.

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

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$i$ = time varying Current → mmf time varying AT
↓
→ $\phi$ time varying flux.

Coil A stationary and flux time varient. Nature of induced Emf in coil A is statically induced Emf. But this induced Emf is due to time varying Current flowing through its own coil is called "Self induced Emf."

Magnitude of Self induced Emf by faraday 2nd law.

$E_s$ (Self induced Emf) given by rate of change of flux linkages at that coil.

$$\therefore E_s = -\frac{d}{dt}(N_1\phi)$$

to satisfy lenz's law.

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

multiply & devide with Current.

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



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

**Self Inductance :-** Rate of variation of flux linkages due to time varying Current flowing through its own coil.

$$L_{self} = \frac{d}{di}(N_1\phi)$$

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

Whenever self inductance exists self induced Emf also exists. Direction of self induced Emf find by Lenz's law..

**Lenz's law :-** The induced quantity is always opposes change in Very Cause producing..

$$E_{self} = -N \cdot \frac{d\phi}{dt} \qquad E_{self} = -L_{self} \cdot \frac{di}{dt}$$

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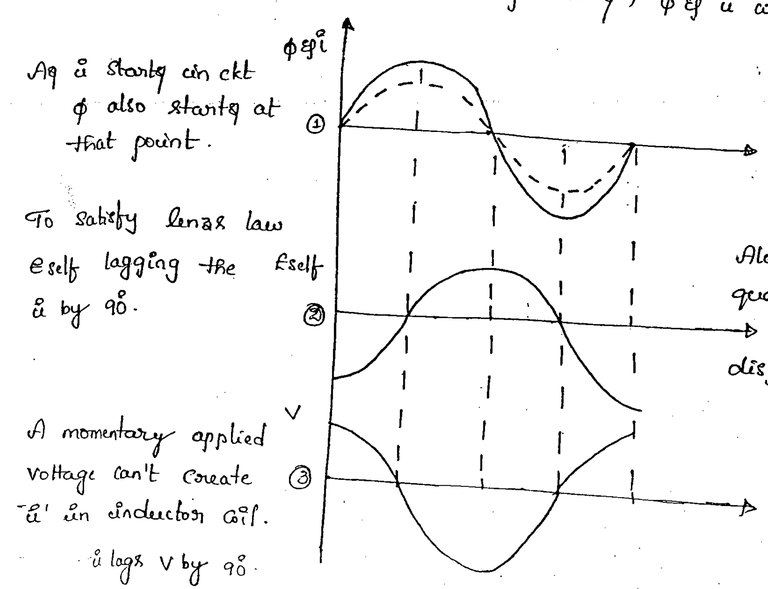
Self induced Emf opposes changes in $\phi$ & changes in $i$

If 'N' absence in above expressions; $\phi$ & $i$ wave is shown below.




As $i$ starts in ckt $\phi$ also starts at that point.

To satisfy lenz's law $e_{self}$ lagging the $E_{self}$ $i$ by 90°.

A momentary applied voltage can't create 'i' in inductor coil.

$i$ lags V by 90°.

Always any induced ~~Emf~~ quantity to satisfy lenz's law, both quantities displaced by 90°.

As $E_{self}$ opposes changes in 'i' to satisfy lenz's law in that process. Self induced Emf directly opposing the applied voltage.

Two quantities opposing phase displace $-90°$.

Two quantities directly opposing phase displace $-180°$.

$$v_1 = -E_{self}$$

* If 'N' keep differentiation before quantity with -ve sign, then quantities displaced by $90°$.

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

* If 'N' directly keep -ve sign before quantity then quantities displaced by $180°$.

$$v = -E_{self}.$$

<u>Mutually Induced Emf</u>:-

It is the induced Emf in a coil due to time varying current flowing through the other coil which is magnetically coupled to it.

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Magnitude of mutually induced Emf found by Faraday 2nd ~~law~~ law.

i.e., $E_m$ = rate of change of flux linkages in 2nd coil.

$$E_2 = -N_2 \cdot \frac{d\phi}{dt}$$

$$E_2 = -N_2 \cdot \underbrace{\frac{d\phi}{di}} \cdot \frac{di}{dt}$$

Mutually Inductance :- Variation of flux linkages due to variation of current flowing through other coil.

Rate of change of flux linkages at a coil w.r.t. time varying current flowing through other coil which is magnetically coupled to it.

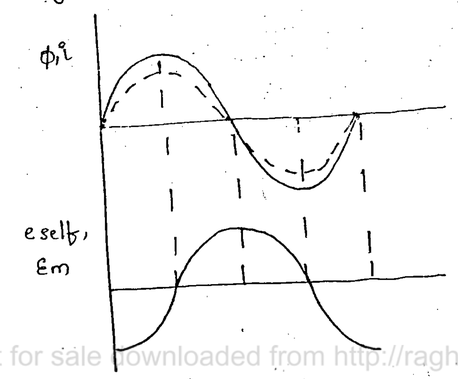
$$M = \frac{d}{di}(N_2\phi)$$

$$E_m = -M.\frac{di}{dt}$$



Whenever there is mutual ~~inductance~~ induction property there is a possibility for mutually induced Emf. Direction of mutually induced Emf given by lenz's law. Mutual induced Emf always opposes the changes in i to very cause of producing.

That means similar to $E_{self}$; $E_m$ also opposes changes in current and changes in flux to satisfy lenz's law.

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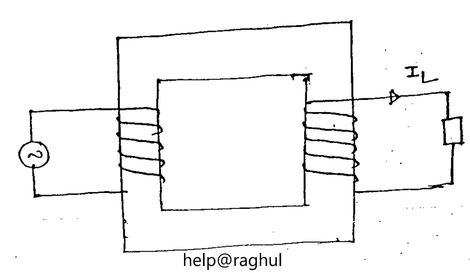
$E_{self}$, $E_m$ are in phase. and no time delay between induced Emfs self and mutual.

For any coupled circuit this principle valids even for a Transfo. also.

By seeing this discussion, How Transformer works ON?

→ Transformer basically coupled circuit; So
possibility of $E_{self}$ @ primary.
possibility of $E_m$ @ Secondary.



So main principle behind T/F can be said as mutual induction principle. Because of this secondary side Emf inducing so $i_2$ can flow through load that means power ~~transformer~~ transferred.

So Transformer is a magnetically coupled and works on mutual induction principle.

Mutual Induction depends on polarity of magnetic coupling. we can understand by magnetic coupling.

→ Types of Magnetic Coupling :-

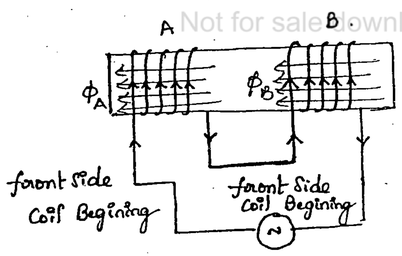
↳ +ve Magnetic Coupling :- Mutual Inductance b/w coils +ve.

↳ −ve Magnetic Coupling :- Mutual Inductance b/w coils −ve.

Knowing sense of winding is important to know about type of coupling.

ex :- (1).

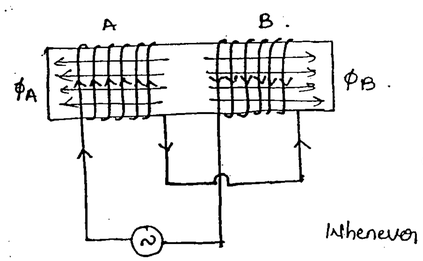
+ve Coupling




A & B coils said to be having same sense. Carry currents in same directions. So flux will be produced in core. Direction of flux found by thumb rule.

Whenever fluxes produced by two coils aiding together then type of coupling is positive coupling.

ex :- (2)




A & B coils same sense but i want direction of current to change. Current entering @ back side of coil B. Due to this two fluxes opposing.

Whenever fluxes produced by two coils opposing together then type of coils coupling is −ve coupling.

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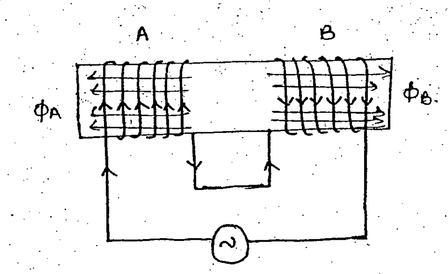
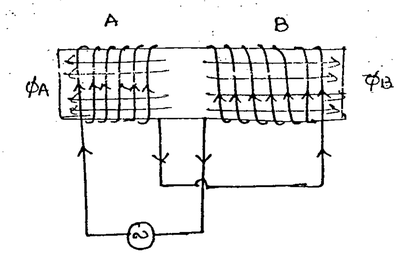
ex :- 3, For more clarity of coupling.




Consider 2 more cases. change sense of one coil. opposing fluxes together, so type of coupling −ve coupling.

ex :- 4,




Type of coupling is +ve coupling.

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By sensing above 4 examples type of coupling not depends on sense of coil, but depends on current direction for given sense of winding.

ex 1 & 2 :- Same sense but +ve & −ve coupling.

ex 3 & 4 :- Same sense but +ve & −ve coupling.

* That means by changing direction of current ~~in the~~ it can change +ve couple to −ve couple circuit vice versa.

Drawbacks :-

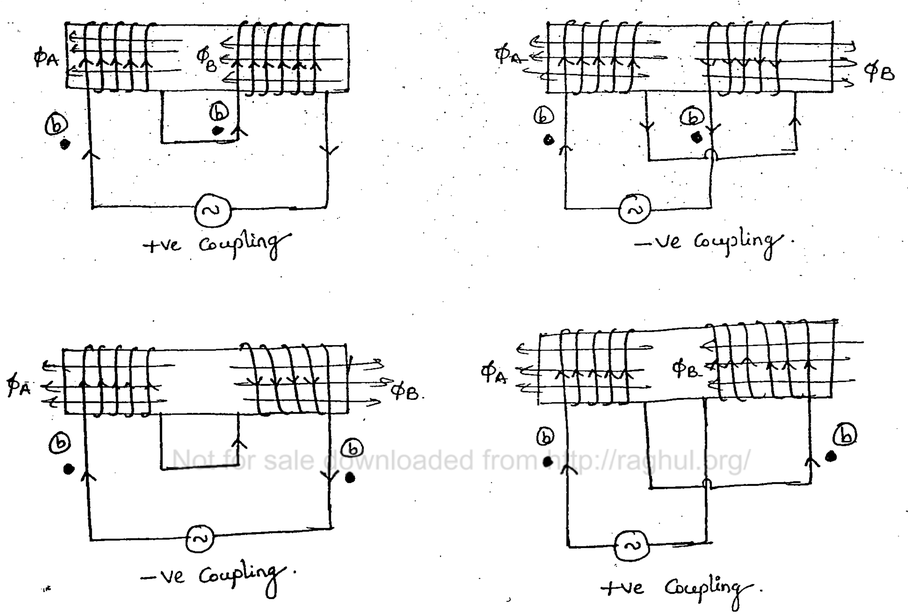
But we can't observe flux aiding or opposing physically because 'ϕ' invisible. and after keeping box type of coupling we can decide. (once design completed)

By dot notation we can said type of coupling and overcome above drawbacks.

After assuming begining Ends or Ending Ends, just observe Current Entering or leaving @ ~~dot~~ dot.

Front Side of Coils — Begining Ends.

Back Side of Coils — Finishing Ends.




I want to assume dots @ begining Ends of Coils.

Now after putting dots just observe dots whether Currents Entering dot or leaving dot.

If Current @

| one dot | other dot | definitely type of flux. |
|---|---|---|
| Entering | Entering | Aids. |
| leaving | leaving | Aids. |
| Entering | leaving | opposes. |
| leaving | Entering | opposes. |

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Flux aiding — +ve Coupling.

Flux opposing — −ve Coupling.

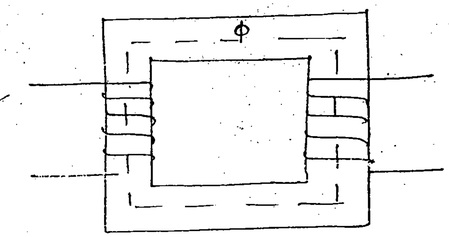
Same principle applicable in Transformer also. (positive Coupled and hence positive mutual induction).

→ Constructional Details of Practical Transformer :-

By Seeing this design we can, find ~~mail~~ mainly

✓ Transformer Core.

✓ Transformer winding.




Transformer Core :-

→ Material used for Core is Silicon Steel. Almost all Electrical machines designed by Silicon Steels only. It is also called Electrical Steel.

Features of Silicon Steel :-

1. Silicon Steel belongs to Ferro magnetic materials. among all magnetic materials ferro is superior magnetic material.

2. Silicon Steel allows low reluctance and high permiability.

Permiability — Conductivity — Analogus

↳ fairness of ~~flow~~ flow flux.

↳ fairness of flow of Electrons.

3. Silicon Steel has low hysterysis Coefficient.

To understant hysteresis Coefficient :- As time varying flux present in Core it develops loss in the Core known as hysteresis loss. To Estimate hysteresis loss

$P_h = \eta B_{max}^{n} f \cdot V$ watts.

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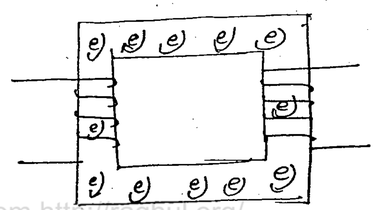
'x' varies from material to material. 'x' generally varies between 1.5 to 2.5. Silicon steel 'x' value is 1.6 which is lower limit of x. So hysteresis loss will be less using Silicon steel.

4. Silica + pure steel ⇒ Silicon steel.

Now doubt arises that pure steel why not used for Transformer Core ?

Pure steel good magnetic and conducting properties also. But T/F core requires good magnetic material only. If we use steel it is as a T/F core also acts as one of solid conducting path.

As Transformer flux is time varying nature.



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According to faradays law of electromagnetic induction there is a relative time variation between T/F core and flux so that induced Emfs possible in core which creates circulating currents causes additional power loss in core. i.e Eddy current loss in core.

So to avoid this loss only way is

→ Reduce conducting property of core.

→ Reduce strength of Eddy currents.

Here advantage of Silica adding is resistivity of pure steel increases. and practical difficulty over here is that the more silica increases brittleness of material means so that ~~to~~ Transformer core mechanical strength get decreases.



5. About 4 to 5% Silica added to steel to reduce conductance to reduce Eddy currents (We).

For further reduction of Eddy current loss in core is just laminate the core by which conducting path of Eddy current reduced. So that Eddy current ~~is~~ loss kept at minimum level.

6. Silicon Steel having crystaline structure.

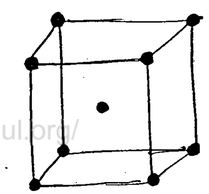
Any material having crystaline structure. That contains crystals in materials, with crystals having different shapes.

Silicon steel having body centred cubic structure.

Normally cube has — 8 corners.

8 corners — 8 atoms

Center — 1 atom.



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Silicon steel allows more permiability along its cube edges & offer low permiability along its cube diagonals.

Reason is simple :-

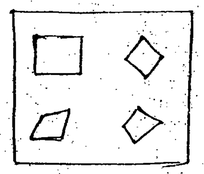
Conductor length is more — Conductance less (∵ R↑)

Magnetising length is more — Permiability less (∵ R↑).

∵ Edges — less length — more permiability possible.

∵ Diagonals — more length — So less possible of permiability

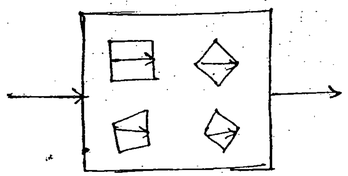
In normal Silicon steel slab the orientation of grains different.



Normal Silicon Steel Slab.

⇒ Also called ~~irregularity~~ irregularly distributed grains. This is drawback of normal silicon steel.

If this is the case; i want to magnetize this normal silicon steel.



Because of irregular distribution of grains overall silicon steel permiability comparatively less here.

If this case practically there is a possibility to increase permiability by orienting the irregular grain. By a heat treatment process known as <u>cold Rolling Grain Orientation.</u> <u>(CRGO)</u>

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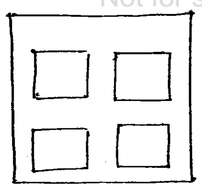


CRGO Steel Slab.

The name itself indicating that it is a "Grain Orientation process." After this process silicon steel called as <u>CRGO steel.</u>

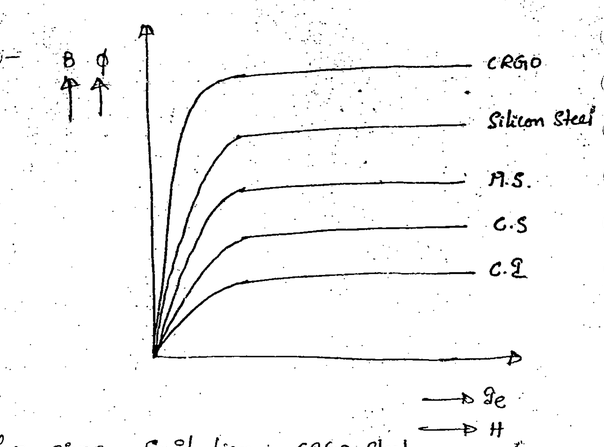
Because of high permiability of CRGO steel T/F core is practically made by CRGO steel. which has uniformly distributed grains or crystals.

CRGO steel permiability > Silicon steel permiability.

To observe the superiority of CRGO steel with other materials we must observe;



Magnetisation Curve :- (B Vs H) or ($\phi$ Vs $I_e$)




→ from above for given Excitation CRGO steel offering more flux densities.

→ If we observe flux densities;

B ⇒ Silicon steel ⇒ 1 to 1.4 Tesla

B ⇒ CRGO steel ⇒ 1.6 to 2 Tesla.

→ Practical Transformer generally operated between 1.6 to

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Advantage of Higher Flux Densities ?

As $\phi = B.A$

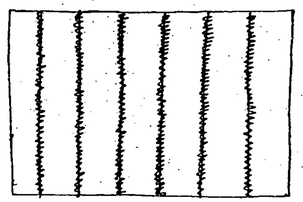
we usually maintain ~~flux~~ constant flux $\phi$ to get constant Emfs so for constant flux; if i use higher flux density materials cross-section of transformer reduces.

$\phi = \uparrow B \; A \downarrow$ As $A \downarrow \rightarrow$ Size $\downarrow \rightarrow$ Cost $\downarrow \rightarrow$ wt

So from the above discussion; we decide material used for transformer core is <u>CRGO steel.</u>

## Core Construction :-

Practically Core is not maintained as a solid structure. Solid core cutted into small pieces as silicon wafer known as laminations, To reduce Eddy Current loss. All these laminations must be electrically isolated. For that provide insulation between each lamination to reduce strength of Eddy Currents.



By simply laminating core we ~~con~~ cant get reduced currents so isolate laminations by Insulating materials. Those are

→ Oxide paints (Red oxide)

→ china clay

→ Commercially available Varnish (Japan Varnish)

→ Some cases, Thin Impregnated paper.

process of dipping Insulating paper (Bethoroid) in insulating oil or T/F oil known as Impregnation.

→ Similarly impregnated cloth.

* Whenever insulating material used in the laminations, there is two x sections present in core.

1, Magnetic Material x Section.

2, Insulating Material x Section.

So that here we can define two types of cross-sections areas.

1, Gross x Section of Core : Sum of Area occupied by
(Ag) Magnetic Material + Insulating Material



2, Net x Section of Core : Area occupied only by
($A_n$) Magnetic Material.

But flux flowing through magnetic material only permiability of any material $\mu = \mu_0 \mu_r$.

Absolute permiability $\mu_0$ always constant.

Relative permiability $\mu_r$ varies with material.

$\mu_r$ — high — for Magnetic Material.

$\mu_r$ — low — for Insulating Material.

* Flux has tendency to complete its path through low reluctance path only. Means most of flux passes through the net x section area of core.

$\phi = B \cdot A_n$ ↳ A must be net cross-section only. ∵ flux passes through $A_n$ only.

But in this case Impossible.

Transformer design once completed we can know overall length and breadth of core. i.e., Gross x Section of core. But for our calculations we need net x section of core only. So some factor necessary to know $A_n$ from $A_g$. known as <u>Stacking factor (ks)</u>.

$$\text{Stacking factor } (k_s) = \frac{A_n, \text{ Net x Section of Core}}{A_g, \text{ Gross x Section of Core}}$$

$k_s$ always $< 1$

$A_n = A_g \times k_s$.

This $k_s$ value is defined or mentioned by designer data sheets of purchased Transformer. ks generally 0.5 to 0



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This 'ks' we can substitute in Emf equation of T/F.

$$E_1 = 4.44\, N_1 B_m \left(\frac{k_s A_g}{A_n}\right) f$$

n – laminations requiring (n-1) insulations.

ks = 1 for solid core.

| | | | |
|---|---|---|---|
| * More laminations | More insulation | less net x section | ks low |
| * More thick laminations | Less insulation | More net x section | ks more. |

All these laminations must be bunched. Process of this bunching laminations known as <u>Core Stragering.</u>

## <u>Undesirable Consequence Due to Poor Straggering</u> :-

### 1, <u>More Excitation Current</u> :-

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Poor straggering means ~~been~~ looseness in core. So airgap comes between laminations, so air has more reluctance.

$$\phi = \frac{mmf}{\text{reluctance}}$$

$$= \frac{N_1 I_e}{\mathcal{R}}$$

For poor core straggering to induce proper Emfs $\phi$ must be sufficient.

As reluctance $\uparrow \rightarrow \phi \downarrow$

To maintain $\phi$ constant $I_e \uparrow$. That means core demands or draws more excitation current for developing desirable flux. to avoid this undesirable consequence, core laminations tightly straggered or rivited such that no airgap present in core.



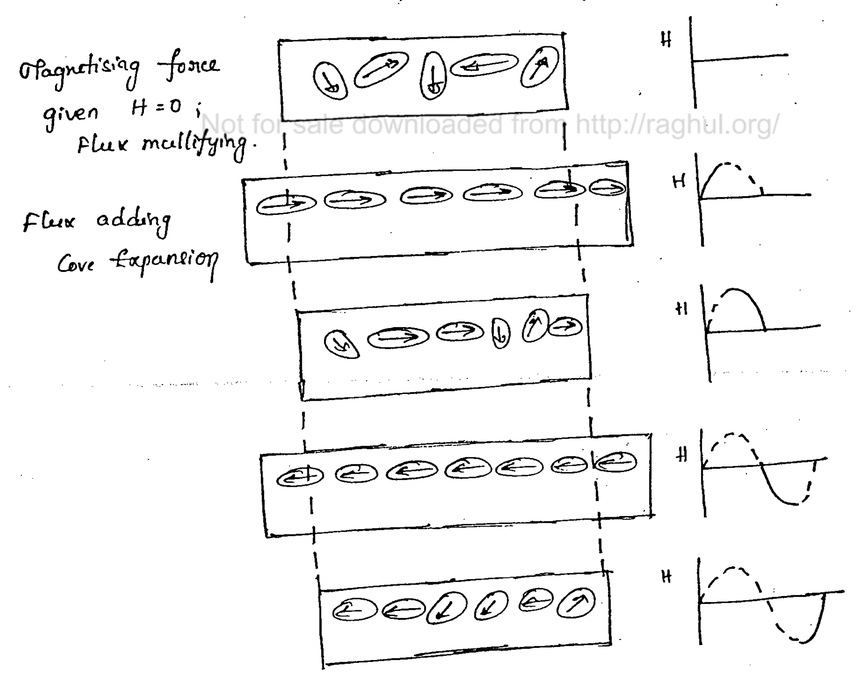
### 2, <u>Magnetic Humming</u> :-

Due to poor straggering magnetic humming comes into picture. Main reason behind production of sound in Transformer is due to phenomenon of <u>Magneto Stiction.</u>

Tendency of any magnetic material possibility of slight changes in its dimensions whenever it is subjected to alternating currents.

→ To understand Magneto Stiction :-

We must know magnetisation process. Consider a magnetic material.

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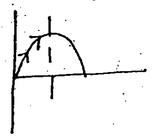
→ Magnetic Materials consists Magnetic Dipoles. ⊖ (symbol) which are irregularly (or) randomly distributed in material if magnetising force is H = 0.

→ whenever dipoles random, Flux Carried by one dipole nullified by other ~~ele~~ di pole known as magnetic neutral state. means no magnetic flux.

→ Now i want to magnetise this magnetic slab.
let +ve Magnetising force.



Then all dipoles gets a Orientation that means all dipoles Comes into single line.

To produce flux in one direction with increasing nature. Because previously dimensions in zig zag. to accomodate the single line dipoles Core previous dimensions not enough. Due to this Core length gets increase known as <u>Core Expansion</u> or <u>magnetic Expansion</u>.

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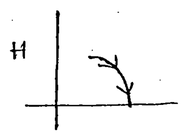



Similarly in demagnetising, process Core gets Contracted. and again dipoles Comes into zig zag passion. Magnetic Contraction takes place.

During all these slight changes in dimensions Creates large mechanical stresses in lamination. If laminations are loosely held mechanical ~~vo~~ vibrations are very high due to these mechanical stresses. This phenomenon is invitable means unavoidable.

If these vibrations produced in Audible frequency known as <u>Magnetic Humming</u>.

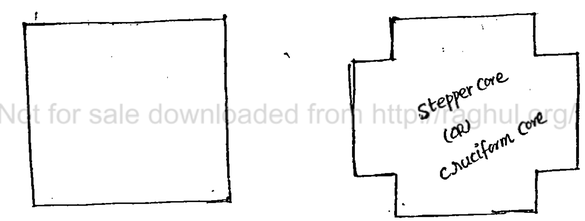
ex:- This Magnetic Hum can listen at tube light choke also. So whenever coil subjected to Alternating Currents mechanical stresses exists in the coil.



We ~~can~~ Cant avoid this phenomenon but we can reduce mechanical stresses in the Core laminations by proper Core Straggering. So that proper Core Straggering helps in reducing mechanical stresses in Core & reduces magnetic Humming also.

→ <u>Shape of X Section of Core</u> :-

In actual practice Core may not be in Square Shape. Some steps will be given known as Stepped Core or Cruciform Core.

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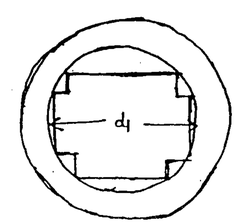
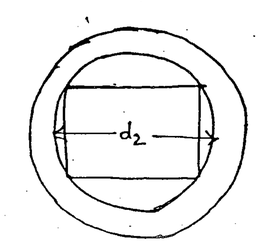
To Compare both must have Same X Sections.

| Cruciform Core (or) Stepper Core | Square Stepped Core. |
|---|---|
| 1, Amount of Insulation reduced. Before placing winding we must provide insulation. | 1 Amount of insulation required more. |




Dia of Circum circle less.
Effective utilisation of Core done.




Dia of Circum Circle more.

| | |
|---|---|
| length/turn less. ∵ diameter of Circum Core less. | 2. length/turn of winding more. |
| Amount of Copper required less. | 3, Amount of Copper required more. |
| Size, wt, Cost less. Since Saving in insulation and Copper. | 4, Size, wt, Cost more. |
| practically we use these only. | practically not adopted. |
| More number of steps, more the advantages. | 5, No steps at all. |

## Types of Magnetic Circuits :-

At this instat we shal discuss above Single phase magnetic Circuits.

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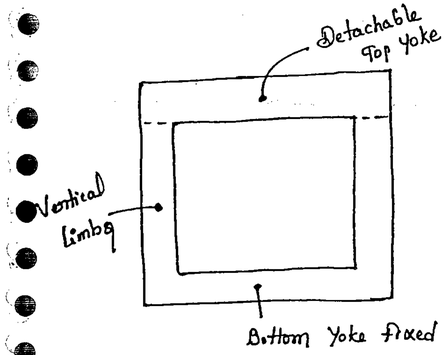
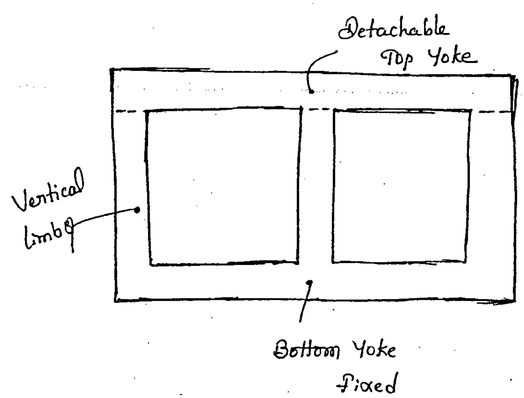
1, Core type Magnetic Circuit

2, Shell type Magnetic Circuit.




② limbs

② Yokes




② limbs

② Yokes.



Horizontal members : Yokes.

Vertical members : limbs.

$J = \sigma E$, $\sigma_0 = \sigma_0 \sigma_r$, $J = \frac{i}{A}$, $E = \frac{V}{d}$

$B = \mu H$, $B = \frac{\phi}{A}$, $H = \frac{mmf}{l} = \frac{NI}{l}$, $\mu = \mu_0 \mu_r$

→ placement of windings :-

| | |
|---|---|
| Winding placed on both limbs; no limb Empty. | outer limbs Empty both HV & LV available on middle limb. |
| Core is Surrounded by windings. | Winding Surrounded by outer limbs |

→ Fundamental Difference :- Flux path.

| | |
|---|---|
| If any winding Excited flux Comes into picture. | If middle limb winding Excited flux Comes into picture. |
| No flux deviation in Entire magnetic Circuit. So this Circuit is Series Magnetic Circuit. | Here flux deviation takes place ½ to one limb and ½ $\phi$ to other limb. So this circuit is parallel Magnetic Circuit. |

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→ Flux Ratings :-

| | |
|---|---|
| $\phi$ analogous to I. | parallel circuit: I is additive. |
| Series Circuit low I. Lower flux densities. | Higher flux densities. |

→ X Section :-

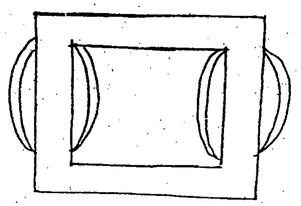
| | |
|---|---|
| All limbs same X Section. $\phi$ - Same in Entire circuit. | ½ of X Section for outerlimbs. |

→ Mechanical Support to Winding :-

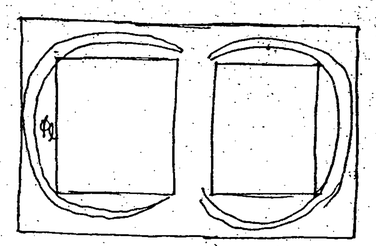
| | |
|---|---|
| Mechanical Strength of Core poor. during mechanical Vibrations winding may shift. | Good Mechanical Support to winding by External limbs : (During Mechanical stresses). |

→ **Magnetic Leakage Flux :-**

$\phi_l$ doesn't flows through core. Leakage $\phi$ : flows through air and acts with any one winding only.



No External magnetic path to catch up this leakage flux.




Leakage flux can be Easily tappered by External limbs So $\phi_l$ becomes common flux. So leakage flux less.

→ **Copper Requirement :-**

~~Requires less amount of insulating material.~~ Requires more Copper shortly we will discuss in placement of windings.

Requires less Copper.

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→ **Insulation Requirement :-**

Requires less amount of insulating material.

Demands more insulating material.

→ **Voltage Application :-**

Voltage rating $\propto$ thickness of insulation.

Economical : High Voltage Applications.

Economical : Low voltage Applications.

→ **Current Application :-**

Current rating $\propto$ volume of Copper.

Economical : Low Current Application.

Economical : High Current Applications.

HV, Small kVA rating T/F

$\frac{kVA}{HV}$ = Small Current.

LV, Large kVA rating T/F

$\frac{kVA}{LV}$ = Large Current.



**Construction Features of Transformer Windings :-**

Normally Transformer winding made with Copper and alluminium.

| | Copper | Alluminium |
|---|---|---|
| Advt :- | • Low Resistance<br>• Low $I^2R$ loss.<br>• $I = \uparrow JA \downarrow$ | • High Resistance. |

Copper has high current density (J) So less C X section. So size of Transformer reduce.

- Since low losses good $\eta$ and performance good.
- long life.

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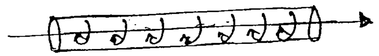
**Drawbacks :-**

- Cost of Copper more.

$$\text{Al. choke Cost} = \frac{\text{Copper choke Cost}}{2}.$$

- If we need good performance Transformer rather than Cost go for Copper.

**Solid Conductor :-**



Since large X section of Conductor some part of load currents may complete its path with in Conductor (∵ high X Sec). These currents are called as Stray Current.

Stray Currents aids with normal Copper losses known as Stray load losses.

→ How to reduce Stray load loss?

Same technique of eddy Current reduction use here means instead of using Solid Conductor cut in strips as standard Conductors to get same x Section and twist those strands. At the same time all strands must be Enamelled Coated. to limit the strength of Currents.

Since Now area offer to stray Current reduced so that strength of stray Current reduced.

∴ Stray Currents losses are limited.

practically strandard Conductor only we are using.

→ Skin Effect :-

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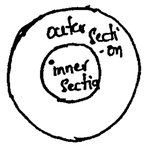
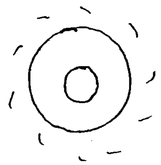
As ~~Standard~~ alternating Currents flowing through Coils this Effect Comes into picture.




Whenever Current flowing through Conductor flux linkages of inner Section – more. (Reactance more)

Flux linkage of outer Section – less. ( Reactance less)



So amount of Current flow through the low ~~reluctance~~ reactance path only. So most of Currents flows through outer Section only.

$R_{ac} = 1.6\, R_{dc}$

↳ Skin Effect factor.



Reactance in DC = 0.

for DC outer section reactance = 0

inner Section reactance = 0

As reactance uniform (0) so uniform distribution of Current.

$$\text{Skin Effect} \propto \left(\text{Diameter of Conductor}\right)^{\gamma} \propto D^{\gamma}.$$

Skin Effect more – Solid Conductor

Skin Effect less – Strandard Conductor.

~~Stra~~ Standard Conductor has (2) advantages :

1, To avoid stray load losses.

2, To reduce Skin Effect.

Winding Procedure :-

1, placement of winding in Core type Transformer Core :

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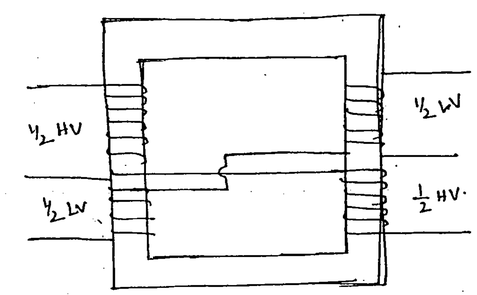



To avoid leakage flux $\frac{1}{2}$ of HV & $\frac{1}{2}$ LV on one limb. Remaining $\frac{1}{2}$ of HV & $\frac{1}{2}$ of LV on Second limb. This type of winding known as Interleaving nature of winding.

→ Interleaving Winding : ② purposes

$\phi_M = K\sqrt{L_1 L_2}$

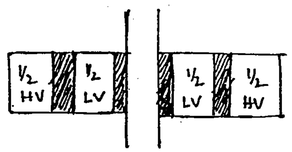
1. Magnetic leakage flux reduced.
2. Net flux improved so Coefficient of Coupling improved.

* If seperate windings ~~provided~~ provided HV on one limb and LV on one limb then leakage fluxes wont interact. So magnetic leakage flux more.

So by interleaving winding common flux gets improved meang Coefficient of Coupling increased.

→ How to place LV ½ and HV ½ on Same limb :-

1. placing LV ½ near to Core is most advantageous. ~~That means~~




* Core types : Interleaving & Concentric winding.

* Core ⇒ LV Insulation ⇒ ½ of LV ⇒ HV Insulation ⇒ ½ of HV.

Insulation for LV nearer to Core :-

let Transformer is 11/3.3 kV ∵ Core – 0 potential.

LV Insulation α to (LV – Core potential)
α (3.3 kV – 0)
α 3.3 kV.

HV Insulation α to (HV – LV)
α (11 – 3.3 kV)
α 7.7 kV

∴ Total Insulation thickness for one limb = LV thick + HV thick.
= 3.3 + 7.7
= 11 kV

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* Insulation for HV Nearer to Core :-

let Transformer is 11/3.3 kV ∵ Core – 0 potential

HV Insulation α to (HV – Core potential)
α (11 kV – 0)
α 11 kV.

LV Insulation α to (HV – LV)
α (11 kV – 3.3 kV)
α 7.7 kV.

∴ Total insulation thick for one limb
= LV thick + HV thick
= 11 + 7.7 kV
= 18.7 kV.

→ Advantages of LV Nearer to Core :-

1. less Insulation required. (Saving in insulation) thickness low.
2. Winding diameter reduced. (Saving in Copper)

Because of these two reasons Size ↓, wt ↓, Cost ↓ with LV winding placing ~~near~~ nearer to Core.

→ Disadvantages with HV Nearer to Core :-

1. Insulation thickness more,
2. Windings / turn more.
3. Size ↑, wt ↑, Cost ↑.
4. Tap changes generally placed in HV, in this case HV winding inside so not good access for tapping.

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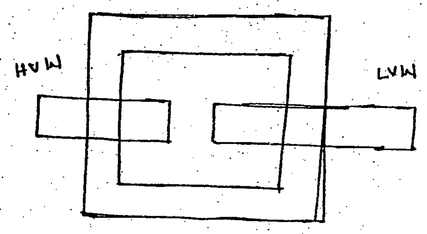
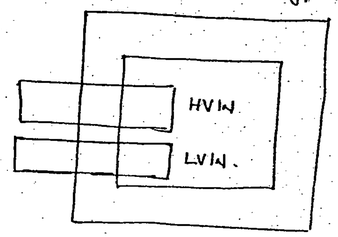
## Current directions in LV & HV both on Same limb :-

Case I :-



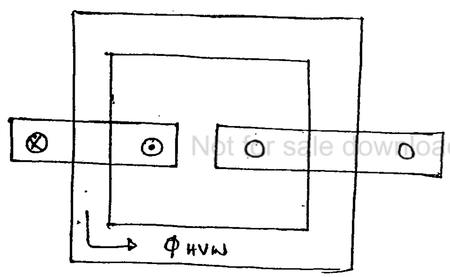

Case II :-

Interleaved type.




To know direction of current lenz's law to be followed for that 1st assume direction of main field flux.

* Main flux follows depends on primary current.

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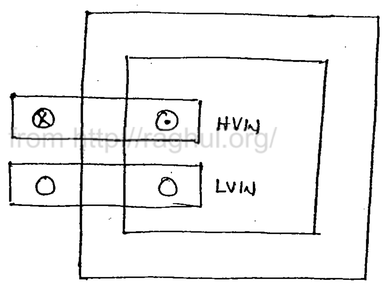
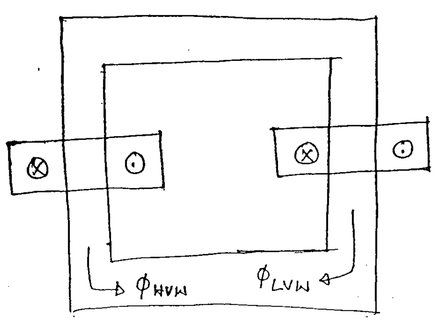
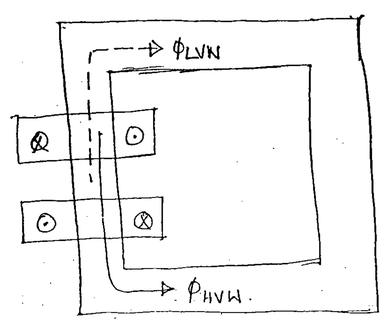
To satisfy lenz's law, due to change in flux linkages LVW current should produce flux must oppose the HVW flux.



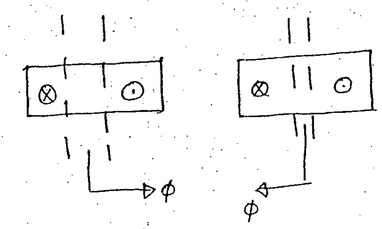

Assume primary current direction. Once we know primary flux to satisfy lenz's law secondary flux $\phi'$ must oppose primary flux.

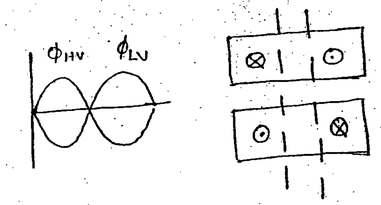




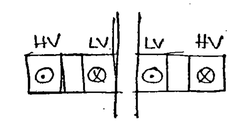

So once u know LVW $\phi$ direction just follow thumb rule to find direction of current.




To satisfy lenz's law for seperate windings on seperate limbs. The current directions on in both limbs same as shown.

To satisfy lenz's law if both windings placed on same limb they must carry currents in opposite direction.




→ Mechanical Forces Due to Currents in windings :-

Lorentz's Principle :- Conductor experience force towards weak field.

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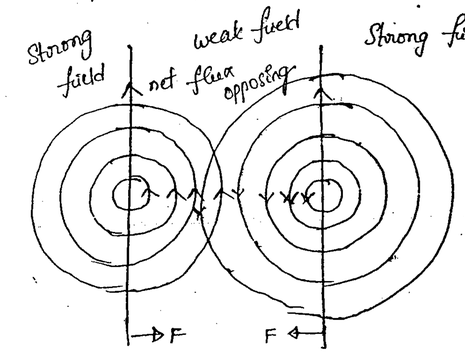
* Current carrying in both conductors (parallel) same direction.

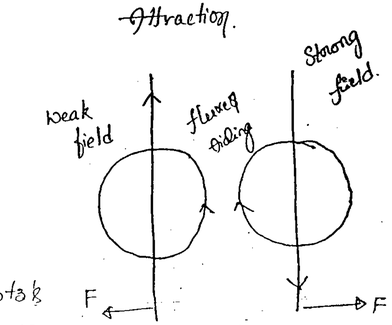
Strong flux has tendency to move conductor towards weak field.




Attraction.

* Current carrying in both conductors (llel) opposite direction.

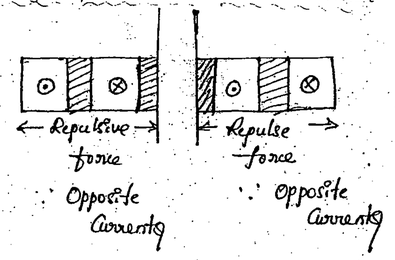
force developed is repulsion.




Corresponding force developed is lorentz's force. Direction of force depends on the direction of current.

Repulsion

Force in two wdgs placed on same limb:




* During normal operation these forces equal and opposite.

∵ Primary AT = Secondary AT

So Net force developed = zero. (Even repulsive forces present).

So no shifting of winding under normal operating conditions.

* In this case repulsive forces are ⊥ to core. So these forces are called radial force.

→ During Abnormal Conditions :-

Some thing like ex: Auto Transformer tapping.

Suddenly HV winding 80% changed. Then primary AT ≠ Secondary AT. (for a moment)

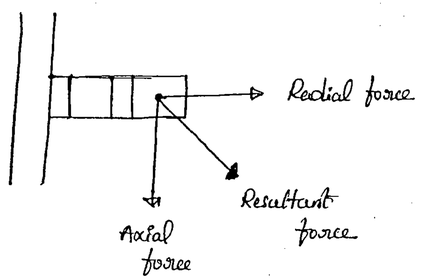
So resultant force comes into picture.

∵ unbalanced forces developed.

The resultant force may be in any direction. Can be divided into 2 directions.

→ Radial force

→ Axial force.




During Abnormal Conditions resultant radial force = 0. But axial forces developed acts in one direction only. no counter axial force so winding

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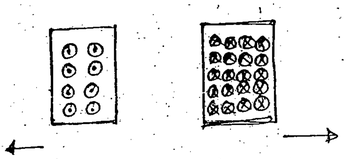
gets mechanically vibrated in axial direction.

Axial force: force parallel to core.



Whole LV Conductors carry current in same direction.

Nature of force between LV Conductors – Attraction

Whole HV Conductors carry current in same direction.

Nature of force between HV Conductors – Attraction.

Nature of force between two windings : Repulsion

(Both between bunch of LV & bunch of HV)

(Carrying current in opposite direction between LV & HV).

(2) Shell Type of Core Winding :-

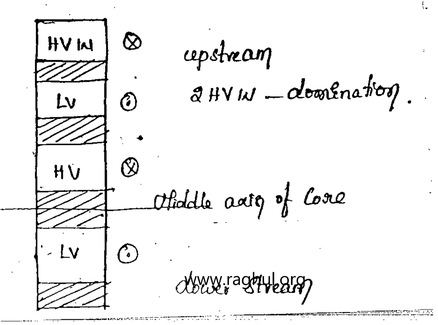
Type of winding is Sandwich type.

Sandwich : placing diff winding ~~between~~ between same windings.

In this procedure winding must placed as a bunches use to place as sections.

let HV winding : 3 sections

LV winding : 3 sections.




This type of winding not maintain symmetry. In this case to satisfy lens's law as they placed in same ~~winding~~ 9

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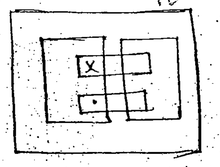
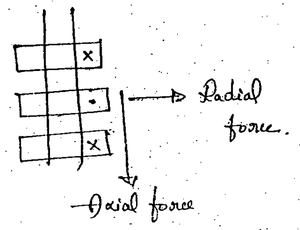
→ opposite currents → force of repulsion — axial force.



During these forces ∵ symmetry not maintained axial forces are not well balanced under normal conditions itself some resultant forces presenting i.e., Radial forces come into picture. So winding may vibrate radially.

For this remedy eg

Dont place complete LV winding section @ bottom place.



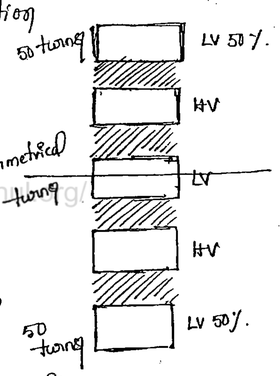

$\frac{1}{2}$ of LV at bottom.

$\frac{1}{2}$ of LV at top.

Now you will find symmetrical distribution of winding.

So

(n+1) LV sections required — for (n) HV sections.




So now radial forces gets eliminated. Now axial forces well ~~shifted~~ balanced and under normal condition. No radial forces coming with 50% LV at top 50% LV at bottom.

| | Core | Shell |
|---|---|---|
| Normal Condition | Radial forces balanced | Axial forces balanced |
| Abnormal Condition | Axial forces comes into picture<br>Axial shift of winding changes. | Radial forces comes into picture.<br>Radial shift of winding changes. |

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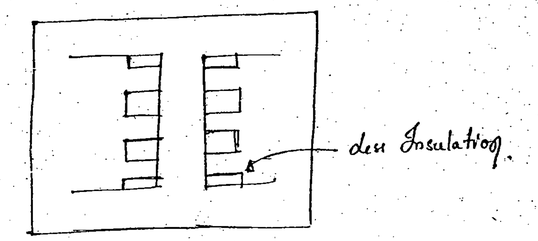
For getting saving in insulation place LV $\frac{1}{2}$ section @ extreme ends.




∵ both LV & HV near to core

→ length/turn LV & HV same so saving in copper more.

→ Insulation requirement more because more no. of sections.

| | Core | Shell |
|---|---|---|
| Insulation | less (HV applications) | High (LV applications) |
| Copper | More (Low current applications) | less (High current applications) |

→ Actual Design of the Transformer by Considering Ideal Transformer :-

Assumptions Made In Ideal Transformer :-

(1) Permiability $\mu_r = \infty$ of Transformer core $= \infty$.

$H = \frac{B}{\mu_0 \mu_r}$

$\frac{NI}{l} = \frac{B}{\mu_0 \mu_r}$

$mmf = \frac{lB}{\mu_0 \mu_r}$

$= 0$ (∵ $\mu_r = \infty$)

Acting analogous to conductivity $= \infty$ in conductor.

MMF required to produce flux $= 0$.

practically finite permiability only exists. So that core drawing some finite excitation current to create flux.

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Ideal Transformer assuming loss less medium.

Practically once flux exists in core two losses will present i.e.. Eddy current loss, & Hysteresis loss.

3. Resistance of winding = 0

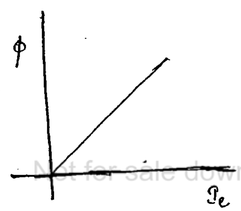
Ideal Transformer winding made with non resistive materials. Practically these is definite resistance in winding so once 'R' Exists ② Consequences

IR drop

$I^2R$ loss Exists.

4. There is no magnetic leakage flux:

5. Magnetisation curve of Transformer core is linear.




As Excitation current increases flux goes on increasing.

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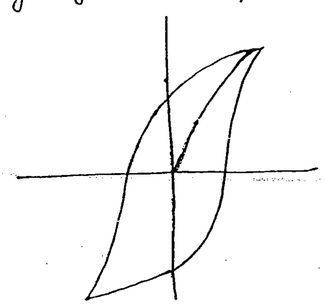
Practically two non linearities present in any magnetic materials.

→ Saturation Non-linearity

→ Hysteresis Non-linearity.

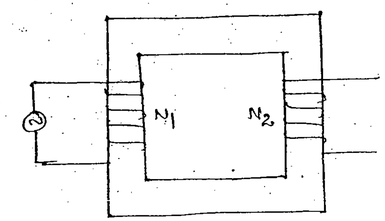


[PTO]



(1). Effect of Finite Permiability On Operation of Transformer :-

In case of Ideal Transformer we assumed permiability ∞. Instead of considering Ideal case.




If one of winding Excited small Excitation current required to produce flux in the Transformer core.

That Excitation current also called magnetising current $I_m$.

$I_e = I_m \sin\omega t$

Primary mmf $= N_1 i_e$

$= N_1 I_m \sin\omega t$

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

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As 'i' time varying $\phi$ also time varying in nature. According Faradays law of Electromagnetic Induction time varying flux induce Emfs in primary & Secondary.

Emf induced in primary = Self Induced Emf.

Emf induced in Secondary = Mutually Induced Emf.

To observe magnitude of induced Emfs:

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

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

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

$$e_1 = -N_1 \phi_m \omega \cos\omega t$$

Instantaneous Induced Emf in primary.

$$e_1 = -N_1 \phi_m \omega \cdot \sin(\omega t - \pi/2).$$

From above self induced Emf lagging the flux by 90° to satisfy

→ At what instant [illegible] maximum?

@ $\omega = \pi$

- Maximum value of Emf in primary;

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

RMS value of Sinusoidal Quantity;

$$E_{rms} = \frac{E_{max}}{\sqrt{2}} = \frac{N_1 \phi_m \omega}{\sqrt{2}} = \frac{N_1 \phi_m 2\pi f}{\sqrt{2}}$$

$$E_{rms} = 4.44 N_1 \phi_m f.$$

Generally $\phi_m$ not directly given $B_m$ in that core given. If Area of X section also given.

$$\phi_m = B_m \times A.$$

$$E_{1(rms)} = 4.44 N_1 B_m A. f.$$

If Transformer core is laminated; Consider Net X-Section of core $A_n$.

$$E_{1(rms)} = 4.44 N_1 B_m A_n. f.$$

'$A_n$' also not directly given; stacking factor given data sheet.

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$$E_{(rms)} = 4.44 N_1 B_m k_s. A_g f.$$

$$(\because l \times b = A_g)$$

This time varying flux not only induce in primary. also induce Emf in Secondary.

Magnitude of Emf @ Secondary

= Rate of change of flux linkage

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

$$\phi = \phi_m \sin\omega t \quad \text{--- Ref.}$$

Substitute;

$$e_2 = -N_2 . \frac{d}{dt}(\phi_m \sin\omega t)$$



$$e_2 = -N_2 \phi_m \omega \cos\omega t$$

As induced Emf lagging corresponding flux by 90° lag to satisfy Lenz's law. Now.

Instantaneous Secondary Emf;

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

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

$$E_{2(rms)} = 4.44 N_2 B_m A_n f$$

$$E_{1(rms)} = 4.44 N_1 B_m A_n f$$

By considering Quantities obtained upto now we can draw Vector Diagram;

$\phi_{ref}$; $I_u$, $E_1$, and $E_2$.

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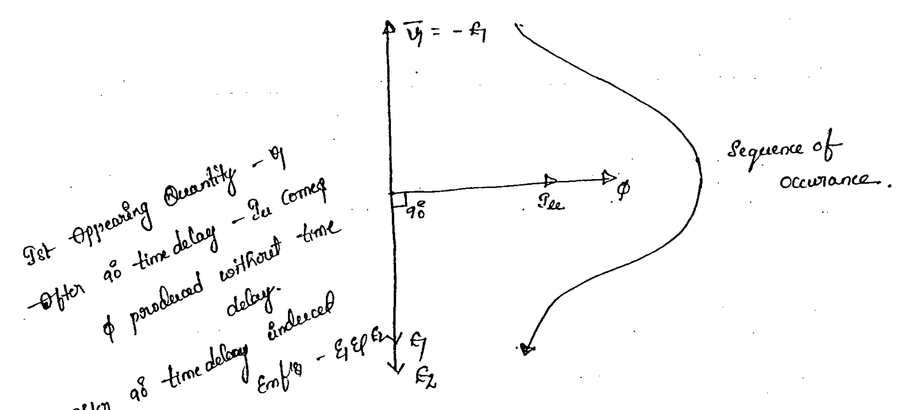
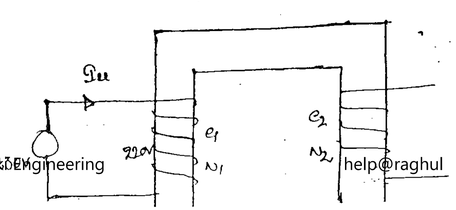
One $I_u$ present in winding $\phi$ Exists at same winding.

$E_1$ & $E_2$ lags $\phi$ by 90°.

Applied Voltage $V_1$ leads $I_u$ by 90°. (∵ Inductive Coil primary).




$I_u$ developed due to 230 - 210 Volts.

Observation :-

(1) $\frac{E_1}{N_1} = 4.44\, B_m . A_n f$.

$\frac{E_2}{N_2} = 4.44\, B_m . A_n f$.

Emf/Turn is Constant in both sides of Transformer.

Emf/Turn in Transformer $= 4.44\, B_m . A_n f$.

Primary Induced Emf $= \frac{Emf}{Turn} \times$ Primary Turns

Secondary Induced Emf $= \frac{Emf}{Turn} \times$ Secondary Turns.

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

We can realised as;

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

Transformation Ratio always defined between induced Emfs only. Not between applied voltage or terminal voltage.

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In some text books turns ratio is referred, as;

Turns Ratio $= \frac{N_1}{N_2}$

Transformation Ratio $= \frac{1}{\text{Turns Ratio}}$

Transformation Ratio reciprocal of Turns Ratio.

(2) In Name plate Details mentioned voltages are Induced Emfs;

$\frac{E_1}{E_2} = \frac{2000}{200}$

Name plate Details

2000/200 V

$E_1/E_2$

That means we can calculate the mentioned voltages by Emf Equations.



(3) For suppose Transformer design completed.

i.e., $E_1$ & $E_2$ obtained.

Applied Voltage $V_1$, Frequency $F$ } - operational parameters.

I want put my designed Transformer;

$$E = 4.44 N_1 B_m A_n f.$$

One design completed; $4.44$, $N_1$, $A_n$ } Constant

But $B_m$ depends on $\frac{E_1}{f} \propto \frac{V_1}{f}$.

That means $B_m$ is depending on Applied voltage to frequency ratio.

For Example :-

In operation of Transformer ; if you want Constant $B_m$ $\frac{V_1}{f}$ ratio must be Constant. To maintain flux density in Transformer Core Constant ; Hence Important thing is $B_m \propto \frac{V_1}{f}$.

For Example :- Transformer operated @ 240V ; 60 Hz @ $B_m = 1.6$ Tesla

Now I am operating @ 160 V ; $f_2 = ?$ @ $B_m = 1.6$ Tesla

so To maintain Constant $B_m$; $\frac{V}{f}$ ratio must be Constant.

$$\frac{V_1}{f_1} = \frac{V_2}{f_2} \Rightarrow f_2 = \frac{V_2 f_1}{V_1}$$

$$= \frac{160 \times 60}{240}$$

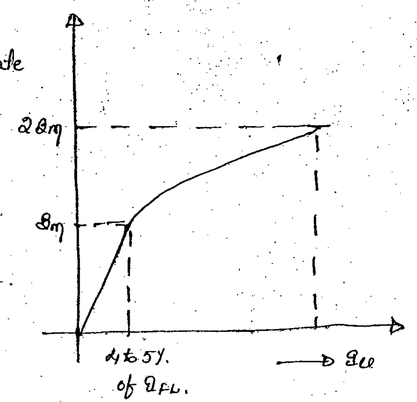
$$= 40\ Hz$$

(4) We shall observe Consequences if V & f changing;

~~Later~~ saturation ~~&~~ It clearly practically draws much Excitation Current.

→ Its Excitation Current to create flux only. But if increasing very much means it's a undesirable consequence.

That means keeping V constant & reducing leads to the sharp increasing in Excitation Current.




* So if you want to operate (or) if it is necessary to operate Transformer @ reduced frequency;

→ You Reduce Applied voltage also along with frequency to maintain $\frac{V_1}{f}$ ratio of $B_m$ in Core to maintain constant.

* If, you reduce frequency flux only; over flux comes into picture, to maintain this flux Transformer Core draws deep magnetizing Curves.

5, Generally Transformer rating is representing with kVA only. i.e Apparent power.

Active power = voltage × Current × p.f.

Apparent power = Voltage × Current

To understand this we need some more discussion later on we shall discuss.

Rating of Transformer = $E_1 I$

$\because E \propto f$.

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wherever frequency ↓, $E_1$ ↓, kVA also ↓

if frequency $\frac{1}{2}$ ⇒ kVA also $\frac{1}{2}$.

For ex:- If Transformer 100kVA in USA imported to India. Reduced kVA = ?

USA frequency – 60Hz

India frequency – 50Hz

$kVA_1 \propto f_1$

$kVA_2 \propto f_2$.

$$\frac{kVA_1}{f_1} = \frac{kVA_2}{f_2}$$

$$\Rightarrow kVA_2 = \frac{kVA_1 \times f_2}{f_1} = \frac{100 \times 50}{60} = 83\ kVA$$

* $E_1 = 4.44\, N_1 B_m A_n f$

Desired of Designing Parameters.

f : Decided before designing only i.e designed frequency.

* If I want fix up kVA to Design;

fixed up one kVA ; let = 100 kVA.

$E_1 = 10V$

fix up Current rating ; let = 10 Amp.

$10 = 10V$

Now you can decided Current density & ⊗ X Section depending on Economy.

One Current rating you fixed up;

$I_1 = \frac{100k}{10} = 10000\ Volt$ ⇒ $(4.44 f B_m A_n f)$ ↑

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→ For a given kVA rating and current rating; if a increase design frequency of Transformer.

$E_1 = 4.44\, a\, B_m A_n f \downarrow \uparrow$

∵ kVA fixed $E_1$ also fixed.

For same kVA if designing frequency increases we can obtained reduced 'x' section of core.

→ ? which of the Transformer has less in size ?

(a) 100 kVA, 25 Hz (b) 100 kVA, 100 Hz

(c) 100 kVA, 60 Hz (d) 100 kVA, 400 Hz

Explanation:- ⇒ For fixed kVA if frequency more x section of Transforme less; so size is less.

* Even though ~~the~~ it is advantageous with increased frequencies (∵ size, x-section, wt, cost of Transformer ↓).

But practically not possible.

∵ Consumer has to purchase diff frequency Transformer and loads. So forcably we have to design our Transformer (a) 50 Hz only.

But in Electronic Transformer's this application increasing frequency is advantageous.

* $E_1 = 4.44\, N_1 B_m A_n f$

for given kVA rating;

So During Design State you can't ↑ frequency to reduce x-section. But ~~als~~ during design if you used high $B_m$ material for core. i.e., use CRGO instead of Silicon steel.

So that $E_1 = 4.44\, a_1 B_m \uparrow A_n \downarrow f$

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* For superior magnetic material, less x-section.

So size and wt and cost of Transformer.

* Light weight T/F → Heavy weight T/F

CRGO Steel. | Silicon Steel | Mild Steel | Cast Steel | Cast Iron

→ If I replaced my cast iron core $B_m = 0.8T$ with silicon steel $B_m = 1.2T$. what is the % reduction in volume of core. for same kVA.

⇒ $\frac{E_m f}{T_{cog}} = 4.44\, B_m A_n f$

$B_m A_n$ should be constant for maintaining kVA constant.

So Cast Iron Silicon Steel

$B_{m_1} A_1 = B_{m_2} A_2$

$0.8 A_1 = 1.2 A_2$

$\frac{A_2}{A_1} = \frac{0.8}{1.2} = 0.667$

$A_2$ = Area of Silicon Steel Core.

$A_1$ = Area of Cast Iron Core.

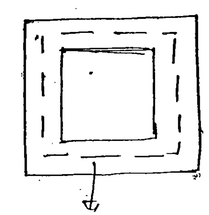
% Reduction in x section in area;

⇒ $1 - 0.667 = 33.7\%$

Volume of Core = Area of x section × Mean length of Core

$V = A \times l$ constant

∴ $V \propto$ Area of Transformer Core.



Mean length of Core constant - even T/F material increased to mile.

% Reduction in volume

$V_1 - V_2$ ...

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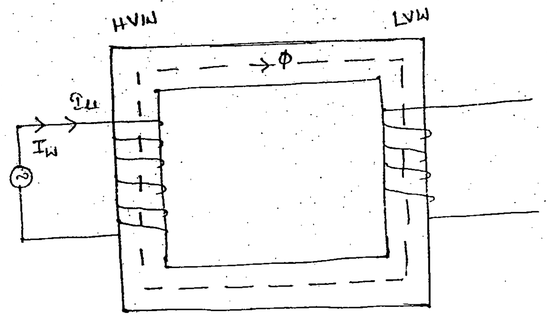
$= 1 - 66.7 \times 100$

$= 33.7\%$ Reduction in Volume.

∴ That means for superior magnetic material Transformer core less.

## 2, Effect of Iron losses On Operation Of Transformer :-




One flux present in core two iron losses present in T/F.

→ Hysteresis loss &

→ Eddy current loss.

These losses are inevitable.

Iron losses means simply power loss only.

∵ Transformer singly excited machine only one source available. So Iron loss must be supplied by source only.

So as Transformer iron losses present in core. Some additional current has to be drawn by ~~source~~. core. Known as Iron loss current ($I_w$)

So no load current drawn by Transformer

$$I_0 = \bar{I}_w + \bar{I}_{\mu}$$

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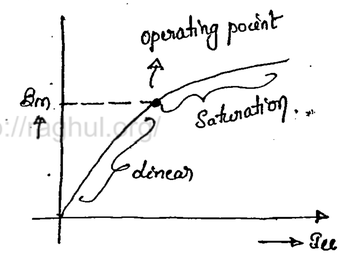
| $I_{\mu}$ | $I_w$ |
|---|---|
| (1) To create flux in Transformer core, so where related to loss. | (1) This component supplied to satisfy losses. |
| (2) Analogous to reactive power component. wattless component. | (2) Analogous to active power component. wattfull component. |
| (3) Any reactive current quadrature with applied voltage. $I_{\mu}$ lags V by 90°. | (3) Any active current inphase with applied voltage. $I_w$ inphase to V. |

* Both these currents are ⊥ to each other.

(4) $I_{\mu} >> I_w$

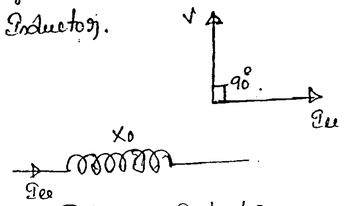
∵ To achieve higher flux densities & to get reduced core normally T/F's operated @ just begining of saturation point of magnetising current.

Means Magnetising current definitely more.



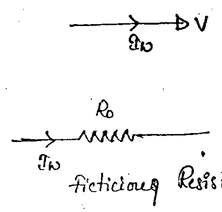

(5) 4 to 6% of $I_{FL}$ | (5) 1 to 2% of $I_{FL}$.

(6) ∵ $I_{\mu}$ lags V by 90°. Suitable circuit component to represent the $I_{\mu}$ current is Inductor.



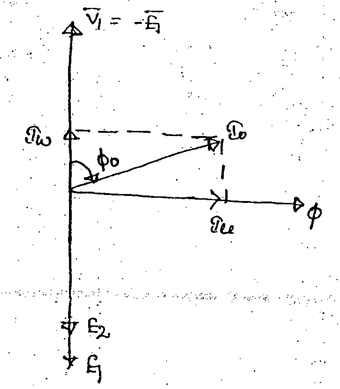

Fictitious Inductor.

(6) ∵ $I_w$ inphase with V. So suitable component to represent for circuit analysis of Transformer.




Fictitious Resistor.

## 1.2 Assumptions :-




$\phi_0$ : No-load phase angle of Transformer

Normally $\phi_0$ in order of 70 to 75°.

$\cos\phi_0$ Normally $= 0.2$ lag.

→ Reason for poor No-load power factor :-

∵ Magnetising Component of Current is very very high Compared with Iron loss. Component Current of Transformer. Normally $I_\mu$ is 3 to 4 times of $I_w$.

* Whenever $I_\mu$ Current is increases (With Constant V & reduced f) under no load if you reduced on frequency no-load power facts of Transformer further reduced.

∵ (1) $I_\mu$ increases ↑ with f ↓

(2) poor no-load power factor < 0.2 with f ↓

So to get satisfactory operation don't reduce frequency only without changing the applied voltage.

~~Not~~ Normal Condition no-load power factor = 0.2

If reduced frequency @ applied voltage Constant then no-load p.f < 0.2

* If no-load Current given in polar form;

i.e., $I_0 \angle -\phi_0$.

you can resolve this into ⊥ Components of no-load Current.

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i.e., $I_w = I_0 \cos\phi_0$

$I_\mu = I_0 \sin\phi_0$

No-load power Consumption of Transformer

$= V_1 I_0 \cos\phi_0$

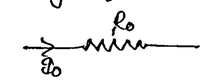
$= V_1 I_w$

Iron loss only.

* power Consumption under no-load used. Supply only for Iron loss This case Exists until winding resistances not Considered.

Based on this we can draw Equivalent Circuit of Transformer under no-load Condition.

Generally if :




$I_0$ flows through winding Causes no-load primary Copper losses.

Then No-load loss

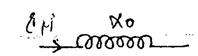
= No load Cu loss + Iron loss (Hajov loss under no-load.)

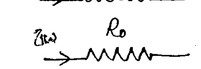
But this is negligible

→ No-load Equivalent Transformer :-

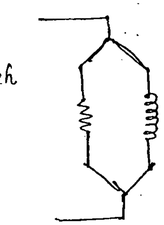
$I_0 = I_w + I_\mu$

Sum of Current possible in parallel Circuit Components only.

$I_\mu$ flowing to 

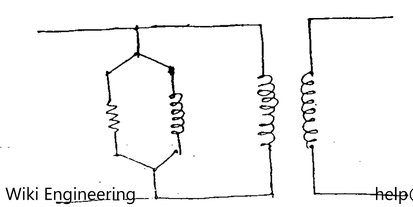

$I_w$ flowing to 


To get $I_w + I_\mu$ must be shunt branch



This shunt branch must be parallel to primary not in series.

Since no load Current Exists in primary only. If a plac in series this shunt branch to primary that must be transfer-ble to Secondary side.



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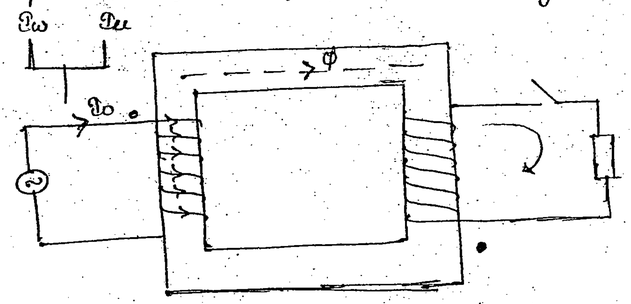
Before considering other assumptions we shall discuss operation of Transformer under loading.






To understand loading knowing sense of winding compulsory. place dots @ begining or Terminating end.

As source connected $I_{ee}$ flows through primary which creates mmf in primary.

i.e $N_1 I_{ee}$ = primary mmf.

This mmf creates main field flux

or

operating flux

or

Working flux.

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Direction of flux can be observe by means of thumb rule. This alternating flux induces the Emfs in primary and Secondary i.e. EP.

Now you close the load switch, then voltage appears across the load. i.e.; $V_2$ : Secondary terminal voltage.

As $V_2$ appears across load it draws some current i.e $I_2$ load current.

$I_2$ load current direction find by lenz's law. i.e., the current $I_2$ flows in such a way that to oppose very cause of its producing. i.e., variable main field flux.

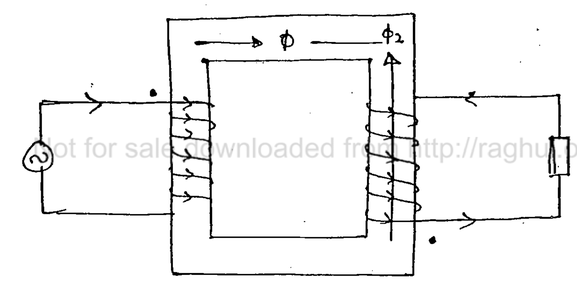


$\therefore$ $\phi_2$ acts in opposition to $\phi_m$.

As $I_2$ flowing in $N_2$ ; $I_2 N_2$ creates secondary mmf. This secondary mmf creates $\phi_2$ which opposes the main field flux. So u just draw opposite magnetic lines to main flux w.r.t its changes. Then by thumb rule u can find $I_2$ direction.

In this case :

$I_0$ Entering dot } Type of Coupling
$I_2$ leaving dot } -ve Coupling.

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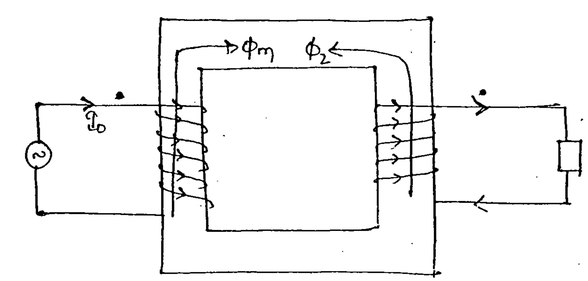
For better understand about $I_2$ direction we shall go for another sense of winding.

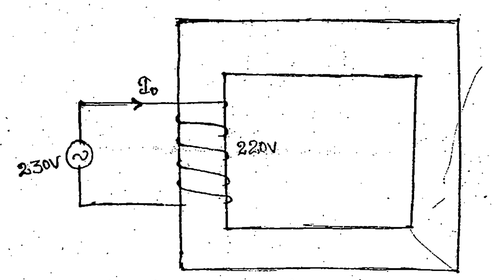



One dot Entering Current } -vely Coupled.
Other dot leaving Current

be acting like a -vely coupled circuit to satisfy lenz's law.

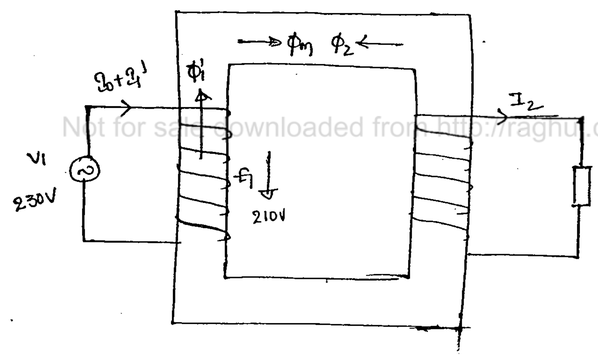
As supply voltage $V_1$ – constant.

Induced Emf $E_1$ – reduced.




Under No-load.

Under load :-

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This reduced $E_1$ draws additional component current to satisfy lenz's law. (∵ $E_1$ & $V_1$ inphase opposition 180° directly)

∴ $I_0+I_1'$ comes from primary.

$I_1'$ creates additional mmf in primary. i.e., $N_1 I_1'$ primary additional mmf. creates $\phi_1'$ flux. which is in ~~as~~ aiding direction to $\phi_m$.



So now in Transformer

③ fluxes present. 1, $\phi_m$ – No load or Main flux.

2, $\phi_2$ – } load component

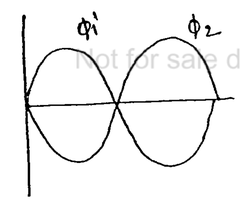
3, $\phi_1'$ – } flux in core.

This $\phi_1'$ used to oppose $\phi_2$ exactly 180° opposition.

So that irrespective of load acting flux presenting in Transform remain constant. That was T/F defined as a constant flux device.

Inorder to transfer power from one circuit to other

$\phi_1'$ must $= \phi_2$. & both must equal in magnitude & both should be 180° phase opposition.




How if $\phi_1' = \phi_2$ power transfer happen?

∵ This condition exists only if primary A.T = Secondary A.T.

That means load component of primary A.T deflected to load component of Secondary A.T.

Now exact Transformation Ratio $K = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1'}{I_2}$.

$K \neq \frac{I_1}{I_2}$ ∵ $I_1$ not exactly transforming to $I_2$.

$\frac{E_2}{E_1} = \frac{I_1'}{I_2}$. $\boxed{I_1' = K I_2}$

$E_1 I_1' = E_2 I_2$.

Load component of primary ~~VA~~ VA = load component of Secondary V.A.

That drawing [illegible] component [illegible] deflected to [illegible] of primary of Secondary.

Whatever the developed primary Ampere turns load component supplied to Secondary Ampere turns load component. without changing magnitude of power. So Transformer is a constant power device not a magnifier.

* If $I_0$ Neglected;

$I_1 \simeq I_1'$ (Approximately)

then $I_1 N_1 \simeq N_2 I_2$ (Approximately)

No-Load A.T not transferred to Secondary. Since there is no counter acting. from Secondary under no-load condition.

$\therefore N_1 I_1 \simeq N_2 I_2$ (Approximately).

$K \simeq \frac{I_1}{I_2}$ (Approximately)

$\therefore E_1 I_1 \simeq E_2 I_2$ (Approximately).

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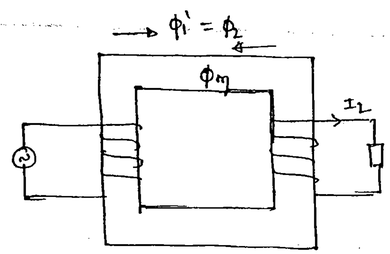
So we can treat T/F now as a constant power device.

## Transformer As a Control Circuit:-

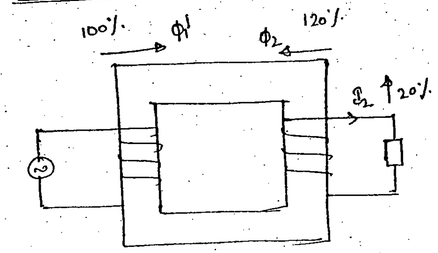
Case 1:- Let: Introduced load acting @ Secondary.




If $\phi_1'$ & $\phi_2$ Equal & opposite. Then 100% of load flux nullified So 100% power transferred.



Case II:-




Now let us suddenly load increase then $I_2$ ↑ 20%. So $\phi_2$ also 20%..

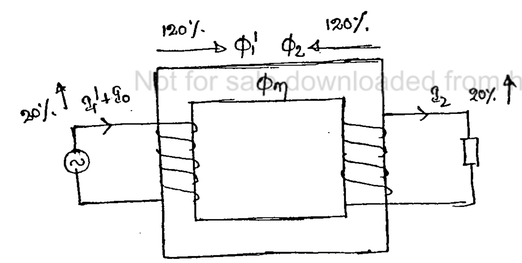
So Instantaneously;

$\phi_1' \neq \phi_2$.

$\because$ 100% ≠ 120%.

So Error opposition due to $\phi_2$ is 20%.

So that main flux reduced by 20%; now $E_1$ reduced so that V- Constant.



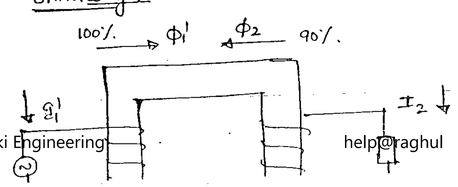

Error voltage generating $I_1'$. This $I_1'$ Creates additional primary mmf until $\phi_1' = \phi_2$.

One if $\phi_1' = \phi_2$ Control action completed or terminated.

So the increased A-T required by load satisfied by source then smoothly over load satisfied by source like a control action ~~will take~~ until the load component satisfied.

So this Entire action is ~~gon~~ performed until Error flux becomes zero. By this we can tell Transformer acting like a Control Circuit.

Similarly:- For sudden load reduction also;




As $I_2$ ↓ to 90%.

$\phi_2$ ↓ to 90%..

$\because \phi_1'$ 100% $\phi_m$ ↑

from primary to Secondary. With a Smooth Control action preventing until Error produced, becomes = zero (0)

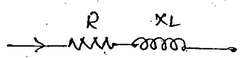
→ Under normal Conditions No Error Signals generated so no Control action Comes into picture.

So Transformer is acting like a Control Circuit with -ve feedback Circuit.

→ Now by Considering all these assumptions ; we shall draw Vector diagram.

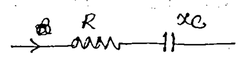
phase of $I_2$ with $V_2$. depends on nature of load Connected

if R-L load :-




$\phi_2 = \tan^{-1}\left(\frac{X_L}{R}\right)$ lag

if R-C. load :-




$\phi_2 = \tan^{-1}\left(\frac{X_C}{R}\right)$ lead.

for power transfer in Transformer

$I_1'$ must be 180° opposition to $I_2$.

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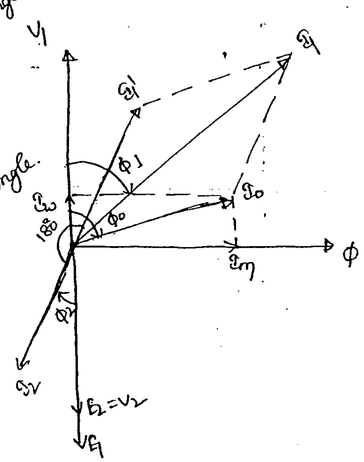
$\therefore \phi_1'$ 180° opposition to $\phi_2$.

$\phi_2$ : load power factor angle.
$\phi_0$ : No load power factor angle.
$\phi_1$ : primary load component power factor angle.



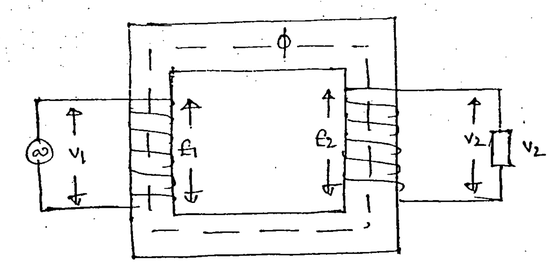



Normally load power factor specified; but we have to find power factor for No-load.

Assumptions in Ideal Transformer :-

③ Winding resistance of Ideal Transformer = zero.

Effect of 'R' on operation of Transformer.




$V_1 = -E_1$ $E_2 = V_2$

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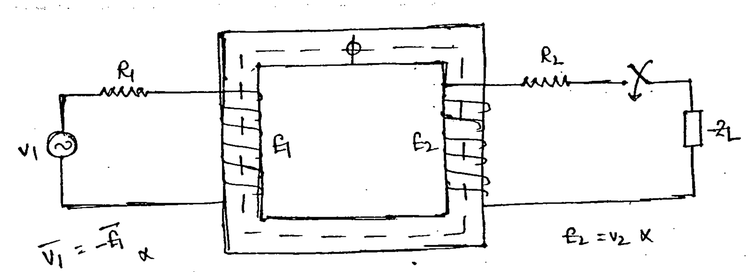
Resistance is not a Connected parameter. It is a distributed parameter. Instead of Considering as distributed parameter for Easy calculations better represent R as a lumped parameter.

Equivalent Circuit with Winding Resistance :-




Assume No load Current ~~neglected~~ neglected; $I_0 = 0$.

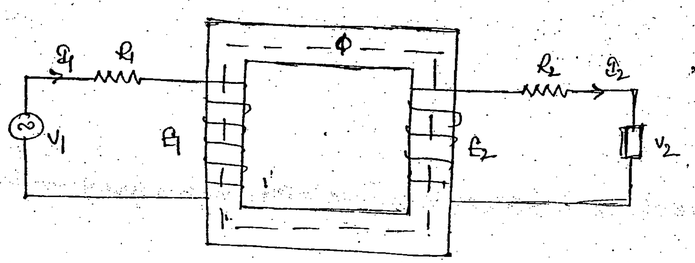
[∵ $I_0$ = 4 to 6 % of $I_F$]

R ~~becomes~~ Creates ② Consequences which are undesirable;

1. IR drop
2. $I^2R$ loss

The applied voltage component has ② component

1. Drop in winding
2. Inducing Emf to satisfy Lenz's law.




$\bar{V}_1 = -\bar{E}_1 + \bar{I}_1 R_1$ ↳ To satisfy Lenz's law

$\bar{E}_2 = \bar{V}_2 + \bar{I}_2 R_2$

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

∴ Modified voltage equations; $\bar{V}_1 = -\bar{E}_1 + \bar{I}_1 R_1$

$\bar{E}_2 = \bar{V}_2 + \bar{I}_2 R_2$.

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Instead of considering resistance both sides of Transformers to make calculations easy i.e., for worked out calculations on single side i.e., obtaining calculations from one circuit. Calculations only.

That means the process of transferring from one side to other is called Referee process. Here important thing is the transferee resistance should not effect operation, performance, calculations. For that transferring resistance must satisfy one condition.

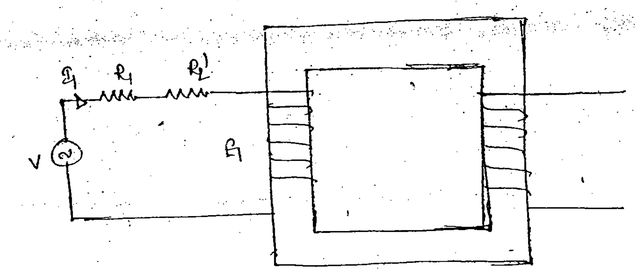
i.e Condition must be satisfied :-

Copper loss in the resistance must be maintained constant.



Cu. loss in resistance before transfer = Cu. loss in resistance after transfer.

Now I want to transfer secondary to primary :-




Secondary side loss $= I_2^2 R_2$.

primary side loss $= I_1^2 R_2'$

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

$R_2' = \frac{I_2^2}{I_1^2} R_2$

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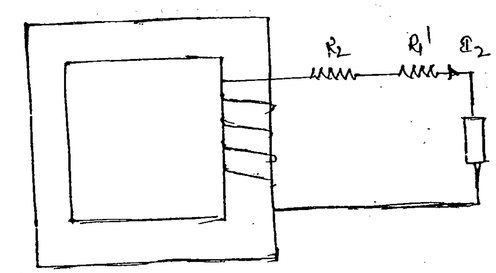
If Io neglected $\frac{I_1}{I_2} = k$.

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

Total Resistance referred to Secondary :-




loss before Transfer $= I_1^2 R_1$

loss after Transfer $= I_2^2 R_1'$

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

$R_1' = \frac{I_1^2}{I_2^2} R_1$

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

If Total resistance of Transformer referred to primary $R_{01} = R_1 + R_2'$

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

If Total resistance of Transformer referred to Secondary $R_{02} = R_2 + R_1'$

$$= R_2 + k^2 R_1.$$

Depending on ~~Equivalent~~ Convinient of calculations for you can Consider $R_{01}$ or $R_{02}$.

Total Copper loss refer to primary $= I_1^2 R_{01}$.

Total Copper loss refer to Secondary $= I_2^2 R_{02}$.

Both side of Total definitely equal;

$$I_1^2 R_{01} = I_2^2 R_{02}.$$

∵ Both Sides Cu. loss maintained as Constant Even transfer.

Unit for IR drop is voltg.

Generally ~~this~~ resistive drop Expressed with Corresponding base voltage known as per unit drop.

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Per unit primary resistance drop $= \frac{I_1 R_1}{E_1}$

% pu resistance drop on primary $= \frac{I_1 R_1}{E_1} \times 100$.

Per unit Secondary resistance drop $= \frac{I_2 R_2}{E_2}$.

% pu resistance drop on Secondary $= \frac{I_2 R_2}{E_2} \times 100$.

$E_1$ & $E_2$ Considered as base voltages. Since mentioned on name plate. which always Constant parameter for rated values.

Total primary resistance drop refer to primary $= \frac{I_1 R_{01}}{E}$.



Total Secondary resistance drop refer to Secondary ~~primary~~ $= \frac{I_1 R_{01}}{E_1} = \frac{I_2 R_{02}}{E_2}$.

Both Sides pu drops are Equal in Transformer.

$$\frac{I_1 R_{01}}{E_1} = \frac{I_2 R_{02}}{E_2}$$

$$\Rightarrow \frac{I_1 R_{01}}{E_1} \times \frac{I_1}{I_1} = \frac{I_2 R_{02}}{E_2} \times \frac{I_2}{I_2}$$

$$\Rightarrow \frac{I_1^2 R_{01}}{E_1 I_1} = \frac{I_2^2 R_{02}}{E_2 I_2}$$

Numerators Copper loss on both Sides are Equal in Transformer.

Denominators VA on both Sides are Equal in Transformer.

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→ If a Transformer pu resistance drop on primary = 2%. then Secondary pu resistance drop = 2%.

→ pu resistance drop & pu resistance of Transformer both are Sam.

i.e., If pu resistance drop of Transformer = 2%.

Then pu resistance of Transformer = 2%.

% Resistance of Transformer refer to primary $= \frac{I_1 R_{01}}{E_1} \times 100$.

% Resistance of Transformer refer to Secondary $= \frac{I_2 R_{02}}{E_2} \times 100$.

$$\frac{I_1 R_{01}}{E_1} = \frac{I_2 R_{02}}{E_2}.$$

This is the advantage with pu. i.e., if resistance Expressed in ohms while transfering we need multiplications.

But there is no calculations for transfer in Transfer when resistance Expressed in pu.

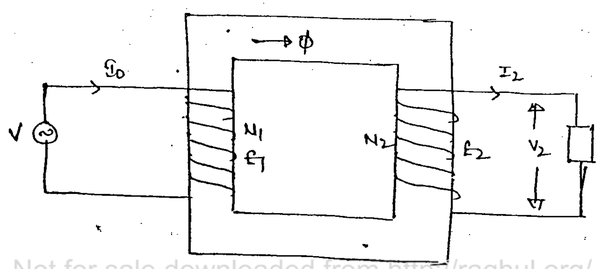
In actual practice for Easy calculation Transformer resistance

If produced flux for both winding same then Coefficient of Coupling $k=1$.

But in actual practice it's not happened. Before that we ~~want~~ must know :

- → Magnetic leakage flux ?
- → Origin of leakage flux ?
- → Difference between normal flux ($\phi$) & Magnetic $\phi_l$ ?
- → Effect of $\phi_l$ or behaviour of $\phi_l$ in operation of Transformer ?

For this we need to recollect load condition discussion.

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As load switch closed direction of $I_2$ find by Lenz's law.

Secondary load current produce flux opposed the main flux.
So that peak main flux reduced.
So $E_1$ reduced.
So $V_1$ pump additional current to primary.
So additional mmf @ primary $\phi_1'$.

∴ To transfer power from one circuit to other

$\phi_1'$ must $= \phi_2$

then voltampere are Equal.
Ampere turns are Equal.

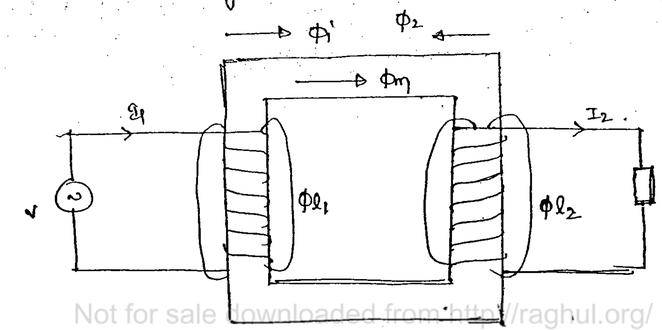


As control action terminated after complete satisfaction of load

Here small deviation :-

i.e., the secondary load component flux not entirely pass through core also; goes into air randomly.

Similarly some primary load component flux also goes into air randomly.

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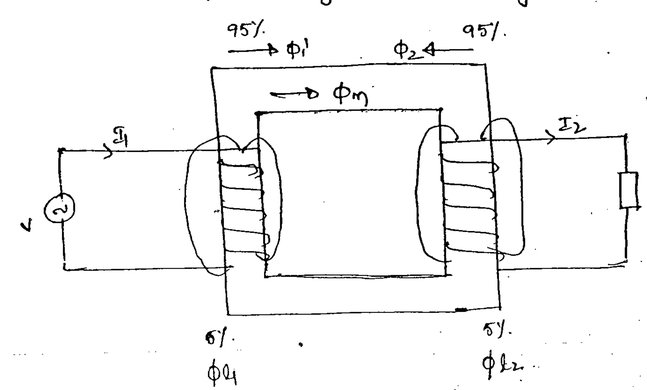
$\phi_{l_1}$ due to $\phi_1 + \phi_1'$.
$\phi_{l_2}$ due to $\phi_2$ only.

But we neglect leakage flux due to main flux

$\because \phi_1' >> \phi$.

i.e., $\phi_{l_1}$ mainly due to $\phi_1'$
$\phi_{l_2}$ mainly due to $\phi_2$ only.



i.e., Load Current flux produced $\phi l_2 = 5\%$. When load Component flux in Core = 95%.

Similarly $\phi l_1$ also = 5%.

So $\phi_1'$ nullifying $\phi_2$ @ 95% only. But 5% not going to nullify.

$\because$ $\phi l_1$ and $\phi l_2$ not interacting.

→ Means 95% VA only transfered from one side to other side.

Magnetic leakage flux is part of the load Component flux which links HV winding or LV winding but not both winding links.

This leakage flux not having its hand in transferring the power from one circuit to other.

i.e., primary leakage flux cutting primary only.

Secondary leakage flux cutting Secondary only.

As magnetic leakage flux increasing amount of power transfer will reduce. That means magnetic leakage flux is a undesirable consequence.

$\because$ As minimum as leakage flux we can transfer much the power from one circuit to other circuit.

<u>Difference Between Common $\phi$ and $\phi_l$</u> :-

(1) whenever $I_2 \uparrow$ $\phi_2 \uparrow$ $\phi l_2 \uparrow$ $\because \phi l_2$ part of $\phi_2$.

as $I_2 \uparrow$ $I_1' \uparrow$ $\phi_1' \uparrow$ $\phi l_1 \uparrow$ $\because \phi l_1$ part of $\phi_1$.

That means leakage $\phi l$ not a constant as load current varies leakage flux varies.



But Main field flux @ Constant irrespective of load. (from No-load to Full-load).

(2) Under No-load Condition ; $I_2 = 0$ ; $\phi_2 = 0$.

$\therefore \phi l_2 = 0$.

But under no-load $\phi_m$ = Constant.

(3) $\phi_m \propto \frac{V_1}{f_1}$ $B_m \propto \frac{V_1}{f_1}$

Flux in the Core is voltage dependent one. ($\phi_m$ not varies with load changes).

Leakage flux is a Current dependent.

(4) Main field ($\phi_m$) is a Constant flux.

($\because$ under normal Condition 'V' Constant).

Leakage flux ($\phi l$) is a variable flux.

(5) As $I_2 - \phi_2$ inphase $- \phi l_2$ also inphase with $I_2$.

But $\phi l_1$ is part of $\phi$ If $\phi_1'$ as $I_0$ considered.

$\phi_1'$ due to $I_1'$

$\phi$ due to $I_{fl}$ or $I_0$ $\because I_{fl} > I_{ws}$.

$$\phi l < \begin{matrix} \phi_1' - I_1' \\ \phi_0 - I_{fl} \end{matrix} > I_1$$

$\therefore$ $\phi l_1$ in phase with $I_1$ Current.

$\therefore$ $\phi l_1$ not only due to $I_1'$ also due to $I_1$.



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## → Effect of Magnetic leakage Flux on Operation of Transformer :-

**Primary**

primary linking with $\phi$ & $\phi l_1$

**Secondary**

Secondary linking with $\phi$ & $\phi l_2$.

Common Flux.

$\phi l_1$ – Individual to primary only

$\phi$ – Induced – $E_1$

$\phi l_1$ – Induced – $E_{x1}$

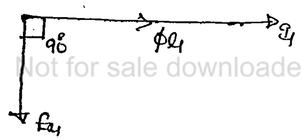
$E_{x1}$ lags $\phi l_1$ by $90°$ to satisfy lenz's law.

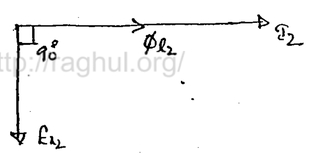
$\phi l_2$ – Individual to Secondary only.

$\phi$ – Induced – $E_2$.

$\phi l_2$ – Induced – $E_{x2}$.

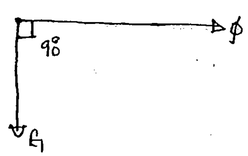
$E_{x2}$ lags the $\phi l_2$ by $90°$ to satisfy lenz's law.

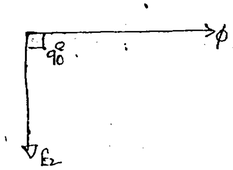



$E_1$ lags $\phi$ by $90°$ to satisfy lenz's law.

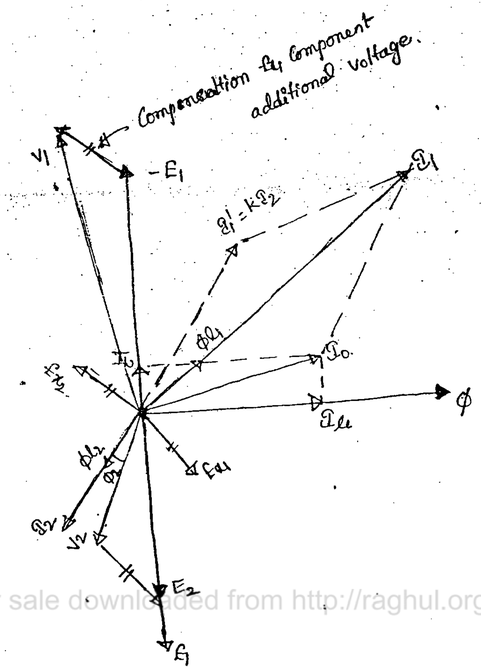
$E_2$ lags $\phi_2$ by $90°$ to satisfy lenz's law.




→ How to consider $E_{x1}$ & $E_{x2}$ into account for analysis of Transformer ?. This is possible only with considering Vector Diagram of Transformer.






Whenever Magnetic leakage $\phi l$ present $V_1 \neq -E_1$.
∵ $E_{x1}$ comes into picture

∴ $E_1$ only.

After connecting load, $I_2$ present.

previously we considered $E_2 = V_2$; but now $E_2 \neq V_2$ ∵ $E_{x2}$ comes into picture due to presence of $\phi l_2$.

So

phase of $I_2$ w.r.t. $V_2$ ; not $E_2$.

phase of $V_2$ depends on type of load for the sake of clarity takes lag load p.f.

Load p.f or Sec. power factor ; $\cos\phi_2 = \frac{R_L}{Z_L}$.

$\phi l_1$ in phase with $I_1$.

$\phi l_2$ in phase with $I_2$.



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or $\phi l_1$.

$\phi l_2$ induced $E_{x_2}$ in Secondary $E_{x_2}$ lags the $I_2$ or $\phi l_2$ by 90°.

Now question is that how to consider these $E_{x_1}$ and $E_{x_2}$ effect.

Instead of considering $E_{x_1}$ and $E_{x_2}$ i want to inject additional component to $V_1$ to compensate $E_{x_1}$ & $E_{x_2}$.

∵ $E_{x_1}$ and $E_{x_2}$ are not a useful emf. ∵ $E_{x_1}$ and $E_{x_2}$ not having any role in power transfer of Transformer. That's why i want compensate these emfs.

For that i am assuming;

If Normal case; $E_{x_1} = 20V$ ; $V_1 = 200V$.

Now increase; $V_1 = 200+20 = 220V$.

Now $V_1$ has two components → To get induced emf $-E_1$
→ To get compensate the emf $E_{x_1}$.

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So to have compensation of $E_{x_1}$. Imaginary component $E_{x_1}$ in $V_1$

$V_1$ must contain one component of voltage; that should be

(1) 180° out of phase with $E_{x_1}$,

(2) Same magnitude as $E_{x_1}$

Now draw the additional component to satisfy above two conditions

Similarly; Secondary side

$E_2$ – Source ; $V_2$ – Load.

Add additional voltage of $E_{x_2}$ component to nullify $E_{x_2}$. for that follow;

(1) 180° out of phase with $E_{x_2}$. And

(2) Same magnitude as $E_{x_2}$ conditions.

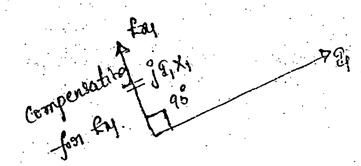


The drop in inductor is leads the current by 90°

capacitor drop is lags behind the current by 90°

How to represent this compensation component.

So in primary compensating emf; leads the $I_1$ exactly by 90°.




which will represent the same phenomenon in circuit parameters eg; Inductor.

∵ Reactive drop leads the current in reactor. So now assume a ficticious inductor present in primary. i.e $X_1$. (or) Imaginary inductor. (or) Hypothetical inductor.

$X_1$ } Primary leakage Reactance
$X_2$ } Secondary

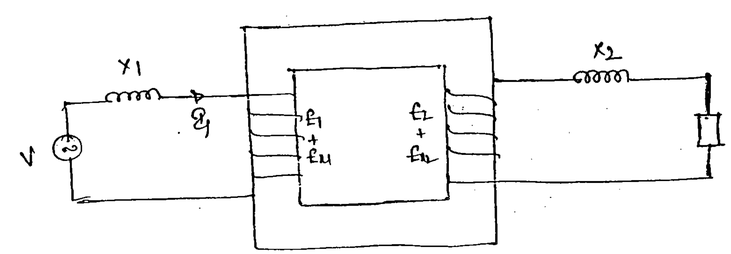
$jI_1X_1$ = leading.

$-jI_1X_1$ = lagging.

$|I_1X_1| = E_{x_1}$

$X_1 = \left|\frac{E_{x_1}}{I_1}\right|$ $X_1$: primary leakage Reactance.

That means once you connected $X_1$ reactor in primary its drop will compensate $E_{x_1}$.




To compensate $E_{x_1}$

Now primary side equations; $\overline{V_1} = -\overline{E_1} + j\overline{I_1}X_1$

Similarly; Secondary side equations; $\overline{E_2} = \overline{V_2} + j\overline{I_2}X_2$.

$x_2$ : Secondary Leakage Reactorg.

Both $x_1$ and $x_2$ are imaginary reactorg just to Compensate the induced Emfs in windings due to leakage flux.

$x_1$ drop due to Compensate $E_{x_1}$.

$x_2$ drop due to Compensate $E_{x_2}$.

In this case we got doubt. This $x_1$ is imaginary reactance. Now where is physical inductance of winding.

→ physical Inductance need not to Consider

∵ It is already present in

$E_1$ : Self Induced Emf.

$E_2$ : Mutual Induced Emf.

$V_1 = -E_1 + j I_1 x_1$ $\qquad$ $E_2 = V_2 + j I_2 x_2$.

$e_1 = -L_{self} \frac{di}{dt}$ $\qquad$ $e_2 = M \frac{di}{dt}$

So physical reactance on both sides need not to Seperately Considering.

∵ Already present in normal Emfs ∴

Now Emf Equations :

$$V_1 = -\bar{E}_1 + \bar{I}_1 R_1 + j \bar{I}_1 x_1$$
$$= -\bar{E}_1 + \bar{I}_1 (R + j x_1)$$
$$= -E_1 + I_1 Z_1.$$

$Z_1$ : primary Leakage Impedance of Transformer.

∵ physical reactance not consider only reactance Considering is imaginary that why assuming leakage Impedance.



$E_1 = -L_{self} \frac{di}{dt}$

$E_2 = -M \frac{di}{dt}$ } Physical Inductance of the winding Considering in $E_1$ & $E_2$.

$$E_2 = V_2 + I_2 R_2 + j I_2 x_2$$ → Intern used to Compensate $E_{x_2}$

$$= V_2 + I_2 (R_2 + j x_2)$$
$$= V_2 + I_2 Z_2.$$

$Z_2$ : Secondary leakage Impedance of Transformer. These are the final Emf Equations of Transformer.

* Similar to ~~reactances~~ Resistances, for Easy Calculations Leakage Reactance also we want to Consider at one side only.

for that Condition to be satisfied.

∵ Here no Cu.loss as resistance Case. That Condition we should not take.

→ But reactor can Cause only drop. Induced Emfs are the basis for drops. But here basis $E_1$ & $E_2$ different.

In Copper loss basis is power. There power on both sides of Transformer Constant. There no need to Consider power loss. loss as it is we can take

But here $E_1$ and $E_2$ are not Same. So per unit drops on both sides must be Constant.

while transfering per unit reactance drop must be Constant.

per unit reactance drop in reactance before Transfer = per unit reactance drop in Same reactor after transfer.

To obtain above Conditions we must know Reactance Drop. For this you just Consider only magnitude.

per unit primary reactance drop = $\frac{I_1 x_1}{}$



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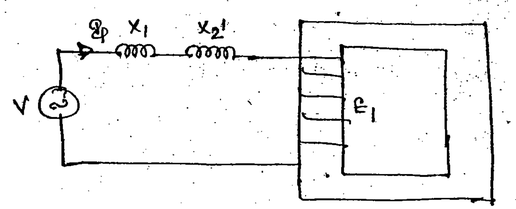
per unit secondary reactance drop $= \frac{I_2 X_2}{E_2}$

Now I want to transfer Secondary to primary.




According to Condition : $\frac{I_2 X_2}{E_2}$ must $= \frac{I_2' X_2'}{E_1}$

$$X_2' = X_2 \left(\frac{I_2}{I_p}\right)\left(\frac{E_1}{E_2}\right)$$

$$\boxed{X_2' = \frac{X_2}{K^2}}$$

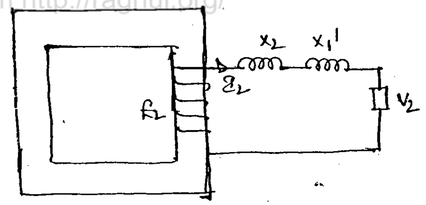
Here Conditions are different but ultimate result ~~with~~ we will get is same as resistance only.

Now primary to Secondary :

$$\frac{I_1 X_1}{E_1} = \frac{I_2 X_2'}{E_2}$$

$$X_1' = X_1 \left(\frac{I_1}{I_2}\right)\left(\frac{E_2}{E_1}\right)$$

$$\boxed{X_1' = K^2 X_1}$$




Entire reactance refer to primary $= X_{01} = X_1 + X_2'$

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

Entire reactance refer to Secondary $= X_{02} = X_2 + X_1'$

$$= X_2 + X_1 K^2$$

Total per unit reactance drop refer to primary

$$= \frac{I_1 X_{01}}{E_1}$$

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Total per unit reactance refer to Secondary $= \frac{I_2 X_{02}}{E_2}$

These per unit reactance refer to primary = per unit reactance drop refer to Secondary.

Both Equal. ~~∴ with~~ Since while transfering we ~~mat~~ maintain per unit drops on both sides same.

→ If % pu reactance drop primary side 5% ; The % pu reactance drop on Secondary = 5% only.

Similarly ; to resistance case.

% pu reactance drop on primary = pu reactance on primary.

% Reactance of Transformer refer to primary = % Reactance of Transformer refer to Secondary.

→ If % Reactance drop refer to primary : 3%
% Reactance drop refer to Secondary : 3% only.

This is the advantage with per unit ; no need of calculation for primary side and Secondary side while transfering.

Actual unit of reactance is Ohms.

But in practical Transformer per unit is most usefull tool for simplifying calculations.

$$\% Z = \sqrt{\% R^2 + \% X^2}$$

% impedence of Primary Side = % impedence of 2ndry Side

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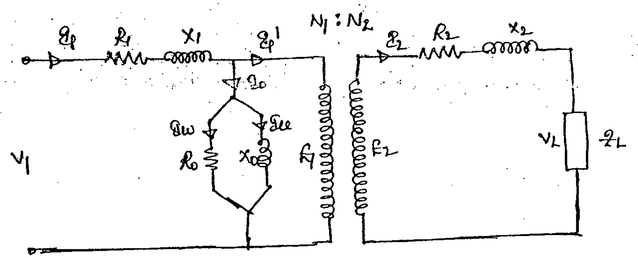
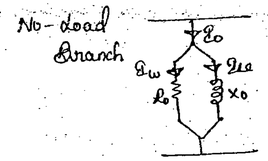
* Now by considering all the above (7) assumptions we shall draw Exact Equivalent Circuit of Transformer.

Even you want Consider 5th assumption; ~~we shall~~ we shall draw Exact Equivalent Circuit of Transformer also.

~~Even you want Consider~~

∵ 5th assumption will effect in Emf wave only. This is impor-tant for wave shapes as non-linearities considered, we shall discuss it @ 3-phase Transformer.




To Bypass $I_0$ without allowing transferable to load branch must be shunt branch.

Why No-load Branch after primary Impedance?

Voltage driven Branch so it should be shunt

Resistance is distributed. Iron loss obtaining after flowing current in primary resistance only. So after produce primary copper loss only Iron loss coming into picture.

During No-load to produce small leakage flux present @ primary only.

* Three conditions of Transformer; we can represent if the No-load branch shunted after primary impedance.

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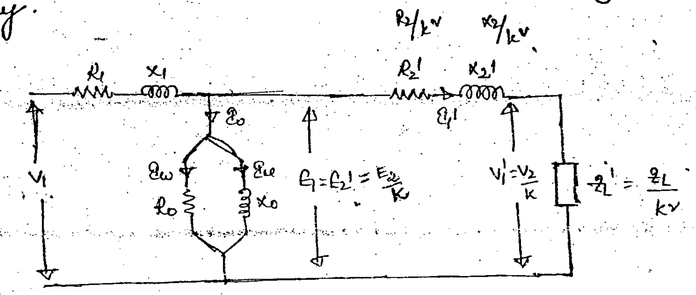
Equivalent Circuit of Transformer Refer to primary:-

It is usually better for considering Secondary @ primary only.




$E_2' = \frac{E_2}{k}$ ∵ $\frac{E_2}{E_1} = k \Rightarrow E_1 = \frac{E_2}{k}$

$E_1' = k E_2$ ∵ $\frac{E_1'}{E_2} = k$.

Equivalent Circuit of Transformer refer to Secondary:-

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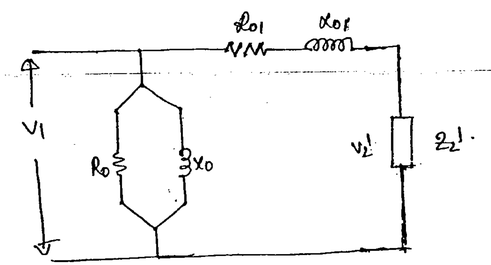
Until you consider some approximation @ No-load branch you can't transfer.

(1) Assumption: 1st approximation Equivalent Circuit.




used @ OC & SC Test.

Definitely some deviations come into picture from Exact Equivalent circuit.

Deviation in 1st Approximation:-

(1) Since No-load current allowed to primary impedance; No-load primary impedence drop $I_0 Z_1$ neglected.

(2) No [illegible] [illegible] [illegible] [illegible] [illegible]

Copper loss under estimated.

Since $I_0$ flowing through $R_1$ primary No-load Copper loss not considered; by this Copper losses are slightly underestimated.

$I_0^2 R_1$ Neglected.

(3) Leakage flux @ primary under No-load condition neglected. Since $I_0$ not flowing $X_0$; leakage flux under primary no-load compensations neglected.

$I_0^2 X_1$ neglected.

(4) For Simplification intentionally we transferred $E_1$ to $V_1$ but practically;

$|V_1| > |E_1|$

$\therefore I_0 \uparrow \quad I_\mu \uparrow \quad I_w \uparrow$

Hence No-load Current slightly over Estimated.

(5) Iron loss are more than actual value. Since Iron loss ~~Expressing~~ Experiencing more Current.

$\because |V_1| > |E_1|$

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In fact that underestimated Copper loss under no-load compensated or counted against by over Estimating the Iron losses.

Ex:- $W_0$ = 220 watts no-load power

② power → Iron loss $W_i$ = 200 W

→ Copper loss $I_0^2 R_1$ = 20 W.

Even all above assumptions deviation but these create very ~~little~~ little Error.

$\because$ practical $I_0$ 4 to 5% of $I_{FL}$.

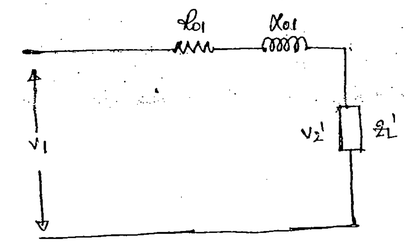
$W_0$ = $W_i$ = 220, $W_{cu(FL)}$ = '0'



So in all practical cases we can consider this as a 1st approximation circuit for calculations with very little Error.

* If you completely deleted $I_0$ you find 2nd approximation circuit.

2nd Approximation Equivalent Circuit:-




used @ voltage Regulation.

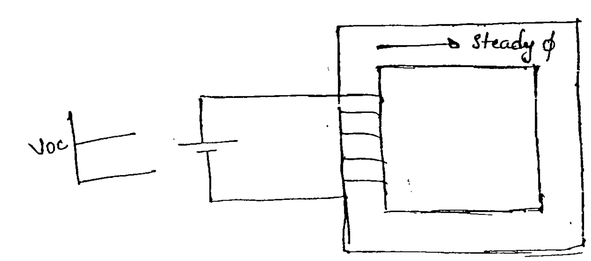
2nd approximation obtained.

Since $I_0$ very negligible. 2nd approximation deals ~~data~~ without the no-load Current.

— Depending on degree of ~~accuracy~~ Accuracy required or requirement we use any of the Equivalent Circuit of Transformer.

Imp. Before going to analysis of Transformer: I want to have discussion that general discussion on Transformer.

(a) Transformer Fitted with DC Source or Unit Step :-



power not transfered from one side to other.

∵ DC produces steady flux.

As Transformer static device, we required time varying Constant flux, for inducing Emfs.

→ ∵ DC produce steady flux; that flux linkages = 0.

Induced Emf = 0.

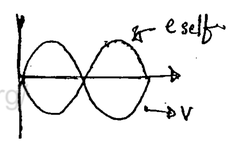
undesirable consequence due to DC Source.

* Even 6V, 12V DC Source connecting may burn total primary winding.

## Reason for Burning :-

* In AC Induced Emf (Self Induced Emf), and Applied Voltage always in phase opposition.

That means;

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If $V_1 = 200V$; $e_{self} = 195V$.

Derived

$I_0$ = Causing Voltage $V_1 - e_{self}$.

= 5V.

As self induced emf present always counter action to restrict $I_0$ current.

→ But in DC there is no counter action. only one thing i.e., resistance of the winding but it is very small.

$$\frac{\text{change in flux linkages}}{\text{change in Current}} = 0 \quad \text{So } L = 0$$

$$= 0 \quad \text{So } X_L = 0.$$



So $I_0$ may allowed large Currents.

↑ $I_a = \frac{V - (E_b)}{R_{a\,min}}$ $E_b = 0$ in DC Similar to Back Emf.

So this large amount of Current may burn the primary winding. ∵ $E_s = 0$ & $R_1$ = very low.

So never Energise Transformer Even with small voltage of DC.

→ If it is necessary or must and should operate Transformer with DC. You just connect DC across HV winding for a momentarily only. Not Continuous.

∵ HV winding Resistance > LV Winding Resistance.

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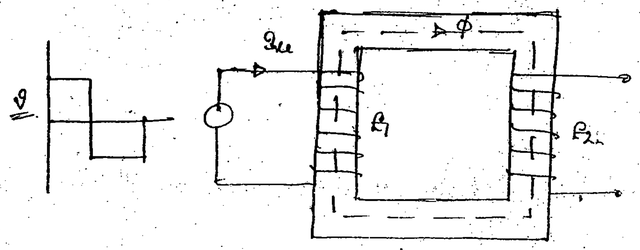
This situation generally arises i.e., operating with DC operation of Transformer. In polarity test, there we generally connected momentarily with HV winding only.

→ Operation of Transformer with signals other than sinusoidal

(1) Operation of Transformer with Square Wave Input :-




$Emf = -N.\frac{d\phi}{dt}$

$i_u = \int v(t)\,dt$

$i = \phi$

$\boxed{E = \frac{d\phi}{dt}}$

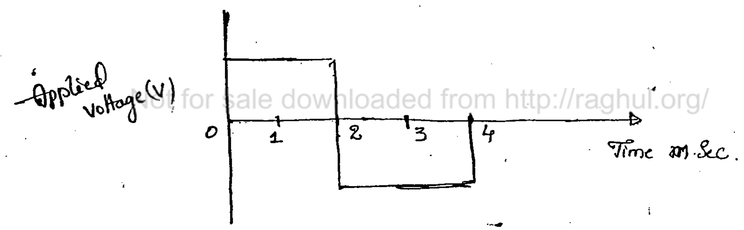
$v = L\frac{di}{dt}$

$\boxed{i = \int v}$

* Operation of Transformer is possible with Square wave.

∵ Alternating quantity input definitely Emf will be induce.

? But question is for given Square wave input what is the output Emf shape ?

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Shape of Emf depends on Shape of $\phi$ depends on Shape of $i_u$.

$E = \frac{d\phi}{dt}$

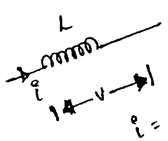
? How to get shape of $i_u$.

$v = L\frac{di}{dt}$

$\Rightarrow i = \frac{1}{L}\int v\,dt$

$i_u$ can be obtained by integrating applied voltage.

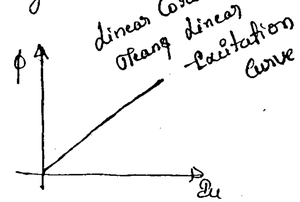
∵ Input feeding to Inducting Coil @ primary.




$i = \frac{1}{L}\int v\,dt$

Assume linear Core ;

Shape of $i_u$ & $\phi$ wave Same.






Shape of Emf obtained by differentiate '$\phi$' w.r.t negative (−) sign. to get induced Emf.

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

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

Shape of $i_u$

* Integrating Square wave give triangular output.

→ But the moment applied voltage given you can't get '$i$' or '$\phi$'.

∵ Delay in Sinusoidal V to $i$ 90° deg.

But in non Sinusoidal Signals time delay Expressed in time only not in degrees. This time delay depends on the Time Constant of winding here $L/R$.

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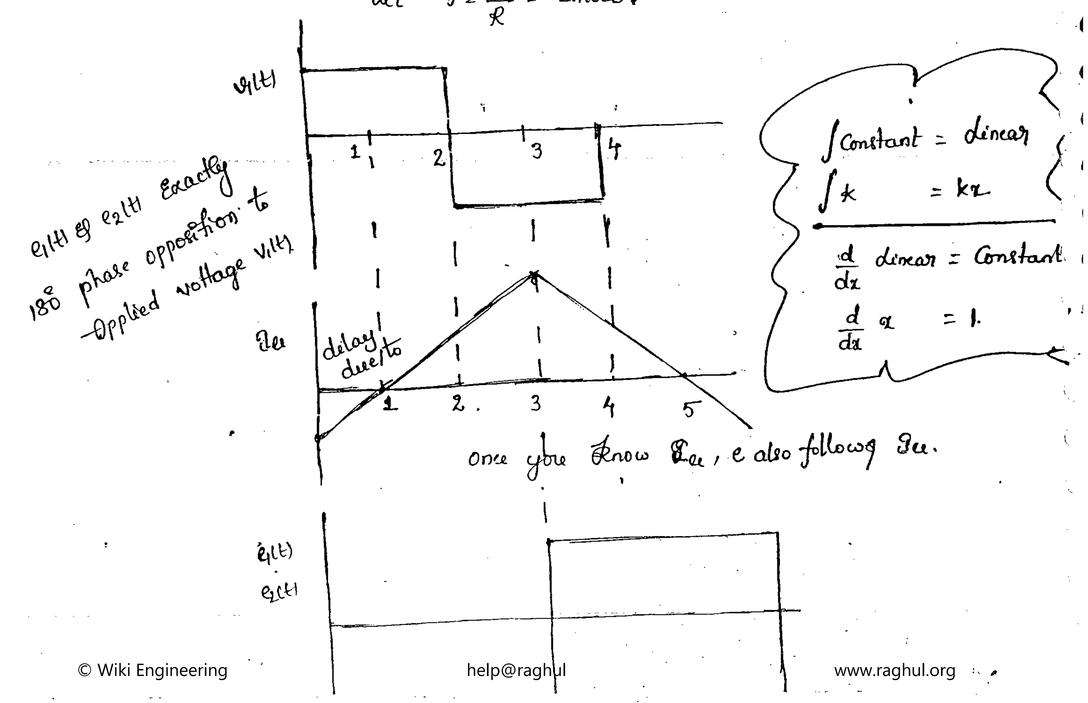
dt $T = \frac{L}{R}$ = 1mSec.




$\int$ Constant = linear

$\int k = kx$

$\frac{d}{dx}$ linear = Constant

$\frac{d}{dx}x = 1.$

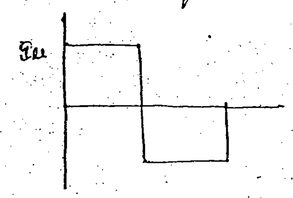
once you know $i_u$, e also following $i_u$.

$\frac{\text{Height}}{\text{Width}}$ ratio same — square wave.

$\frac{\text{Height}}{\text{Width}}$ ratio not same — Rectangular wave.

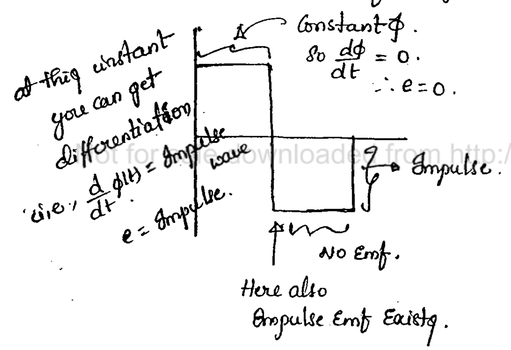
Shape of Emf induced is Square (or) Rectangular depends on Number of Turns.

* If Shape of $i_u$ is Square then Transformer Emf Shape ?



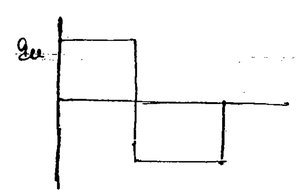

To get Emf wave differentiate flux wave; $i_u$ given $\phi$ also follow same.

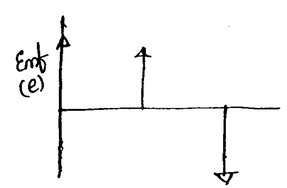
To obtain induced Emf differentiate $i_u$ wave.




$\frac{d}{dx}$ Constant = 0

$\frac{d}{dx}\ 1 = 0.$

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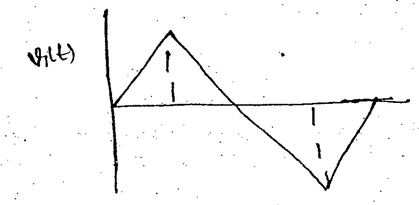
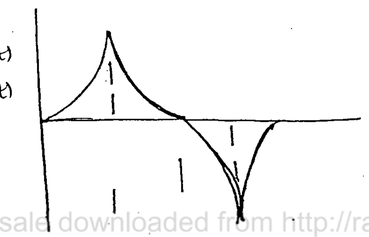
* Induced Emf due to applied voltage Triangular Input ?




$\int$ Triangular wave = you will get $x^2(t)$ Expression.
i.e parabolic waveform.

$\frac{d}{dt}$ Square = Impulse

$\frac{d}{dt}$ Triangular = Square

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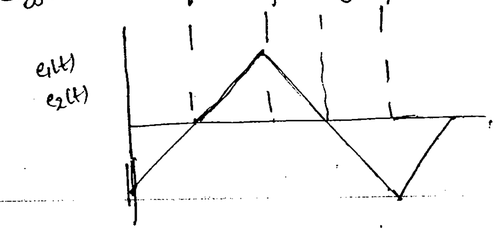
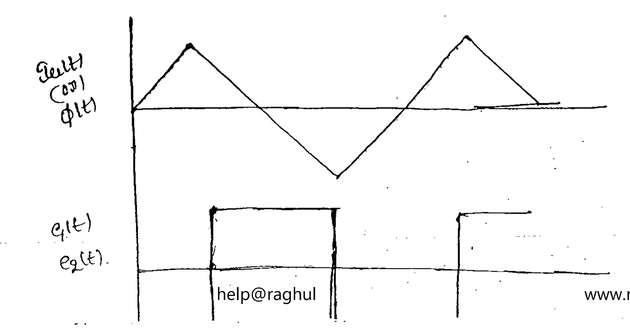
Differentiation of Impulse gives Induced Emf = Triangular wave



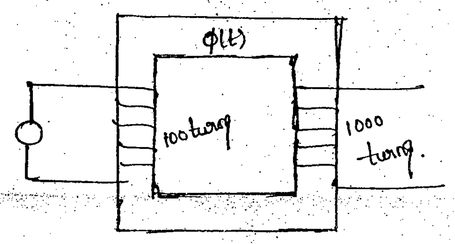

* If Input of $i_u$ = Triangular; $i_u$ Triangular then Shape of $\phi$ = Triangular.

$$\frac{d}{dt}(\phi) = \frac{d}{dt}(\text{Triangular}) = \text{Square wave}.$$

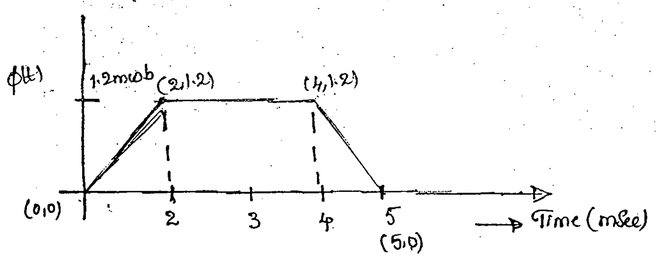


obtain dt

$\phi$ given $\Rightarrow \frac{d}{dt}(\phi) \Rightarrow$ Emf.




Shape of $\phi$ given;
Shape of $e_2 = ?$




$e_2(t) = -N_2 \cdot \frac{d}{dt}(\phi(t))$ $\qquad$ $e_2(t) = -N_2 \cdot \frac{d}{dt}(\phi(t))$

$0 < t < 2$ms. $\quad \phi(t) = \frac{1.2}{2} t = 0.6t$.

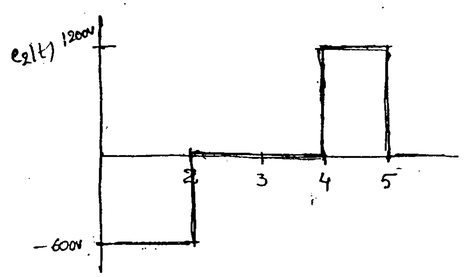
$2 < t < 4$ms. $\quad \phi(t) = 1.2$ mwb.

$4 < t < 5$ms. $\quad \phi(t) = \frac{(0-1.2)}{1} = -1.2t$.

$0 < t < 2$ msec $\Rightarrow e_2(t) = -1000 \times \frac{d}{dt}(\phi(t)) = -1000 \times 0.6 = -600$V.

$2 < t < 4$ msec $\Rightarrow e_2(t) = 0$.

$4 < t < 5$ msec $\Rightarrow e_2(t) = -1000 \times \frac{d}{dt}(\phi(t)) = -1000 \times -1.2 = +1200$ Volts.






## Various losses in Transformer :—

Takes place in

Major losses { Copper loss → Transformer winding
Iron loss → Transformer Core

Minor Losses (Small losses) { ① Imp — Stray load losses — In Copper & Core also (Parts, i.e. composite)
② — Dielectric losses — In Insulation parts of Transformer.

### 1. Copper loss :—

Total Copper loss in Transformer $= I_1^2 R_1 + I_2^2 R_2$.

these two are same only { Total Copper loss refer to primary $= I_1^2 R_{01}$.
Total Copper loss refer to Secondary $= I_2^2 R_{02}$.

* If $I_1$ is full load current of primary and $I_2$ is full load current of Secondary.

Then Corresponding Copper loss is full-load Copper loss.

? How to get $I_1$ full load current? ($I_{FL}$)

full load current on primary $(I_1)_{FL} = \frac{VA}{E_1}$ ( Mentioned on Name Pla

full load current on Secondary $(I_2)_{FL} = \frac{VA}{E_2}$ ( " )

* Copper loss $\propto$ (load current)$^2$.

As load current varies Copper loss varies. Copper loss are variable loss.

One if you know full-load Copper loss, full load current ($I_1$)

full load Copper loss $\Rightarrow I_1^2 R$.

½ full load Copper loss $\Rightarrow \left(\frac{I_1}{2}\right)^2 R$.

$\Rightarrow \frac{1}{4} I_1^2 R$ $\qquad$ full load Copper lo

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$= x^2 \times$ full load Copper loss.

per unit full load Copper loss $=$ $\frac{\text{full load Copper loss in watts}}{\text{VA rating of Transformer (or name plate given)}}$

One design Completed VA Rating Constant. But $I_1$ Variable. So $I_1^2 R_{01}$ Variable.

If VA rating choosen as base (∵ Mentioned on Name plate); Relation between per unit Copper loss and load Current.

per unit Copper loss $\propto I_1^2$ (Square of load Current)

One you know per unit full load Copper loss; then you can find different loading Copper loss.

per unit Copper at ½ Full-load = ¼ per unit Full-load Copper loss

*** pu 'x' load of full load Cu.loss $= x^2 \times$ pu full load Cu.loss.

If % Full load Cu.loss = 4%.

% ½ Full load Cu.loss = 1%.

% x of full load Cu.loss $= x^2 \times$ % of full load Cu.loss.

Total pu resistance drop refer to primary $= \frac{I_1 R_{01}}{V_1}$.

(or)

Total pu resistance ~~drop~~ refer to primary $= \frac{I_1 R_{01}}{V_1}$.

Multiply and Devide with $I_1$;

$$\frac{I_1 R_{01}}{V_1} \times \frac{I_1}{I_1} = \frac{I_1^2 R_{01}}{V_1 I_1} = \text{pu full-load Cu.loss.}$$

*** i.e., pu full-load Cu.loss = pu resistance drop of Transformer

Imp

(or)

pu resistance of Transformer.



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~~One~~ One you know % R of Transformer you can find Copper loss at any load.

% Full-load Cu.loss = % R of Transformer.

In actual practice for Easy Calculations instead of having Cu.loss in watts; we treat it as pu.loss.

Cu.loss variable loss.

∵ Cu.loss dependent on Current or loading.

(2) Iron loss :-

One flux present in Core (2) types of iron losses present. which are unvitable.

(a) Hysteresis loss

(b) Eddycurrent loss.

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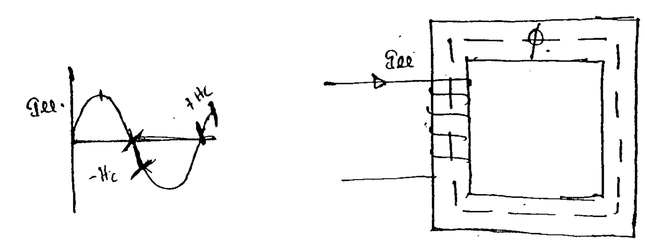
(a). Hysteresis loss :-

Due to reversal of magnetisation of Core; due to alternating flux presenting (or) flowing in Transformer Core.

If Steady $\phi$ present in Core no magnetic reversal.

So no hysteresis loss with DC Supply.

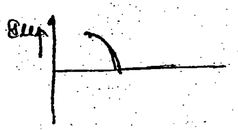
Magnetisation Reversal :-



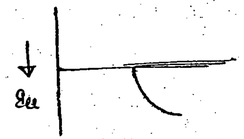

Fee — Alternation

Applying Alternating Magnetising Force.

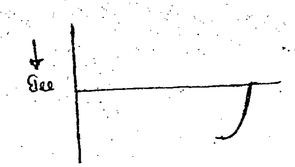
— Magnetising T/F Core.



— Same Transformer Core Subjected to Demagnetising.



— Magnetising Transformer Core in Reversal.



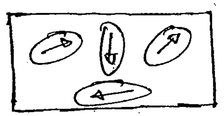
— Demagnetising Transformer Core in Reversal.

⊗ magnetic dipole is a flux carrier

electric dipole - is a charge carrier

Same Concept we discussed in magneto striction phenomenon.

i.e., Magnetic Domain at $B_m = 0$



unexcited state of Transformer Core.

No. $\phi$.; $\phi = 0$.

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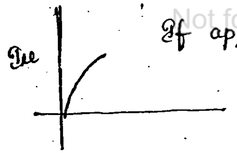
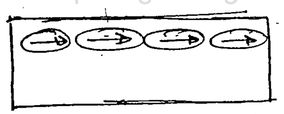


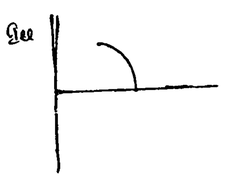
If apply $B_m$ +vely gradually



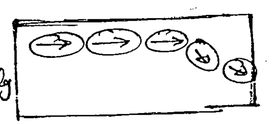
① Magneto Striction
② Saturation

If $B_m$ increase small; $B_m$ it aids domaing. Suppose $\phi$ reaching peak value due to $B_m$ maximum.

$\phi$ by one domain aids with other domain.



Now while decreasing $B_m$; domaing gradually leaves the string.



magnetizing Process Rate = Demagnetizing Process Rate then Hysteresis loss is zero



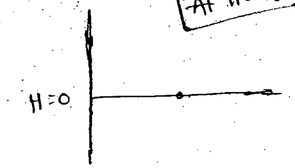
magnetizing rate > demagnetizing rate

③ Magnetic Inertia.

④ Retentivity → even $H = 0$ but $\phi \neq 0$ this flux is called Residual flux.

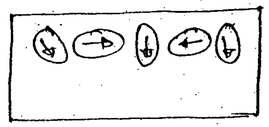
⑤ coerhisive force = to bring Residual flux to zero.

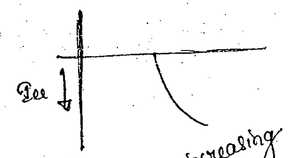
At $H = H_c$ only $\phi = 0$



$H = 0$

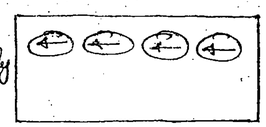
Domaing Completely Disturbed.

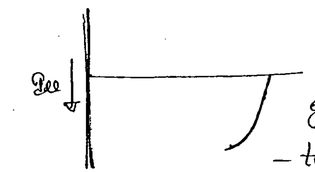




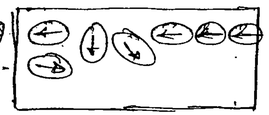
$H$ = -ve increasing

Now all domaing ~~producing~~ gradually takes reversal direction.





Now all domaing gradually demagnetising (or) getting free from string.



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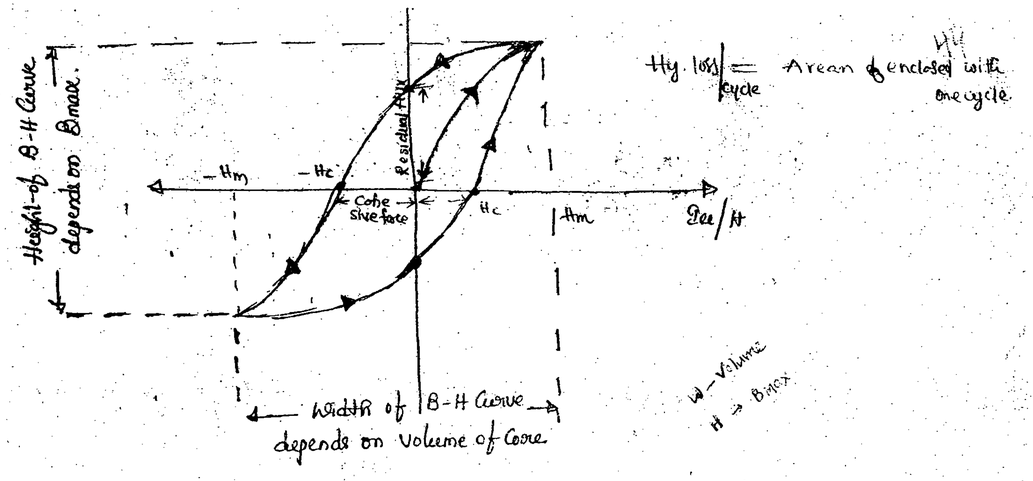
From above Transformer getting Magnetising and Demagnetising for Every ½ cycle. i.e for Every $\frac{1}{2}$ cycle the domaing have to change their (or) its orientation.

Domaing Can't reverse its orientation by its own. which requires some power. for Every half (½) cycle.

∴ The power required by domaing to change its Orientation. For Every ½ cycle known as hysteresis loss.

This hysteresis loss simply wasted in core for magnetic reversals. By magnetisation Curve; we can draw ($\phi$ vs $B_m$). The behaviour of magnetisation and Demagnetisation. as shown in fig.




Whenever some situation free domains or molecules completely absent. (i.e. all domains what ever present in core formed a storing to give its flux). Such situation is called <u>Magnetic Saturation.</u>

This saturation comes into picture at certain limits that if magnetising force is beyond the limits of core domains requirement.

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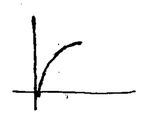
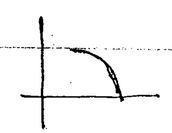
<u>Ex:-</u> If one lack domains present in core ; for given

(1) Apply Im until it reaches saturation.



(2) Now gradually reduce Im but demagnetisation process is slow compared with magnetisation.



Due to this a property of magnetism comes into picture ~~is~~ i.e., <u>Retentity</u>.

i.e., Even though excitation current reduced to '0' ; the rate of demagnetisation process is ~~called~~ slow. compared to the rate of magnetisation process.

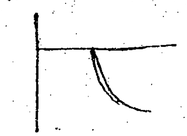


Due to this some of flux is retaining by core even though excitation current reduced to <u>zero (0)</u>:-

(∵ Since domains in core still in aiding process).

But if you want a complete demagnetisation i.e ($\phi = 0$) to bring this situation ~~is~~ u just apply :-

(3) The magnetising force is in reverse direction, at some −ve magnetising force, +ve magnetising flux ($\phi$) becomes zero.



The force required to bring the complete demagnetisation, (Even ($I_m = 0$)) to bring residual flux known as co-hersive force.

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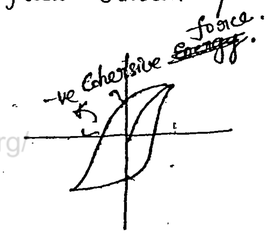
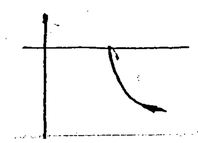
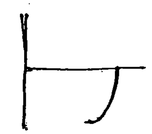
Corresponding property known as cohersive property.



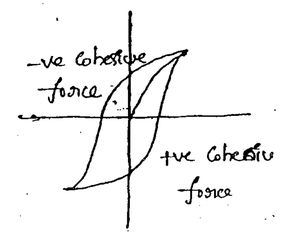

(4) For magnetising the core in −ve direction, the force to be applied must be more than the > cohersive force.



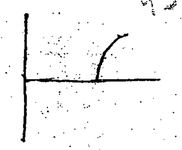
(5) Now core gets negatively magnetised completely upto −ve saturation. Now reduced the Im to demagnetising but the $\phi \neq 0$ even $I_m = 0$.



Now force required to bring retentity flux to complete demagnetise state is cohersive force but since here cohersive force is +ve half increasing. This force is also called as +ve cohesive force.

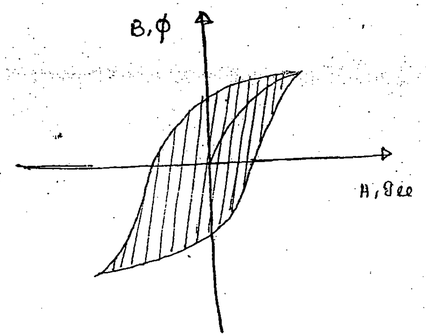


Saturation peak. which again continues from there.



? Why magnetising path and demagnetising path not coinciding ?

Due to Coherscivity, Retentivity } Two important properties any Magnetic Material.




Area under magnetising path & Demagnetising path gives the Hysteresis loss for one complete cycle of magnetic reversal.

Hysteresis loss per one magnetic cycle reversal = Area under one Hysteresis loop.

→ For 50 Hz supply total 50 Hysteresis loops will present. But those are superimposed ~~one~~ on one another.

Then Hysteresis loss due to 50 Hz supply = 50 x (Hysteresis loss of one loop)

∴ Hysteresis loss increases with increasing frequency.

→ For representing these Hysteresis loss an Empherical formula defined i.e.,

Steinmetz formula:

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

x : hysteresis Coefficient (Steinmetz Coefficient (1.5 to 2.5))  x = 1.6 for Silicon steel or CRGO steel.



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$\eta$ : Steinmetz Constant.

f : frequency of supply.

V : volume of core.

Volume more, hy. loss more.

* According to Steinmetz :-

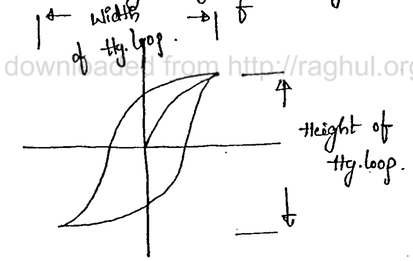
Area under one hysteresis loop

$$= \eta \cdot B_{max}^{x} \cdot V.$$

decides mostly by $B_{max}$ & V.

One design completed;

$B_{max}$ changed by $\frac{V}{f}$ change;

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* Width of Hysteresis loop Constant → If volume Constant.

if $B_{max}$ ↑ Height of Hy loop ↑

The area of Hysteresis loop ↑ ⇒ Hysteresis loss ↑.

Whenever volume more; it can store more residual flux so much Coehersive force required so Hysteresis loop Expands Horizontally. So in this case also Hysteresis loss increases (↑).

→ Depending factors
- Width of the loop — Volume.
- Height of loop — $B_{max}$.
- No. of loops — frequency.

more the Hysteresis losses.

During operation of Transformer :

operating @ Same voltage & frequency ; $B_{max} \propto \frac{V_1}{f}$.

Case 2 :- I want to reduce $V_1$ & $f$ to $1/2$ without changing $B_{max}$

i.e $\frac{V_1}{f}$ ratio Constant.

During operation ; $\frac{V_1}{f}$ Constant.

Area under one Hy. loop remains Constant.

Since $B_{max}$ Constant Even reduced voltage & reduced frequency.

$\because \frac{V_1}{f}$ ratio maintained Constant.

* But ~~area~~ Even area of Hy. loop maintained Constant. Hysteresis loss now depends on frequency only.

No. of Hysteresis loop $\propto$ frequency.

$W_h \propto f$.

$\boxed{W_h = Af}$ if $\frac{V}{f}$ maintained Constant only.

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Case II :- I want to reduce 'f' without changing 'V'., (or) double $V_1$, $1/2$ the 'f'

then $\frac{V_1}{f}$ ratio $\neq$ Constant.

$B_{max} \propto \frac{V_1}{f}$

Now $W_h \propto (\eta) \left(\frac{V_1}{f}\right)^{\alpha} \cdot f^{(\vartheta)}$

$W_h \propto V_1^{\alpha} \cdot f^{(1-\alpha)}$

During operation if $\frac{V}{f}$ ratio not Constant. ; then $W_h$ not only depends on the frequency also ~~def~~ depends on applied voltage.

If V/f ratio not Constant;

$\boxed{W_h = A \cdot V_1^{1.6} f^{-0.6}}$.



Problems like this :-

Ex: 240V; 60Hz Transformer $\rightarrow W_h = 100W$.

160V; 40Hz " $\rightarrow W_{h_{new}} = ?$

Sol: First check $\frac{V}{f}$ ratio Constant or not.

$\frac{V_1}{f_1} = \frac{240}{60} = 4$.

$\frac{V_2}{f_2} = \frac{160}{40} = 4$. ; problems belongs to Case ①.

$\frac{V}{f}$ ratio Constant, $B_{max}$ Const; $\phi$ Constant.

$W_h$ depends only on frequency;

At 60Hz $\rightarrow W_h = 100$ watts.

At 40Hz $\rightarrow W_{h_{new}} = ?$

$W_{h_{new}} = 100 \times \frac{40}{60} = 66.6$ watts

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Ex:- 240V; 60Hz, Transformer $\rightarrow W_h = 100$ watts.

160V; 30Hz, " $\rightarrow W_{h_{new}} = ?$

$\frac{V_1}{f_1} = \frac{240}{60} = 4$ ; $\frac{V_2}{f_2} = \frac{160}{30} = 5$.

$\frac{V}{f}$ ratio not Constant.

So problem belongs to Case ②. Cleary $W_h$ depends not only on frequency also depends on voltage.

$W_h \propto V_1^{1.6} \cdot f^{-0.6}$

$W_h \propto$ 160V; 30Hz $\Rightarrow 100 \times \left(\frac{160}{240}\right)^{1.6} \times \left(\frac{30}{60}\right)^{-0.6}$.

= _____ Ans.

→ you tell me by keeping applied voltage constant if frequency only reduced. what is Hysteresis loss ?

(a) Decrease (b) Increase (c) No. change.

going through the [illegible] case-II.

$\because \frac{V}{f} \neq$ Constant.

$\uparrow B_m \propto \frac{V}{f}\downarrow$ Height of loop increases.

from case (II) $w_h \propto V_1^{x} \cdot f^{1-x}$ $w_h \propto \frac{1}{f^{0.6}}$ if V Constant.

$\uparrow w_h \propto \frac{V_1^{1.6}}{f^{0.6}}\downarrow$ Constant so hysteresis loss $\uparrow$.

→ If frequency keep Constant applied voltage only reduced then Hy. loss is?

(a) Reduce (b) Increase (c) No change.

$\because \frac{V}{f} \neq$ Constant.

$\downarrow B_m \propto \frac{V}{f}\downarrow$ Height of loop reduces.

from case (II); $w_h \propto V_1^{x} \cdot f^{1-x}$.

$\downarrow w_h \propto \frac{V_1^{1.6}}{f^{0.6}}\downarrow$ (Constant)

$w_h \propto V_1^{1.6}$ if f Constant.

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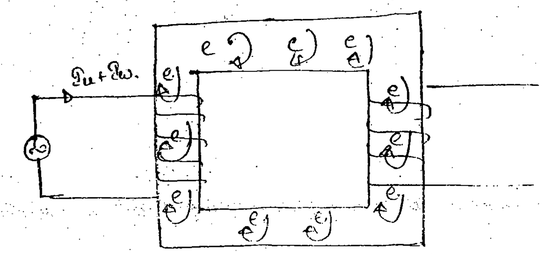
(2) Eddy Current losses in Transformer :-

Main reason behind Eddy Current loss due to Eddy Current present in ~~loop~~ Core; Eddy Current due to finite Conductivity of Core.

Due to finite Conductivity of Core by Faraday's law of Electromagnetic Induction some emf induces in Core; drives Circulating Current in Core.






Core even magnetic material; but some Conductivity there;

$\because$ Core base material – steel (Conductivity material also).

Core offers some resistance also; to, flow of these Circulating Currents or Eddy Current. These produces Eddy Current loss.

Eddy Current loss $= I_e^2 R_{ce}$.

If you consider Eddy Current loss;

$\left(\text{Eddy Current loss}\right) \propto \left(\text{Eddy Current}\right)^2 \propto \left(\text{Eddy Current Strength}\right)$

If Eddy Current strength is more; Eddy Current also more.

$I_e \propto \sigma$ of Core $\sigma$ : Conductivity.

$R_{ce}$ : Resistance offered by Core to Eddy Currents

$R_{ce} \propto \frac{1}{\sigma \text{ ~~cond~~ of Core}}$.

$W_e \propto \sigma^2 \times \frac{1}{\sigma}$

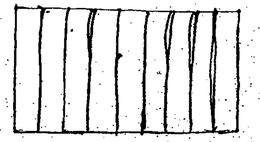
$\boxed{W_e \propto \sigma}$

→ Core Conductivity 1:1 ratio then Eddy Current loss = 1:1

If you reduced Conductivity of Core; you can reduce Eddy Current loss. For that purpose (2) methods to reduce $\sigma$.

(1) Add Silica to Core :- To reduce Conductivity without disturbing the magnetic properties but due to practical [illegible] Silica than allowable 1.4 to 5% Silicon

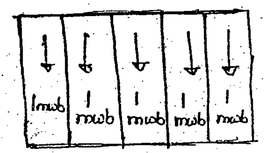
(2) Lamination Technique



Due to presence of insulation between each lamination, area offered to Eddy Currents reduced.

i.e., $\uparrow R_{ce} \propto \frac{1}{A_{ce}} \downarrow$

then $\sigma \downarrow$ $\quad \because R_{ce} \propto \frac{1}{\sigma}$




Flux taking parallel path.

Due to lamination Conductivity only reduced without disturbing total flux in Core.

Eddy Current loss ; $W_e = k \cdot B_{max}^{\nu} f^{\nu} t^{\nu}$

$$k = \frac{\pi^{\nu}}{6\rho} = \frac{\pi^{\nu}\sigma}{6}$$

$\rho$ = Resistivity of Core.

$f$ = frequency.

$t$ = thickness of lamination.

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$W_e \propto f^{\nu}$ ; if thickness of lamination reduced to $1/2$.

$W_e \propto (1/2)^{\nu}$ $\quad$ i.e., $W_e \propto \frac{1}{4}$.

Case-I. i.e., During design process :-

If you reduce lamination thickness. Eddy Current loss reduces so choose less thickness.

Case-II :- During Design stage :-

If you want increased frequency ($f$) operation. Then to maintain same Eddy Current loss, reduce the thickness.



$\because W_e \propto f^{\nu} t^{\nu}$

$W_e \propto (2f)^{\nu} \cdot (t/2)^{\nu}$ if $f$ doubled

$t$ must be $1/2$ed.

for Constant $W_e$ { More frequency — less thickness. → to maintain $W_e$ constant
less frequency — More thickness.

$W_e \propto t^{\nu}$

$W_e \propto f^{\nu}$

normally $f = 60\,Hz$; $t = 0.35\,mm$.

$f = 50\,Hz$; $t = 0.5\,mm$.

* Stacking factor $= \frac{A_n}{A_g}$ → More lamination (More thickness)

Stacking factor more if thickness of lamination more.

Stacking factor less if thickness of lamination less.

used in high frequency Transformer.

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* During Operation of Transformer (Design Completed) :-

$W_e = k \cdot B_{max}^{\nu} f^{\nu} \cdot t^{\nu}$

$B_{max} \propto \frac{V_1}{f}$.

→ Case-I :- If $\frac{V_1}{f}$ Constant. ⇒ $B_{max}$ also Constant.

then $W_e \propto f^{\nu}$ only.

If $\frac{V}{f}$ ratio Constant. Both $W_h$ & $W_e$ independent of $B_m$.

∴ Total Ironloss

$W_i = W_h + W_e$ $\quad$ @ $\frac{V}{f}$ = Constant.

$$\boxed{W_i = AF + BF^{\nu}}$$

* Case-II :- If V doubled ; $f$ Constant.

$\frac{V}{f} \neq$ Constant.

$B_m \neq$ Constant

$W_e \propto k \cdot (V_1)^{\nu} f^{\nu} \cdot t^{\nu}$

$W_e \propto V_1^2 \Rightarrow \boxed{W_e = B.V_1^2}$

In this case; if $\frac{V}{f} \neq$ Constant ; $B_{max} \neq$ Constant.

$W_i = W_h + W_e$.

$$\boxed{W_i = A.V_1^{1.6} f^{-0.6} + B.V_1^2}$$

→ At 60Hz → $W_i = 90W$.

At 40Hz → $W_i = 50W$.

If $B_{max}$ is Transformer Constant. What is at 50Hz → $W_i = ?$

Q At Constant $B_{max}$ ; $W_i = Af + Bf^2$

at 60Hz; $W_i = A(60) + B(60)^2$

at 40Hz; $W_i = A(40) + B(40)^2$

By Solving $A = 0.9$; $B = 0.01$

$W_i$ @ 50Hz Supply $= A(50) + B(50)^2$

$= 0.9(50) + 0.01(50)^2$

$= 70W$.

→ change in Eddy Current loss by keeping applied voltage Constant; frequency reduced; then;

(a) Increase (b) Reduce (c) No-change.

Q If $\frac{V}{f} \neq$ Constant.

$W_e \propto V_1^2$

∵ V Constant ; $W_e$ also Constant.

For constant voltage with variable frequency Eddy Current loss Constant.

Even you ↑f or ↓f as long as V Constant $W_e$ Constant



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The Eddy Current loss

(a) Increase (b) Reduce (c) No-change. 50

If $\frac{V}{f} \neq$ Constant

$W_e \propto V_1^2$

if $V_1 = \frac{V}{2}$ ; $W_e \propto \frac{1}{4} \cdot V$.

For constant frequency ; $W_h \propto V_1^{1.6}$ ($V_1^{0.4}$ Error)

$W_h \propto V_1^2$

If variable voltage

Iron losses ($W_i \propto V_1^2$) Approximately.

→ Flux in core dependent of ~~core~~ voltage ; independent of load current. ∵ $W_i$ iron loss dependent of ~~loss~~ Flux.

∵ $\phi$ constant irrespective of load.

Iron loss also constant.

Iron loss dependent on voltage and $\phi$ & frequency not on load current.

→ Iron loss — Voltage dependent loss — Constant loss.

Copper loss — Current dependent loss — variable loss.

~~For normal operating Conditions, Since voltage Constant;~~ Iron loss also Constant.

⇒ Per Unit Iron loss Representation :-

Iron losses can also be Expressed in per unit instead of watts; w.r.t. KVA rating of Transformer.

$$\text{per unit Iron loss} = \frac{\text{Iron loss in watts}}{\text{VA rating of Transformer}}$$

↳ Mentioned on Name Plate.



If VA rating of Transformer Base.

Numerator, Denominator both Constant. So per unit Iron loss always Constant.

→ per unit loss @ full load = 2% then per unit iron loss @ 1/2 Full load = 2% only.

But Copper loss $\propto I^2$ ; if pu Cu loss @ full load = 5%.

then pu Cu loss @ No-load = 0%.

Stray losses :-

Are 2 types : (1) Stray load losses taking place in metallic parts of Transformer.

(2) Dielectric losses : taking place in Insulating parts of Transformer.

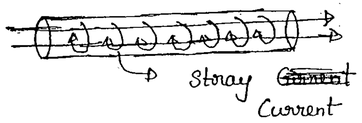
(1) Stray load losses :

(a) Copper Stray load losses

(b) Iron Stray load losses.

(a) Copper Stray load losses :

Due to solidness of Copper. If winding made with Copper with larger x-section. A part of current which circulated with in the Conductor known as Stray Current.

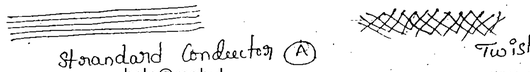



Due to 'R' offered to stray current by Solid Conductor these produce Copper power loss known as Stray load Copper loss.

* Elimination :-

Just like Transformer Core lamination Technique.

use




(1) To get Mechanical Strength



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of Strands by twisting to get same X - Section as previous. So that effective X - Section referred to circulating currents reduce and each strand laminated and coated enamelled.

This Technique also reduce Skin Effect.

* Dependency :-

This is part of load current only.

If load current absent — Stray currents '0'.

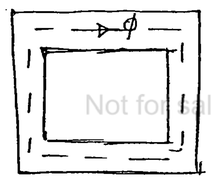
load current high — Stray current high.

So stray load copper loss high.

∴ Copper Stray load loss depending on $I_L$; so it is also "variable loss".

(b) Iron Stray load losses :-

Under no-load conditions (leakage flux almost $\phi_l = 0$).




Normal flux (or) Operating flux = Created Normal Iron loss.

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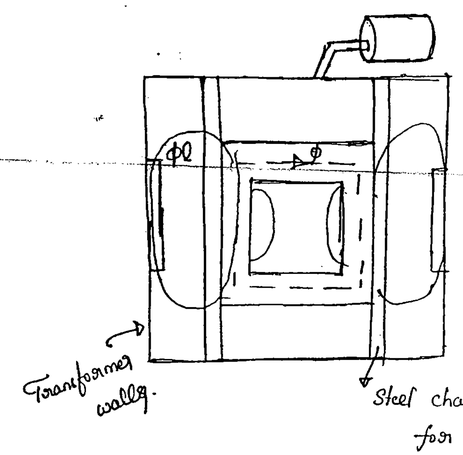


The additional iron loss takes place in auxiliary iron parts. Due to ~~leakage~~ flux linkage in them. Under loading condition.

Ex:- Iron Stray load loss @ Conservator tank, T/F wall steel channels.



Stray load iron loss only in auxiliary parts not in Transformer Core.

→ Elimination :-

Core type : Interleaving type winding.

Shell type : Sand which type winding.

→ Dependency :-

Main φ dependency — Normal Iron losses — ~~Current~~ Voltage dependent loss — Constant loss.

due to leakage φ only — Stray load Iron loss — Current dependent loss — variable with load — variable lo

⇒ Stray load loss = Copper Stray load loss + Iron Stray load loss

Stray load loss = 0.5% of total output.

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(2) Dielectric loss :-

Takes place in insulating material of Transformer.

Transformer Insulating Materials (1) Solid type Carrose Material (Cellulose)

(2) liquid type.

Solid type : Carrose Material eg. Cellulose materials. (Good HV Applications).

liquid type : Coolant + Insulation

If impurity present in insulating materials some loss present in Insulations i.e., Dielectric loss.

For Better understanding;

insulated thickness & impressed voltage.

Here $V_{impressed}$ = 11 − 3.3 = 7.7 kV. (voltage across insulating material) or Dielectric.

As insulation impressed voltage crosses certain limit. Some current comes into picture. This current different from conduction current. i.e polarised current.

| Conduction Current | polarised Current. |
|---|---|
| Close valanced electrons → So conduction current takes place. | No valacy electrons. So Displacement current takes place (charge transfer without actual movement) |

For better understanding polarised :-

Case-I:- Consider Non-polarised (or) voltage an impressed dielectric.

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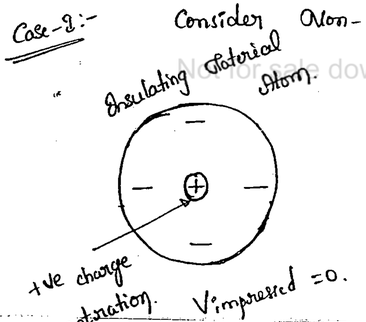
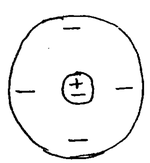



Electrons equally distributed @ symmetry around atom.

if $V_{impressed} = 0$.

Then electron concentration (or) electron center & atom center same.

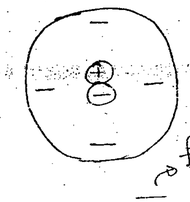


Case-II: If you increase impressed voltage more than breakdown current free electrons come into picture.



Break down current comes into picture if $V_{impressed} > V_{Break}$.

If Break Down voltage < Impressed voltage.



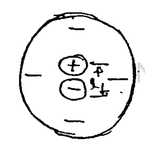

Outer most valance electron atom gets detached from parent atom, so symmetric of −ve net charge not maintained. As free electron comes into picture. Condection current starts Creates Dielectric loss.

Case-III: $V_B > V_{impressed}$ $(0 - V_{imp})$

Due to

Impressed voltage (<) Applied voltage.

$(0 - V_{imp})$ < Applied voltage (or)



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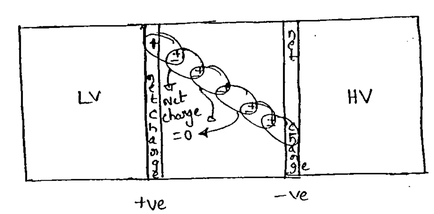
So net −ve charge point not coincides with net +ve charge without getting free electrons. This situation as Polarisation

The formation of two charge points with in atom is known as Electric Dipole.

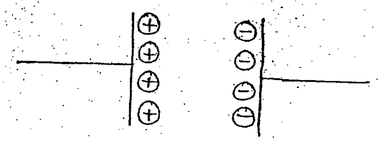


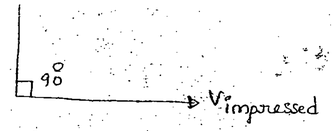

Now charge takes placed @ Ends of plates only.

Charge only transfering. Transfer of current is due to not by Condec simply by charge transfer. So that, this current is Displacement current.

(Just like Capacitor)

$I_d$ leads $V_{imp}$






Appropriate word of charging Current = Displacement Current.

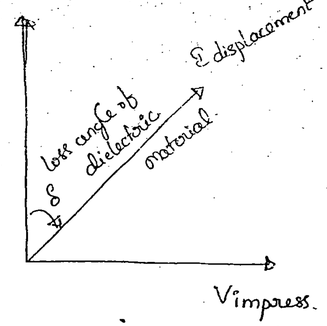
Here no power loss Component along $V_{imp}$.

So. Pure dielectric power loss = 0.

(2) Practical Dielectric Material :-

Quality or purity of dielectric material decided by loss angle of dielectric material ($\delta$).

pure dielectric $\delta = 0$.




Tan $\delta$ : Dissipation of dielectric.

Tan $\delta$ : within limits ; the healthy dielectric material.

Tan $\delta$ : More ; poor dielectric.

(poor healtyness of dielectric)

$$\text{Dielectric loss} = \left(V_{impressed} \text{ across Dielectric}\right)\left(\text{Horizontal Component in displacement Current}\right)$$

$$= V_{impressed} \times I_{displacement} \times \sin\delta.$$

$\therefore$ Dielectric loss $\propto \sin\delta$.

* Dependency :-

Dielectric loss depends on voltage Excited across winding

Dielectric loss independent of load Current.

under normal operating Conditions — Voltage Constant — Dielectric loss Constant — Constant loss.

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* Order :-

Dielectric loss is 0.25% of total output.

for approximate operation analysis of Transformer, these loss can be neglected.

All losses in Transformer devided into

| Constant loss | Variable loss |
|---|---|
| → voltage dependent loss | → Current dependent loss. |
| Iron loss (M.L) & Dielectric loss (m.l) | Copper loss (M.L) & Stray load loss (m.l) |

M.L = Major loss.

m.l = minor loss.

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Testing of Transformer :-

Upto now we observe Equivalent circuit;

Inorder to get Eq. circuit ~~par~~ parameters & various losses.

These tests are Conducted.

Commercially types of tests :

(1) Routine Test

(2) Type Test.

(3) Special Test.

→ Routine Test :- Compulsory Test.

If you want some Transformer; you need to place order for manufacturer, ~~Tf~~ will design Transformer as per our specifications.

One Transformer design : Manufacturer will (or) has

-|: Conduct Routine test.

or
Compulsory Test.

For this test Customer need not to tell manufacturer to Conduct test. No Standards for these Routine Test.

→ Type Test :-

We have to tell to manufacturer to Conduct this test. Manufacturer Conduct to this test. Only based on Consumer interest. During this type test Bewoc of Indian Standards must be accepted by our design Transformer.

If T/F not Comparing BIS rules manufacturer has to redesign and reproduce to Customer.

→ Special Test :-

This test not Conducted as routine. Its Conducted depends on Situation or requirements. These are not Conducted to all Transformers.

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These are Situational tests of Transformer.

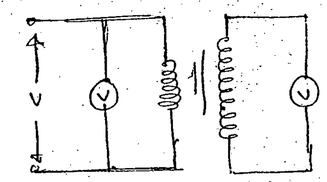
Ex:- ~~per~~ for Suppose : near by Communication line there. Then interference test Conducted to know that how much distance away placed between Communication lines & Transformer so that interference ~~avoided~~. avoided.

→ (1) Routine Test :-

↳ Polarity Test :- After design of Transformer to find dotted & undotted terminals of Transformer. It is a simple routine test.

↳ Voltage Ratio Test :- After design of Transformer to measure and to mention the no-load voltages on both sides of Transformer. to mention on name plate details.



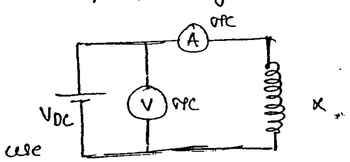



↳ Winding Resistance Measurement Test :-

Order of winding resistance is very low.

* DC Ammeter – voltmeter method should not be used as like some other Electric machines Similarly.

$R_{dc} = \frac{V_{dc}}{I_{dc}}$ => $R_{ac} = 1.6 R_{dc}$




This procedure should not use in Transformer. Since Counter portion of V = 0. ∴ $R_s = 0$.

* Normally Kelvins double bridge method used. Most accurate measurement of finding unknown resistance.

↳ Insulation Resistance Measurement Test :-

Normally Insulation resistance inorder of MΩ.

For such high resistance best instrument is Meggar.

↳ phasor Identification :- (only for 3-phase).

In 1-φ ; Input and output 180° displacement.

But in 3-φ; it may be +30° or −30° or any other.

To know this displacement of output. This test Conducted in 3-φ.

↳ O.C. Test :-

To know shunt branches of Transformer eq. ckt.

Transformer need not be satisfied standards.

↳ S.C. Test :-

(2) TYPE TESTS:

(a) Sumpners Test (Back to Back Test) :-

Main objective is to measure temperature rise of Transformer. Transformer has to be with in temp. standard limits. If designed Transformer temperature not in limits (or) not satisfactory. BIS rules means Consumer wont ~~time~~ accept.

So that manufacturer will redesign and reproduce the transformer.

(b) Tan δ Test :-

Conducted both on solid and liquid insulating materials. to know the dissipation factor. If Tan δ more than BIS. standards consumer wont accept.

(c) Noise level Test :-

During operation of Transformer noise measured in Db. If noise is more interference with Communication lines also.

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132/33 kV Transformer noise 60 Db.

So noise ~~level~~ level must be with in BIS.

(d). Impulse Voltage With Stand Test :-

During transient periods means (Switching transients, lightening transient). Consumer may ask that whether Transformer able to withstanding transients or not. Transients mentioned in peak values. Transformer must satisfied the BIS dependd on its rating.



(3) Special Test :-

Not Conducted on Routine depending on Situation.

↳ Harmonic Analyser Test :-

Some times the output wave is pure Sinusoidal or not.

If pure Sinusoidal — Harmonic Component = 0.

If Non-Sinusoidal — Harmonic Exist.

So 5th Harmonic
3rd Harmonic
7th Harmonic
⋮

Voltages Concentration
~~% S we have to~~

↳ Interference Test :- Interference with Communications lines near by Transformer.

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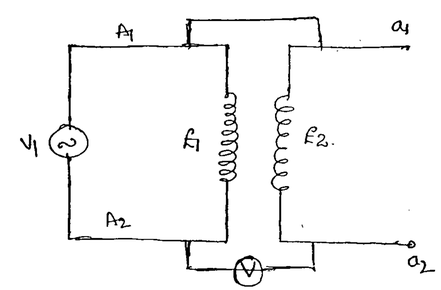
Some Important Routine Tests :-

Main objective is to find polarities of Transform after design.

Method - I :-




Connect @ one End LV - HV in Series.

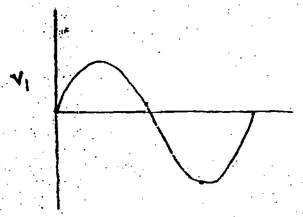
Connect @ other End Voltmeter of rating $\left[\begin{matrix} LV + HV \\ V \quad V \end{matrix}\right]$

Coupled ckt ② Connections

Two windings $\phi$ aids so (V) voltmeter reads both the induced Emfs ($E_1 + E_2$) in meter.

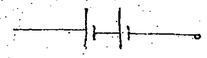
**Series opposive polarity :-**

Diff of voltages presents in voltmeter indicates.

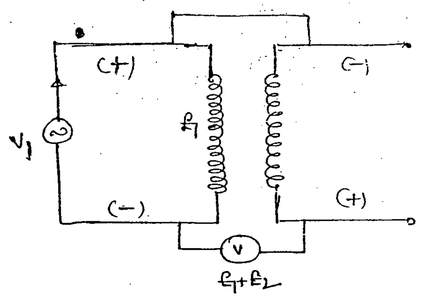



As in AC polarities; Continously change; Consider in AC only at one instant of time.

$V = E_1 + E_2$



**Case-I :-**




Assume one polarity of Source side at ① instant. If (V) reads $E_1 + E_2$ reading; then assign Secondary side Series aiding ~~polarities~~ polarity.

then (V) = $E_1 + E_2$.

Assign • opposite polarities to Secondary.

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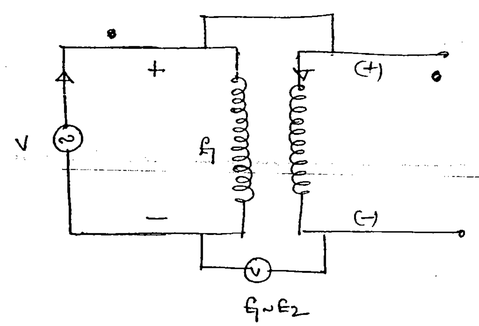
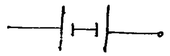
**Case-II :-**




$V_1 = E_1 - E_2$.



If (V) reads the $E_1 + E_2$ then assign Same polarities of primary to Secondary. Assign • @ Same polarities.



Main drawback of polarity test is not appr. suitable for HV Transformers.

**Ex:-** (1) 200/400V Transformer:

Voltmeter range (200+400) = 600V (No-problem).

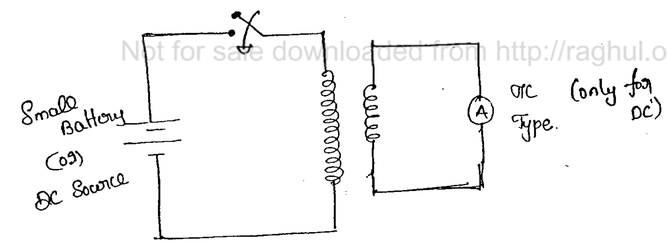
(2) 3.3/11 kV Transformer;

Voltmeter range (3.3+ 11kV) = 14.3kV (voltmeter not available).

So we have to conduct other test (practically using) to know polarities.

**DC Kick Test :-**

Advantage: On Any (LV or HV) T/F you can conduct.




OR (Both for AC & DC)

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* In this Excited HV with DC Source (or) by small battery at momentarily.

That to DC must be @ HV only.
Since LV winding has very low resistance. Possibility of winding burning.

* place MC type Ammeter @ LV terminals. Finds unidirectional ~~Current~~ Current.

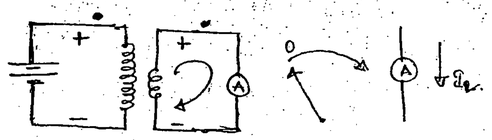
* At the moment of DC applied just observe Ammeter getting Forward kick (or) Backward kick.

At the moment Switch closed applied Current [illegible] changes in Core w.r.t. time

Any changing Φ flux is cuts the conductor, e.m.f induced in windings.

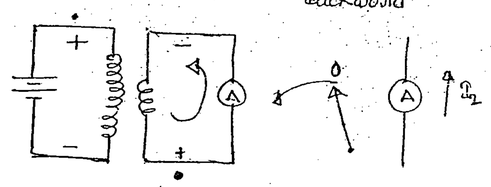
$E_2$ produce $I_2$ in Ammeter.

* For Ex:- If first kick you observe;



Direction of Current, Assign same polarity of HV to LV.

For Ex:- If reverse kick you observed; (or) Backword



Direction of Current. Assign opposite polarities of HV to LV.

* Now assign dots @ same polarities.

→ Routine Test :-

Open Circuit Test on Transformer :-

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Objective :- 1. To find shunt branches of Eq. circuit of Transformer. ($R_0$ & $X_0$)

(2). To find out constant losses in the Transformer. (or) voltage dependent losses / Iron losses.

(3) To seperate Iron losses. ⇒ Eddy Current loss and Hysteresis loss.

* Whenever losses depending on voltage only means no-need to develop load Current. So that rated voltage Enough to apply.

* Keep one winding open; & Excite other winding with rated voltage & frequency.

$\because B_m \propto \frac{V}{f}$.

In OC Test $\left(\frac{V}{f}\right)$ Constant.



* So flux density in OC test maintaining constant.. So they test conducted @ constant flux.

* Easy to conduct on LV Side

frequency both sides constant.

rated voltage
LV Side – less.
HV Side – more.

For Ex:- 11/132 kV Transformer

Main objective of OC Test : To get rated flux in the core.

132 kV @ HV
or
11 kV @ LV

Both cases you can obtain rated Φ only.

So it is Easy to apply 11kV.

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* In OC Test we have to measure no-load Current;

Generally no-load Current ; $I_0$ = 5% of $I_{FL}$.

To measure this $I_0$ it must be appreciable value.

other side we cant find exact value in meter.

As LV side high full load Current.

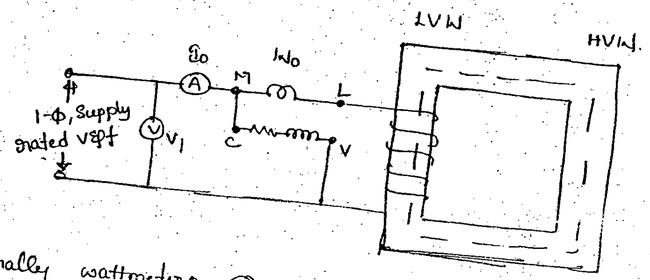
Ex:-

| | LV | HV |
|---|---|---|
| $I_{FL}$ | 100 Amp | 10 Amp |
| $I_0$ | 5 Amp | 0.5 Amp. |

(It is Easy to measure 5 Amp rather than 0.5 Amp)

So place Ammeter also @ LV Side only.

- Rated $\phi$ ( V/f constant) @ HV
- Low Applied voltage @ LV.
- Appreciable No-load current @ LV.




Normally wattmeters ② types (1) LPF
(2) UPF

In OC Test; Low power factor wattmeter used.

LPF wattmeter accurate @ $< 0.5$ p.f

UPF wattmeter accurate @ $\geq 0.5$ p.f.

No-load power factor of Transformer 0.2 lag like that for better accurate found with LPF wattmeter. only suitable.

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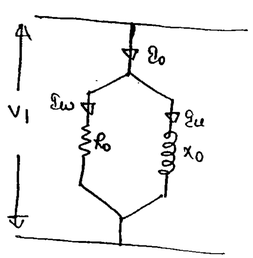
(1) keep HV open
(2) Excite LV with rated V & f.
(3) Note down all readings.
(a) $V_0$
(b) $I_0$
(c) $W_0$.

$R_0 = \frac{V_1}{I_w}$ ; $X_0 = \frac{V_1}{I_\mu}$

$I_w = I_0 \cos\phi_0$ , $I_\mu = I_0 \sin\phi_0$

(1) To find out $R_0$ & $X_0$ :-




$R_0 = \frac{V_1}{I_w}$ ; $X_0 = \frac{V_1}{I_\mu}$

$I_w = I_0 \cos\phi_0$ ; $I_\mu = I_0 \sin\phi_0$

Step 1:- $W_0$ : No-load power.

$W_0 = V_1 I_0 \sin\phi_0$

$\cos\phi_0 = \frac{W_0}{V_1 I_0}$

$\sin\phi_0 = \sqrt{1 - \cos\phi_0}$.



Now you can find $I_w$ & $I_\mu$. then you can find

2, To find out Constant losses :

As Secondary not loaded, the $W_0$ indicate no-load losses in Transformer.

No-load losses :- @ rated voltage → Iron losses in Core
↳ Dielectric losses in Insulation

@ No-load Current → No-load primary Copper loss ($I_0^2 R_1$)

No-load wattmeter Reading.

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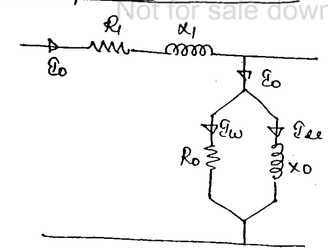
Exact Equivalent Circuit :-




Strictly Speaking

Constant losses $= W_0 - I_0^2 R_1$ (No-load primary Copper loss)

" $R_1$ " is primary winding resistance measured by Kelvin Double Bridge.

For Approximation : If minor losses (1) Dielectric losses & (2) No-load primary Copper loss are neglected, then wattmeter reading ($W_0$) - we can directly consider $W_0$ = Iron losses.

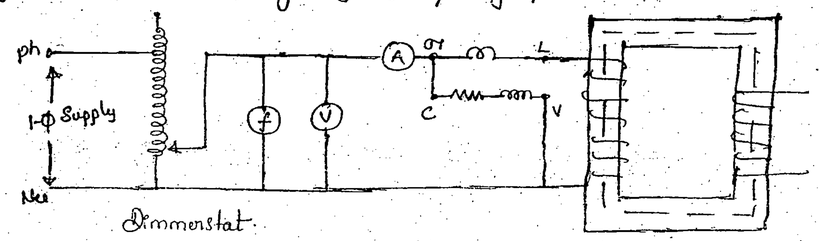
(3) To Seperate Iron loss into ( Eddy Current loss & Hysteresis loss) :-

Inorder to get seperation of Eddy Current loss & Hysteresis loss.

(2) By doing conducting test @ rated voltage & rated frequency.

Now, obtained ; $W_i$, $f$. i.e., rated Eddy loss & Hysteresis loss.

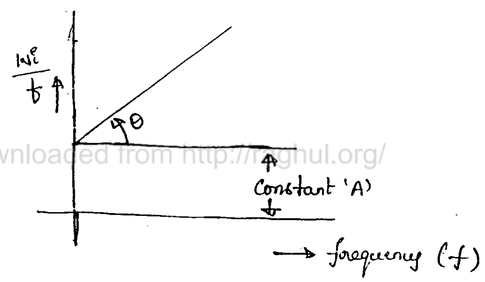
(2) To find @ reduced voltage & frequency place another meter




obtain $W$ & $f$ @ different and frequencies @ $\frac{V}{f}$ ratio constant

As $\frac{V}{f}$ ratio constant ⇒ $B_m$ constant.

| | $W_i$ | $f$ |
|---|---|---|
| $V_1, f_1$ | " | " |
| $V_2, f_2$ | " | " |
| $V_3, f_3$ | " | " |
| " " | " | " |




$\tan\theta$ = Slope of $\tan\theta$.

= Constant B.

$$W_i = Af + Bf^2.$$

$$\frac{W_i}{f} = A + Bf.$$

Once you ~~can~~ know A & B ; you can find $W_h$ & $W_e$ @ rated frequency

$W_h$ @ $f_{rated}$ = $A \cdot f_{rated}$.

$W_e$ @ $f_{rated}$ = $B \cdot f^2_{rated}$.

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Deviations :-

(1) If I conducted OC Test @ rated voltage & frequency < rated freq

What is change in $I_0$ ?

What is change in $\cos\phi_0$ ?

All possible deviations (a) ↑ $B_m \propto \frac{V_{rated}}{f}$ ↓ ①

∴ $B_{max} > B_{max,\,rated}$.

Since $B_m$ more than rated values conducted.

* Deep Saturation
* $I_0$ more.

(2) $I_{\mu}$ ↑.

(3) Iron loss ↑ $W_h \propto \frac{V_1^{1.6}}{f^{0.6}}$ ↓

$W_e \propto V_1^2$

No-change in Eddy Current loss. But Hysteresis loss increased

overall Iron Loss ↑ $W_i$ = ↑ $W_h$ + $W_e$.

Increase in Iron Loss takes place.

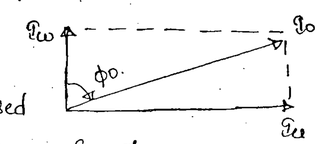
(4) As Iron loss increased to satisfy Transformer draw more iron loss component. $I_w$ ↑

(5) ∵ $I_{\mu}$ ↑ $I_w$ ↑ $I_0$ ↑ Since ↑ $I_0 = \sqrt{I_w^2 + I_{\mu}^2}$

(6) Ammeter reading more than actual.

(7) Wattmeter reading more than rated value.

(8) $\cos\phi_0$




If $I_w$ & $I_{\mu}$ increased in same proportion ; no-change in $\phi_0$.

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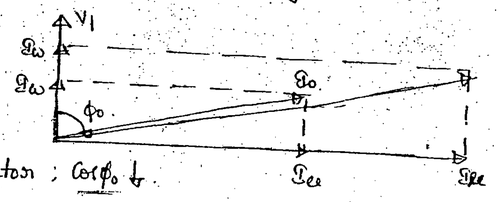
no proportion.

Since $I_{ee}$ increases shalply in deep saturation.

So..

$\phi_0 \uparrow$ ; $I_w$.

So no-load power factor ; $\cos\phi_0 \downarrow$.




## * Routine Test :-

### (2) Short Circuit Test :-

Objective :- (1) To find variable losses or load current dependent losses.

(2) To find series component parameters of equivalent circuit in ohmic values.

(3) To find %R, %X and %Z of Transformer in per unit values.

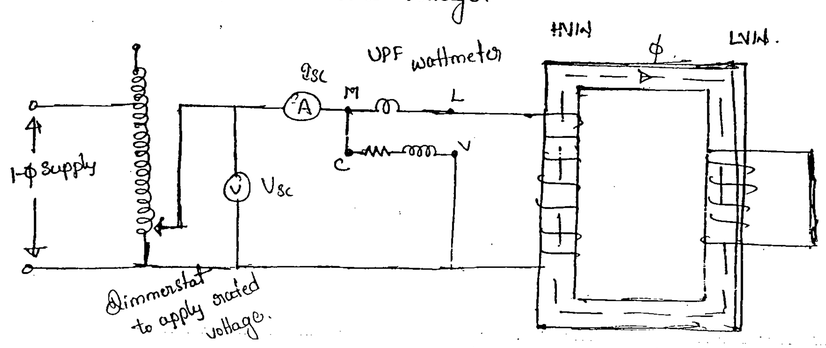
Since here we are measuring current dependent losses, so rated current must be subjected.

~~Conduct @ very low voltages to avoid Effect of~~

In SC Test only copper losses to be measured not Iron loss.

Without loading only we can obtain by short circuiting one side of Transformer.

Conduct this test @ HV Side. ∵ Since HV side rated current less and short circuit LV is low voltage.



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### Steady Short Circuit Current :-

It is the current that would flow @ short circuited terminals, due to applying rated voltage @ primary.

Steady Short Circuit Current = (10 – 15) times of rated current.

Dont conduct the SC Test @ rated voltage.

(1) Vary dimmerstat until rated current flows (or) rated short ckt current. (∵ not loaded really just due to short circuit).

(2) Note Down $V_{SC}$ ; Meter readings $I_{SC}$ ; $W_{SC}$.

### Rated Short Circuit Current :-

This is the amount of current that would flows during short circuit condition with reduced voltage.

Rated Short Circuit Current = Rated full load current.

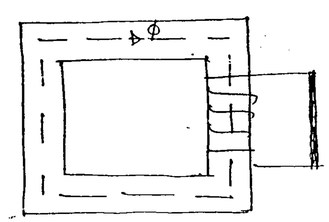
$V_{SC}$ : Reduced rated voltage required to apply to get rated short circuit current.

$I_{SC}$ : Rated short circuit current.

$W_{SC}$ : Power consumed under short circuited secondaries.

$I_{SC} = I_{SC}$.

$V_{SC}$ 5 to 8% of rated voltage enough to produce the rated short circuit current ($I_{SC}$).




∵ $V_2 = 0$ (short circuit)

power output = 0.

So $W_{SC}$ is totally wasted within Transformer.

(1) Rated load current (2) Full load copper loss (or) Rated load loss



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as $B_m \propto \frac{V\downarrow}{f}$ $B_m \downarrow$ (5 to 8% of 1.6 Tesla) So Small Iron loss.

Variable loss = $W_{sc}$ — (Iron loss @ $V_{sc}$)

If minor losses neglected;

$W_{sc}$ : Full load Copper loss



Objective :-

(2) To find out ohmic values of Series elements ; $R_{01}$ & $X_{01}$.

If Stray load & Iron losses neglected.

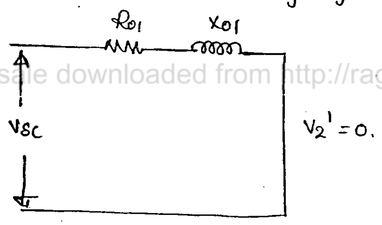
| $V_{sc}$ | $I_{sc}$ | $W_{sc}$ |
|---|---|---|
| | | |

$W_{sc}$ : Full load Copper loss

$W_{sc} \simeq I_{sc}^2 R_{01}$.

$R_{01} = \frac{W_{sc}}{I_{sc}^2}$ $I_{sc}$ we know from meter

To find out $X_{01}$ we should draw Equivalent circuit of SC Test from there $Z_{01}$ found. & found $X_{01}$ from $Z_{01}$.




$R_{01} = \frac{W_{sc}}{I_{sc}^2}$

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

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

$I_0$ = 5 to 6% of $I_{FL}$ in OC Test.

$I_0$ = Very Small of $I_{FL}$ in Short Circuit test.

almost $I_0 < 1\%$ of $I_{FL}$.

So neglect No-load branch;

From fig: $V_{sc} = I_{sc} R_{01} + j I_{sc} X_{01}$

$= I_{sc}(R_{01} + jX_{01})$

$= I_{sc} Z_{01}$.

$Z_{01}$ is Simply ~~refer to~~ Impedance referg to HV Side.

$Z_{01} = \frac{V_{sc}}{I_{sc}}$. Already we know $I_{sc}$ & $V_{sc}$ from Rating.



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∵ Already we know $R_{01}$;

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

By using Transformation Ratio we can Convert these ~~$R_{01}$ & $X_{01}$~~ $R_{01}$, $X_{01}$ & $Z_{01}$ i.e refer to LV Side.

Objective :- To find out %R, %X, %Z of Short Circuit data in per unit System

To findout %R :-

In per unit System %R and % Full load Copper loss both are Same

$\%R = \%\text{ Full load Copper loss} = \frac{\text{Full load Copper loss}}{\text{VA rating of Transformer}} \times 10$

VA rating given on name plate. Full load Copper loss taken as $W_{sc}$.

$\%R = \%\text{ Full-load Copper loss}$

$= \frac{W_{sc}}{\text{VA rating of Transformer}} \times 100.$

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Note:- You need to place voltmeter, Ammeter, wattmeter to findout ohmic value of (R.)

But wattmeter is Enough to findout %R (or) pu resistance.

To find out %X :-

$V_{sc} = I_{sc} Z_{01}$

$\left(\frac{V_{sc}}{E_1}\right) = \frac{I_{sc} \cdot Z_{01}}{E_1}$

Function of rated voltage required to get to produce rated SC Current.

$\frac{I_{sc} Z_{01}}{E_1}$ : Impedance drop @ SC Condition, as a function of rated voltage.

of Transformer

$$\frac{V_{sc}}{E_1} = \frac{I_{sc} Z_{01}}{E_1}$$



pu.Z = Function of rated voltage required to allow rated $I_{sc}$.

$$\% Z \text{ of Transformer} = \frac{V_{sc}}{E_{HV}} \times 100 \quad \begin{cases} V_{sc} - \text{from meter} \\ E_{HV} - \text{Mentioned on T/F.} \end{cases}$$

→ During short circuit (SC) test if 5% of rated voltage is enough to produce rated short circuit current then what is the % impedance of Transformer?

5% only ($\because$ % Impedance of Transformer = % rated voltage to produce rated SC. Current)

→ During SC Test 3% of rated voltage is enough to produce ½ the rated short circuit current, then what is the % impedance of Transformer.

$V_{sc} \propto I_{sc}$

3% to produce ½ rated $I_{sc}$.

6% to produce Full rated $I_{sc}$.

$$\frac{V_{sc1}}{V_{sc2}} = \frac{I_{sc1}}{I_{sc2}}$$

So 6% is the impedance of Transformer.

One you know % impedance of Transformer,

$$\% X \text{ of Transformer} = \sqrt{\% Z^2 - \% R^2}$$

* In %R, %X, & %Z values no need of ammeter, voltmeter & wattmeter is enough.

Objective :-

(4) power factor of Transformer under short circuit condition :-

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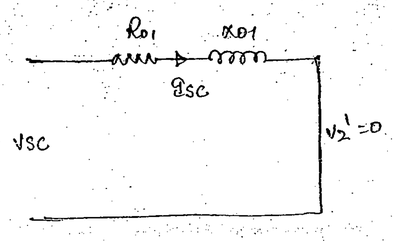
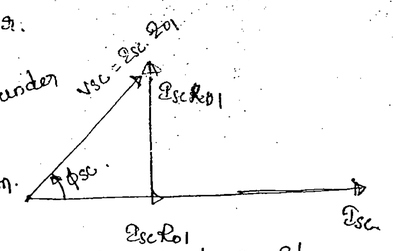



$$V_{sc} = I_{sc} R_{01} + j I_{sc} X_{01}$$

To find power factor, draw the vector diagram of Equivalent circuit

Take $I_{sc}$ : ref. vector.

voltage drop of Transformer under short circuit condition.




$\phi_{sc}$ : phase angle of Transformer under short circuit condition.

$\phi_{sc}$ : $\tan^{-1}\left(\frac{X_{01}}{R_{01}}\right)$ (Always lagging)

$$\cos\phi_{sc} = \frac{R_{01}}{Z_{01}} = \frac{\% R}{\% Z}$$

One you know % Resistance and % Impedance of Transformer you can find easily short circuit power factor.

practically short circuit power factor ⇒ 0.5 to 0.6

Thats way $\because \cos\phi_{sc} > 0.5$ practically.

we are using UPF wattmeter in SC Test.

Case :- Find out value of Steady Short Circuit Current in SC Test.

Theoretically only this we will calculate.

" The Short Circuit Current that flows in windings during rated voltage applied in Short Circuit Test".

$$\underset{(\text{Rated SC})}{I_{sc}} = \frac{V_{sc}}{Z_{01}\,(\Omega)}$$

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Short Circuit Current.

? But if Y.Z given; how to find out steady S.C. $I_{sc}$ ? 63

$$I_{sc\,(steady)} = \frac{E_1}{Z_{01}(\Omega)}$$ (Actually if $Z_{01}$ is ~~Ω~~ in ohm)

$$\frac{I_{sc\,(steady\ S.C)}}{I_{rated}} = \frac{E_1}{I_{(rated)}\,Z_{01}(\Omega)} = \frac{1}{\left(\frac{I_1 Z_{01}}{E_1}\right)}$$

$$\text{per unit steady short circuit current} = \frac{1}{\text{per unit 'Z'}}$$

(per unit S.C. current = Reciprocal of p.u. Impedance.)

Same applicable to power system also.

→ If in Transformer per unit impedance = 10%. then what is steady Short Circuit Current?

Sol: per unit steady ~~short~~ SC current $= \frac{1}{0.1\ pu}$

10% = 0.1 pu $= 10$.

Meaning 10 times of rated current.

If steady short circuit current in Amps;

pu steady SC current × $I_{rated}$.

→ 10 kVA, 400/200 V Transformer has Y.Z = 5%; then steady short circuit current in Amp = ?

Sol: pu steady SC current $= \frac{1}{pu\ Z} = \frac{1}{0.5} = 20\ pu$

$$I_{rated} = \frac{10\ kVA}{400} = 25\ Amp.$$

steady short circuit current = pu $I_{sc}$ steady × $I_{rated}$

$= 25 \times 20\ pu$

$= 500$ Amp.

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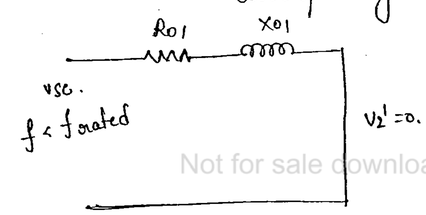
* Generally this finding $I_{sc}$ is given analysing, regarding; (steady short circuit current)

"During fault how much current might flowing in short circuit condition of Transformer."

* More the % impedance ⇒ less the $I_{sc}$ (steady SC).

## Deviations in Short Circuit Test:-

case – 1:- If frequency reduced and voltage impressed same; then corresponding deviations in SC test:

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Following are the consequences;

(a) As frequency varied $R_{01}$ (No change)

$X_{01}$ (Reduces)

$f\downarrow \quad X_{01}\downarrow \quad Z_{01}\downarrow$ in this case.

(b) $\uparrow I_{sc} = \frac{V_{sc}}{Z_{01}\downarrow}$ ⇒ constant

short circuit current more; then rated value.

(c) ↑ Copper loss $= \uparrow I_{sc}^2 R_{01}$

(d) As copper loss ↑ wattmeter, reading also more $W_{sc}\uparrow$.

(e) Effect on power factor

$$\uparrow \cos\phi_{sc} = \frac{R_{01}}{Z_{01}\downarrow}$$

Definite increase in short circuit power factor.

→ A short circuit test conduct @ 16V, 50 Hz → $I_{sc}$ = 30 Amp;

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To know $(\cos\phi_{sc})_{new}$ ; we must know

Keeping voltage constant ; if frequency (f) ↑

$X_{01}$ ↑ $Z_{01}$ ↑ $\because \downarrow \cos\phi_{sc}(new) = \frac{R_{01}}{Z_{01}}$ ↑

Definite reduction in new power factor.

16V, 50Hz ; $I_{sc} = 30$ Amp.

$\cos\phi_{sc} = 0.25$ lag.

$$Z_{sc} = \frac{V_{sc}}{I_{sc}} = \frac{16}{30} = 0.533\ \Omega.$$

$$\cos\phi_{sc} = \frac{R_{01}}{Z_{01}}$$

$$0.25 = \frac{R_{01}}{0.533} \Rightarrow R_{01} = 0.133\Omega.$$

This $R_{01}$ constant irrespective of frequency.

Then @ 50Hz ;

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

$$= \sqrt{0.533^2 - 0.133^2}$$

$$= 0.516\Omega$$

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@ 16V ; 75 Hz ;

$R_{01} = 0.133\ \Omega.$

$X_{01} \propto f.$

$$(X_{01})_{new} = (X_{01})_{old} \times \left(\frac{f_{new}}{f_{old}}\right)$$

$$= 0.516 \times \left(\frac{75}{50}\right) = 0.774 \text{ ohm}.$$

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

$$(Z_{01})_{new} = \sqrt{(0.133)^2 + (0.774)^2} = 0.785 \text{ (ohm)}$$

$$\cos\phi_{sc} = \frac{R_{01}}{(Z_{01})_{new}} = \frac{0.133}{0.785} = 0.169 \text{ lag}.$$

With this we completed : SC Test



→ **Rating of Transformer :-**

Generally specified with KVA or MVA rating.

KVA or MVA is Voltampere rating.
(or)
called as Apparant power.

* Apparant power is not actual power consumed ;

V-A × Cos φ = True power.

Why Transformer rating in KVA only ?

② reasons :-

①. Not only for Transformer for any Electrical Machine.

" Rating of any machine depends on temperature dissipation capability system".

Temp. dissipation capability depends on type of cooling system ; adopted.

Main reason for temp developing is mainly due to losses present in system.

For a given cooling systems rating of any machine defined by losses present in that machine.

If you have good cooling system ⇒ you can raise the rating of system.

In Transformer normally specified with ② rating

i.e., Generally for power system Transformer 10/16 MVA.

10/16 MVA means two ratings for same Transformer.

10 MVA : Due to natural cooling of Transformer.

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Applicable to any Electrical Dev

For a given Transformer; if cooling system improved.

rating of Transformer also improved ∴

For a given Cooling System; if loss is more; temperature rise of Transformer ~~raise of T~~ also more. So rating of Transformer decreased.

**Conclusion on Transformer:-**

For ex:- If i want to maintain forced air cooling to T/F. then losses present in Transformer.

| Constant losses | Variable losses |
|---|---|
| ⇓ are | ⇓ are |
| Voltage dependent losses | Current dependent losses |
| ⇓ are | ⇓ |
| power factor not required. | power factor not required. |

→ So ~~for~~ ~~both~~ both losses not depending on the power factor.

Rating depends on ⇒ Temp ⇒ depends on losses ⇒ depends on V-A only.

No. need of power factor.

Total losses of Transformer = (Volt × Ampere) only of Transformer

So 1st reason satisfying that any Electrical Machine depending on temp. raise, losses in machine only. In Transformer losses not depending on power factor. So 1st reason satisfying that

Rating of Transformer = Volt-Ampere rating only = Apparant power only.

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Reason ②. At what stage rating fixed?

Transformer rating fixed @ design stage itself by manufacturer.

During design manufacturer can't determine the power factor at which consumer might ~~the~~ operate the Transformer. So manufacturer can't assess type of load & type of power factor. At which Transformer going to operate, after design. Even ~~the~~ he can't assess some power factor.

Ex:- like 0.8 lag ∴ Transformer may operate.

@ 0.6 or 0.9

(or) 0.8 lead any load.

Manufacturer consider that at design stage only what is voltage rating required. & current rating required. So manufacturer design the Transformer with (Volt-Ampere) rating only. not depends on power factor.

That's way manufacturer declare that Transformer rating ~~can~~ on name plate in kVA (or) MVA only.

For ex:- 100 kVA Transformer designed.

Consumer ① operating @ upf ; 100kVA × 1 = 100kW.

" ② " @ 0.8 ; 100kVA × 0.8 = 80kW

" ③ " @ 0.8 ; 100kVA × 0.8 = 80kW.

So from above observation through out the Transformer operation MVA rating only maintained constant.

But Active power output of Transformer ~~varying~~ varying

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In fact power factor is operational parameter when we can't ~~loss~~ assess @ design stage.



for ex:- If kVA rating 100kVA given means it's referes to load side kVA., not refers ~~to~~ to source side.

∵ If you neglect $I_0$

$$\left(\text{kVA source } E_1 I_1 = \text{kVA load } E_2 I_2\right)$$

If you consider $I_0$

$$\left(\text{kVA source} = \text{kVA load}\right)$$

$$E_1 I_1' = E_2 I_2$$

Case. If you neglect really $I_0$ means;

$$\text{Input kVA} = \text{output kVA}$$

$$E_1 I_1 = E_2 I_2$$

that means Transformer of 100% $\eta$ ; which is practically impossible.

So always we are neglecting $I_0$ means, ~~but~~ that we are considering approximate only. With this rating of Transforme completed.

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## Performance Indexes of Transformer :-

These defines the Transformer performance once design completed, for that two parameters we have to found;

✓ Indexes ✓ Figure of merit.

(1) Efficiency

(2) Regulation.



## Efficiency :-

for any machine $\eta = \dfrac{\text{output power}}{\text{Input power}}$

To get Input power simply add losses to output power. No need to measure o/p and I/p power to find $\eta$.

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

In case of Transformer;

$$\eta = \frac{E_2 I_2 \cos\phi_2}{E_2 I_2 \cos\phi_2 + \underbrace{\text{Variable losses}}_{\text{obtained from SC Test}} + \underbrace{\text{Constant losses}}_{\text{obtained from OC Test}}}$$

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Variable losses → full load copper loss $\propto I_2^2$

→ Stray load losses $\propto I_2^2$

→ All the calculations must be on load side.

∵ output power = o/p kVA × load. p.f.

→ Actually stray load loss & load current not have a particular relation but simply for getting calculation easy we will take relation;

Stray load loss $\propto I^2$

also.

Now variable losses $= C I_2^2$.

Constant losses $= WC$.

$$\eta_{\text{full-load}} = \frac{E_2 I_2 \cos\phi_2}{E_2 I_2 \cos\phi_2 + x^2 (C I_2^2) + WC}.$$

In above case; we need to load the transformer to know

its predetermination process. with out loading the Transformer.

Under what Condition the Efficiency will be maximum ? 67

## Condition for Maximum Efficiency $\eta_{max}$ :-

It is a desirable thing;

Since without wasting much power VA transfered from primary to Secondary. i.e losses are minimum at the maximum Efficiency Condition.

(2) Variable in $\eta$ Equation;

(1) % loading

(2) power factor of loading.

Two different Conditions we can define for $\eta_{max}$.

(1) Variable $I_L$ & $\cos\phi_L$ kept Constant. Then $\eta_{max} = ?$

(2) Variable $\cos\phi_L$ & $I_L$ kept Constant; Then $\eta_{max} = ?$

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## Conditions :-

(1) change % loading 100% @ $\cos\phi_2$ Constant.
90%
80%
70%
⋮

Then $\left.\dfrac{d\eta}{dx I_2}\right|_{\phi_2 \text{ Constant}} = 0$.

(2) change load power factor 1.0 @ $I_2$ Constant.
0.9
0.8
0.7
⋮

then $\left.\dfrac{d\eta}{d\phi_2}\right|_{x I_2 = \text{Constant}} = 0$.



## Condition (1) :-

$$\left.\frac{d\eta}{dx I_2}\right|_{\phi_2 = \text{Constant}} = 0.$$

No - need to calculate just obtain from formula.

$$\eta_{x \text{ of F.L}} = \frac{1}{1 + \left(\dfrac{x^2(CI_2^2) + WC}{x(V_2 I_2)\cos\phi_2}\right)}$$

Must be minimum for $\eta_{max}$.

For a given output power $\eta$ will be maximum, only if the losses are minimum; otherwise

Constant loss = Variable loss.

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Condition for $\eta_{max}$; $x^2(CI_2^2) = WC$.

Variable loss = Constant loss

Variable loss → Major Copper loss; Minor Stray load loss (Neglect)

Constant loss → Major Iron loss; Minor Dielectric loss (neglect).

Approximately for $\eta_{max}$ Condition ⇒ Copper loss = Iron loss.

**Note:-** By varying load Current, you can obtain at one state Copper loss = Iron loss.

* Dont say Iron loss = Copper loss $x$
replace variable with Constant i.e ⇒ $x = 2$. ✓
don't replace Constant with variable i.e $2 = x$.
So always you must said of replace Copper loss = Iron loss ✓

always replace, copper losses with iron loss.

∵ In any Transformer we cant vary iron loss. but Copper loss vary upto any Extent.



for Ex:-

Full-Load; $W_c = 500W$
$W_i = 600W$ Total loss = ?

for $\eta_{max}$:

for Maximum $\eta$; Total loss $= W_i + W_c$
$= 500 + 500$ ✗

replace Copper loss with iron loss only; ∵ $W_i$ always Constant.

Then Total $\eta = W_i + W_c$
$= 600 + 600$ ✓
$= 1200$ ✓

→ $W_{cu}$ = Copper loss
$W_i$ = Iron loss
For max. $\eta$ ; ∴ Total losses $= 2\times(W_i)$

at any cost for max $\eta$ ; Total loss $= 2\times$ (Total Iron loss).

* Copper loss at any function of full-load;

i.e., $x^2$ (F.L Copper loss) = Iron loss.

fraction of load at which max $\eta$:

$x$ of full load; $\eta_{max} = \sqrt{\dfrac{\text{Iron loss}}{\text{F.L. Cu loss}}}$

* I want to design a Transformer which gives max $\eta$ @ full load:

Then we would design Transformer losses in such a way that

full load Copper loss ≅ Iron loss.

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* I want a Transformer whose $\eta$ must be maximum @ ½ full-load.

Then design Transformer;

If F.L. Copper loss = Iron loss ; $x = 1$

F.L. Copper loss = 4× Iron Loss ; $x = 1/2$.

* To get $\eta_{max}$ @ 70% of full-Load;

design Fullload Copper loss = Two times of Iron losses.

Full-Load Copper loss ≅ 2× Iron loss

$x = \sqrt{1/2} = 0.707$.

* By adjusting losses @ design ~~State~~ Stage. we can make Transformer $\eta$ maximum at any load condition, that we require.

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Secondary Current for max $\eta$:

$x^2(I_2^2 R_{02}) = W_i$ $I_{2m}$: Secondary Current @ $\eta_{max}$.

$x I_2 = I_{2m}$

$I_{2m}^2 R_{02} = W_i$

$$\boxed{I_{2m} = \sqrt{\frac{W_i}{R_{02}}}}$$

KVA rating for Max $\eta$:-

Simply multiply above Equation with $\frac{E_2}{1000}$.

$$\frac{E_2}{1000} I_{2m} = \frac{E_2}{1000}\sqrt{\frac{W_i}{R_{02}}}$$

$$\frac{E_2}{1000} I_{2m} = \frac{E_2}{1000} \times \frac{I_2}{I_2}\sqrt{\frac{W_i}{R_{02}}}$$

$$\boxed{\frac{E_2 I_{2m}}{1000} = \frac{E_2 I_2}{1000}\sqrt{\frac{W_i}{I_2^2 R_{02}}}}$$

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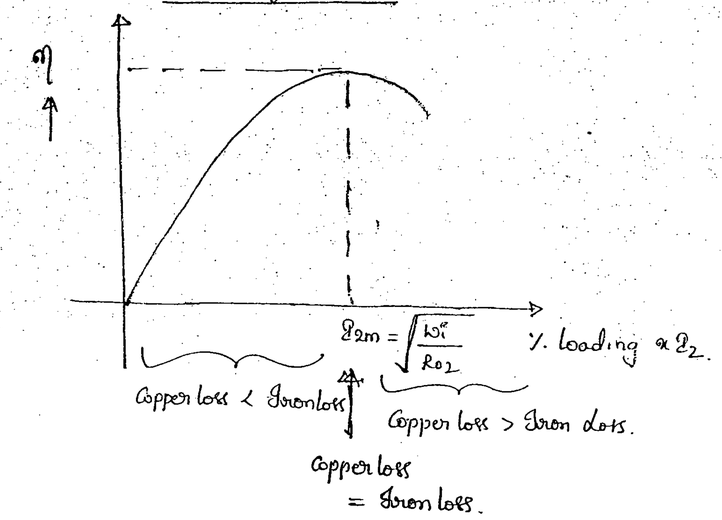
$$KVA\ @\ \eta_{max} = \text{Full load KVA} \times \sqrt{\frac{\text{Iron loss}}{\text{F.L. Copper loss}}}$$



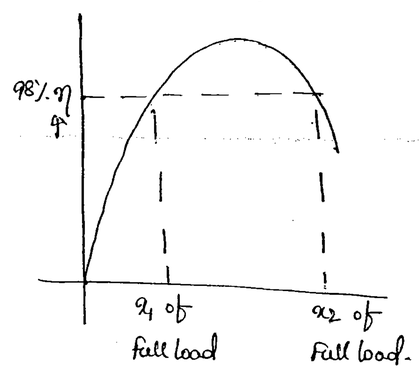
Efficiency varies with load current to observe this variations we must draw **Efficiency Curve:-**




Variation of η w.r.t % loading. By seeing η curve its not a single valid function.

Transformer η curve is a double valid function.

That means for given load power factor; Same 'η' can be obtained by @ two loading conditions.




→ A 20kVA Transformer has $\eta_{F.L}$ & $\eta_{1/2\ F.L}$ = 0.98 or 98% at up.f. what is the $\eta_{3/4\ F.L}$ = ? @ ~~up~~ upf.

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So $\eta_{1/2\ F.L} = \eta_{F.L}$ = 98% possible. ∵ Since curve double valid function.

$$\eta_{F.L}\ @\ upf = \frac{20kVA \times 1}{(20\times10^3 \times 1) + W_c + W_i} = 0.98.$$

$$W_c + W_i = 408\ watts \longrightarrow (1)$$

$$\eta_{F.L}\ @\ upf = \frac{(1/2)\ 20k \times 1}{(1/2 \times 20k \times 1) + (1/2)^2 W_c + W_i} = 0.98.$$

$$1/4\ W_c + W_i = 204\ watts \longrightarrow (2).$$

By solving equations (1) & (2)

$W_c$ = 272 watts.

$W_i$ = 136 watts.

$$\eta_{3/4\ F.L}\ @\ upf = \frac{(3/4)(20k) \times 1}{(3/4 \times 20k \times 1) + (3/4)^2 \times 272 + 136} = \underline{\underline{\ \%\ ?}}$$

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Condition (2) for Maximum η :-

change power factor w.r.t. $x I_2$ Constant.

i.e., $\left.\frac{d\eta}{d\phi_2}\right|_{x I_2 = Constant} = 0.$ (If we differentiate)

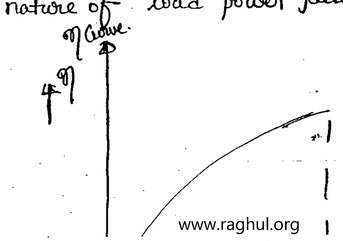
$\phi_2 = 0.$

@ $\cos\phi_2 = 1.$

That means @ upf we will get max η i.e pure resistive loads only.

Theoretically no derivation between nature of load power factor

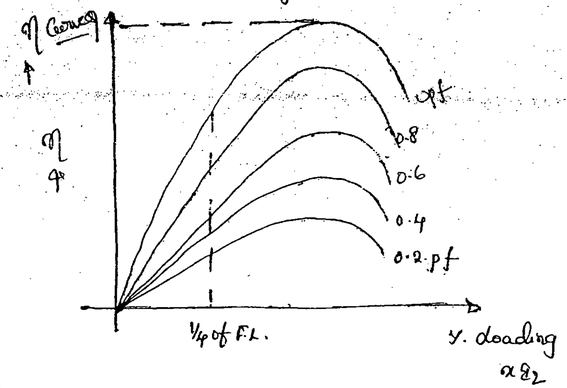
i.e., $\cos\phi_2\ (0.8)_{lag} = \cos\phi\ (0.8)_{lead}.$



of power factor (p.f).

For given load condition the $\eta$ will be maximum for more power factor. Here $\eta$ is single valid function.
Since $\eta$ we can't get at different power factors.

If you want $\eta$ curves of power factor & loading; to combine you can obtain family of.




For given loading (1/4 F.L) max $\eta$ coming @ u.p.f.

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In some cases losses may given in per unit instead of watts. Procedure to find out $\eta$; if losses given in per unit:

$$\eta_{x\text{ of F.L}} = \frac{x(S_2 S_2)\cos\phi_2}{x(S_2 S_2)\cos\phi_2 + x^2(CS_2^2) + W_i}$$

In per unit system without knowing kVA also we can find; $\eta$:

let per unit Full-Load Copper loss = $W_C$
per unit Full-Load Iron loss = $W_i$

$$\eta_{F.L\ @\cos\phi_2} = \eta_{1/2\ F.L\ @\cos\phi_2} = ? \qquad \eta_{x\text{ of F.L}\ @\cos\phi_2} = ?$$



Simply assume full-load kVA = Base kVA.
By default; consider full-load kVA = 1 per unit (PU)

1/2 F.L. kVA = 0.5 pu.
3/4 F.L. kVA = 0.75 pu.

$$\eta_{F.L\ @\cos\phi_2} = \frac{1\times\cos\phi_2}{1\times\cos\phi_2 + W_{C_{F.L}} + W_i}$$

$$\eta_{1/2\ F.L\ @\cos\phi_2} = \frac{1/2(1)\cos\phi_2}{1/2(1)\cos\phi_2 + (1/2)^2 W_C + W_i}$$

$$\eta_{3/4\ F.L\ @\cos\phi_2} = \frac{3/4(1)\cos\phi_2}{3/4(1)\cos\phi_2 + (3/4)^2 W_C + W_i}$$

For any fraction of full-load (per unit loss given); for given power factor:

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$$\boxed{\eta_{x\text{ of F.L}\ @\cos\phi_2} = \frac{x\cdot\cos\phi_2}{x\cdot\cos\phi_2 + x^2 W_C + W_i}}$$

→ % R = 2%; % X = 6% & % Constant loss = 1%.

Then $\eta_{F.L\ @\text{upf}} = ?$ $\qquad \eta_{1/2\ F.L.\ @\text{upf}} = ?$

Since % values given; so no-need of kVA;
Consider Base kVA = 1 per unit.

$$\eta_{F.L\ @\text{upf}} = \frac{1\times1}{1\times1 + 0.02 + 0.01} = \frac{1}{1.03}\times100 = 97.08\%$$

% R = 2% ⇒ 0.02 pu = Copper loss in per unit.
don't put ohmic values in per unit values.

Constant loss; $W_i$ = 1% ⇒ 0.01 pu = Iron loss in pu

$$\eta_{1/2\,F.L} = \frac{\quad}{0.5\times 1 + (1/2)^2\times 0.02 + 0.01}$$

$$= 97.08\%$$



→ If $\frac{\text{output power}}{\text{Input power}}$ ; we are using for $\eta$ of Transformer ; This is power $\eta$ of Transformer.

(or)

Commercial $\eta$ of Transformer.

This $\eta$ only suitable ; where load on Transformer almost constant for any time. So these $\frac{o/p}{i/p}$ $\eta$ used in power transformers in power system.

→ Where as in distribution Transformer ; where load continuously varies requires Energy $\eta$ of the Transformer.

→ As $\eta$ defined based on power is known as "power $\eta$".

In power system we install on more Transformer is "Distribution Transformer".

Distribution T/F base is Energy. So distribution T/F $\eta$ is Energy $\eta$

Distribution Transformer performance index can be found

- Energy $\eta$
  (or)
- All day $\eta$
  (or)
- Operational $\eta$.

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What are the operational differences between power & distribution Transformer :- (Design Differences also).

| Power Transformer | Distribution Transformer. |
|---|---|
| 1. In power system two networks | → Transmission Networks. → Distribution Networks. |
| (a) Used in Transmission n/w of power system. | |
| (b) Operates @ High voltage so rating > 33 kV | (2) Operates ; So rating ≤ 33 kV. |
| (3) 220/132 kV ; 132/33 kV. | (3) 33/11 kV ; 11/440V) Distribution Transformer. |
| (4) Rating of power Transformer > 1MVA | (4) Rating Transformer ≤ 1MVA, 100kVA, 500kVA |
| (5) In Transmission Networks consumers allowed. No direct link to Consumer. | (5) In Distribution network consumers directly connected ; 33/11 kV T/F ⇒ Industrial Consumer ; 11/440V T/F ⇒ Domestic Consumer |
| (6) Load fluctuations are almost negligible. So ~~almost~~ constant loading. | (6) Load fluctuations are very high from time to time. So variable loading |
| (7) power Transformers are always fully loaded (or) Almost nearly full-loaded. power Transformer are @ fully-loaded through out 24 Hrs. | (7) Loading of distribution transformer depends on loading requirement of Consumer. Distribution Transformer depends on ~~load~~ ~~loadin~~ loading cycle of that locality. |

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load demand 6pm – 11 pm — F.L ⟶ 500 kVA o/p.

11pm – 6am — 1/4 F.L ⟶ 125 kVA o/p.

Normally Distribution Transformer core adopted in a colony after surveying the peak load demand at that locality. After deciding peak load they will assess which rating of Transformer to be adopted.

| | |
|---|---|
| (7) Ag. power Transformer fully loaded for 24 Hrs. | (8) Ag Distribution Transformer load always continuously changing with respect to load cycles. |
| Iron losses – fully takes place for 24 Hrs. | Iron loss – fully takes place for 24 Hrs – Since T/F Energised on & present throughout the 24 Hrs. |
| Copper losses – fully takes place for 24 Hrs. | Copper loss – depends on load cycle – not Exactly Constant. |
| No. reduction in any losses through out the 24 Hrs. | |

If full load $W_{cu} = 400W$. and $W_i = 200W$.

500 kVA T/F.

| | | | Iron loss | Copper loss |
|---|---|---|---|---|
| 6-am – 6pm | – 1/2 Load | – 250 kVA | 200W | 100W. |
| 6 pm – 11 pm | – Full load | – 500 kVA | 200W | 400W. |
| 11 pm – 6 amp | – 1/4 Load | – 125 kVA | 200W | 25W. |

| | |
|---|---|
| (9) Copper loss should kept at minimum while designing stage. | (9) Iron loss should kept at minimum while designing stage. |

Since Any Transformer generally have Copper loss > Iron loss in operation.

| | |
|---|---|
| (10) No. reduction of Iron loss required. ∵ Reasonably taking place. So No. reduction in '$B_m$' required. | (10) $W_h \propto B_m^{1.6}$ <br> $W_e \propto B_m^{2}$. <br> approximately $W_i \propto B_m^{2}$. |
| Generally $B_m$ – 1.6 to 2 Tesla. | To reduce Iron losses in Distribution Transformer, $B_m \downarrow$. |
| In power Transformer we have to bother about Copper loss. | So distribution T/F required (or) designed @ low peak value of flux |

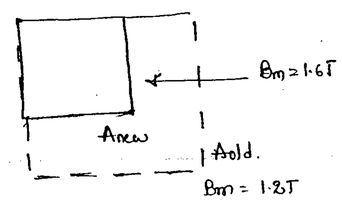


Generally $B_m \Rightarrow 1$ to 1.4 Tesla.

| | |
|---|---|
| (11) for higher flux densities power Transformer use laminations of CRGO steel. | (11) for reduced flux densities practically Distribution T/F using Amorphous steel. <br> Generally on Distribution Transformer will find a name Amorphous. That means inside steel used is Amorphous. |
| (12) As CRGO steel is used weight of T/F low. | (12) Directly we should not compare weights of power T/F & Distribution T/F. For this to compare we use Specific kVA. |

$$\text{Specific kVA} = \frac{\text{Weight}}{\text{kVA}}.$$

| | |
|---|---|
| (13) low Specific kVA | (13) High Specific kVA. |
| (14) As $E_1 \propto \phi_m$ | (14) In any Transformer $E_1$ must be constant. <br> $E_1 \propto \phi_m \rightarrow$ Constant. |




$\phi_m \propto B_m A \uparrow$

∵ power T/F has to operate @ higher flux densities, x-section of core is less.

As we required $B_m$ low.

$\phi_m \propto B_m A \uparrow$

So x-section more and Specific weight of Transformer also more.

∴ x-Section More.

| | |
|---|---|
| (15). $\frac{\text{Iron weight}}{\text{Copper weight}}$ is less. | (15) $\frac{\text{Iron weight}}{\text{Copper weight}}$ is more. |
| (16). Average load of power T/F = Full load (or) Nearly Full-Load | (16) Average load on present days Distribution T/F = 70% of full load to 75%. |



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*Load Demand

6 Am — 6 pm — ½ F.L → 250 kVA o/p

6 pm — 11 pm — F.L → 500 kVA o/p

11 pm — 6 Am — ¼ F.L → 125 kVA o/p

Normally Distribution Transformer are adopted in a Colony after surveying the peak load demand at that locality. After deciding peak load they will assess which rating of Transformer to be adopted.

| | |
|---|---|
| (8) Ag power Transformer fully loaded for 24 Hrs. | (8) Ag distribution Transformer load always continuously changing with respect to load cycles. |
| Iron losses — fully taken place for 24 Hrs. | Iron loss — fully taken place for 24 Hrs. — Since T/F Energised 00 ϕ present throughout 24 Hrs. |
| Copper losses — fully taken place for 24 Hrs | Copper loss — Depends on load cycle — Not Exactly constant. |
| No. reduction in any losses through the 24 Hrs. | |

If full load $W_c$ = 400 Watts.
$W_i$ = 200 Watts.

500 kVA Transformer;

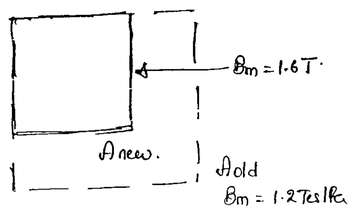
| | | | Iron loss | Copper loss |
|---|---|---|---|---|
| 6 Am — 6 pm | : ½ load | — 250 kVA — | 200W | 100W |
| 6 pm — 11 pm | : Full load | — 500 kVA — | 200W | 400W. |
| 11 pm — 6 Am | : ¼ load | — 125 kVA — | 200W | 25W. |

| | |
|---|---|
| (9) Copper loss should kept at minimum while designing. | (9) Iron loss should kept at minimum while designing stage. |

Since In any Transformer generally have Copper loss > Iron loss in operation.



| | |
|---|---|
| (10) No - reduction of Iron loss required. Since reasonably taking place. No - reduction in $B_m$ required. Generally $B_m$ 1.6 to 2T. In power Transformer we have to bother about Copper loss. | (10) $W_h \propto B_m^{1.6}$ <br> $W_e \propto B_m^2$ <br> Approximately $W_i \propto B_m^2$. <br> To reduce Iron losses in distribution Transformer, $B_m^{\downarrow}$ <br> So Distribution Transformer required (or) designed (or) low peak value of flux density |
| (11) For higher flux densities power transformer use laminations of CRGO Steel. | (11) For reduced flux densities practically distribution transformer using Amorphous Steel. <br> Generally on distribution Transformers we will find a name Amorphous. That means inside Steel used in ag Amorphous. |
| (12) Ag CRGO Steel Eg used ~~wt~~ weight of Transformer low. | (12) Directly we should not compare weight of power Transformer & Distribution Transformer. For this to compare we use specific KVA. <br> Specific KVA = $\frac{\text{weight}}{\text{KVA}}$. |
| (13) low Specific KVA | (13) High Specific KVA. |
| (14) Ag $A \propto \phi_m$. | (14) In any Transformer, A must be constant. <br> $A \propto \phi_m$ → Constant. <br> Ag we required $B_m$ low. <br> $\phi_m \propto B_m \downarrow . A \uparrow$ |




$\phi_m \propto B_m \uparrow . A \downarrow$

So X - Section more and specific weight of Transformer also more.

X - Section more.



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Consumption by Consumer greatly increased.



(17) So to get minimum benifit from design Transformer must designed in such a way to get max. $\eta$ @ Avg load of that Transformer. @

$\eta_{max}$ @ full load (or) Nearly full Load.

(17). In case of Distribution Transformer must be in such a way, to get

$\eta_{max}$ @ 40% of full load.

(18) Design @ full load

$WC_{FL}$ = Iron loss $W_i$

(18) Design @ full load

Copper loss $WC_{FL} \cong 2$(Iron loss) $\cong 2(W_i)$.

Generally by seeing (or) knowing the amount of the losses, in T/F we can generalised its power Transformer (or) Distribution Transformer.

Odden days Avg load = 100%.

Design Criterial => Full Load Copper loss = Iron loss

(19) Design Criteria in odden days

Avg. load = 50%.

Design Criteria => Full Load Copper loss $\cong 4$(Iron loss)

operation of Transformer independent of time.

Throughout the time Copper loss & Iron loss Constant.

(20) operation of Transformer depends on load cycle.

Copper loss dependent on time. Iron loss independent on time.

So operation of T/F not only depends on power also depends on time also.

~~So Energy $\eta$ required (or) All day required.~~

21. performance of power Transformer independent of time. So power $\eta$ only.

(21) performance of Distribution T/F depends on time also.

So Energy '$\eta$' required (or) All day '$\eta$' required.



These are the reasons for

All day $\eta$ = ratio of $\frac{\text{output Energy in kWH}}{\text{Input Energy in kWH}}$ @ day.

Energy ~~Contits~~ Consists time factor also. As time doesn't have bounds or limit. So to limit time we consider for a 24 Hr that's way distribution T/F $\eta$ ← all day $\eta$ of Transformer.

$$\text{All day } \eta = \frac{\text{output in kWH}}{\text{output in kWH + losses in kWH}} \Big|_{\text{@ 24 Hrs or 1 day}}$$

* unless we doesn't know load cycles on distribution Transformer; we can't find all day '$\eta$'.

So let us :-

→ A 500kVA Distribution Transformer operating @ UPF i.e delivering to lighting load, load cycle as follows:

$WCu_{F.L}$ = 400 W ; $W_i$ = 200 W.

| | | | | Copper loss | Iron loss |
|---|---|---|---|---|---|
| upf : | 6 am – 6pm | – 1/2 F.L | – 250 kW | 100 W. | 200 W. |
| upf : | 6pm – 11pm | – F.L | – 500kW | 400 W. | 200 W. |
| upf : | 11 pm – 6am | – 1/4 F.L | – 125kW | 25 W. | 200 W. |

$$\eta_{all\ day} = \frac{\left[(250\times1\times12)+(500\times1\times5)+(125\times1\times7)\right]}{(\quad)+\frac{(100\times12+400\times5+25\times7)}{1000}+\frac{200\times24}{1000}}$$

* All day $\eta$ continuously varies depending on load cycle. load cycle may changes from season to season.

* But power Transformer is always constant $\eta$.

As operational circumstances changes all day $\eta$ of T/F, so ~~as~~ all day $\eta$ can also be called as operational '$\eta$'



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Cu. weight — eq less.

(15) Avg. load of power Transformer = Full-load (or) Nearly Full-Load.

(16) So to get maximum benifit from design Transformer must designed in such a way to get max $\eta$ @ Avg. load of that Transformer.

$\eta_{max} \overset{@}{\Rightarrow}$ Full load (or) Nearly full-load.

(17) Design @ Full-load Copper loss $W_{CFL}$ = Iron loss ($W_i$)

(17) Cu. weight — 0 — eq more.

(15) Avg. load on present days. 75

Distribution Transformer = 70% to 75% of Full-load.

In olden days 10 to 20 years back.

Distribution T/F Avg. load = 50% of Full-load.

This is the way that power consumption by consumer greatly increased.

(16) In case of Distribution Transformer design must be in such a way to get

$\eta_{max} \overset{@}{\Rightarrow}$ 70% of Full-load.

(17) Design @ Full-load Copper-loss $W_{CFL} \cong 2$ (Iron loss) $W_i$

Generally by seeing the amount of the losses in Transformer (or) knowing we can generalised it at power Transformer (or) Distribution Transformer

(18) olden days Avg. load = 100%.

Design Criteria $\Rightarrow$ F.L. Copper loss $\Rightarrow$ Iron loss.

(18) Design Criteria in olden days Avg. load = 50%.

Design Criteria = F.L. Copper loss $\cong$ 4 (Iron loss)



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19. Operation of Transformer independent of time.

Throughout time copper loss & iron loss Constant.

(19) operation of Transformer dependent on load cycle.

Copper loss dependent on time. Iron loss independent of time.

So operation of Transformer not only depends on power also depends on the time.

20). Performance of power T/F independent of time.

& power $\eta$ only.

(20) Performance of Distribution T/F depends on time also.

So Energy $\eta$ required (or) All day $\eta$ required.

These are the reasons for

All day $\eta$ = ratio of $\frac{\text{output Energy in kWH}}{\text{Input Energy in kWH}}$ @ day.

Energy consists time factor also. Eq time doesn't have boundary or limit. So to limit this time we consider for a 24 Hrs that's why Distribution Transformer $\eta$ — All day $\eta$ of Transformer.

$$\text{All day } \eta = \frac{\text{output in kWH}}{\text{output in kWH + losses in kWH}} \Big|_{@\ 24\ \text{Hrs (or) } 1\ \text{day}}$$

→ Unless we don't know load cycles on distribution Transformer; we can't find all day $\eta$.

So let us:

* a 500kVA Distribution Transformer operating @ upf i.e delivering to lightening load; load cycle as following:



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Regulation :-

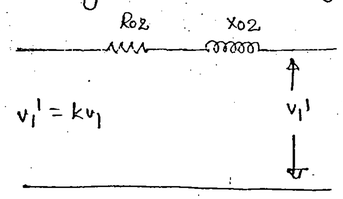
This is the change in Secondary terminal voltage from no-load to full-load at a particular power factor of load and the change in voltage is Expressed as percentange of fraction of no-load Secondary terminal voltage $V_1'$.

(or)

Full load Secondary terminal voltage $V_2$.

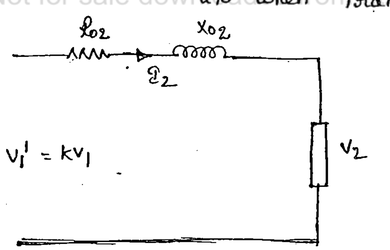
To understand the meaning draw Equivalent Circuit of T/F @ Secondary side.

No-load Secondary Terminal voltage :- (neglecting No-load branch)




Full-load Secondary Terminal voltage :-

i.e when Transformer delivering full load Curre




If 1/4 Full-load Current ~~fol~~ flowing, the 1/4 full load terminal voltage @ Secondary ($V_2$).

If 1/2 Full load Current following the 1/2 Full load terminal voltage @ Secondary ($V_2$).

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Change in voltage from No-load to Full-Load $= V_1' - V_2$.

Can be Expressed fraction of No-load terminal voltage @ No load (or Full load)

$$\text{Voltage Regulation} = \frac{V_1' - V_2}{V_1'} \quad (\text{or}) \quad \frac{V_1' - V_2}{V_2}$$

By default, voltage regulation means, Reg. down only;

$$\text{Regulation down} = \frac{V_1' - V_2}{V_1'}$$

$$\text{Regulation up} = \frac{V_1' - V_2}{V_2}$$

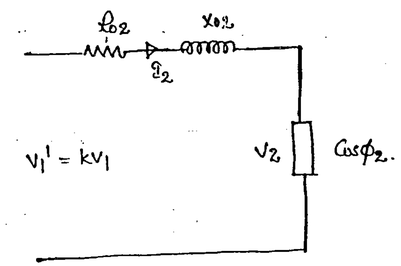
Voltage Regulation :-

It is the % voltage drop of Transformer at a Specific power factor of load.

$$\%\ \text{voltage drop} = \frac{V_1' - V_2}{V_1'}$$

? How to know this voltage drop.

By vector diagram possible.




$$V_1' = V_2 + I_2 R_{02} + j I_2 X_{02}.$$

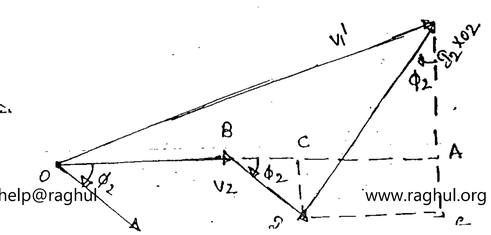
Vector diagram refer to Secondary @ unity power factor. after neglecting No-load branch.

(a) lag-load :-

AB : voltage drop in T/F.

AB : BC + CA

BC + DE

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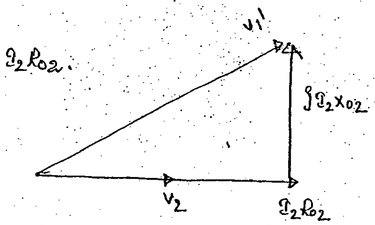
$= I_2 R_{02} \cos\phi_2 + I_2 X_{02} \sin\phi_2$

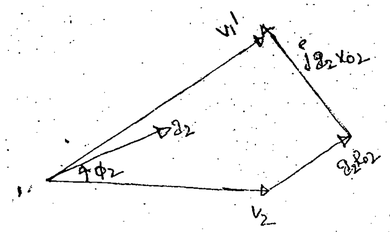


@ Unity ~~only~~ power factor :-

Voltage drop @ upf $= I_2 R_{02}$.




@ Lead Load :-




Transformer voltage drop @ lead power factor =

$= I_2 R_{02} \cos\phi_2 - I_2 X_{02} \sin\phi_2$.

* We don't want only magnitude of load, we also need power factor of load also.

In general voltage drop of Transformer :-

at a specific power factor of Load

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$\Rightarrow I_2 R_{02} \cos\phi_2 \pm I_2 X_{02} \sin\phi_2$ + lag p.f, − lead p.f.

at upf, $\phi_2 = 0$ $\Rightarrow I_2 R_{02} \cos(0) + 0$.

$\Rightarrow I_2 R_{02}$

$$\% \text{ Regulation} = \left[\frac{I_2 R_{02} \cos\phi_2 \pm I_2 X_{02} \sin\phi_2}{V_1'}\right] \times 100 \longrightarrow (1)$$

$$= \left[\frac{I_2 R_{02}}{V_1'} \cos\phi_2 \pm \frac{I_2 X_{02}}{V_1'} \sin\phi_2\right] \times 100.$$

$$= \left[\text{per unit Resistance drop} \times \cos\phi_2 \pm \text{per unit Reactance drop} \times \sin\phi_2\right] \times 100.$$

% voltage Regulation of Transformer

$= [\text{pu Resistance} \cos\phi_2 \pm \text{pu Reactance} \sin\phi_2] \times 100.$



% Regulation of Transformer

$= (\% R) \cos\phi_2 \pm (\% X) \sin\phi_2$. + lag p.f, − lead p.f.

If Resistance and reactance in ohmic values given use Eq (1).. once you conduct SC test %R and %X you can easily find. So for given power factor you can find voltage Regulation of Transformer.

→ Under what condition this Regulation is Maximum?

Condition for Maximum Regulation?

~~If it~~ It is an undesirable thing. Since it indicate poor performance of Transformer due to large drop in Transformer.

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During operation of Transformer this condition should not be satisfied.

$$\% \text{ Regulation} = (\% R) \cos\phi_2 \pm (\% X) \sin\phi_2.$$

$$\frac{d}{d\phi_2}(\text{Reg}) = 0.$$

Maximum Regulation is possible only if two drop terms are additive. i.e. +ve sign i.e @ lag power factor loads only.

with lag pf load much regulation possible.

with lead p.f load less regulation possible.

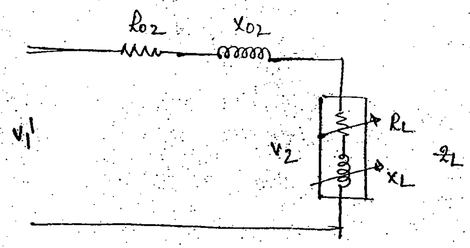
Now differentiate regulation;

$$\tan\phi_2 = \frac{\% X}{\% R}.$$

$$\phi_2 = \tan^{-1}\left(\frac{\% X}{\% R}\right)$$

$X_{02}$ : leakage Reactance;

$$\phi_2 = \tan^{-1}\left(\frac{X_{02}}{R_{02}}\right) \text{ lag}..$$




$\phi_2 = \tan^{-1}\left(\frac{X_L}{R_L}\right)$

As once Transformer designed; $R_{02}$, $X_{02}$ } T/F parameters fixed.

But load parameters ; $R_L$, $X_L$ } load parameters ~~not~~ variable.

$$\therefore \phi_2 = \tan^{-1}\left(\frac{X_L}{R_L}\right) = \tan^{-1}\left(\frac{X_{02}}{R_{02}}\right)$$

Maximum Regulation Possible ; @ $\frac{X_L}{R_L} = \frac{X_{02}}{R_{02}}$.

i.e if load $\left(\frac{X}{R}\right)$ ratio = Transformer $\left(X/R\right)$ ratio. Hence, Regulation becomes Maximum. So never operate Transformer at these low Conditions.

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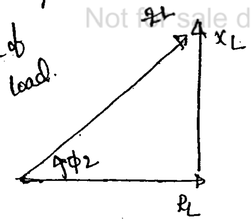
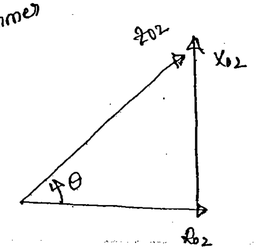
Impedence angle of load.




$\phi_2$ : Impedence angle of load variable.

Impedence angle of Transformer




$\theta$ : Internal impedence angle of Transformer Const

Maximum Regulation,

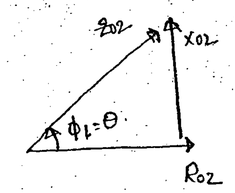
$$\phi_2 = \theta = \tan^{-1}\left(\frac{X_{02}}{R_{02}}\right) \text{ deg.}$$

If Impedance $\Delta^{le}$ of Transformer = Impedence $\Delta^{le}$ of load.

Maximum Regulation occurs.



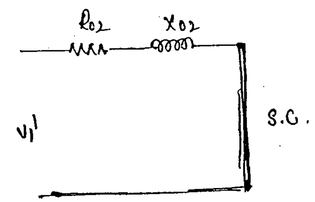
Impedance Triangle of Transformer @ Max. Regulation:




power factor @ Maximum Regulation:

$$\cos\phi_2 = \frac{R_{02}}{Z_{02}} = \frac{V.R}{V.X} \text{ deg.}$$

Case :- Instead of placing load @ Secondary. if I kept short circuit @ Secondary.




Maximum Regulation

$$\cos\phi_2 = \frac{R_{02}}{Z_{02}} = \frac{V.R}{V.Z} \text{ deg.}$$

$$\cos\phi_2 = \cos\phi_{SC}.$$

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If load power factor varied such that at some power fa

load power factor = S.C. Secondary power factor of T/F = Maximum voltage Regulation.

Generally Transformer S.C power factor between : 0.5 to 0.6.

→ At Maximum Regulation:

(1). $\frac{X_L}{R_L} = \frac{X_{02}}{R_{02}}$.

(2) $\phi_2 = \theta = \tan^{-1}\left(\frac{X_{02}}{R_{02}}\right)$ deg.

(3) Impedance $\Delta^{le}$ of load Identical with Impedance ~~Triangle~~ $\Delta^{le}$ of Transformer.

(4) $\cos\phi_2 = \frac{R_{02}}{Z_{02}}$ (or) $\cos\phi_2$ = Transformer power factor @ Short Circuit.

Don't operate Transformer at any above (4) conditions.

$$\%\ \text{Regulation} = \%R\cos\phi_2 + \%X\sin\phi_2.$$

$$\%\cos\phi_2 = \frac{\%R}{\%Z}$$

$$\%\sin\phi_2 = \frac{\%X}{\%Z}$$

$$\text{Max. } \%\ \text{Regulation} = (\%R)\left(\frac{\%R}{\%Z}\right) + (\%X)\left(\frac{\%X}{\%Z}\right)$$

$$= \frac{(\%R)^2 + (\%X)^2}{\%Z} = \frac{(\%Z)^2}{\%Z} = \%Z.$$

Highest possible Regulation in Transformer = % Impedance of Transformer

% Impedance of T/F = Rated voltage Required to produce rated S.C. Current.

∴ The value of Maximum Regulation in Transformer = % Impedance of Transformer.

<u>Condition of Zero Regulation :—</u>

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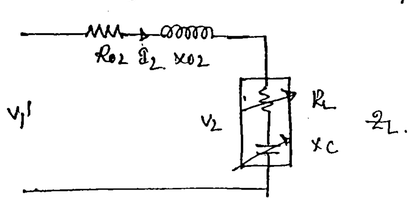
$$\%\ \text{Reg} = (\%R)\cos\phi_2 - (\%X)\sin\phi_2.$$

Zero Regulation possible only if the both Components are Subtractive. i.e., @ leading power factors loads only.

$$\tan\phi_2 = \frac{\%R}{\%X}.$$

$$\phi_2 = \tan^{-1}\left(\frac{\%R}{\%X}\right) = \tan^{-1}\left(\frac{R_{02}}{X_{02}}\right) \text{ lead power factor only.}$$

It is possible only with Creative Loads.






At Zero Regulation;

$$\phi_2 = \tan^{-1}\left(\frac{X_C}{R_L}\right) = \tan^{-1}\left(\frac{R_{02}}{X_{02}}\right) \text{ @ lead power factor load}$$

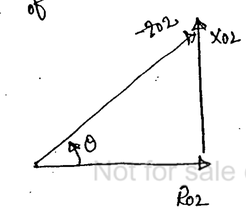
$$\frac{X_C}{R_L} = \frac{R_{02}}{X_{02}}.$$

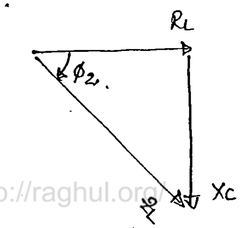
If $\frac{X}{R}$ ratio of load = $\frac{R}{X}$ ratio of T/F, Regulation '0'.

$\frac{X}{R}$ ratio of load = $\frac{X}{R}$ ratio of T/F; Regulation Maximum.

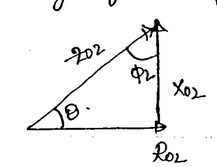
No change in Impedance Δle of Transformer

But due to capacitive load Impedance Δl of load.




Impedance Triangle of Transformer @ Zero Regulation.




power factor of load Corresponding to Zero Regulation:

i.e., $\cos\phi_2 = \frac{X_{02}}{Z_{02}} = \frac{\%X}{\%Z}$ lead.

One ~~you~~ we know %R, %X, %Z at Transformer; we can find Easily power factor @ Maximum Regulation.

power factor @ Zero Regulation.

By ~~default~~ default, Regulation means at full load only.

$$\text{Full \% Regulation} = (\%R)\cos\phi_2 \pm (\%X)\sin\phi_2$$

$$\%R = \frac{I_2 R_{02}}{\ldots} \times 100.$$

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% X at 'x' of full-load = x (% X).

∴ Regulation at any 'x' of full load :

$= x[\% R \cos\phi_2 \pm \% X \sin\phi_2]$

$= x$ [Full load Regulation]

Similar to η; Regulation also you can find at any fraction of load, once if you know full load Regulation.

→ Regulation @ UPF :-

@ UPF $\cos\phi_2 = 1$

$\sin\phi_2 = 0$ (Reactance drop = 0)

Regulation @ UPF = % R = % Full load Copper loss.

If % Full load Copper loss = 4%.

Then that Transformer, % Resistance of Transformer also = 4%.

i.e., % Full load Copper loss = % Resistance of Transformer.

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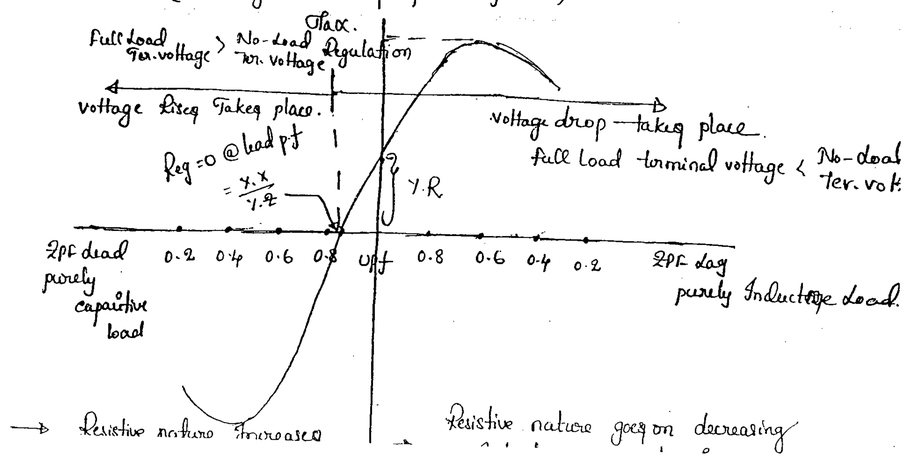
This is the only relation between Efficiency and Regulation.

* From Entire discussion; Regulation not only depends on magnitude of power factor also depends on nature of load power factor.

<u>Regulation Curve</u>:- (% Regulation Vs power factor).






* At each and every power factor you find full load Regulation.

Than point it to observe.

* Regulation doesn't flows through zero or Origin.

Since @ upf Reg ≠ 0.

Regulation @ upf = % R of Transformer.

Max. Regulation = % Z of Transformer.

@ Max. Regulation, $\cos\phi_2 = \frac{\% R}{\% Z}$ lag (Normally b/w 0.5 to 0.6).

* At all lagging loads of upf of Transformer : +ve Regulation (Full Load Terminal < No-load Ter. voltage; $V_2 < V_1'$ $V_0$)

+ve Regulation : takes place corresponds to drop in T/F.

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At all ~~load~~ lead load not −ve.

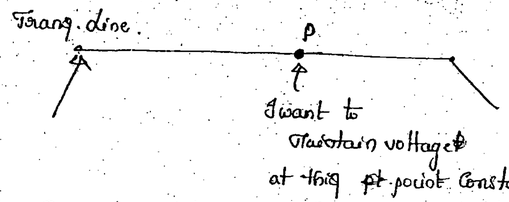
but @ low leading power factor load −ve Regulation.

~~−ve Regulation : At which Transformer Corresponds~~ to

Voltage Controlled by Reactive power.

Frequency Controlled by Active power.

**Regarding power System :-**




If at that point Reactive power balanced then we can said voltage at that point Constant.

Reactive power balanced Means : Reactive power injected at that point = Reactive power absorbed at that point.

So this Reactive power Supplied by : Reactive ~~power~~ Source ; phase Condensors ; over Excited Synchronous Motor, Static Compensators and Capacitor banks.

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Sinks of Reactive Power : loads which absorbs Reactive power.

Ex: Tube light choke coil; Fans, Induction Motor } All these to Create flux in their mediums for its functioning.

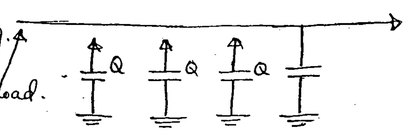
So all loads are Sinks of reactive power.

Transformer under no-load also Sink of reactive power.

* If $Q_{absorbed}$ less ; $Q_{injected}$ more. The voltage raise takes place.

Ex:- Transmission line @ No-Load.

Ferranti Effect during Trans. line @ No-load.




At this Case Reactive power Supplied more and Since no-load Reactive power absorption less.



That's way no-load voltage in long Transmission line receiving End voltage more due to ferranti Effect.

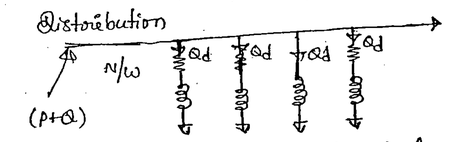
* If Reactive power absorbed more than Reactive power Supplied ; Then voltage drop takes place.

Ex:- Drops in Distribution Network.

Design Criteria of Distribution Network — voltage drop minimum

Design Criteria of Transmission Network — $\eta$ Should be Maximum

Small Reactive power feeding large absorption power by loads in distribution Network. & voltage drop takes place.




To over Come this Consumer of Induction loads Suggested to keep Capacitor banks in parallel with loads.

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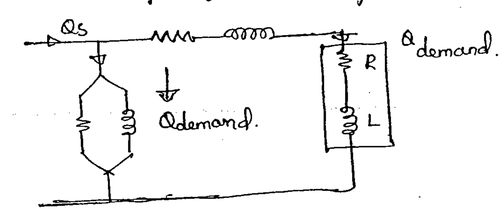
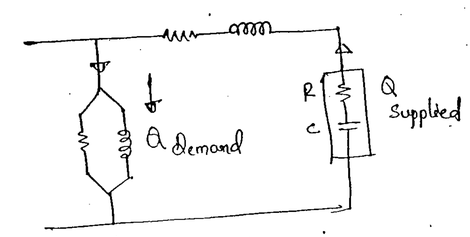
→ Same above Concept of Reactive power applicable to Transformer.




Transformer no-load branch Consumes reactive power (or) demands Reactive power (or) draws Reactive power @ R-L. loads.




Due to Resistance domination with low Capacitive 'C' load.

Still Transformer acts like a Sma Reactive power Sink.

If Reactive power Supplied = Reactive power absorbed.

$Q_D$ of $X_0$, the Transformer now Enter into

$Q_S > Q_d$

At this Situation voltage raise will takes place.

**Conclusions on Reactive power loads of Transformer :-**

(1) Inductive load — Transformer Reactive power Sink — T/F $Q_D$ large — voltage drop.

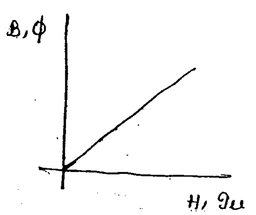
(2) low value of 'C' in RC load — Transformer Reactive power Sink — T/F $Q_D$ low — voltage drop takes place

(3) RC load; $Q_D = Q_S$ — Neither Sink, nor Source of Q — No drop, No-raise.

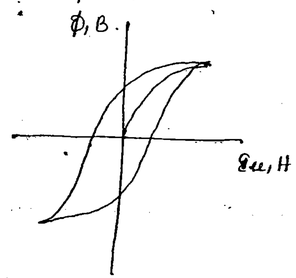
(4) large value of 'C' in RC load — Transformer Reactive power Source — Transformer $Q_D$ zero, $Q_S$ starts — voltage Raise takes place

→ **Assumption :-**

(5) Effect of Non-linearity of magnetisation Curve on practical Transformer :




Ideal Transformer




Practical Transformer.

Practically (2) Non-linearities

(1) Hysteresis non-linearity.

(2) Saturation non-linearity.

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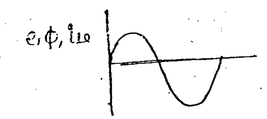
→ what Ever the internal non-linearities are want output Emf must be Sinusoidal only.

For Satisfactory operation of loads @ Secondary;

Since Electric load Satisfactory operate @ pure Sinusoidal inputs only.

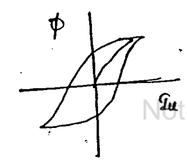
Main objective of Transformer :-

& To get output Sinusoidal Emf :




ϕ in Core must be Sinusoidal;

In this case means, during nonlinearity of Core, we want Sinusoidal only.




As ϕ vs. Iu is not linear (or) Non-linear relationship.

Induced quantity (Emf 'E') also non-linear or non-Sinusoidal.

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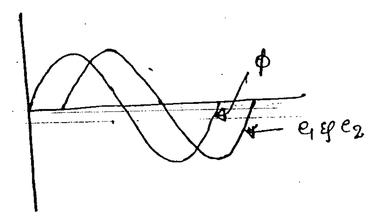
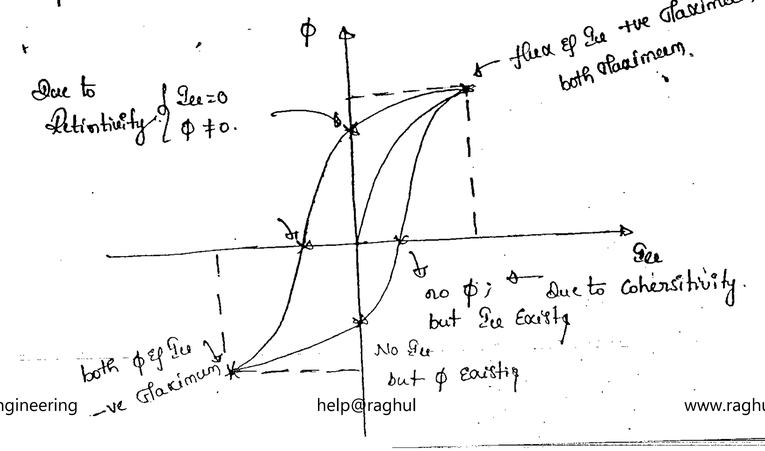
**Desirable waves :-**

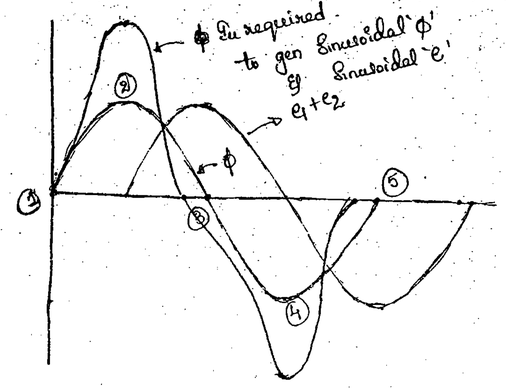



Now, we need to obtain required Iu wave shape to get these quantities, like this.



(1) $I_u = 0$ & $\phi = 0$ not occuring at same point.

(2) Both $\phi$ & $I_u$ occuring simultaneously at same point at +ve maximum and −ve maximum.




→ To produce sinusoidal flux in core the required magnetising current shape is peaky wave.

* Non-linearity of core are inevitable because its a magnetic nature. So for our requirement of 'E' wave; we must supply to satisfy that saturation points.

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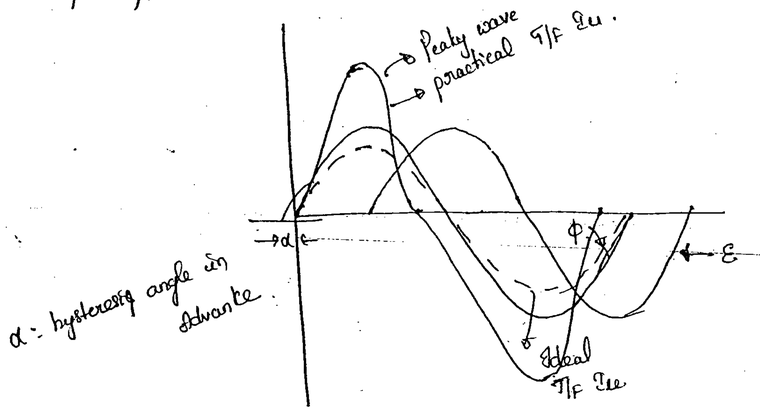





Different Deviations :-

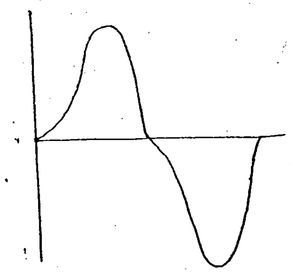
α: Hysteresis angle of advance.

(1). practical Transformer $I_u$ & $\phi$ not coinciding @ 0.

(2) $I_u$ in Ideal Transformer $I_u$ – Sinusoidal (∵ $I_u$ vs $\phi$ linear).

$I_u$ in practical Transformer $I_u$ – peaky (∵ $I_u$ vs $\phi$ no-linear).

Fourier analysis can gives sinusoidal expressions to any wave. So



→ If any wave form symmetric to x-axis. means if wave mirror image.

Then wave contains odd harmonics only.

If ~~the~~ +ve half wave mirror image to −ve half cycle.

If any wave not giving mirror images. i.e., +ve half cycle. not mirror image of −ve half cycle.

(or)

Wave not symmetric waves; then that wave contains both even and odd harmonic components to its formation.

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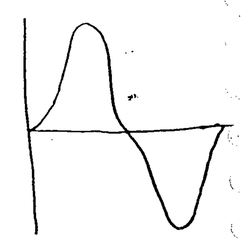
* But our peak $I_u$ is symmetric with x-axis, so.



3, 5, 7, 9, 11, 13, 15 ..... harmonic component. Any quantity with multiple frequency is called Harmonic component.

That may be voltage or current or any thing so for we concerned with fundamental ~~frequency~~ sinusoidal only.

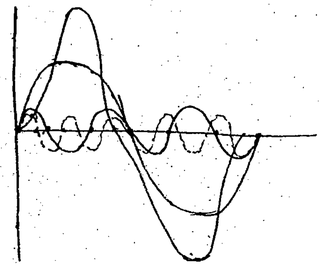
i.e., fundamental $i_1 = I_m \sin\omega t$ ; $\omega = 2\pi f$

$i_3 = I_m \sin 3\omega t$ ; $\omega = 2\pi(3f)$

$i_{5} = I_m \sin 5\omega t$ ; $\omega = 2\pi(5f)$

current point to point then we will get Ie current wave. This process of obtaining harmonic components to complete wave known as synthesis of wave form.

→ As goes on to higher order harmonics, it effect on system gets reduces.



As order of : harmonic ↑
Frequency ↑
Reactance ↑
Impedance ↑
Current ↓

Dominant current fundemental; So dominant harmonic 3rd.

$i_1 = I_m \sin\omega t = Z_1 = R_1 + jX_1$ ; $X_1 = 2\pi f L$.

$i_3 = I_m \sin 3\omega t = Z_3 = R_3 + jX_3$ ; $X_3 = 2\pi(3f).L$

$i_5 = I_m \sin 5\omega t =$ ; $X_5 = 2\pi(5f).L$.

$i_7 = I_m \sin 7\omega t =$

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(3), 5, 7, 9, 11, . . . . .

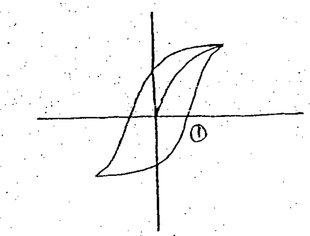
upto 50% of total harmonic current. Among all harmonic current present the contribution of 3rd harmonic current is 40 to 50%.

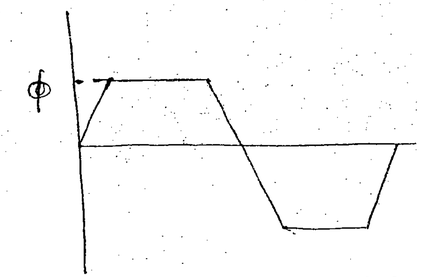
So to get Ie it must have all odd components and 3rd harmonic current is must in Ie. Since it is dominant so possibility of getting peak is must.

* If our Ie current not containing 3rd harmonic current means we wont get peaky. Then more or less shape of Ie becomes ~~nearer~~ nearer to peaky, then $\phi$ not be sinusoidal.



→ By same procedure of trace out from magnetisation curve; you can get $\phi$ wave also.





If 3rd harmonic mixed in the shape of $\phi$ in core is Trapezoidal or flat topped wave just like DC Machines.

→ As this $\phi$ ~~is~~ wave is non-sinusoidal wave, we can use fourier analysis to obtain sinusoidal expression for our $\phi$ wave

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Since $\phi$ wave symmetric with x-axis.

(or)

+ve half of $\phi$ mirror image to -ve half of $\phi$.

So the $\phi$ wave contains odd harmonic components only.

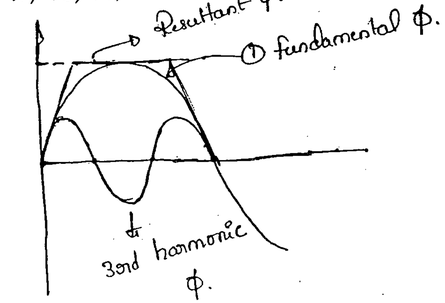
i.e., 3, 5, 7, 9, 11, 13, 15, . . . . . $\phi$.

$\phi_1 = \phi_m \sin\omega t$

$\phi_3 = \phi_m \sin 3\omega t$

$\phi_5 = \phi_m \sin 5\omega t$

$\phi_7 = \phi_m \sin 7\omega t$




$\phi_m = \phi_1 + \phi_3 + \phi_5 + \phi_7 + \cdots$

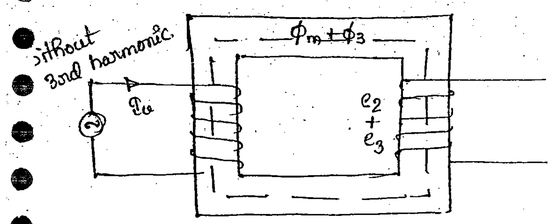
So here also 3rd harmonic is dominant.

3rd harmonic absent @ $I_u$.

3rd harmonic present @ $\phi_m$.

→ So flux '$\phi$' should not contain 3rd harmonic. for that $I_u$ must have 3rd harmonic component.

If $\phi$ containing 3rd harmonic, In Transformer $\phi_m$ also containing $\phi_3$.




Two Emfs @ load $e_2 + e_3$

i.e $v_2 + v_3$.

So no satisfactory operation of loa

To get pure sinusoidal from Transformer :-

$\phi$ must be sinusoidal (with out 3rd harmonic component) for that

$I_u$ must be peaky (Presence of 3rd harmonic must).

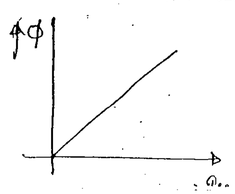
In case of ~~Ideal~~ Ideal Transformer we made ⑤ assumptions. Till now ④ practical assumptions we have seen now.

⑤th Assumption :-

Effect of non-linearity in core on Operation of Transformer :-

(or) operation of Transformer with non-linear magnetisation curve.

In case of Ideal Transformer we assumed linear magnetisation curve.

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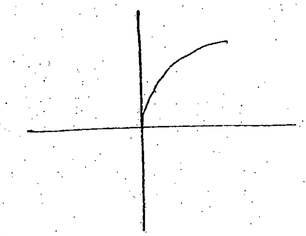
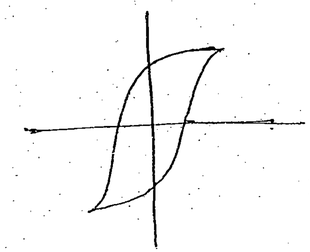
But practically core has ② non-linearities.

Saturation non-linearity.



Hysteresis non-linearity.



This non-linearity presenting due to alternating current application in core. Already we discussed.

That magnetisation path — demagnetisation path not coinciding.

Due to ② important properties of practical core.

(1) Retentivity.

(2) Coercitivity.

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from above :-

What Ever may be non-linearities in core, we require pure sinusoidal voltage wave forms for satisfactory operation of loads.

To obtain pure sinusoidal Transformer — Shape of flux in core must be pure sinusoidal.

In Ideal core :- ∵ linear relation between $I_u$ & $\phi$.

To generate pure sinusoidal voltage wave — flux in Transformer core must be pure sinusoidal — $I_u$ to be applied in Transformer core pure sinusoidal.

In practical core :- Here also same requirement that we want pure sinusoidal voltage output form.

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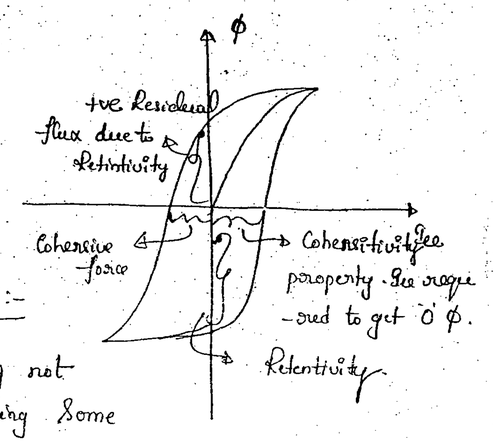
Sinusoidal $\phi$ (non-linear relation between $i_e$ & $\phi$.)
non-Sinusoidal



So here we need to obtain; what is the $i_e$ shape required to get sinusoidal $\phi$ in core.

This $i_e$ shape to get sinusoidal flux can be obtained from the magnetisation curve.




Observations from Magnetisation Curve :-

(1) Current '0' & flux '0' points not occuring simultaneously. Taking some time delay due to practical core magnetic properties.

(2) peak value of current and peak value of flux ($\phi$) occuring same time.

From above; To get $i_e$ shape;

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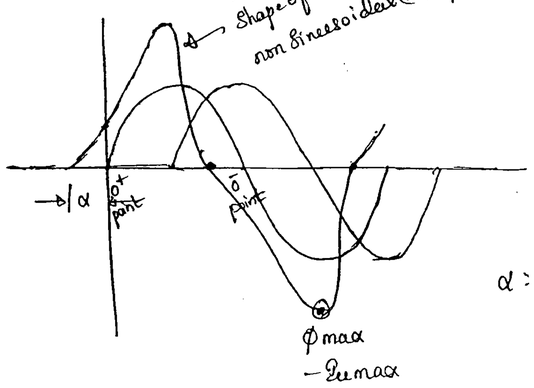
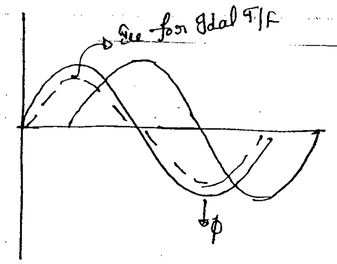
Desirable waves { let sinusoidal $\phi$, assume; produce sinusoidal emf $e_1$ & $e_2$ (both primary side & secondary side)

Now we have to trace out $i_e$ required to get these $\phi$ & $e_1$, $e_2$ sinusoidal shape.



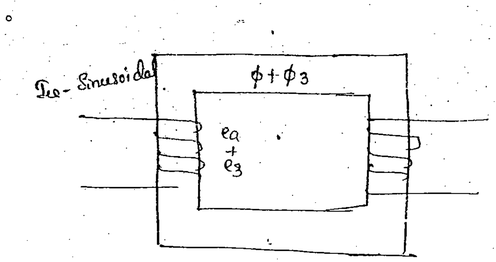



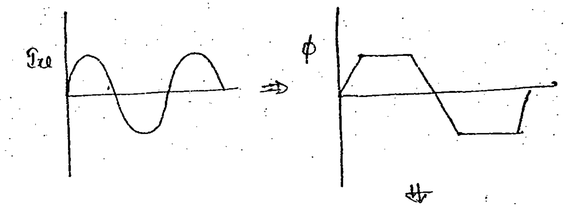

$\alpha$ : Due to hysteresis non linearity in practical core. $i_e$ advancing $\phi$ by small angle this is called hysteresis angle of advance.



In this case (If $i_e$ sinusoidal)

$\phi$ - Flattopped consists 3rd harmonic flux $\phi_3$ in addition to fundamental flux '$\phi$'.



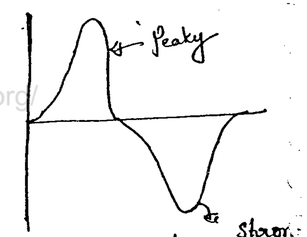

$e = \frac{d}{dt}(\phi)$

$= \frac{d}{dt}$ (flat top) = peaky

→ If $i_e$ sinusoidal;

$\phi$ - ~~flat top~~ Flattopped consists 3rd harmonic — In Transformer core (2) fluxes $\phi_1 + \phi_3$ — Induces (2) emfs $e_1 + e_3$

net e - peaky ; with strong 3rd harmonic which may damage some times connected




∴ Contains strong 3rd Harmonic

→ If $i_e$ peaky

$\phi$ sinusoidal free from 3rd harmonic flux (∵ $i_e$ consists 3rd harmonic) ⇒ In core only one flux fundamental $\phi_1$ ⇒ Induces emf of pure sinusoidal fundamental ⇒ Safely a to loads.

i.e., How to supply 3rd harmonic to $i_a$ ?



(1) In any case supply can't provide 3rd harmonic component. Since it can supply only fundamental.

(2) So system (1φ or 3φ) itself has to generate 3rd harmonic by itsq eqn. to get pure sinusoidal.

System means — 1-φ system
— 3-φ system — Y - Connected 3-φ system
— Δ - Connected 3-φ system.

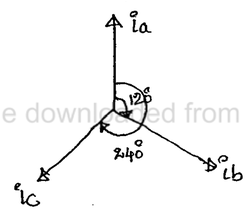
→ Now we have to observe which system is able to generate 3rd harmonic currents by its own:

First we shall observe in 3φ.

hence same applicable to 1φ.

In 3-φ fundamental currents displaced by 120° apart.

i.e.,

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Fundamental frequency of 3-φ system:

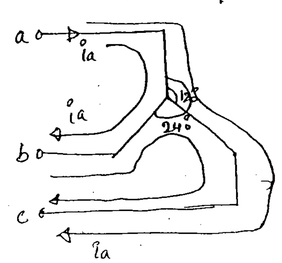
Instantaneous values of currents = 0.

$i_a(t) + i_b(t) + i_c(t) = 0$.

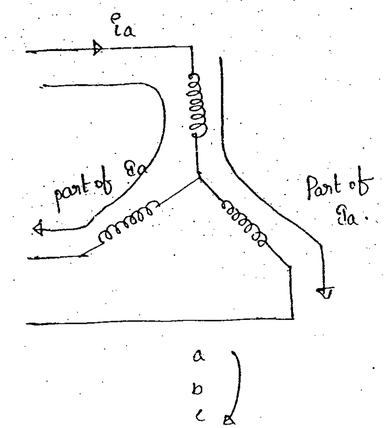
Has possible with 120° apart currents only.

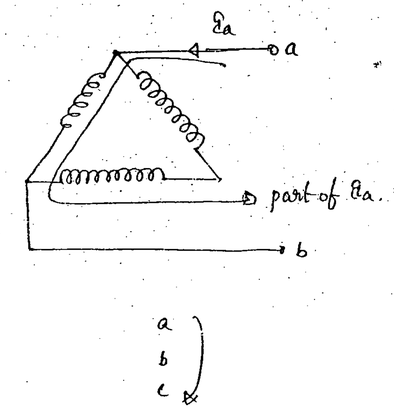
If any current satisfying the fundamental property of 3-φ system, i.e., 120° apart of each current. These currents can complete its path from one line to other line.

| $i_a$ | $i_b$ | $i_c$ |
|---|---|---|
| 0° | 120° | 240° |






Behaviour of 3rd harmonic in 3-φ systems:

To know this it would like to devided odd harmonics into two groups.

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Group - I.

5, 7, 11, 13, ... etc.

Group - II.

3, 9, 15, 21 ... etc.

Group - I Mathematical harmonic order: $n = 3k \pm 1$ where k : Even

$n = 3k$ where k = odd.

det eq Consider 5th Harmonic :-

Fundamental frequency - ω

displacement (0, 120°, 240°)

5th Harmonic frequency - 5ω

displacement (5×0°, 5×120°, 5×240°)

(0°, 240°, 120°)

a b c.

det eq Consider 3rd Harmonic :-

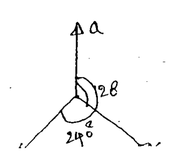
Fundamental frequency - ω.

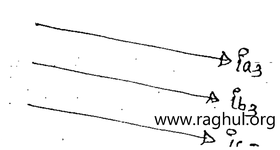
displacement (0°, 120°, 240°).

3rd Harmonic frequency - 3ω

displacement (3×0°, 3×120°, 3×240°)

(0°, 0°, 0°)



Fundamental frequency – $\omega$.

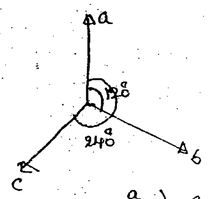
displacement $(0°, 120°, 240°)$

7th Harmonic frequency – $7\omega$

displacement $(7\times0°, 7\times120°, 7\times240°)$

$(0°, 120°, 240°)$

a b c




a, b, c — Same phase sequence of fundamental.

11th Harmonics:

phase sequence opposite to fundamental Currents.

Simply:

$n = 3k+1$ order; k – Even.

7, 13, 19 — displaced 120°

phase sequence same as fundamental.

$n = 3k-1$ order; k – Even

5, 11, 17 ... displaced by 120°.

phase sequence same as fundamental.

$n = 3k\pm1$ ; k = Even.

i.e., Group – I odd Harmonics all displaced by 120° apart means it is satisfying fundamental property of 3-$\phi$.

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Just similar to zero sequence Currents. ~~differ from 3rd harmonic~~ in power system.

In fact sequential Currents differ from 3rd Harmonic Currents

Sequential Current:

(1) Frequency same as fundamental.

(2) produced due to unbalance present in source or load.

An unbalanced situation created → unbalanced current flows.

unbalanced Currents → Zero Seq. Currents, +ve Seq. Currents, –ve Seq. Currents.

(3) Cophasor nature, but 3rd Harmonic Currents.

(1) Frequency = order (fundamental frequency)

$= 3\omega$

(2) Co-phasor in Nature.

(3) Harmonics produced due to non-linearities in ~~some~~ wave.

Harmonics of order odd multiples known as Triplen Harmonics.

Ex: $3k$ ; k-odd.

Triplen Harmonics :- 3, 9, 15, 21, ...

These 3rd Harmonic Components exactly displaced by 0 apart.

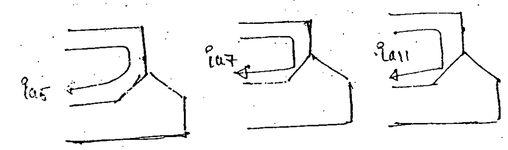
i.e. Cophasor nature.



So Instantaneous value of Currents = 0.

So $i_{a5}, i_{a7}, i_{a11}, i_{a13}$ ....

all can complete its path from line to line.

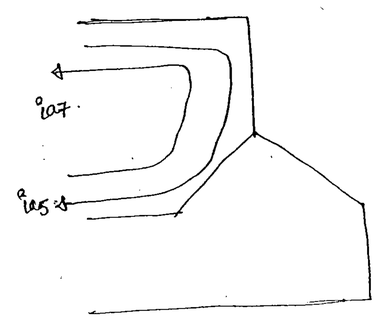



Only difference between the 5th and 7th Harmonic is opposite phase sequences.

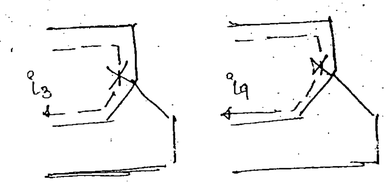
5th – Opposite to fundamental.

7th – Same as fundamental.

If 5th Harmonic Current flowing source to load. Then 7th Harmonic Current flows load to source.



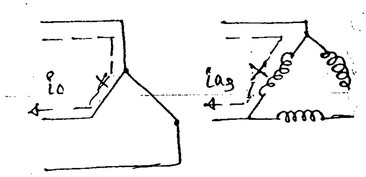

As cophasor nature it won't satisfying fundamental property of the 3-$\phi$ system.




Can't complete its path from one line to other line.

Similarly zero sequence Currents as Co-phasor nature these also won't satisfy 3-$\phi$ fundamental property.

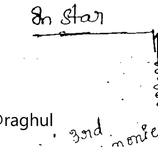
So zero sequence Currents can't complete its path from line to line.




Note:- But these cophasor nature Currents (Triplen harmonic Currents, zero sequence Currents)

In 3-$\phi$ can complete its path; if there is a closed path within its phase.

In star



3rd harmonic Current absent.

closed path available from – line to line.

But closed path not

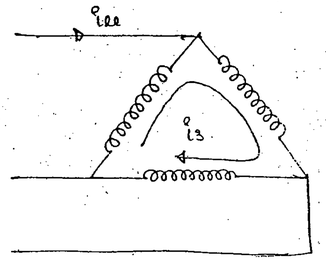
∴ 3rd Harmonic absent in Y.

$i_{ee}$ — Shape: Sinusoidal.

$\phi$ — getg flat topped (∵ presence of 3rd Harmonic $\phi$).

e — peaky.

But in Delta System:




∴ closed path within itg phaseg.

Conclusion in 3-phase System:-

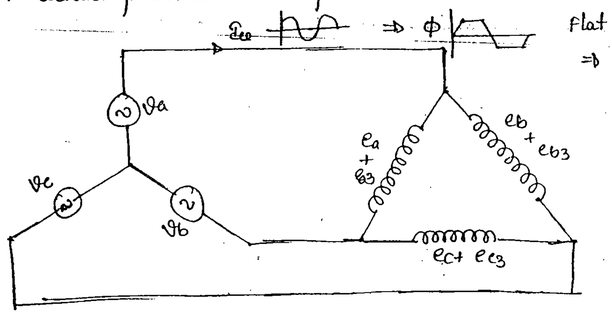
To generate pure Sinusoidal Emf — $\phi$ must be Sinusoidal — $i_{ee}$ must contain 3rd Harmonic Current — So System must contain ~~closed~~ closed paths within itg phaseg.

(for flow of Cophasor nature ~~for~~ Currentg)

→ To have clear Concept Y, Δ System:

Regarding generation of 3rd Harmonic Currentg.

In actual practice most practical Source are Y Connected.

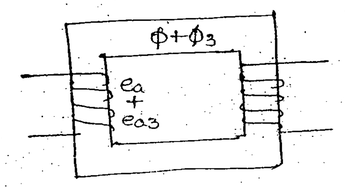



Flat topped

$\Rightarrow \phi = \phi_1 + \phi_3$ → Due to non-linearity of Core.



Forget 5th & 7th Higher order Harmonics.




upto this instant induced Emf Non-Sinusoidal

$V_1 = -e_1$

i.e., $e_a, e_b, e_c$ well balanced by Source voltages, $V_a, V_b, V_c$ to satisfy Kirch's law.

But 3rd Harmonic Emf; $e_{a3}, e_{b3}, e_{c3}$ not balanced by Source. Since not Consisting 3rd Harmonic Emf.

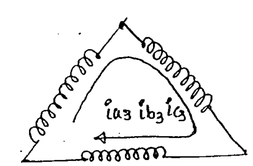
So $e_{a3}, e_{b3}, e_{c3}$ left unbalanced and these unbalanced Emfs cause drive some harmonic Current if there is closed path in Circuit.

∴ 3rd Harmonic Emfs — Cophasor nature.

Can produce 3rd Harmonic Currentg — also Cophasor nature.

3rd Harmonic Currentg can't complete itg path in line to line as not satisfying fundamental property of 3-$\phi$.

In Δ - System:- There is a closed path within itg phase. So $i_{a3}, i_{b3}, i_{c3}$ can flow in Δ. Now;




Shape of Emf ⇒ Sinusoidal.

One Harmonic Currentg present;

(1) Harmonic Current flux compensateg the actual 3rd Harmonic flux.

So Δ ~~of~~ itself generating peaky wave of $i_{ee}$.



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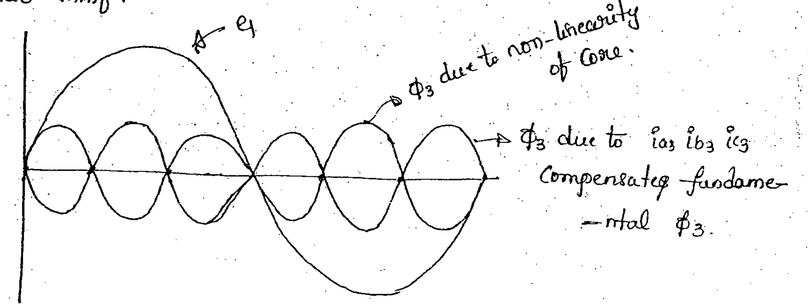
3rd Harmonic current direction found by Len's law. It opposes very cause of its producing. Main cause of production of $i_{a3}$, $i_{b3}$ and $i_{c3}$ is the non-linearity in 3rd Harmonic flux.

These 3rd Harmonic currents produce a flux in such a way that it produce a compensating 3rd Harmonic mmf. to nullify original 3rd Harmonic mmf.




So continuously $\phi_3$ compensated resultant $\phi$ in core at any instant of time is sinusoidal. So induced emf is pure sinusoidal, as $i_{a3}$, $i_{b3}$, $i_{c3}$ present in system.

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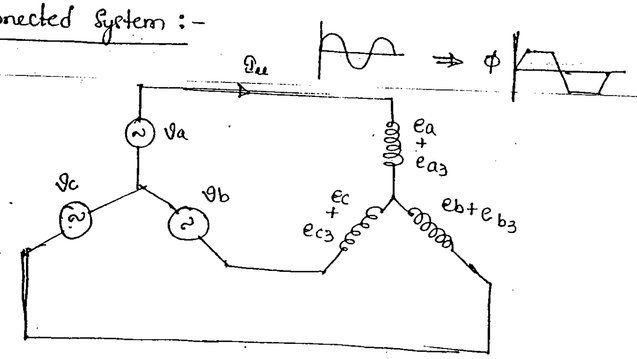
## Observation in this case :-

Even source not supplying 3rd Harmonic component of current. Δ connected system able to supply peaky current.

## In Y- Connected system :-






$e_a$, $e_b$ and $e_c$ well balanced by $v_a$, $v_b$ and $v_c$. $e_{a3}$, $e_{b3}$, and $e_{c3}$ not balanced by source voltage. Unbalanced $e_{a3}$, $e_{b3}$ and $e_{c3}$ can produce $i_{a3}$, $i_{b3}$ and $i_{c3}$ currents, if there is closed path with in its phases.

So 3rd Harmonic component current absent means 3rd Harmonic $\phi$ continuously present in core not nullified. So non-sinusoida emf induced.

## Conclusion on Y- System :-

As there is no provision for closed path with in its phases $\phi_3$ wont nullified so no chance to get pure sinusoidal emf.

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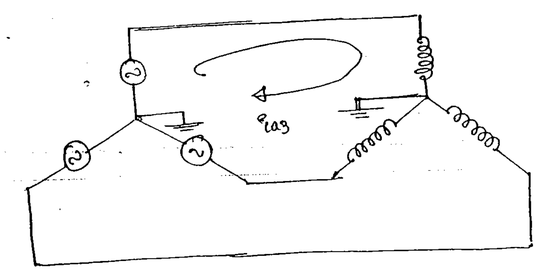
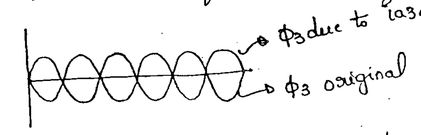
## Remedy to get Sinusoidal emf in Y- System :-

Simply ground neutral in source of load.

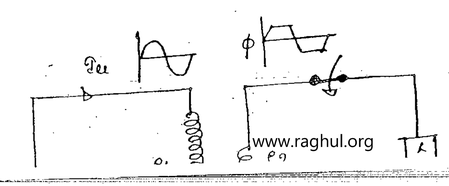



As source and load neutral grounded you can creates the closed path with in its phases means $i_{a3}$ $i_{b3}$ $i_{c3}$ flow

By Len's law $i_{a3}$, $i_{b3}$, $i_{c3}$ flow in such a direction to produce flux to compensate original $\phi_3$ so in core only fundam $\phi$ present. So pure sinusoidal emf obtained.




## In Single-phase system :-

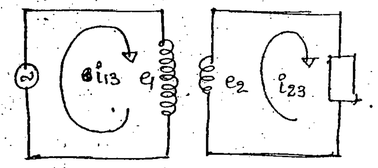



$V_1 = -e_1$

phase system. If there is closed path within in this phase.

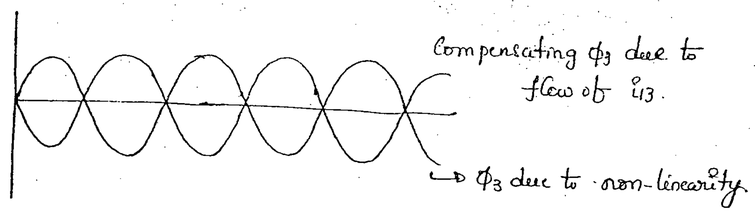
As phases having closed path $i_{13}$ and $i_{23}$ flows.






As in single phase only one phase – only one 3rd Harmonic current flows.

By Lenz's law:-




∴ Resultant Harmonic at any instant = 0 in 1-$\phi$.

So shape of Induced Emf = pure Sinusoidal.

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* Δ and 1-$\phi$ able to produce 3rd Harmonic currents by itself.

Y – without grounding unable to produce 3rd Harmonic current.

So far we have seen the sinusoidal or not. Now we shall see degree of sinusoidal (or) pure sinusoidal.

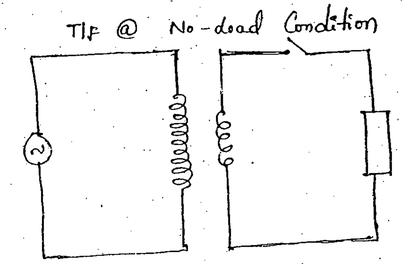
## Degree of Sinusoidal :-

Conditions required to get pure sinusoidal Emf : decided by ② factors :

**Factor (1) :-** whether 3rd Harmonic current present in both sides or not.



for ex:-




If secondary open; secondary side I will not flow. So 100% $\phi_3$ compensation not possible. May be primary side compensation of 3rd Harmonic "$\phi$".

for ex:- let @ No-load;

Compensation of 3rd Harmonic Flux only by primary let us 60%.

Compensation of 3rd Harmonic flux on secondary let us 0%.

∴ The total nullification of 3rd Harmonic $\phi$ 60% possible

Remaining 40% $\phi_3$ induces Emf in Transformer. So shape of Emf not pure sinusoidal.

for ex:- let @ on-load:-

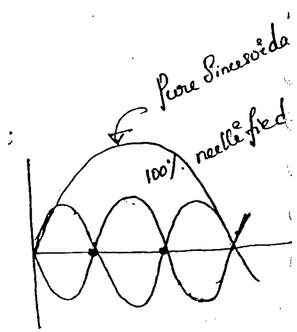
Compensation of 3rd Harmonic Flux:

from primary let us 100%.

from secondary let us 100%.

100%

Total compensating $\phi_3$ present in core.




So shape of Emf pure sinusoidal – 1-$\phi$ loaded.

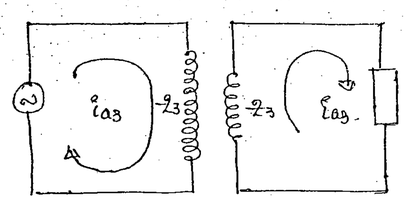
→ How Strong the 3rd Harmonic Currents ?

whenever 3rd Harmonic Current Strong Compensating 3rd Harmonic flux also Strong. So Shape of Emf pure Sinusoidal.

If 3rd Harmonic Current weak, Compensating 3rd Harmonic flux also weak.

100% nullification of $\phi_3$ not possible.

So Shape of Emf Slightly non Sinusoidal.




This strength of 3rd Harmonic Component Currents decided by 3rd Harmonic Impedance path offered by ~~the~~ System. i.e $Z_3$.

So for pure Sinusoidal voltage wave form — $Z_3$ must be low.

i.e., Impedance path offered to 3rd Harmonic Currents must be low.

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## Final Conclusion :-

For getting high degree of pure Sinusoidal :

(1) 3rd Harmonic Currents must present in both Sides of Transformer.

(2) Winding Should offer less 3rd Harmonic Impedance $Z_3$ & path must be low. to Strengthen the 3rd Harmonic Current.



## In fact :-

Non-linearity of Core is inevitable. Because Every magnetic material will have Some amount of non-linearity.

So we have to Compensate or Satisfy this non-linearity by providing different modifications in design and Connections and operation.

Before going to 3-$\phi$ Transformer discussion we shall discuss Transient Conditions in Transformer.

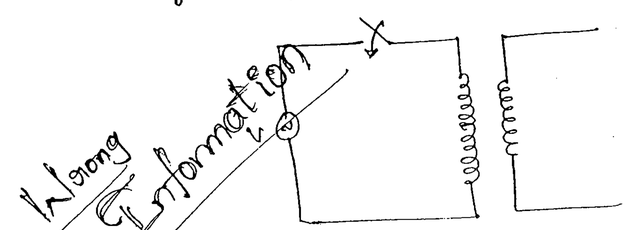
## [ Switching Transients :-

**Transient :-** Sharp and fast vibrations takes place in Electrical quantities under disturbance ~~to~~ occured on System.

Transients @ (2) types :

- ✓ Switching Transients
- ✓ Lightning Transients.

* Switching Transients more Sevious in Transformer Compared to ~~Lightn~~ lightning transients.




process of Connecting primary across Supply is ;

(1) charging the Transformer (or)

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## Transient :-

Fast and Sharp Vibrations in Electric quantities due to disturbance occured on the System.

Electric Quantities — V, I.

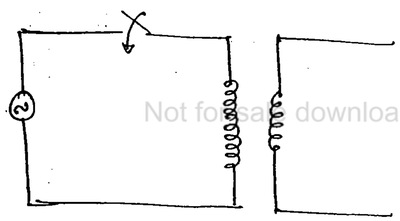
Magnetic Quantities — $\phi$.

There are Considerably (2) Transients.

(1) Lightning Transients ⇒ ∵ less occurant on System no-need to Consider.

(2) Switching Transients ⇒ ∵ Most occurant on System So more Seviour.

## Switching Transients :-



If Circuit Breaker is closed, Transformer said to be charged or Excited.

If Switch (CB) closed the moment large vibrations takes place in System quantities like V, I, $\phi$.

These Sudden large vibrations in Electric quantities said to be disturbance.

The Switching disturbance intensity depends up on the at what position of voltage wave-form Transformer Excited.

i.e., Seriousity of Switching transient decided by instant of Switching at which CB is closed.

During Switching Operation there is two cases:

(1) Most Seviour (2) Not Seviour.

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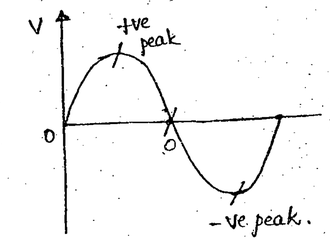
Let us Switch closed at:




**Case - I :-** Zero Crossing point :

At this Switching transients are more Seviour.

**Case - II :-** +ve peak or -ve peak :-

At this Switching transients are less Seviour (or) almost absent.

Here bad thing is Seviourity of Switching transient that can takes place is Simply our FATE.

Because we can't close our mechanical CB at what instant of wave form we want to close. i.e., we can't Switch ON Exactly @ +ve peak or -ve peak of waveform to avoid the Seviourity of Transients.

So only thing in our hands is to protect the Transformer against Switching transients irrespective of Switching position of wave.

i.e our Transformer design itself must able to withstand maximum Switching Transient.

To understand the Seviourity of Transients at different position it is must to know well about the phase relation between voltage (V) & flux ($\phi$) waveforms.

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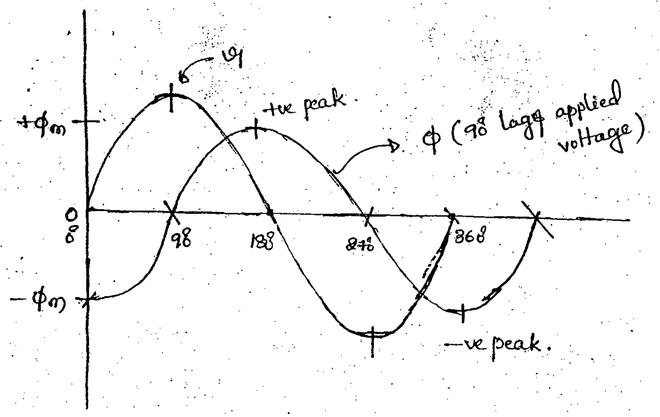
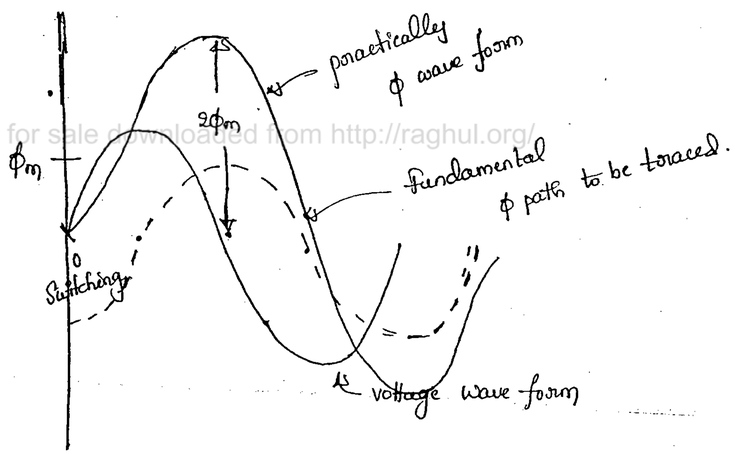



Case – I :- Switch closed @ '0' position of voltage wave : If this is the case magnetisation of core not followed by fundamental flux i.e., magnetic flux in core gets raised as shown.




If we observe the above zero switching $\phi$ wave form it is not tracing fundamental path of flux.



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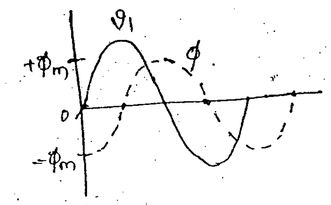
Let switch closed exactly at the '0' position of $V_1$, then theoretically fundamental flux requirement at '0' position of voltage is $-\phi_m$.




According to "Theorem of Constant flux linkages"

Instant flux can't be produced ~~to~~ due to magnet inertia. i.e., momentarly we can't create magnetic fields (flux)

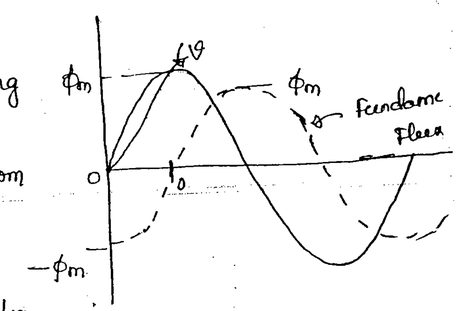
(or)

Instantaneously we cant destroy (or collapse) magnetic fields (flux)

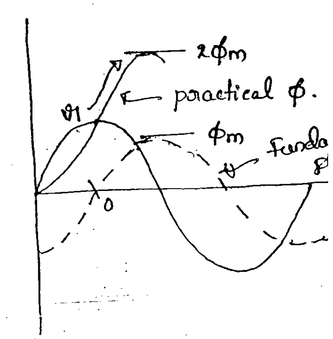
So during 1st quarter cycle of $v_1$, practically $\phi$ starts from '0' position only.

As fundamental flux raising from $-\phi_m$ to 0.

practical flux takes path from 0 to $+\phi_m$.




Now during 2nd quarter cycle of $v_1$ fundamental flux raising from 0 to $+\phi_m$ as practical flux already @ $+\phi_m$, practically flux raises from $+\phi_m$ to $+2\phi_m$.

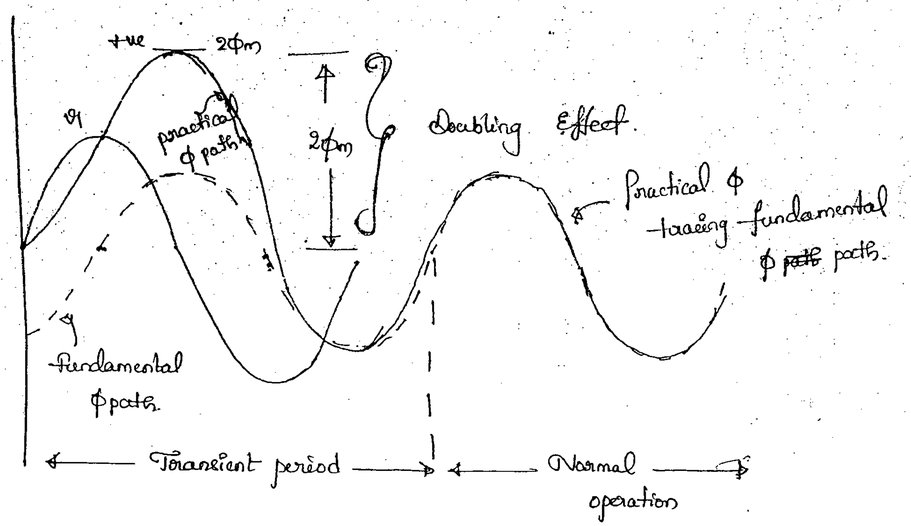



This doubling of flux is core also known as Doubling Effect

So many discomforts we shall discuss shortly.



After Doubling Effect flux again comes to its fundamental $\phi$ path as shown.




Case II :- Switch closed @ +ve or -ve peak of voltage.

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There is no complex variations in this case because if you observe the fundamental voltage & $\phi$ shape relations, this switching will satisfy same relations.

i.e., @ +ve peak $v_1$ — fundamental flux requirement '0'

So practical the moment switched $\phi = 0$.

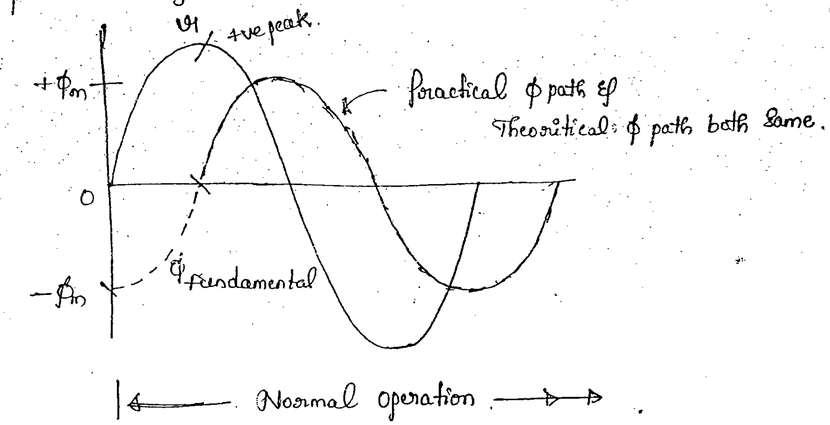
From +ve peak to 0 of $v_1$ wave;

— Fundamental $\phi$ has to raise from 0 to $\phi_m$.

— practical $\phi$ also satisfy follow the fundamental phase relation between $v$ & $\phi$.



So there is no transient behaviour in this case i.e. practical & theoritical $\phi$ paths are same as shown.

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From above two cases we can conclude that

Switching @ 0 crossing of $v_1$ — More Severer Transient (Doubling Effect)

Switching @ +ve peak or -ve peak — Absence of Transients.

## Effects of Doubling Effect on Transformer :-

As normally $E_1 = 4.44\, N_1 \phi_m f$.

$E_2 = 4.44\, N_2 \phi_m f$.

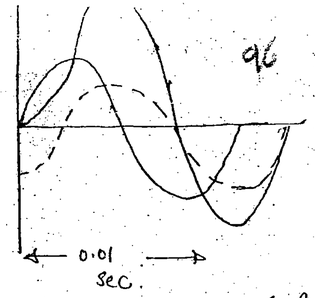
During Doubling Effect;

$E_1 \times 2 = 4.44\, N_1 \phi_m \times 2\, f$

$E_2 \times 2 = 4.44\, N_2 \phi_m \times 2\, f$.

So Induced Emf on both primary and secondary is doubling due to Doubling Effect.

But this transient Emf (or) impulse Emf occuring due to doubling Effect is Even though magnitude is very high, Existance time is very low almost 0.01 Sec.



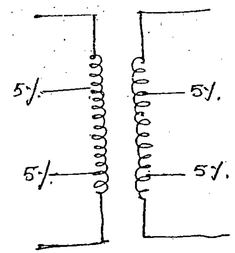

→ The Steeping nature of impulse wave is very high. i.e rate of rise of voltage during doubling is very high.

→ As transient period is 0.02 sec; as no. of turns in Transformer more, inductance also more.

Time Constant of Transformer is

$$\tau_0 = \frac{L}{R} = 0.5 \text{ Sec.}$$

of T/F



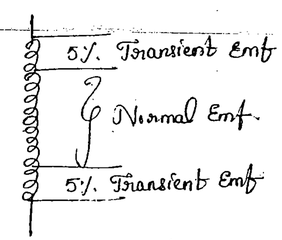

But our transient period is = 0.02 Sec.

So Doubling Effect transient Emfs are unable to penatrate into Entire winding of Transformer.

So practically these impulse voltages will ~~produce~~ penetrate upto maximum 5% of End turns on both sides of winding.

i.e., most Emf induced @ Extremes of 5% of End turns.

So remaining 90% of winding Experiencing normal voltages only.



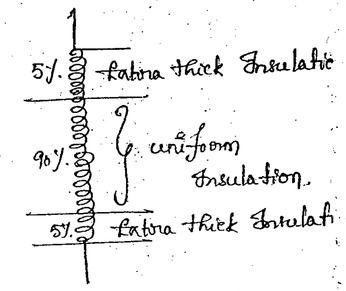

Because of higher potential stresses on the Extreme 5% turns is very much. So possibility of puncture of Inst Insulation @ Extreme turns is very high.



## Remedy for avoiding puncture of Insulation :-

Extra Insulation is provided @ both Ends of 5%.

Practically all power Transformers are like these only.



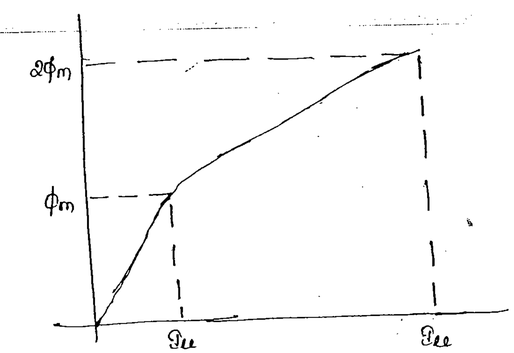

practical T/F winding.

During Doubling Effect magnetisation required for Transformer also more. So that $I_u$ required during Transient is very high.

In general : Normal magnetising Current ($I_u$) for $\phi_m$ is 5% of Full load Current.

$$I_u = 5\% \text{ of } I_{FL}.$$

i.e in PU $I_{FL} = 1$ PU ; $I_u = 0.05$ pu.




5% of $I_{FL}$
$I_u = 0.05$ pu.

100 times of $I_u$ normal.
i.e $I_u = 0.05 \times 100$
$= 5$ pu

For getting Double the $\phi_m$ during Doubling. we required [illegible] Current.



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i.e., 5 times of full load current required during doubling effect this current also called as Magnetic Inrush Current. which makes Transformer Core as deep Saturation.



## Normal Condition :-

No-load Current, $I_0$ = 5 to 6% of $I_{FL}$.

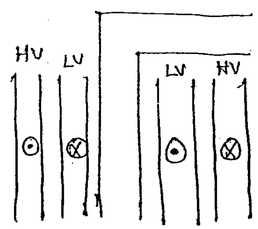
$I_1 = I_0 + I_1'$ | $I_1' = kI_2$

$I_0$ is almost negligible. $\therefore I_0$ = 5-6%.

then $N_1 I_1 \cong N_2 I_2$.

- Both sides two Ampere turns same. As per lorenta's force between two current carrying conductors.

As opposite current carrying conductors attracts. These windings are mechanically stable.




→ But due to magnetic Inrush current

No-load Current > Full load Current. → Tightly Magnetic Attraction ←

at this Situation $N_1 I_1 > N_2 I_2$.

i.e., primary Ampere turns are more. and as Ampere turns are not equal., hence repulsive force in windings are much in one direction so large mechanical stresses vibration will present which creates vibrations some times windings may dislocate also which is dangerous.

## Remedy for this Vibrations :-

To avoid this vibration we can't avoid magnetic inrush current, so we will place external mechanical support to windings by steel channels.

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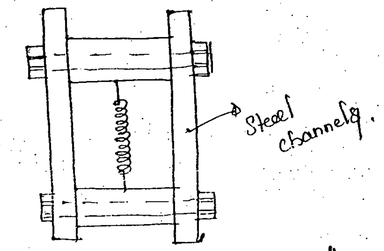
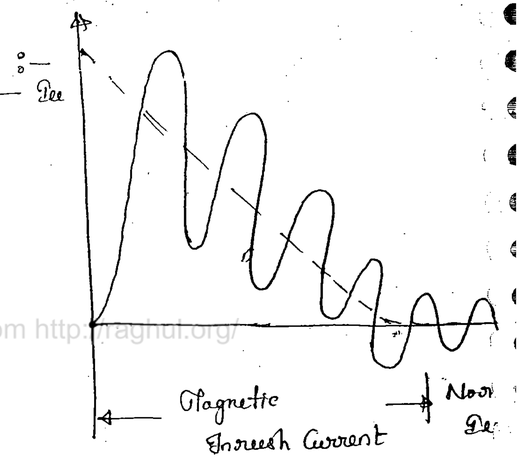



## Shape of Magnetic Inrush Current :-

If we observed magnetic Inrush current using CRO.

you will find very high +ve peaks only.




Why shape is like this ?

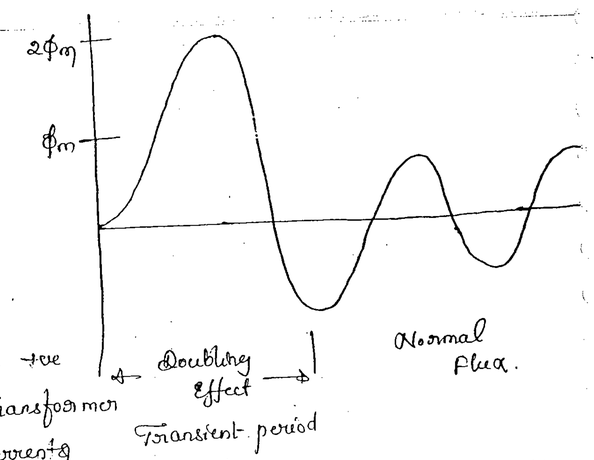
During transient in Transformer Core almost unidirectional flux only.

i.e from; 0 to $\phi_m$

$\phi_m$ to $2\phi_m$

$2\phi_m$ to $\phi_m$

$\phi_m$ to 0.




So to produce strong +ve or unidirectional flux Transformer Core it must draw DC currents from source.

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in addition with AC during transient case. So AC -ve cycles are depressed by DC current.



→ Here whole magnetic inrush current not symmetric with x-axis. Fourier analysis tells that if any wave not symmetric with x-axis. Contains both the even & odd Harmonics.

So magnetic Inrush current contains → ~~Even~~ odd Harmonics ③ 5 7 9 11 ...
→ ~~odd~~ Even Harmonics ② 4 6 8 ...

→ As normal Iu is symmetric with x-axis; normal Iu contains odd Harmonics only. i.e., 3, 5, 7, 9, 11, .....

* Richest or Dominant Harmonic in Normal Iu is 3.

Richest or Dominant Harmonic in Magnetic Inrush Iu is 2.

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* As Transformer always supplied with switching transients we don't want to trip Transformer for magnetic inrush currents.

But some times ~~tent~~ unnecessarily tripping of Transformer takes place due to magnetic inrush current.

## Transformer Generally protected by Differential protection :-

By using CT's on both sides of Transformers along with trip coil (or) operating coil.



3, So mechanical stresses during switching transients less.

4, possibility of dislocation of winding very less.

| | |
|---|---|
| Copper required more. | Copper required less. |
| ∴ Insulation required less. | High current applications. |
| HV, Small KVA applications. | Insulation required more |
| | low current applications. |
| | LV, large KVA applications. |

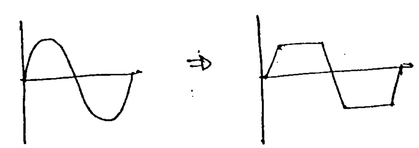
## Major Difference :-

In 1-ϕ As Iu in core sinusoidal — ϕ in core flat topped.

Consists 3rd Dominant Harmonic ϕ

(fundamental flux + 3rd Harmonic flux)

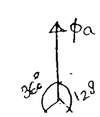
In 3-ϕ;



Fundamental flux (3ϕ) + 3rd Harmonic flux (3ϕ)

## Behaviour of 3rd Harmonic flux (ϕ) in 3-ϕ :-

3ϕ fundamental flux (ϕ) displaced by (0 120° 240°)
aph bph cph



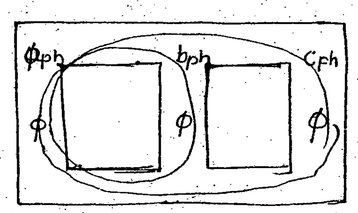

fundamental flux, ϕ satisfying 3-ϕ fundam

$\phi_a + \phi_b + \phi_c = 0$.

As fundamental flux satisfying the 3-$\phi$ fundamental property as this - '$\phi_{fund}$' can complete its path from line to line that means it can flow between any phase in core.

In core line means limbs:

$\phi_{ph}$, $\phi$ complete path through $b_{ph}$, $\phi$ and $C_{ph}$, $\phi$.




## 3rd Harmonic flux:-

3rd harmonic frequency = 3 (fundamental frequency)

$= 3\omega$.

$\Rightarrow (3\times 0 \quad 3\times 120^\circ \quad 3\times 240^\circ)$

$\Rightarrow (0 \quad 0 \quad 0)$

So displacement of 3rd Harmonic flux = 0.

$\phi_{a3}$, $\phi_{b3}$, $\phi_{c3}$ Co-phasor nature.

As 3rd Harmonic currents co-phasor nature,

So 3rd Harmonic $\phi$ also co-phasor ~~nature~~ nature.

So (1) 3rd Harmonic flux — not displaced by $120^\circ$.

(2) 3rd Harmonic flux - not instantaneous $\phi \neq 0$.

($\because$ Co-phasor Nature)

~~3rd Harmonic flux not satisfying the 3-$\phi$.~~

So 3rd Harmonic flux can't complete its path through line to line ×.

but it can complete its path phase to phase.

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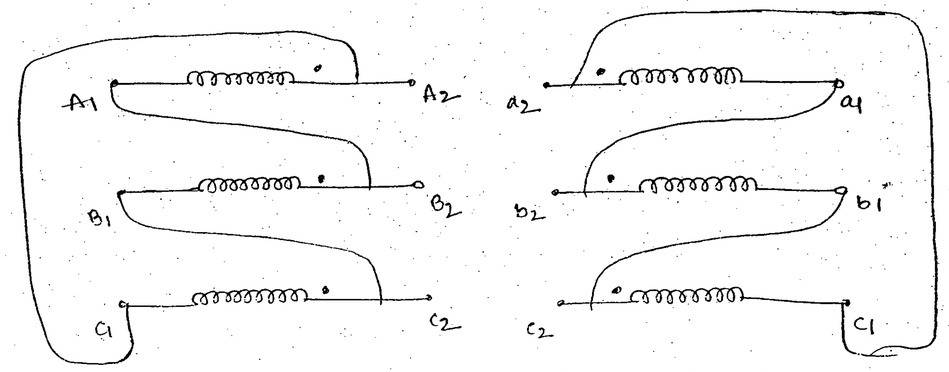


Generally phase sequences used in 3-$\phi$ mostly.

A, B, C — $A_2 - B_2$, $B_2 - C_2$, $C_2 - A_2$.

Rarely in 3-$\phi$ we ~~also~~ use reverse of ABC phase sequence.

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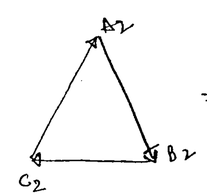
Based on vertices you have to keep phases.

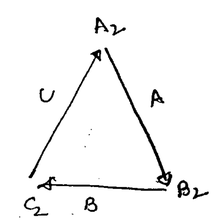
Draw Obbitory - $\Delta$ - on primary

Consider on phase sequence; A, B, C — $A_2 \rightarrow B_2$, $B_2 \rightarrow C_2$, $C_2 \rightarrow A_2$

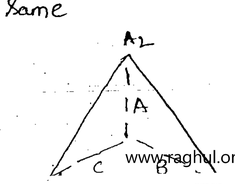
put vertices as per phase sequence

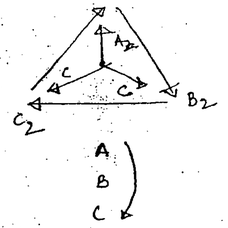


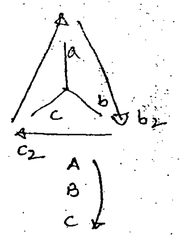

$\Rightarrow$ put phases based on connection diagram




To draw equivalent Y keep phases same as touching point vertices.



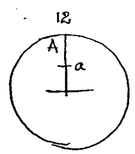



Now Superimpose the Secondary phases on primary; then you find '0' displacement. Commercially to know the displacement on vector group ~~they~~ we use clock notation.

In which primary indicates — minutes needle
Secondary indicates — Hours needle.

In above Δ – Δ Case :–




$Dd_{12}$ Connections.

In Some text books $Dd_{12}$ Considered as reference So $Dd_{12} = Dd_0$.

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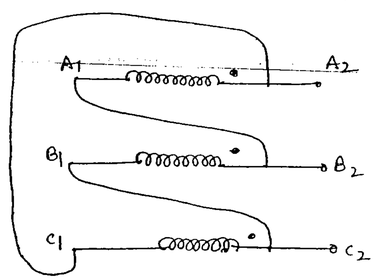
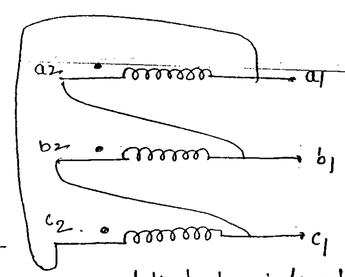
→ If you want one more displacement diagram; Just change Secondary Connections i.e., dotted terminals phase Connected to undotted phase.



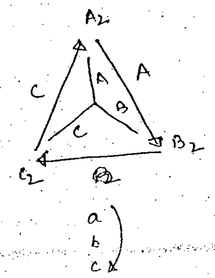

dotted terminals out

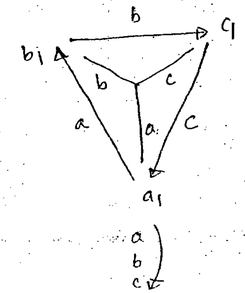



undotted terminals out.

So draw Secondary ~~pat~~ parallel in opposite direction.



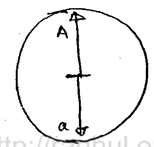



Source

output Induced

To know Commercial vector group :–




Dd6

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In clock 1 hour = 30°

∴ 6 '0' clock = 6 × 30° = 180°

In Δ – Δ Even you change primary side Connections also you will find only 180° or 0° displacement only.

→ Before going to discuss about Δ – Δ features i would like to give Emf equation in 3-ϕ Transformer :-

Emf Equation in 1-ϕ Transformer

$E_1 = 4.44\, N_1 B_m A_n f$.

$E_2 = 4.44\, N_2 B_m A_n f$.

In 3-ϕ, total we Consist 3-phases.

Each phase Consists Some number of turns.

per phase turns :-

$N_1/ph$ = No. of turns/ph on primary

$N_2/ph$ = No. of turns/ph on Secondary

$E_1/ph = 4.44\ N_1/ph\ B_m A_n f.$

$E_2/ph = 4.44\ N_2/ph\ B_m A_n f.$

* line voltages can be obtained from connection diagram:

  for ~~fa~~ Δ - Connection ⇒ line voltage = phase voltage.

  for ~~fa~~ Y - Connection ⇒ line voltage = $\sqrt{3}$ × phase voltage.

* generally turns Ratio ⇒ $N_1 : N_2 = E_1 : E_2$.

  In 3-φ we can define two turns ratios.

  phase turns Ratio ⇒ $E_1/ph : E_2/ph$

  $N_1/ph : N_2/ph$.

In 3-φ

* line turns ratio can be obtained after knowing connection diagram only.

  line turns Ratio = primary line voltage : Secondary line voltage.

So we can obtain two transformation ratios:

i.e., (1) phase Transformation ratio

(2) line Transformation ratio.

One ~~deg~~ design completed phase turns ratio constant, line turns ratio not constant.

∵ line turns ratio varies with type of connection.

**Note:-**

unless otherwise specified turns ratio means phase turns ratio only.

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Ex:- In name plate if $N_1 : N_2 = 3:1$ given then it is phase turns ratio only.

→ **Note:-** Name plate details specified line turns ratio only.

Ex: i.e 220 kV/132 kV on name plate gives the line turns ratio.

Y/Δ Transformer

Ex: 220 kV/132 kV Y/Δ —Converted to→ Δ/Y turns ratio's = ?

| Y | Δ |
|---|---|
| $V_1/ph$ | : $V_2/ph$ |
| $\frac{220}{\sqrt{3}}$ kV | : 132 kV. |

once design completed phase turns ratio constant.

so $V_1/ph$ : $V_2/ph$.

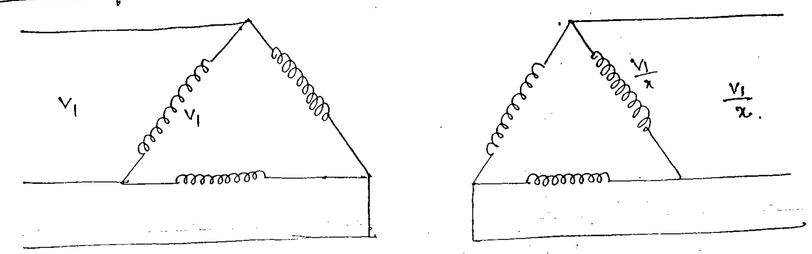
$\frac{220}{\sqrt{3}}$ : 132 kV.

for line (turns ratio) voltages you need to know connections.

| Δ | Y |
|---|---|
| $\frac{220}{\sqrt{3}}$ kV | : $132 \times \sqrt{3}$. |

* phase turns ratio depends on design conditions.
* line turns ratio depends on type of connections.

*** Features of Δ - Δ Transformer Connection:-




phase turns ratio x : 1.

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the $\boxed{\text{phase turns ratio} = \text{line turns ratio}}$

If phase voltage on primary $= V_1$ Secondary voltage per phase $= \frac{V_1}{2}$.

| Δ | Δ | Y | Y |
|---|---|---|---|
| $V_1/ph$ | $= V_L$ | $V_1/ph$ | $= V_L/\sqrt{3}$ |
| $I_1/ph$ | $= I_L/\sqrt{3}$ | $I_1/ph$ | $= I_L$. |

→ In any Transformer number of turns required decided by phase voltage required:

So phase voltage can't increased untill turns increased.

$$\boxed{V_1/ph \propto N_1/ph}$$

But line voltage can varied by changing connections.

Example:

| Δ – Δ | Y – Y |
|---|---|
| 220 kV / 132 kV | 220 kV / 132 kV |
| $N_1/ph \propto 220$ kV. | $N_1/ph \propto \frac{220}{\sqrt{3}}$ kV |
| $N_2/ph \propto 132$ kV. | $N_2/ph \propto \frac{132}{\sqrt{3}}$ kV. |

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57.7% turns in Y-Y Transformer $\frac{1}{\sqrt{3}} = 57.7\%$

* from above Δ – Δ – requires – 100% turns.
for certain fixed voltage Y – Y – requires – 57.7% turns only.



→ Insulation Requirement based on phase voltage:-

Design the Insulation:

| Δ – Δ | Y – Y |
|---|---|
| 220/132 kV. | 220 kV / 132 kV. |
| LV insulation thickness $\propto$ 132 kV. | LV Insulation thickness $\propto \frac{132}{\sqrt{3}}$ kV. |
| HV Insulation thickness $\propto$ (220 – 132 kV) | HV Insulation thickness $\propto \left(\frac{220}{\sqrt{3}} - \frac{132}{\sqrt{3}}\right)$ kV |

57.7% Insulation in Y-Y Transformer.

From above for Δ – Δ requires 100% insulation.
a fixed phase voltage Y – Y requires 57.7% insulation.

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* X-Section of Conductor required based on phase current rating. Iph

Line current : is resultant currents due to phases.
it wont flow through phase winding.

phase current : flows through phase windings.

Design Conductor X-Section:

| Δ – Δ | Y – Y |
|---|---|
| $I_1/ph = \frac{I_L}{\sqrt{3}}$ | $I_1/ph = I_L$ |

57.7% X-Section in Δ – Δ Transformer.

for a fixed phase current rating : Δ – Δ requires 57.7% X-Section.
Y – Y requires 100% X-Section.

Economical : HV applications – Y–Y  Saving in Insulation
(∵ voltage/ph possible with less turns)

High Current Applications – Δ–Δ. Saving in Conductor X-Section)
(∵ Current/ph possible with less X-Section)

| | |
|---|---|
| Δ – Δ | : Low Voltage, Large kVA Transformer |
| Y – Y | : High Voltage; Small kVA Transformer |

~~Most Economical Cases~~ :–

~~Δ/Δ – Low Voltage~~

$V_L = V_{ph}$ | $V_L = \sqrt{3} V_{ph}$

$I_L = \sqrt{3} I_{ph}$

Δ – Δ Drawbacks :-

(1) Mechanical Strength of Winding :-

Δ – Δ less X-Section  Y–Y large X-Section.
So good Mech. strength of winding.

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(2) More Striking Voltage during Transients :-

Any Conductor can be treated as Cylindrical Capacitor.
Medium Surrounding Conductor air acts like – dielectric.

Conductor

$\uparrow C = \pi \varepsilon_0 d \uparrow$  $\varepsilon_0$ : air permitivity
d : dia. of Conductor.

If dia more : Electro Static Capacitance More.

→ If more the dia of Conductor, more the Electrostatic Capacitance of winding more.



During Switching of Transients Conditions :

the impulse voltage generated easily bypassed on striking voltage during transient period very less.

So for large dia winding – Impulse Voltage Impact low
Transients gets less Effects to winding.

∵ C↑ larger capacitance Tank
large dielectric strength,
less effected to sudden change in voltages.

So damage to winding low in transient period.

→ As Y–Y – large dia winding – less Effected in transient period
Δ–Δ – less dia winding – Most Effected in Transient period.

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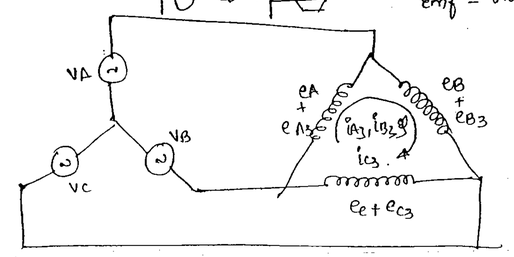
* Degree of priority in Sinusoidal Emf of Δ–Δ Connection :-

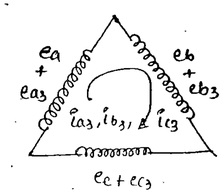
As Δ–Δ closed path with in its phases possibility to flow 3rd Harmonic Current.

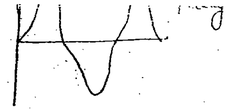
So priority of Sinusoidal Emf is very high. Even you used 5 limbed shell type core, with Δ–Δ winding degree of priority in Sinusoidal ~~emf~~ very high.

Basic Concept required to analyse any Transformer Connection :-

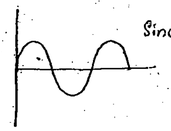
In ⇒  Emf – Non Sinusoidal.



⇒ 

$V_A, V_B, V_C$ well balanced by $e_A, e_B, e_C$ to satisfy Lenz's law.

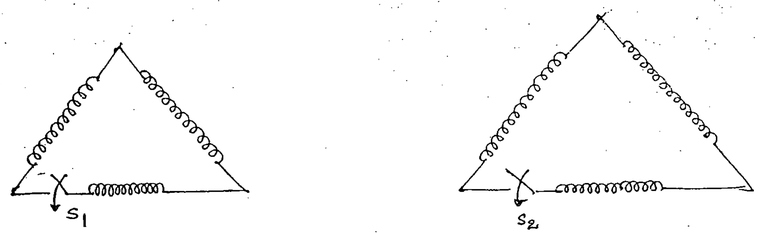
⇒ Emf, e  Sinusoidal

But $e_{A3}, e_{B3}, e_{C3}$ not balanced & driven current. $i_{A3}, i_{B3}, i_{C3}$.

As $i_{A3} + i_{B3} + i_{C3}$ presents.

* at any instant shape of induced Emf Sinusoidal.
* If shape of $i_u$ is peaky.

→




If $S_1$ & $S_2$ open ⇒ primary $i_u$ Sinusoidal ; $\phi$ flattopped with strong 3rd Harmonic

$S_1$ & $S_2$ open ⇒ Secondary $i_u$ - no current ; Emf, e - non-Sinusoidal.

If $S_1$ & $S_2$ close ⇒ primary $i_u$ - peaky ; $\phi$ - Sinusoidal.

Secondary $i_u$ - only 3rd Harmonic present ; E - Sinusoidal.

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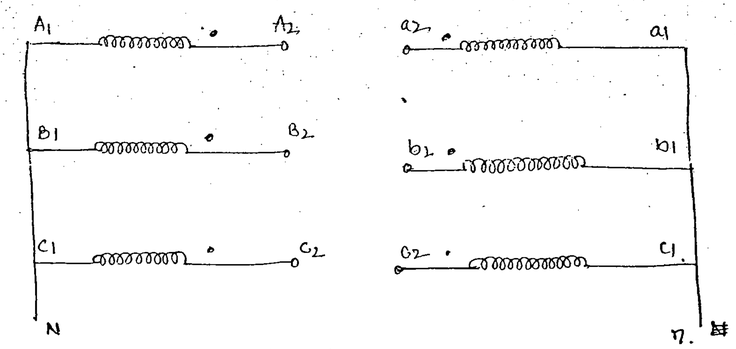
## (2) Y – Y Transformer Connection :-

Mostly Economical for :




After Polarity test : both sides dot outs.

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One of Y – Connection :-

Join undotted terminals @ primary to obtain N.

Join undotted terminals @ Secondary to obtain n.

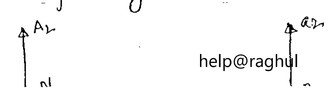
To get vector group (or) phase displacement for given Connection :

(1) Draw Orbitary Y @ primary with A B C ↓ phase Sequence.

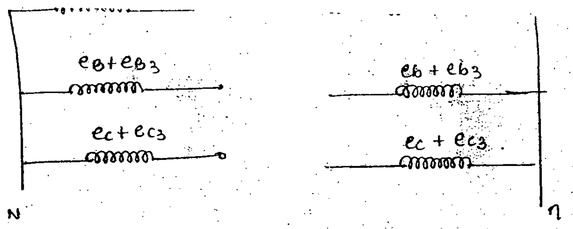
Name phases as per Connection.

As both sides dot outs draw Secondary phases parallel with primary in same direction follow A B C ↓ phase Sequence.

As both sides same phase sequence you can compare Secondary phases with primary.




Commercial Star replace




Fundamental Emfs $e_A$ $e_B$ $e_C$ displaced Exactly — 120° Elec.

If you use $\Delta - \Delta$ : $e_{A3}$ $e_{B3}$ $e_{C3}$ displaced Exactly — 0° E

$\because$ $i_{A3}$ $i_{B3}$ $i_{C3}$ presents So $e_{A3}, e_{B3}, e_{C3} = 0$.

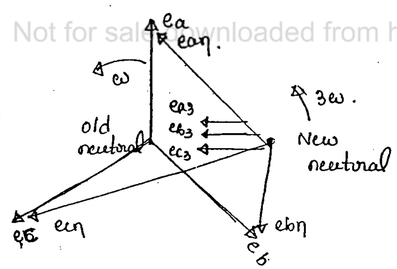
If you use Y – Y $e_{A3}$ $e_{B3}$ $e_{C3}$ presents and displaced by 0° Elec.

Since 3rd Harmonics Cophasor nature.

$i_{A3}$ $i_{B3}$ $i_{C3} = 0$ So $e_{A3}$ $e_{B3}$ $e_{C3} \neq 0$.

If you observe the phase voltages and line voltages with 3rd Harmonic Emfs in Y – Y Connection.

Vector diagram @ 0° E position.




phase voltages ; $e_{an} = e_a + e_{a3}$

$e_{bn} = e_b + e_{b3}$

$e_{cn} = e_c + e_{c3}$.

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Drawbacks of Y – Y in 5 limbed Shell :– If 3-φ Bank only not in Core type :–

(1) So neutral shifted from its original position.

(2) And phase voltages not maintained their 120° phase shift.

(3) $e_{an}$ – medium $e_{bn}$ – low $e_{cn}$ – very High.

at one instant.

at one neutral position different phase voltages obtaining.

possibility of phase loads damages

(4) 3rd Harmonic Speed = (fundamental speed) × 3.

fundamental rotating @ ω rad/sec.

3rd Harmonic rotating @ 3ω rad/sec.

Relative Speed between fundamental & 3rd Harmonic vector

@ $(3\omega - \omega) = 2\omega$ rad/sec.

So Neutral not only shifted its position neutral point rotating continuously rotating.

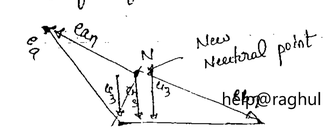
This phenomenon (or) condition of neutral rotation in Y – Y binding is

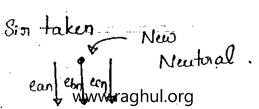
Floating point of Neutral ✗ Floating point of Neutral ✓

(or)

Oscillating Neutral Oscillating Neutral. ✓

After 30° shift of fundamental vector :

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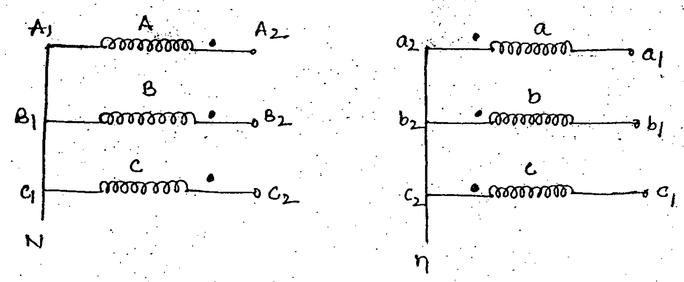
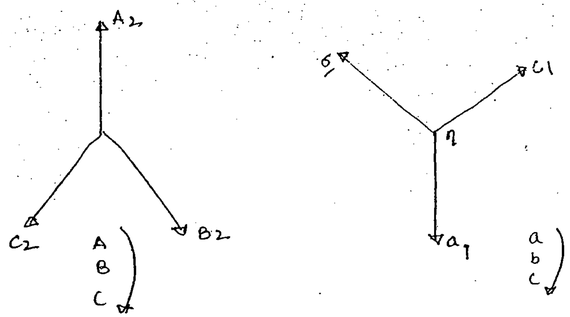
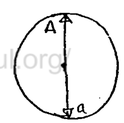
Just join Secondary Side all dotted terminals.




Vector group : Yy 6.

∴ 180° phase displacement.

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Features of Y-Y Connection:

Y . . Y

Turns Ratio : $x$ : 1.

* As both sides Connections Same ( Δ-Δ or Y-Y)

$$\boxed{\text{phase Voltage ratio} = \text{line Voltage ratio}}$$

* line Voltages $V_1$ : $\frac{V_1}{x}$.
* phase voltages $\frac{V_1}{\sqrt{3}}$ : $\frac{V_1}{\sqrt{3}\,x}$.



* Amount of Insulation in (Y-Y) – 57.7% only Compared to Δ-Δ
* X-Section Conductor in (Y-Y) is more ( ∵ $I_{ph} = I_L$)
* Economical (Y-Y) for High Voltage, Small kVA applications.

Example:- 1000 kVA, 132/220 kV Transformer, which winding = ?

15MVA Large MVA; 1000 kVA means low kVA So here } Y-Y Economical.
132/220 kV large voltage So here

* Since X-Section more damage due to impulse voltage strikes in Y-Y is very very low.
* No closed paths within its phases in Y-Y So no path for 3rd Harmonic Currents.
* So shape of Emf non Sinusoidal, if 5 limbed shell or 3φ Bank } Core used.

→ Drawbacks of Y-Y Connections :-

∵ In 5 limbed shell type Core of 3-φ bank Construction.

1. Shape of Emf non-Sinusoidal.
2. So non-Sinusoidal Emf means two Emfs induced in each phase : fundamental Emf ($e_A$ $e_B$ $e_C$)
   + +
   3rd Harmonic Emf ($e_{A3} + e_{B3} + e_{C3}$)

$e_A$ $e_B$ $e_C$ well balanced by $V_A$ $V_B$ $V_C$.

$e_{A3}$ $e_{B3}$ $e_{C3}$ not balanced of no closed paths for $i_{A3}, i_{B3}, i_{C3}$ within its ~~phase~~ phase.

3rd Harmonic rotation = (rotation of Fundamental Vector) × 3.

= 30 × 3

= 90° shift.

So 3rd Harmonics — Cophasors Comes into ⊥ state.

So now new neutral point Comes into picture.

So now voltages at different phases.

So as phase voltages levels largely fluctuations in Y-Y Connections due to floating point neutral Condition.

(4) * Y-Y winding unfit for Single-phase loads So dont Connect Y-Y to 1-φ load operation.

But line to line voltages not changing due to floating point neutral.

* due to line voltage not getting Effected in Y-Y winding Even presence of 3rd Harmonic Emf Component in 5 limbed Core.

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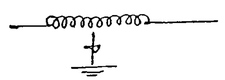
* 3rd Harmonics are nullifying, due to its Cophasor nature, while Coming into line to line. That why no Effect of 3rd Harmonic in line to line.

Since No 3rd Harmonic in lines, so you can operate 3-φ loads.

→ Earth Fault failure :-

5, Most dangerous fault in Transformer is Earth fault.



To avoid this we will place Earth fault relay. Major parts of Earth fault Current is Zero Sequence Current. Now this Earth fault relay Searching or gets activated for Zero Sequence Current in winding.



If Earth fault Current is very weak Earth fault wont operate, no tripping takes place, Even physically Earth fault Current Existing.

At this Condition if Transformer not tripped diffinitely it Causes very big damage or Serious Situation in Transformer.

This Situation (weak Earth Current) raises only if Y-Y Connection used in 5 limbed shell type or 3-φ Bank.

As Earth fault raised Zero Sequence Current present in winding, so Zero Sequence flux Comes into Transformer winding.

As Zero Sequence Current — Cophasor

Zero Sequence φ — also Cophasor just like 3rd Harmonic φ.

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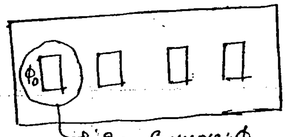
So this Cophasor Zero Sequence φ can Complete its path in 5 limbed Shell Core (or) 3-φ bank Core.

Now in addition with — fundamental Emf
+
Zero Sequence Emf
due to Earth fault Zero Sequence Current φ.




Zero Sequence Emf's direction by lenz's opposes its Cause of direction.
i.e., Earth fault flow of Current.

That means Earth fault Current restricted ~~to~~ or weakend or opposed by Zero Sequence flux 'φ'.

So Earth Current weakend to so Earth fault relay is not able to detect which is undesirable thing, it may damages Crores of rupees due to Earth fault occur.

This draw back of Earth fault current is very most serious in the Synchronous generators / Transformers of power systems.



So the moment Earth fault raise / Earth fault relay must trip transformer.

But this zero sequence flux ~~taking~~ takes placing in Y-Y 5 limbed shell of 3-φ Bank only.

But in 3-limbed core type;

No change to Existance of Cophasor φ in core. (∵ No closed path with in ith phase).

So no restriction to Earth fault current. So Earth fault current is strong so our Earth fault relay can easily detect.

* All above draw backs in Y-Y are simply due to no closed path providing in Y-Y for 3rd Harmonic Component Current.

Remedy is to overcome draw back of Y-Y Transformer with 5 limbed core of 3-φ Bank. To avoid this situation, we have to take some modifications in windings.

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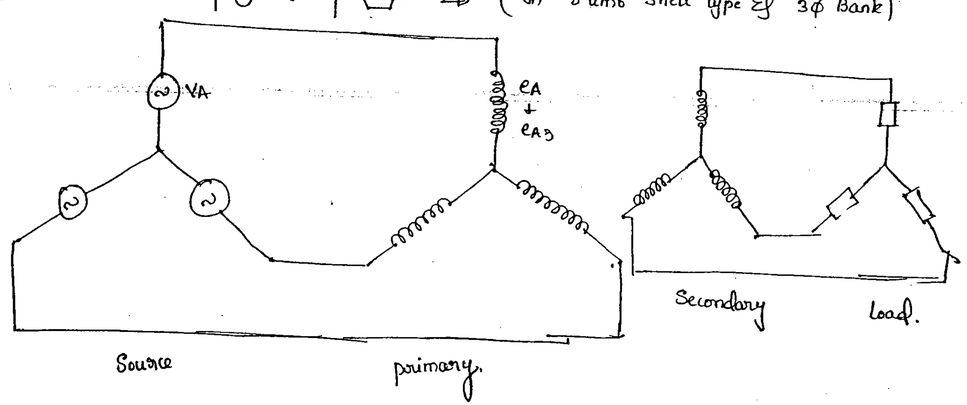
① $i_u$ ⇒ φ ⇒ (In 5 limb shell type of 3φ Bank)






Since closed path with in ith phase;

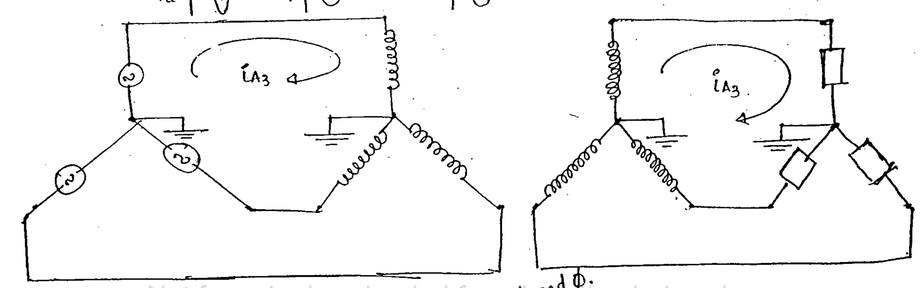
$i_u$ — Sinusoidal

φ — Flat topped

emf, e — Non-Sinusoidal

After modification:-

$i_u$ ⇒ φ ⇒ emf, e

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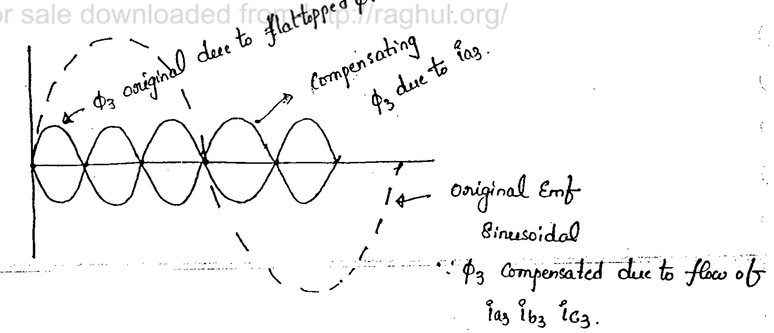



As source of primary neutral ground provides, paths to 3rd Harmonic Current $i_{A3}$ $i_{B3}$ $i_{C3}$ with in ith phase.

Which produces flux $\phi_3$ to compensate original $\phi_3$.

So induced Emf @ primary, Similarly @ Secondary.

One Harmonics Absent :-

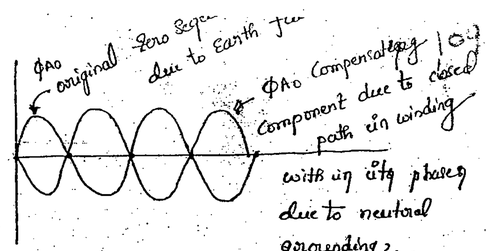
(1) Emf Sinusoidal.

(2) no floating point neutral.

(3) no neutral shifting.

inducing $e_{A0}$ $e_{B0}$ $e_{C0}$.

But these zero sequence emfs not well balanced by source voltages so the $e_{A0}$ $e_{B0}$ $e_{C0}$ drive $i_{A0}$ $i_{B0}$ $i_{C0}$. Since closed path with in city phase windings due to neutral, which producing a compensating flux $\phi_{A0}$ to nullify original zero sequence flux.




100% elimination of all problems not solved by neutral grounding.

Since 100% neutralisation possible, if perfect neutral present. and if 3rd Harmonic current impedance path low, but practically 3rd Harmonic impedance offered by system not a low value.

Ex:- In power system 100 km line length have to consider for 3rd Harmonic Impedance path. ∴ G.S. far away from T/F @ receiving end, some amount of 3rd Harmonic is present. So again slight oscillation of neutral is small.

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[ By neutral ground intensity of problem only reduced but not 100% fault nullification; but if you have low 3rd Harmonic Impedance path to flow of $i_{a3}$ $i_{b3}$ $i_{c3}$, it is possible 100% of nullification of 3rd Harmonics possible. It is practically possible by providing tertiary winding of ~~low~~ low impedance winding provided @ Secondary with in Transformer itself. So problem in neutral grounding overcome by Tertiary winding.]



For complete elimination of problems in Y-Y connection, we must use tertiary winding @ Secondary. This also called as ③ winding T/F. Since one winding in primary & two windings in Secondary. & tertiary must be in Δ with low impedance path.

## Features of Tertiary Winding (or) Stabilising Winding :-

(1) Tertiary winding makes or eliminates zero sequence & 3rd Harmonic flux.

(2) Tertiary winding shifts the neutral point to original position.

(3) Tertiary winding stabilised the neutral point in Y-Y Transformer.

(4) Tertiary winding allows the Transformer phase load applications so we can use as distribution network.

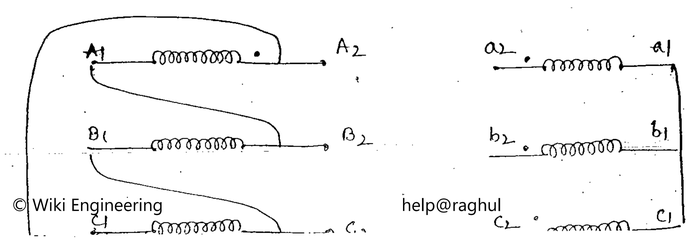
(5) It reduces restriction for the flow of Earth fault current.

One Tertiary winding present in Transformer satisfactory operation we can obtained.

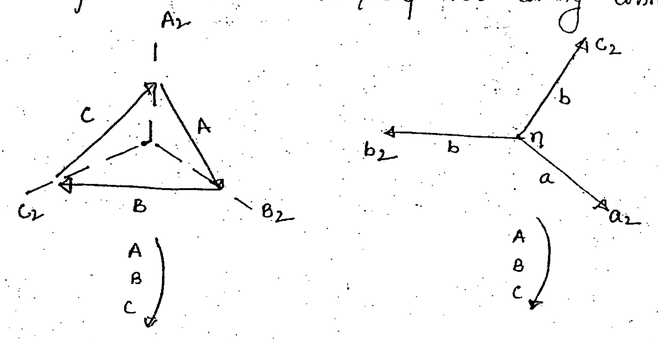
Most popular in power system.

## → Δ/Y Connected Transformer :-

possible connection diagram:



must provide dotted terminals out coming connections.




First directions of vectors must be assign based on the phase sequence.

Generally usual phase sequence of 3-ϕ is A B C

Vertices touching points gives phases of equivalent star.

As phase sequence on both sides same you can compare both primary & secondary.

To find vector group (or) phase group;

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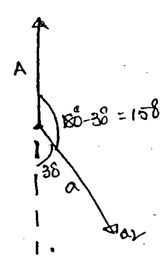
Simply over impose secondary on primary;




150° Connection

Source voltage & secondary voltage displaced by 150°.

Commercially phase group (or) Vector group ⇒ Dy5

5 '0' clock connection ;

Secondary
a - Hing (5)
primary
Δ - mins (12).

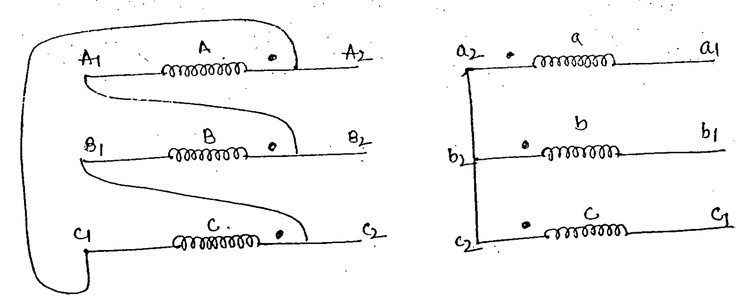


Δ - Y not producing 0° connection.

for observing one more Δ/Y connection.

dont change primary dot outs.

Simply change secondary.

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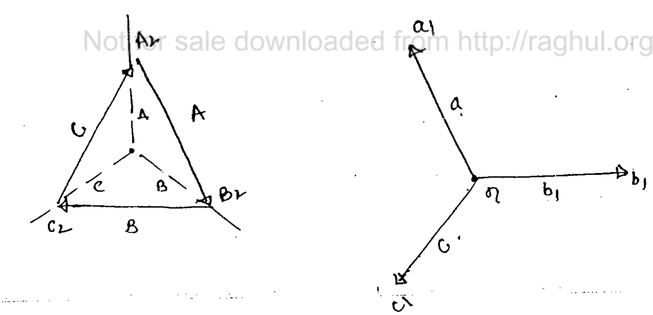
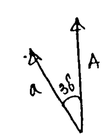



11° clock.

Vector group : Dy11

+30° Connection.

That means load voltage advanced by 30° to source voltage.

To get one more connection change primary side connections in such a way;

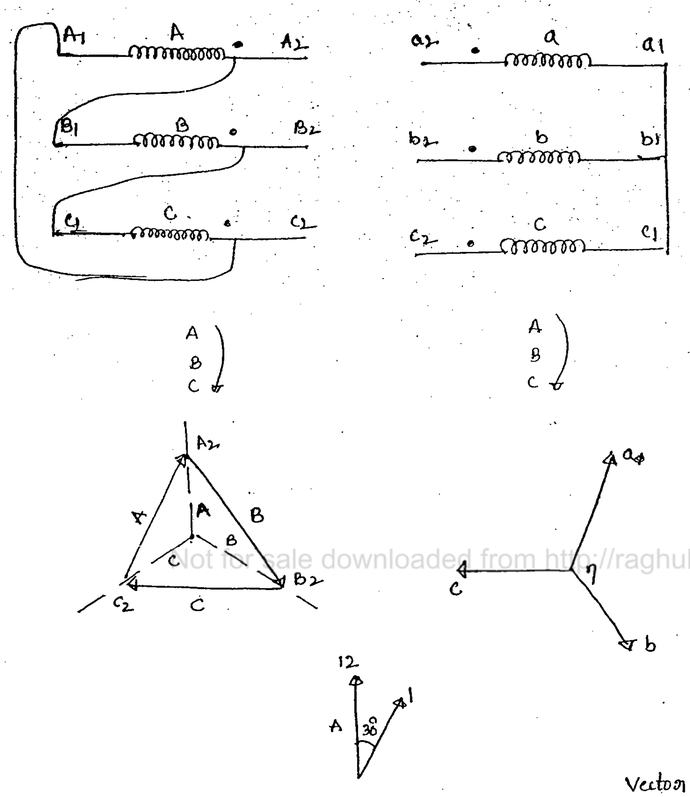
outcoming primary — dotted terminals.

change primary in — connected dotted terminals

## ② different Connections of Transformer.

(1) Neutral @ Secondary all dotted short ckt.

(2) Neutral @ Secondary undotted short ckt.




Source Voltage leads load voltage by 30°.

1 'O' clock Connection

− 30° Connection

Vector group of $DY_1$.

For one more Connection keep primary as it is & change Secondary with dotted terminals out.

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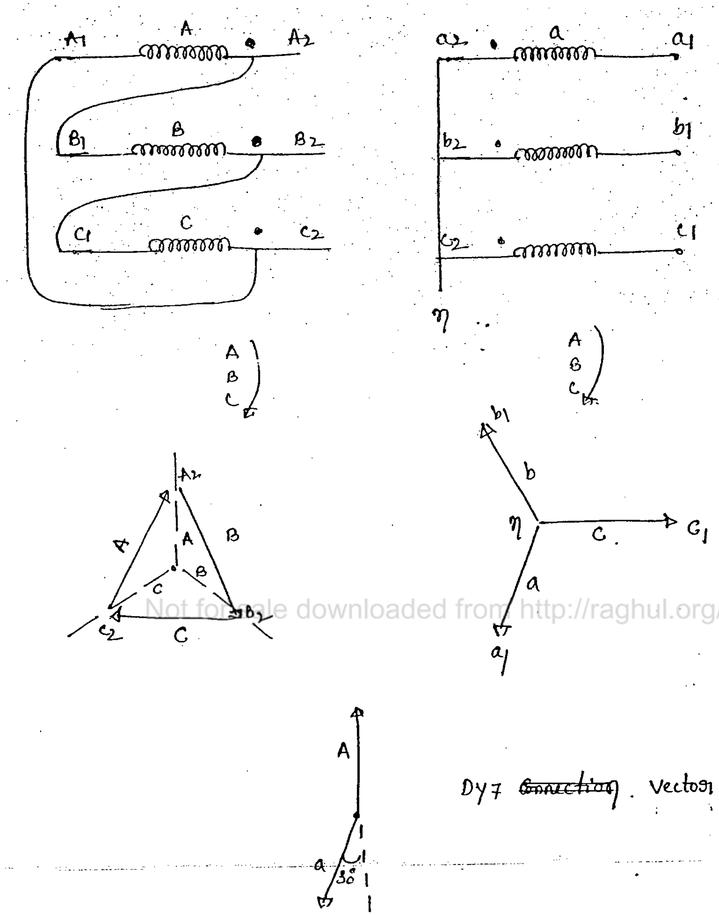



DY7 ~~connection~~ vector group.

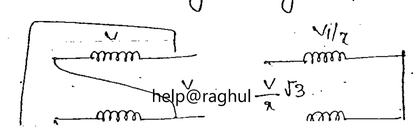
→ **Features of Δ-Y :-**

(1) If 2:1 turns ratio.

what is line turns ratio

Assume phase voltage = $V_1$

then Secondary voltage = $V_1/2$.

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line turns ratio $V_1 : \frac{V_1}{x}$.

$\Rightarrow x : \sqrt{3}$

(2) Δ – Δ, Δ – Y, Y – Y, Y – Δ } all cases phase turns ratio assumed $x:1$ & phase voltage applied $V_1$. But connections only changed.

| $x : 1$ | | line Turns Ratios. | |
|---|---|---|---|
| Δ | Δ | 100% | $V_1 : \frac{V_1}{x}$ |
| Y | Y | 100% | $V_1 : \frac{V_1}{x}$ |
| Δ | Y | 173.2% | $V_1 : \frac{\sqrt{3}V_1}{x}$ Highest terminal voltage |
| Y | Δ | 57.7% | $V_1 : \frac{V_1}{\sqrt{3}x}$ least terminal voltage. |

If you consider ΔΔ, YY as reference of 100%.

For same turns ratio & applied voltage we are getting

73.2% more voltage at Δ – Y connection.

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For same turns ratio & applied voltage ~~we are~~ are getting 43.2% less voltage at Y – Δ connection.

(3) Instead of having 173.2% voltage in Δ – Y connection.

for 100% voltage Δ – Y requires very less number of turns/ph. compared with all connections.

for 100% voltage in Y – Δ requires some more addition turns/ph to compared 43.2% reduced voltage.



(4) Δ – Y produce highest voltages @ secondary for same applied voltage & for same number of turns.

Y – Δ produce least voltages @ secondary.

(5) To get more economy i.e., lot of saving in copper & insulation

Δ – LV side

Y – HV side

Δ/Y ⇒ LV/HV i.e. step up connections most economical.

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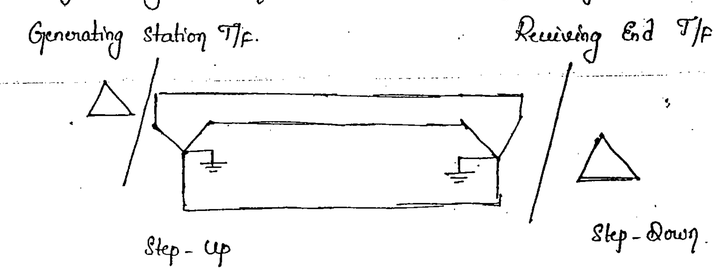
(6) In actual practice also at begining end of power system i.e. generating transformer in Δ/Y type only.




physically 3 - wires transmitted in ~~turns lines~~ Transmission lines. Neutrals both sides grounded above shown in figure.

More Economical power system connection.

In practical Δ/Y is most ideal choice in distribution network.

(4) × Δ – Δ

✓ Y – Y } These only suitable for distribution applications.

✓ Δ – Y } Since distribution network secondary neutral point.

× Y – Δ

- Y – Y – Core restriction only for 3 limbed core used.

  Δ – Y – No core restriction any type of core used.

Since No – neutral shift due to internal Δ.

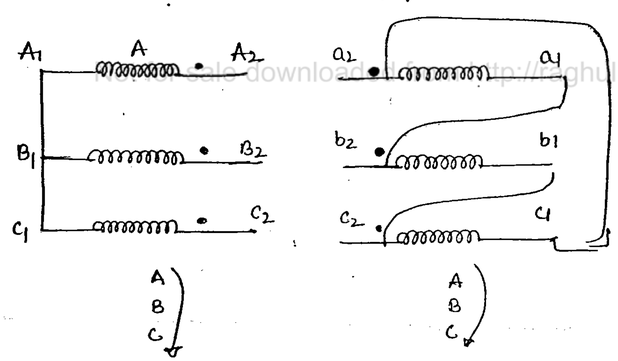
No – restriction for Earth fault current ∵ Δ.

Less number of turns in Δ/Y, so lot of savings.

## → Y – Δ Transformer Connection :-

In this case also we can get (4) types of connections.

i.e., ±30° & 180 ± 30° connections.




Throughout Y/Δ connections primary must be like that i.e., dot outs only.

Since primary is reference.

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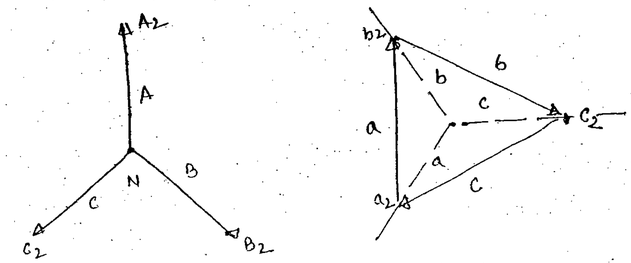
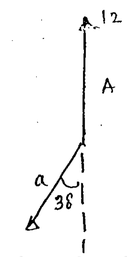



b2 — b2 must be here to satisfy phase sequence of connection diagram).




210° connection

Vector group is : Yd7.

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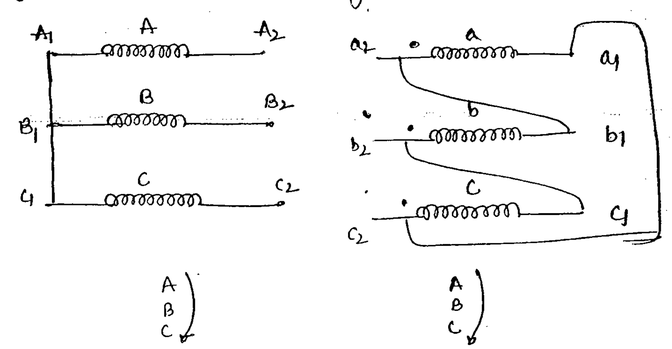
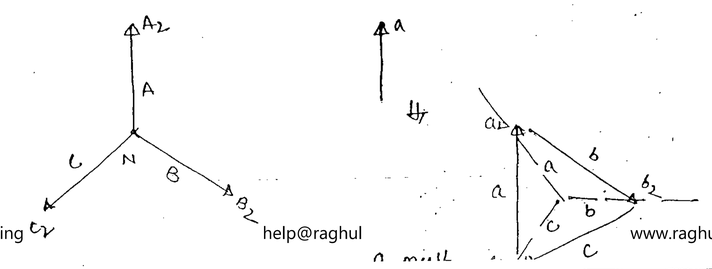
For one more connection ; keeping primary as it is, choose secondary connection in such a way to connect dotted to undotted.



Vector group Yd11

+30° Connection.

For remaining two more connections with Y-Δ T/F.

→ This phasor group identification is very important parallel operation of Transformer.

Since parallel operation of Transformer vector or phasor group of Transformer must be same.

Same ~~Some~~ phasor groups are:

| Group - I | Group - II |
|---|---|
| ΔΔ | ΔY |
| YY | YΔ. |

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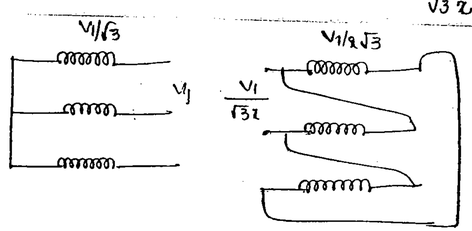
Features of Y - Δ Transformer Connection:

(1) If phase turns ratio $a : 1$

phase voltages $V_1 : \frac{V_1}{\sqrt{3}\,a}$.




$a : \frac{1}{\sqrt{3}}$

$a : 0.577.$



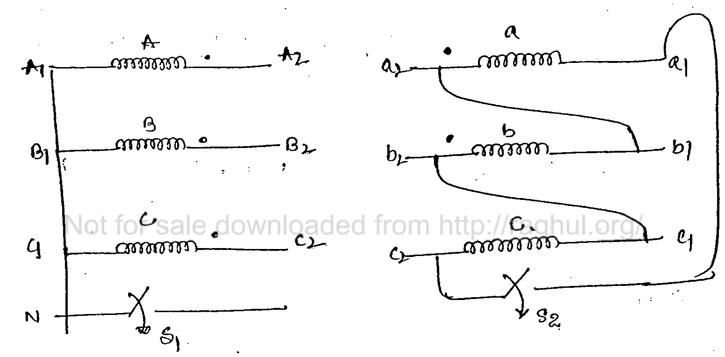
(2) Employed @ termination end of transmission lines.

(3) Not suitable for distribution ∵ No neutral @ Secondary.

(4) Shape of emf sinusoidal ∵ Internal Δ.

(5) More Economical for HV/LV connections.
i.e step down applications.

Gate-09:-




If $S_1$ $S_2$ open : primary Secondary.

If $S_1$ $S_2$ closed : primary Secondary.

If $S_1$ open, $S_2$ closed : primary Secondary

$I_u$ : Sinusoidal only 3rd Harmonic

$\phi$ : Flat topped in core

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(1) Open Δ Transformer Connection  L L
(2) Scott Connection.

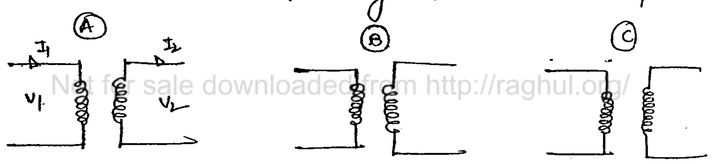
(1) Open Δ Transformer Connection :-
(or)
L L Transformer Connection.

→ In 3-ϕ bank we studied that in case of one phase in fault remaining 2 healthy phase can satisfy the load.

→ As 3-ϕ bank not magnetically coupled, remaining two phases can operated as open Δ connection.

→ Open Δ connection not possible in single unit of 3-ϕ Transformer.

Instead of considering 3-ϕ bank consider closed Δ – Δ Bank formed by 3 individual 1-ϕ Transformer bank.

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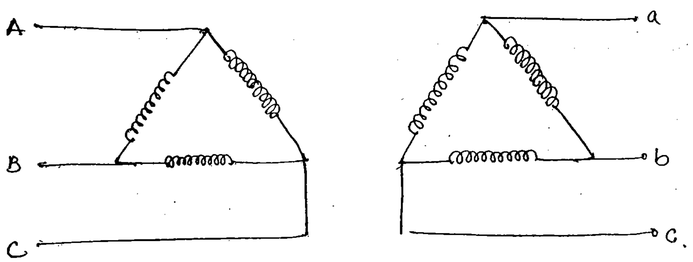
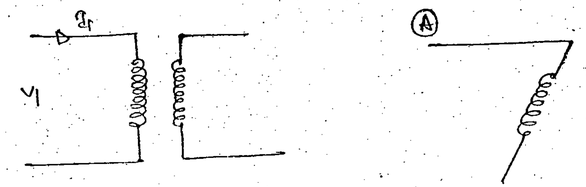
(A) $kVA = V_1 I_1$
or
$V_2 I_2$






Capacity of Δ – Δ Bank we need to find out,




once 1-ϕ convert to Δ bank.

phase voltage $V_1$ in 1-ϕ — Δ Bank also phase $V_1$ voltage.

phase current $I_1$ in 1-ϕ — Δ Bank also $I_1$ – phase current.

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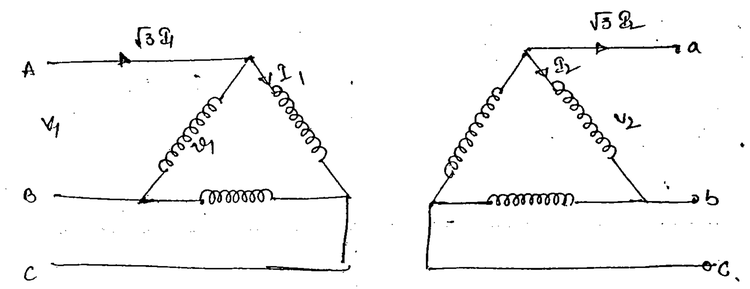



Capacity of Δ – Δ Bank:

$$(kVA)_{\Delta-\Delta} = \sqrt{3}\, V_L I_L$$

$$V_L = V_1$$

$$I_L = I_1$$

$$(kVA)_{\Delta-\Delta} = \sqrt{3}\, V_1 \times \sqrt{3}\, I_1$$

utilisation factor = 100% $= 3 V_1 I_1$
$= 3\,(kVA)_{1-\phi}$.

Capacity of LL Bank: $(kVA)_{LL} = \sqrt{3}\, V_1 I_1$

Capacity of open Δ is 57.7% of that closed Δ capacity of Transformer.



If 100% loaded on Δ Connection; % loading of Each Transformer is 173.2% more on Each 1-φ Transformer.

If 57.7% of total load placed on open Δ Connection

KVA supplied by Each 1-φ Transformer $= \frac{\sqrt{3} V_1 I_1}{2}$

∵ only ② Transformer in LL.

$= \frac{\sqrt{3}}{2} V_1 I_1$

$= 0.866 (kVA)_{1-\phi}$

That means particularly loaded to 1-φ Transformer.

For 3-φ;

If 100% loaded → In open Δ Connection
Each 1-φ Transformer overloaded by 173.2%.
i.e kVA supplied 73.2% more.

If 57.7% loaded → In open Δ - Connection
Each 1-φ Transformer under loaded by 86.6%.
i.e kVA supplied 13.4% less.

Utilisation factor of open Δ

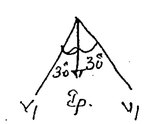
$= \frac{(kVA)_{LL}}{\text{Available kVA}} = \frac{\sqrt{3} V_1 I_1}{2 V_1 I_1}$

$= \frac{\sqrt{3}}{2} = 0.866.$

utilisation factor of LL = 86.6%

In open LL Connection;

If one winding operating @ +30°
other winding operating @ −30°

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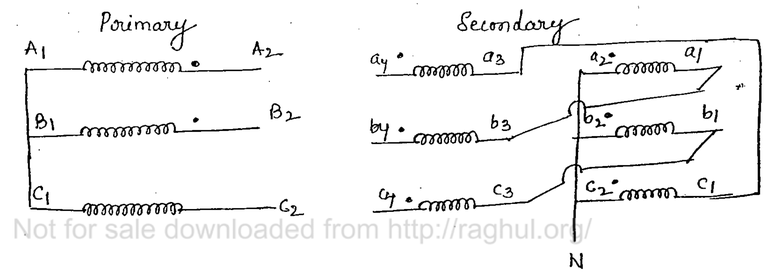
one Transformer operated @ cos30° lag $(\cos 30 + \phi)$
other Transformer operated @ cos30° lead $(\cos 30 - \phi)$

Type of power factor depends on type of load.

→ ② Special Transformer Connection:

Y – Zig zag Y Connection –

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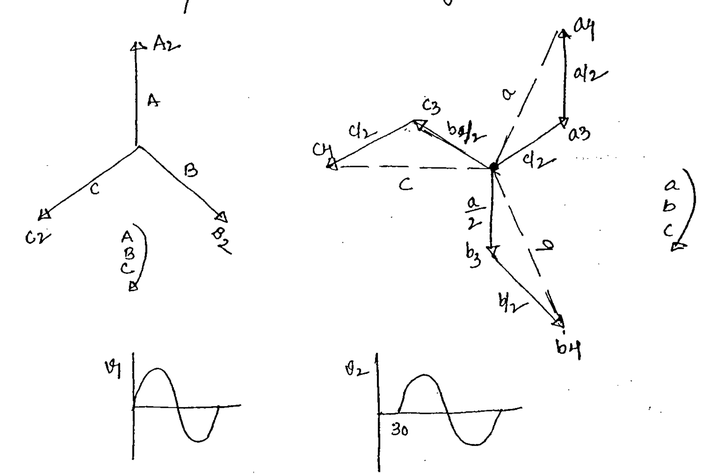
For this to observe vector group:




Vector group of Connection – YZ1.

## Phase Conversion Transformer Connection :-

In some practical cases 1-$\phi$ to some number of 'm' phases we have to convert because of requirements in industry. In this popular connections are :

(1) $3\phi$ to $2\phi$ (Scott Connection)

(2) $2\phi$ to $3\phi$ (T-T Connection).

### (1) $3\phi$ to $2\phi$ Conversion (or) Scott Connection :-

We know universally available supply — AC ($3\phi$). But in practice some industrial applications we need $2\phi$.

Ex:- Electric Arc Furnaces
Welding Machines.

So some connections must be adopted to get $2\phi$ from $3\phi$. For this two identical Transformers required. to get

$3\phi$ to $2\phi$ } vice-versa
& $2\phi$ to $3\phi$ } — possible with Scott Connection.

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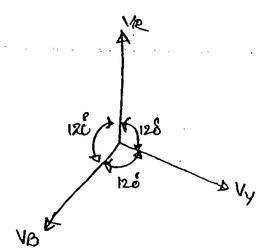
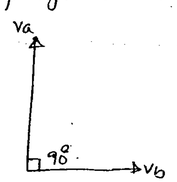
In 3-$\phi$ System voltages displaced by $120^\circ$ & voltage displaced in $2\phi$ System : $90^\circ$.




Generalised Expression;

For m$\phi$ System : displacement can be obtained by

$\frac{2\pi}{m}$ rad (not valid for $2\phi$ System)
$(m > 2)$



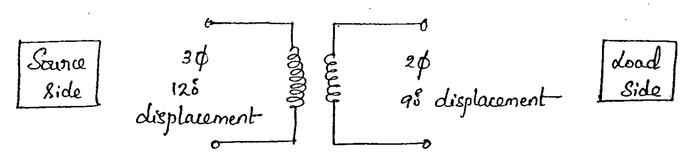
* For $3\phi$ — $\frac{2\pi}{3} = \frac{2\times180}{3} = 120^\circ$

$6\phi$ — $\frac{2\pi}{6} = \frac{2\times180}{6} = 60^\circ$

* But in $2\phi$ system — displacement — $\pi/2$ only.

* By using $3\phi$ — $120^\circ$ displacement source have to convert as $2\phi$ — $90^\circ$ displacement.

We need

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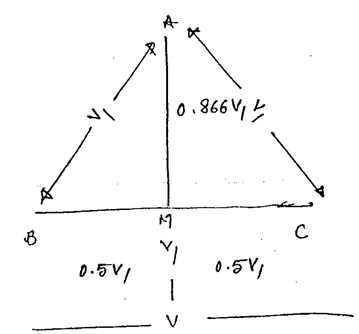
To obtain above significance; Easy to go with vector diagram.




Initially det Vg :

(1) Take 100% $V_1$ vector as reference.

(2) & join 86.6% $V_1$ vector join @ mid point of 100% $V_1$.

Now you will find displacement between both sides of AM — $90^\circ$.

By vector sum

Resultant voltage between AB = $V_1$

AC = $V_1$

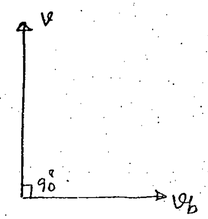
That means obtained voltage is well balanced 3φ system. ( because all sides voltages same) whatever the phase angle.



To satisfy balanced 3φ system:

Displacement between 0.866 $V_1$ & $V_1$ vector is 100%.

If you applied this system to source you will get induced voltages @ secondary as shown.




One you obtained 90° displacement voltages then it is 2-φ system.

* From based on above vector diagram you can find actual Transformer construction also.

practically to develop this we need two identical Transformers.

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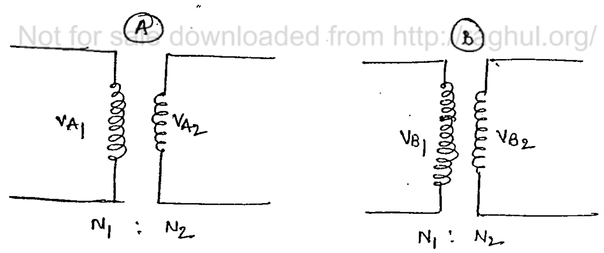
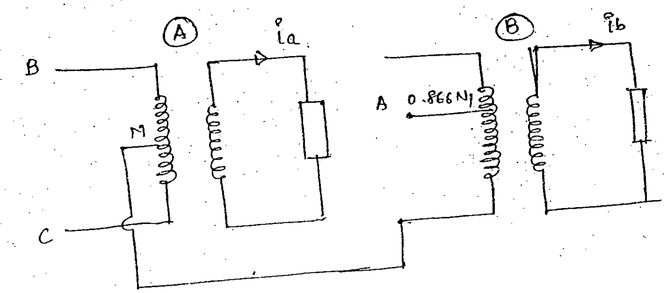



I want $V_{A1}$ 100% with mid point tap from (A) T/F & 0.866 $V_{B1}$ from (B) T/F with 86.6% turns.

* So put tapping @ mid point @ (A) T/F.
* So put tapping @ 86.6% turns @ (B) T/F.






That means you can connect a 2φ load @ Secondaries

* Now 100% turns are using in (A) T/F.
  13.6% turns idle in (B) T/F.

No connection required between Secondaries.

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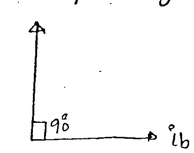
* A – B – C displaced by – 90°.
  as all voltages same and balanced from vector diagram.

As source displaced by 90° secondary also we ~~see~~ will get 90° displacement.

AB, BC, CA } At all side voltages $V_1$

Now load currents @ Secondaries also displaced by 90°.

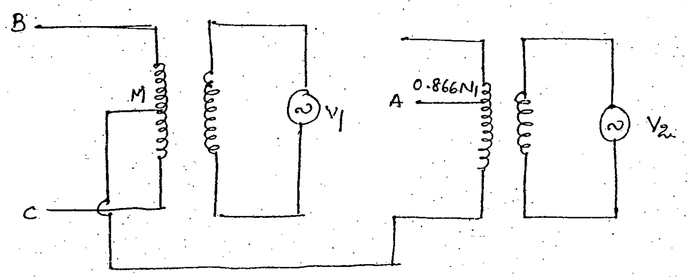
So it is 2φ system.




So we ~~need~~ obtained 2-φ system from 3-φ system.

In vice versa connection 2φ to 3φ Scott connection. Interchange primaries and secondaries, applied source side @ 90° displaced voltages.

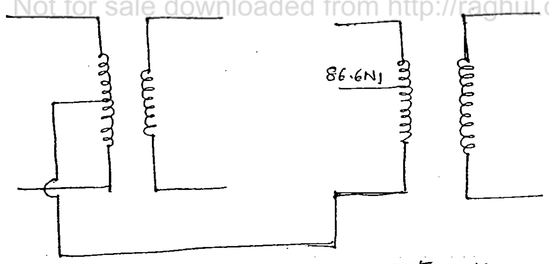
turns ratio, you can get same 90° displacement in Secondary also. 119
i.e., you can obtain 2ϕ to 3ϕ system:




$V_1, V_2$ displaced by 90°.

AB, BC, CA — 90° displaced; resultant voltage 3-ϕ balanced system.

* Transformer used in Scott Connection are named as:




T.F with 100% turns in Main T/F

T.F with 86.6% turns in Teasure T/F.

For better clarity i want to change the looking view of Scott Connection as follows.

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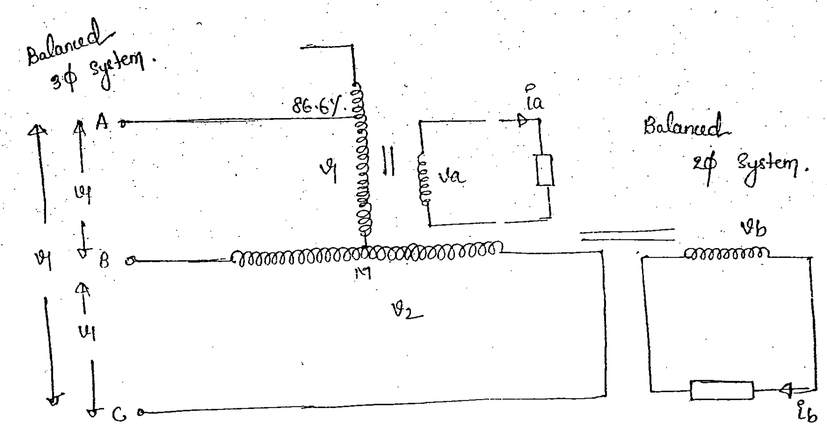


By keeping this diagram don't think primary & Secondary displaced by 90° physically.

We are following vector diagram only. Just for better understanding only this diagram.

As and when 3-ϕ supplied between A-B-C you will obtain voltages internally displaced by 90°. So we will get induced Emfs with 90° displaced. So you can connection 2ϕ load across ~~Secondary~~ Secondaries of Main Transformer & Teasure Transformer.

In this case i want to put neutral point in primary (or) Identify as our primary (in Scott Connection) looking like Y.

In general 'N' point maintained @ $\frac{V_1}{\sqrt{3}}$ from any side.

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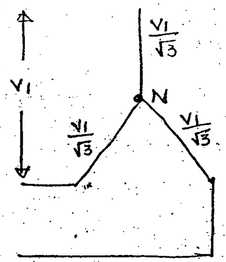
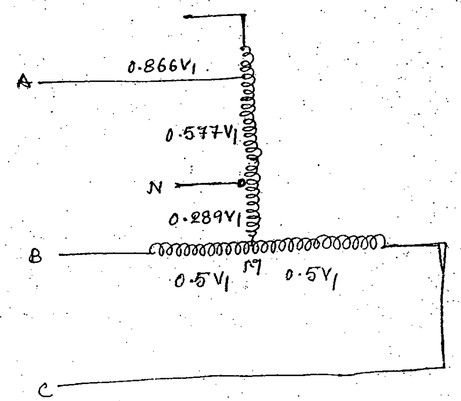



In any 3ϕ System; voltage between any terminal and Neutral is 57.7% $V_l$.




$V_{AM} = 0.866 V_l$

$V_{AN} = 0.577 V_l$

$V_{MN} = V_{AM} - V_{AN}$

$= (0.866 V_l - 0.577 V_l)$

$= 0.289 V_l$

$V_{AN} : V_{MN} = 0.577 V_l : 0.289 V_l$

$\boxed{2 : 1}$

* So Neutral point 'N' is differentiating Teasure Transformer primary @ 2:1 turns ratios.

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* location of Neutral point on Teasure T/F primary from Top $= 0.866 N_1 \times \frac{2}{3}$.

location of Neutral point on Teasure T/F primary from bottom $= 0.866 N_1 \times \frac{1}{3}$.

* How we need to identify whether 'N' is balanced or not?

$V_{AN} = 0.577 V_l$

$V_{BN} = \sqrt{(0.5 V_l)^2 + (0.289 V_l)^2} = 0.577 V_l$.



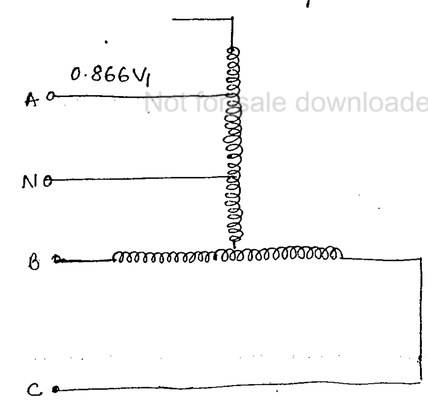
$V_{CN} = \sqrt{(0.5 V_l)^2 + (0.289 V_l)^2}$

$= 0.577 V_l$

As balanced voltage from all points Neutral point also well balanced.

So just like normal star you can bring this neutral 'N' to connect phase outside.

As neutral is not an oscillating one, possible out coming terminal of Scott Connection.

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## Scott Connected Transformer On load :-

→ Operation of Scott Connection @ Balanced 2-ϕ load & upf:

Balanced load means $i_a$ and $i_b$ are same value.

As system from 3ϕ to 2ϕ.

We need to identify source currents.

$I_A, I_B, I_C$.

You simply forget about connection treat as two 1-ϕ

provide to find secondary currents

Forgot Connection

⇓

Consider Currents @ primary (or) Source.

⇓

Now apply Connection

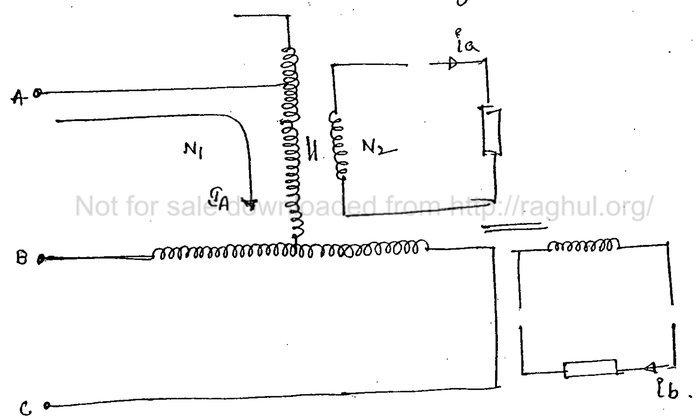
⇓

find primary Current

⇓

By load p.f obtain Secondary Currents also.

Case I :- Consider Teasure Transformer only.

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From Transformation Ratio : $\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = k.$

$$\frac{I_A}{i_a} = \frac{N_2}{0.866 N_1}$$

$$I_A = \frac{N_2}{0.866 N_1} \times i_a.$$



Normally Secondary Currents are given in problems.

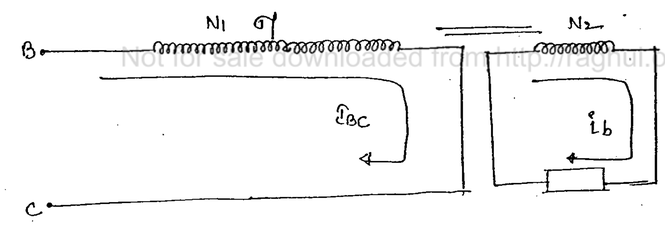
for analysis purpose;

Assume $N_1 : N_2 = 1 : 1$

then $I_A = \frac{1}{0.866} \times i_a$

$$\boxed{I_A = 1.15 i_a}$$

Case II :- Consider Scott Transformer.

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As No tapping in Scott Transformer.

From Transformation Ratio:

$$\frac{I_{BC}}{i_b} = \frac{N_2}{N_1}$$

$$I_{BC} = \frac{N_2}{N_1} i_b$$

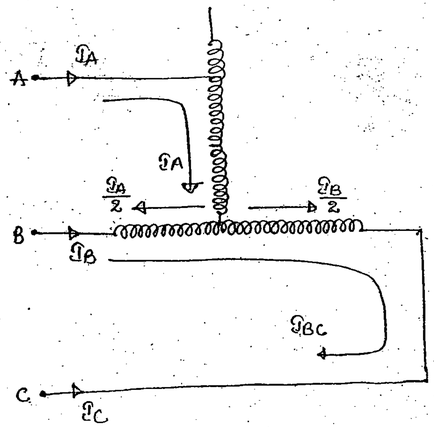
For Simplicity

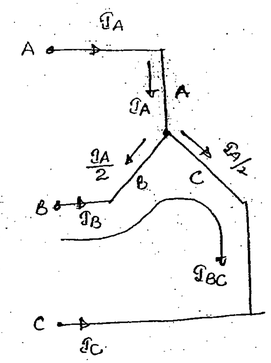
if you Assume $N_2 : N_1 = 1:1$

$$\boxed{I_{BC} = i_b}$$

But practically as mid point Connected @ Scott Transformer,

$\frac{1}{2}$ of $I_A$ flows towards TB.




Currents Entering @ primary :-

$$\overline{I_A} = \frac{N_2}{0.866\,N_1}\, i_a$$ No-change in Teascar T.F Current.

$$\overline{I_B} = \overline{I_{BC}} - I_A/2.$$

$$\overline{I_C} = -\overline{I_{BC}} - I_A/2.$$

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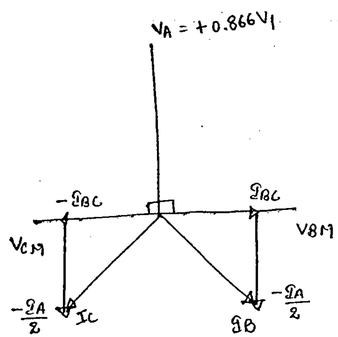
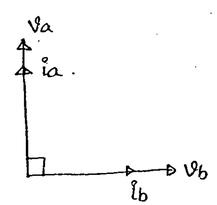
Now you can draw vector diagram for present situation.

Take Main Transformer Voltage as reference. ~~(VBC no W~~

from Std point to 0.866 VA
$V_{STB}$
$V_{STC}$.






For balanced ~~two~~ phase load $i_a = i_b$.

$\because$ UPF load assumed $i_b$ — in phase $V_b$.
$i_a$ — in phase $V_a$.

If $I_0$ neglected;

$I_A$ in parallel with $i_a$.

i.e., $I_A$ in phase to $V_A$.

$I_{BC}$ is in phase with $V_{BC}$ or $V_{CA}$. to obtain actual $I_B$ & $I_C$ draw $I_A/2$ in −ve direction @ $I_{BC}$ & $I_{BC}$.

For analysing purpose; assume $i_a = i_b = 1$ Amp.

Ag $i_a = i_b = 1$ Amp.

$I_A = 1.15$ Amp.

$$-\frac{I_A}{2} = \frac{1.15}{2} \text{ Amp.}$$

$$\therefore I_B = \sqrt{(I_{BC})^2 + \left(\frac{I_A}{2}\right)^2}$$

$$= \sqrt{(1)^2 + \left(\frac{1.15}{2}\right)^2} = 1.15 \text{ Amp.}$$

$$I_C = \sqrt{(-I_{BC})^2 + \left(\frac{I_A}{2}\right)^2}$$

$$= \sqrt{(1)^2 + \left(\frac{1.15}{2}\right)^2} = 1.15 \text{ Amp.}$$

Only Magnitude equal is not balanced 3-$\phi$, Hence consider phase angles also.

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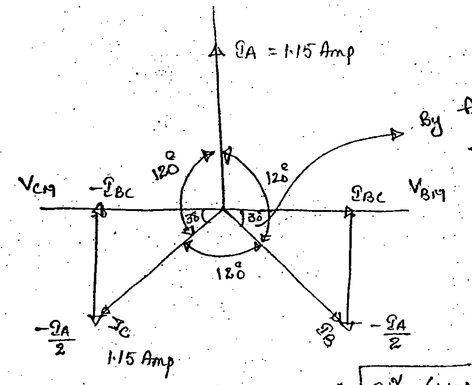


By Applying Tan⁻¹ for this right angle Δle) you will obtain the 30°.

$= \sqrt{(1)^2 + \left(\frac{1.15}{2}\right)^2} = 1.15$ Amp.

So we get phase angles also.

So 3-$\phi$ to 2$\phi$ system & vice versa also we balanced.

In this case $V_A, I_A$ — In phase
$V_a, I_a$ — In phase @ upf.

i.e., primary p.f = Secondary p.f.

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But in Main Transformer

$I_C$ leading $V_{COT}$ by Cos 30° lead.

$I_B$ lagging $V_{BOT}$ by Cos 30° lag. @ UPF load.

So no change in ~~Trans~~ Teasure Transformer power factor on both sides.

But in Main Transformer @ UPF load.

Teasure Transformer — UPF.

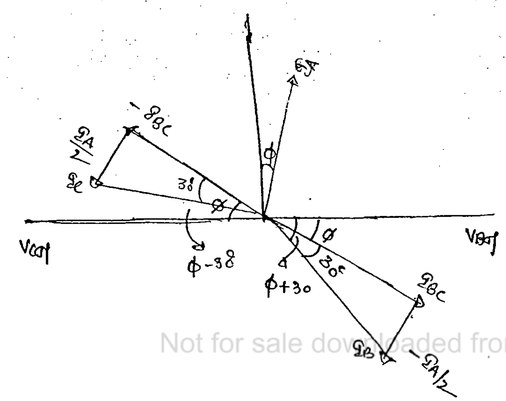
1st $\frac{1}{2}$ winding Main T.F = Cos 30° lag.

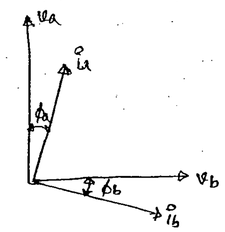
2nd $\frac{1}{2}$ winding Main T.F = Cos 30° lead



One you know Secondary load power factor you can find the power factor @ primary also.

Let us add load @ Secondary, balanced load.




$\phi_a = \phi_b = \phi$.

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In this case also load power factor = Teasure Transformer P.f.

for Cos — $(\phi - 30)$ & $30 - \phi$ same.

So here 1st $\frac{1}{2}$ of Main T.F @ $30+\phi$ p.f lag.

2nd $\frac{1}{2}$ of Main T.F @ $30 - \phi$. P.f

We can't define type of load power factor but we can define after knowing complete vector diagram.

## Capacity of Scott Connection :—

Each Identical TF used $(kVA)_{1\phi} = V_1 I_1$.

$(kVA)_{Scott} = \sqrt{3}\, V_L I_L$.

$V_L = V_1$

$I_L = I_1$.

$(I_A = I_B = I_C = I_1)$ ∵ 1$\phi$ T.F

$(kVA)_{Scott} = \sqrt{3}\, V_1 I_1$

If designed for 10 Amp Transf we should not allow more than

→ If i choose two 1-ϕ Transformers of 100 kVA rating then Scott Connection rating = 173.2 kVA.

U.F ≠ 100%.

$$\text{U.F of Scott Connection} = \frac{(kVA)_{scott}}{\text{Available kVA}} = \frac{\sqrt{3}\,V_1 I_1}{2V_1 I_1}$$

$$= \frac{\sqrt{3}}{2} = 86.6\%.$$

That means just like open Δ Scott Connection rating 86.6%.

One of the reason for this reduced capacity of Scott Connection is 13.4% idle turns. (not contributing in operation).

But contributing in Available kVA.

As no performance of 13.4% idle turns you can remove & save 13.4% turns.

That means

take ① T/F 100% turns } for Scott
② T/F 86.6% turns } Connection.

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Here you are using dissimilar Transformers.

So now

$$U.F = \frac{(kVA)_{scott}}{\text{Available kVA}} = \frac{\sqrt{3}\,V_1 I_1}{V_1 I_1 + 0.866 V_1 I_1}$$

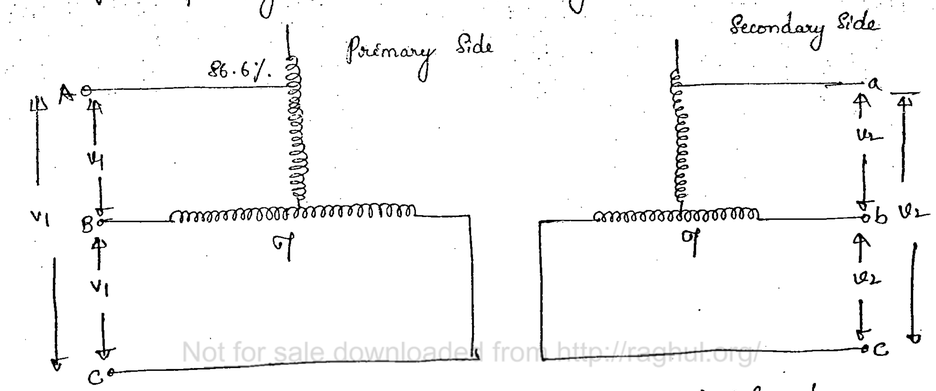
$$= \frac{\sqrt{3}}{1.866} = 0.926\%.$$

That means utilisation factor with two dissimilar capacities is improved from 0.866 to 0.926.



## T – T Connection :- 3ϕ to 3ϕ Conversion :

Instead of having secondary with 100% turns, simply follow primary procedure @ secondary also.




3-ϕ Balanced 3-ϕ Balanced.

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In this case also two Transformers required.

as AB, BC, CA voltages displaced by 90°.

ab, bc, ca voltages also displaced by 90°.

Capacity of T-T Connection same as Scott Connection.

U.F of T-T Connection same as Scott Connection.

With this Connections Completed.

## Parallel Operation of Transformer :-

In any system, generally all loads not supplied by one large Transformer. There are more small T/F why ?

What are the advantage of instead of single unit Transformer.

Let us in a some location 100 MVA load has to supply.

| Single unit Transformer | parallel operation Transformer |
|---|---|
| (1). During fault reliability<br>100 MVA Source T/F<br>100 MVA load.<br>If fails of T/F ; no supply to load. | 100 MVA load ; 50 MVA T/F, 50 MVA T/F<br>If fail of T/F ; some % of load can be satisfy. |

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(2) If load demand increased :-

If load demand increased to 120 MVA from 100 MVA

| | |
|---|---|
| Remove — 100 MVA T/F. | No removal of 50 MVA, 50 MVA. |
| Install — 120 MVA T/F. | Install — 20 MVA T/F. |

parallel operation enabling the expansion of power system increased demands.

(3) $\eta$ of power T/F :-

As power Transformer gives max $\eta$ @ full load only ; assume all are power Transformer.

If load suddenly decreased during nights single large T/F may not operate at full load.

So max '$\eta$' not possible. So overall $\eta$ decrease.

As 100 MVA load present — 50 MVA, 50 MVA } fully loaded $\eta_{max}$.

night load ↓ to 50 MVA.

Remove one T/F from parallel operation; only one 50 MVA

50 MVA — fully loaded $\eta_{max}$

overall $\eta$ of system ↑.

(4) Stand by Transformer :-

In Sub-stations we use stand by T/F, to replace the operating Transformer in case of emergency, to meet emergency ;

If in my substation :

Some 2 crores of single units T/F of 100 MVA.

If stand by requirement also required one more 100 MVA T/F.

Cost towards standby unit ↑.

If one Transformer fails 50 MVA, 50 MVA ✗

Standby to be substituted 50 MVA T/F.

Cost toward standby T/F ↓

Necessary (Must of Should) Conditions of Desirable Conditions (not must of should) for parallel operation of Transformer :-

We should not blindly connect parallel operation of Transformer, because if you violate necessary conditions T/F may damage also.

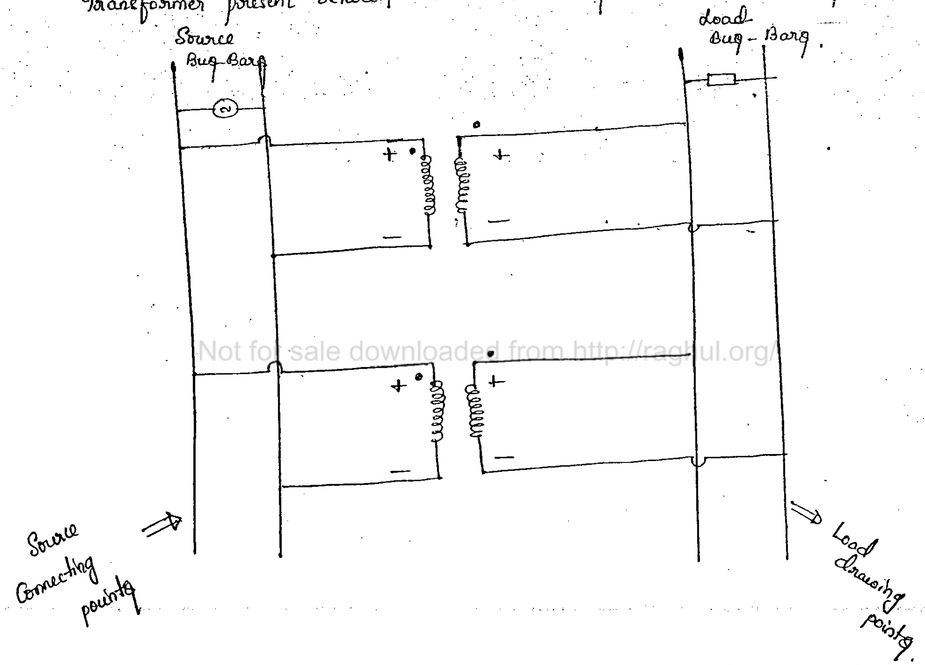
If you violate desirable condition of transformer, transformer may operate @ poor performance levels, But not a big damages.



## Necessary Conditions to Satisfy parallel Operation :-

(1) Correct Polarity Connection :- To Source busbars & dead busbars practically

for better understanding practically in any Sub-Station Transformer present between Source bus-bars and load bus bars.




To obtain polarities +ve & -ve simply conduct polarity or kick test.

for dot notation put +ves with • dots

(or) put -ves with • dots.

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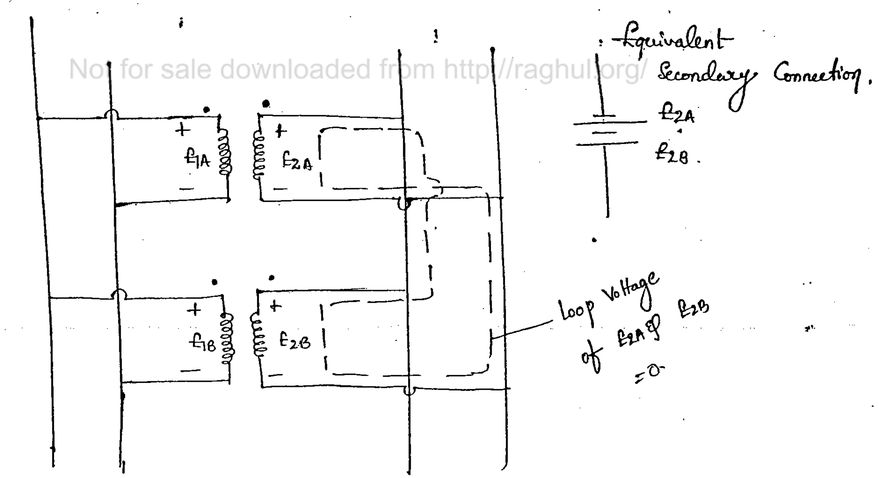
Now Connect • dots — to Same bus bar.

undotted — to other bus bar.

→ If you changed polarities dead short circuit of Transformer possible.

If you Excite primary voltages with $E_{1A}$ & $E_{1B}$.

you find voltages induced Emfs @ Secondary $E_{2A}$ & $E_{2B}$.




If Correctly you Connected the dot Convention;

If you Connected $E_{2A}$ & $E_{2B}$ — both Series opposing;

No change in loop voltages, so no Circulating Currents in loop between Transformers.

∵ No loop voltages $E_{loop} = 0$

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If you connected wrongly doing you find.

$E_{DA}$ & $E_{AB}$ } Series aiding polarity.

Loop voltage very high ⇒ $E_{loop} \neq 0$.

very large circulating currents $I_c \neq 0$.

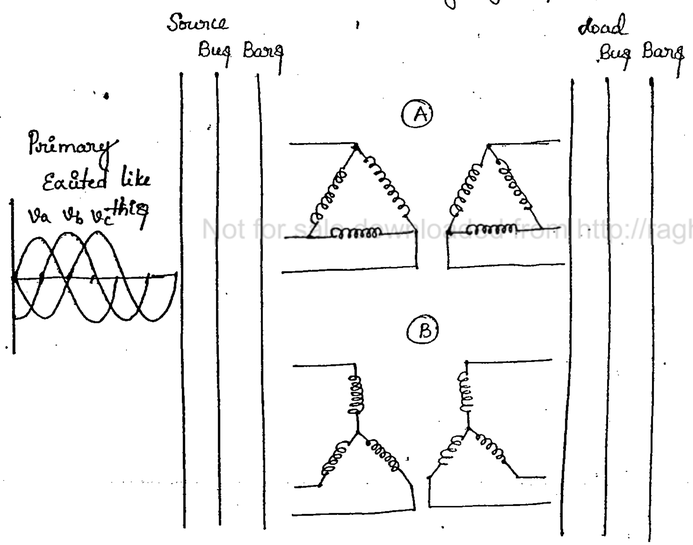


## (2) phase Sequence :-

Both the Transformer phase sequences must be same.

What is correct phase matching.

for this let us consider Incoming bus bars (Source bus bar)
&
outgoing bus bars (Load bus bar)




As Transformer it self dont have any phase sequence Source only consists phase sequences. So Transformer just follows the applied source phase sequence.

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## phase Sequence :-

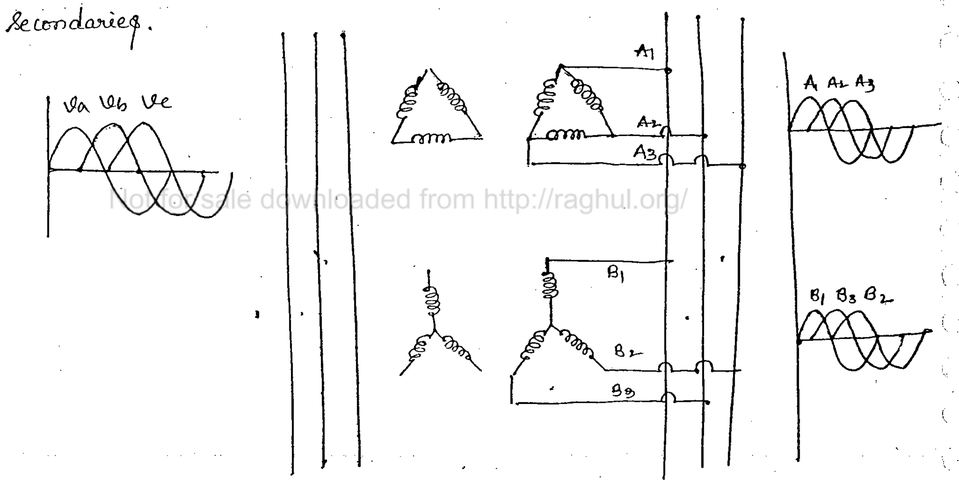
This is the order of given 3ϕ supply, in which terminals attain the peak values.

So Bluntly you connect primaries of Transformer to source bus bars.

Now Transformers primary got phase sequence.

Now induced emfs in T/F, you dont know at what phase sequence.

for Example let us you obtained following phase sequence @ secondaries.

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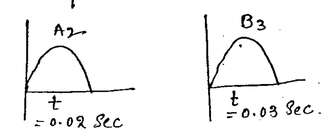
Connect terminals of Secondary in such a way to peak attaining position at any terminals of two secondaries of T/F must connect to same as bus bars.

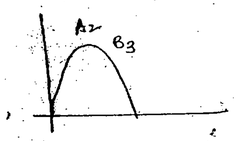
That means




So Connect $A_2$-$B_3$ for same bus bar.

as these are attaining peak potential at same potential.

If you are connecting same peak [illegible] at same time to same busy bars.

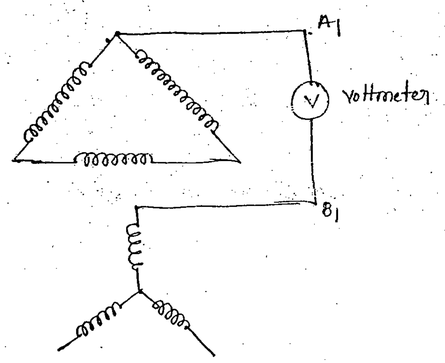



Meaning there is no loop voltage develops or P.D = 0 between $A_2$ & $B_3$.

125

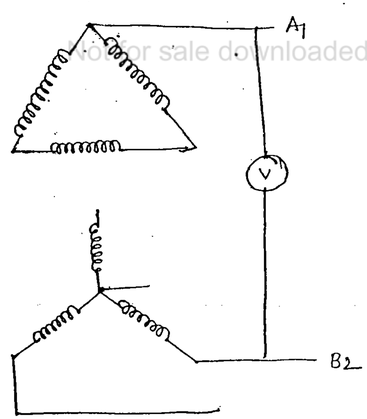
To know phase sequence @ secondaries before parallel operation, connect voltmeter between -

(1)




If V = 0
Simply you can connect both terminals at same busy bar.

(2)




If V ≠ 0
dont connect these terminals to same busy bars.

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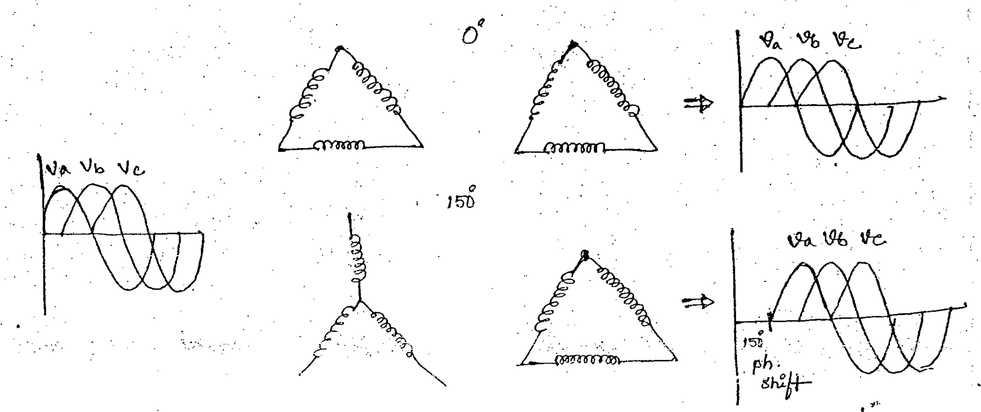
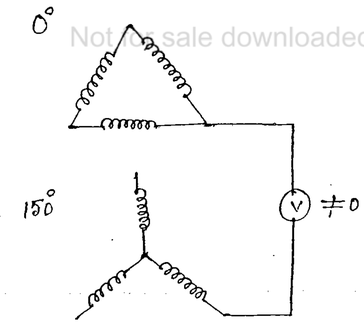
In 3ϕ system primary and secondary side not always displaced @ 180°.
They may displace from primary to secondary as 0°, +30°, −30°, 150°, 180°, 210° phase shifts






due to type of connection in 3ϕ.

Here seq order same Va – Vb – Vc
Va – Vb – Vc

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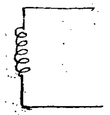
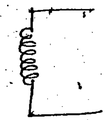
You never find voltages between any terminal = 0.
because of phase displacement.
This is impossible ~~connection~~ condition to connect in parallel.
Since large loop voltage, so large circulating current present.

(3) So for parallel operation both transformer must ~~have~~ have same phasor group.

What is phasor group?
Observed we already diff. displacements of 3ϕ transformer by diff connections.

phasor group I 

phasor group II 

| | | |
|---|---|---|
| 0° | Δ/Δ | Y/Y |
| 180° | Δ/Δ | Y/Y |
| ±30° | Δ/Y | Y/Δ |
| 180 ± 30° | Δ/Y | Y/Δ |

From above we find that;

0°, 180° Connection possible with same type of T/F with same Connections on both sides &

±30°, 180°±30° Connection possible with same type of T/F with diff. Connections of both sides.

So depending on possible Connections;

for particular phases.

We got two phasor groups :-

| phasor group I | | phasor group II | |
|---|---|---|---|
| 0° | 180° | ±30° | 180° ± 30° |

* For parallel operation both Transformer must be Comes under same group. parallel Connection

Ex :-

Dd 0 — group I
Yy 6 — group I — possible

Dy 1 — group II
Yd 11 — group II — possible

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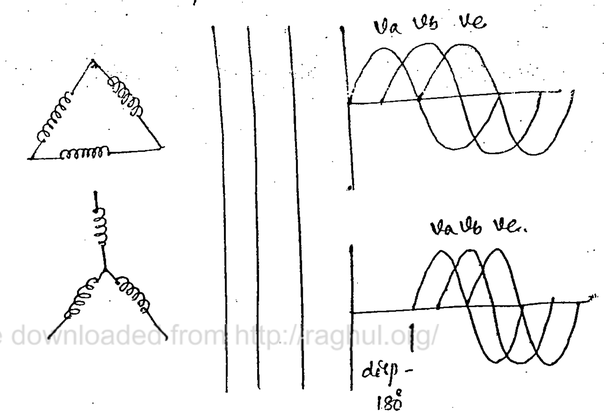
Dd 0 — group I
Yd 11 — group II } diff groups not possible.

* Even phase group of Transformers same ~~as~~ we should not blindly Connect those terminals to same bus bar.

Ex :-

Ddo

Yy6




As there is 180° phase displacement between two T/F Secondaries Even same order, we shouldn't directly Connect.

Here both Secondaries;

belongs to same phase group - so parallel operation possible.

But it requires some modifications to Connect for same bus bar.

That we need displacement must make = 0.

for that you simply;

change Connection of one of the Secondary of two Transformers., by keeping one Transformer primary kept constant.

Ex:- i.e Dy1 Yd 11

−30° +30°

By changing Connection

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of get connection are phase groups transformers;

| Dd0 | Yd11 |
|---|---|
| | ⇓ |
| Required $\delta$ 0° | +30° possible |
| 180° | −30° possible |
| | 150° " |
| | 210° " |

No possibility for getting 0° or 180°, so different phase groups Transformers we can't connect in parallel ~~they~~ even we change the connection also.

→ **Necessary Conditions :-**

(1) polarity

(2) phase sequence

(3) phase displacement between secondary ~~also~~ side wave forms must be '0'.

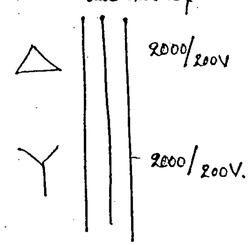
Yeang Transformer must belongs to same phasor group.

**Desirable Conditions :-**

(1) Voltage ratio must be same :-

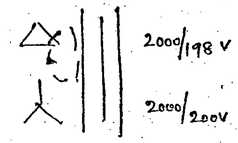
Generally voltage ratings are equal to parallel ~~side~~ load side seq Transformer's.

That yeang Even though voltage ratings same during operation the voltages may not be same due to no. of turns present in each T/F may not be exactly same, so that






One Transformer may produce −200V.
other Transformer may produce −198V.




Due to diff. of voltages circulating currents comes into picture.

$I_{RA} = I_A + I_C$

$I_{RB} = I_B - I_C$.

This circulating current flow in such a way that which aids to normal current in one T/F & at the same time which opposes ~~the~~ to normal current in other T/F.

This is overloading of one Transformer.

That means parallel operation may not be satisfactory.

∵ one T/F — over ~~loading~~ loaded.
other T/F — under loaded.

(2) Load sharing must be ~~proportion~~ proportionate to respective KVA ratings :-

Whenever two T/F's connected in parallel, both the T/F's must be perfectly loaded.

For-la :- If 600 kVA, 300 kVA } T/F are in parallel;

At one condition; if 800 kVA load present;

600 kVA —Supplying→ 480 kVA under loaded.

300 kVA —"→ 320 kVA over loaded.

T/F under loaded — no problem

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perfect load sharing $\begin{cases} 600\ kVA \longrightarrow 520\ kVA \text{ under load} \\ 300\ kVA \longrightarrow 280\ kVA \text{ under load.} \end{cases}$

Transformer (A) should have;

Ohmic value of impedance connected in parallel should have inverse relation with its kVA rating:

i.e $\downarrow Z_A(\Omega) \propto \dfrac{1}{S_{A\,rated}\uparrow}$ $(I\uparrow)$

$\uparrow Z_B(\Omega) \propto \dfrac{1}{S_{B\,rated}\downarrow}$ $(I\downarrow)$

For Ex:-

A Transformer large rating;

$\downarrow Z_A \propto \dfrac{1}{S_A\uparrow}$ to satisfy this condition less ohmic value of Impedance.

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$Z_A\downarrow$ $I_A\uparrow$

So it supplying more load current,

Similarly; $\uparrow Z_B \propto \dfrac{1}{S_B\uparrow}$ $Z_B\uparrow$ $I_B\downarrow$

$\because$ less rating less load supplied.

Instead of giving ohmic impedance ~~not~~ values pu values given:

$$\frac{Z_A(\Omega)}{Z_B(\Omega)} = \frac{S_B(\text{rated})}{S_A(\text{rated})}$$

$$\frac{Z_A(\Omega)}{Z_B(\Omega)} = \frac{V_2 \cdot I_B\ \text{rated}}{V_2 \cdot I_A\ \text{rated}}$$



$$\Rightarrow \frac{I_A\ \text{rated} \times Z_A(\Omega)}{V_2} = \frac{I_B\ \text{rated} \times Z_B(\Omega)}{V_2}$$

$Z_B\,(pu) = Z_B\,(pu)$

$\downarrow$ $S_A$ rated $\qquad$ $\downarrow$ $S_B$ rated.

Without causing overloaded for perfect load sharing

$Z_A(pu)$ must be $Z_B(pu)$

If $Z_A(pu) \neq Z_B(pu)$ imperfect load sharing takes place undesirable conditions.

(3) $\dfrac{X}{R}$ ratios of connecting Transformer in parallel must be Equal:-

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To avoid.

If T/F (A) operating @ 0.8 lag p.f.

means T/F (B) also must operate @ 0.8 lag p.f; other wise load sharing deviated,

$$\frac{X_A}{R_A} = \frac{X_B}{R_B}$$

(for perfect load sharing condition)

$$\phi_A = \tan^{-1}\left(\frac{X_A}{R_A}\right)$$

$$\phi_B = \tan^{-1}\left(\frac{X_B}{R_B}\right)$$

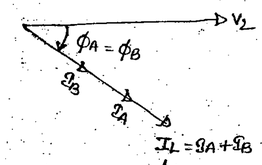
$$\boxed{\phi_A = \phi_B}$$

(perfect load sharing) $(\cos\phi_A = \cos\phi_B = \cos\phi_L)$

This condition possible only if $\frac{X}{R}$ ratio's of both T/F's are same.

Vectorially : (If T/F having equal $\frac{X}{R}$ i.e $\phi_A = \phi_B$.

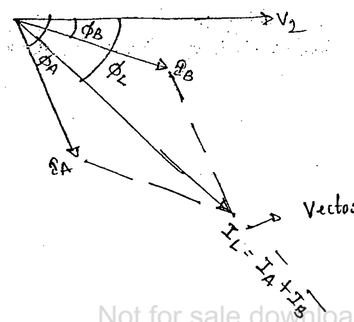





↳ Total load Current Supplied

(Simply Arithmatic Sum, due to same p.f of inphase Component)

Vectorially :- (If Transformer having unequal $\frac{X}{R}$ ratio's)
i.e $\phi_A = \phi_B$.




Vectorial Sum.

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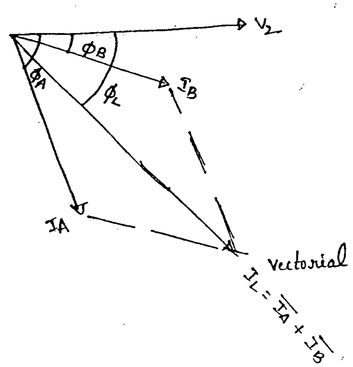
Vectorially :- (If T/F having unequal $\frac{X}{R}$ ratio's)
i.e $\phi_A = \phi_B$.




Vectorial Sum.

Vectorial Sum < Arithmatic Sum.

So In this case load Current delivered by both Transformers to load less.

T/F less $\frac{X}{R}$ Ratio — operates @ Superior power factor

T/F more $\frac{X}{R}$ Ratio — operates @ poor power factor



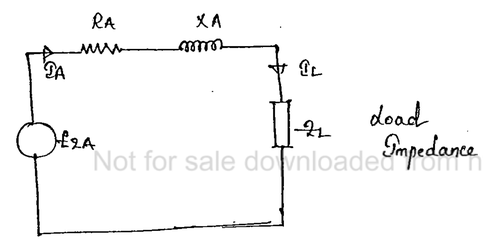
So for getting equal power factors both Transformer must have Same or Exactly equal $\frac{X}{R}$ ratios.

---

## Equivalent ckt of Transformer's Connected in Parallel :-

1st draw any one Transformer equivalent circuit & next draw 2nd Transformer Equivalent Circuit perfectly parallel.

as $V_2$ Same in both Transformer.

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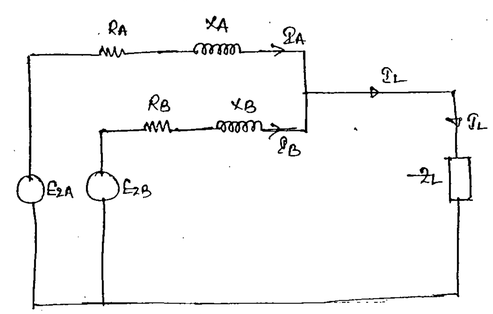
Equivalent Circuit of Transformer 'A' refer to Secondary or load side.

If No-load Current ($I_{0A}$) neglected;

$I_A = I_L$.

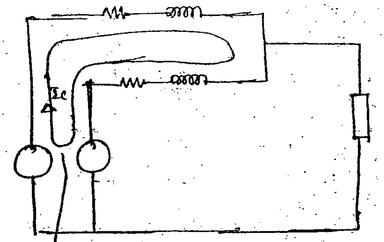
So draw parallel Transformer (B) Circuit.




$I_L = I_A + I_B$ if $\left[\begin{array}{l} \cos\phi_A = \cos\phi_B \\ \left(\frac{X}{R}\right)_A = \left(\frac{X}{R}\right)_B \end{array}\right]$

$I_L = \overline{I_A} + \overline{I_B}$ if $\left[\begin{array}{l} \cos\phi_A \neq \cos\phi_B \\ \left(\frac{X}{R}\right)_A \neq \left(\frac{X}{R}\right)_B \end{array}\right]$

If $\frac{X}{R}$ ratios not Same




Circulating Current due to this – one T/F – over loaded.
other T/F – under loaded.

## Loop Drop :–

outer loop : $V_2 = E_{2A} - I_A Z_A$

Inter loop : $-V_2 = E_{2B} - I_B Z_B$

$$E_{2A} - I_A Z_A = E_{2B} - I_B Z_B$$

If Two Transformers having equal voltage ratios in parallel;

$E_{2A} = E_{2B}$.

$$\Rightarrow \cancel{E_{2A}} - I_A Z_A = \cancel{E_{2B}} - I_B Z_B$$

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$$I_A Z_A = I_B Z_B$$

If Transformer having Equal voltage ratios ; then impedance drops of both T/F also Equal.

If drop across Each impedance drops Same; you can Connect impedance of both Transformer in parallel.

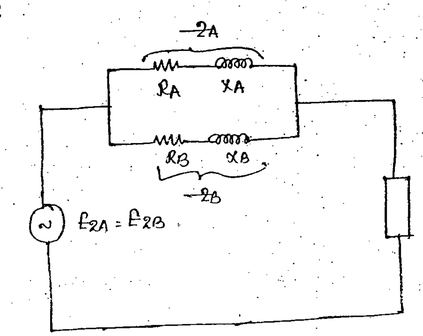
$Z_A = R_A + X_A$

$Z_B = R_B + X_B$.



## Equivalent Circuit :–

If Equal voltage ratios:




Current & load sharings if voltage ratios same;

$$I_A = I_L \times \frac{Z_B}{Z_A + Z_B} \longrightarrow (1) \qquad I_B = I_L \times \frac{Z_A}{Z_A + Z_B} \longrightarrow (2)$$

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$$\frac{V_2}{1000} \times I_A = \frac{V_2 I_L}{1000} \times \frac{Z_B}{Z_A + Z_B}$$

$$S_A = S_L \times \frac{Z_B}{Z_A + Z_B} \longrightarrow (3)$$

$$S_B = S_L \times \frac{Z_A}{Z_A + Z_B} \longrightarrow (4)$$

Current and load sharings if voltage ratios not same.

If voltage ratios not Equal, we have another additional Current i.e Circulating Current.

$$I_{RA} = I_A + I_C.$$

$$I_C = \frac{E_{2A} \sim E_{2B}}{Z_A + Z_B}.$$

$$I_{RB} = I_B - I_C$$

→ There is no seperate formulaes for;

if $Z_A$ & $Z_B$ given in Ω.

or

$Z_A$ & $Z_B$ given in pu.

Ohmic values you can directly substitute no problem.

But

pu Impedance given:

$Z_A$ pu dependent on (or) respective to kVA rating of Transformer (A).

$Z_B$ pu dependent on kVA rating of Transformer (B).

Transformer (A), Transformer (B) kVA rating may not be same.

In this case we shouldnot directly substitute $Z_A$pu & $Z_B$pu in Common formula.

→ i.e., Before substituting in Common formula. –

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$Z_A$ pu & $Z_B$ pu must bring to one reference kVA i.e Base kVA.

This pu impedances of both Transformers with same base kVA can be obtained as similar to power systems.

i.e $Z_{new}(pu) = Z_{old}(pu) \times \frac{(kVA)_{new}}{(kVA)_{old}}$.

Let us T/F (A) — 600 kVA $Z_A = (0.01 + j0.06)$

T/F (B) — 300 kVA $Z_B = (0.03 + j0.1)$

i taken 600 kVA as base kVA;

$Z_{A(new)}(pu) = (0.01 + j0.06) \times \frac{600 \text{ (base)}}{600 \text{ (kVA)}_A}$



$Z_{B(new)}$ pu $= (0.03 + j0.1) \times \frac{600 \text{ (base)}}{300 \text{ (kVA)}_{B\,old}}$

Now impedances came into common base.

So you can substitute now directly into formulas.

↓

for obtaining load currents & kVA rating etc.

→ <u>Auto Transformer :–</u>

Transformation Ratio $\boxed{(k) = \frac{LV}{HV}}$

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Always Auto T/F $k < 1$.

If % tapping @ 50% $k = \frac{50\%}{100\%} = 0.5$.

% tapping @ 60% $k = \frac{60\%}{100\%} = 0.6$

% tapping @ 75% $k = \frac{75\%}{100\%} = 0.7$.

% Tapping = Transformation Ratio of Auto T/F.

Both % tapping & Transformation Ratio of auto Transformer is same only.

* Lot of Saving in Copper (∵ part of HV only LV)

* Lot of Saving in Insulation

(No need to Separate LV & HV).

for same rating.

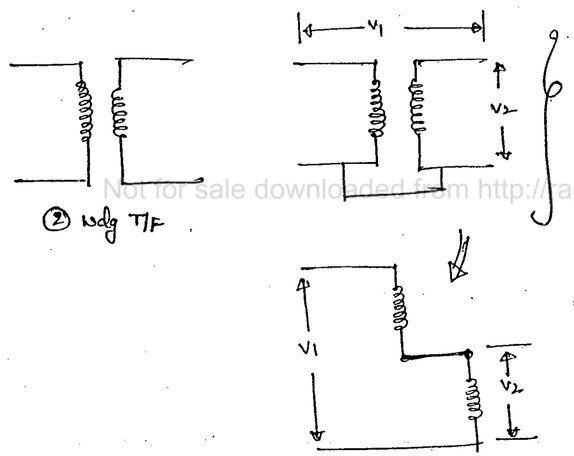
→ performance of Auto T/F very good compared to ② winding T/F for same rating.

In Auto Transformer leakage flux also involves in operating T/F i.e acts like a common flux or operating flux.

As leakage flux low — leakage ~~not~~ reactance low

leakage drop $I_2 X_l$ — drop also low.

* Auto Transformer can be realised by 2, winding Transformer.




② wdg T/F

Common part of both primary & secondary.

* If Auto Transformer ~~made~~ realised from ② winding T/F; Anormously Auto Transformer KVA rating reduces with same voltage and currents of two windings of T/F.

* All the advantages of Auto Transformer comes proper tapping point also pricture with.

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* Break even point:

of Auto Transformer = 3 : 1

(Advantages & Disadvantages of Auto T/F here not exact or Auto T/F advantages just begin)

i.e. $N_1 : N_2 > 3:1$ — Advantages of Auto T/F not possible.

$k < 33\%$ undesirable.

i.e $N_1 : N_2 < 3:1$ — Advantages of Auto T/F possible.

$k > 33\%$ desirable.

* power Transfer in Auto Transformer

② modes

(1) Induction Mode

(2) Conduction Mode

Total input KVA = $V_1 I_1$

Induction KVA transferred = $(1-k)$ (I/P KVA)

* By knowing % of tapping we can conclude;

How much Induction KVA transferred from primary to secondary

Conduction KVA transferred from primary to secondary

If tapping @ 75%

Induction KVA — 25% (Transferred from one side to other side)

Conduction KVA — 75% ( " )

If tapping @ 30%

Induction KVA — 70% ( " )

Conduction KVA — 30% ( " )

* Find the % tapping — find the advantages

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$k = 75\%$. det 2 wdg T/F — looking

$$(\text{wt of Cu})_{\text{Auto T/F}} = (1-k)\,(\text{wt of Cu})_{\text{in 2 wdg T/F}}$$
$$= (1-0.75)\,(100\text{ kg})$$
$$= 0.25\,(100\text{ kg})$$
$$= 25\text{ kg only.}$$

∴ Auto Transformer required = 25 kg only.

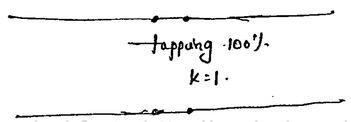
If % tapping @ 100%.

$k$ — 100%.

$$(\text{wt of Cu})_{\text{Auto T/F}} = (1-1)\,(100\text{ kg})$$
$$= 0\%$$

No Copper required;

(∵ Here total power transferred is by Conduction; so no requirement of Cu).




Cu. Saving ∝ % of tapping.

* $(\%\text{ Full load losses})_{\text{Auto T/F}} = (1-k)\,(\%\text{ Full load losses})_{\text{2 wdg T/F}}$

↑ F.L Copper loss + Iron loss

More than % tapping

(or)

More than $k$ — less Full load losses.

If the % tapping 75%. $k = 0.75$.

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$$(\%\text{ F.L. losses})_{\text{A.T}} = (1-0.75)(100\text{ W})$$
$$= 25\text{ W.}$$

* $(\%\text{ V.D})_{\text{Auto T/F}} = (1-k)\,(\%\text{ V.D})_{\text{2 wdg T/F}}$

* $(\text{KVA})_{\text{Auto T/F}} = \left(\frac{1}{1-k}\right)(\text{KVA})_{\text{2 wdg T/F}}$

If $k$ approaching to unity or near to unity;

Anormous rise in Auto Transformer KVA rating compared to KVA rating of 2 wdg T/F.

Auto Transformer can be ~~raised~~ realised by 2 winding T/F.

But Condition is: Auto T/F should not exceed voltage & current limits of 2 winding Transformer.

Total losses in 2 winding T/F = Total losses in Auto T/F.

(If Auto T/F voltage & current readings are with in limits of 2 winding Transformer)

→ To have feasible (more advantages) Auto Transformer common part of winding must be HV winding only.

* whether (2) winding Transformer windings connected;

In series Aiding polarity (or) Series opposing polarity } Induction KVA transferred is same (for realised Auto T/F).

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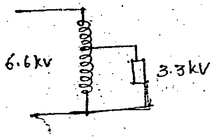
1, Auto Transformer not suitable where "perfect Electric isolation required" applications.

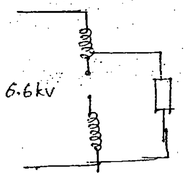
2, Fault on load directly Effect on Source Side.

3, Steady Short ckt Current $\propto \dfrac{1}{\text{pu Impedance of Auto T/F}}$

as $\phi_l \downarrow$ $X_l \downarrow$ $Z \downarrow$ So $I_{sc} \uparrow$

4, Dangerous voltage appearance across loads due to open circuited Common ~~path~~ path.




as most 6.6 kV Due to open ckt in HV windings or Common winding

5, large number of turns not possible in Auto Transformer, due to its limited turns ratio.

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## Applications of Auto Transformers:-

(1) Different possible places for Auto T/F

| | | | Auto T/F |
|---|---|---|---|
| Generating Station T/F | 13.8kV/220kV | $\frac{LV}{HV} < 33\%$ | × not possible |
| | 220 kV / 132 kV | $\frac{LV}{HV} > 33\%$ | ✓ possible |
| | 132 kV / 33 kV | LV/HV < 33% | × |
| | 66kV / 33kV | LV/HV > 33% | ✓ |
| | 33 kV / 11kV | LV/HV > 33% | ✓ |
| | 11 kV / 440V | LV/HV < 33% | × |
| Modern T/F | 440 kV/220kV | LV/HV > 33% | ✓ |



(2) Auto Transformer find wide applications as variac (or) Dimmerstat.

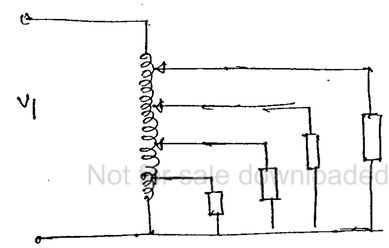
(3) Auto Transformer as a boosting Transformer to inject voltage (i.e Auto T/F in Series with lines)

(or)

Auto Transformer as a voltage Booster.

(4) Auto Transformer as a voltage Balanced Coil.

by taking Suitable tapping multi loads can be satisfied by Single Auto T/F.

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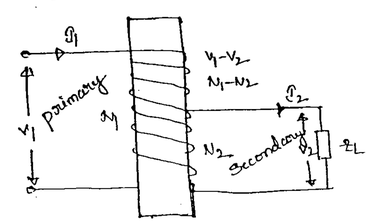
## Auto Transformer:-

Auto Transformer is a T/F in which two circuits are electrically as well as magnetically coupled.

Auto T/F in which some part of winding common to both primary and secondary.




part of HV nothing but LV.

HV devided into = (2) parts

(1) Upper Section of HV

(2) lower Section of LV.

Transformation ratio in Auto Transformer.

HV

Transformation usually expressed in % in Auto transformer.

If tapping @ 50 ; $k = 0.5$

@ 75% $k = 0.75$

@ 30% $k = 0.3$.

It is having many advantages compared with ② winding Transformer of same rating.

| 2 Winding | Auto T/F |
|---|---|
| (1) physically two windings are acomodated volume of core more | (1) physically single winding accomodated so volume of core required less. |
| (2) HV diff & LV diff; so insulation must be provided individually. Amount of insulation required more | (2) No insulation between HV & LV. ∴ part of HV = LV. Insulation only between HV ~~& HV~~ & core only. So insulation required less. |
| (3) ∵ HV & LV seperate windings turns for HV & LV separate so more copper required. | (3) No seperate windings. amount of Cu. required less. |

Because of all above discussion; size ~~of~~ wt & cost for auto Transformer is less. for same rating of 2 winding Transformer.

(4) Practically 30% less cost than 2 winding Transformer.
Performance of Auto Transformer more.



Performance indexed decided by — Efficiency, Regulation.

Ag core ↑ iron loss ↑

Ag copper ↑ Cu. loss ↑

In any Machine; $\boxed{\text{losses} \propto \text{volume of core}}$

Since Auto Transformer have less volume & less copper; ag loss ∝ volume; so losses in Auto Transformer less.

→ Magnetic leakage flux :-

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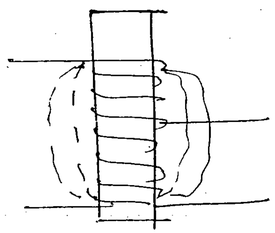
Magnetic flux @ HV can link with LV.

So leakage flux links at both windings.

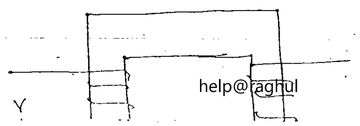


∴ Coefficient of Coupling more;
leakage flux ~~more~~; less;
leakage reactance less;
voltage drop less;
ag voltage drop less % voltage Regulation less.

Voltage Regulation good ag compared to 2 winding Transformer.

Auto Transformer not only cheap; it also have — good η, good Rg.

Auto Transformer can also be realized by ② winding Transformer.



To get auto Transformer;

(1) Connect two windings in Series and place tapping @ Center of winding.

(2) No need to Construct Seperate T/F.

If 2 winding Transformer changed to Auto Transformer, its KVA rating becomes very high. Almost 10 to 20 time with same voltage & current ratings.

Ex: If 10KVA 2 winding T/F changed to Auto Transformer; then KVA become — 100 KVA or 200 KVA.

With same voltages & Current; we are going to prove this also.

But don't think always Auto Transformer more advantages because it depends on "Tapping Location".

To get more advantages there is Breakeven point.

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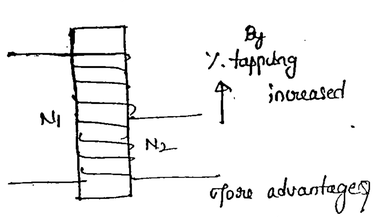
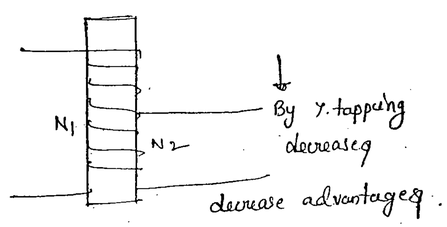
| | | | |
|---|---|---|---|
| BEP Start | $N_1 : N_2$ | $\geq 3:1$ | good (Advantages begins but less) |
| BEP | $N_1 : N_2$ | $\leq 3:1$ | advantages possible. |
| BEP | $N_1 : N_2$ | $\geq 3:1$ | advantage not possible. |

* Whenever Common part of winding less advantage of Auto Transformer not ~~post~~ possible.

More the % tapping more the advantages as BEP Starts @ $N_1 : N_2 = 3:1$

That means @ 33% Common path Auto Transformer Advantages Starts.






Between Auto T/F Turns Ratio 3:1 to 1:1 more advantageous & most Economical & more feasable.

## Important Features of Auto Transformer:-

(1) power transferred from oneside to anotherside by (2) processes.

→ Induction process.

→ Conduction process.

power transfer from upper Section HV to LV. done by Induction process.

power transfer from lower Section HV to LV. done by Conduction process.

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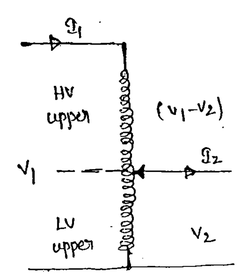
* In 2 winding Transformer power transferred by Conduction process = 0.

What is the amount of power transferred (KVA transferred) by Induction and Conduction.




Input KVA $= V_1 I_1$

$(KVA)_{Induction} = (V_1 - V_2) I_1$

$$\frac{(KVA)_{Induction}}{I/p \text{ KVA}} = \frac{(V_1 - V_2) I_1}{V_1 I_1}$$

$$= \left(1 - \frac{V_2}{V_1}\right) = (1 - k)$$

$k = \frac{V_2}{V_1}$ ; Transformation ratio or % tapping of Auto T/F.

Power Transfer by Induction

power Transfer by Conduction;

$KVA_{conduction}$ = Input KVA — Induction KVA Transferred

= k. Input KVA.

* One you know % tapping; you can find power transfer due to Conduction and Induction. This is called as Bifurcation of power transfer.

## Quantification of Advantages :-

(1). $(\text{weight of Cu})_{\text{Auto T/F}} = (1-k)\,(\text{weight of Cu})_{\text{2 winding T/F}}$

If tapping is 50%.

2 winding Transformer requires — 100% Cu.

Auto Transformer requires — 50% Cu.

% Cu. Saving in Auto Transformer α % Tapping.

Saving in Copper in Auto Transformer always α to k.

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(2) As auto Transformer voltage Regulation less ↓ ; ∵ % Reactance less.

$(\%\ \text{Impedance})_{\text{Auto T/F}} = (1-k)\,(\%\ \text{Impedance})_{\text{2 winding T/F}}$.

If 2-winding Transformer % Impedance — 12%.

with 50% tapping

% Impedance of Auto Transformer — 6%.

(3). As Auto Transformer more Efficient; why because losses less.

you can't Compare directly losses w.r.t. 2 winding Transformer;

But you can Compare loss by % losses.



$(\%\ \text{Full load Losses})_{\text{Auto T/F}} = (1-k)\,(\%\ \text{Full Load})_{\text{2 winding T/F}}$

If % tapping is 60%. If % F.L. losses of 2 winding T/F is 10%.

% Full load of Auto T/F = (1−0.6)(10%) = 4%.

As k approaches to unity then denominator becomes '0'; Since KVA of Auto Transformer becomes ∞ Even though voltage & Current rating kept Same.

Dont apply these relations during problems. Because all this is mean to only for analysis that to for Step down Auto T/F.

I will give another Convinient procedure to for solving problem.

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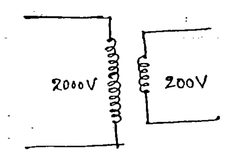
→ Realisation of Auto Transformer By using 2 Winding Transformer :-

If you want to realise Auto T/F ~~as~~ by 2 winding better to go with Example.

If you want to realise 2 winding Transformer ; you must Connect a Series Connection;




2000/200V
20kVA 2 winding T/F.

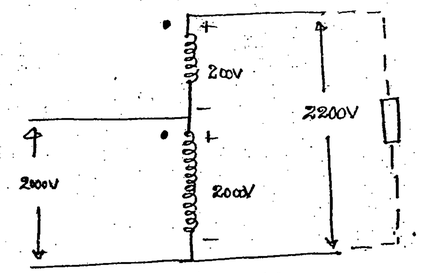
By Magnetic Coupling there are ② types of Series Connection.

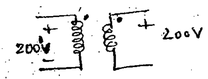
(1) Series Additive

(2) Series Opposive.

So Conduct polarity test; you can find polarities by dots.

~~Case I: Series Additive polarity~~




point

Voltage Rating ?

Tapping generally decided by Source Voltage available & load required meet.

As Series additive polarity flux will be additive.

Connect tapping @ mid point of winding then you can obtain :

Maximum Voltage = 2000 + 200 = 2200 V.

Voltage Rating of Auto Transformer = 2000/2200 V.

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→ You can connect load @ any side as depends on your load ~~voltages~~ ratings.

Always use common path for HV winding because

(1) If you use HV common path

k = More advantage ∴ k ≈ 1.

(2) If you use LV common path

$k = \frac{200}{2000} = \frac{1}{11}$ less advantage.

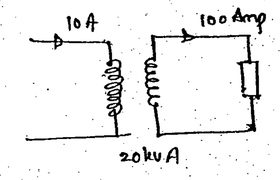
KVA Rating :-

Dont apply previous given formula.



2 winding you must know current rating :-

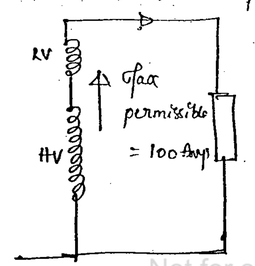
↳ Max permissible I in HV.




$I_{rated} = \frac{20 \times 10^3}{2000} = 10$ Amp.

$I_{rated} = \frac{20 \times 10^3}{200} = 100$ Amp.

Max 100 Amp




∵ Same winding converted to Auto T/F.

Secondary allowable current in Auto T/F is 100 Amp.

KVA rating of A-T

$= V_2 I_2$

$= 2200 \times 100$

$= 220$ kVA.

∴ Auto T/F KVA >> 2 winding T/F KVA.

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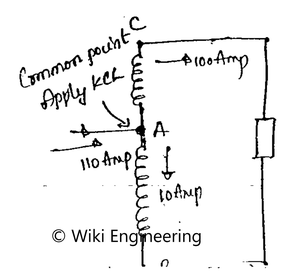
→ Primary Current ?

primary kVA = Sec. kVA = 220 kVA

$I_1 = \frac{220 \times 10^3}{2000} = 110$ Amp.

Current in common part of Auto T/F ?




Simply apply @ common part ; but direction of current important

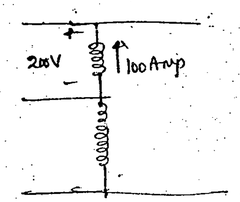
i.e., Current in common part of A-T = 110 − 100 = 10 A

* so ultimately the maximum allowable currents in 2 winding Transformer only we allowing in Auto Transformer.

Similarly voltages also applied ~~by~~ as per their same rating in 2 winding T/F ; But still why kVA rating becoming high.

kVA transfer due to Induction ?

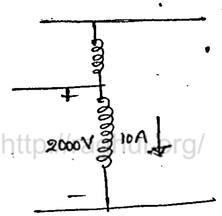
$(kVA)_{Induction} = 200 \times 100$
$= 20\ kVA$




That means same as 2 winding T/F same Induction kVA transferred by Induction.

→ kVA transfer due to Conduction ?

$(kVA)_{Conduction} = 220\ kVA - 20\ kVA$
$= 200\ kVA.$




In 2 winding Transformer,
Conduction kVA = 0.

* ∴ As more common path increasing Conduction kVA also increasing.

Because of Conduction kVA only ~~two~~ Auto Transformer kVA is more compare to 2 winding T/F.

If η 2 winding T/F = 96% @ full load upf.
Then η of Auto Transformer = ? @ full load & upf.

When even Auto Transformer there by converting 2 winding T/F ?

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No change between
Voltage ratings same in both T/F.
Current ratings same in both T/F.
losses also same in both T/F.

As Auto T/F obtained by 2 winding T/F ; there is no ~~Conduction~~ reduction in losses, voltages, currents, η ↑ etc. ... no insulation & copper & size saving.

But if you construct original Auto Transformer you can find more advantages.

like insulation savings, copper saving, volume reduction, low losses etc...

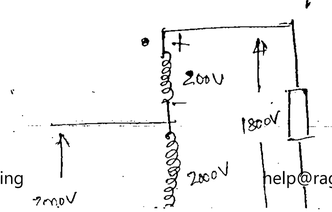
losses same in both T/F as Auto T/F constructed from 2 winding T/F @ 2 winding T/F

$\eta_{FL\ UPF} = \frac{o/p}{o/p + losses} = \frac{20 \times 10^3 \times 1}{20 \times 10^3 \times 1 + \text{Total losses}} = 0.96$

Total losses = 833 watts.

$\eta_{FL\ UPF\ @\ Auto\ T/F} = \frac{o/p}{o/p + losses} = \frac{220 \times 10^3 \times 1}{220 \times 10^3 \times 1 + 833} = 99.6\%$

Case II :- (Auto T/F with series ~~Substrac~~ Substractive polarity).




you change source and load positions.

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Voltage rating of Auto T/F = 1800 V.

(2) kVA rating of Auto T/F $= V_2 I_2$

$= 1800 \times 100$

$= 180$ kV.

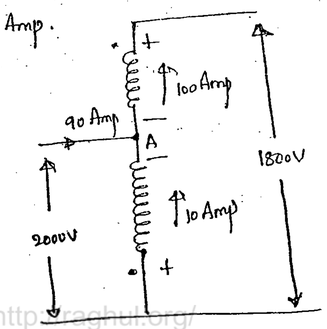
9 times of 2 winding T/F.

~~(3) Primary rating of Auto~~

(3). primary Current in Auto T/F.

primary kVA = Sec. kVA = 180 kVA.

$$I_1 = \frac{180 \times 10^3}{2000} = 90 \text{ Amp.}$$




(4) Current in Common part of Auto T/F = By KCL

10 A ↑ (B to A)

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(5) $(kVA)_{Indic} = ?$ $(kVA)_{cond} = ?$

$(kVA)_{Induction} = 200 \times 100$

$= 20$ kVA

$= (kVA)_{Two\ winding\ T/F}$.

$(kVA)_{conduction} = 180$ kVA $- 20$ kVA

$= 160$ kVA.

(6) $\eta_{FL}$ @ 96% $\eta$. UPF @ Two Winding

$$= \frac{20 \times 10^3 \times 1}{20 \times 10^3 \times 1 + \text{Total loss}} = 0.96.$$

Total loss = 833 watts.



$$\eta_{F.L\ Auto\ T/F} = \frac{180 \times 10^3 \times 1}{180 \times 10^3 \times 1 + 833} = 99.5\%.$$

In Series Substractive polarity also we are getting almost same $\eta$ as in Series aditive.

Draw Backs in Auto Transformer :-

(1) Source & load Electrically not isolated. So not suitable where Ever electric isolation required ~~@ load~~.

(2) LV fault :- whenever fault occurs @ load it directly effects @ Source side since no Electrical isolation.

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(3) Reactance of Auto Transformer less :-

$$\therefore \text{Steady Short Ckt Current} \propto \frac{1}{\text{pu Impedance}}.$$

So Short Circuit Current levels high in Auto Transformer Compared to (2) Winding Transformer..

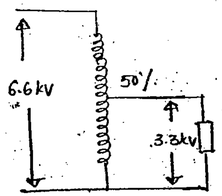
(4) Auto Transformer advantages not possible with all tapping points.

Turns Ratio : 4:1, 5:1; 6:1; 7:1, .... not advantages,

Turns Ratio : 3:1, 2:1; 1:1 ..... more advantages.

Transformation Ratio : 33% to 100% more advantages.

proper protection @ Common path accidentally opening




whenever some open ~~open~~ ~~op~~ path occured in Common path of Auto T/F Cause HV across LV Load. So proper protection ~~against~~ must provide for ~~Common~~ high voltage i.e 6.6 kV (Common path opening) appears across load.

All these are ~~minor~~ very minor drawbacks Compare to their advantages.

Only drawback turns ratio 3:1 to 1:1 only most popular.

## Applications of Auto Transformer :-

1, Auto Transformer using in some Substations instead of 2 winding Transformer.

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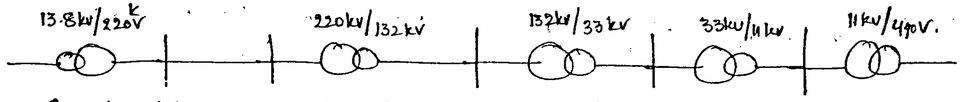



| Generating station | All modern | ∵ large voltage | All modern |
|---|---|---|---|
| ∵ large voltage variation | Substations replacing 220kV/132kV by Auto T/F | variation. % tapping less than 33% so not suggestable. | 33/11kV Transformers replacing by Auto T/F. |
| Auto T/F not possible | | | |

Normally —— 220kV grid — state grid — Maintained by APTRANCO.

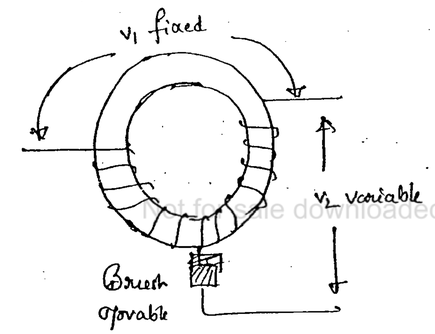
② grid —— 400kV grid —— Central grid Maintained by — PGDCIL.

To Connect Central grid to State grid we need Interconnecting grid T/F must allow Bidirectional.

for that we need 400kV/220kV T.F.

All practical modern Intergrid Substations with Auto Transformer only

(2) Variac (or) Auto T/F :- for getting variable voltages in laboratories.

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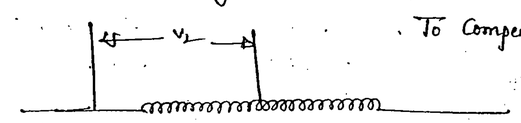
(3) To start 3-φ Induction Motors :-

During starting to reduce starting Currents we usually apply gradual voltages in Induction Motors..

(4) Auto Transformer as Voltage Booster :-




To Compensate voltages in Transmission lines.

Auto T/F ~~for~~ in Trans. lines is placed in Series for getting advantage of voltage Boosting.

If voltage raise happend D.L.... Common path then injecting voltage to

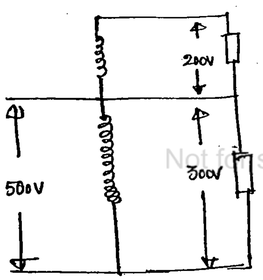
## (5) Auto Transformer as voltage Balanced Coil :-

(Similar to potential devider) 145

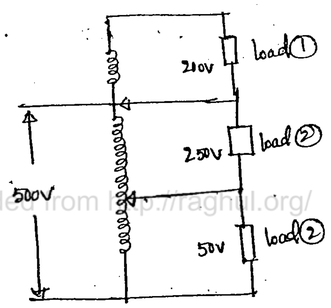
By Single Source you can generate only one voltage, you can get if only one load you can operate but in practical situations ;

only ① Source
- ① load requires 200V
- ② load requires 400V
- ③ load requires 600V
- ④ load requires 1500V.

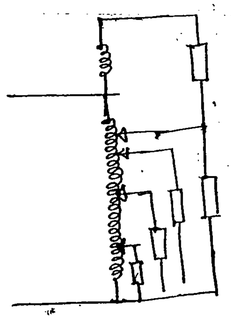
By ② winding T/F this application not possible but Auto Transformer makes possible.




Simultaneously ② load operate with ① tapping.




Simultaneously ③ loads operating with ② tappings. which is not possible with two winding T/F.



n loads T/F

for which Separate winding necessary @ Secondary.

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## Multiwinding Transformers :-

### 3 winding T/F :-

Tertiary winding :- Y/Y with ⑤ limbed Core of Bank Construction T/F.

By tertiary winding (stabilizing winding)

(1) Maintains Stable Neutral point.

(2) Makes pure Sinusoidal working flux of induced Emf.

(3) Restriction for Earth Current reduced ∵ It allows Zero Sequence Current so, Earth fault relay operates.

(4) Allows Zero sequence Current.

Not only in Y/Y tertial used practical, in almost all T/F's it is used.

→ General functions of Tertiary Winding :-

(1) Auxiliary Supply in Substation :-

for 220 kV/132 kV Substation you can get two voltages
- 220 kV
- 132 kV.

But by placing small winding (Tertiary); of 440V you can operate loads i.e., Battery charging, lighting, Supply for protection panel.

These are called Auxiliary loads in Substations.

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Generally we use phase compensating devices like

Capacitor Banks
Syn. phase Modifiers
phase advancers
Stat Comps

} To inject or withdraw reactive into system (or) to control voltages.

are used.

Usually rating of capacitor banks not more than 3.3 kV or 6.6 kV.

If in 220 kV / 132 kV Substation we can't directly required so that we have to PT for connections.

Instead of having PT use tertiary winding, which can also allow to connect phase compensating devices across it.

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(3) Let in some area situation like this;

132 kV / 33 kV / 11 kV feeders.

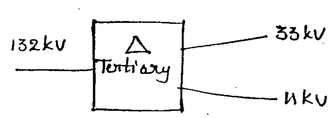
Industry User — 11 kV Supply.

Domestic Consumer — 440V, 230V.

If a industry is nearer to substation then instead of using one core T/F of 33/11 kV.

By placing (tertitiary) winding in side T/F; you can obtain directly (2) out feeders. 11 kV, 33 kV.

∴ one source




Two out feeders.



(4) To Conduct Tests on High Voltage Transformers :—

To conduct OC & SC test; whatever the tests directly of 220/132 kV T/F, If is not possible so that at that situation conduct your ~~test~~ test at least voltage winding i.e Tertiary winding.

One you know turns ratio; you can find tertiary voltage levels; so that tertiary winding you can use as testing coil.

~~Tertiary~~ Teritiary Coil — Testing Coil.

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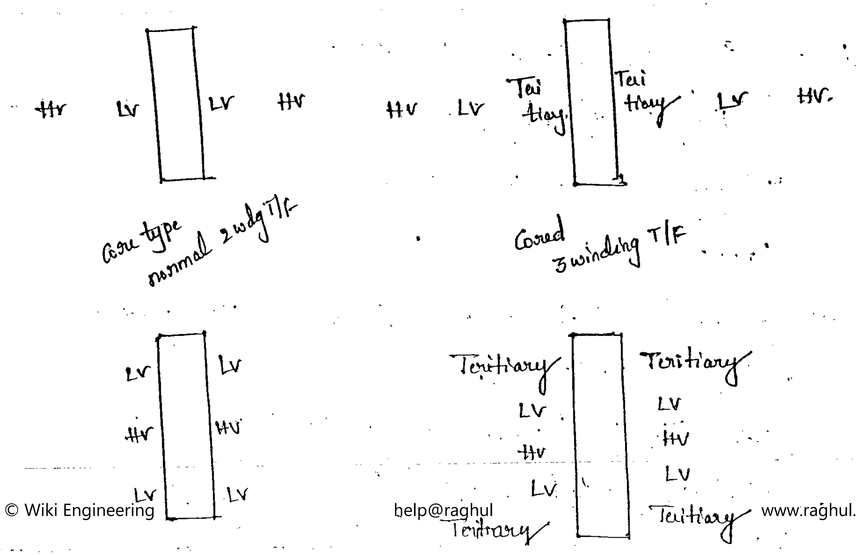
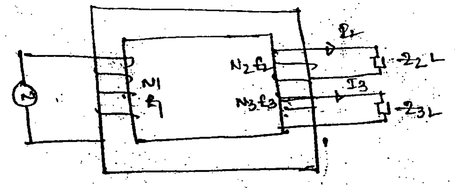
* So to get all these above advantages; usually almost all T/F's provided with Teritiary winding T/F.

Analysis of Teritiary Winding :—






As Transformer ③ windings you can define ② transformation ratio. (∵ Transformation ratio define between source to load)

(1) $k_{2\,b/n}$ Source to Secondary.

(2) $k_{3\,b/n}$ Source to tertiary.

$$k_{21} = \frac{N_2}{N_1} = \frac{E_2}{E_1}$$

$$K_{31} = \frac{N_3}{N_1} = \frac{E_3}{E_1}$$

Secondary Current refer to primary;

$$I_2' = -k_{21} I_2$$

In vector diagram; $I_2'$ & $I_2$ (displaced by 180°)

Tertiary Current refer to primary :-

$$I_3' = -k_{31} I_3.$$

Let no load Current $= I_0$.

By $I_0$ neglecting $(\bar{I}_1 = \bar{I}_0 + \bar{I}_2' + \bar{I}_3')$

load Component in primary $\bar{I}_1 = \bar{I}_2' + \bar{I}_3'$

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→ Problems are like this :—

(1) $I_2 \angle -\phi_2$ $I_3 \angle -\phi_3$ $I_2, I_3$ both given;

in polar form no need to transfer Secondary & Tertiary components to primary side.

Rectangular form Suitable — Addition & Substraction

polar form we use Easy — Multiplication & division

If $N_2/N_1$ give ;- you can find k.

you convert $I_2$ & $I_1$ into rectangular.

$$I_2' = -k_{21} I_2 = -\frac{N_2}{N_1} I_2 = (\quad) - j(\quad)$$

$$I_3' = -k_{31} I_3 = -\frac{N_3}{N_1} I_3 = (\quad) - j(\quad)$$

$$I_1 = I_2' + I_3' = (\quad) - j(\quad)$$

Again you convert into $I_1 \angle -\phi$ polar form.

(11) As no-load Current neglect;

primary kVA = Secondary kVA (in Auto T/F).

But in Tertiary winding T/F ; Even no-load Current neglected;

primary kVA ≠ Secondary kVA + Tertiary kVA (until p.f @ both loads equal)

If $\cos\phi_2 \neq \cos\phi_3$.

$(kVA)_{3w} \neq (kVA)_{sec} + (kVA)_{Tertiary}$

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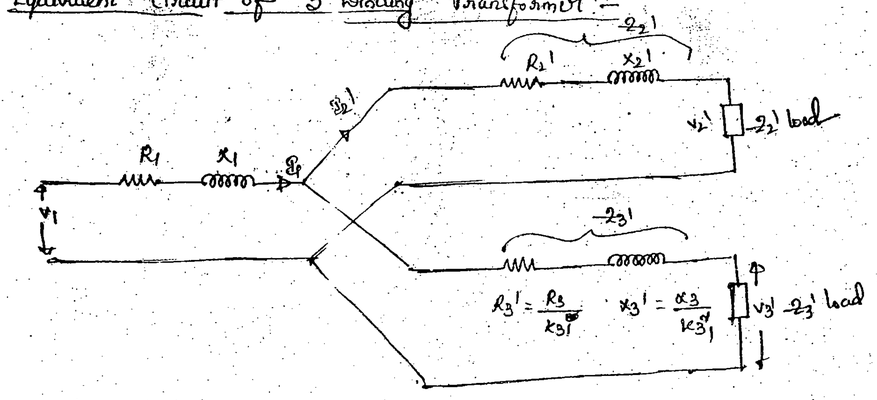
→ Equivalent Circuit of 3 winding Transformer :-




Here only one primary ⟲ Two Secondaries :-

Neglect no-load Current;

* It is Easy to Conduct O.C Test on both windings
  - Just Excite primary = open Circuited ~~both~~ both windings.

But SC test difficult;

(1) we need to Conduct @ ③ Short Circuit tests.

→ SC Test primary — Exists Second — short Teritiary — open.

→ SC Test primary — Excite Second — open Teritiary — Shorted.

→ SC Test primary — open Second — Excite Teritiary — Short.

→ SC Test :- Increase voltag across primary until rated Current occurs in Secondary; then note down meter reading.

i.e., $Z_{12} = \frac{V_{sc1}}{I_{sc1}} = Z_{sc1}$ (Total primary & Secondary Impedance)

$Z_{sc1} = Z_1 + Z_2'$ ..... ①

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(2) SC Test :-

Excite primary; Sec — open; tertiary — short;

Short Circuit between Teritiary & primary

↑ Increase voltage @ primary until teritiary; rated Current flows them; then note down readings;

$V_{sc2}$, $I_{sc2}$

$Z_{13} = \frac{V_{sc2}}{I_{sc2}} = Z_{13} = Z_1 + Z_3'$

(3). SC Test :-

primary — open Secondary — Excite.

No Current in primary (∵ opened)

↑ voltage @ Secondary until rated Current (I) flows in tertiary.

$Z_{23} = \frac{V_{sc3}}{I_{sc3}} = Z_2' + Z_3' = Z_{23}$

One you know Combination impedances you can find Easily individual winding impedance.

$Z_1 = \frac{1}{2}\left(Z_{12} + Z_{13} - Z_{23}\right)$

$Z_2' = \frac{1}{2}\left(Z_{12} + Z_{23} - Z_{13}\right)$

$Z_3' = \frac{1}{2}\left(Z_{13} + Z_{23} - Z_{12}\right)$

By these you can solve. $Z_2 = k_{21}^2 Z_2'$

$Z_3 = k_{31}^2 Z_3'$

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