UNIT: III

TRANSFORMERS: Constructional details, principle of operation, Ideal and Practical single-phase transformer, losses in transformer, OC-SC tests, regulation and efficiency - simple problems.

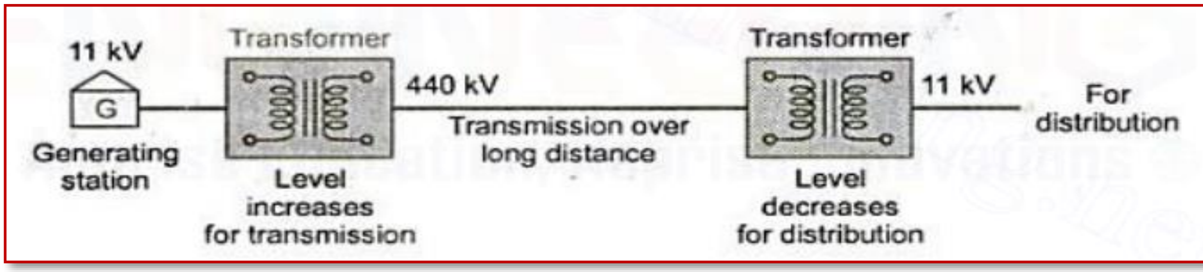


Fig: Transformer in Transmission System

3.1 Construction of a transformer:

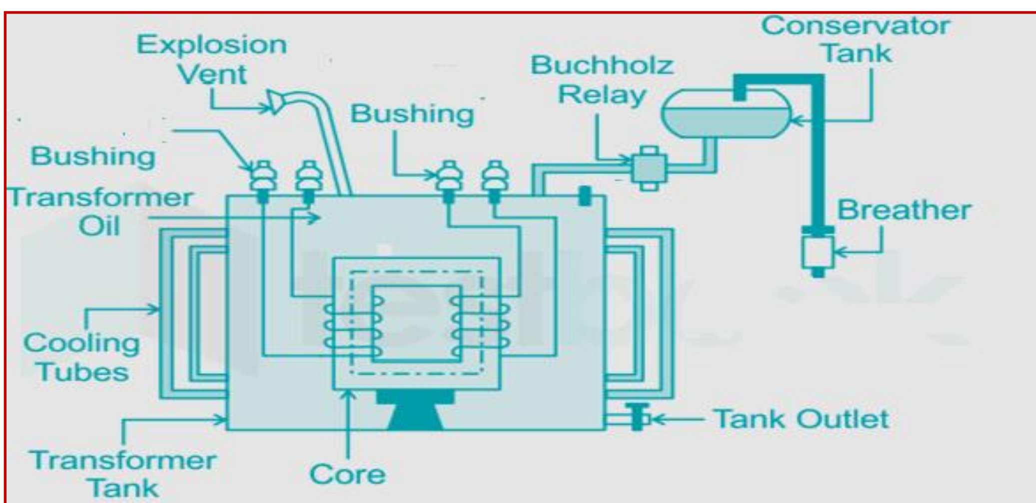
There are basic parts of a transformer:

(1) Magnetic core (2) Windings or coils

(3) Transformer Tank (4) Radiator

(5) Breather (6) Conservator Tank

(7) Bushings



Construction of Transformer

Core: The transformer core is made of silicon steel& laminations. Because of laminated type of construction, eddy current losses get minimized. These laminations are insulated from each other by using insulation like varnish.

The purpose of the core is to provide magnetic path of low reluctance between the two windings so that the total flux produced by one of the windings will be linked fully with the other winding without any leakage.

Windings: A transformer has two windings. The winding which receives electrical energy is called Primary winding and the winding which delivers electrical energy is called Secondary winding. Windings are generally made up of High- grade copper. The windings are provided with insulation so that one winding may not come in contact with the other winding. Generally, cotton, Paper and Oxide layer is used as insulating medium.

Transformer Tank: It is part which is meant to carry the transformer and the oil used in the transformer. The tank used for a transformer should be air tight so that moisture should also not enter into the tank so as to maintain the properties of the transformer oil.

Radiator fins: These are used for natural cooling.

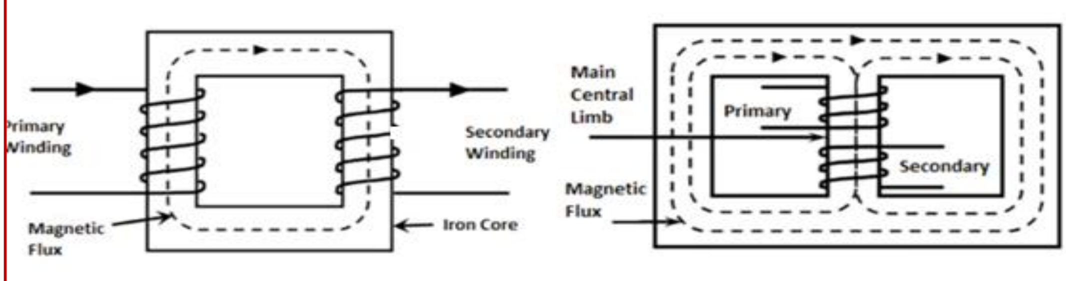
Conservator Tank: When a transformer is oil filled and self- cooled the oil in the tank is subjected to heat and thus will naturally expand and contract due to variations in the load current and is also subjected to seasonal variations. The conservator tank provides the means for the oil to settle down by expanding under heavy loads.

Breather: Transformer oil should not be exposed to atmosphere directly because it may absorb Moisture and dust from the environment and may lose its electrical properties in a very short time. To avoid this from happening a breather is provided. The breather completely prevents the moisture and dust from coming into contact with the oil in the conservator tank when it expands or contracts.

Bushings: The purpose of Bushings is to connect the RYB phases &provide proper insulation for the output leads to be taken out from the transformer tank.

3.1.1 Types of transformers:

Transformers can be classified on different basis, like types of construction(A) On the basis of construction, transformers can be classified into two types as; (i) Core type transformer and (ii) Shell type transformer, which are described below.



Core Type Transformer

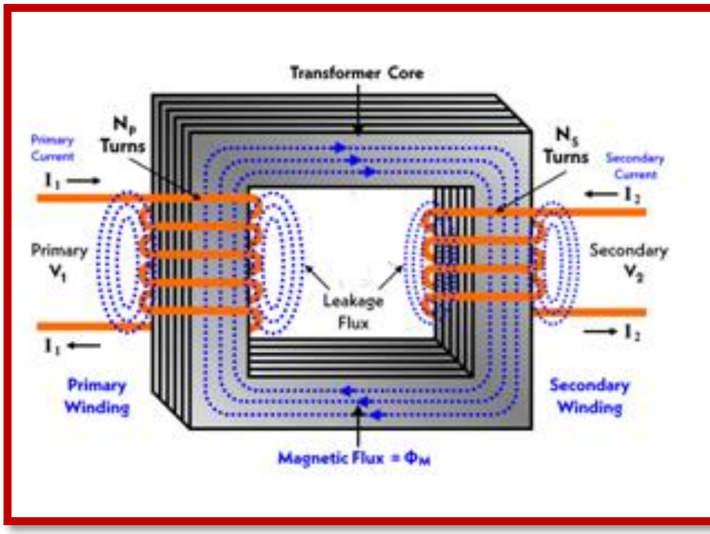
Shell Type Transformer

	Core Type	Shell Type
1.	The winding encircles the core.	The core encircles most part of the winding.
2.	It has single magnetic circuit.	It has a double magnetic circuit.
3.	The core has two limbs.	The core has three limbs.
4.	The cylindrical coils are used.	The multilayer disc or sandwich type coils are used.
5.	The windings are uniformly distributed on two limbs hence natural cooling is effective.	The natural cooling does not exist as the windings are surrounded by the core.
6.	The coils can be easily removed from maintenance point of view.	The coils can not be removed easily.
7.	Preferred for low voltage transformers.	Preferred for high voltage transformers.

3.2 Working principle of transformer:

1. Transformer works on Faraday's law of mutual induction.
2. Faraday's law of electromagnetic induction states that, when a change takes place in the magnetic flux which is linked with a circuit, an electromotive force current will induce in the circuit.
3. The transformer consists of two separate winding placed over the laminated silicon steel core.
4. The winding to which AC supply is connected is called primary winding and to which load is connected is called secondary winding.
5. It works on the alternating current only because an alternating flux is required for mutual induction between the two winding.

6. When the AC supply is given to the primary winding with a certain voltage, an alternating flux sets up in the core of the transformer, which links with the secondary winding and as a result of it, an emf is induced in it called Mutually Induced emf.
7. The direction of this induced emf is opposite to the applied voltage.



3.2.1EMF Equation of Transformer:

In a transformer, source of alternating current is applied to the primary winding. Due to this, the current in the primary winding (called as magnetizing current) produces alternating flux in the core of transformer. This alternating flux gets linked with the secondary winding, and because of the phenomenon of mutual induction an emf gets induced in the secondary winding. Magnitude of this induced emf can be found by using the following **EMF equation of the transformer**.

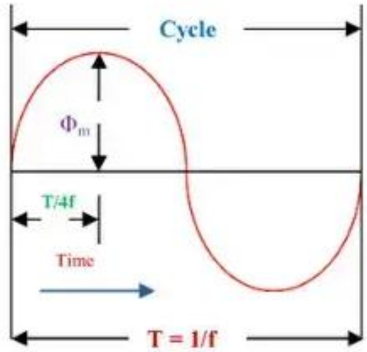
Let,

N_1 = Number of turns in primary winding

N_2 = Number of turns in secondary winding

Φ_m = Maximum flux in the core (in Wb) = (B_m x A)

f = frequency of the AC supply (in Hz)



As, shown in the fig., the flux rises sinusoidally to its maximum value Φ_m from 0. It reaches to the maximum value in one quarter of the cycle i.e. in T/4 sec (where, T is time period of the sin wave of the supply = 1/f).

Therefore,

$$Average\ rate\ of\ change\ of\ flux = \frac{\emptyset_m}{\left(\frac{T}{4}\right)} = \frac{\emptyset_m}{\left(\frac{1}{4f}\right)}$$

Therefore,

$$average\ rate\ of\ change\ of\ flux\ =\ 4f\ \Phi m\ Wb/sec$$

Now,

$$Induced\ emf\ per\ turn\ =\ rate\ of\ change\ of\ flux\ per\ turn$$

Therefore,

$$average\ emf\ per\ turn\ =\ 4f\ \Phi m\ Volts$$

Now, we know $$Form\ factor\ =\ RMS\ value\ /\ average\ value$$

Therefore, $$RMS\ value\ of\ emf\ per\ turn\ =\ Form\ factor\ X\ average\ emf\ per\ turn.$$

As, the flux Φ varies sinusoidally, form factor of a sine wave is 1.11

Therefore, $$RMS\ value\ of\ emf\ per\ turn\ =\ 1.11\ x\ 4f\ \Phi m\ =\ 4.44f\ \Phi m.$$

RMS value of induced emf in whole primary winding (E_1) = RMS value of emf per turn X Number of turns in primary winding

$$\boxed{E1\ =\ 4.44f\ N1\ \Phi m\ - - - - - (1)}$$

Similarly, RMS value of induced emf in secondary winding (E_2) can be given as

$$E2 = 4.44f\ N2\ \Phi m - - - - - (2)$$

Equation 1&2 are called the **emf equation of transformer**, which shows, emf / number of turns are same for both primary and secondary windings.

For an ideal transformer on no load, $E_1 = V_1$ and $E_2 = V_2$.
where, V_1 = supply voltage of primary winding
V_2 = terminal voltage of secondary winding

3.2.2 Voltage Transformation Ratio (K)

As derived above,

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

Where, K = constant
This constant K is known as **voltage transformation ratio**.

- If $N_2 > N_1$, i.e. $K > 1$, then the transformer is called step-up transformer.
- If $N_2 < N_1$, i.e. $K < 1$, then the transformer is called step-down transformer.

3.3 Ideal & Practical Transformer:

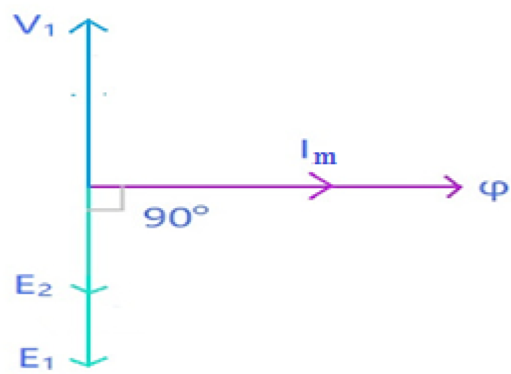
Ideal Transformer:

An ideal transformer is an imaginary transformer which has:

a) **Zero Winding Resistance:** Resistance of both primary and secondary winding is 0 i.e. both the coils are purely inductive in nature.
b) **100% Efficiency:** There are no losses in ideal transformer so the input power = output power
c) **No leakage flux:** The whole amount of flux is linked from primary to secondary winding, so there is no leakage flux.
d) **No losses:** As the iron core is subjected to alternating flux there occurs eddy current and hysteresis loss in it. These two losses together are called Iron loss. It is 0 in ideal transformer.

3.3.1 Ideal Transformer on No Load:

When an alternating voltage V_1 is supplied to the primary winding of an ideal transformer, counter emf E_1 is induced in the primary winding. Since there is no resistance, this induced emf E_1 will be exactly equal to the applied voltage but in 180 degrees opposite in phase. The current drawn from the source produces required magnetic flux. As the primary winding resistance is 0, the current lags emf E_1 by 90 degrees. This is current is called Magnetizing current I_μ. These magnetizing current produces alternating magnetic flux φ. This flux gets linked with the secondary winding and emf E_2 is induced by mutual induction. This E_2 is in phase with E_1. If the circuit is closed at secondary winding, then secondary current I_2 is produced.

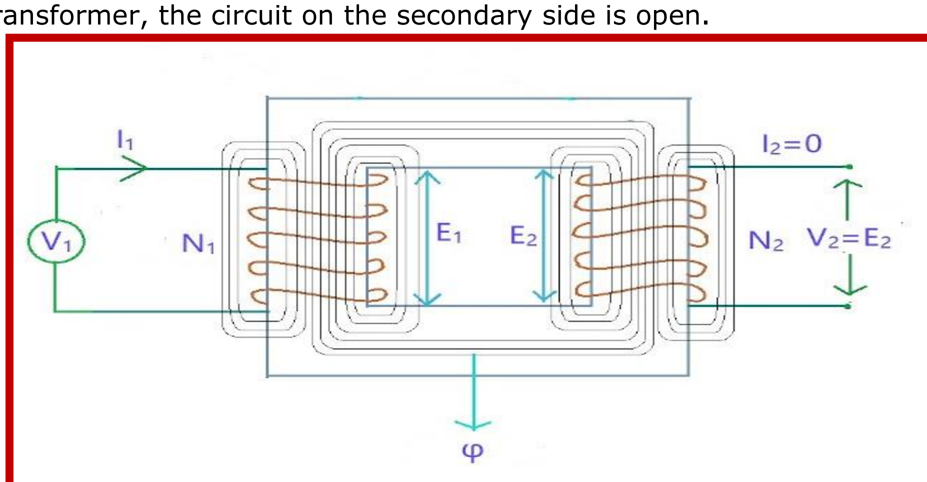


3.3.2 Practical Transformer:

In practical transformer, we have two cases:
(a) No load
(b) On load

Practical Transformer on No Load:

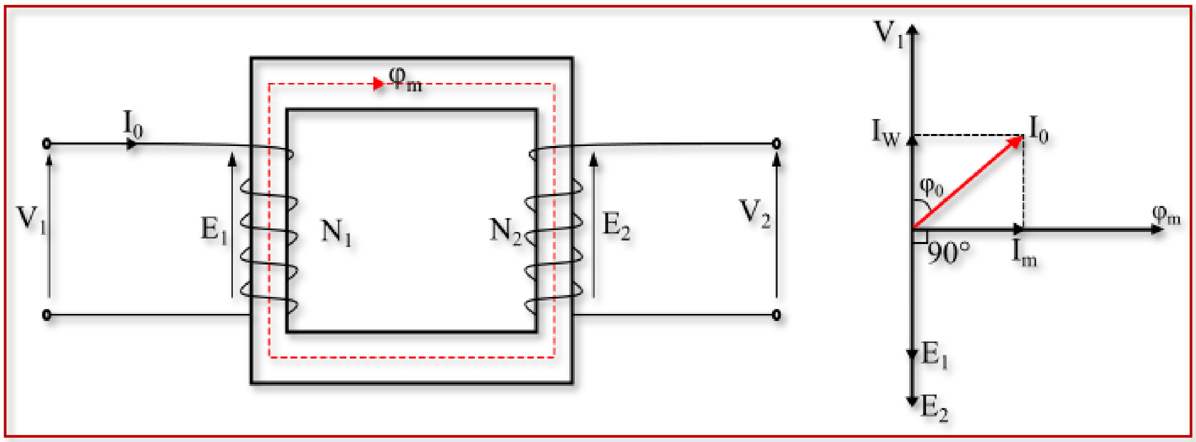
In no load transformer, the circuit on the secondary side is open.



A transformer is said to be operated in no-load condition if no electrical load is connected across its secondary winding terminals. In other words, when the secondary winding of a transformer remains open-circuited and no current flows through it, then the transformer is said to be in no-load condition.

When a transformer operates in no-load condition, no current flows in the secondary winding, but a small current called no-load current (I_0) which is around 2% to 10% of the rated current flows in the primary winding.

This no-load current I_0 magnetizes the core of the transformer and results in some core losses (i.e., iron losses and copper losses).



we can express the no-load current of the transformer as the phasor sum of the magnetizing component and the power component i.e.,

$$\boxed{I_0 = \sqrt{I_m^2 + I_w^2}}$$

Operation of Transformer on No-Load:

Here is the operation of a transformer in no-load condition:

- Firstly, the input voltage V_1 is applied across the primary winding of the transformer. It magnetizes the core of the transformer by setting up a magnetic flux (ϕ) in it.
- This magnetic flux induces EMFs in the primary and secondary windings due to electromagnetic induction. These induced EMFs lag the applied voltage by an angle of 90°. Here, we are neglecting the primary winding copper loss and the secondary winding copper loss is zero because I_2=0.

- The no-load current I_0 lags behind the supply voltage V1 by an angle of ϕ_0 which is called the no-load power factor angle.
- It is also important to note that the EMF E_1 induced in the primary winding is equal to the supply voltage V_1.
- There are also some losses in the primary winding (copper loss) and the core (iron losses) of the transformer which are represented by the active component (I_w) of the no-load current. This component is equivalent to the resistive effect and hence remains in-phase with the supply voltage (V_1).
- This is how an electrical transformer operates under no-load conditions.

This complete operation of the transformer on no-load can be illustrated with the help of a phasor diagram which is shown in the following figure.

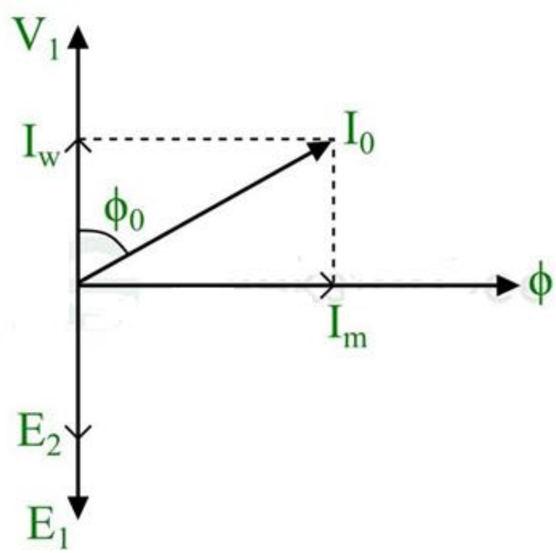


Fig: Phasor Diagram of Transformer on No-Load

Phasor Diagram Explanation:

- The induced EMF (E_1 and E_2) are out of phase with respect to the supply voltage (V_1) and lags the magnetic flux by 90°.
- The reactive component Im lags the supply voltage V_1 by 90°.
- The active component Iw is in-phase with the supply voltage (V_1).
- The no-load current I_0 lags the supply voltage V_1 by an angle φ_0 which is the no-load power factor angle of the transformer.

From this phasor diagram, we can derive the important relations of different electrical parameters of the transformer. They are,

(1). The magnitude of no-load current:

$$\boxed{I_0^2 = I_m^2 + I_w^2}$$

(2). The magnetizing component of no-load current:

$$\boxed{I_m = I_0 \sin\phi_0}$$

(3). The active component of no-load current:

$$\boxed{I_w = I_0 \cos\phi_0}$$

(4). The no-load power factor:

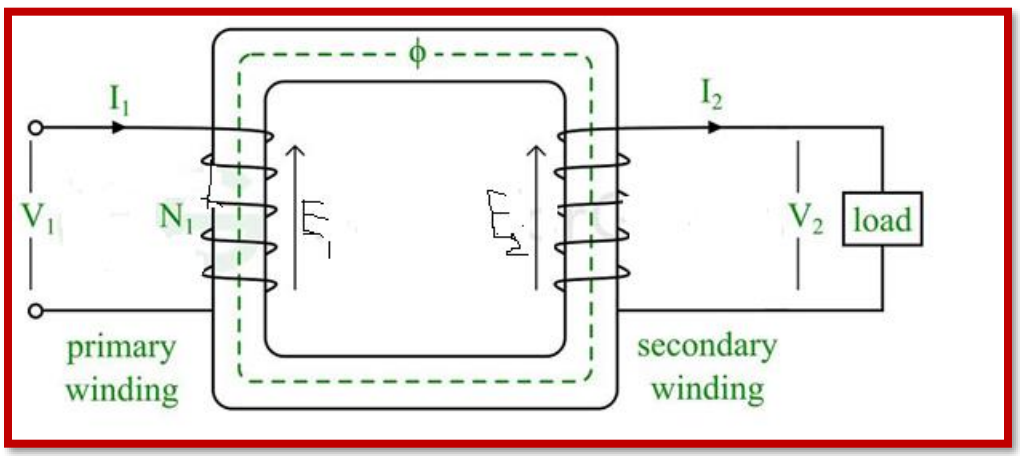
$$\boxed{\cos\phi_0 = I_w / I_0}$$

(5). The power consumed under no-load:

$$\boxed{P_0 = V_1 I_0 \cos\phi_0;\ \cos\phi_0 = P_0 / V_1 I_0}$$

3.3.3 Practical Transformer on Load:

A transformer is said to be on load condition if an electrical load is connected to its secondary winding and a current circulates in the secondary winding circuit. The load connected across the secondary winding can be a resistive load or an inductive load or a capacitive load or a combination of the three. Therefore, the magnitude of the secondary winding current also called load current depends on the load impedance and secondary voltage (V2). Also, the phase angle between the secondary voltage and load current depends on the type of the load. For example, if the load is of inductive nature, the load current will lag the secondary voltage.



Operation of Transformer on Load:

Here is the operation of an electrical transformer operation under loaded condition:

- An electrical input supply voltage V_1 is connected across the primary winding. Due to the application of this voltage an electric current I_1 will starting flowing in the primary winding and sets up a magnetic flux in the core as shown in the above figure.
- This magnetic flux follows a path through the core and links to the secondary winding.
- An EMF E_2 is induced in the secondary winding that developes a voltage V_2 across its terminals.
- When a load is connected between the secondary winding terminals, a current will flow in the secondary winding and load circuit which is denoted by I2.
- The secondary winding current also induces a counter magnetic flux that reduces the main flux in the core. But the main flux must be maintained at a constant value for operation of the transformer.
- Thus, an additional current is taken by the primary winding from the supply to cancel out the demagnetizing effect of secondary winding current. This is represented by I'_1 which is in-phase with the secondary winding current (I_2). Thus, the total current flowing in the primary winding under loaded condition of the transformer is I'_1.

Therefore, if N1 and N2 are the primary and secondary winding turns and I'_1 and I_2 are the primary and secondary currents.

Also, the total primary winding current (I1) has two main components namely,

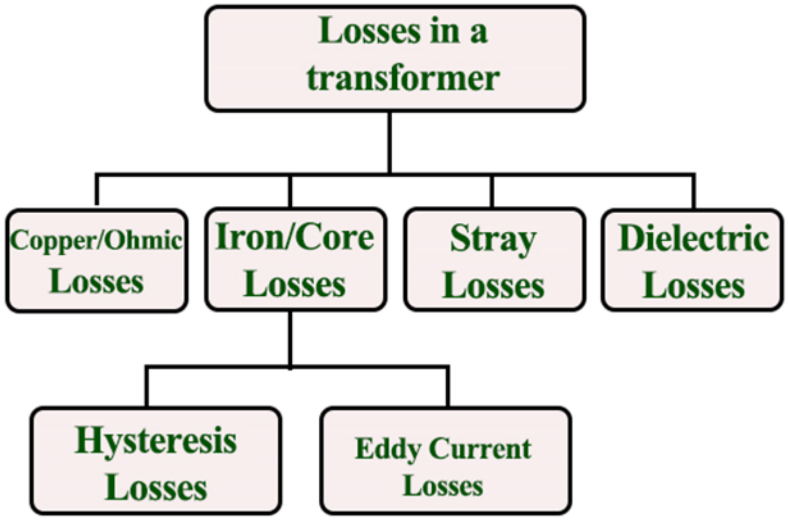
- **No-load component** – to set up main magnetic flux in the core and supply the losses.
- **Counter balancing component** – to overcome the effect of secondary winding current.

Thus, the total primary winding current of the transformer on load condition is given by,

$$\boxed{I_1 = I_0 + I'_1}$$

In practice, the transformers mostly have inductive loads. So, let's assume the load connected across the secondary of the transformer and draw the phasor diagram of it on load condition.

3.4 Losses in a Transformer:



3.4.1 Types of losses in transformers:

There are different kinds of losses that will be occurred in the transformer i.e.

1. Core Losses or Iron Losses:

Eddy current loss and hysteresis loss depend on the magnetic properties of the material used for the construction of the core. So, these losses are also known as core losses or iron losses.

- **Hysteresis loss in transformer:** The reason is the reversal of magnetization in the transformer core. This loss depends on the volume and grade of the iron, frequency of magnetic reversals and value of flux density. We have the Steinmetz formula:

$$\boxed{W_h = \eta B_{max}^{1.6} f V \text{ (watts)}}$$

Where, η = Steinmetz hysteresis constant

V = volume of the core in m^3

- **Eddy current loss in transformer:** The AC current is supplied to the primary winding which sets up alternating magnetizing flux in the transformer. When this flux flow to a secondary winding, it produces induced emf in it. But some part of this flux also gets linked with other conducting parts such as steel core or iron body or the transformer, which will result in induced emf in those parts, causing small circulating current in them. This current is called as eddy current. Due to the current, some energy will be dissipated in the form of heat.

$$\boxed{W_e = K_e B_m^2 f^2 t^2 V \text{ Watts}}$$

$Where \quad K_e = Eddy\ current\ constant$

$B_m = Maximum\ flux\ density$

$f = supply\ frequecy$

$t = thickness\ of\ the\ laminatin$

$V = volume\ of\ the\ core$

2. Copper Loss:

The ohmic resistance of the transformer windings creates copper loss. The copper loss for the primary winding is $I_1^2 R_1$ and for the secondary winding is $I_2^2 R_2$. Where, I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively. We can see that Cu loss is proportional to square of the current, and current depends on the load. So that copper loss in transformer varies with the load.

3.5 Efficiency of Transformer:

The efficiency of a transformer can be defined as the output power divided by the input power.

$$\boxed{Efficiency = \frac{output}{input}}$$

In electrical devices, transformers are the most highly efficient ones. It is due to the fact that most of the transformers have full load efficiency between 95% to 98.5%.

As a transformer being highly efficient, the output value is equivalent to input value, and hence it is impractical to measure the efficiency of the transformer by using output/input.

O/P =I/P-Losses **I/P =O/P +Losses**

3.5.1 VoltageRegulation of Transformer:

When a transformer is loaded, with a constant supply voltage, the terminal voltage changes due to voltage drop in the internal parameters of the transformer i.e., primary and secondary resistances and inductive reactance. The voltage drop at the terminals also depends upon the load and its power factor. The change in terminal voltage from no-load to full-load at constant supply voltage with respect to no-load voltage is known as voltage regulation of the transformer.

Let, E2 = Secondary terminal voltage at no-load.

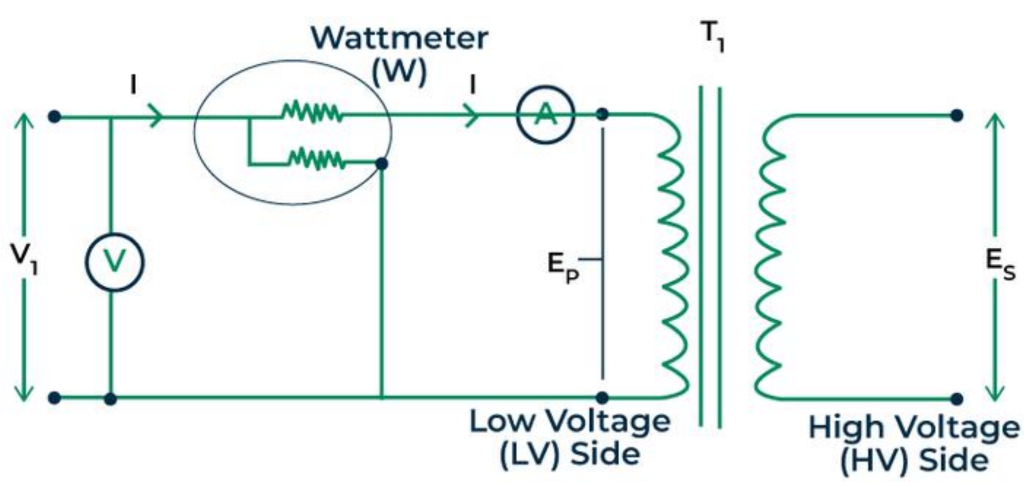
V2 = Secondary terminal voltage at full-load.

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

3.6 Testing of Transformer:

3.6.1 Open Circuit Test of Transformer:

It is a method in electrical engineering used to determine the iron or core loss and it determines the exciting current of the transformer when it operates at rated voltage. The circuit diagram of this is shown below. In this, the secondary winding or the high voltage side is left open and the low voltage side is used to perform the test completely. Using this test we calculate no-load circuit parameters(X_0, R_0) and iron loss.



In the circuit diagram, the voltmeter(V), ammeter (A) and wattmeter(W) were all connected on the low-voltage side of the transformer, which is supplied at rated voltage(V1). The secondary winding side is left open, so which a small amount of current(I_0) is flowing in primary winding. Here, I0 is called as no – load current. The reading of the wattmeter gives the iron loss.

Calculation of open-circuit test:

Let,

- W_0 – wattmeter reading
- V_1 – voltmeter reading
- I_0 – ammeter reading

Then the iron loss of the transformer $P_i = W_0$ and

$$\boxed{W_0 = V_1 I_0 \cos \emptyset_0}$$

The no-load power factor is

$$\boxed{\cos \emptyset_0 = \frac{W_0}{V_1 I_{0_1}}}$$

Working component I_w is

$$\boxed{I_W = \frac{W_0}{V_1}}$$

Putting the value of W_0 from the equation (1) in equation (2) you will get the value of the working component as

$$\boxed{I_W = I_0 \cos \emptyset_0}$$

Magnetizing component is

$$\boxed{I_m = \sqrt{I_0{}^2 - I_W{}^2}}$$

No-load parameters are given below:

Equivalent exciting resistance is

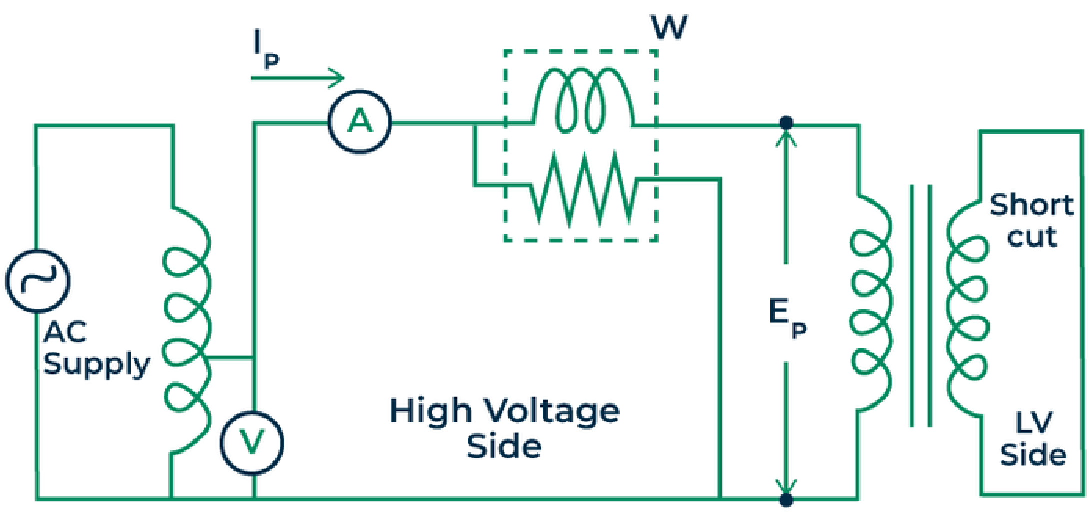
$$\boxed{R_0 = \frac{V_1}{I_W}}$$

Equivalent exciting reactance is

$$\boxed{X_0 = \frac{V_1}{I_W}}$$

3.6.2 Short Circuit Test of Transformer:

It is a method in electrical engineering used to determine the copper or winding loss and also it determines the impedance of the transformer. The circuit diagram of this is shown below. In this, the secondary winding (low voltage side is shorted by a thick conductor) and on primary side (high voltage side) Ammeter(A), Voltmeter(V) and wattmeter(W) are connected.



so, generally short circuit test is performed on high winding side and short circuited on low winding side. It will read copper losses because of high current passing through windings

Calculation of Short Circuit Test: Let

- W_c – Wattmeter reading
- V_{2sc} – voltmeter reading
- I_{2sc} – ammeter reading

Then the full load copper loss of the transformer is given by

$$\boxed{P_C = \left(\frac{I_{2fl}}{I_{2sc}}\right)^2 W_C \text{ and } {I_{2sc}}^2 R_{sc} = W_C}$$

Equivalent resistance referred to the secondary side is

$$\boxed{R_{sc} = \frac{W_C}{{I_{2sc}}^2}}$$

Equivalent impedance referred to the secondary side is given by

$$\boxed{Z_{sc} = \frac{V_{2sc}}{I_{2sc}}}$$

The equivalent reactance referred to the secondary side is given by

$$\boxed{X_{sc} = \sqrt{(Z_{sc})^2 - (R_{sc})^2}}$$

In the short circuit test the wattmeter record, the total losses, including core loss but the value of core loss are very small as compared to copper loss so the core loss can be neglected.