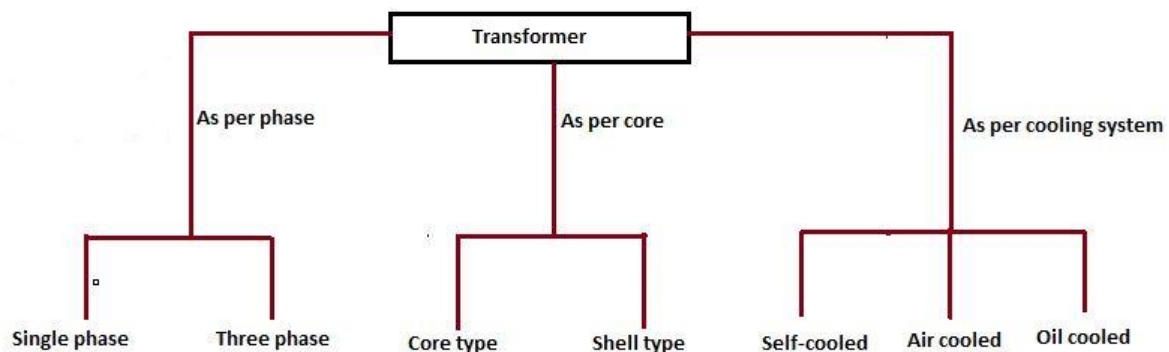# Unit #3_Transformer

INTRODUCTION

- ➢ A TRANSFORMER is a device that transfers electrical energy from one circuit to another by electromagnetic induction (transformer action).
- ➢ The electrical energy is always transferred without a change in frequency, but may involve changes in magnitudes of voltage and current.
- ➢ Transformer works on the principle of electromagnetic induction, it must be used with an input source voltage that varies in amplitude.

Types of Transformer:

Transformers are used in various fields like power generation grid, distribution sector, transmission and electric energy consumption. There are various types of transformers which are classified based on the following factors;

- Working voltage range.
- The medium used in the core.
- Winding arrangement.
- Installation location.

Types of Transformer

Based on Voltage Levels

Commonly used transformer type, depending upon voltage they are classified as:

- **Step-up Transformer:** They are used between the power generator and the power grid. The secondary output voltage is higher than the input voltage.
- **Step down Transformer:** These transformers are used to convert high voltage primary supply to low voltage secondary output.

Based on the Medium of Core Used

In a transformer, we will find different types of cores that are used.

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- **Air core Transformer:** The flux linkage between primary and secondary winding is through the air. The coil or windings wound on the non-magnetic strip.
- **Iron core Transformer:** Windings are wound on multiple iron plates stacked together, which provides a perfect linkage path to generate flux.

Based on the Winding Arrangement

- **Autotransformer:** It will have only one winding wound over a laminated core. The primary and secondary share the same coil.

Based on Install Location

- **Power Transformer:** It is used at power generation stations as they are suitable for high voltage application
- **Distribution Transformer:** Mostly used at distribution lanes in domestic purposes. They are designed for carrying low voltages. It is very easy to install and characterized by low magnetic losses.
- **Measurement Transformers:** These are further classified. They are mainly used for measuring voltage, current, power.
- **Protection Transformers:** They are used for component protection purposes. In circuits some components must be protected from voltage fluctuation etc. protection transformers ensure component protection.

The major parts of a single-phase transformer:

1. Core

The core acts as a support to the winding in the transformer. It also provides a low reluctance path to the flow of magnetic flux. The winding is wound on the core as shown in the picture. It is made up of a laminated soft iron core in order to reduce the losses in a transformer. The factors such as operating voltage, current, power etc decide core composition. The core diameter is directly proportional to copper losses and inversely proportional to iron losses.

2. Windings

Windings are the set of copper wires wound over the transformer core. Copper wires are used due to:

- ➢ High conductivity of copper. This minimizes the loss in a transformer. since conductivity increases, resistance to current flow decreases.

- ➢ High ductility of copper. Ductility is the property of metals that they can be made into very thin wires.

There are mainly two types of windings. Primary windings and secondary windings.

- ➢ Primary winding: The set of turns of windings to which supply current is feed.
- ➢ Secondary winding: the set of turns of winding from which output is taken.

The primary and secondary windings are insulated from each other using insulation coating agents.

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3. Insulation Agents

Insulation is necessary for transformers to separate windings from shorting the circuit and thus facilitating the mutual induction. Insulation agents have influence in durability and the stability of a transformer.

Following are used as an insulation medium in a transformer:

➢ Insulating oil
➢ Insulating tape
➢ Insulating paper
➢ Wood-based lamination

Working Principle of a Transformer:

BASIC WORKING PRINCIPLE OF TRANSFORMER A transformer can be defined as a static device which helps in the transformation of electric power in one circuit to electric power of the same frequency in another circuit. The voltage can be raised or lowered in a circuit, but with a proportional increase or decrease in the current ratings. The main principle of operation of a transformer is mutual inductance between two circuits which is linked by a common magnetic flux. A basic transformer consists of two coils that are electrically separate and inductive, but are magnetically linked through a path of reluctance. The working principle of the transformer can be understood from the figure below.
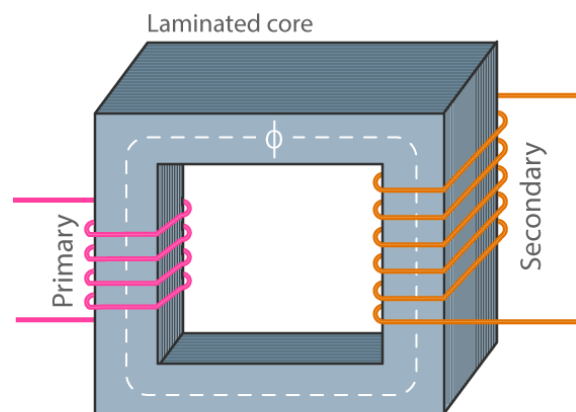

As shown above the transformer has primary and secondary windings. The core laminations are joined in the form of strips in between the strips you can see that there are some narrow gaps right through the cross-section of the core. These staggered joints are said to be 'imbricated'. Both the coils have high mutual inductance. A mutual electro-motive force is induced in the transformer from the alternating flux that is set up in the laminated core, due to the coil that is connected to a source of alternating voltage. Most of the alternating flux developed by this coil is linked with the other coil and thus produces the mutual induced electromotive force. The so produced electro-motive force can be explained with the help of Faraday's laws of Electromagnetic Induction as e=M*dI/dt If the second coil circuit is closed, a current flows in it and thus electrical energy is transferred magnetically from the first to the second coil.

The alternating current supply is given to the first coil and hence it can be called as the primary winding. The energy is drawn out from the second coil and thus can be called as the secondary winding.

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In short, a transformer carries the operations shown below:

➢ Transfer of electric power from one circuit to another.
➢ Transfer of electric power without any change in frequency.
➢ Transfer with the principle of electromagnetic induction.
➢ The two electrical circuits are linked by mutual induction.

:
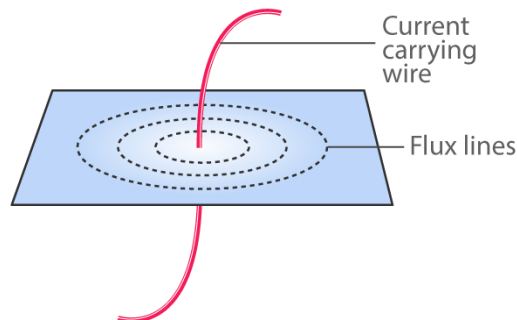
The figure shows the formation of <u>magnetic flux</u> lines around a current-carrying wire. The normal of the plane containing the flux lines are parallel to normal of a cross-section of a wire.
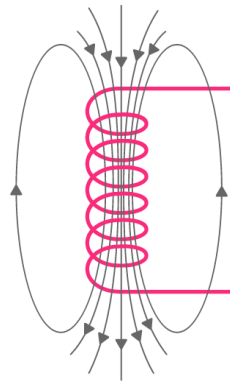
The figure shows the formation of varying magnetic flux lines around a wire-wound. The interesting part is that reverse is also true, when a magnetic flux line fluctuates around a piece of wire, a current will be induced in it.

Ideal Transformer

The ideal transformer has no loses that means there is no magnetic leakage and ohmic resistance in its windings. There won't be any core losses or I^2R.

The current passing through the primary coil creates a magnetic field. The primary and secondary coils are wrapped around a core of very high magnetic permeability, such as iron, so that most of the magnetic flux passes through both the primary and secondary coils.

EMF Equation of Transformer:

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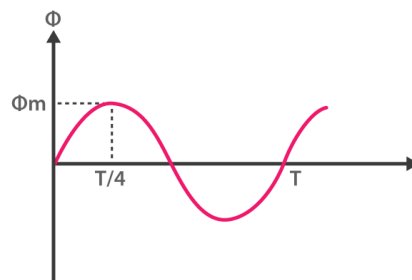
N_1 – number of turns in primary.

N_2 – number of turns in secondary.

Φ_m – maximum flux in weber (Wb).

T – time period. Time is taken for 1 cycle.

The flux formed is a sinusoidal wave. It rises to a maximum value Φ_m and decreases to negative maximum Φ_m. So, flux reaches a maximum in one-quarter of a cycle. The time taken is equal to T/4.

Average rate of change of flux = $\Phi_m/(T/4) = 4*f\Phi_m$

Where f = frequency

T = 1/f

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

Form factor = RMS value / average value

RMS value = 1.11 * $(4*f\Phi_m)$ = 4.44 fΦ_m [form factor of sine wave is 1.11]

RMS value of emf induced in winding = RMS value of emf per turn * no of turns

Primary Winding

RMS value of induced EMF = E_1 = 4.44 fΦ_m * N_1

Secondary winding:

RMS value of induced EMF = E_2 = 4.44 fΦ_m * N_2

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44f\ \Phi m$$

This is the emf equation of the transformer.

For an ideal transformer at no load condition,

E_1 = supply voltage on the primary winding.

E_2 = terminal voltage (theoretical or calculated) on the secondary winding.

Voltage Transformation Ratio

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

K is called the voltage transformation ratio, which is a constant.

Case1: if $N_2 > N_1$, K>1 it is called a step-up transformer.

Case 2: if $N_2 < N_1$, K<1 it is called a step-down transformer.

Applications of Transformer

- The transformer transmits electrical energy through wires over long distances.
- Transformers with multiple secondary's are used in radio and TV receivers which require several different voltages.

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- Transformers are used as voltage regulators.

Voltage Transformation Ratio.

The ratio of secondary voltage to primary voltage is known as the voltage transformation ratio and is designated by letter K. i.e. Voltage transformation ratio,

K = V2/V1 = E2/E1 = N2/N1

Current Ratio.

The ratio of secondary current to primary current is known as current ratio and is reciprocal of voltage transformation ratio.

Transformer on No Load Condition

When the primary of a transformer is connected to the source of an ac supply and the secondary is open circuited, which means there is no load on the secondary side of the transformer and, therefore, current in the secondary will be zero. While primary winding carries a small current I_0 called no-load current which is **2 to 10% of the rated current**.

This current is responsible for supplying the iron losses (hysteresis and eddy current losses) in the core and a very small amount of copper losses in the primary winding. The angle of lag depends upon the losses in the transformer. The power factor is very low and varies from **0.1 to 0.15**.
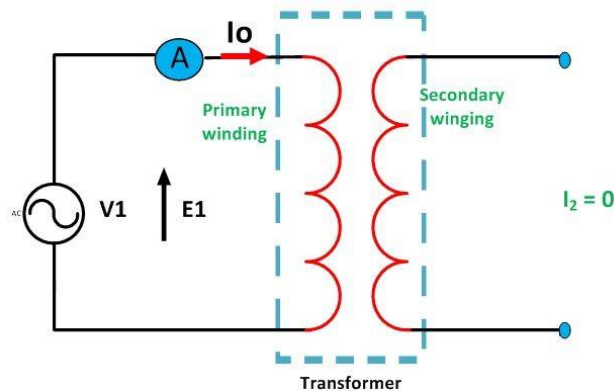

The no-load current consists of two components:

- **Reactive or magnetizing component I_m** (It is in quadrature with the applied voltage V_1. It produces flux in the core and does not consume any power).

- **Active or power component I_w,** also know as a working component (It is in phase with the applied voltage V_1. It supplies the iron losses and a small amount of primary copper loss).

The following steps are given below to draw the phasor diagram:

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1. The function of the magnetizing component is to produce the magnetizing flux, and thus, it will be in phase with the flux.
2. Induced emf in the primary and the secondary winding lags the flux ϕ by 90 degrees.
3. The primary copper loss is neglected, and secondary current losses are zero as $I_2 = 0$.
   Therefore, the current I_0 lags behind the voltage vector V_1 by an angle ϕ_0 called the no-load power factor angle and is shown in the phasor diagram above.
4. The applied voltage V_1 is drawn equal and opposite to the induced emf E_1 because the difference between the two, at no load, is negligible.
5. Active component I_w is drawn in phase with the applied voltage V_1.
6. The phasor sum of magnetizing current I_m and the working current I_w gives the no-load current I_0.
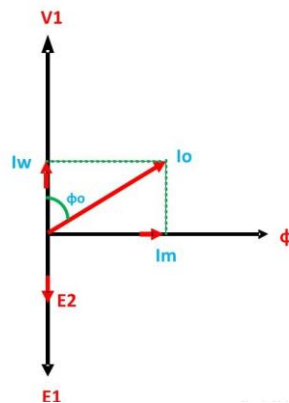
From the phasor diagram drawn above, the following conclusions are made

$$\text{Working component} \quad I_w = I_0 \cos\varphi_0$$

$$\text{No load current} \quad I_0 = \sqrt{I_w^2 + I_m^2}$$

$$\text{Magnetizing component} \quad I_m = I_0 \sin\varphi_0$$

$$\text{Power factor } \cos\varphi_0 = \frac{I_w}{I_0}$$

$$\text{No load power input} \quad P_0 = V_1 I_0 \cos\varphi_0$$

Equivalent Circuit of a Transformer

The equivalent circuit diagram of any device can be quite helpful in the pre-determination of the behavior of the device under the various condition of operation. It is simply the circuit representation of the equation describing the performance of the device.

The simplified equivalent circuit of a transformer is drawn by representing all the parameters of the transformer either on the secondary side or on the primary side. The equivalent circuit diagram of the transformer is shown below:

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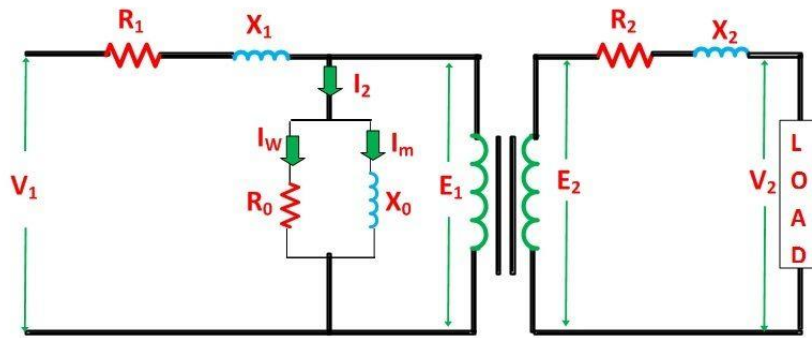
Let the equivalent circuit of a transformer having the transformation ratio $K = E_2/E_1$

The induced emf E_1 is equal to the primary applied voltage V_1 less primary voltage drop. This voltage causes current I_0 no-load current in the primary winding of the transformer. The value of no-load current is very small, and thus, it is neglected.

Hence, $I_1 = I_1'$. The no-load current is further divided into two components called **magnetizing current** (I_m) and **working current** (I_w).

These two components of no-load current are due to the current drawn by a non-inductive resistance R_0 and pure reactance X_0 having voltage E_1 or (V_1 – primary voltage drop).

The secondary current I_2 is

$$I_2 = \frac{I_1'}{K} = \frac{I_1 - I_0}{K}$$

The terminal voltage V_2 across the load is equal to the induced emf E_2 in the secondary winding less voltage drop in the secondary winding.

Equivalent Circuit when all the quantities are referred to Primary side

In this case, to draw the equivalent circuit of the transformer all the quantities are to be referred to the primary as shown in the figure below:

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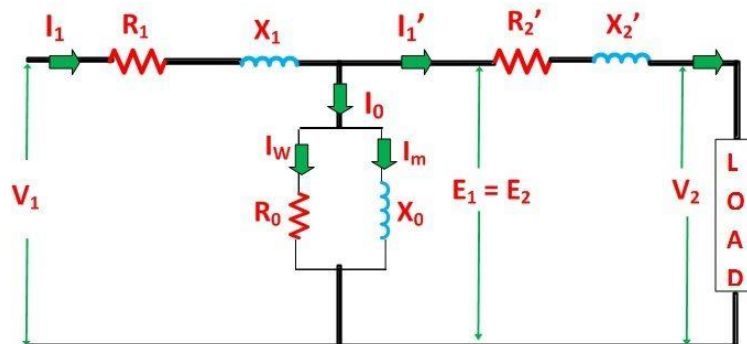
Circuit Diagram of Transformer when all the Secondary Quantities are Referred to Primary Side

The following are the values of resistance and reactance given below

Secondary resistance referred to the primary side is given as:

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

The equivalent resistance referred to the primary side is given as:

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

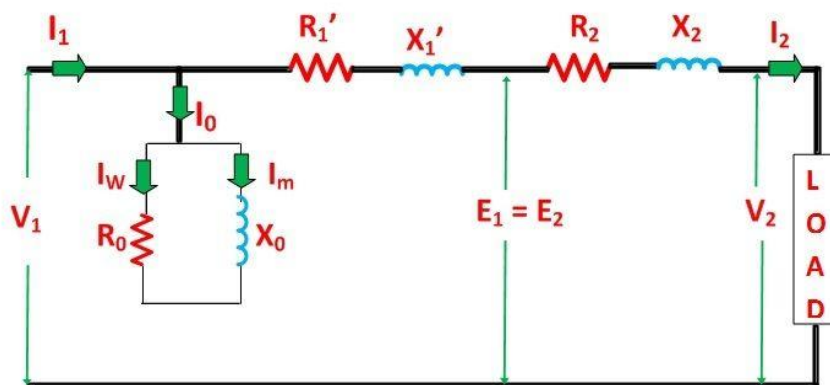Secondary reactance referred to the primary side is given as:

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

The equivalent reactance referred to the primary side is given as:

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

Equivalent Circuit when all the quantities are referred to Secondary side

The equivalent circuit diagram of the transformer is shown below when all the quantities are referred to the secondary side.

Circuit Diagram of Transformer When All the Primary Quantities are Referred to Secondary Side

The following are the values of resistance and reactance given below

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Primary resistance referred to the secondary side is given as

$$R_1' = K^2 R_1$$

The equivalent resistance referred to the secondary side is given as

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

Primary reactance referred to the secondary side is given as

$$X_1' = K^2 X_1$$

The equivalent reactance referred to the secondary side is given as
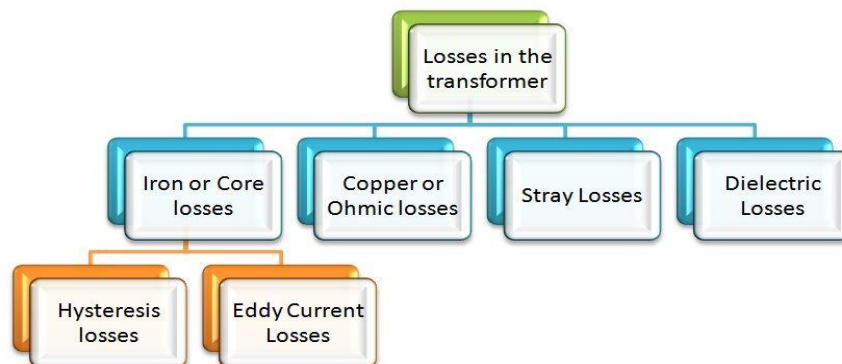
$$X_{eq} = X_2 + X_I'$$

No-load current I_0 is hardly **3 to 5%** of full load rated current, the parallel branch consisting of resistance R_0 and reactance X_0 can be omitted without introducing any appreciable error in the behavior of the transformer under the loaded condition.

Further simplification of the equivalent circuit of the transformer can be done by neglecting the parallel branch consisting of R_0 and X_0.

Types of Losses in a Transformer

There are various types of losses in the transformer such as iron loss, copper loss, hysteresis loss, eddy current loss, stray loss, and dielectric loss. The hysteresis losses occur because of the variation of the magnetization in the core of the transformer and the copper loss occurs because of the transformer winding resistance.

The various types of losses are explained below in detail.

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Iron Losses

Iron losses are caused by the alternating flux in the core of the transformer as this loss occurs in the core it is also known as **Core loss**. Iron loss is further divided into hysteresis and eddy current   loss.

Hysteresis Loss

The core of the transformer is subjected to an alternating magnetizing force, and for each cycle of emf, a hysteresis loop is traced out. Power is dissipated in the form of heat known as hysteresis loss and given by the equation shown below:

$$P_h = K\eta B_{max}^{1.6} f\, V \quad \text{watts}$$

Where

- $K\eta$ is a proportionality constant which depends upon the volume and quality of the material of the core used in the transformer,
- f is the supply frequency,
- B_{max} is the maximum or peak value of the flux density.

The iron or core losses can be minimized by using silicon steel material for the construction of the core of the transformer.

Eddy Current Loss

When the flux links with a closed circuit, an emf is induced in the circuit and the current flows, the value of the current depends upon the amount of emf around the circuit and the resistance of the circuit.

Since the core is made of conducting material, these EMFs circulate currents within the body of the material. These circulating currents are called Eddy Currents. They will occur when the conductor experiences a changing magnetic field. As these currents are not responsible for doing any useful work, and it produces a loss (I^2R loss) in the magnetic material known as an Eddy Current Loss. The eddy current loss is minimized by making the core with thin laminations.
The equation of the eddy current loss is given as:

$$P_e = K_e B_m^2 t^2 f^2 V \qquad \text{watts}$$

Where,

- K_e – coefficient of eddy current. Its value depends upon the nature of magnetic material like volume and resistivity of core material, the thickness of laminations
- B_m – maximum value of flux density in wb/m^2

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- T – thickness of lamination in meters
- F – frequency of reversal of the magnetic field in Hz
- V – the volume of magnetic material in m^3

Copper Loss Or Ohmic Loss

These losses occur due to ohmic resistance of the transformer windings. If I_1 and I_2 are the primary and the secondary current. R_1 and R_2 are the resistance of primary and secondary winding then the copper losses occurring in the primary and secondary winding will be $I_1^2R_1$ and $I_2^2R_2$ respectively.

Therefore, the total copper losses will be

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

These losses varied according to the load and known hence it is also known as variable losses. Copper losses vary as the square of the load current.

Stray Loss

The occurrence of these stray losses is due to the presence of leakage field. The percentage of these losses are very small as compared to the iron and copper losses so they can be neglected.

Dielectric Loss

Dielectric loss occurs in the insulating material of the transformer that is in the oil of the transformer, or in the solid insulations. When the oil gets deteriorated or the solid insulation gets damaged, or its quality decreases, and because of this, the efficiency of the transformer gets affected.

Open Circuit and Short Circuit Test on Transformer:

The open circuit and short circuit test are performed for determining the parameter of the transformer like their efficiency, voltage regulation, circuit constant etc. These tests are performed without the actual loading and because of this reason the very less power is required for the test. The open circuit and the short circuit test gives a very **accurate result** as compared to the full load test.

Open Circuit Test

The purpose of the open-circuit test is to determine the no-load current and losses of the transformer because of which their no-load parameters are determined. This test is performed on the primary winding of the transformer. The wattmeter, ammeter and the voltage are connected to their primary winding. The nominal rated voltage is supplied to their primary winding with the help of the ac source.

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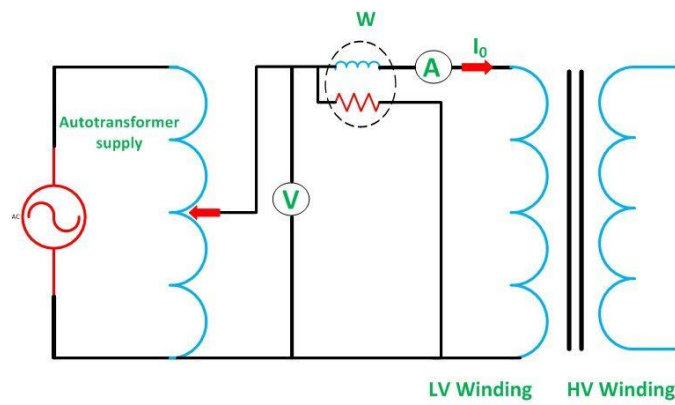
Circuit Diagram of Open Circuit Test on Transformer

The secondary winding of the transformer is kept open, and the voltmeter is connected to their terminal. This voltmeter measures the **secondary induced voltage**. As the secondary of the transformer is open, thus no-load current flows through the primary winding.

The value of no-load current is very small as compared to the full rated current. The copper loss occurs only on the primary winding of the transformer because the secondary winding is open. The reading of the wattmeter only represents the core and iron losses. The core loss of the transformer is the same for all types of loads.

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

$$W_0 = V_1 I_0 \cos\varphi_0 \qquad ....(1)$$

The no-load power factor is

$$\cos\varphi_0 = \frac{W_0}{V_1 I_0}$$

Working component I_w is

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$$I_w = \frac{W_0}{V_1} \dots \dots \dots \dots (2)$$

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

$$I_w = I_0 \, Cos\varphi_0$$

Magnetizing component is

$$I_m = \sqrt{I_0^2 - I_w^2}$$

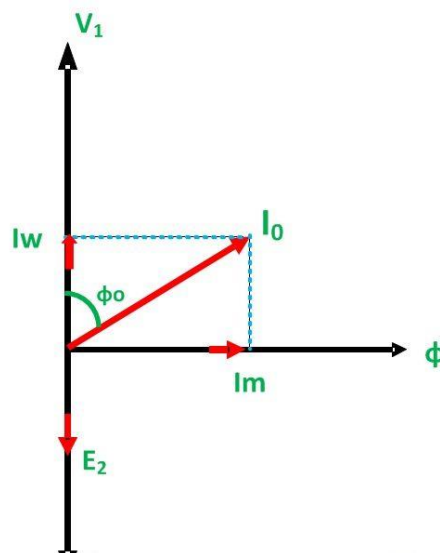No-load parameters are given below:

Equivalent exciting resistance is

$$R_0 = \frac{V_1}{I_w}$$

Equivalent exciting reactance is

$$X_0 = \frac{V_1}{I_m}$$

The phasor diagram of the transformer at no load or when an open circuit test is performed is shown below

Phasor Diagram of Open Circuit Test

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The iron losses measured by the open circuit test is used for calculating the efficiency of the transformer.
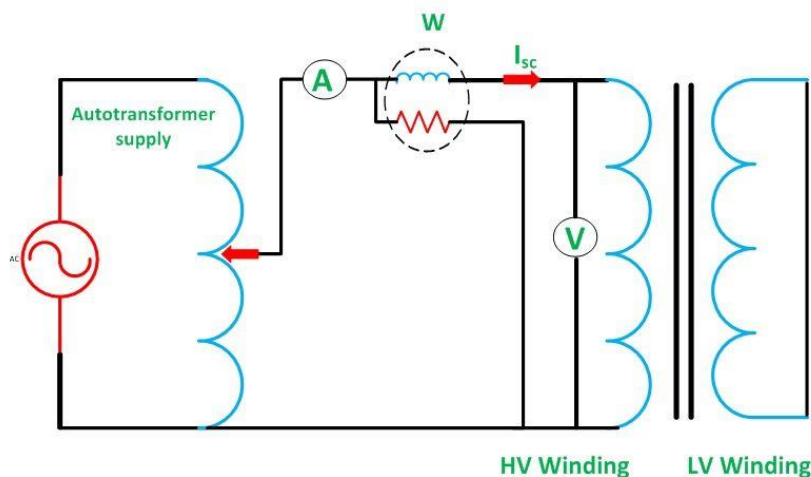
Short Circuit Test

The short circuit test is performed for determining the below mention parameter of the transformer.

- It determines the copper loss occur on the full load. The copper loss is used for finding the efficiency of the transformer.

- The equivalent resistance, impedance, and leakage reactance are known by the short circuit test.

The short circuit test is performed on the secondary or high voltage winding of the transformer. The measuring instrument like wattmeter, voltmeter and ammeter are connected to the high voltage winding of the transformer. Their primary winding is short-circuited by the help of thick strip or ammeter which is connected to its terminal.

The low voltage source is connected across the secondary winding because of which the full load current flows from both the secondary and the primary winding of the transformer. The full load current is measured by the ammeter connected across their secondary winding.

The circuit diagram of the short circuit test is shown below:

Circuit Diagram of Short Circuit Test on Transformer

The low voltage source is applied across the secondary winding, which is approximately **5 to 10%** of the normal rated voltage. The flux is set up in the core of the transformer. The magnitude of the flux is small as compared to the normal flux.

The iron loss of the transformer depends on the flux. It is less occur in the short circuit test because of the low value of flux. The reading of the wattmeter only determines the copper

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loss occurred, in their windings. The voltmeter measures the voltage applied to their high voltage winding. The secondary current induces in the transformer because of the applied voltage.

Calculation of Short Circuit Test

Let,

- W_c – Wattmeter reading

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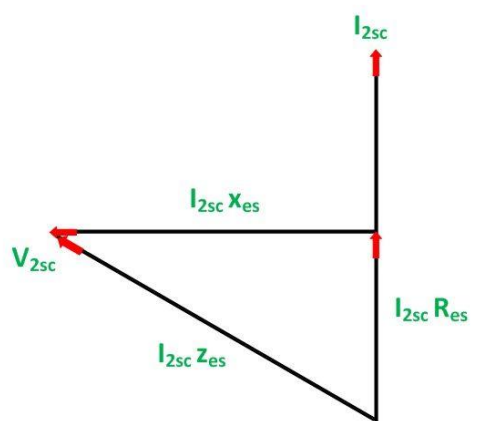
- I_{2sc} – ammeter reading

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

$$P_c = \left(\frac{I_{2fl}}{I_{2sc}}\right)^2 W_c \qquad \text{And} \qquad I_{2sc}^2 R_{es} = W_c$$

Equivalent resistance referred to the secondary side is

$$R_{es} = \frac{W_c}{I_{2sc}^2}$$

The phasor diagram of the short circuit test of the transformer is shown below

Phasor Diagram of Short Circuit Test

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From the phasor diagram

$$I_{2sc}Z_{es} = V_{2sc}$$

Equivalent impedance referred to the secondary side is given by

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

The equivalent reactance referred to the secondary side is given by

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

The voltage regulation of the transformer can be determined at any load and power factor after knowing the values of $\mathbf{Z_{es}}$ and $\mathbf{R_{es}}$.

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.

Transformer Efficiency

Transformer efficiency (η) can be explained as the ratio of the output power to the input power.

$$\eta \triangleq \frac{\text{output power}}{\text{input power}}$$

$$= \frac{\text{output power}}{\text{output power } + \text{ copper loss} + \text{iron loss}} \text{ pu}$$

Therefore the per unit efficiency at load current I_2 and power factor $\cos \Phi_2$ will be

$$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + I_2^2 . R_{e_2} + P_i} \text{ pu}$$

And the per unit efficiency at full load is

$$\eta_{fl} = \frac{V_2 I_{2fl} \cos\phi_2}{V_2 I_{2fl} \cos\phi_2 + I_{2fl}^2 . R_{e_2} + P_i}$$

If $S_{2fl} = (VA)_{2fl} = V_2 I_{2fl} = $ full- load VA = rated VA

Then

$$\eta_{fl} = \frac{S_2 \cos\phi_2}{S_2 \cos\phi_2 + P_{cfl} R_{e_2} + P_i}$$

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As we know that in a transformer there is no rotational part so there are no rotational losses such as windings and frictional losses in a rotating machine. Therefore, we can obtain a maximum efficiency as high as 99% in a well-designed transformer.

Transformer Voltage Regulation

Voltage Regulation of single-phase transformers is the percentage (or per unit value) change in its secondary terminal voltage compared to its original no-load voltage under varying secondary load conditions. In other words, regulation determines the variation in secondary terminal voltage which occurs inside the transformer as a result of variations in the transformers connected load thereby affecting its performance and efficiency if these losses are high and the secondary voltage becomes too low.

A transformers voltage regulation change between its secondary terminal voltage from a no-load condition when $I_L = 0$, (open circuit) to a fully-loaded condition when $I_L = I_{MAX}$ (maximum current) for a constant primary voltage is given as:

Transformer Voltage Regulation

$$\text{Regulation} = \frac{\text{Change in Output Voltage}}{\text{No-load Output Voltage}}$$

$$\therefore \text{Regulation} = \frac{V_{(no\text{-}load)} - V_{(full\text{-}load)}}{V_{(no\text{-}load)}}$$

Transformer Voltage Regulation as a Percentage Change

$$\% \text{ Regulation} = \frac{V_{no\text{-}load} - V_{full\text{-}load}}{V_{full\text{-}load}} \times 100$$

Where

$V_{no\text{-}load}$ is the no-load voltage and
$V_{full\text{-}load}$ is the full-load voltage.

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