Module 4- Transformers

Walchand College Of Engineering,sangli.

Contents

- Magnetic circuits
- Construction, working principle and types of single-phase transformer,
- Open circuit and short circuit tests: Losses, efficiency, all-day efficiency and regulation.
- Autotransformer.

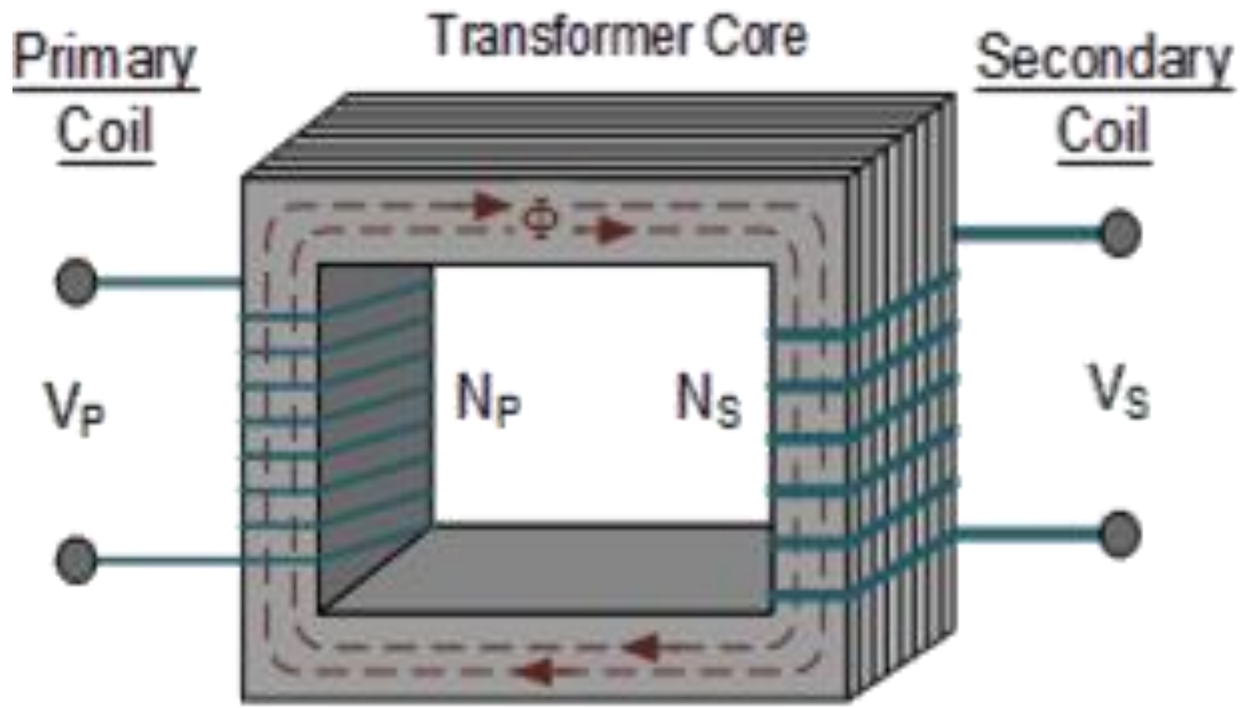
Transformer

- A static device
- Transfers electrical energy from one circuit to another with change in voltage level without a change of frequency
- Faraday's Law of electromagnetic induction.
- The two electric circuits are in mutual inductive influence of each other.
- Step up and Step Down Transformer

Transformer

- Static Electro-magnetization
- Voltage levels (230V, 400 V, 3.3 kV, 11kV, 132 kV ….)
- Generation, Transmission and Distribution
- Changing current and voltage levels
- Highly efficient device
- Heart of Power System
- KVA Ratings

Transformer



Types of Transformer

A) Based on voltage level:

1) Step up transformer: Voltage increases (with subsequent decrease in current) at secondary.

2) Step down transformer: Voltage decreases (with subsequent increase in current) at secondary.

B) Based on type of supply:

1) Single phase transformer 2) Three phase transformer

C) Based on construction:

1) Core type 2) Shell type

D) Based on winding:

1) Single winding (Auto) transformer 2) Two winding transformer

3) Three winding transformer

E) Based on cooling method used:

1) Natural air cooled transformer

2) Oil cooled transformer

3) Forced air cooled transformer

4) Water cooled transformer

F) Based on their use:

1) Power transformer: Used in transmission network, high rating

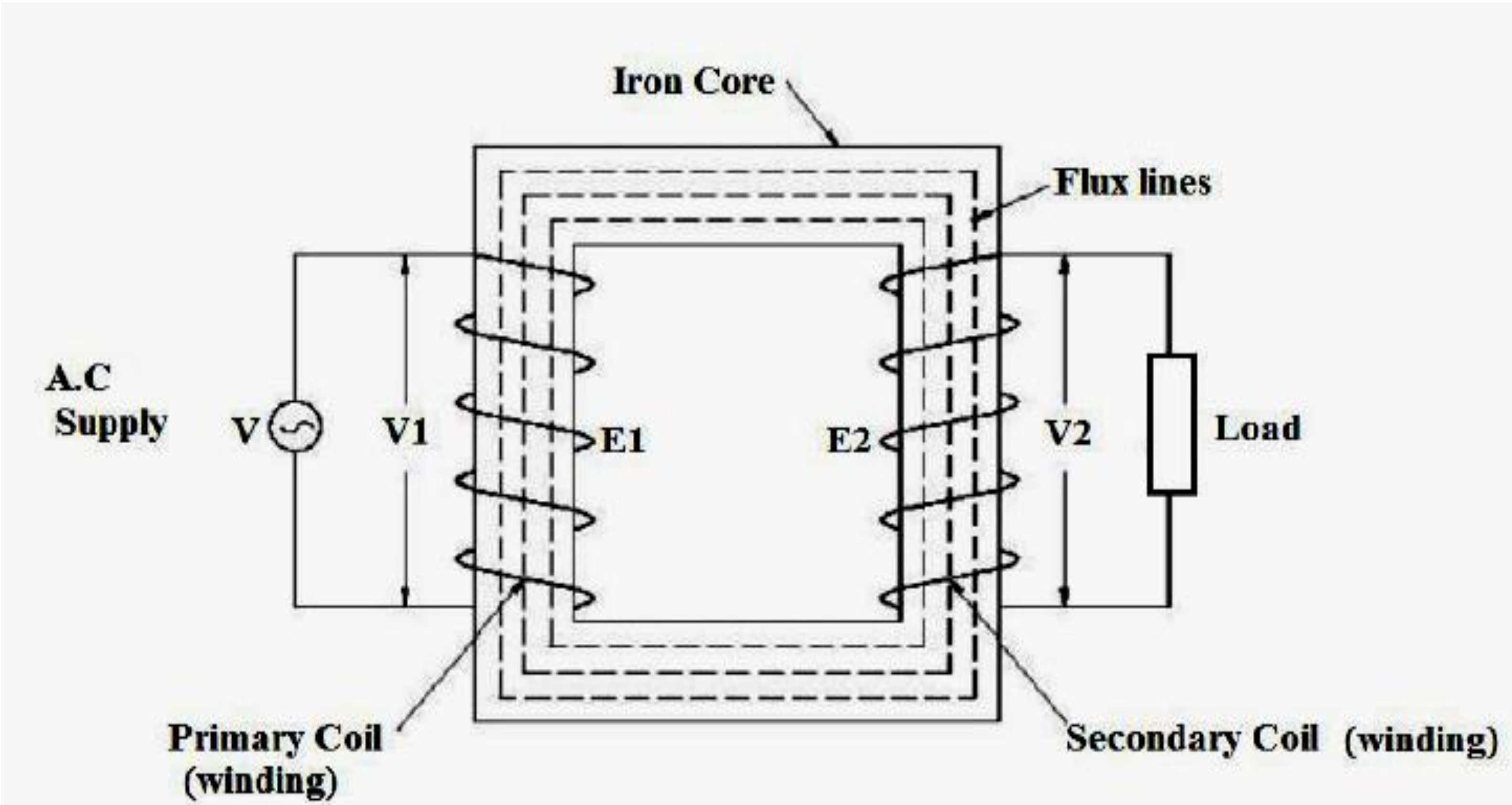
2) Distribution transformer: Used in distribution network, comparatively lower rating than that of power transformers.

3) Instrument transformer: Used in relay and protection purpose in different instruments in industries

   a) Current transformer (CT)

   b) Potential transformer (PT)

Construction of transformer



Construction of transformer

- A silicon steel core and two windings placed on it.
- The winding are insulated both from core and each other.
- The core is built up with thin soft iron silicon steel laminations to provide path of low reluctance to the magnetic flux.
- Copper or aluminum is used as winding material for Primary and Secondary Winding

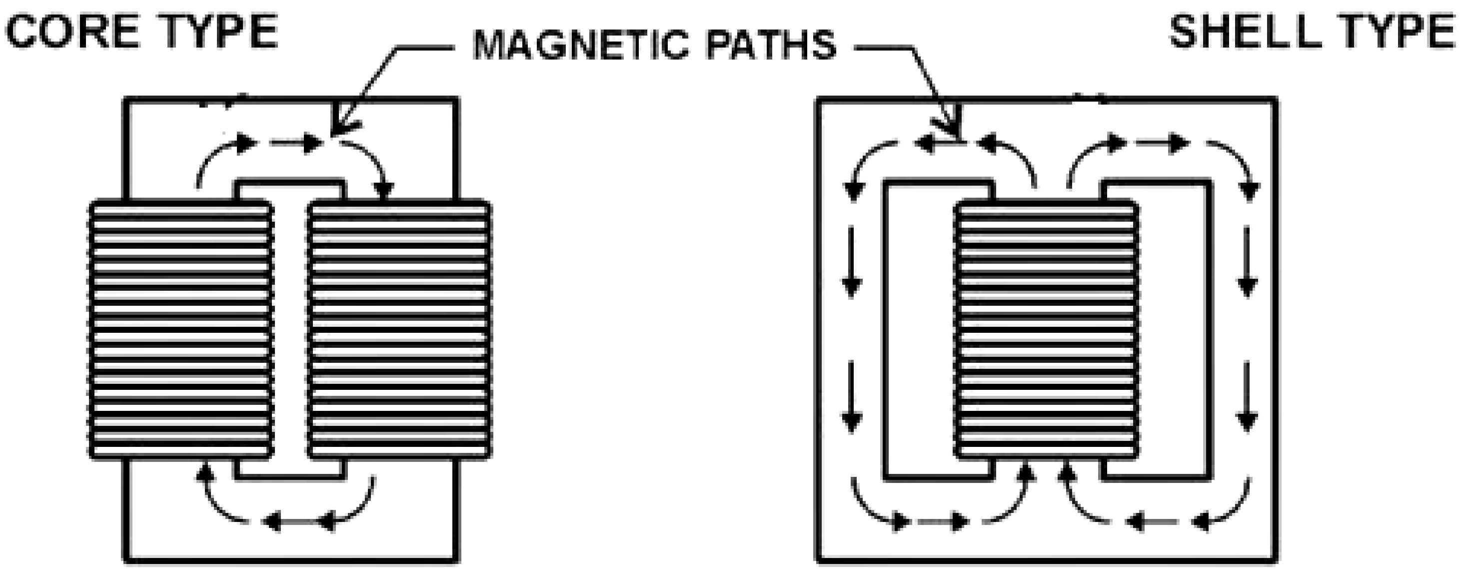
Principle of Operation

- Works on **Faraday's Law** of electromagnetic induction principle
- Alternating current flowing through primary – -Alternating EMF - Alternating flux in core.
- Self induced EMF: E1
- Alternating flux links to the secondary winding
- Alternating EMF is induced in secondary winding by principle of **mutual induction.**
- Mutual induced EMF: E2
- The energy transferred to load by secondary is taken from primary via flux set in the core.

- When current in the primary coil changes being alternating in nature, a changing magnetic field is produced.
- This changing magnetic field gets associated with the secondary through the soft iron core.
- Magnetic flux linked with the secondary coil changes.
- It induces EMF in the secondary.
- If the secondary winding is closed circuit, then mutually induced current flows through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit (secondary).

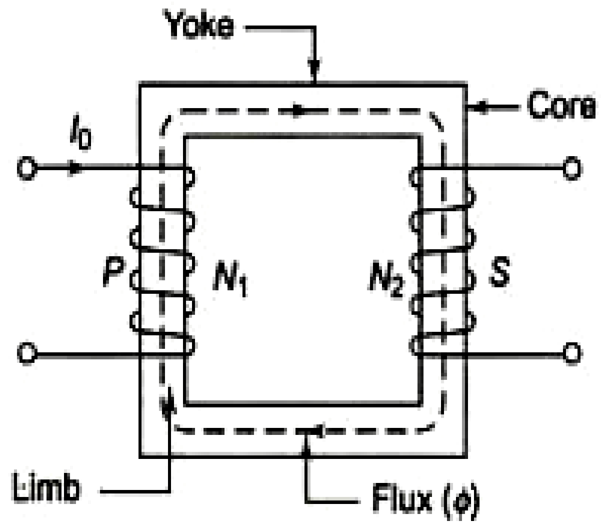
Types based on construction

- Core type transformer
- Shell type transformer

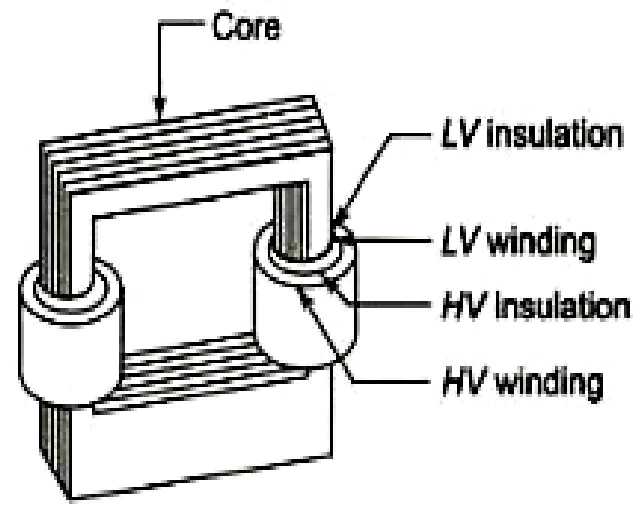


Core Type Transformer

- Single magnetic circuit
- Core will be rectangular in shape and the coils used are cylindrical.
- Windings are uniformly distributed on two limbs of the core
- Winding encircles the core
- The cylindrical coils have different layers and each layer is insulated from each other. Materials like paper, cloth or mica can be used for insulation.
- Low voltage coil is placed inside near the core while high voltage coil surrounds the low voltage coil.
- Core with large number of thin laminations.



(a) Representation

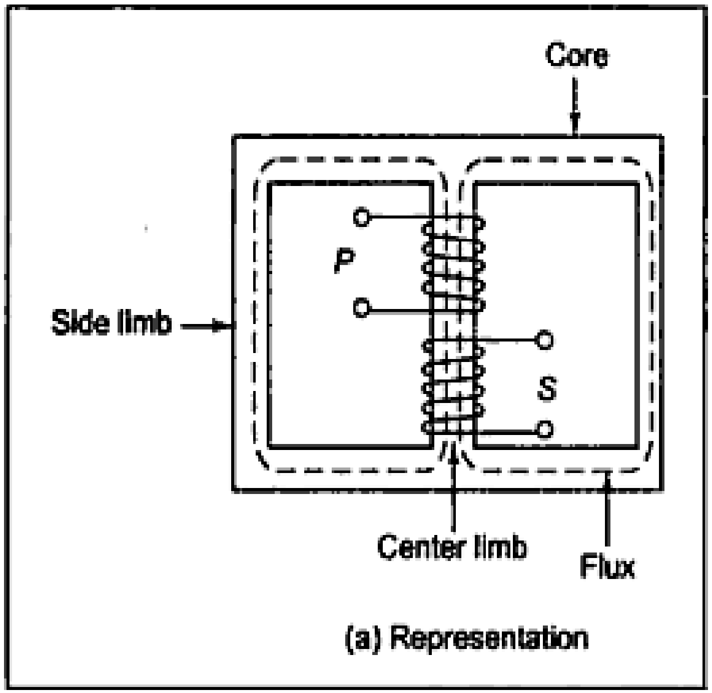


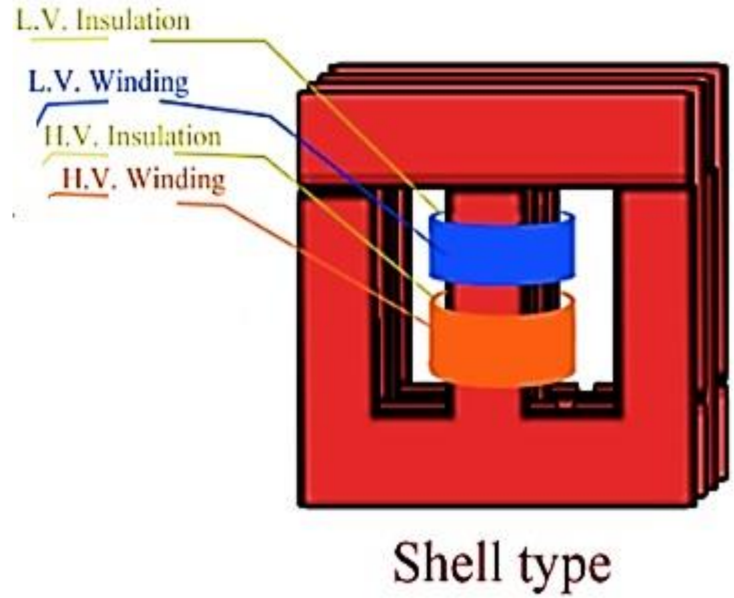
(b) Construction

Shell Type Transformer

- Double magnetic circuit
- Core has three limbs and windings are placed on the central limb.
- Multilayer disc type or sandwich coils
- Core having large number of thin laminations.
- Better mechanical protection for winding

Shell Transformer





Comparison

S.R	Core Type Transformer	Shell type transformer
1	The core has only one magnetic circuit.	It has two magnetic circuits.
2	Core has two limbs.	Core has three limbs.
3	Cylindrical windings are used	Sandwitch type windings are used
4	The winding is encloses considerable part of core.	Core encloses part of winding of transformer.
5	It has less mechanical protection to coil.	It has better mechanical protection to coil.
6	Natural cooling is provided.	Natural cooling cannot provide
7	It has better natural cooling since more surface is exposed to atmosphere.	Cooling is not very effective.
8	This transformer is easy to repair & maintenance.	This transformer is not easy to repair & maintenance.
9	Preferred for high voltage (less output)	Preferred for low voltage (high output)
10	Losses are more hence efficiency is less as compare to shell type	Losses are less hence efficiency is more as compare to core type

Symbol of Transformer

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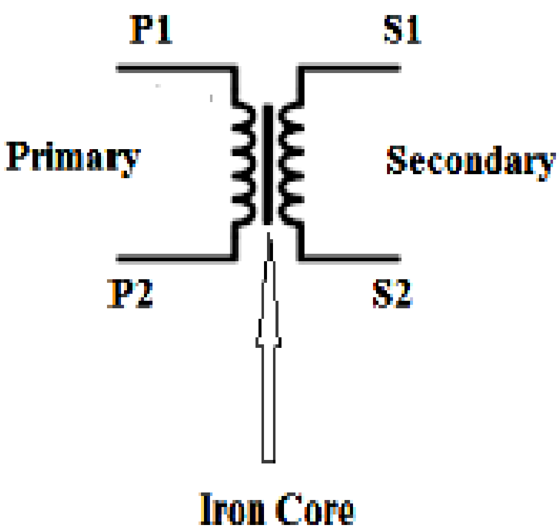
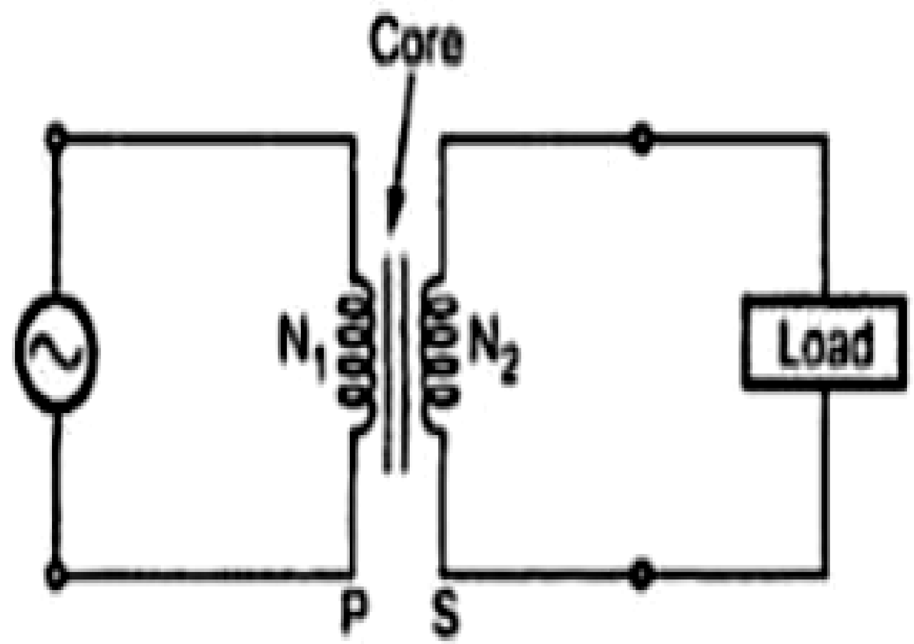
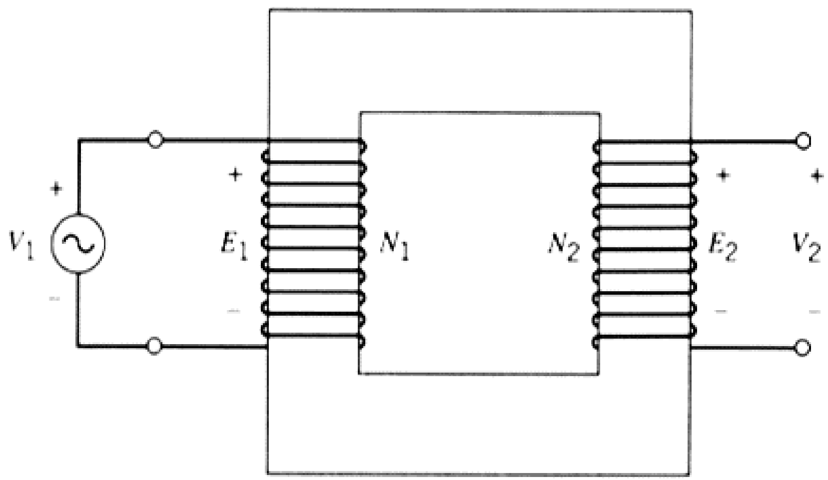
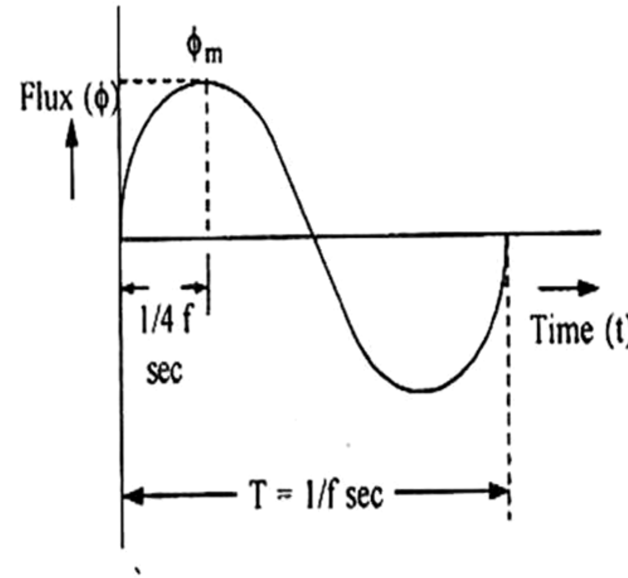




EMF Equation of transformer





EMF Equation of transformer

Φ = Flux

Φ_m = Maximum value of flux = $B_m * A$

N_1 = Number of primary winding turns

N_2 = Number of secondary winding turns

f = Frequency of the supply voltage (Hz)

E_1 = R.M.S. value of the primary induced EMF in volts

E_2 = R.M.S. value of the secondary induced EMF in volts

A = Cross-sectional area of core in m^2

- As shown in figure above, the core flux increases from its zero value to maximum value $\varnothing_m$ in one quarter of the cycle , that is in T/4 second. Therefore,

  average rate of change of flux = $\varnothing_m$/ (T/4) = 4f $\varnothing_m$ Wb/s

- Now, rate of change of flux per turn means induced emf in volts. Therefore,

  average emf induced/turn = 4f $\varnothing_m$ Volt

- If flux Ø varies sinusoidally, then r.m.s value of induced e.m.f is obtained by multiplying the average value with form factor.
- Form Factor = r.m.s. value/average value = 1.11

- Therefore,

  r.m.s value of e.m.f/turn = 1.11 X 4f $Ø_{max}$ = 4.44f $Ø_{max}$

- Now, r.m.s value of induced e.m.f in the whole of primary winding

  = (induced e.m.f./turn) X Number of primary turns

- Therefore,

  $\mathbf{E_1 = 4.44\ f\ N_1 Ø_m = 4.44\ f\ N_1 B_m A}$

- Similarly, r.m.s value of induced e.m.f in secondary is

  $\mathbf{E_2 = 4.44\ f\ N_2\ Ø_m = 4.44\ f\ N_2 B_m A}$

- In an ideal transformer on no load,

  $V_1 = E_1$ and $V_2 = E_2$, where V_2 is the terminal voltage

Voltage Transformation Ratio (K)

- From the above equations we get
  $E_2/E_1 = V_2/V_1 = N_2/N_1 = K$

(1) If $N_2 > N_1$, that is $K > 1$, then transformer is called step-up transformer.
(2) If $N_2 < N_1$, that is $K < 1$, then transformer is known as step-down transformer.

- Again for an ideal transformer,

  $V_1 I_1 = V_2 I_2$ (Constant power)
  $I_1/I_2 = V_2/V_1 = K$

Losses in Transformer

- Transformer Losses
  - Copper Losses (P_{cu}) (Variable Losses)
    - Primary winding Losses ($I_1^2 * R_1$)
    - Secondary winding Losses ($I_2^2 * R^2$)
  - Iron Losses (P_i) (Core Losses) (Constant Losses / Fixed Losses)
    - Hysteresis Losses
    - Eddy Current Losses

Copper Losses

- Power wasted in the form of I^2R loss
- Resistances of the primary and secondary windings
- Copper losses are called variable losses as it changes(current changes) as load changes.

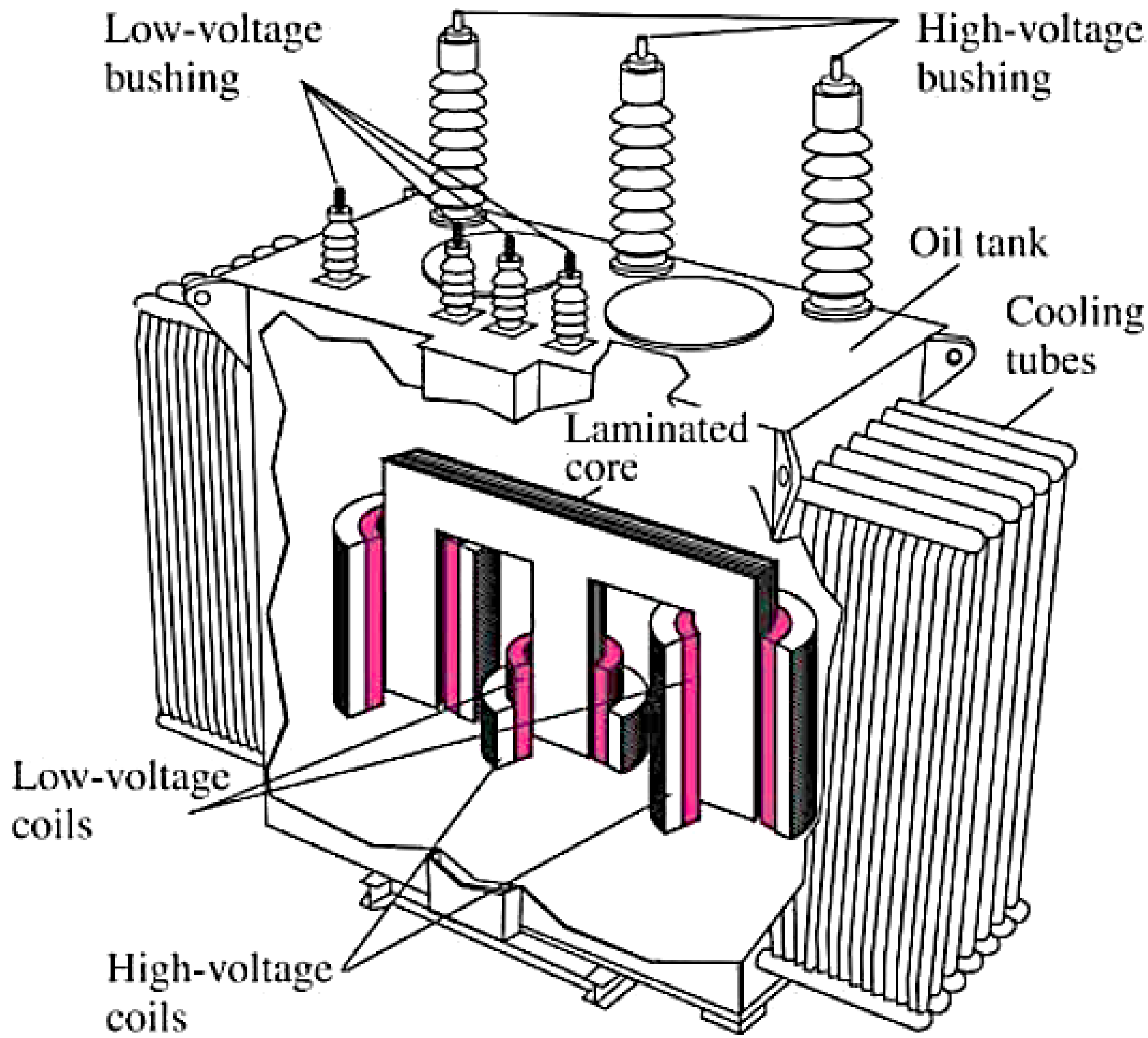
Core or Iron Losses

- Losses are proportional to flux density & supply frequency
- Independent of load current
- Constant losses
- Types of iron loss:

1. Hysteresis Losses (Materials used for core)
2. Eddy current Losses (Laminated soft iron core)

Rating of Transformer

- Power losses appear in the form of heat
- Output rating is the product of output voltage and output current.
- Copper loss in the transformer depends on the current through the winding.
- Iron or core loss depends on the voltage (f=const.)
- Losses don't depend on the power factor of the load.
- So transformer rating is in KVA


Low-voltage bushing
High-voltage bushing
Oil tank
Cooling tubes
Laminated core
Low-voltage coils
High-voltage coils

Efficiency of a Transformer

- Power input = Power output + Total losses

  = Power output + P_i + P_{Cu}
- The efficiency of any device is defined as the ratio of the power output to power input.

$$\% \eta = \frac{(\text{VA rating x } \cos \Phi)}{(\text{VA rating x } \cos \Phi) + (P_i + P_{cu\ F.L})} \times 100$$

$$\% \eta = \frac{x\,(\text{VA rating})\cos Ø}{x\,(\text{VA rating})\cos Ø + P_i + (x)^2\ P_{cu\ F.L}} \times 100$$

All day efficiency of a transformer

- Distribution transformer serves residential and commercial loads which fluctuate throughout the day. For example, the distribution transformers are energized for 24 hours, but they deliver very light loads for the major portion of the day, and they do not supply rated or full load.
- There are various losses in the transformer such as iron and copper loss. The iron or core loss occurs for the whole day in the distribution transformer. The second type of loss known as copper loss occurs only when the transformers are in the loaded condition.

- Hence, the performance of such transformers cannot be judged by the commercial or ordinary efficiency, but the efficiency is calculated or judged by All Day Efficiency also known as operational efficiency or energy efficiency which is computed by energy consumed during 24 hours.
- The maximum efficiency in such transformers occurs at about 60-70 % of the full load.

$$\text{All day efficiency, } \eta_{\text{all day}} = \frac{\text{output in kWh}}{\text{input in kWh}} \quad (\text{for 24 hours})$$

Voltage Regulation of Transformer

- The voltage regulation is the percentage of voltage difference between no load and full load voltages of a transformer with respect to its full load voltage.

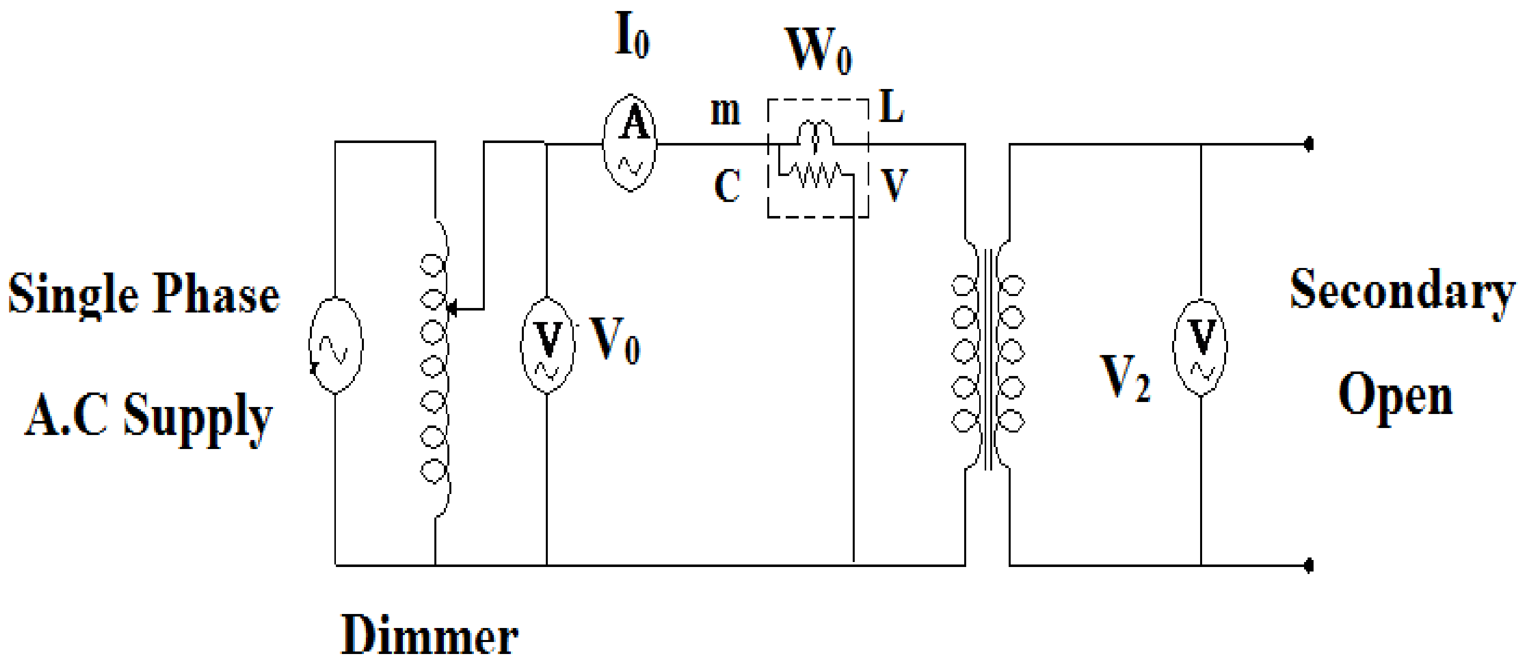
- Suppose, electrical power transformer is open circuited, means load is not connected with secondary terminals. In this situation, the secondary terminal voltage of the transformer will be its secondary induced emf E_2. Whenever full load is connected to the secondary terminals of the transformer, rated current I_2 flows through the secondary circuit and voltage drop comes into picture. At this situation, primary winding will also draw equivalent full load current from source.

- The voltage drop in the secondary is I_2Z_2 where Z_2 is the secondary impedance of transformer.
- Now at this loading condition, voltage V_2 will be present across load terminals which is obviously less than no load secondary voltage E_2 and this is because of I_2Z_2 voltage drop in the transformer.

$$Voltage\ regulation(\%) = \frac{E_2 - V_2}{V_2} \times 100\%$$

Open Circuit(O.C.) Test:

- Experimental setup:



Note : Usually H.V winding is Kept open

Primary winding is connected to a.c supply through dimmer. Voltmeter, Ammeter & wattmeter are connected to primary side to measure primary voltage, current & power (V_o, I_o, W_o).

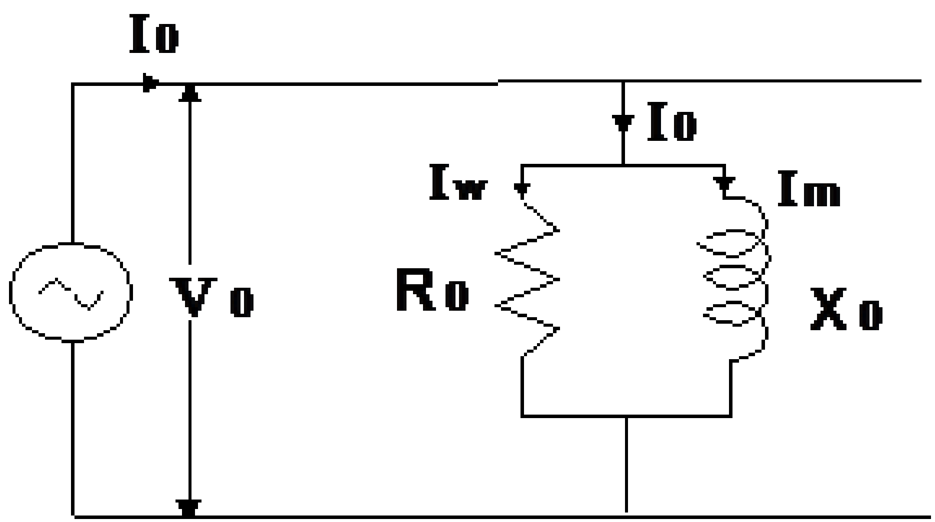
One voltmeter is connected at secondary side to measure no load voltage at secondary side ($V_2 = E_2$).

- **Procedure:**

1. Connect circuit as per the circuit as shown.
2. Keep dimmer at its minimum position.
3. Switch on a.c supply & adjust dimmer to get rated primary voltage (230 V) as measured by voltmeter across primary winding.
4. Measure primary current & power (I_o & W_o)

Two components of $\mathbf{I_{oc}}$ (no load current) are as ;

- $I_m = I_o \sin\varnothing_o$
- $I_w = I_o \cos\varnothing_o$



Equivalent Circuit Diagram for O.C. Test

Since no load power is given as

$$W_o = V_o\, I_o \cos \text{Ø}_o$$

Hence no load p.f is given as

$$\cos \text{Ø}_o = W_o / V_o\, I_o$$

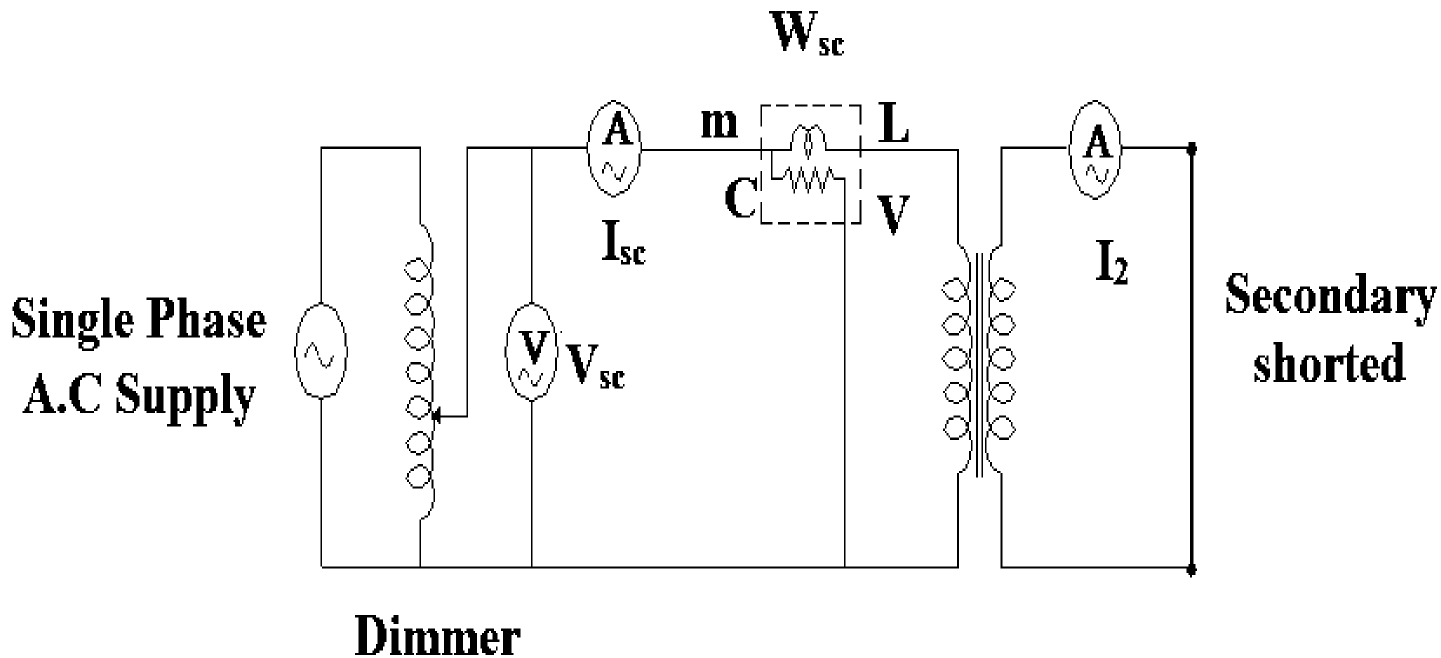
- I_{oc} is very small compared to full load current (about 3 % to 5% of full load) so primary copper losses are negligible and as I_2 = 0 therefore secondary losses = zero.Therefore total coper losses are very small hence assumed to be zero. Hence reading W_o represents the Iron loss.

$$\mathbf{W_o = P_i = Iron\ Loss}$$

Calculations:

- $I_m = I_o \sin Øo$
- $I_w = I_o \cos Øo$
- $\text{Cos } Ø_o = W_o / V_o I_o$
- $R_0 = V_o / I_w$ ohm
- $X_0 = V_o / I_m$ ohm.

S.C. Test:



Note : Usually L.V winding is short circuited

Primary winding is connected to a.c supply through dimmer. Voltmeter , Ammeter & wattmeter are connected to primary side to measure primary voltage, current & power (V_{sc}, I_{sc}, W_{sc}). One Ammeter is connected at secondary side to measure short circuit current.

- **Procedure:**

1. Connect circuit as per the circuit as shown.
2. Keep dimmer at its minimum position.
3. Switch on a.c supply & adjust dimmer to get rated current I_{sc} as measured by ammeter connected in primary winding it will be obtained at a low voltage about 10% of its rated value.

(do not increase the primary voltage further)

4. Note down W_{sc} , V_{sc}, I_{sc}

At full load, Iron loss is very small. Hence they are neglected. Total loss is equal total copper loss at full load. Therefore wattmeter W_{sc} gives almost entirely the full load copper losses.

$$\mathbf{W_{sc} = full\ load\ copper\ loss = P_{cu}}$$

- Calculations-

$W_{sc} = V_{sc}\ I_{sc}\ \text{Cos}\ \text{Ø}_{sc}$

Hence full load p.f is given as

$\text{Cos}\ \text{Ø}_{sc} = W_{sc} / V_{sc}\ I_{sc}$

But W_{sc} indicates full load copper loss

Therefore: $W_{sc} = I_{sc}^2 \ R_1$

Therefore: $R_1 = W_{sc} / I_{sc}^2$

- $Z_1 = V_{sc} / I_{sc}$

$$Z_1 = \sqrt{R_1^{\ 2} - X_1^{\ 2}}$$

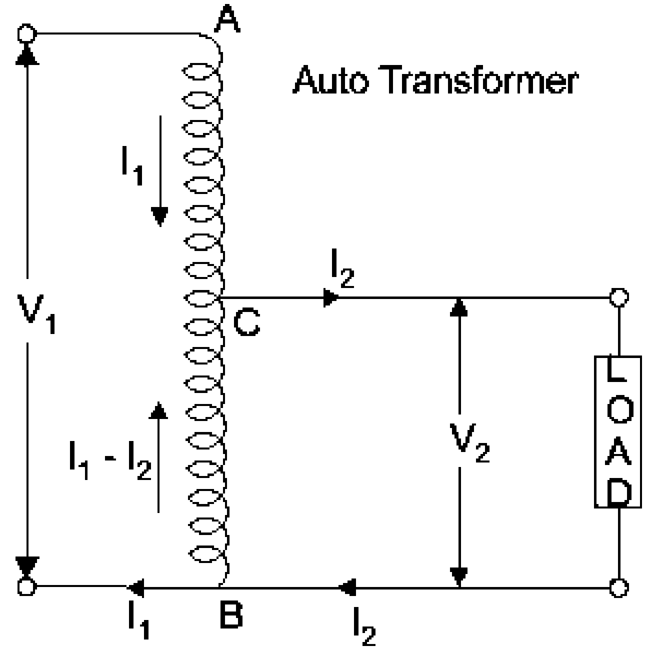
- Therefore:

$$X_1 = \sqrt{Z_1^{\ 2} - R_1^{\ 2}}$$

Autotransformer

- Auto transformer is kind of electrical transformer where primary and secondary shares same common single winding. So basically it's a one winding transformer.

- In Auto Transformer, one single winding is used as primary winding as well as secondary winding. But in two windings transformer two different windings are used for primary and secondary purpose.



The winding AB of total turns N_1 is considered as primary winding. This winding is tapped from point 'C' and the portion BC is considered as secondary. Let's assume the number of turns in between points 'B' and 'C' is N_2.

- If V_1 voltage is applied across the winding i.e. in between 'A' and 'C'.

$$So\ voltage\ per\ turn\ in\ this\ winding\ is\ \frac{V_1}{N_1}$$

- Hence, the voltage across the portion BC of the winding, will be,

$$\frac{V_1}{N_1} X N_2\ and\ from\ the\ figure\ above,\ this\ voltage\ is\ V_2$$

$$Hence,\ \frac{V_1}{N_1} X N_2 = V_2$$

$$\Rightarrow \frac{V_2}{V_1} = \frac{N_2}{N_1} = Constant = K$$

- As BC portion of the winding is considered as secondary, it can easily be understood that value of constant 'K' is nothing but turns ratio or voltage ratio of that **auto transformer**. When load is connected between secondary terminals i.e. between 'B' and 'C', load current I_2 starts flowing. The current in the secondary winding or common winding is the difference of I_2 and I_1.

Advantages of using Auto Transformers

- For transformation ratio = 2, the size of the auto transformer would be approximately 50% of the corresponding size of two winding transformer. Thus auto transformer is **smaller in size and cheaper.**
- An auto transformer has **higher efficiency** than two winding transformer. This is because of less copper loss and core loss due to reduction of transformer material.
- Auto transformer has **better voltage regulation** as voltage drop in resistance and reactance of the single winding is less.

Disadvantages of Using Auto Transformer

- The main disadvantage of an autotransformer is that it does not have the primary to secondary winding isolation of a conventional double wound transformer. Then an autotransformer can not safely be used for stepping down higher voltages to much lower voltages suitable for smaller loads.
- If the secondary side winding becomes open-circuited, load current stops flowing through the primary winding stopping the transformer action resulting in the full primary voltage being applied to the secondary terminals.
- If the secondary circuit suffers a short-circuit condition, the resulting primary current would be much larger than an equivalent double wound transformer due to the increased flux linkage damaging the autotransformer.

Applications of Auto-Transformers

- Compensating voltage drops by boosting supply voltage in distribution systems.
- Auto transformers with a number of tapping are used for starting induction and synchronous motors.
- Auto transformer is used as variac in laboratory or where continuous variable voltage over broad ranges are required