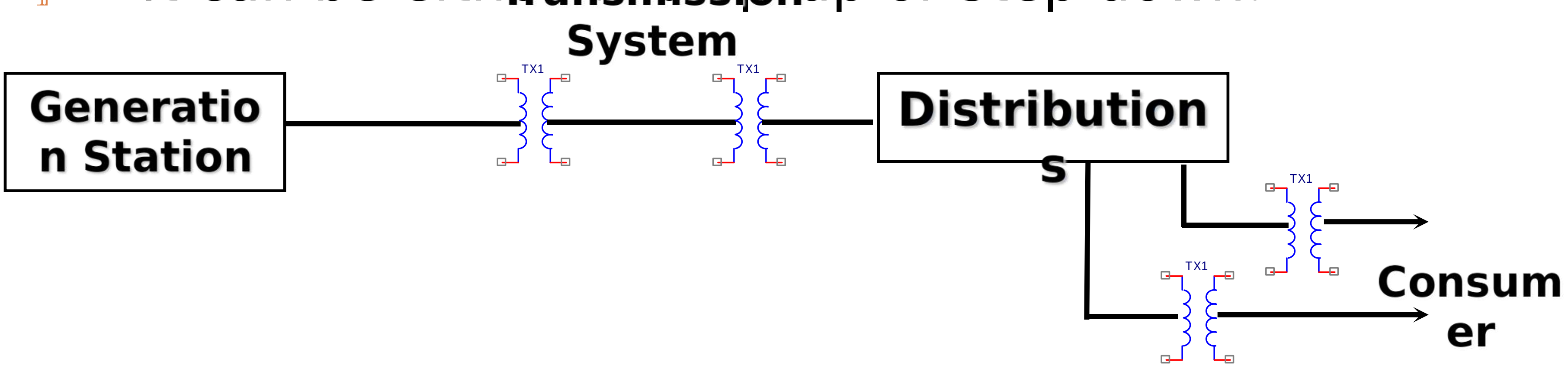
TRANSFORMER

Introduction

- A transformer is a static Electrical machines
- The word ‘transformer’ comes form the word ‘transform’.
- Transformer transforms electrical energy from one circuit to another circuit through the action of magnetic field (Induction), without a change in frequency.
- It can be either to step-up or step down.



Applications of Transformer

- Electric **power transmission** over long distances.
- Large, specially constructed power transformers are used for **electric arc furnaces** used in steelmaking.
- A transformer–like device is used for **position measurement**. as linear variable differential transformer.
- Small transformers are often used internally to couple different stages of **radio receivers and audio amplifiers.**
- For supplying power from an alternating current power grid to equipment which uses a different voltage.

Transformer is therefore , an essential piece of

Transformer Construction

- Two basic parts of a Transformer:
  1. Magnetic Core.
  2. Winding or Coil.

Transformer Core :

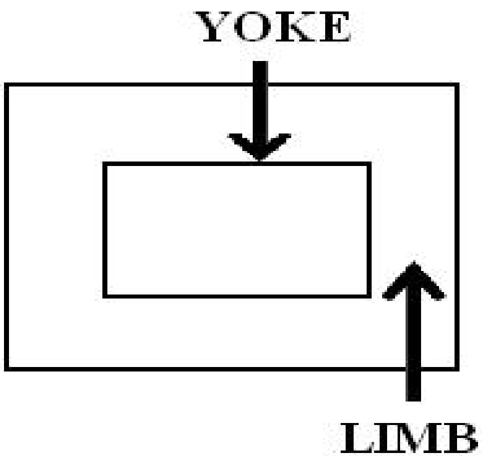
Material used for transformer core should have two properties:

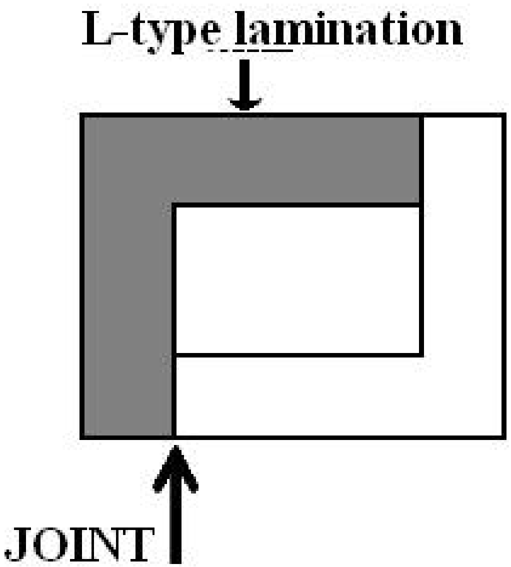
- (1) Less magnetic losses (Hysteresis loss & Eddy current loss)
- (2) High permeability

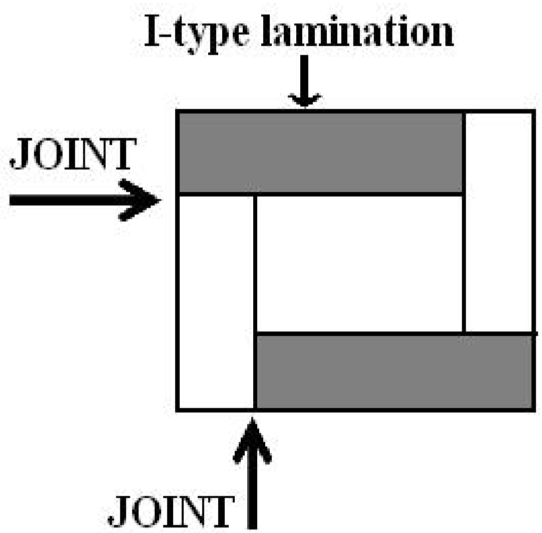
To reduce eddy current loss, Core is laminated.

To reduce hysteresis loss, CRGO(Cold Rolled Grain Oriented) material is used.

Transformer Construction

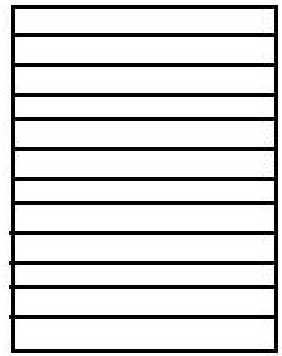






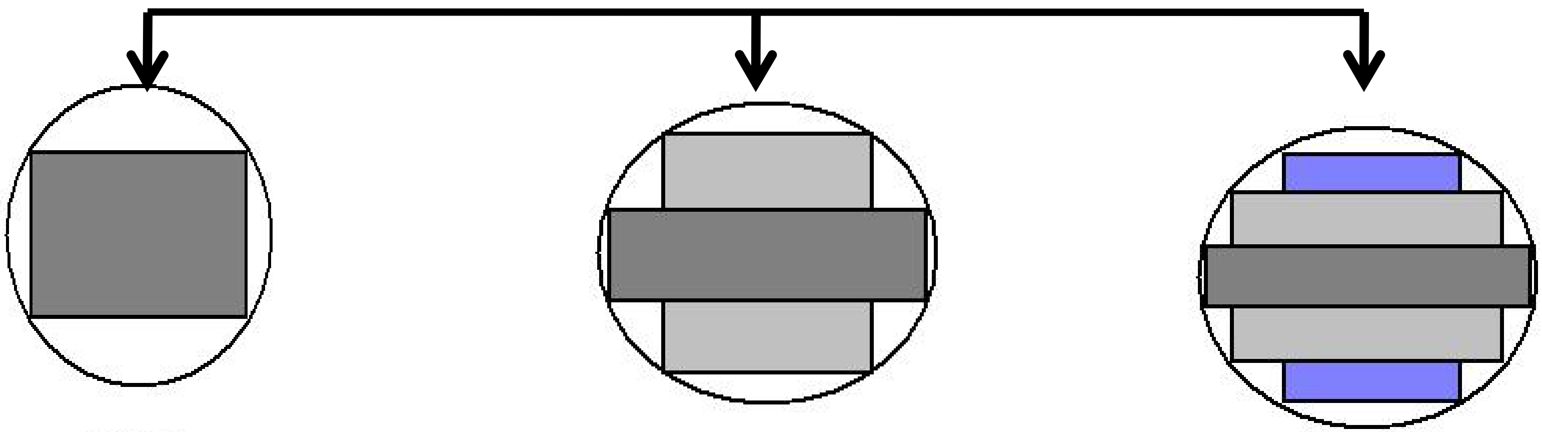
The cross-section of the limb

For Small Transformer



Rectangular

For Large Transformer



Square

Cruciform

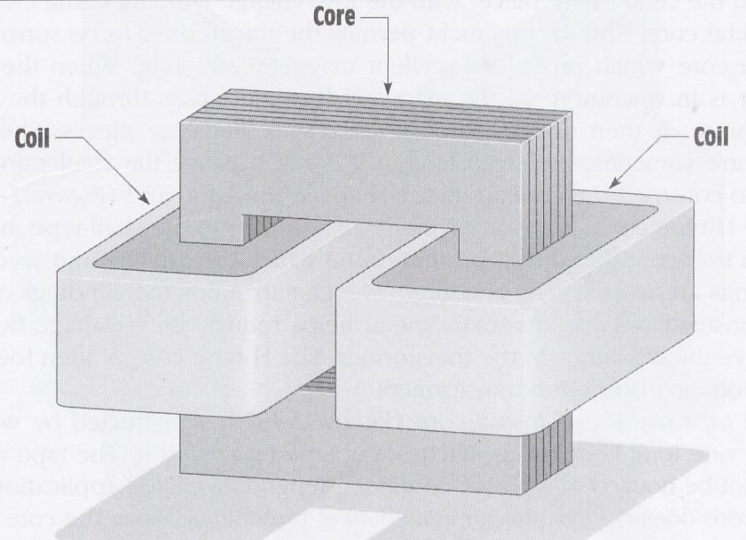
3-stepped cruciform

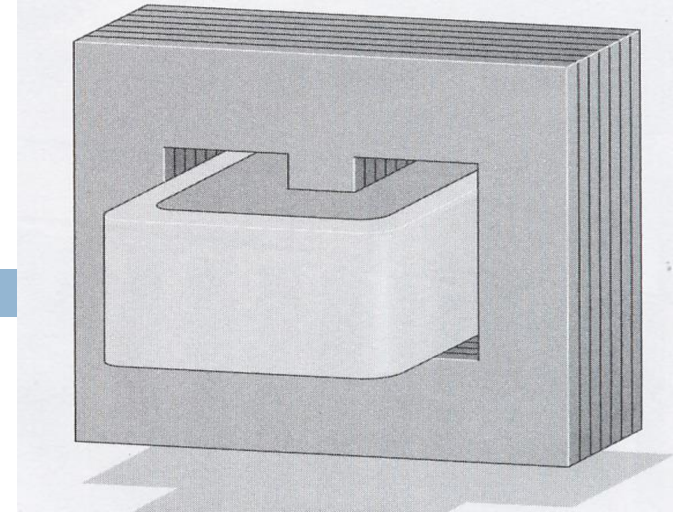
Construction of 1-Phase Transformer

Two types:

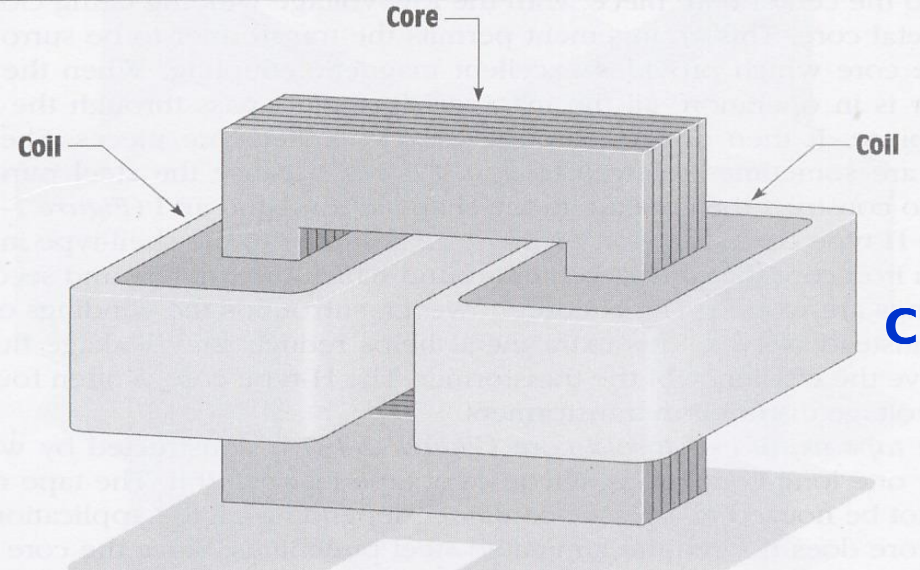
1. Core - type
2. Shell – type

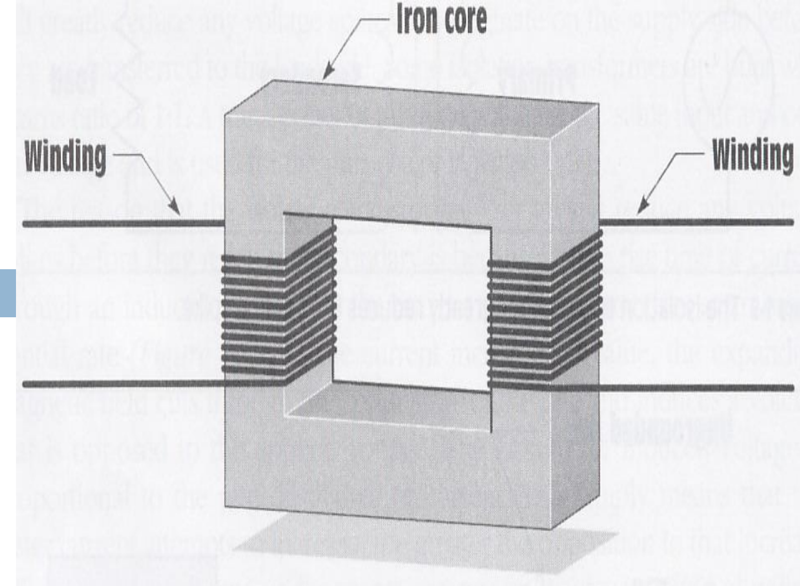
These differ from each other by the manner in which the windings are wound around the magnetic core.



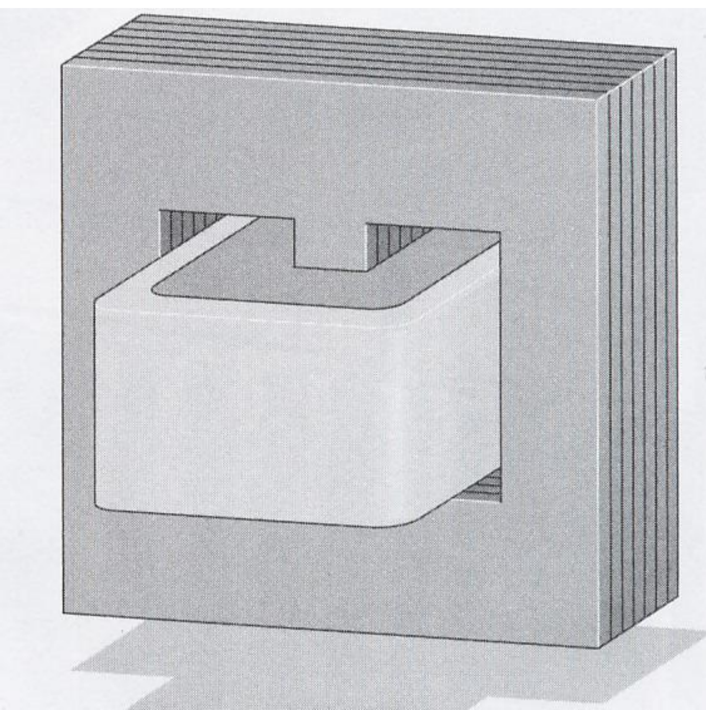


CORE-TYPE	SHELL-TYPE
Windings surround a considerable part of core.	Core surround a considerable part of windings.
More conductor & less core is required	More core & less conductor is required
To reduce leakage flux, half of the L.V. & half of the H.V. winding is placed over one leg and other half over other leg	
Concentrated coil is used	Sandwich coil is used on central limb
For high voltage and power	For small voltage and power

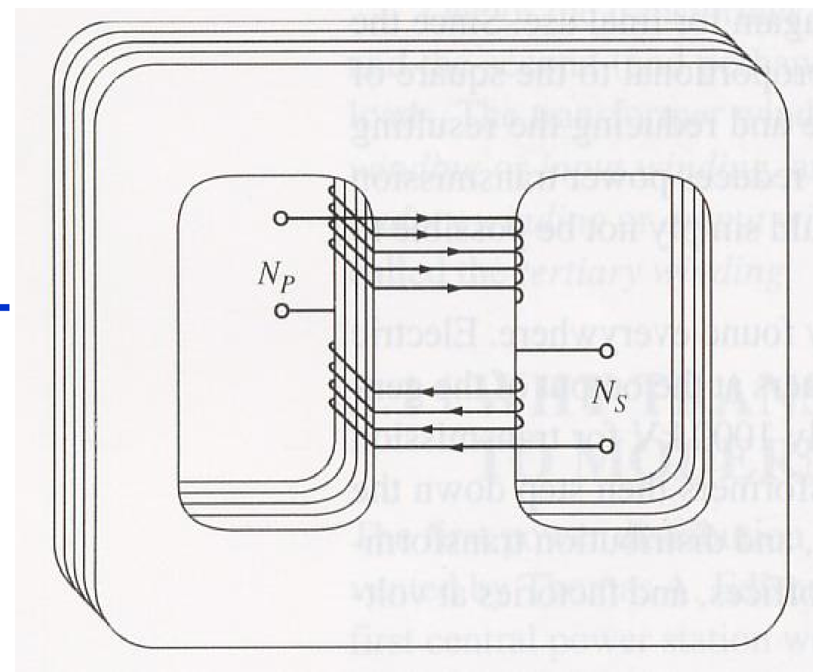




CORE



SHELL



TYPES OF WINDINGS

Coil wound around limbs and are insulated from each other.

Winding should be very closes to each other to have high mutual inductance.

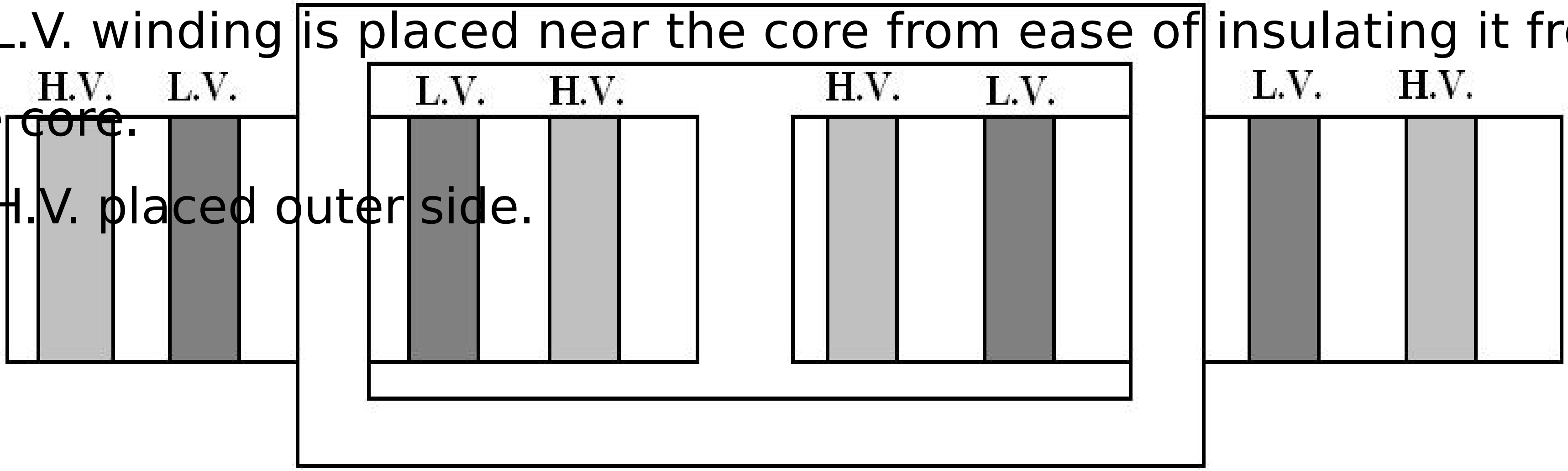
Cylindrical Concentric Coil

Cylindrical coil are used in the core type transformer.

The different layers are insulated from each other by paper, cloth or mica.

L.V. winding is placed near the core from ease of insulating it from the core.

H.V. placed outer side.



Sandwich Coils

Sandwich coil used in shell type transformer.

Such subdivision of winding into small portion reduces the leakage flux.

Higher degree subdivision , smaller is the reactance.

Tanks and Other Accessories

Tanks

The assembled transformer with magnetic core and windings is housed in proper tank.

That contains **transformer oil**, used for cooling and insulation.

Tanks for small transformers are fabricated from welded sheet steel,

and for large transformers from plane boiler plates.

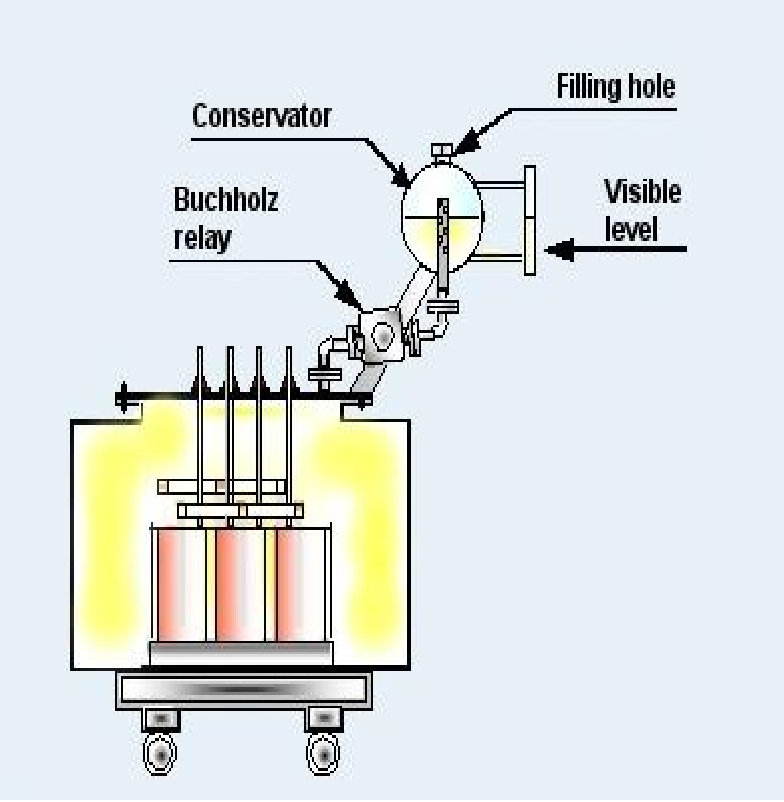
Various accessories with the transformer tank are

Conservator

Oil immersed transformer have conservator.

The conservator consist of an airtight cylindrical metal drum .

Normally the conservator capacity should be approximately 10 to 12 percent of the oil volume in the tank.



Breather

A breather mounted in the transformer tank contains calcium chloride or silica gel, which has the tendency to extract moisture from air.

Bushings

- The terminal connections of the windings are taken to the insulator bushing mounted on the transformer tank top.
- The bushings consists of a current carrying part in the form of the conducting rod, and porcelain cylinder installed in the hole of the cover and used to isolate the current carrying part.

Insulation

- The insulation used in the case of electrical conductors in a transformer is **varnish or enamel** in **dry type of transformers**.
- In larger transformers to improve the heat transfer characteristics the conductors are insulated using **un-impregnated paper or cloth** and the whole core-winding assembly is immersed in a tank containing transformer oil.
- The transformer oil thus has dual role. It is an **insulator** and also a **coolant.**

Cooling of transformers

As the rating increases better cooling techniques are needed.

Air Cooling:

- Simple **air cooling** of the transformers is adopted in **dry type transformers**.
- air cooling is used in **low voltage machines**.
- This method of cooling is termed as **AN(Air Natural).**

Oil Natural

The oil reaches the conductor surface and extracts the heat and transports the same to the surface of the tank by convection. This is termed as ON (Oil Natural) type of cooling.

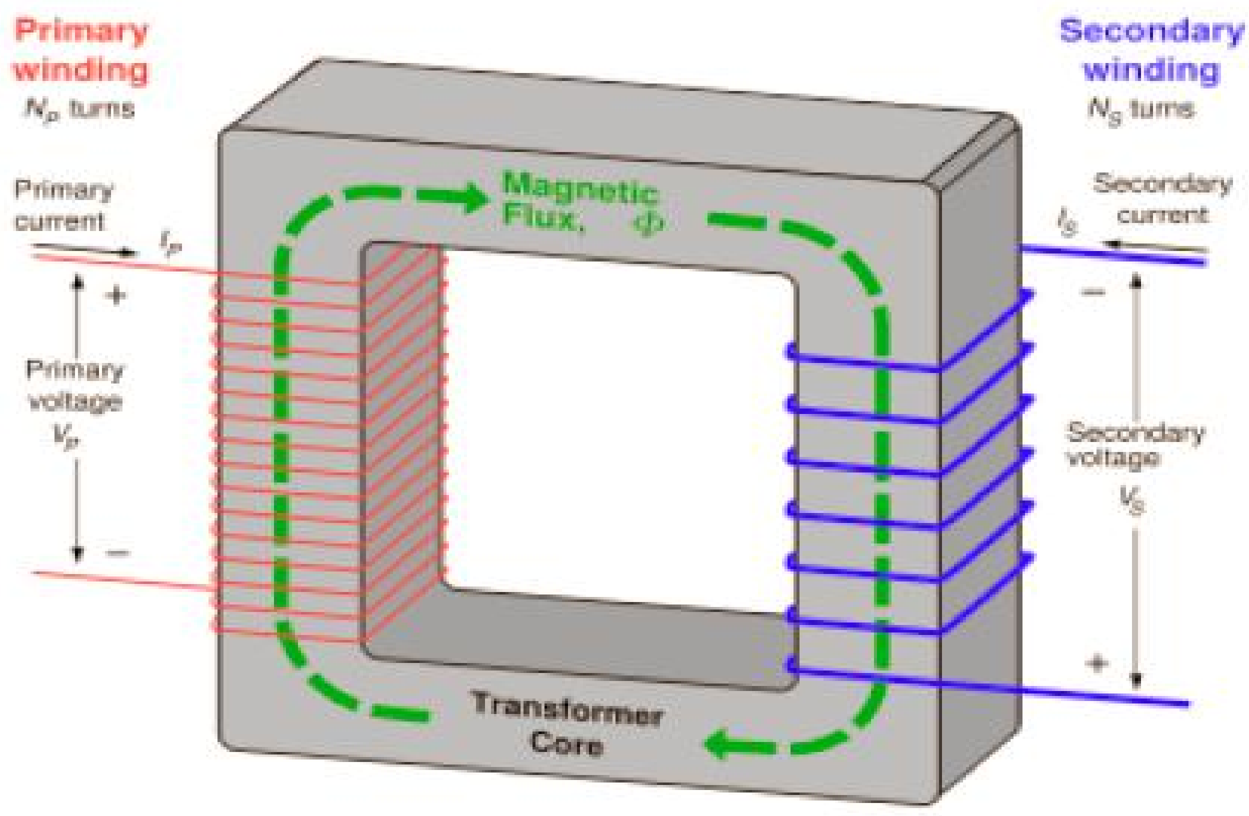
- **OB(Oil Blast)** method is an improvement over the ON-type and it directs a blast of air on the cooling surface.
- In the above two cases the flow of oil is by natural convective forces.
- The rate of circulation of oil can be increased with the help of a pump, with the cooling at the

Oil Forced Blast

If forced blast of air is employed, the cooling method become **OFB(Oil Forced Blast)**.

- A forced circulation of oil through a radiator is done with a blast of air over the radiator surface.
- Substantial amount of heat can be removed by employing a water cooling. Here the hot oil going into the radiator is cooled by a water circuit. Due to the high specific heat of water, heat can be evacuated effectively.

Basic principles (Electro magnetic Induction)



As the Flux is alternating according to faradays law of an electromagnetic induction ,

induced e.m.f. get developed in the primary & secondary winding

Basic principles (Electro magnetic Induction)

When primary winding is excited by an alternating voltage , it circulates an alternating current.

This current produce an alternating flux (Ø) which completes its path through common magnetic core.

So, flux(Ø) links with the primary & Secondary winding.

$$f = f_m \cos wt$$

As the Flux is alternating according to faradays law of an electromagnetic induction , induced e.m.f. get developed in the primary & secondary winding.

Transformer Equation

- For an **ac sources**,
  - Let $V(t) = V_m \sin\_t$

    $i(t) = i_m \sin\_t$

  Since the flux is a sinusoidal function;

Then:

$$\pm(t) = \pm_m \sin wt$$

Therefore:

$$V_{ind} = Emf_{ind} = -N \frac{d \pm_m \sin wt}{dt}$$

$$= -N w \pm_m \cos wt$$

Thus:

$$V_{ind} = Emf_{ind\,(\max)} = Nw\pm_{m} = 2pfN\pm_{m}$$

$$\mathrm{Emf}_{\mathrm{ind\,(rms)}} = \frac{\mathrm{N}\ell\ \pm_{\mathrm{m}}}{\sqrt{2}} = \frac{2\in\mathrm{fN}\pm_{\mathrm{m}}}{\sqrt{2}} = 4.44\,\mathrm{fN}\pm_{\mathrm{m}}\,\mathrm{Volts}$$

Transformer Equation

- For an ideal transformer .... (i)

$$E_1 == 4.44 fN_1 \pm_m$$
$$E_2 == 4.44 fN_2 \pm_m$$

- In the equilibrium condition, both the input power will be equal to the output power, and this condition is said to ideal condition of a transformer.

$$Input \quad power = output \quad power$$
$$V_1 I_1 \cos q = V_2 I_2 \cos q$$
$$‘ \quad \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

- From the ideal transformer circuit, note that, $E_1 = V_1$ *and* $E_2 = V_2$

Transformer Equation

$$\text{Therefore,} \quad \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = a$$

Where, '**a**' is the **Voltage Transformation Ratio;** which will determine whether the transformer is going to be **step-up** or **step-down**

For a >1 ⟶ $E_1 > E_2$

For a <1 ⟶ $E_1 < E_2$

Transformer Rating

- Transformer rating is normally **written** in terms of **Apparent Power**.
- Apparent power is actually the product of **its rated current and rated voltage**.

$$VA = V_1 I_1 = V_2 I_2$$

- Where,
  - I_1 and I_2 = rated current on primary and secondary winding.
  - V_1 and V_2 = rated voltage on primary and secondary winding.

- **Rated currents are actually the full load currents in transformer**

Ideal Transformer

Assumption for ideal transformer:

(1) No winding resistance

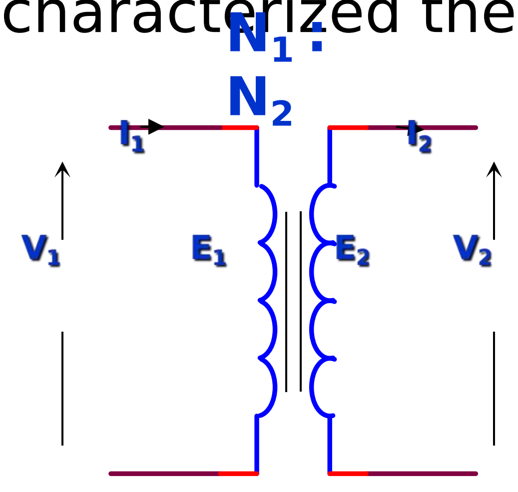
(2) No leakage flux

(3) No core losses

(4) Constant permeability

However, it is impossible to realize such a transformer in practice.

Yet, the approximate characteristic of ideal transformer will be used in characterized the practical transformer.



V_1 – Primary Voltage

V_2 – Secondary Voltage

E_1 – Primary induced Voltage

E_2 – secondary induced Voltage

Transformer on No–Load

$$I_0 = I_\mu + I_w$$

$$|\ I_\mu\ | = |\ I_0\ |\ cos\theta$$

$$|\ I_w\ | = |\ I_0\ |\ sin\theta$$

$$|\ I_0\ | = \sqrt{(\ |\ I_\mu\ |^2 + \ |\ I_w\ |^2\ )}$$

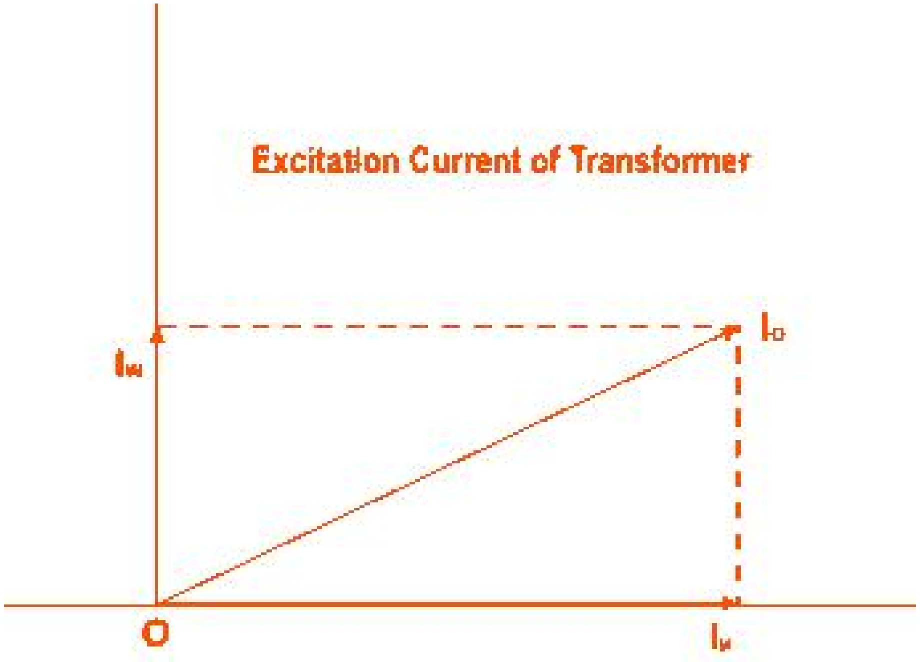
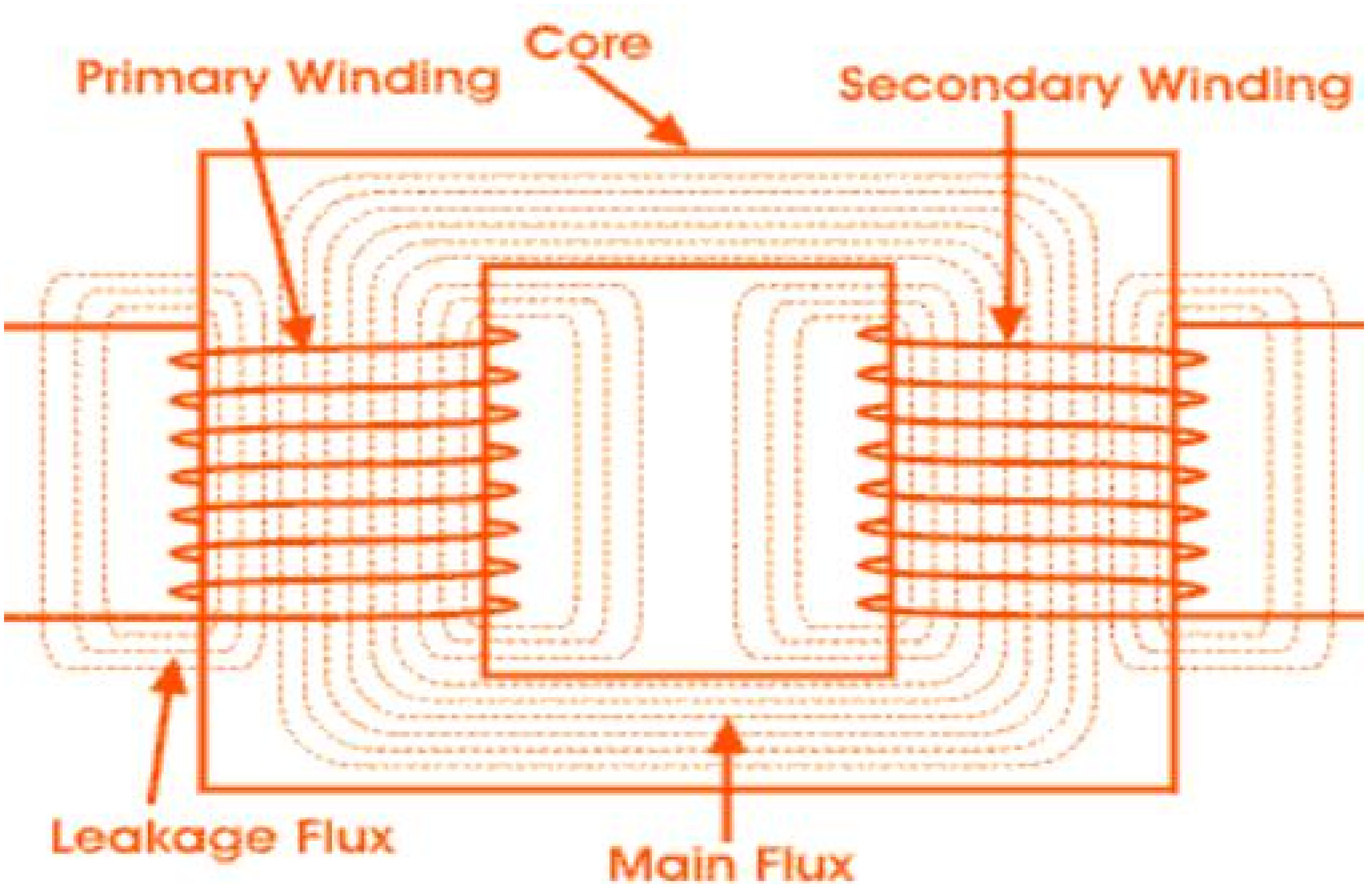


Fig - 1

Leakage Flux in Transformer



Leakage Reactance of Transformer

- All the flux in transformer will not be able to link with both the primary and secondary windings. A small portion of flux will link either winding but not both. This portion of flux is called leakage flux.
- Due to this **leakage flux in transformer**, there will be a self-reactance in the concerned winding. This self-reactance of transformer is alternatively known as **leakage reactance of transformer**.

Resistance of Transformer

- Internal resistance of both primary and secondary windings is collectively known as **resistance of transformer**.

Impedance of Transformer

- If R_1 & R_2 and X_1 & X_2 are primary & secondary resistance & leakage reactance of transformer respectively, then Z_1 & Z_2 impedance of primary & secondary windings are respectively,

$$Z_1 = R_1 + jX_1$$
$$Z_2 = R_2 + jX_2$$

Impedance of Transformer

- Impedance is combination of resistance and leakage reactance of transformer.
- If we apply voltage V_1 across primary of transformer, there will be a component I_1X_1 to balance primary self induced emf due to primary leakage reactance.
- Now if we consider voltage drop due to primary resistance of transformer, then voltage equation of a transformer can be written as,

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

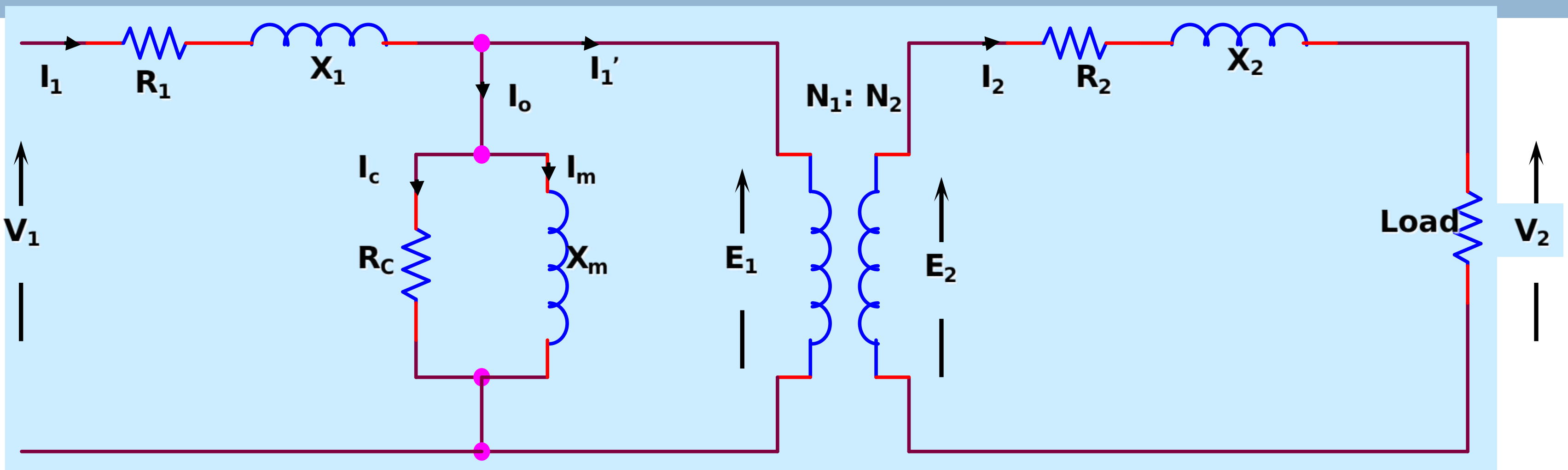
$$\Rightarrow V_1 = E_1 + I_1R_1 + jI_1X_1$$

- Similarly for secondary leakage reactance, the voltage equation of secondary side is,

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

$$\Rightarrow V_2 = E_2 - I_2R_2 - jI_2X_2$$

Practical Transformer (Equivalent Circuit)



V_1 = primary supply voltage

V_2 = 2nd terminal (load) voltage

E_1 = primary winding voltage

E_2 = 2nd winding voltage

I_1 = primary supply current

I_2 = 2nd winding current

I_1' = primary winding current

I_o = no load current

I_c = core current

I_m = magnetism current

R_1= primary winding resistance

R_2= 2nd winding resistance

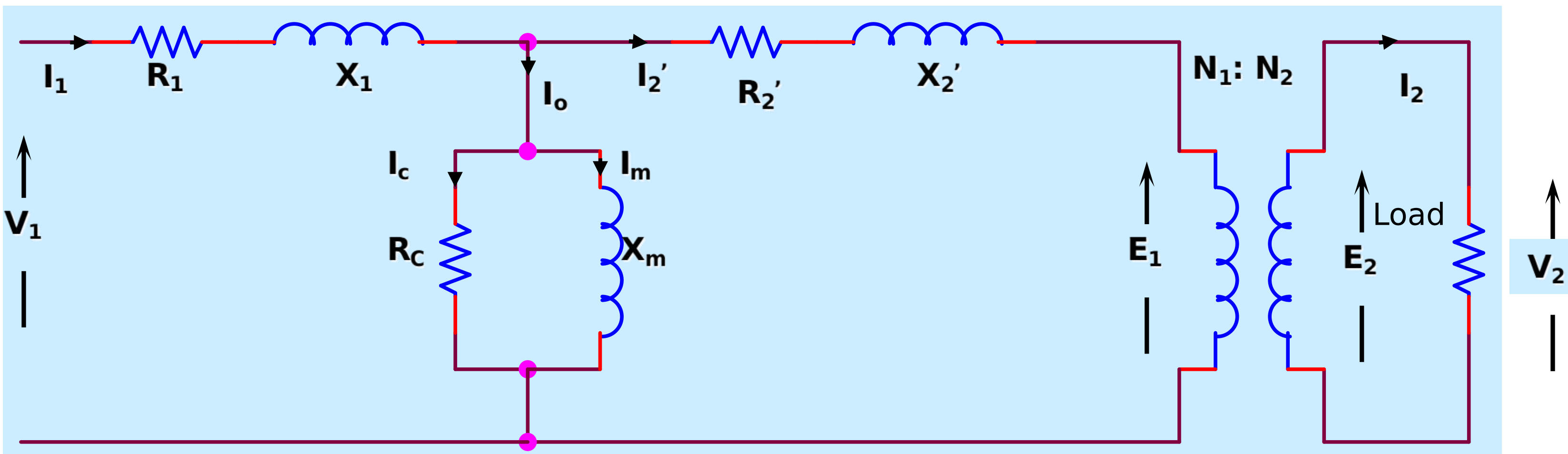
X_1= primary winding leakage reactance

X_2= 2nd winding leakage reactance

R_c= core resistance

X_m = magnetism reactance

Single Phase Transformer (Referred to Primary)



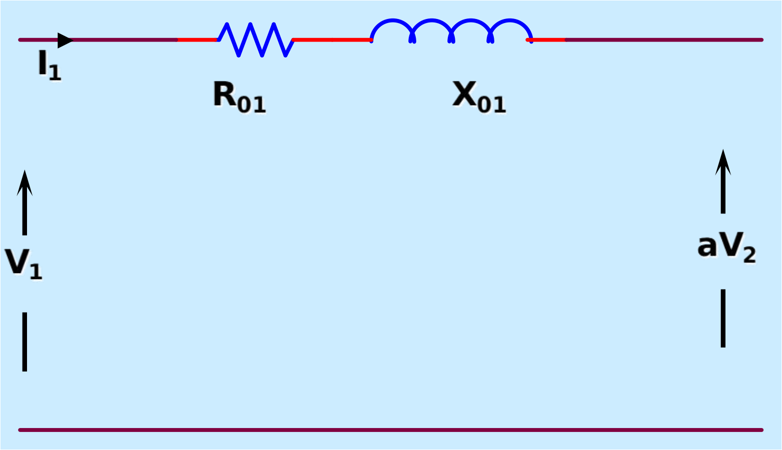
$$R_2' = \left(\frac{N_1}{N_2}\right)^2 R_2 \quad OR \quad R_2' = a^2 R_2$$

$$X_2' = \left(\frac{N_1}{N_2}\right)^2 X_2 \quad OR \quad X_2' = a^2 X_2$$

$$E_1 = V_2' = \left(\frac{N_1}{N_2}\right) V_2 \quad OR \quad V_2' = aV_2$$

$$I_2' = \frac{I_2}{a}$$

Single Phase Transformer (Referred to Primary)



In some application, the excitation branch has a small current compared to load current, thus it may be neglected without causing serious error.

$$R_2' = \left(\frac{N_1}{N_2}\right)^2 R_2 \quad OR \quad R_2' = a^2 R_2$$

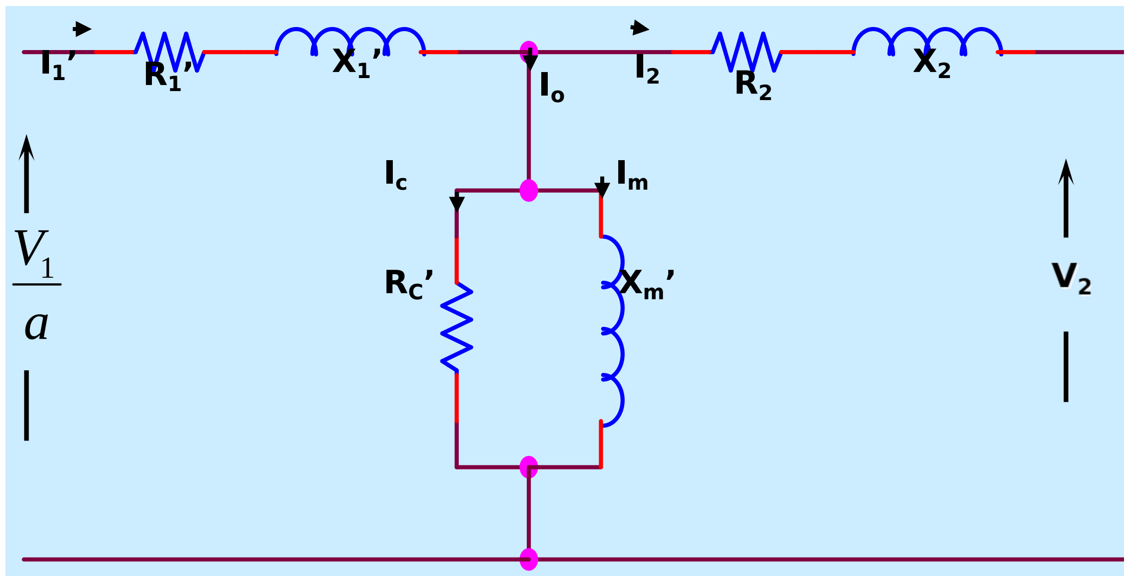
$$V_2' = \left(\frac{N_1}{N_2}\right) V_2 \quad OR \quad V_2' = aV_2$$

$$X_2' = \left(\frac{N_1}{N_2}\right)^2 X_2 \quad OR \quad X_2' = a^2 X_2$$

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

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

Single Phase Transformer (Referred to Secondary)

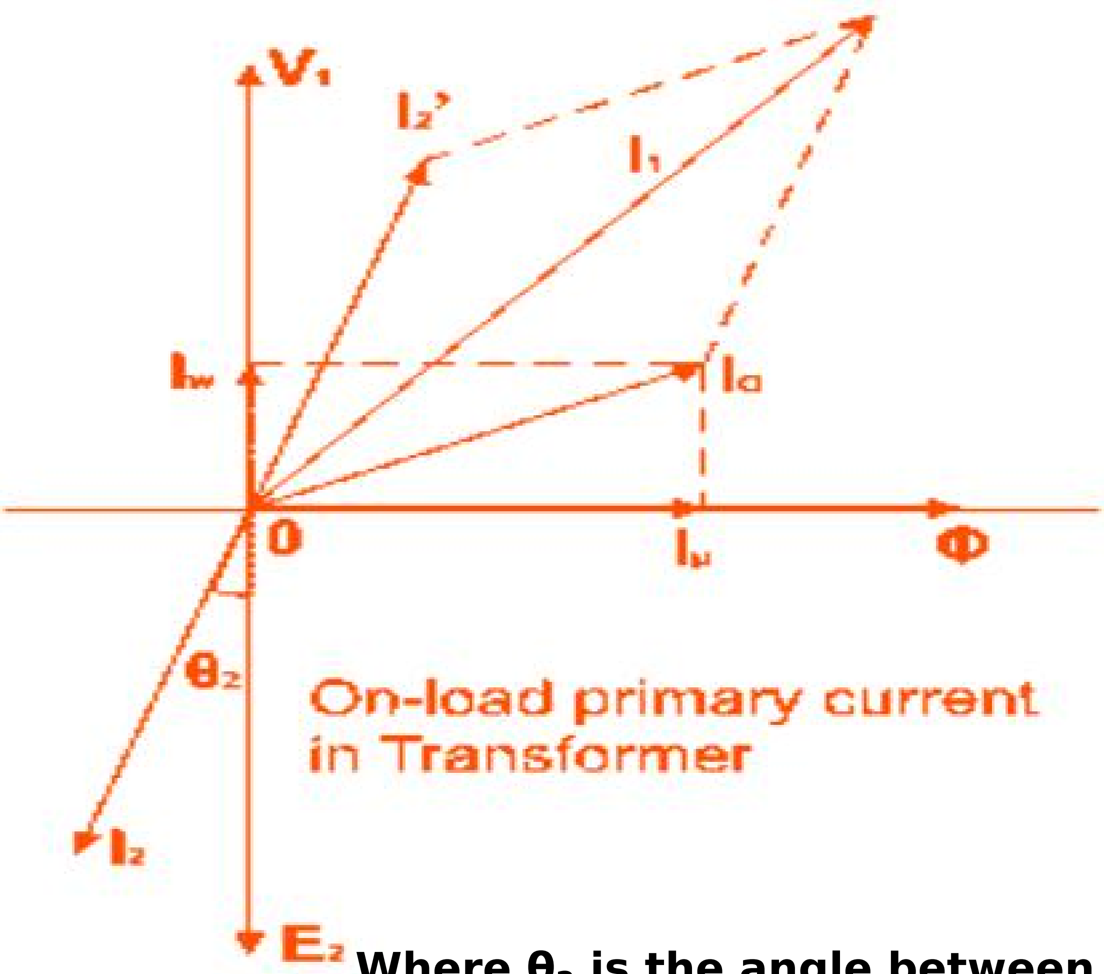


$$R_1' = \left(\frac{N_2}{N_1}\right)^2 R_1 \quad OR \quad R_1' = \frac{R_1}{a^2}$$

$$X_1' = \left(\frac{N_2}{N_1}\right)^2 X_1 \quad OR \quad X_1' = \frac{X_1}{a^2}$$

$$V_1' = \left(\frac{N_2}{N_1}\right) V_1 \quad OR \quad V_1' = \frac{V_1}{a}$$

Theory of Transformer on Load



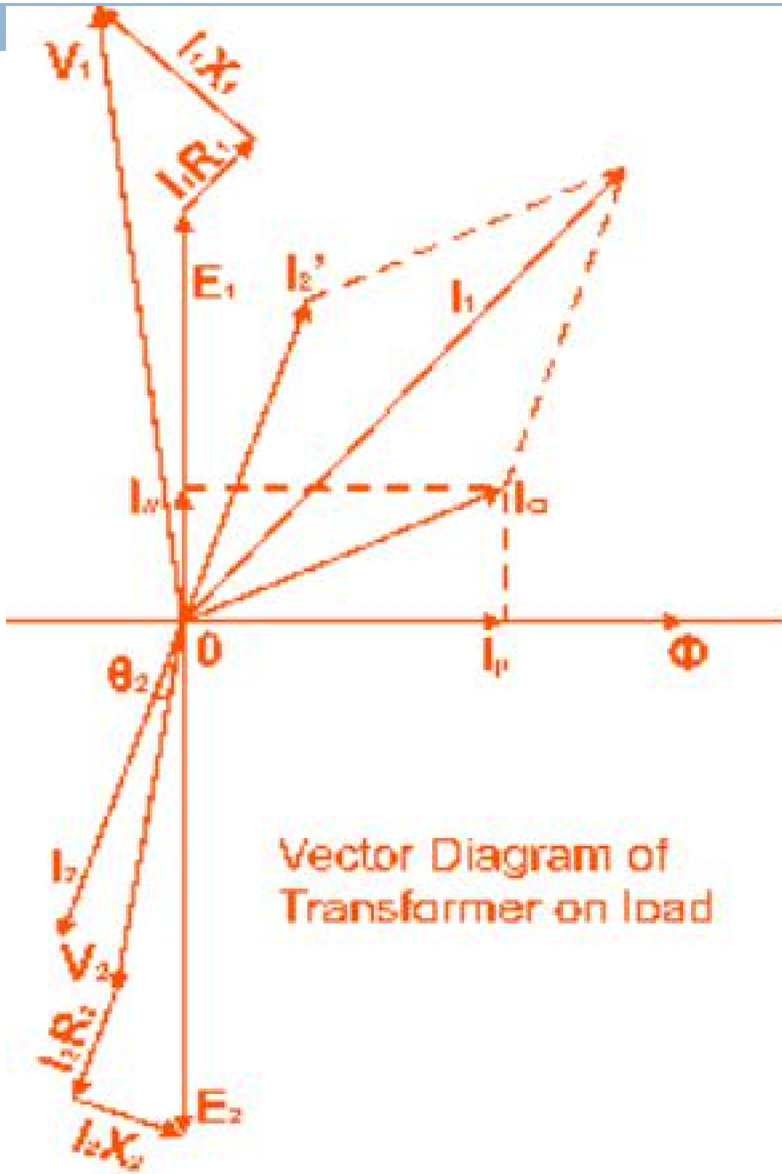
Where θ_2 is the angle between Secondary Voltage and Secondary Current of transformer

- So total current, the transformer draws from source can be divided into two components, first one is utilized for magnetizing the core and compensating the core loss i.e. I_o. It is **no–load component of the primary current**.
- Second one is utilized for compensating the counter flux of the secondary winding. It is known **as load component of the primary current**
- **no load primary electric current I_1 of a electrical power transformer having no winding resistance and leakage reactance can be represented as follows**

$$I_1 = I_0 + I_2'$$

- This extra primary electric current I_2' produces extra flux φ' in the core which will neutralize the secondary counter flux φ_2.
- Hence the main magnetizing flux of core, Φ remains unchanged irrespective of load.

Theory of Transformer On Load



Vector Diagram of Transformer on load

$$V_1 = E_1 + I_1 Z_1 \; \& \; V_2 = E_2 - I_2 Z_2$$

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

$$\Rightarrow V_1 = E_1 + I_1 R_1 + jI_1 X_1$$

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

$$\Rightarrow V_2 = E_2 - I_2 R_2 - jI_2 X_2$$

Losses in a Transformer

Two type of Losses:

1. Core Losses(Iron losses)
2. Copper Losses(Ohmic losses)

1. Core or Iron Losses:

Due to alternating flux setup in the magnetic core of the X'mer, it undergoes a cycle of magnetization and demagnetization.

Due to hysteresis effect there is loss of energy in this process which is called hysteresis loss.

$$\text{Hysteresis loss} = K_h B_m^{1.67} fV \text{ watts}$$

K_h = hysteresis constant depends on material

B_m = Max. flux density

f = frequency

V= volume of the core

The induced e.m.f. in the core tries to set up eddy current in the core and hence responsible for eddy current losses.

$$\text{Eddy Current loss} = K_e B_m^2 f^2 t^2 \text{ watts/unit volume}$$

K_e = Eddy Current constant

t = Thickness of the Core

Flux and frequency Š Constant

So, Core or iron losses are called Constant losses.

2. Copper Losses:

Cu-losses due to power wasted in the form of I^2R loss due to resistance of Primary and Secondary winding.

$$\text{Total Cu-loss} = I_1^2 R_1 + I_2^2 R_2$$
$$= I_1^2 (R_1 + R_2^{'}) = I_2^2 (R_2 + R_1^{'})$$
$$= I_1^2 R_{1e} = I_2^2 R_{2e}$$

Cu-losses is Variable losses

$$\text{Total Losses} = \text{Iron Losses} + \text{Copper Loss}$$
$$= P_i + P_{cu}$$

Transformer Efficiency

Power Output = Power Input – Total Losses

Power Input = Power Output + Total Losses

= Power Output + P_i + P_{cu}

$$\text{Efficiency}\ ,\eta = \frac{\text{Output Power}}{\text{Input Power}} \times 100\%$$

$$= \frac{P_{out}}{P_{out} + P_{losses}} \times 100\%$$

$$= \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + P_i + I_2^2 R_{2e}} \times 100\%$$

$$\eta_{(full\ load)} = \frac{VA\cos\theta}{VA\cos\theta + P_i + P_{cu}} \times 100\ \%$$

$$\eta_{(load\ n)} = \frac{nVA\cos\theta}{nVA\cos\theta + P_i + n^2 P_{cu}} \times 100\ \%$$

Where, if ½ load, hence n = ½ ,

¼ load, n= ¼ ,

90% of full load, n =0.9

Condition for Maximum Efficiency

$$\eta = \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + P_i + I_2^2 R_{2e}}$$

For Max. efficiency

$$\frac{d\eta}{dI_2} = 0$$

Copper Losses = Iron Losses

All Day Efficiency

- There are number of transformers whose performance can’t be monitored according the above general efficiency.
- Those distribution transformers which supply electrical energy to lighting and other general circuits, their primary energize for 24 hours, but the secondary windings does not energize all the time.

Secondary windings supply eclectic power for very small load or no load for maximum time in 24 hours. It means that core loss occurs for 24 hours regularly but copper loss occurs only when transformer is on loaded.

All Day Efficiency

$$\text{ordinary commercial efficiency} = \frac{\text{out put in watts}}{\text{input in watts}}$$

$$h_{all\ \text{day}} = \frac{\text{output in kWh}}{\text{Input in kWh}} (\ for\ \ 24\ \text{hours})$$

- All day efficiency is always less than the commercial efficiency

Voltage Regulation

It can be defined as the percentage change in terminal voltage from
full load to no load condition and is expressed as the percentage of
the full load voltage.

$$\%\ \text{Voltage Regulation} = \frac{E_2 - V_2}{V_2} \times 100$$

Voltage Regulation of Transformer for Lagging Power Factor

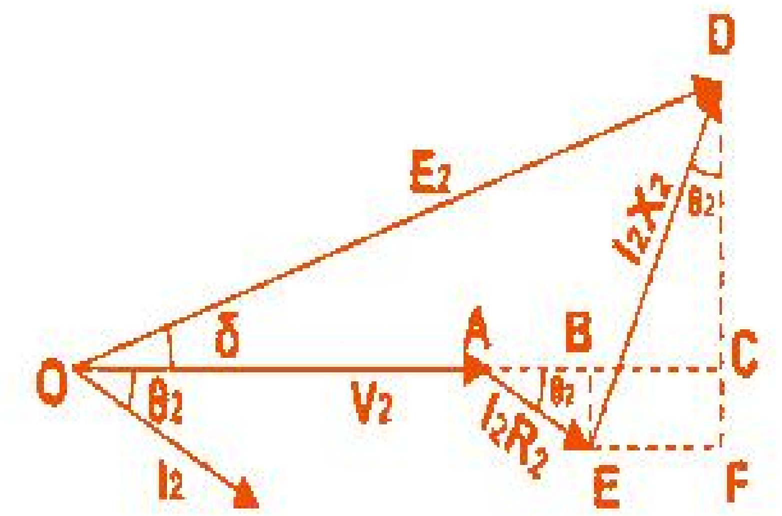
- lagging power factor of the load is $\cos\theta_2$, that means angle between secondary electric current and voltage is θ

$$OC = OA + AB + BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$



Voltage Regulation at Lagging Power Factor

- Angle between OC & OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB + BC$$

$$E_2 = OC = V_2 + I_2R_2cos\theta_2 + I_2X_2sin\theta_2$$

Voltage regulation of transformer at lagging power factor,

$$\text{Voltage regulation (\%)} = \frac{E_2 - V_2}{V_2} X\ 100\% = \frac{I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2}{V_2} X\ 100\%$$

Voltage Regulation of Transformer for Leading Power Factor

$$OC = OA + AB - BC$$

$$Here,\ OA = V_2$$

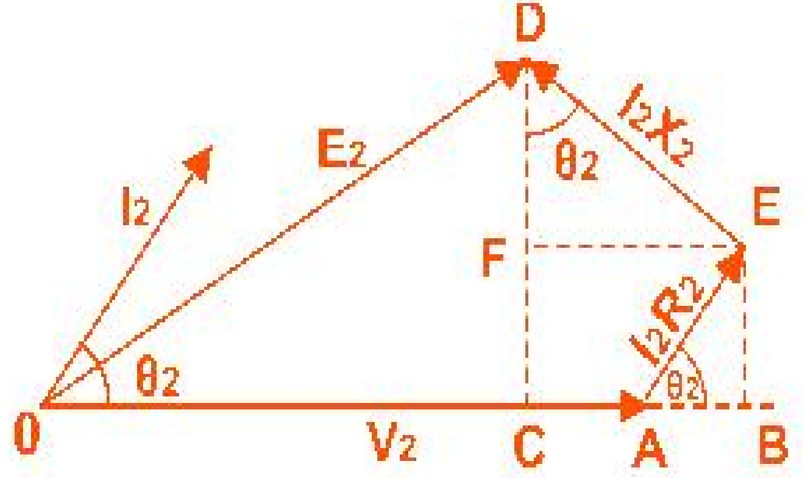
$$Here,\ AB = AE\cos\theta_2 = I_2 R_2 \cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2 X_2 \sin\theta_2$$

Angle between OC & OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB - BC$$

$$E_2 = OC = V_2 + I_2 R_2 cos\theta_2 - I_2 X_2 sin\theta_2$$



Voltage Regulation at Leading Power Factor

- **Voltage regulation of transformer** at leading power factor,

$$\text{Voltage regulation (\%)} = \frac{E_2 - V_2}{V_2} \times 100\% = \frac{I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2}{V_2} \times 100\%$$

Short and open Circuit Tests

- These two tests are performed on a transformer to determine

(i) equivalent circuit of transformer

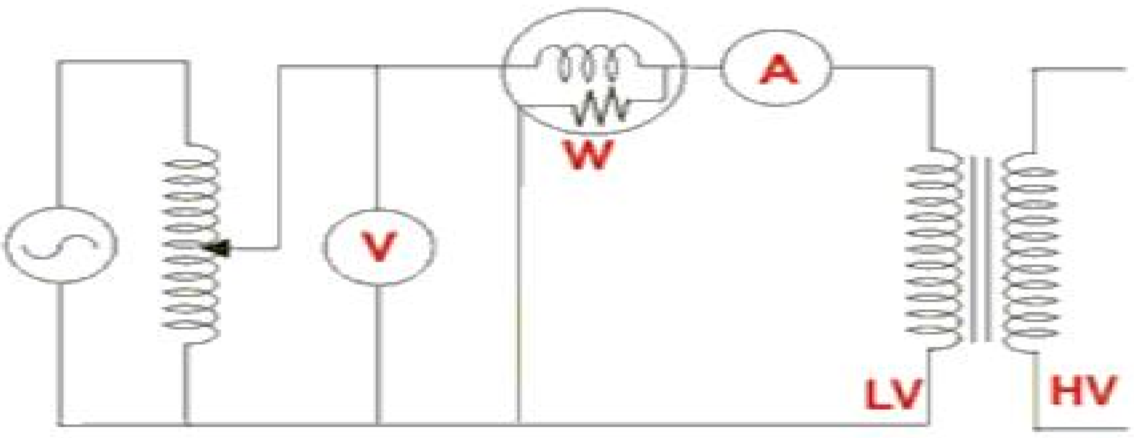
(ii) voltage regulation of transformer

(iii) efficiency of transformer.

- The power required for these **open circuit test and short circuit test on transformer** is equal to the power loss occurring in the transformer.

Open Circuit Test on Transformer

The **open circuit test on transformer** is used to determine core losses in transformer and parameters of shunt branch of the equivalent circuit of transformer.



Open Circuit Test on Transformer

The two components of no load current can be given as,

$I_{\mu} = I_0 \sin\Phi_0$ and $I_w = I_0 \cos\Phi_0$.

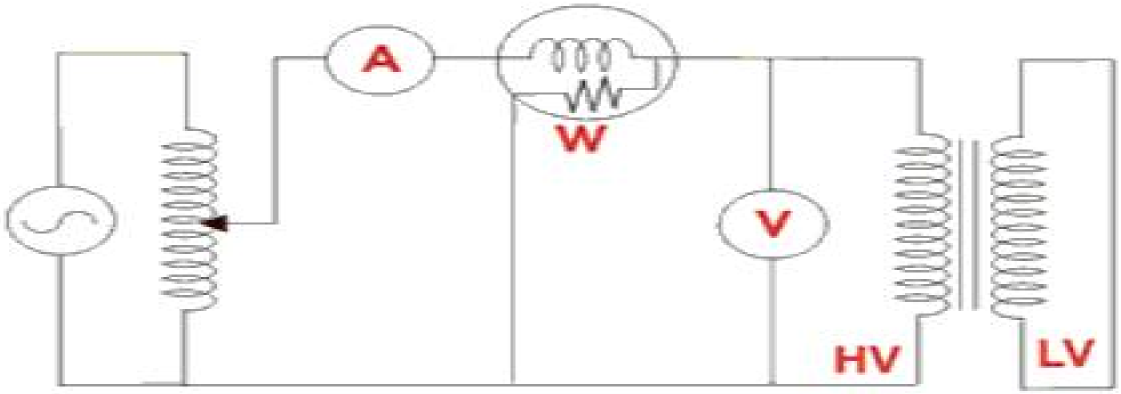
$\cos\Phi_0$ (no load power factor) $= W / (V_1 I_0)$

From this, shunt parameters of equivalent circuit parameters of equivalent circuit of transformer (X_0 and R_0) can be calculated as

$X_0 = V_1/I_{\mu}$ and $R_0 = V_1/I_w$.

Short Circuit Test on Transformer

The short circuit test on transformer is used to determine copper loss in transformer at full load and parameters of approximate equivalent circuit of transformer.



Short Circuit Test on Transformer

$W = I_{sc}^2 R_{eq}$....... (where R_{eq} is the equivalent resistance of transformer)

$Z_{eq} = V_{sc}/I_{sc}$

Therefore, equivalent reactance of transformer can be calculated from the formula

$$Z_{eq}^2 = R_{eq}^2 + X_{eq}^2.$$

Parallel Operation of Transformer

It is economical to install numbers of smaller rated transformers in parallel than installing a bigger rated electrical power transformers.

Advantages are:

- To maximize electrical power system efficiency
- To maximize electrical power system availability
- To maximize power system reliability

Conditions for Parallel Operation of Transformers

- Same voltage ratio of transformer.
- Same percentage impedance.
- Same polarity.
- Same rating.

CAN D.C. SUPPLY BE USED FOR TRANSFORMER?

D.C can't be used for the Transformer. Transformer works on the principle of mutual induction, for which current in one coil must change uniformly.

If D.C. is given the current will not change due to constant supply and transformer will not work.

Practically winding resistance is very small.

For D.C. inductive reactance(X_L) is zero as D.C has no frequency. So, total impedance of winding is very low for D.C.

Thus winding will draw very high current if D.C. Supply is given to it. This may cause burning of winding

There can be saturation of the core due to which transformer draws very large current from the supply when connected to D.C.