# UNIT-III

Transformers

**Topics:**

- Construction and Principle of Operation
- Working principle
- Ideal and practical transformer
- Equivalent circuit
- OC and SC test
- Losses, efficiency, regulation
- Auto-transformer

Transformer is a static device which transfers the electrical energy from one circuit to other circuit without changing the frequency.

It works on the Principle of mutual induction.

Construction of transformer:

Main parts:

1.Transformer Core

2. Windings

3. Insulation

4. Tank & Cooling

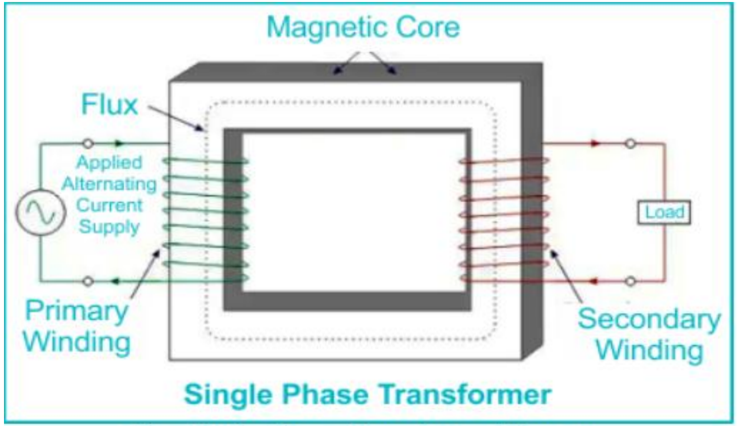



Fig- Single Phase Transformer Diagram

1. **Transformer Core** :-Made of high-grade laminated silicon steel.

Laminations are made to reduce eddy current losses.

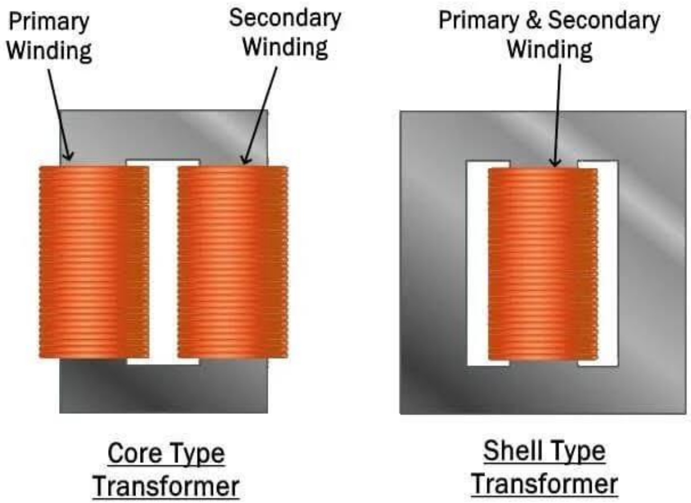
Provides low reluctance path for magnetic flux.

Common core types

a. Core-type (windings surround the core limbs)

b. Shell-type (core surrounds the windings)

c. spiral-type




2. **winding:-**

Primary winding: Connected to the input AC supply.

Secondary winding: Delivers the transformed voltage.

Made of copper or aluminum conductors.

Windings are placed concentrically and insulated from each other on the core

Spiral type

**3.Insulation System**

Provides electrical isolation between Windings and core

Materials used: Pressboard, kraft paper, varnish, epoxy resins

Designed to withstand thermal and dielectric stress.

**4. Tank and Cooling System:**

**Tank**: Encloses the core and windings; made of steel. •

**Cooling Methods**: 1. Air cooled , 2. Oil cooled

3. Oil Immersed Forced Air

Cooling medium (transformer oil) also acts as an insulating fluid.

## 5. Bushings and Terminals

**Bushings**: Insulated passages for conductors entering/exiting the tank.

Prevent leakage currents and flashovers.

**Terminals**: Connection points for primary and secondary circuits.

## 6. Conservator and Breather (Oil filled transformers)

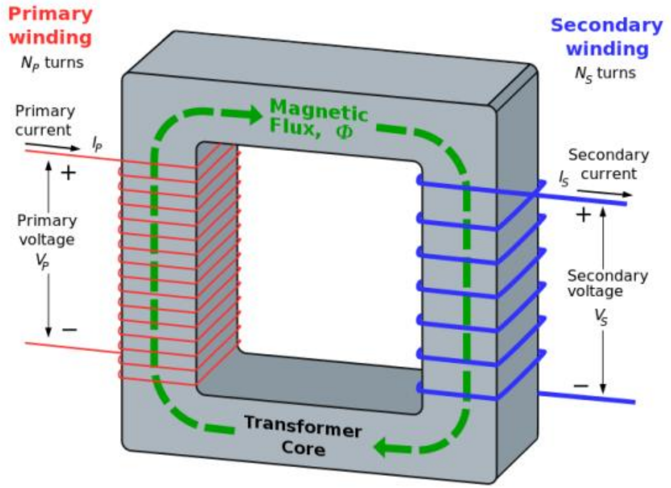
**Conservator**: A cylindrical tank on top of main tank to accommodate oil expansion.

**Breather** (Silica Gel): Attached to conservator to prevent moisture entry.

Silica gel changes color (blue to pink) as it absorbs moisture.

# Principle of Operation:

- Transformer works on the Faraday’s Law of Electromagnetic Induction specifically mutual induction.
- When AC voltage is applied to the primary winding, it creates a time-varying magnetic flux.
- This flux links to the secondary winding and induces an electromotive force (EMF).
- When an alternating current (AC) flows through the primary winding, it creates a changing magnetic field in the core.
- This changing magnetic field then induces a voltage in the secondary winding, allowing for the transfer of electrical energy between the two windings.



## Ideal Transformer

Ideal transformers are the hypothetical transformers used for explanation purposes in electrical engineering. These transformers do not exist in real and they are just imaginary concepts. In terms of ideal transformers, it is said that

**Input power = Output Power**

The form of transformer in which there is no loss of power is termed as ideal transformer. It has no core losses, copper losses, or any other losses in the transformer. The efficiency of the ideal transformers is supposed to be 100%.

## Characteristics of an Ideal Transformer

- The primary and secondary windings are perfectly coupled through the magnetic core with no magnetic leakage and thus it is assumed as the perfect magnetic coupling.
- Inside the core it is assumed that there is no eddy current loss or no hysteresis loss.
- The core of the ideal transformers has infinite magnetic permeability.
- In an ideal transformer, the magnetizing current is assumed to be zero.
- The winding of the ideal transformer have no resistance which allow zero power loss.

# Emf equation of transformer:

Consider a transformer as shown in the figure. If $N_1$ and $N_2$ are the number of turns in primary and secondary windings. When we apply an alternating voltage $V_1$ of frequency f to the primary winding, an alternating magnetic flux $\phi$ is produced by the primary winding in the core.

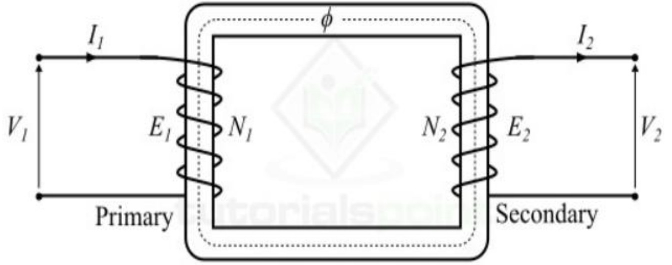


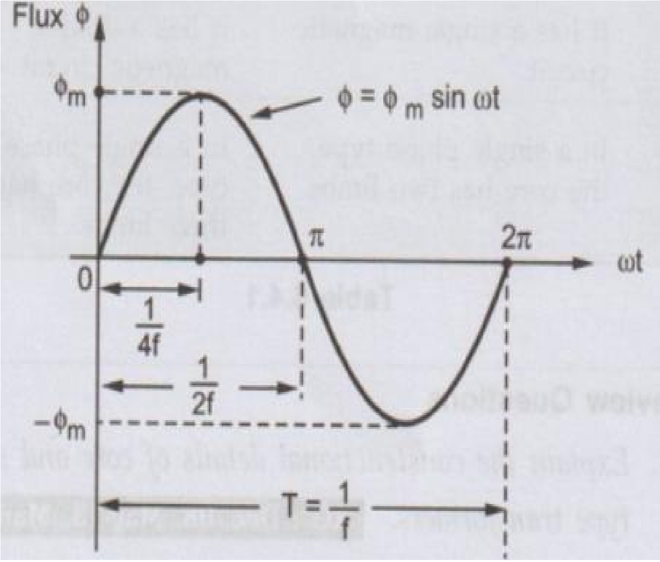

Figure - Electrical Transformer

If we assume sinusoidal AC voltage, then the magnetic flux can be given by,

$$\phi = \phi_m \sin \omega t \cdots (1)$$

Now, according to principle of electromagnetic induction, the instantaneous value of EMF $e_1$ induced in the primary winding is given by,

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



$$\Rightarrow e_1 = -N_1 \frac{d}{dt}(\phi_{\mathrm{m}} \sin \omega t)$$

$$\Rightarrow e_1 = -N_1 \, \omega\phi \, cos\, \omega t$$

$$\Rightarrow e_1 = -2\pi f N_1 \, \phi_m \, cos\, \omega t$$

Where,

$$\omega = 2\pi f$$

$$\because -cos\, \omega t = \sin(\omega t - 90^\circ)$$

Therefore,

$$e_1 = 2\phi f N_1 \, \phi_m \sin(\omega t - 90^\circ) \cdots (2)$$

Equation (2) may be written as,

$$e_1 = E_{m_1} \sin(\omega t - 90^\circ) \cdots (3)$$

Where, $E_{m_1}$ is the maximum value of induced EMF $e_1$.

$$E_{\mathrm{m1}} = 2\pi f N_1 \, \phi_m$$

Now, for sinusoidal supply, the RMS value $E_1$ of the primary winding EMF is given by,

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_{\mathrm{m}}}{\sqrt{2}}$$

$$\therefore E_1 = 4.44 \, f\phi_m N_1 \cdots (4)$$

Similarly, the RMS value $E_2$ of the secondary winding EMF is,

$$E_2 = 4.44 \, f\phi_m N_2 \cdots (5)$$

In general,

$$E = 4.44 \, f\phi_m N \cdots (6)$$

Equation (6) is known as EMF **equation of a transformer**.

For a given transformer, if we divide the EMF equation by the supply frequency, we get,

$$\frac{E}{f} = 4.44 \, \phi_{\mathrm{m}} N = \text{Constant}$$

Which means the induced EMF per unit frequency is constant but it is not same on both primary and secondary side of the given transformer.

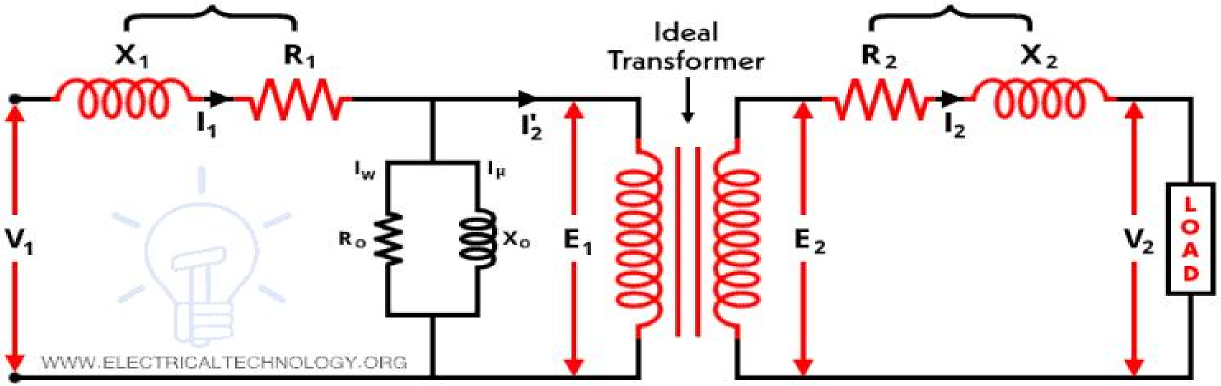
Also, from equations (4) and (5), we have,

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

Hence, in a transformer, the induced EMF per turn in the primary winding is equal to the induced EMF per turn in the secondary winding.

# Equivalent Circuit of Transformer

In the exact equivalent circuit of a transformer based on ideal transformer, we need to consider the no-load current. No-load current is a vector summation of working component $I_W$ and magnetizing component $I_\mu$. The working component of the no-load current passes through the pure resistance $R_0$ and magnetizing component passes through the pure inductance $X_0$.
We can find the exact equivalent circuit of a transformer by adding a no-load component with resistances and reactances as shown in the figure below.



Where,

- $V_1$ = Supply voltage to the primary winding
- $V_2$ = Load voltage

$$V_1 = E_1 + I_1 Z_1$$
$$E_2 = V_2 + I_2 Z_2$$

No-load resistance $R_0$ represents the iron and core losses and the working component IW supplies the core losses. No-load inductance $X_0$ represents a loss-free coil and the magnetizing component $I_\mu$ passes through $X_0$.

Now, to simplify the above equivalent circuit, transfer the resistance, reactance, voltage, and current either to the primary or secondary side.

# Equivalent Circuit Referred to Primary Side

In an equivalent circuit referred to the primary side, we will transfer all elements of the secondary side to the primary side. Secondary induced EMF $E_2$ referred to primary side;

$$E_2' = \frac{E_2}{K}$$

Secondary terminal voltage (load voltage) $V_2$ referred to the primary side;

$$V_2' = \frac{V_2}{K}$$

Secondary resistance $R_2$ referred to the primary side;

$$R_2' = \frac{R_2}{K^2}$$

Secondary reactance $X_2$ referred to the primary side;

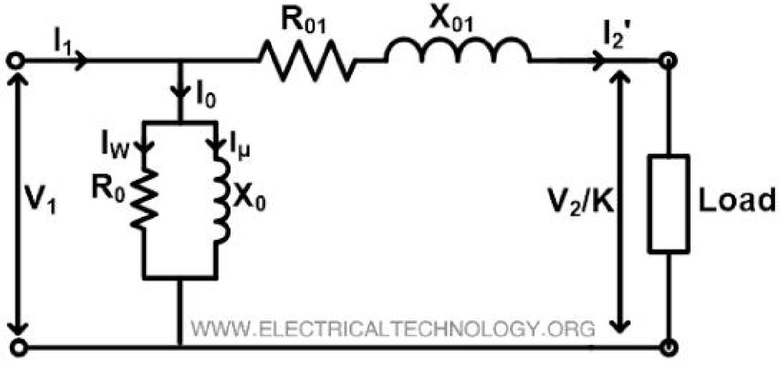
$$X_2' = \frac{X_2}{K^2}$$

Total equivalent resistance and reactance referred to primary

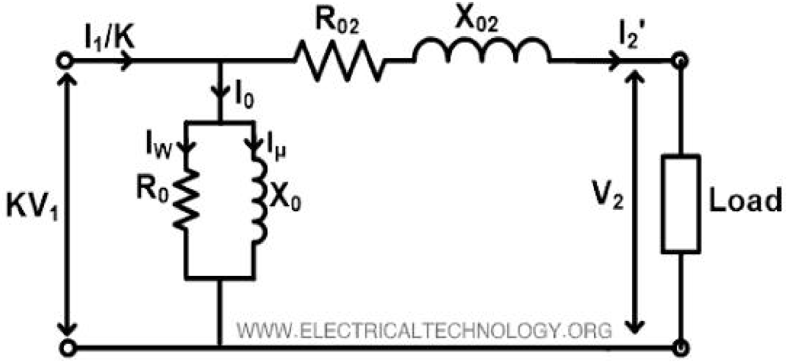
$$R_{01} = R_1 + R'_2$$

$$X_{01} = X_1 + X'_2$$

an approximate equivalent circuit of transformer referred to the primary side is as shown below




the approximate equivalent circuit referred to the secondary side circuit is shown in the figure below.




Where,

Primary resistance referred to the secondary side;

$$R'_1 = K^2 R_1$$

Primary reactance referred to the secondary side;

$$X'_1 = K^2 X_1$$

The total resistance and reactance referred to secondary $R_{02} = R'_1 + R_2$,

$$X_{02} = X'_1 + X_2$$

# Losses in transformer

Transformer consisting of the following losses

1. Iron Loss or Core Loss
2. Copper Loss or Ohmic losses

**1. Iron Loss or Core Loss:** Iron loss occurs in the magnetic core of the transformer due to flow of alternating magnetic flux through it. For this reason, the iron loss is also called core loss. We generally use the symbol (Pi) to represent the iron loss. The iron loss consists of hysteresis loss (Ph) and eddy current loss (Pe). Thus, the iron loss is given by the sum of the hysteresis loss and eddy current loss, i.e.

Iron loss, $P_1$ = Hysteresis loss (Ph) + Eddy current loss(Pe)

The hysteresis loss and eddy current loss (or iron loss) are determined by performing the open-circuit test on the transformer.

The empirical formulae for the hysteresis loss and eddy current loss are given by,

$$P_h = k_h f B_m^x \cdots (1)$$

$$P_e = ke\, B_m^2 f^2 t^2 \cdots (2)$$

Where, The exponent of Bm, i.e. "x" is called the **Steinmetzs constant**. Depending on the properties of the core material, its value is ranging from 1.5 to 2.5.

**kh** is a proportionality constant whose value depends upon the volume and quality of the material of core.

**ke** is a proportionality constant which depend on the volume and resistivity of material of the core.

**f** is the frequency of the alternating flux in the core.

**Bm** is the maximum flux density in the core.

**t** is the thickness of each core lamination.

Therefore, the total iron loss or core loss can also be written as,

$$P_i = k_h f B_m^x + ke\, B_m^2 f^2 t^2$$

## Copper Loss or ohmic Loss:

Power loss in a transformer that occurs in both the primary and secondary windings due to their Ohmic resistance is called **copper loss or loss.** We usually represent the copper loss by PC. Therefore, the total copper loss in a transformer is the sum of power loss in the primary winding and power loss in the secondary winding, i.e.,

Pc =Copper loss in primary + Copper loss in secondary

$$P_c = I_1^2 R_1 + I_2^2 R_2$$

# Transformer Efficiency:

The ratio of the output power to the input power in a transformer is known as **efficiency of transformer**.

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

For a practical transformer, the input power is given by,

$$\text{Input power} = \text{Output power} + \text{Losses}$$

Therefore, the transformer efficiency can also be calculated using the following expression

$$\eta = \frac{\text{Output power}}{\text{Output power} + \text{Losses}}$$

$$\Rightarrow \eta = \frac{\text{VA} \times \text{Power Factor}}{(\text{VA} \times \text{Power Factor}) + \text{Losses}}$$

Where,

$$\text{Output power} = \text{VA} \times \text{Power factor}$$

Therefore, the total losses at full load in a transformer are

$$\text{Total FL losses} = P_i + P_c$$

Now, we are able to determine the full-load efficiency of the transformer at any power factor without actual loading the transformer.

$$n_{FL} = \frac{(\text{VA})_{FL} \times \text{Power factor}}{[(\text{VA})_{FL} \times \text{Power factor}] + P_i + P_c}$$

Also, the transformer efficiency at any load equal to x full load. Where, x is the fraction of loading. In this case, the total losses corresponding to the given load are,

$$(\text{Total losses})_{\text{x}} = P_i + x^2 P_c$$

It is because, the iron loss ($P_i$) is the constant loss and hence remains the same at all loads, while the copper loss is proportional to the square of the load current.

$$\therefore \eta_{\text{x}} = \frac{x \times (\text{VA})_{FL} \times \text{Power factor}}{[x \times (\text{VA})_{FL} \times \text{Power factor}] + P_i + \text{x}^2 P_c}$$

# Condition for Maximum Efficiency

For a given transformer, we have,

$$\text{Output power} = V_2 I_2 cos\phi_2$$

Let the transformer referred to secondary side, then $R_{o2}$ is the total resistance of the transformer. The total copper loss is given by,

$$P_c = I_2^2 R_{o2}$$

Therefore, the transformer efficiency is given by,

$$\eta = \frac{V_2 \mathrm{I}_2 \cos\phi_2}{V_2 I_2 cos\phi_2 + P_i + I_2^2 \mathrm{R}_{o2}}$$

On rearranging the expression, we get,

$$\eta = \frac{V_2 \cos\phi_2}{V_2 cos\phi_2 + \left(\frac{P_i}{I_2}\right) + I_2 \mathrm{R}_{o2}} = \frac{V_2 cos\phi_2}{D} \cdots (1)$$

In practice, the secondary voltage $V_2$ is approximately constant. Hence, for a load of given power factor, the transformer efficiency depends upon the load current ($I_2$). From the equation (1), we can see that the numerator is constant and for the efficiency to be maximum, the denominator ($_D$) should be minimum, i.e.

$$\frac{d(D)}{dI_2} = 0$$

$$\Rightarrow \frac{d}{dI_2}\left[V_2 cos\phi_2 + \left(\frac{P_i}{I_2}\right) + I_2 R_{02}\right] = 0$$

$$\Rightarrow 0 - \left(\frac{P_i}{I_2}\right) + R_{o2} = 0$$

$$\Rightarrow P_i = I_2^2 R_{o2}$$

$$\Rightarrow \text{Iron loss} = \text{Copper loss}$$

Therefore, the transformer efficiency for a given power factor will be maximum when the constant iron loss is equal to the variable copper loss.

The maximum efficiency at any load is given by,

$$\eta_{max} = \frac{x \times (VA)_{FL} \times \text{Power factor}}{[x \times (VA)_{FL} \times \text{Power fctor}] + 2P_i}$$

# Voltage Regulation of a Transformer

The voltage regulation of a transformer can be defined as the percentage change in the secondary voltage from no-load to full load conditions, keeping the primary voltage constant. Mathematically, it is expressed as:

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

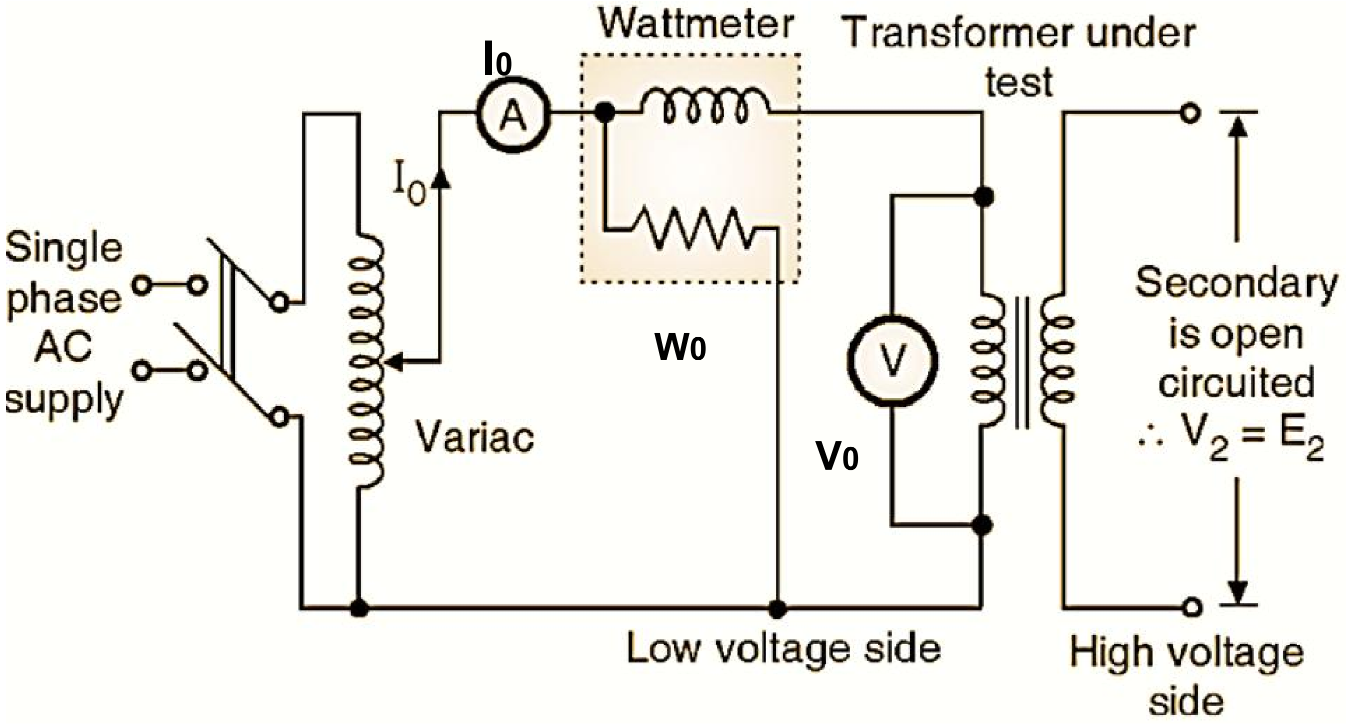
$$\%\ \text{Voltage Regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

where,
E2 – secondary terminal voltage at no load
V2 – secondary terminal voltage at full load

For inductive load $\longrightarrow$ $E_2 - V_2 = I_2 R_{02} \cos\varphi_2 + I_2 X_{02} \sin\varphi_2$

For Capacitive load $\longrightarrow$ $E_2 - V_2 = I_2 R_{02} \cos\varphi_2 - I_2 X_{02} \sin\varphi_2$

## Open circuit test on Transformer:



This test is performed so as to calculate the no load losses (core losses) of a transformer and the values of I0, R0 and X0 of the equivalent circuit. The set up for O.C. test of a transformer is shown in Fig.
An ammeter is used for measuring the no load primary current (I0) and the wattmeter is connected to measure the input power. A voltmeter is connected across the primary winding to measure the primary voltage

Hence, total iron losses = $W_0$ (Reading of Wattmeter)

From the observation of this test, the parameters $R_0$ and $X_m$ of the parallel branch of the equivalent circuit can also be calculated, following the steps given below :

Power drawn, $W_0 = V_0 I_0 \cos \varphi_0$

Thus, no load power factor, $\cos \varphi_0 = \dfrac{W_0}{V_0 I_0}$

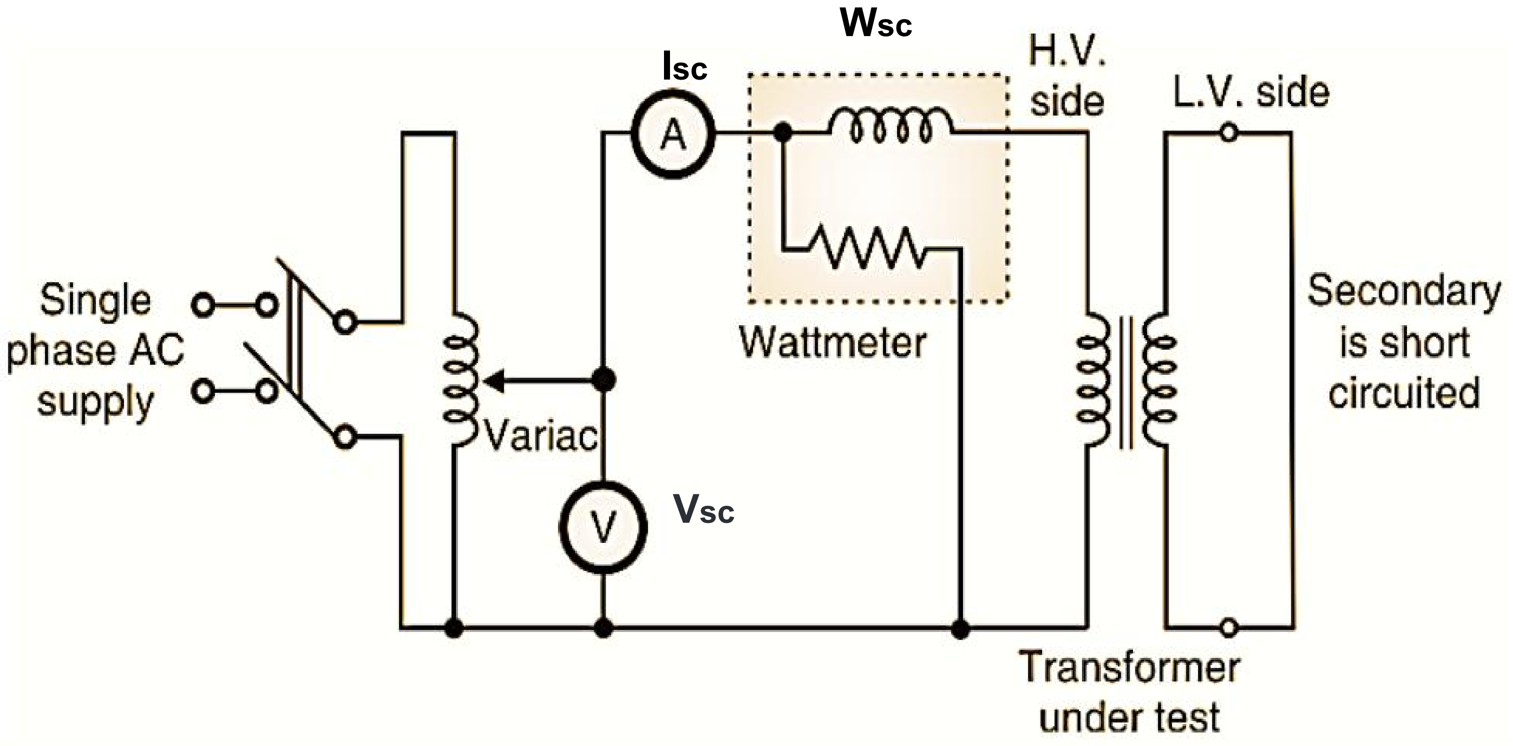
Core loss component of no load current, $I_w = I_0 \cos \varphi_0$

And, magnetising component of no load current, $I_m = I_0 \sin \varphi_0$

Equivalent resistance representing the core loss, $R_0 = \dfrac{V}{I_w}$

Magnetising reactance representing the magnetising current, $X_0 = \dfrac{V}{I_m}$

Short Circuit Test :



In this test, low voltage winding is short circuited and a low voltage hardly 5 to 8 percent of the rated voltage of the high voltage winding is applied to this winding. This test is performed at rated current flowing in both the windings. Iron losses occurring in the transformer under this condition is negligible, because of very low applied voltage. Hence the total losses occurring under short circuit test equal to copper losses.

Thus total full load copper losses = $W_{sc}$ (reading of wattmeter)

The equivalent resistance $R_{eq}$ and reactance $X_{eq}$ referred to a particular winding can also be calculated from the observation of this test, following the steps given below.

Equivalent resistance referred to H.V. winding, $R_{eq} = \dfrac{W_{sc}}{I^2_{sc}}$

Also, equivalent impedance referred to H.V. winding, $Z_{eq} = \dfrac{V_{sc}}{I_{sc}}$

Thus the equivalent reactance referred to H.V. winding $X_{eq} = \sqrt{Z^2_{eq} - R^2_{eq}}$

## Autotransformer :

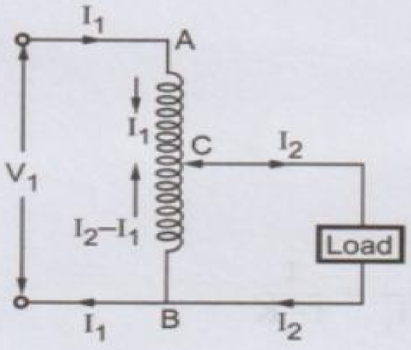
- Autotransformer usually used in the educational laboratory as well as in the testing laboratory.
- An autotransformer has one continuous winding that is common to both the primary and the secondary. Therefore, in an autotransformer, the primary and secondary windings are connected electrically.

**Autotransformer Advantages over a two-winding transformer**

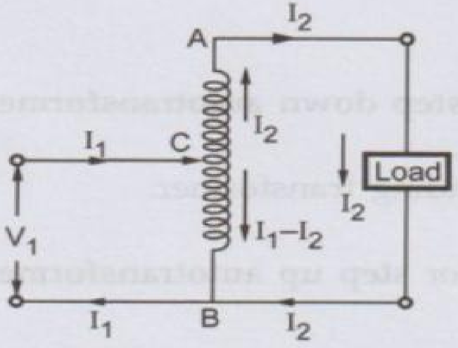
- lower initial investment
- lower leakage reactance
- lower losses compared to conventional transformer
- lower excitation current

**Types of autotransformers**

a) Step up
b) Step down




(a) Step down autotransformer




(b) Step up autotransformer

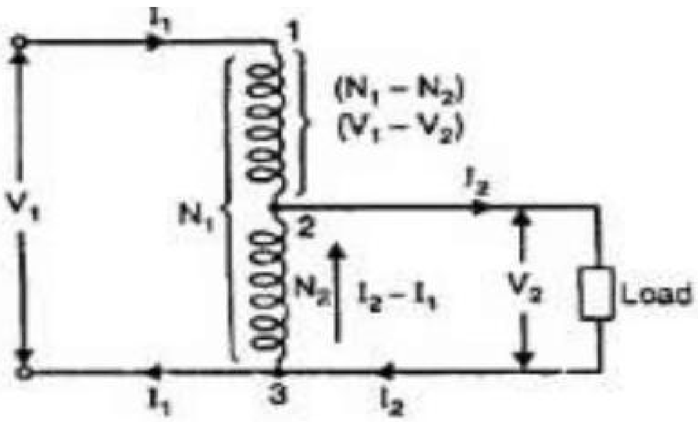
## Step Down-Transformer

A transformer in which Np>Ns is called a step down transformer. A step down transformer is a transformer which converts high alternating voltage to low alternating voltage.

## Step UP Transformer

A transformer in which Ns>Np is called a step up transformer. A step up transformer is a transformer which converts low alternate voltage to high alternate voltage.

- $N_1$=primary turn(1-3)
- $N_2$=secondary turn(2-3)
- $I_1$=primary current
- $I_2$ =secondary current
- $V_1$ =primary voltage
- $V_2$=secondary voltage



(i)

From the above fig. We get

$$\frac{V_2}{V_1 - V_2} = \frac{N_2}{N_1 - N_2}$$

$$V_2(N_1 - N_2) = N_2(V_1 - V_2)$$

$$V_2N_1 - V_2N_2 = N_2V_1 - N_2V_2$$

$$V_2N_1 = N_2V_1$$

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

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = k$$

$$V_1 I_1 = V_2 I_2$$ (That is I/P=O/P)

## Output Power

The primary and secondary windings of an auto-transformer are connected magnetically as well as electrically. So the power transferred from primary to secondary is inductively as well as conductively.

Output apparent power = $V_2 I_2$

Apparent power transferred inductively = $V_2(I_2 - I_1) = V_2(I_2 - K\,I_2)$

$= V_2 I_2 (1 - K) = V_1 I_1 (1 - K)$

Power transferred inductively = Input × (1 − K)

Power transferred conductively = Input − Input (1 − K)

= Input [1 − (1 − K)]

= K × Input

END