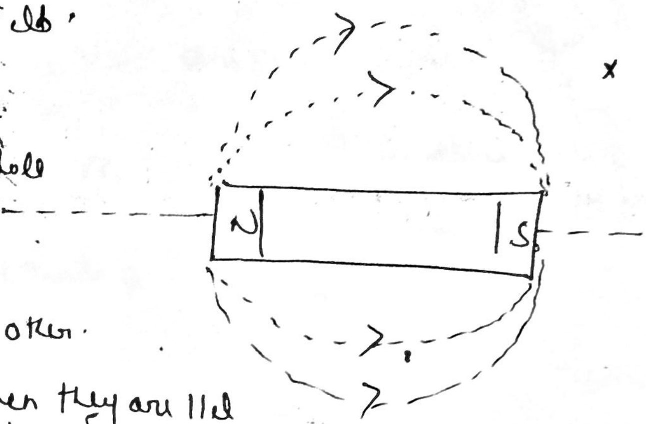
1) Magnetic field :- The region around the magnet where its poles exhibit a force of attraction or repulsion is called magnetic field.

The direction of magnetic field is from N pole to S-pole outside the magnetic ×
They form closed loop.
They never intersect each other.
They repel each other when they are ||el & are in the same direction.



× But inside the magnet their direction is from S pole to N-pole.

2) Magnetic flux :- The amount of magnetic lines of force set up in a magnetic circuit is called magnetic flux.

→ Wb

3) Magnetic flux density is flux per unit area at the right angles to the flux at that point

$$B = \frac{\phi}{A} \quad Wb/m^2 \text{ or Tesla}$$

4) Permeability :- The ability of material to conduct magnetic lines of force through it is called permeability of material. The greater the permeability of material, greater is its conductivity μ for magnetic lines of force

μ_0 - permeability of air is poorer

$$\mu_0 = 4\pi \times 10^{-7} \; H/m$$

5) Relative permeability

permeability of material

$$\mu_r = \frac{\mu}{\mu_0}$$

$$\boxed{\mu = \mu_0 \mu_r}$$

M.M.f :- The magnetic pressure which sets up or tends to set up magnetic flux in a magnetic circuit.

$$m.m.f = NI \text{ ampere-turn (AT)}$$

7. Reluctance (S) :- The opposition offered to the magnetic flux by a magnetic circuit

$$S = \frac{1}{\mu}\frac{l}{a} = \quad S = \frac{1}{\mu_0 \mu_r}\frac{l}{a} \quad AT/wb$$

$B = \frac{\phi}{A}$

8. Magnetic field Intensity :-

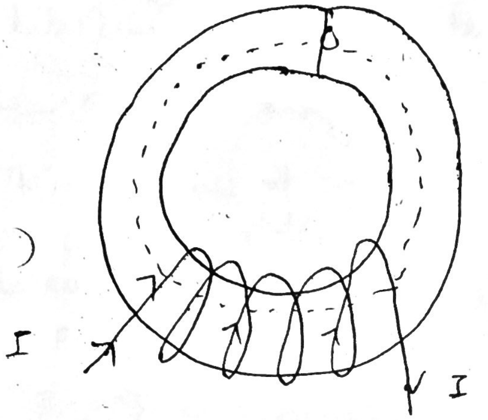
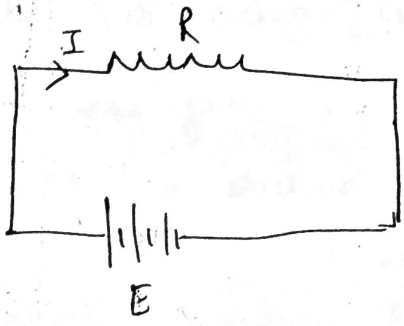
The force acting on a unit north pole when placed at a point in the magnetic field is called magnetic intensity of field at that point

$$H = \frac{mmf}{\text{length of magnetic path}} = \frac{NI}{l} = AT/m$$

$4\Omega\,AT/m$

Comparison between Electrical & Magnetic Circuit :-

Similarities

Magnetic circuit	Electrical circuit
· The closed path for magnetic flux is called magnetic circuit.	1. The closed path for electric current is called electrical circuit
	
2. $\text{flux} = \dfrac{\text{m.m.f}}{\text{reluctance}}$	2. $\text{Current} = \dfrac{\text{emf}}{\text{resistance}}$
flux in Wb	emf in V
m.m.f in AT	resistance in ohm
3. Reluctance $S = \dfrac{l}{a\mu} = \dfrac{l}{a\,\mu_0 4\pi}$ (μ permeability)	3. Resistance $R = \rho \dfrac{l}{a} = \dfrac{1}{\sigma}\dfrac{l}{a}$
· Permeance $= \dfrac{1}{\text{Reluctance}}$	4. Conductance $= \dfrac{1}{\text{resistance}}$
	Conductivity $\sigma = \dfrac{1}{\rho}$
i. flux density $B = \dfrac{\phi}{A}$ Wb/m^2	5. Current density $J = \dfrac{I}{a}$ A/m^2
: Magnetic intensity $= \dfrac{NI}{l}$	6 Electric intensity $E = \dfrac{V}{d}$.

Dissimilarities

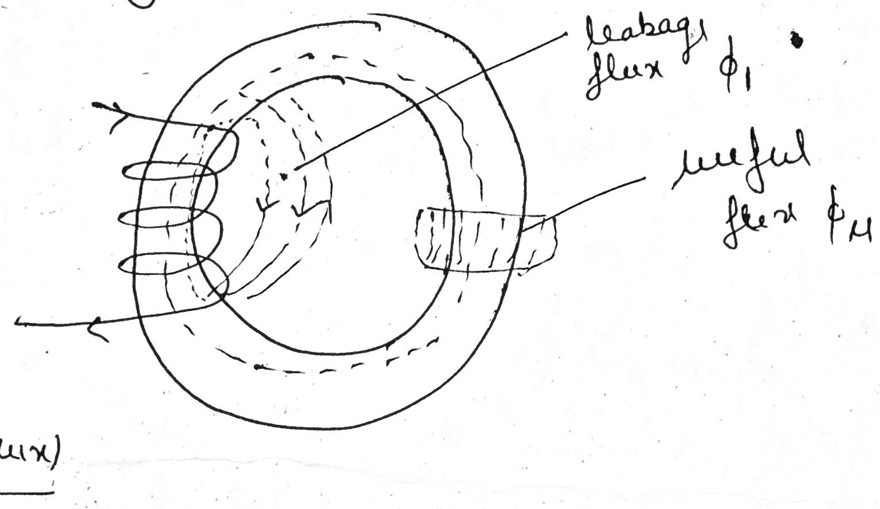
1. Magnetic flux does not flow but it sets up in the magnetic circuit.	1. The electric current flow in an electrical circuit.
2. It can be set up in non magnetic material like air, glass with reasonable m.m.f.	2. There are large no of perfect insulators like glass, air which do not allow it to flow through them.
The reluctance of magnetic circuit is not constant rather it varies with the value of B.	3. The resistance of an electric circuit is almost constant as its value depends upon the value of ρ which is almost constant.

$$B = \mu H$$

$$B = \mu_0 \mu_r H$$

$$S = \frac{l}{\mu_0 \mu_r a} = \frac{l}{\frac{B}{H} a}$$

<u>Leakage flux</u> :- The magnetic flux which does not follow the intended path in a magnetic circuit is called leakage flux.



$$\boxed{\phi = \phi_l + \phi_u}$$

<u>Leakage co-efficient</u>

$$\lambda = \frac{\phi \text{ (total flux)}}{\phi_u}$$

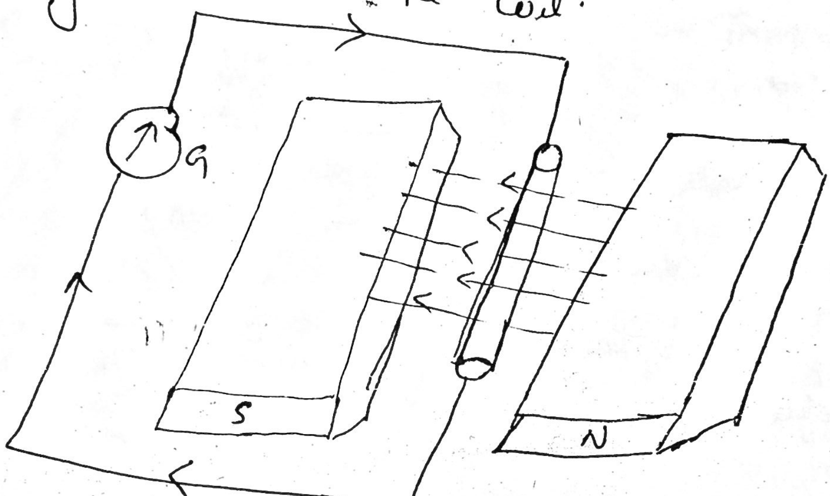
Faraday's law of electromagnetic Induction :

Ist law :-

Whenever a conductor cuts across the magnetic field, an emf is induced in the conductor.

or

Whenever the magnetic flux linking with any coil changes, an emf induced in the coil.



2nd law

The magnitude of induced emf in a coil is directly proportional to rate of change of flux linkages.

Rate of change of flux linkage $= \frac{N(\phi_2 - \phi_1)}{t}$ wb turns/sec

$$e \propto \frac{N(\phi_2 - \phi_1)}{t}$$

$$e = \frac{N(\phi_2 - \phi_1)}{t}$$

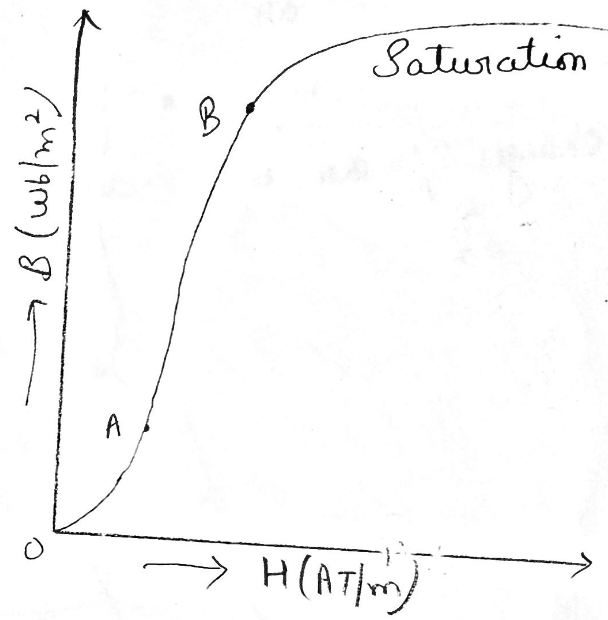
$$e = N\frac{d\phi}{dt}$$

$$e = -N\frac{d\phi}{dt}$$

emf is induced in such a direction which opposes the causes (change of flux)

Magnetisation or B-H characteristics :-

The graph plotted between magnetic flux density B & magnetising force H of a material is called magnetisation or B-H curve.



B-H curve

The shape of curve is non-linear. This indicates that relative permeability

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

of a magnetic material is not constant but it varies. The value ~~indicated~~ of μ_r largely depends upon the value of flux density.

<u>The curve has three parts</u>

i) <u>OA</u> :- In OA, flux density rises with rise of magnetising force H.

ii) <u>AB</u> :- In AB, curve becomes steep and straight. i.e. after point A, rise in flux density is quite high even when magnetising force H increases slightly.

iii) <u>B onwards</u> :- The curve becomes almost a horizontal straight line. This straight lining of magnetisation curve is called magnetic saturation & point B is called saturation point. After B rise in flux density will be negligible.

Types of Magnetic Materials

All material can be classified in terms of their magnetic behavior.

Diamagnetic	Paramagnetic	Ferromagnetic
→ The material which have a weak, negative susceptibility to magnetic fields.	→ The material which have small, positive susceptibility to magnetic fields.	→ The material which have a large, positive susceptibility to an external magnetic field.
→ These materials are slightly repelled by a magnetic field and they do not retain the magnetic properties when the external field is removed.	→ These materials are slightly attracted by a magnetic field and they do not retain the magnetic properties when the external field is removed.	→ These materials exhibit a strong attraction of magnetic fields and are able to retain their magnetic properties after the external field has been removed.
→ In diamagnetic materials all the electrons are paired so there is no permanent net magnetic moment per atom.	→ Paramagnetic properties are due to the presence of some unpaired electron, and from the realignment of the electron paths caused by the external magnetic field.	→ Ferromagnetic materials have some unpaired electrons so their atoms have a net magnetic moment.
→ Diamagnetic elements are : Copper, Silver and Gold. Also water, graphite, bismith.	→ Example : Aluminium, magnesium, lithium.	→ Example : Iron, Nickel, Cobalt.

Properties	Diamagnetic	Paramagnetic	Ferromagnetic
State	They can be solid, liquid or gas.	They can be solid, liquid or gas.	They are solid.
Effect of Magnet.	Weakly repelled by a magnet.	Weakly attracted by a magnet.	Strongly attracted by a magnet.
Behaviour under non-uniform field	Tend to move from high to low region.	Tend to move from low to high field region.	Tend to move from low to high field region.
Behaviour under external field.	They do not preserve the magnetic properties once the external field is removed.	They do not preserve the magnetic properties once the external field is removed.	They preserve the magnetic properties after the external field is removed.
Effect of temperature	No effect.	With the rise of temperature, it becomes a diamagnetic.	Above curie point, it become a paramagnetic
Permeability	Little less than unity.	Little greater than unity.	Very high.
Susceptibility	Little less than unity and negative.	Little greater than unity and positive	Very high and positive.

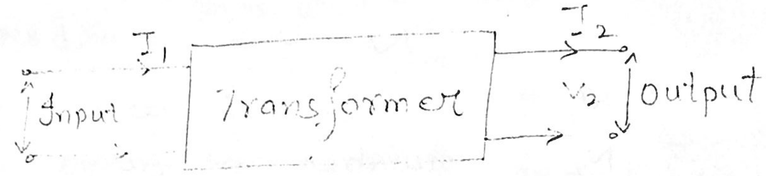
NOTE : Curie Temperature/Point (T_c) : It is the temperature above which certain material lose their permanent magnetic properties, to be replaced by induced magnetism.

e.g. Iron $T_c = 1043\ K$ ($1K = 274°C$)

TRANSFORMER

⇒ A transformer is a static device which transfer a.c. electrical power from one circuit to the other at same frequency but the voltage level is usually changed.

- when $V_2 > V_1$ i.e. voltage is raised on the output side, the transformer is called a step-up transformer.

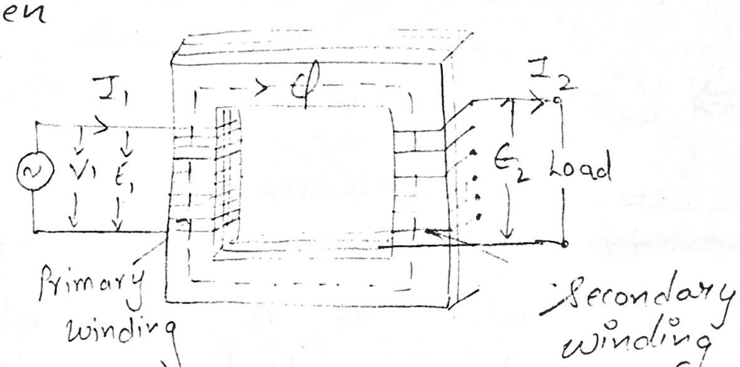


- whereas, when $V_2 < V_1$, i.e. the transformer in which the voltages is lowered on output side, is called step-down transformer.

⇒ WORKING PRINCIPLE :
A transformer is an electrical device that transfers electrical energy between two or more circuits through electromagnetic induction.

→ when ac supply of voltage V_1 is connected to primary winding, an alternating flux is set up in the core.

→ This alternating flux when links with secondary winding, an e.m.f is induced in it called mutually induced e.m.f.



→ direction of induced e.m.f is opposite to the applied voltage V_1, according to Lenz's law.

→ Although there is no electrical connection between primary and secondary winding but electrical power is transferred from primary circuit to the secondary circuit through mutual flux.

→ Induced e.m.f. thus given as,

$$e \propto N \frac{d\phi}{dt}$$

where, $d\phi/dt$ → rate of change of flux

N → number of turns of coil.

(N_1 : number of turns of primary winding,
N_2 : number of turns of secondary winding)

when, $N_2 > N_1$ → transformer is step-up transformer.

$N_1 > N_2$ → transformer is step-down transformer.

→ Turn ratio : Ratio of primary to secondary turns i.e. N_1/N_2.

→ Transformation ratio (K) : Ratio of secondary voltage to primary voltage.

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

⇒ CONSTRUCTION :

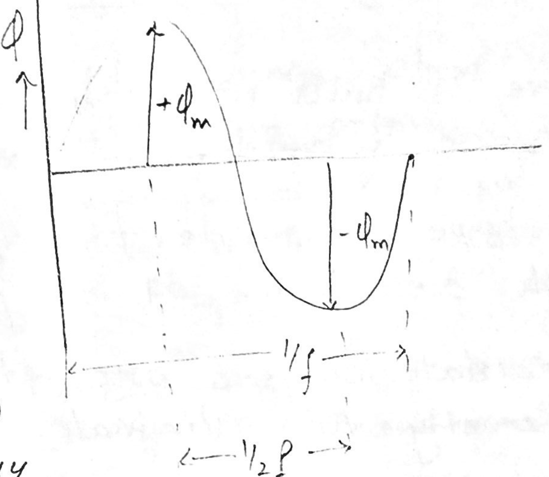
→ main elements are : two coils, and a laminated steel core.

→ Each core is laminated by a light coating of varnish or by an oxide layer to minimise the eddy current loss.

→ thickness of lamination is 0.35 mm – 0.5 mm.

⇒ E.M.F. Equation :

→ Sinusoidal voltage is applied to transformer thus a sinusoidal flux is set up in iron core,



ϕ_m → Maximum value of flux (wb)

f → supply frequency (Hz)

N_1 → no. of turns of primary winding.

N_2 → number of turns of secondary winding. $\frac{d\phi}{dt}$ → $2\phi_m$

Average rate of change of flux : $\frac{\phi_m - (-\phi_m)}{1/2 f}$

$= 4f\phi_m$ wb/s.

and,

Average emf induced per turn $= 4f\phi_m$ volts.

RMS value of e.m.f induced ⇒ $E = 1.11 \times 4f\phi_m$

$= 4.44 f\phi_m$ volts

[∵ form factor of sinusoidal wave $= \frac{\text{RMS Value}}{\text{Average value}} = 1.11$]

thus, RMS value of emf induced in primary and secondary winding is,

$E_1 = 4.44 f\phi_m \times N_1$

$E_2 = 4.44 f\phi_m \times N_2$

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

⇒ According to core construction :-

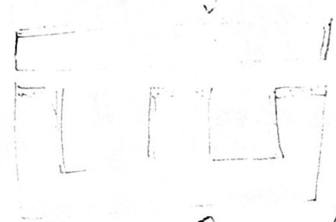
(A) CORE TYPE TRANSFORMER :

→ Core is built up of laminations to form a rectangular frame.

→ L-shape is made to avoid high reluctance at the joints.

→ Alternate layers are stacked differently to elliminate continuous joint.

(B) Shell Type TRANSFORMER :



→ Core has three limbs.

→ Central limb carries whole of the flux, whereas side limbs carry half of the flux.

⇒ AN IDEAL TRANSFORMER :

An ideal transformer is one which has no ohmic resistance and no magnetic leakage flux. Hence, transformer has no copper losses and core losses.

In an ideal transformer, there is no power loss, thus output must be equal to input.

$$E_2 I_2 \cos\phi = E_1 I_1 \cos\phi$$

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

or, Transformation ratio, $\boxed{K = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}}$

↳ Ratio of

⇒ LOSSES IN A TRANSFORMER :

Losses occur in an actual transformer are

(A) **Core or Iron losses** : It occurs when Ac supply is given to the primary winding of a transformer and an alternating flux is set up in the core.

1. Hysteresis Loss → when magnetic material is subjected to reversal of flux, ~~external~~ power required for continuous reversal of molecular magnets this power is dissipated in the form of heat and is known as hysteresis loss.

minimize → using silicon steel material. for core.

2. Eddy Current loss → flux linkage in the core induced an emf in the core and circulates eddy currents. Power is required to maintain these eddy currents. This power is dissipated in the form of heat and is known as eddy current loss.

minimize → making core of thin laminations.

(B) **Copper losses** : It occur in both the windings due to their ohmic resistance.

Total Copper losses $= I_1^2 R_1 + I_2^2 R_2 = I_2^2 R_{es} = I_1^2 R_{ep}$

where, I_1 & I_2 → primary & secondary currents
R_1 & R_2 → primary & secondary resistances.

Also known as variable losses because current in the windings vary according to the load.

⇒ EFFICIENCY OF A TRASFORMER (η)

$$\eta = \frac{\text{Output power (kW)}}{\text{Input power (kW)}} = \frac{\text{Output power}}{\text{Output power + losses}}$$

or,

$$\eta = \frac{\text{Output power}}{\text{Output power + Iron losses + Copper losses}}$$

$$\boxed{\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + P_c}}$$

where,

V_2 → secondary terminal voltage
I_2 → full load secondary current
$\cos\phi_2$ → power factor of load.
P_i → Iron losses
P_c → Copper losses $= I_2^2 R_{es}$

thus.

Condition for maximum efficiency :

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

Here efficiency depends upon load current.

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

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

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

i.e. Iron losses = Copper losses

Thus efficiency of transformer is maximum, when

$$P_i = P_c$$

i.e.

$$\eta_{max} = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + 2P_i}$$

also of η_{max} $\quad I_2 = \sqrt{\frac{P_i}{R_{es}}}$

Also, Iron losses, P_i → constant

Copper losses, P_c → Variable (depend upon load)

if. x is the fraction of load in kVA

thus, $x^2 P_c = P_i$

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

Also,

Efficiency, $$\eta = \frac{x V_2 I_2 \cos\phi_2}{x V_2 I_2 \cos\phi_2 + P_i + x^2 I_2^2 R_{es}}$$

or, $$\eta = \frac{x V_2 \cos\phi_2}{x V_2 \cos\phi_2 + P_i / I_2 + x^2 R_{es} I_2}$$

⇒ **Different type of Transformer and its uses :**

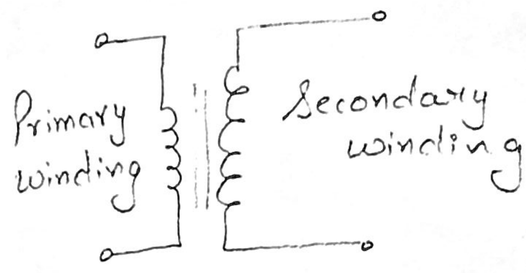
(1) **Based on Voltage levels :**

Depend upon the voltage ratio from primary to secondary :

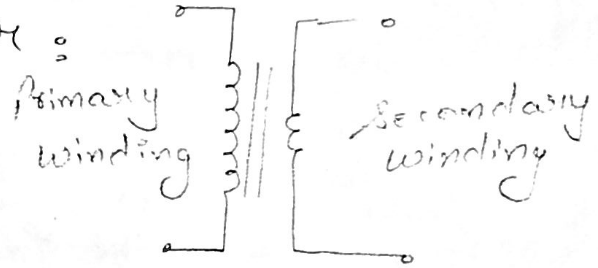
(A) Step-up Transformer ⇒ In this secondary voltage is stepped up with a

→ Number of windings in the secondary is more as compare to primary winding.

→ In power plant, transformer is used as connecting transformer of the generator to the grid.



(B) Step-down transformer :



→ Used to step down the voltage level from lower to higher level at secondary side.

→ Winding turns more on primary side as compare to secondary side.

→ In distribution network, it is used to convert the high grid voltage to low voltage that can be used for home appliances.

(2) Based on the Core Medium used :

Based on the medium placed between the primary and secondary windings :

(A) Air Core Transformer : Here flux linkage between primary and secondary windings wound on a non-magnetic strip is through the air.

(B) Iron Core Transformer : Both primary & secondary windings are wound on multiple iron plate bunch which provide a perfect linkage path to the generated flux. Widely used because of high efficiency.

(3) Transformer based on Usage :

(A) Power Transformer : Used in power generation stations and transmission substation. It has high insulation level.

(B) Distribution Transformer : It is used for the distribution of electrical energy at low voltage is less than 33 kV in industrial purpose and 440 - 220 V in domestic purpose.

(C) Measurement ~~Magnetic~~ Transformer : Used to measure electrical quantity like voltage, current, power etc.

Numericals

Ques :- At full load current, the iron and copper losses in a 100 kVA transformer are each equal to 2.5 kW. Find the efficiency of transformer at a load of 75 kVA and 0.8 power factor lagging.

Sol^n

Transformer rated capacity : 100 kVA

operating load : 75 kVA

fraction of load, $x = \frac{75}{100} = 0.75$ kVA

Iron losses, $P_i = 2.5 kW$

Copper losses, $P_c = 2.5 kW$

Power factor, $\cos\phi = 0.8$ lagging.

Using formula of efficiency,

$$\eta = \frac{x \cos\phi}{x \cos\phi + P_i + x^2 P_c} \times 100$$

$$= \frac{0.75 \times 100 \times 0.8}{0.75 \times 100 \times 0.8 + 2.5 + (0.75)^2 \times 2.5} \times 100$$

$$= 93.88 \%$$

PRACTICAL (ACTUAL) TRANSFORMER

⇒ An actual transformer has primary and secondary winding resistance. Thus there is copper loss in primary and secondary winding due to their resistances.

⇒ These windings also have inductances due to leakage fluxes which develop inductive reactance.

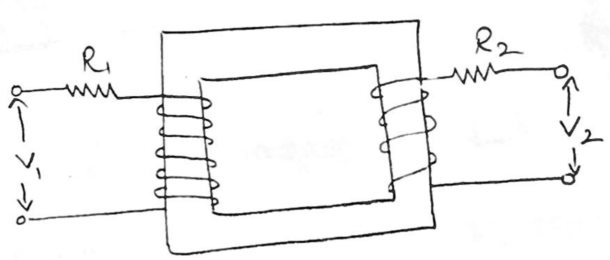
⇒ These effects cause voltage drop in a transformer.

Since Alternating magnetic flux is set-up in core that causes iron or magnetic (hysteresis and eddy current) losses in it.

⇒ Resistance of Transformer Windings

Primary winding resistance → R_1

Secondary winding resistance → R_2

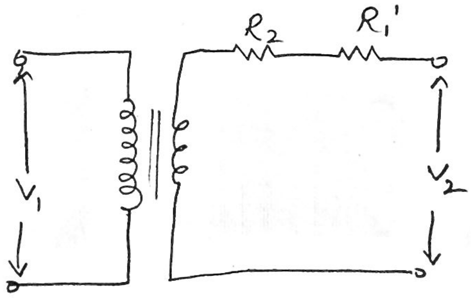


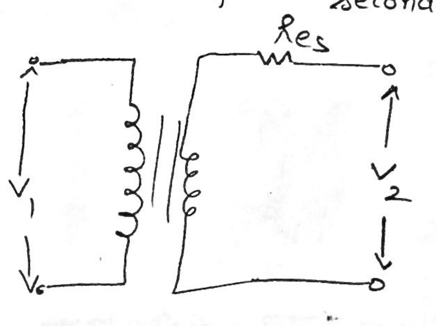
Resistance of primary and secondary winding

Note: Inorder to simplify the equations, resistance of the two windings can be transferred to either side in such a manner that percentage voltage drop remains the same when represented on either side.

(A) Equivalent secondary resistance: (R_{es})

Equivalent R referred to secondary





Primary resistance referred to second...

Let, R_1 referred to secondary side thus it become R_1' : equivalent resistance of primary referred to secondary side.

Also, I_1 and I_2 be the full load primary and secondary currents respectively.

Then, percentage voltage drop would be

$$\frac{I_2 R_1'}{V_2} \times 100 = \frac{I_1 R_1}{V_1} \times 100 \quad -(1)$$

thus,
from (1)

$$R_1' = \frac{I_1}{I_2} \times \frac{V_2}{V_1} \times R_1$$

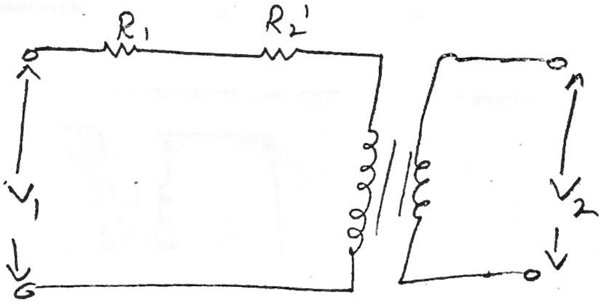
$$\boxed{R_1' = k^2 R_1} \quad -(2)$$

Therefore, total equivalent resistance referred to secondary.

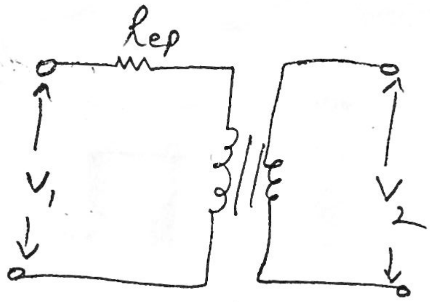
$$R_{es} = R_2 + R_1'$$

$$\boxed{R_{es} = R_2 + k^2 R_1} \quad [\text{from (2)}]$$

(B) Equivalent resistance of primary (R_{ep}) :



Secondary resistance referred to primary.



Equivalent resistance referred to primary

Thus, primary leakage flux $\rightarrow \phi_{l_1}$

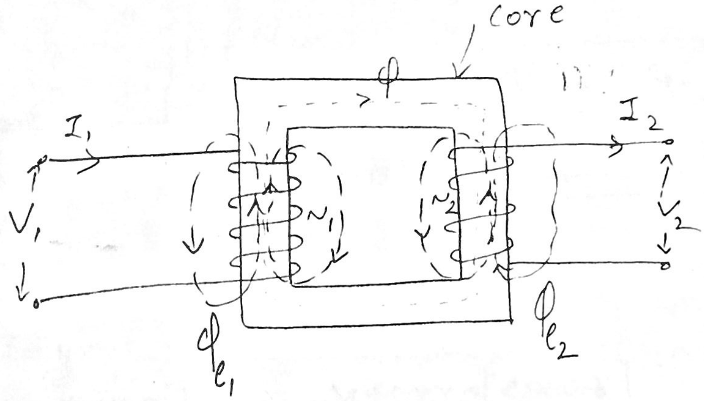
secondary leakage flux $\rightarrow \phi_{l_2}$

primary and secondary winding currents would be I_1 and I_2 respectively.

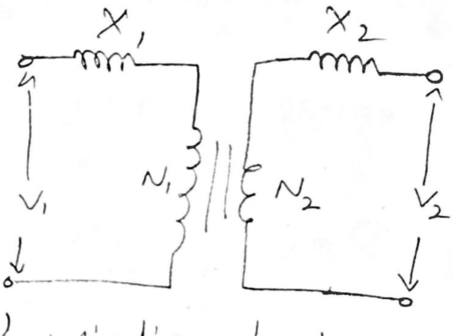
→ ϕ_{l_1} is proportional to I_1 and ϕ_{l_2} proportional to I_2

→ ϕ_{l_1} produces self inductance, $L_1 = \dfrac{N_1 \phi_{l_1}}{I_1}$ which in turn produces leakage reactance $X_1 = 2\pi f L_1$

→ Similarly, ϕ_{l_2} produces leakage reactance, $X_2 = 2\pi f L_2$



(A) Leakage flux of primary and secondary



(B) winding having inductive reactance.

Here, $N_1 \longrightarrow$ Number of turns of primary winding.

$N_2 \longrightarrow$ Number of turns of Secondary winding.

Again, consider R_2, transferred to primary, let new value be R_2' : equivalent resistance of secondary referred to primary.

Then, percentage voltage drop would be :

$$\frac{I_1 R_2'}{V_1} \times 100 = \frac{I_2 R_2}{V_2} \times 100$$

thus,

$$R_2' = \frac{I_2}{I_1} \times \frac{V_1}{V_2} \times R_2 = \frac{R_2}{K^2} \quad -(4)$$

Therefore, resultant resistance referred to primary is

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

$$\boxed{R_{ep} = R_1 + \frac{R_2}{K^2}} \quad [\text{from } (4)]$$

⇒ Reactances in Transformer Windings :

In an actual transformer, both the windings (primary as well secondary) produce some flux that links only with ~~primary~~ winding that produces it.

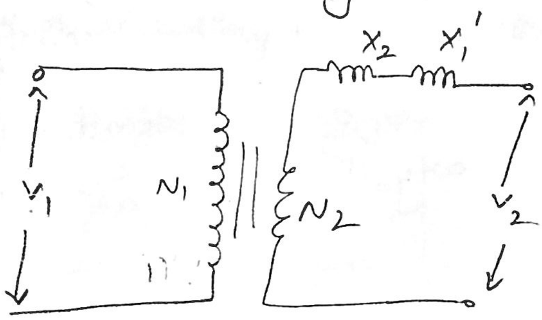
-> The flux that links with both the windings of the transformer is called mutual flux.

-> The flux which links only with one winding of the transformer and not to the other is called leakage flux.

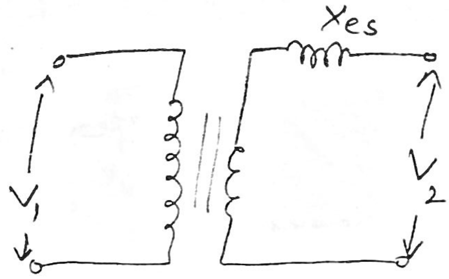
Equivalent reactance of Secondary (X_{es})

For simplification reactance of two windings can be transferred to any one side in such a manner that percentage voltage drop remains the same when represented on either side.

Let, X_1 be transferred to secondary and new value of this reactance is X_1' : equivalent reactance of primary referred to secondary.



(C) Primary reactance referred to secondary



(D) Equivalent reactance referred to secondary

% Voltage drops across primary resistance would be:

$$\frac{I_2 X_1'}{V_2} \times 100 = \frac{I_1 X_1}{V_1} \times 100$$

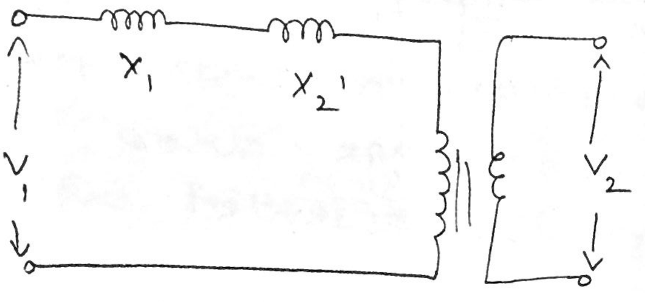
$$\Rightarrow \quad X_1' = \frac{I_1}{I_2} \times \frac{V_2}{V_1} \times (X_1) = K^2 X_1$$

Therefore, total equivalent reactance referred to secondary.

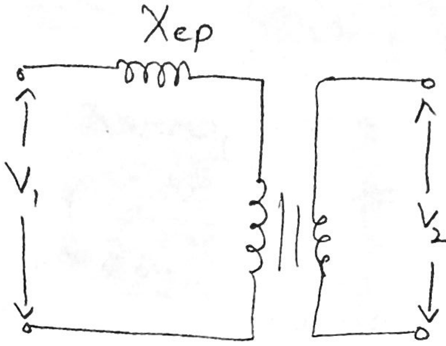
$$X_{es} = X_2 + X_1'$$

$$\boxed{X_{es} = X_2 + K^2 X_1}$$

Equivalent reactance of primary (X_{ep})



(E) Secondary reactance referred to primary



(F) Equivalent reactance referred to primary.

Similarly :
Let, secondary reactance X_2 (from fig. (B)) transferred to primary side and its new value is X_2' : equivalent reactance of secondary referred to primary.

Thus, percentage voltage drop would be :

$$\frac{I_2 X_2}{V_2} \times 100 = \frac{I_1 X_2'}{V_1} \times 100$$

$$\Rightarrow \quad X_2' = \frac{I_2}{I_1} \times \frac{V_1}{V_2} \times X_2 = \frac{X_2}{K^2} \quad \text{—(5)}$$

Therefore, total equivalent reactance referred to primary.

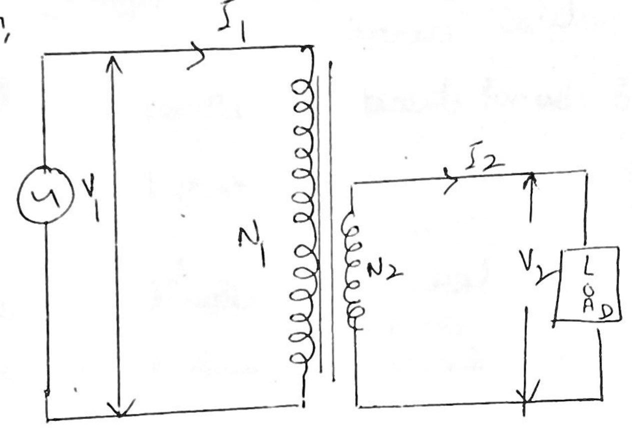
$$X_{ep} = X_1 + X_2'$$

$$\boxed{X_{ep} = X_1 + \frac{X_2}{K^2}} \quad [\text{from (5)}]$$

Auto-Transformer:-

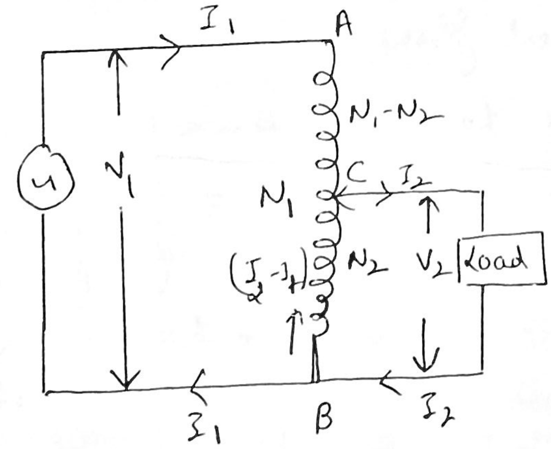
Auto-transformer is a transformer with only one winding on a laminated core. A part of winding is common to both primary & secondary winding.

In Ordinary transformer, primary & secondary winding are electrically insulated from each other but connected magnetically.



Ordinary 2-Winding Transformer

In auto transformer, primary & secondary windings are connected magnetically & electrically.



The primary winding AB from which a tapping C is taken, such that CB acts as a secondary winding. The supply voltage is applied across AB & the load is connected across CB.

When a.c. voltage V_1 is applied across AB, an alternating flux is set up in the core, its induces an emf E_1 in the winding AB. The part of this emf is taken in the secondary circuit

V_1 = applied voltage primary

V_2 = secondary " across the load

I_1 = primary current

I_2 = load current

N_1 = no of turns b/w A & B

N_2 = " " " b/w C & B

Neglecting load current, leakage reactance & losses,

$V_1 = E_1$ & $V_2 = E_2$

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

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

The resultante current flowing through BC is $I_2 - I_1$

Now ampere turns due to section BC $= (I_2 - I_1) \times N_2$ (current × turns)

$$= \left(\frac{I_1}{k} - I_1\right) \times N_2$$

$$= \cancel{\frac{(k-1)I_1}{k} \times N_1 k} = \frac{N_2 I_1}{k}(1-k)$$

As we know that $k = \dfrac{I_1}{I_2}$ $= N_1 I_1 (k-1)$ $= \dfrac{N_1 \cancel{k} I_1}{\cancel{k}}(1-k)$

$I_2 = \dfrac{I_1}{k}$ $= N_1 I_1 (1-k)$ — ①

Ampers turns due to section AC $= I_1 \times (N_1 - N_2)$

$$I_1 N_1 \left(1 - \frac{N_2}{N_1}\right)$$

$$= I_1 N_1 (1-k) \quad \text{— (2)}$$

equations (1) & (2) show that ampere turns due to section BC & AC balance each other, which is the characteristics of transformer action

Saving of Copper:-

Weight of copper of any winding depends upon its length & cross sectional area. Length of conductor in winding is proportional to its numbers of turns and cross-sectional area varies with rated current.

So weight of copper in winding is directly proportional to product of number of turns & rated current of winding

Weight of copper required in an auto-transformer

W_a = weight of Cu in section AC + weight of Cu in section CB

$$= (N_1 - N_2) I_1 + N_2 (I_2 - I_1)$$

$$= N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1$$

$$= I_1 N_1 + I_2 N_2 - 2 I_1 N_2$$

* weight of copper in ordinary transformer

W_o = weight of copper on its primary + weight of Cu on its secondary

$$W_o \propto I_1 N_1 + I_2 N_2$$

Now ratio of weight of copper in auto-transformer to weight of copper in an ordinary transformer

$$\frac{W_a}{W_o} = \frac{I_1N_1 + I_2N_2 - 2I_1N_2}{I_1N_1 + I_2N_2}$$

$$= 1 - \frac{2I_1N_2}{I_1N_1 + I_2N_2}$$

$$1 - \frac{2I_1N_2 / I_1N_1}{\frac{I_1N_1}{I_1N_1} + \frac{I_2N_2}{I_1N_1}}$$

$$= 1 - \frac{2\frac{N_2}{N_1}}{1 + \frac{I_2}{I_1}\frac{N_2}{N_1}}$$

$$= 1 - \frac{2k}{1 + \frac{1}{k} \times k}$$

$$= 1 - \frac{\cancel{2}k}{\cancel{2}} = 1 - k$$

$$W_a = (1-k)W_o$$

Saving of copper affected by using an auto transformer

= wt of copper required in an ordinary transformer − wt of copper required in an auto transformer

$$= W_o - W_a$$

$$= W_o - (1-k)W_o$$

$$= W_o(\cancel{1} - \cancel{1} + k) = kW_o$$

Hence saving in copper increases as transformer ratio approaches to unity, ∴ auto transformers are used when k is nearly equal to unity.

Advantages:-

1) Auto transformer has higher efficiency than two winding transformer. This is because of less ohmic loss + core loss due to reduction of transformer material

2) The auto transformer is small in size + cheaper.

3) It is used as a regulating transformer (the tap point C is variable in this case)

Disadvantage:-

They are not widely used due to one major disadvantage that secondary winding is not insulated from

If an auto transformer is used to supply low voltage from high voltage + there is a break in the secondary winding, full primary voltage come across the secondary terminals which may be dangerous to the operator + load.

Three-phase transformer:-

The three phase system is adopted invariably for generation, transmission & distribution of electrical power. For three phase system, three phase transformer are required.
Power is generated at generating station at 11 kV, whereas it is transmitted at 400kV, 220kV, 132 kV or 66 kV due to economical reasons. At receiving station, voltage level is decreased & power is transmitted through short distances. While delivering power to consumers, voltage level is decreased, to as low as 400V for safety reasons.
To handle 3-phase electrical power & to increase the voltage level at generating station, to decrease the voltage level at the receiving stations, 3-phase step up and step down transformers are employed

Advantages:-

1) It has less weight & occupies less space.
2) It requires smaller quantity of iron & copper.
3) It has smaller size & can be accommodated in smaller tank & hence needs smaller quantity of oil for cooling.
4) It needs fewer number of bushings.
5) It operates at better efficiency & regulation.

Disadvantages:-

i) It is more difficult & costly to repair 3-phase transformer.

ii) It is difficult to transport single large unit of 3 phase transformer than to transport three single phase transformer individually.

Construction of three-phase transformer:-

From constructional point of view, 3-phase transformer are classified as

i) Core type transformer (2) Shell type transformer.

Core type Transformer:- The core has three limbs of equal area of cross-section. Three limbs are joined by two horizontal (top or bottom) members called Yokes. The area of cross section of all the limbs & yokes is same since at every instant mag of flux is set up in each part is same.

The laminations are usually of E and I shape and are staggered alternatively.

The low voltage (LV) winding is wound nearer the core & high voltage (HV) " " " over the low voltage winding.

Insulation is provided b/w core & low voltage winding & b/w low voltage winding & high voltage winding ell type transformer :-

In shell type transform, the area of cross-section of central limb is double to that of side limbs & horizont members. The low voltage & high voltage winding of the three-phase are woued on the central limbs.

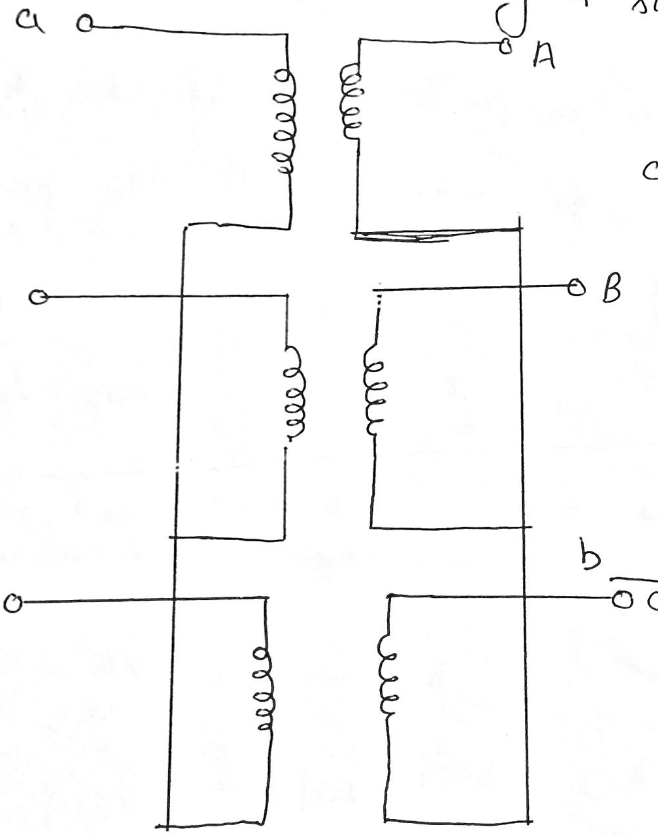
Connection of threephase Transformer:-

The three primary & three secondary windings of a three phase transformer may be connected in star or delta, according the transformer are named as

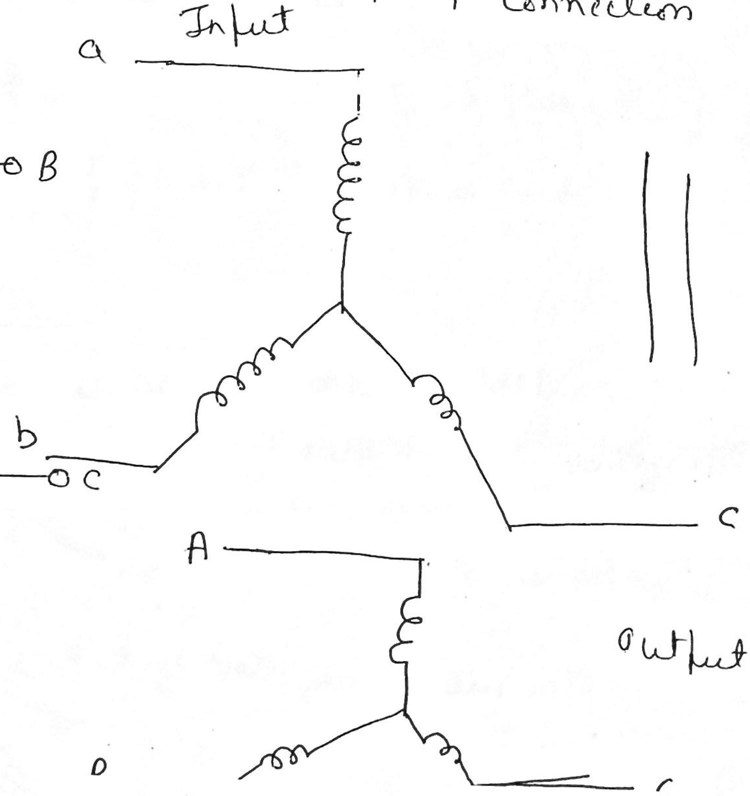
1) Star - star connected 3-phase transformer
2) Delta - delta " " " "
3) Delta - Star " " " "
4) Star - Delta " " " "

Star - star connected 3-phase transformer:-

Three winding of 3-phase transformer connected in (Y) on both primary & secondary sides.



Y - Y Connection



Advantages of star-star connected 3-phase transformer

1) This type of connections require less number of turns as each phase winding carries $\frac{E_L}{\sqrt{3}}$ of the line voltage. Hence it is cheaper.

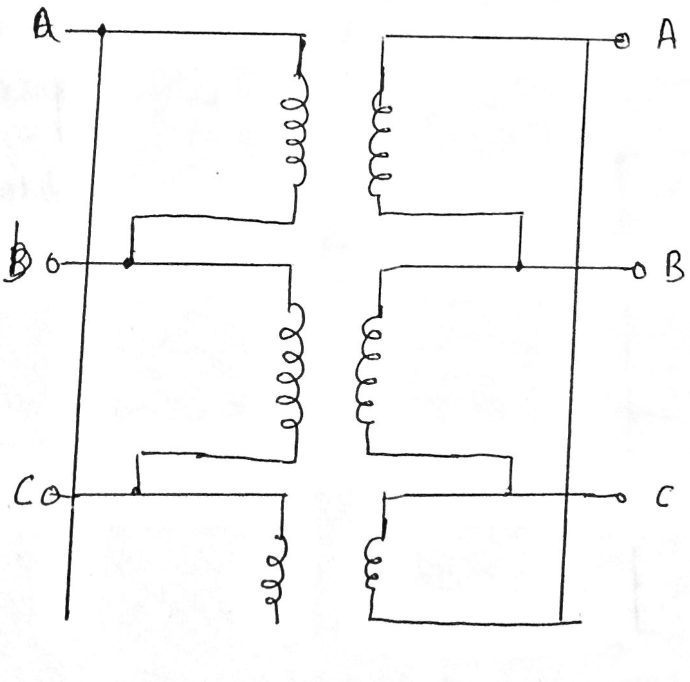
2) Very high voltage are possible as the dielectric stress on insulating material is less due to lesser voltage i.e. $\frac{E_L}{\sqrt{3}}$

Disadvantages

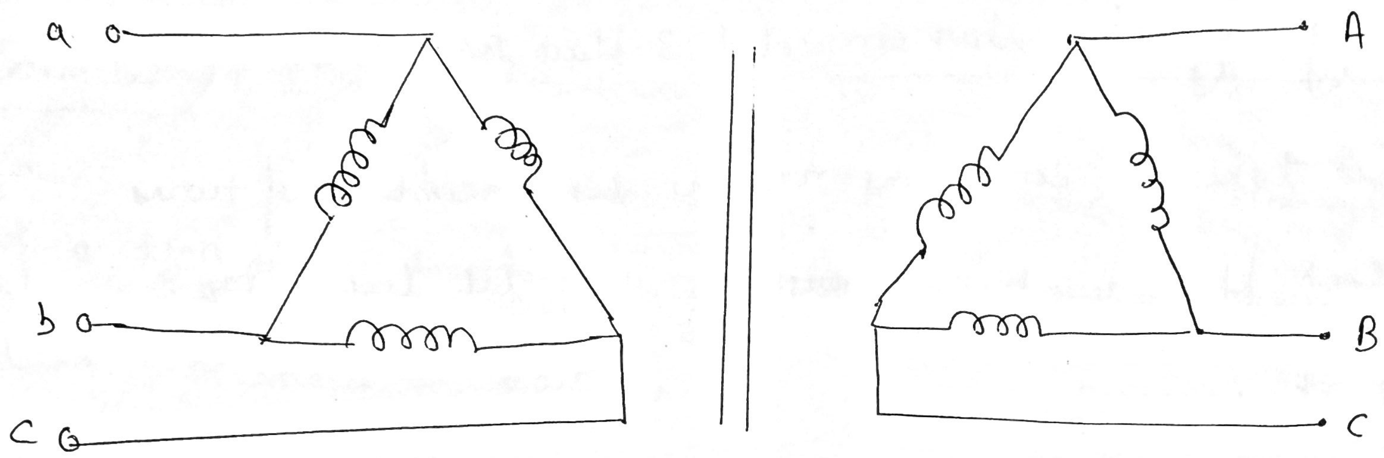
1) If one of phase fails in this connection other phases go out of action & possibly the transformer may shut down.

2) The regulation of the phases will be poor if star points of both primary & secondary are not earthed.

Delta - Delta connected 3 phase transformer :-



Winding connected in Delta - Delta

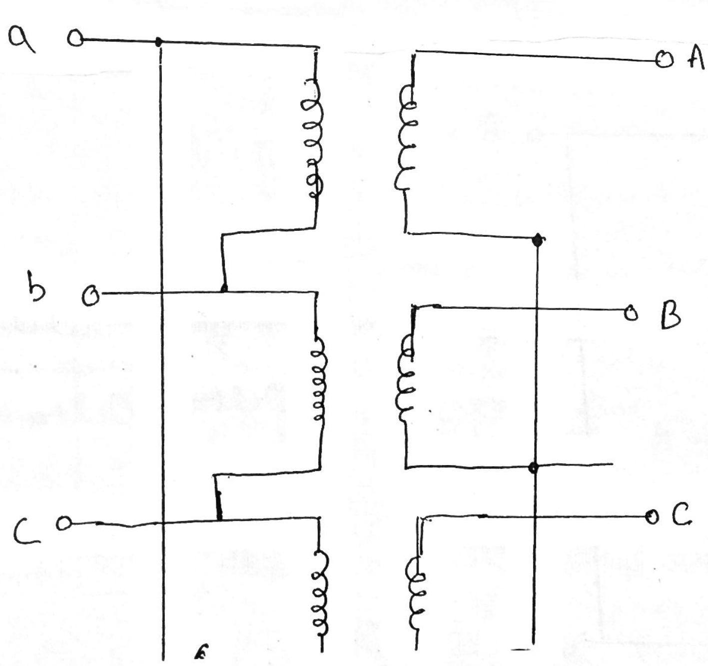


<u>Advantage</u> 1) The area of cross section of wire is reduced as phase current is $\frac{1}{\sqrt{3}}$ times the line current, hence it is comparatively cheaper as the copper used is less.

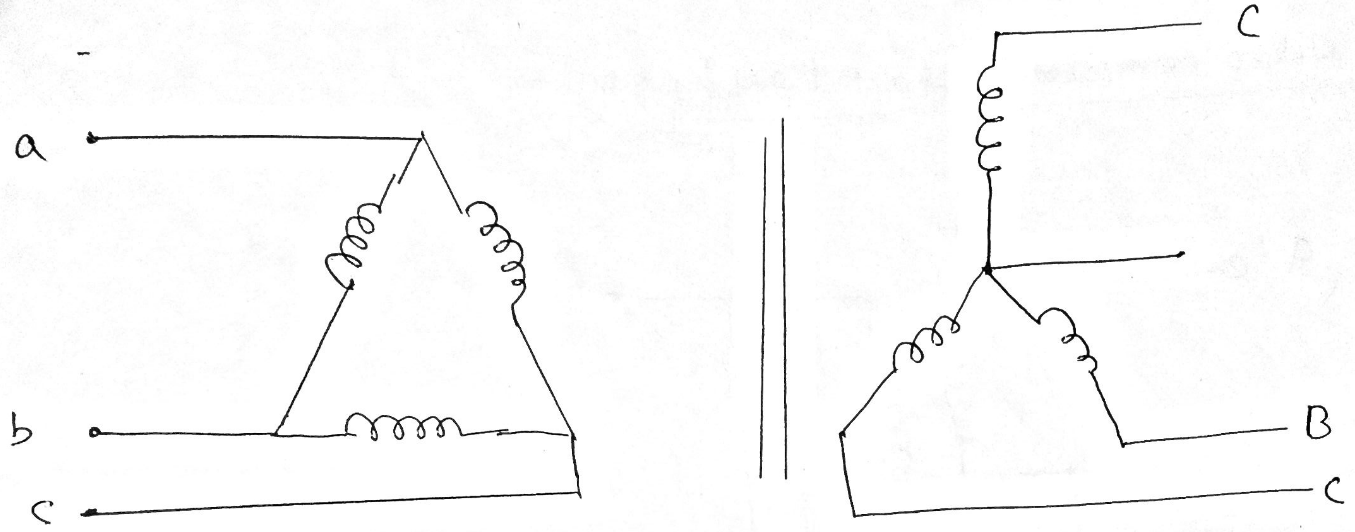
2) If one of winding is disabled for any reason, the delta-delta connection continue to operate uninterrupted in open delta or V-V connection.

<u>Disadvantage</u> No neutral is available.

<u>Delta - Star Connected 3 phase transformer:-</u>



Winding connected in delta - star



D - Y connection

In these connections

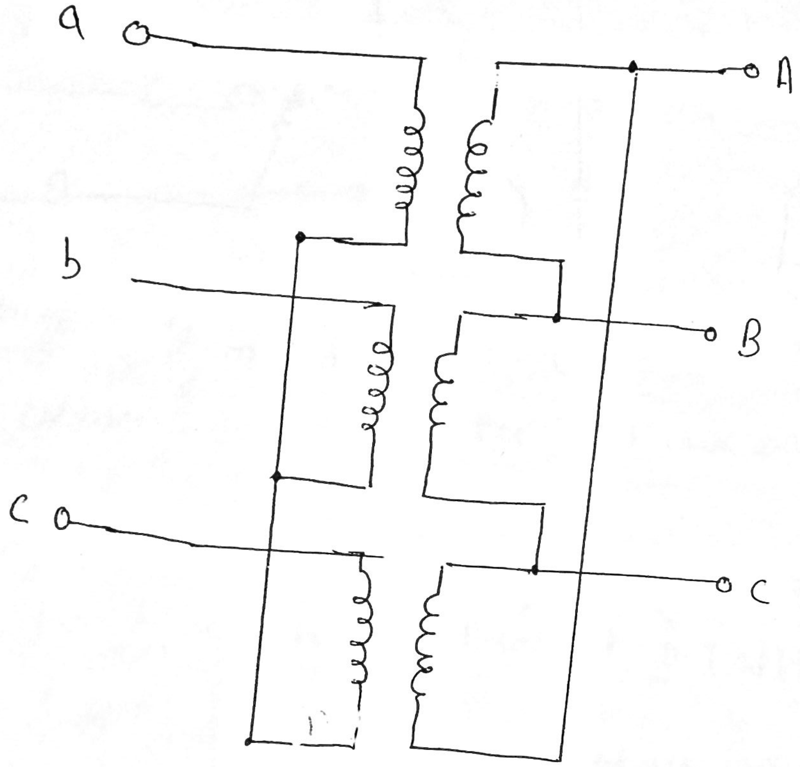
$$\frac{E_2}{E_1} = \frac{\sqrt{3}\,E_2\,ph}{E_1(ph)} = \sqrt{3}\,k$$

E_2 = secondary voltage
E_1 = primary voltage

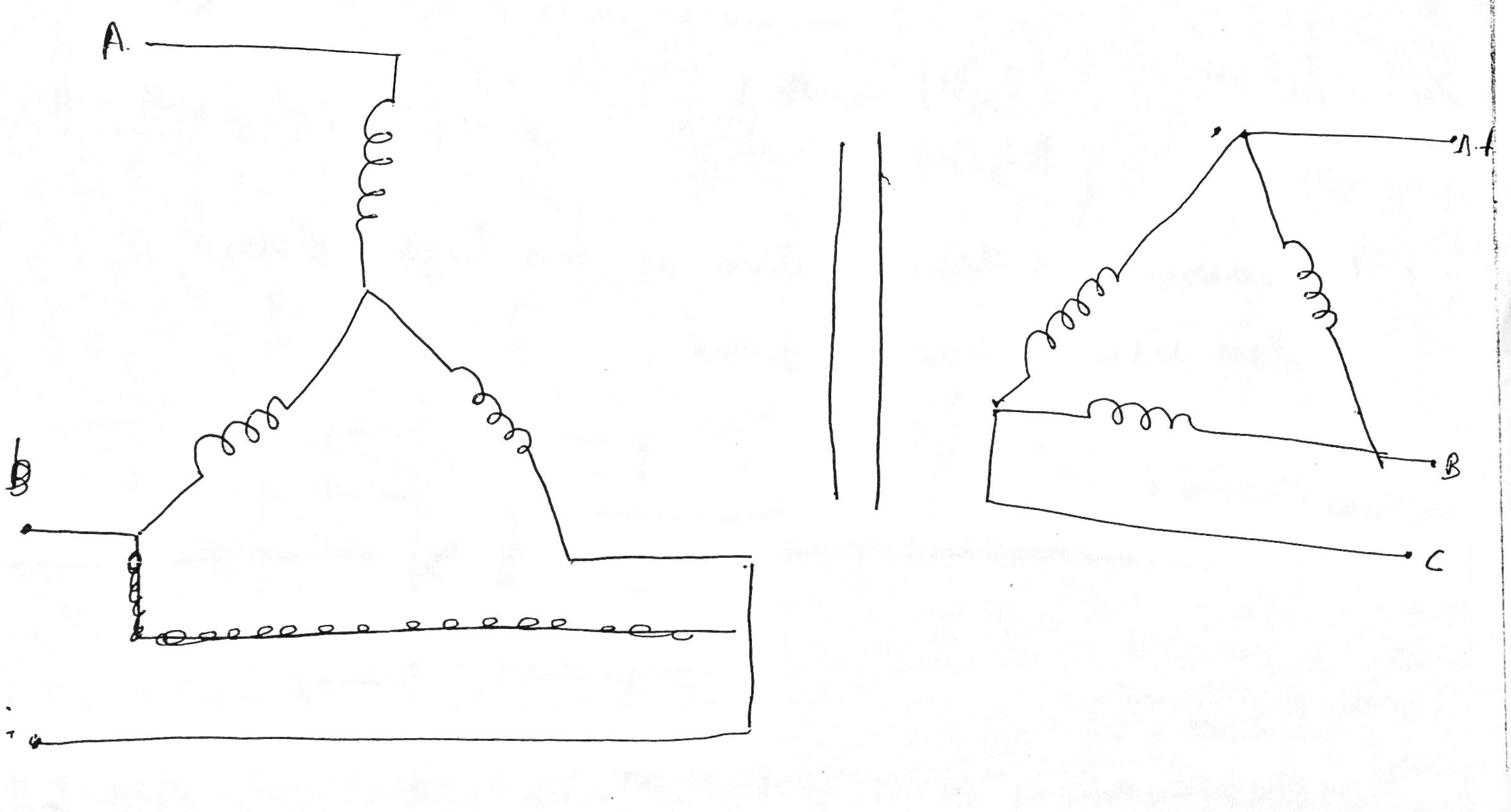
$$\frac{I_2}{I_1} = \frac{I_2(ph)}{\sqrt{3}\,I_1(ph)} = \frac{1}{\sqrt{3}}\frac{1}{k}$$

The advantage of this connection is for high voltage, less insulation are required

Star Delta connected 3-phase transformer:-



Winding connected in star-Delta



In these connections

$$\frac{E_2}{E_1} = \frac{E_2(ph)}{\sqrt{3}\,E_1(ph)} = \frac{1}{\sqrt{3}}\,k$$

$$\frac{I_2}{I_1} = \frac{\sqrt{3}\,I_2(ph)}{I_1(ph)} = \frac{\sqrt{3}}{k}$$

Such a connection is suitable for stepping up the voltages at generating stations.