LNCT GROUP OF COLLEGES

Name of Faculty: NAVEEN ASATI

Designation: ASSO. PROF.

Department: ELECTRICAL & ELECTRONICS ENGINEERING

Subject: BASIC ELECTRICAL & ELECTRONICS ENGINEERING

Subject Code: BT-104

Unit: 3

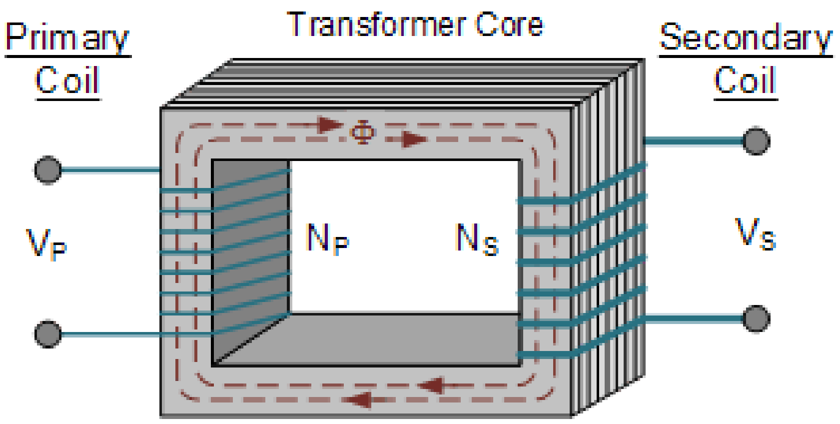
Topic: TRANSFORMER

TRANSFORMER

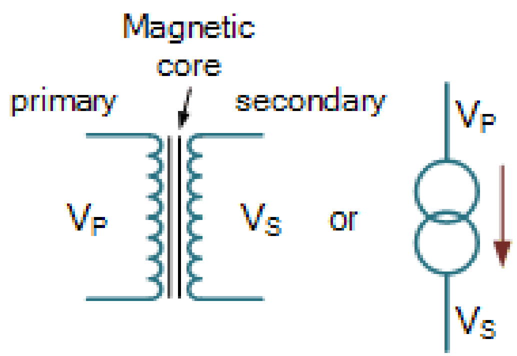
An A.C. device used to change high voltage low current A.C. into low voltage high current A.C. and Vice-versa without changing the frequency

In brief,

1. Transfers electric power from one circuit to another
2. It does so without a change of frequency
3. It accomplishes this by electromagnetic induction
4. Where the two electric circuits are in mutual inductive influence of each other.



Transformer Construction



Transformer Symbols

Working Principle of a Transformer

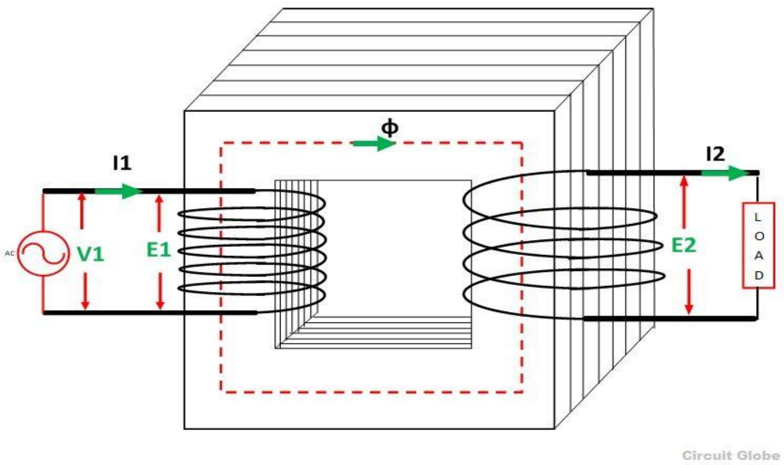
The basic principle on which the transformer works is **Faraday's Law of Electromagnetic Induction** or mutual induction between the two coils.

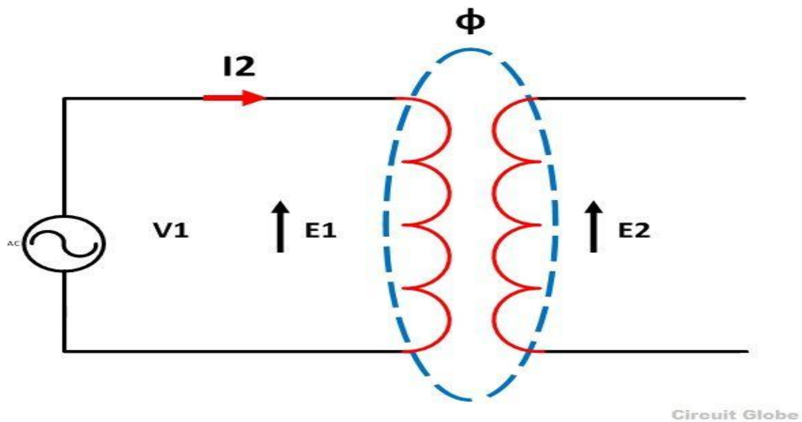
The working of the transformer is explained below.

The transformer consists of two separate windings placed over the laminated silicon steel core.

The winding to which AC supply is connected is called primary winding and to which load is connected is called secondary winding as shown in the figure below.

It works on the **alternating current only** because an alternating flux is required for mutual induction between the two windings.





When the AC supply is given to the primary winding with a voltage of V_1, an alternating flux φ 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**.

The direction of this induced emf is opposite to the applied voltage V_1, this is because of the Lenz's law.

Physically, there is no electrical connection between the two windings, but they are magnetically connected.

Therefore, the electrical power is transferred from the primary circuit to the secondary circuit through mutual inductance.

The induced emf in the primary and secondary windings depends upon the rate of change of flux linkage that is ($N\, d\varphi/dt$).

$d\varphi/dt$ is the change of flux and is same for both the primary and secondary windings.

The induced emf E_1 in the primary winding is proportional to the number of turns N_1 of the primary windings ($E_1 \propto N_1$).

Similarly induced emf in the secondary winding is proportional to the number of turns on the secondary side. ($E_2 \propto N_2$).

Construction of a Transformer

The transformer mainly consists of the Magnetic circuit, electric circuit, dielectric circuit, tanks, and accessories.

The main elements of the transformer are the **primary and secondary windings** and the **steel core**.

The core of the transformer is made up of silicon steel in order to provide a continuous magnetic path. Usually, the core of the transformer is laminated for minimizing the eddy current loss.

Magnetic circuit

The magnetic circuit of a transformer consists of **core** and **yoke**. The circuit provides the path to the flow of magnetic flux.

The transformer consists of a laminated steel core and the two coils. The two coils are insulated from each other and also from the core.

The core of the transformer is constructed from laminations of steel sheet or silicon steel assembled to provide a continuous magnetic path.

At usual flux densities, the silicon steel material has low hysteresis losses.

The vertical position on which the coil is wound is called the **limb** while the horizontal position is known as the **yoke**.

Electric circuit

Construction of the electric circuit of the transformer consists of primary and secondary windings usually made of copper.

The Conductors of the rectangular cross-section are generally used for low voltages winding and also for the high voltage winding for large transformers. Conductors of the circular cross-sectional area are used for high voltage winding in the small transformer.

According to the core construction and the manner in which the primary and secondary windings are placed around it, the transformer is named as **core type** and **shell type**.

Core Type Transformer

In a simple core type construction of the transformer, a rectangular frame laminations are formed to build the core of the transformer.

The laminations are cut in the form of L-shape strips as shown in the figure below.

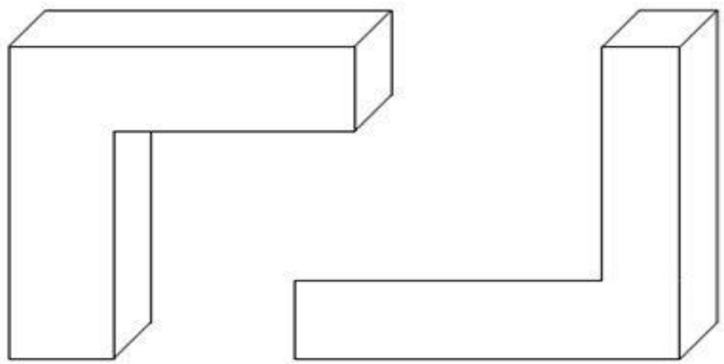
In order to avoid high reluctance at the joints where laminations are butted against each other, the alternate layers are placed differently to eliminate the continuous joints.

The primary and the secondary windings are interleaved to reduce the leakage flux.

Half of each winding are placed side by side or concentrically on either limb of the core.

While placing these windings, insulation of Bakelite former is provided between the core and low voltage winding (LV), between the two windings that are between low voltage (LV) and high voltage (HV) windings and also in between coils and yoke.

To reduce the insulation, the low voltage winding is always placed nearer to the core.



Shell Type Transformer

In a shell-type transformer, the individual laminations are cut in the form of long strips of E and I shape.

It has two magnetic circuits, and the core has three limbs.

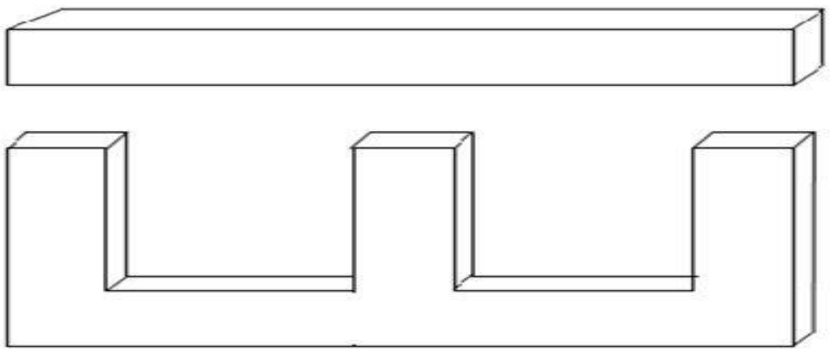
The central limb carries the whole of the flux whereas the side limbs carry half of the flux.

Therefore, the width of the center is double, to that of the outer limbs.

The leakage flux is reduced by the subdivision of the windings which in return have lesser reactances.

Both the primary and the secondary windings are placed on the central limb side by side.

The low voltage winding is placed nearer to the core and the high voltage winding is placed outside the low voltage winding.



The leakage flux is reduced by the subdivision of the windings which in return have lesser reactances. Both the primary and the secondary windings are placed on the central limb side by side. The low voltage winding is placed nearer to the core and the high voltage winding is placed outside the low voltage winding.

To reduce the cost of lamination between the core and the low voltage winding, the windings are formed and are wound to the cylindrical shape and then the core laminations are inserted later.

Dielectric Circuit

The dielectric circuit consists of insulations used in different places in the transformer to insulate the conducting parts.
The core is laminated to minimize the eddy current losses.
The laminations are insulated from each other by a light coating of varnish or by an oxide layer.
The thickness of laminations varies from **0.35mm to 0.5mm** for a frequency of **50 Hz**.

Tanks and Accessories

Other different parts and accessories are also fitted on the transformer for its efficient work as well as for longer life and better services of the transformer. They are as follows:

Conservator

The Conservator is a cylindrical tank placed on the top or on the roof of the main tank of the transformer. A large cover is provided which can be opened from time to time for the proper maintenance and cleaning of the transformer. It acts as a reservoir for the transformer insulating oil.

When the transformer is fully loaded and the temperature of the transformer rises high, an increase in the volume of the air inside the transformer takes place. As the level of the oil increases and decreases simultaneously, thus, a conservator provides adequate space for this expanded oil inside the transformer.

Breather

As in the human body, there is a heart, similarly, a breather acts as a heart for the transformer. When the temperature of the transformer rises, the insulating oil in the transformer gets heated up. This oil expands and contracts.

When the oil heats up and expands, the transformer breaths air in and thus the oil gets cooled and the level of oil goes down and the air is absorbed in it. This process of taking air in and out is called breathing of the transformer.

The level of oil in the chamber increases and decreases when the breather takes the air in and out for cooling of the oil. This air carries moisture, which contaminates the oil and thus the quality of oil gets deteriorate.

For eliminating this moisture content, the breather is filled with Silica Gel. The main function of the silica gel is to separate moisture from the oil, maintaining the quality of the insulating oil. Initially, the color of the silica gel is blue and as it absorbs the moisture from the oil it turns into pink color.

Fresh Silica gel dries down the air to a dew point below **-40 degrees Celsius**.

Explosion Vent

The explosion vent is a thin aluminum pipe placed at both the ends of the transformer to prevent the transformer from the damage. When the temperature increases in the transformer drastically and the excessive pressure is created inside the transformer, the explosive vent helps in releasing the pressure.

Radiator

The main function of the radiator is to cool the oil in the transformer. The radiator is the detachable device whose upper and lower portion is connected by a valve to the transformer tank. When the transformer cleaning and maintenance are done the valve prevents the draining of the oil when the radiator is detached from the transformer.

When the transformer is in the working conditions, the oil of the transformer gets heated and moves up in the main tank and enters the radiator through the upper valve. There it gets cooled and from the lower valve of the radiating unit the oil again enters the transformer tank and this process continues.

Bushings

The Bushings in the transformer are the insulting device that allows an electrical conductor to pass electrical energy safely through it. It provides electrical field strength to the insulation of the conductors to withstand if a large amount of electric energy passes through it. **Solid porcelain** type bushing is used in smaller transformer and **oil-filled condenser** type bushing is used in large transformer.

The most common cause of the failure of the bushing resulting in damage to the transformer is the entrance of the moisture. The power factor of the bushing will always be in stable condition, but if the variation is seen in the power factor that means there is deterioration in the insulation.

Classification of Transformers

Transformers can be classified on different basis like

1. **On the basis of construction**
   (a) Core type transformer (b) Shell type transformer
2. **On the basis of working**
   (a) Step Up transformer (b) Step down transformer
3. **On the basis of application**
   (a) Power transformer (b) Distribution transformer
4. **On the basis of no. of phases**
   (a) Single phase transformer (b) Three phase transformer

5. On the basis of windings

(a) Single winding transformer (b) two winding transformer (c) three winding transformer

6. On the basis of cooling methods

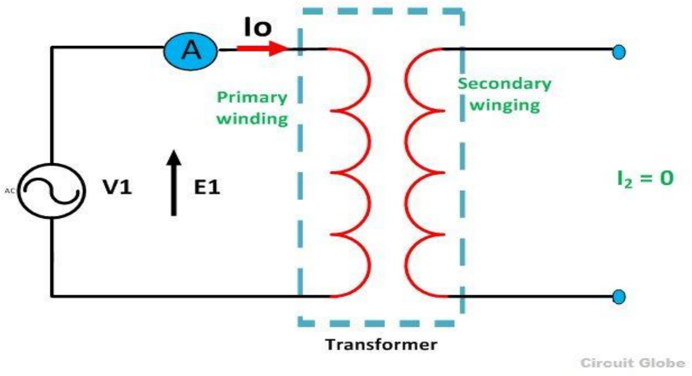
(a) Air cooled transformer (b) Oil immersed transformer

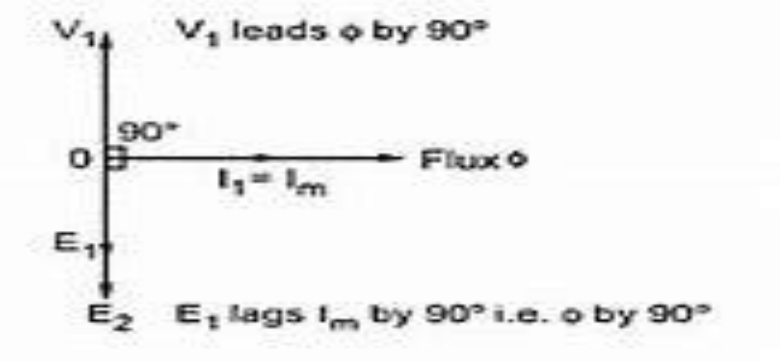
7. Special units

(a) Instrument transformer (b) bell transformer (c) welding transformer (d) pulse transformer

Ideal transformer

- **Zero leakage flux -** Fluxes produced by the primary and secondary currents are confined within the core.
- **The windings have no resistance –** Induced voltages equal applied voltages
- **The core has infinite permeability –** Reluctance of the core is zero
  – Negligible current is required to establish magnetic flux
- **Loss-less magnetic core –** No hysteresis or eddy currents

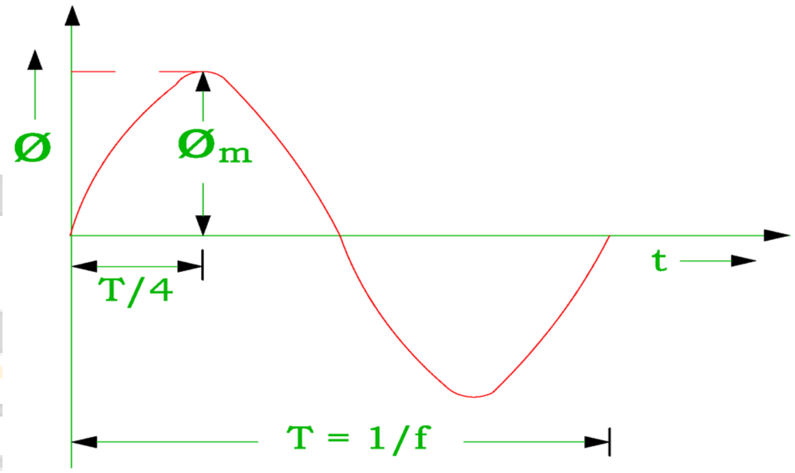




V_1 – supply voltage; **I_1**- no-load input current; **V_2**- output voltage; **I_2**- output current

I_m- magnetising current; **E_1**-self-induced emf ; **E_2**- mutually induced emf

EMF EQUATION OF A TRANSFORMER



Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

ϕ_m = Maximum flux in the core in webers = B_m x A

f = Frequency of ac input

From waveform, flux increases from its zero value to maximum value ϕ_m in one quarter of the cycle i.e. in 1/4f second

Average rate of change of flux = $\dfrac{\phi m}{1/4f}$ = $4f\phi_m$ wb/sec. or volts

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

Therefore , Average emf/turn = $4f\phi m$ volts

If flux ϕ varies sinusoidally, then rms value of emf is obtained by multiplying the average value with form factor.

$$\text{Form factor} = \frac{\text{rms value}}{\text{average value}} = 1.11 \text{ (for sinusoidal wave)}$$

RMS value of emf/turn = $1.11 \times 4f\phi_m$ volts

Now, RMS value of the induced emf in the whole of primary winding,

E_1= induced emf / turn X No. of primary turns

$$E_1 = 1.11 \times 4f\phi_m \times N_1 = 4.44f\phi_m N_1 = 4.44\, f\, B_m\, A\, N_1 \quad \text{------ (1)}$$

Similarly, RMS value of the induced emf in the whole of secondary winding,

$$E_2 = 1.11 \times 4f\phi_m \times N_2 = 4.44f\phi_m N_2 = 4.44\, f\, B_m\, A\, N_2 \quad \text{----- (2)}$$

It is seen from equation (1) and equation (2) that

$$\frac{E1}{N1} = \frac{E2}{N2} = 4.44f\phi_m$$

It means that emf/turn is the same for both the windings.

Voltage transformation ratio (K)

From equation (1) and equation (2)

$$\frac{E2}{E1} = \frac{N2}{N1} = K$$

This constant K is known as voltage transformation ratio.

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

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

For an ideal transformer,

$$\text{Input VA} = \text{output VA}$$

$$V_1 I_1 = V_2 I_2$$

$$\frac{V1}{V2} = \frac{I2}{I1} = \frac{1}{K}$$

Hence, currents are in the inverse ratio of the voltage transformation ratio.

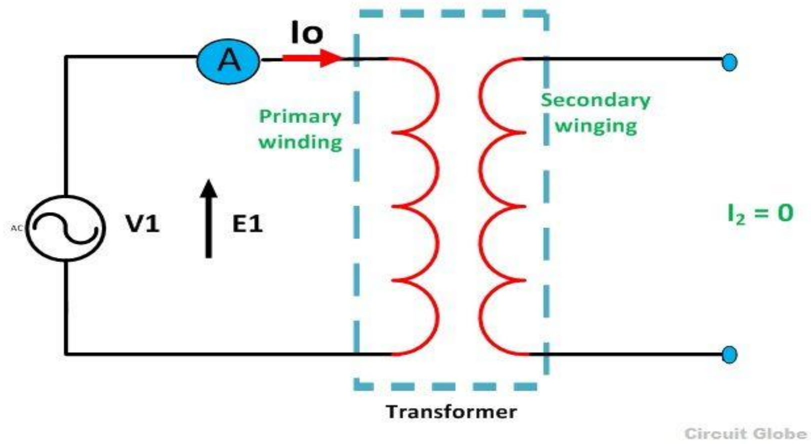
Transformer on No Load Condition

When the transformer is operating at no load, the secondary winding 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**.

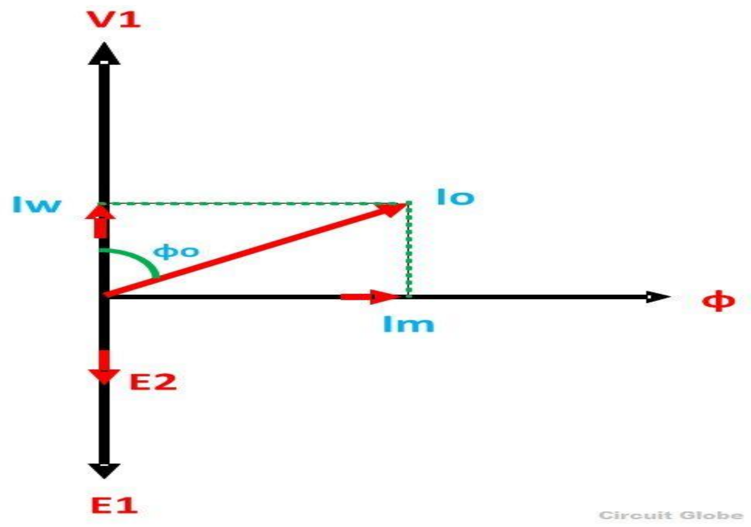
The no-load current consists of two components:

- ✓ **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 known 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:

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

Working component $I_w = I_0 \cos\varphi_0$

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

Magnetizing component $I_m = I_0 \sin\varphi_0$

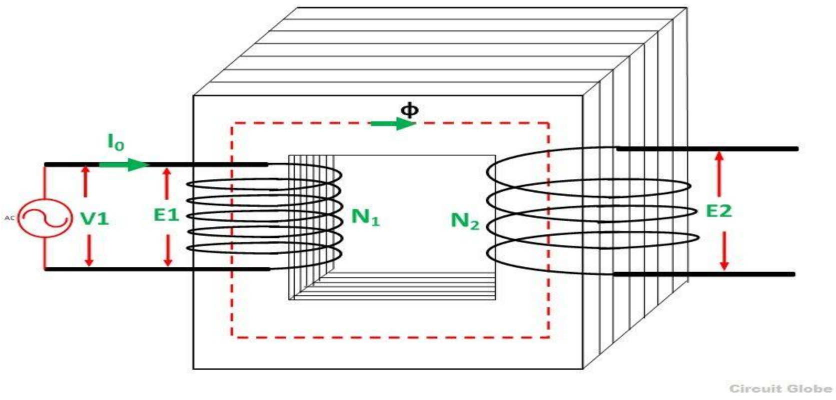
Power factor $\cos\varphi_0 = \frac{I_w}{I_0}$

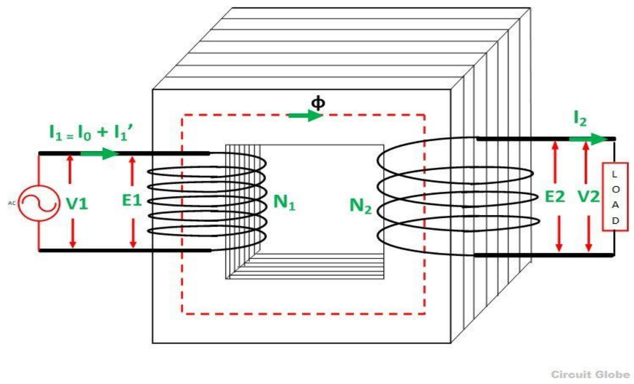
No load power input $P_0 = V_1 I_0 \cos\varphi_0$

Transformer On Load

When the transformer is on the loaded condition, the secondary of the transformer is connected to load. The load can be resistive, inductive or capacitive. The current I_2 flows through the secondary winding of the transformer. The magnitude of the secondary current depends on the terminal voltage V_2 and the load impedance. The phase angle between the secondary current and voltage depends on the nature of the load.

When the secondary of the transformer is kept open, it draws the no-load current from the main supply. The no-load current induces the magnetomotive force $N_0 I_0$ and this force set up the flux Φ in the core of the transformer.





When the load is connected to the secondary of the transformer, I_2 current flows through their secondary winding. The secondary current induces the magnetomotive force N_2I_2 on the secondary winding of the transformer. This force set up the flux ϕ_2 in the transformer core. The flux ϕ_2 opposes the flux ϕ, according to **Lenz's law**.

- As the flux ϕ_2 opposes the flux ϕ, the resultant flux of the transformer decreases and this flux reduces the induced EMF E_1. Thus, the strength of the V_1 is more than E_1 and an additional primary current I'_1 drawn from the main supply.
  The additional current is used for restoring the original value of the flux in the core of the transformer so that $V_1 = E_1$. The primary current I'_1 is in phase opposition with the secondary current I_2. Thus, it is called the **primary counter-balancing current**.
- The additional current I'_1 induces the magnetomotive force $N_1I'_1$. And this force set up the flux ϕ'_1. The direction of the flux is the same as that of the ϕ and it cancels the flux ϕ_2 which induces because of the MMF N_2I_2

Now, $N_1I_1' = N_2I_2$

Therefore,

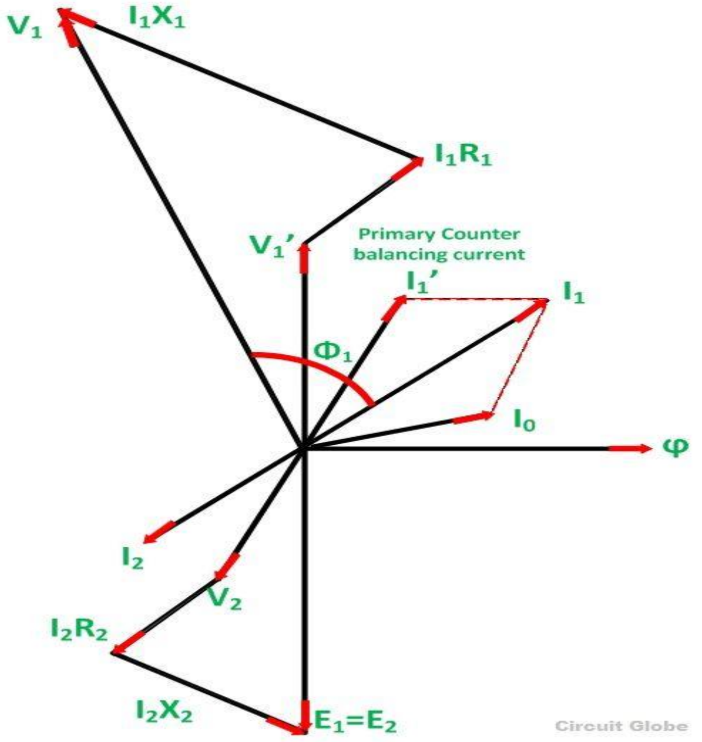
$$I_1' = \left(\frac{N_2}{N_1}\right) I_2 = KI_2$$

- The phase difference between V_1 and I_1 gives the power factor angle φ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.
- If the load is inductive as shown in the above phasor diagram, the power factor will be lagging, and if the load is capacitive, the power factor will be leading. The total primary current I_1 is the vector sum of the currents I_0 and I_1'. i.e

$$\overline{I_1} = \overline{I_0} + \overline{I_1'}$$

Phasor Diagram of Transformer on Inductive Load

Steps to draw the phasor diagram



- Take flux φ, a reference
- Induces emf E_1 and E_2 lags the flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding. E_1 is represented by V_1'.
- Current I_0 lags the voltage V_1' by 90 degrees.
- The power factor of the load is lagging. Therefore current I_2 is drawn lagging E_2 by an angle φ_2.
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phase difference of E_2 and voltage drop.

$V_2 = E_2$ – voltage drops

$I_2 R_2$ is in phase with I_2 and I_2X_2 is in quadrature with I_2.

- The total current flowing in the primary winding is the phasor sum of I_1' and I_0.
- Primary applied voltage V_1 is the phasor sum of V_1' and the voltage drop in the primary winding.
- Current I_1' is drawn equal and opposite to the current I_2

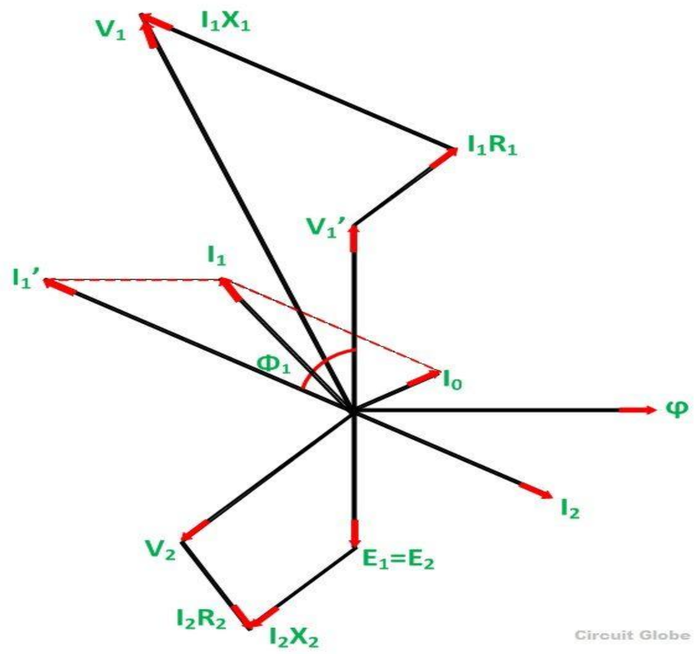
  $V_1 = V_1'$ + voltage drop

  I_1R_1 is in phase with I_1 and I_1X_l is in quadrature with I_1.
- The phasor difference between V_1 and I_1 gives the power factor angle φ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.
- If the load is inductive as shown in the above phasor diagram, the power factor will be lagging, and if the load is capacitive, the power factor will be leading. Where I_1R_1 is the resistive drop in the primary windings I_2X_2 is the reactive drop in the secondary winding

Phasor Diagram of Transformer on Capacitive Load

Steps to draw the phasor diagram at capacitive load

- Take flux φ a reference
- Induces emf E_1 and E_2 lags the flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding. E_1 is represented by V_1'.



- Current I_0 lags the voltage V_1' by 90 degrees.
- The power factor of the load is leading. Therefore current I_2 is drawn leading E_2
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phasor difference of E_2 and voltage drop.
  $V_2 = E_2$ – voltage drops
  $I_2 R_2$ is in phase with I_2 and I_2X_2 is in quadrature with I_2.
- Current I_1' is drawn equal and opposite to the current I_2
- The total current I_1 flowing in the primary winding is the phasor sum of I_1' and I_0.
- Primary applied voltage V_1 is the phasor sum of V_1' and the voltage drop in the primary winding.
  $V_1 = V_1'$ + voltage drop
  I_1R_1 is in phase with I_1 and I_1X_l is in quadrature with I_1.
- The phasor difference between V_1 and I_1 gives the power factor angle φ_1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.

Transformer with resistance and reactance

The primary and secondary windings of a transformer with reactances taken out of the windings. The primary impedance is given by

$$Z_1 = \sqrt{(R_1^2 + X_1^2)}$$

Similarly, secondary impedance is given by

$$Z_2 = \sqrt{(R_2^2 + X_2^2)}$$

The resistance & leakage reactance of each winding is responsible for some voltage drop in each winding.

Hence $$V_1 = E_1 + I_1(R_1 + jX_1) = E_1 + I_1 Z_1$$

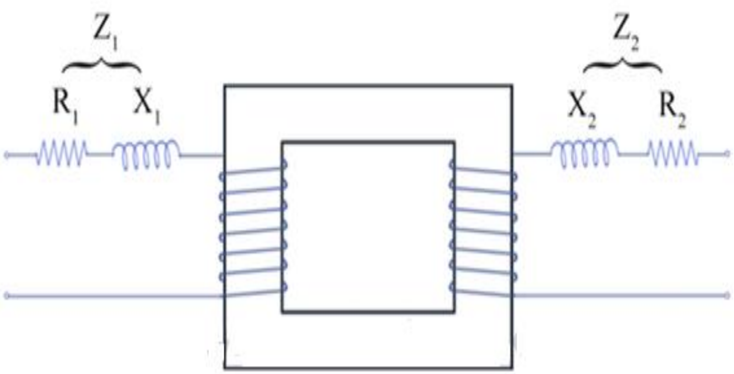
Similarly, there are I_2R_2 & I_2X_2 drops in secondary which combine with V_2 to give E_2.

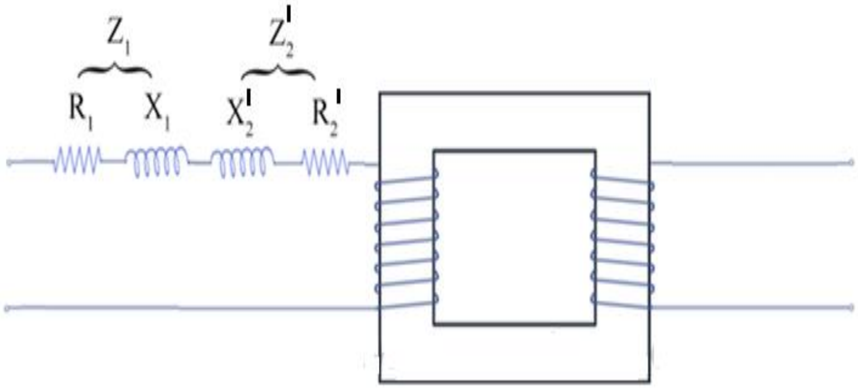
$$E_2 = V_2 + I_2(R_2 + jX_2) = V_2 + I_2 Z_2$$

It is obvious that total impedance of the transformer as referred to primary is given by

$$Z_{ep} = \sqrt{(R_{ep}^2 + X_{ep}^2)}$$

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





Voltage Regulation of Transformer

Whenever a 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.

Voltage Regulation of Transformer for Lagging Power Factor

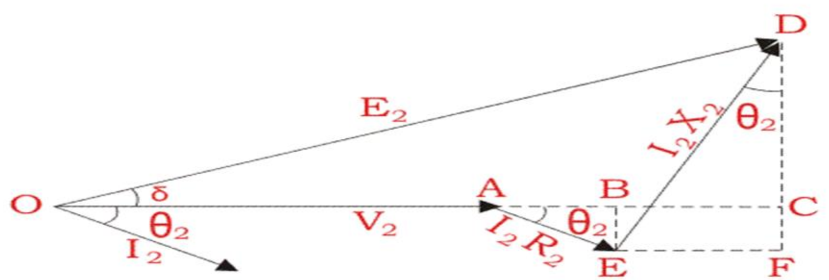
Lagging power factor of the load is $\cos\theta_2$, that means angle between secondary current and voltage is θ_2.

Here, from the below diagram, $OC = OA + AB + BC$

$$Here,\ OA = V_2$$

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

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



Voltage Regulation at Lagging Power Factor

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

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

$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2$$

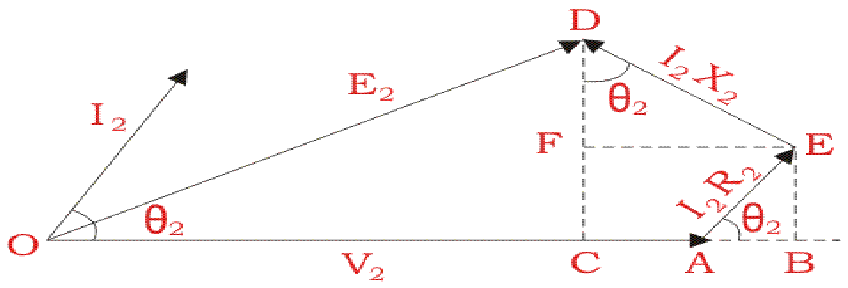
Voltage regulation of transformer at lagging power factor,

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

$$= \frac{I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

Voltage Regulation of Transformer for Leading Power Factor

Leading power factor of the load is $\cos\theta_2$, that means angle between secondary current and voltage is θ_2.



Voltage Regulation at Leading Power Factor

Here, from the diagram,

$$OC = OA + AB - BC$$

$$Here,\ OA = V_2$$

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

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

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

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

$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2$$

Voltage regulation of transformer at leading power factor,

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

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

Zero Voltage Regulation of a Transformer

Zero voltage regulation' indicates that there is no difference between its 'no-load voltage' and its 'full-load voltage'. This means that in the voltage regulation equation above, voltage regulation is equal to zero. This is not practical – and is only theoretically possible in the case for an ideal transformer.

Types of Losses in a Transformer

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, Kη 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, Bmax 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, 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 Or No-Load Test

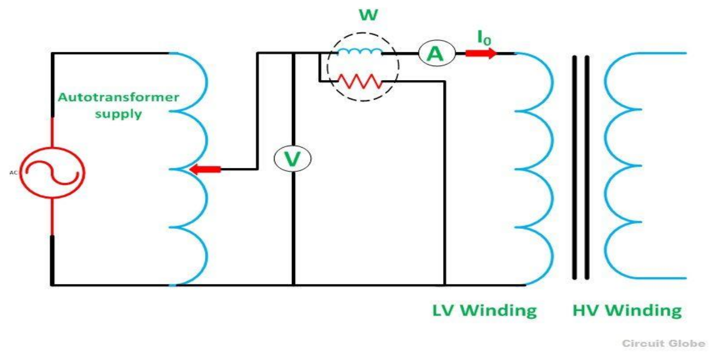
The purpose of the open circuit test is to determine the no-load current and losses of the transformer because of which their no-load parameter are determined. This test is performed on the primary winding of the transformer. The wattmeter, ammeter and the voltage are connected to their primary winding.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

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 the 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 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

$$W_0 = V_1 I_0 \mathrm{Cos}\varphi_0 \quad ....(1)$$

The no-load power factor is $$\mathrm{Cos}\varphi_0 = \frac{W_0}{V_1 I_0}$$

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

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

$$I_w = I_0 \mathrm{Cos}\varphi_0$$

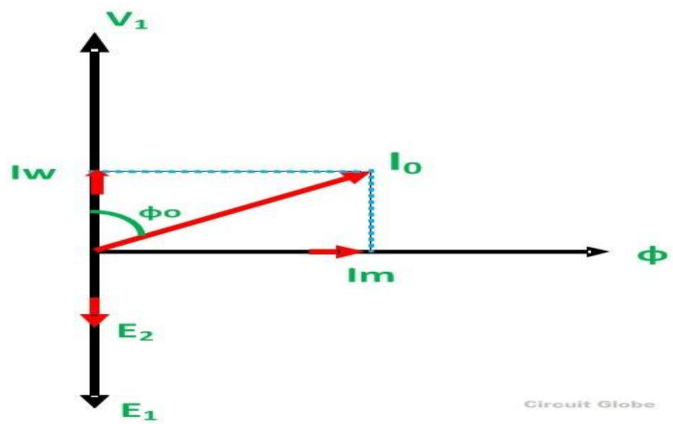
Magnetizing component is $$I_m = \sqrt{I_0^2 - I_w^2}$$

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

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



Short Circuit Test

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

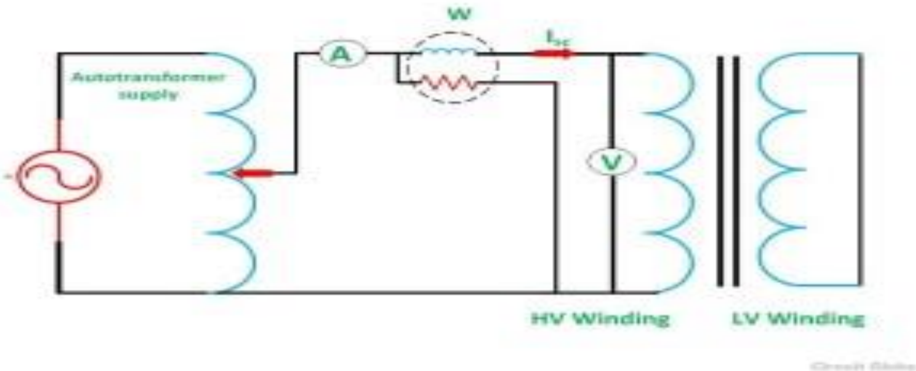
- It determines the copper loss occur on the full load. The copper loss is used for finding the efficiency of the transformer.
- The equivalent resistance, impedance, and leakage reactance are known by the short circuit test.

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 their 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 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 loss occur on 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

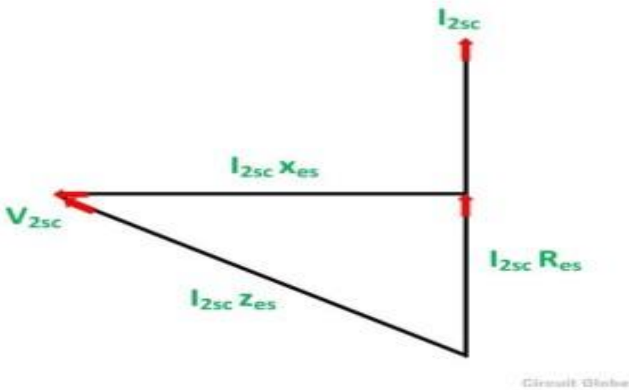
Then the full load copper loss of the transformer is given by

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

Equivalent resistance referred to 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



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

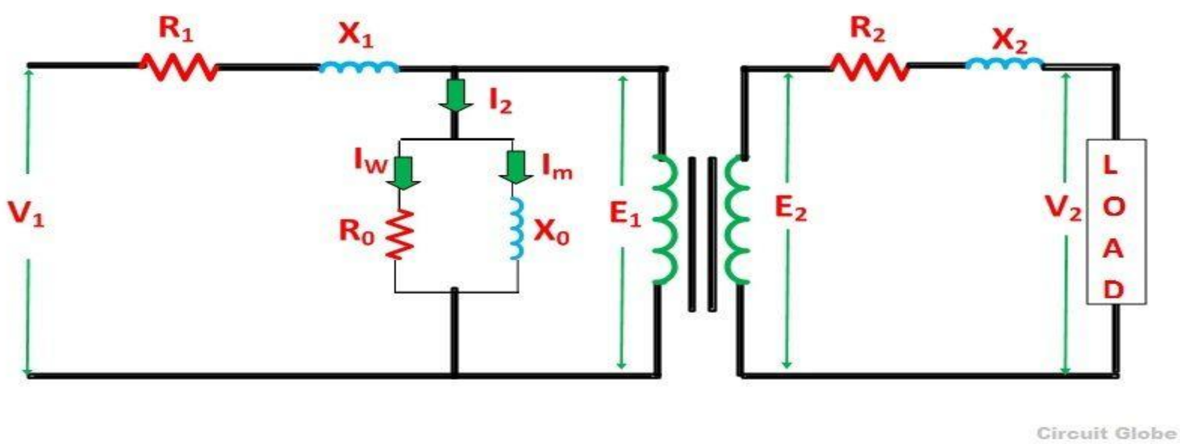
$$X_{es} = \sqrt{(Z_{es})^2 - (R_{es})^2}$$

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

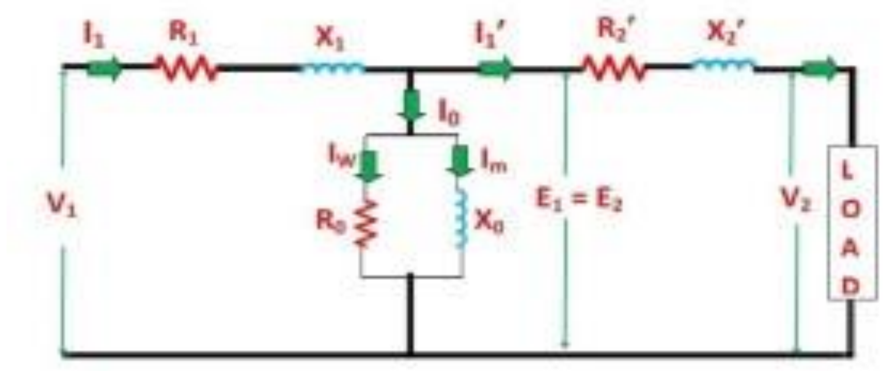
Equivalent Circuit of a Transformer

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:



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:



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:

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

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.

Transformer Efficiency

The **Efficiency** of the transformer is defined as the ratio of useful output power to the input power. The input and output power are measured in the same unit. Its unit is either in Watts (W) or KW. **Transformer efficiency** is denoted by η.

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{output power}}{\text{output power} + \text{losses}}$$

$$\eta = \frac{\text{output power}}{\text{output power} + \text{iron losses} + \text{copper losses}}$$

$$\eta = \frac{V_2 I_2 \mathrm{Cos}\varphi_2}{V_2 I_2 \mathrm{Cos}\varphi_2 + P_i + P_c}$$

Where,

V_2 – Secondary terminal voltage, I_2 – Full load secondary current, $\mathrm{Cos}\varphi_2$ – power factor of the load
P_i – Iron losses = hysteresis losses + eddy current losses, P_c – Full load copper losses = $I_2^2 R_{es}$

Consider, the x is the fraction of the full load. The efficiency of the transformer regarding x is expressed as

$$\eta_x = \frac{x \text{ X output}}{x \text{ X output} + P_i + x^2 P_c} = \frac{x\, V_2 I_2 \mathrm{Cos}\varphi_2}{x\, V_2 I_2 \mathrm{Cos}\varphi_2 + P_i + x^2 I_2^2 R_{es}}$$

Maximum Efficiency Condition of a Transformer

The efficiency of the transformer along with the load and the power factor is expressed by the given relation:

$$\eta = \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + P_i + I_2^2 R_{es}} = \frac{V_2 \cos\varphi_2}{V_2 \cos\varphi_2 + P_i/I_2 + I_2 R_{es}} \dots\dots\dots (1)$$

The value of the terminal voltage V_2 is approximately constant. Thus, for a given power factor the Transformer efficiency depends upon the load current I_2. In equation (1), the numerator is constant and the transformer efficiency will be maximum if the denominator with respect to the variable I_2 is equated to zero.

$$\frac{d}{dI_2} = \left(V_2 \cos\varphi_2 + \frac{P_i}{I_2} + I_2 R_{es}\right) = 0 \qquad \text{or} \qquad 0 - \frac{P_i}{I_2^2} + R_{es} = 0$$

Or

$$I_2^2 R_{es} = P_i \quad \dots\dots\dots..(2)$$

i.e. Copper losses = Iron losses

Thus, the transformer will give the maximum efficiency when their copper loss is equal to the iron loss.

$$\eta_{max} = \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + 2P_i} \qquad as\ (P_c = P_i)$$

From equation (2) the value of output current I_2 at which the transformer efficiency will be maximum is given as

$$I_2 = \sqrt{\frac{P_i}{R_{es}}}$$

If x is the fraction of full load KVA at which the efficiency of the transformer is maximum then,

Copper losses = x^2P_c (where P_c is the full load copper losses)

Iron losses = P_i

For maximum efficiency $x^2 P_c = P_i$

$$x = \sqrt{\frac{P_i}{P_c}} \ldots\ldots\ldots\ldots (3)$$

Thus, output KVA corresponding to maximum efficiency

$$\eta_{max} = x \text{ X full load KVA} \ldots\ldots\ldots\ldots (4)$$

Putting the value of x from the above equation (3) in equation (4) we will get,

$$\eta_{max} = \sqrt{\frac{P_i}{P_c}} \text{ X full load KVA}$$

$$\eta_{max} = \text{Full load KVA X} \sqrt{\frac{\text{iron losses}}{\text{copper losses at full load}}} \quad \ldots\ldots\ldots\ldots(5)$$

The equation (5) is the maximum efficiency condition of the transformer.

All Day Efficiency of a Transformer

Some transformer efficiency cannot be judged by simple commercial efficiency as the load on certain transformer 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, and most of the time the distribution transformer has **50 to 75%** load on it.

As we know, there are various losses in the transformer such as iron and copper loss. The iron loss takes place at the core of the transformer. Thus, the iron or core loss occurs for the whole day in the distribution transformer.

The second type of loss known as a copper loss and it takes place in the windings of the transformer and is also known as the **variable loss**. It 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 the energy consumed for 24 hours.

All day efficiency means the power consumed by the transformer throughout the day. It is defined as the ratio of output power to the input power in kWh or Wh of the transformer over 24 hours. Mathematically, it is represented as

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

All-day efficiency of the transformer depends on their load cycle. The load cycle of the transformer means the repetitions of load on it for a specific period.

The ordinary or commercial efficiency of a transformer is defined as the ratio of the output power to the input power.

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{output power}}{\text{output power} + \text{losses}}$$

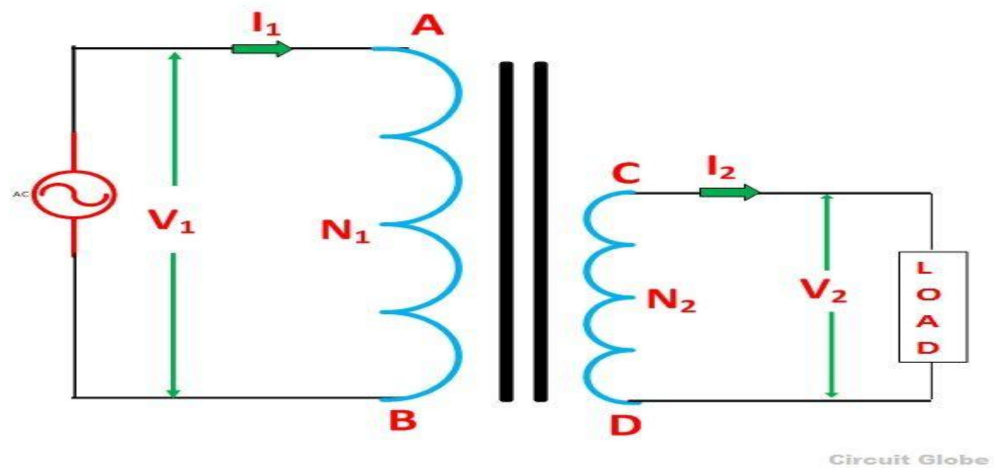
Auto Transformer

An Auto Transformer is a transformer with only one winding wound on a laminated core. An auto transformer is similar to a two winding transformer but differ in the way the primary and secondary winding are interrelated. A part of the winding is common to both primary and secondary sides.

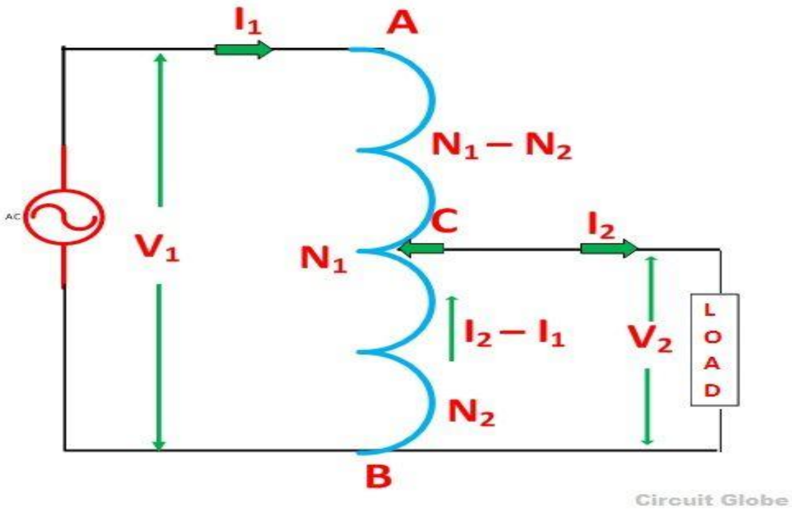
On load condition, a part of the load current is obtained directly from the supply and the remaining part is obtained by transformer action. An Auto transformer works as a voltage regulator.

In an ordinary transformer, the primary and the secondary windings are electrically insulated from each other but connected magnetically as shown in the figure below. While in auto transformer the primary and the secondary windings are connected magnetically as well as electrically. In fact, a part of the single continuous winding is common to both primary and secondary.

There are two types of auto transformer based on the construction. In one type of transformer, there is continuous winding with the taps brought out at convenient points determined by the desired secondary voltage.



However, in another type of auto transformer, there are two or more distinct coils which are electrically connected to form a continuous winding. The construction of Auto transformer is shown in the figure below.



The primary winding AB from which a tapping at C is taken, such that CB acts as a secondary winding. The supply voltage is applied across AB, and the load is connected across CB. The tapping may be fixed or variable. When an AC voltage V_1 is applied across AB, an alternating flux is set up in the core, as a result, an emf E_1 is induced in the winding AB. A part of this induced emf is taken in the secondary circuit.

Let, V_1 – primary applied voltage
V_2 – secondary voltage across the load, I_1 – primary current, I_2 – load current, N_1 – number of turns between A and B, N_2 – number of turns between C and B

Neglecting no-load current, leakage reactance and losses,

$V_1 = E_1$ and $V_2 = E_2$

Therefore, the transformation ratio: $$K = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

As the secondary ampere-turns are opposite to primary ampere-turns, so the current I_2 is in phase opposition to I_1. The secondary voltage is less than the primary. Therefore current I_2 is more than the current I_1. Therefore, the resulting current flowing through section BC is $(I_2 – I_1)$.

The ampere-turns due to section BC = current x turns

$$\text{Ampere turns due to section BC} = (I_2 - I_1)N_2 = \left(\frac{I_1}{K} - I_1\right) x\, N_1 K = I_1 N_1 (1 - K) \dots\dots\dots (1)$$

$$\text{Ampere turns due to section AC} = I_1(N_1 - N_2) = I_1 N_1 \left(1 - \frac{N_2}{N_1}\right) = I_1 N_1 (1 - K) \dots\dots. (2)$$

Saving of Copper in Auto Transformer as Compared to Ordinary Two Winding Transformer

The weight of the copper is proportional to the length and area of a cross-section of the conductor.

The length of the conductor is proportional to the number of turns, and the cross-section is proportional to the product of current and number of turns.

Now, from the above figure (B) shown of the auto transformer, the weight of copper required in an auto transformer is

W_a = weight of copper in section AC + weight of copper in section CB

Therefore,

$$W_a \propto I_1 (N_1 - N_2) + (I_2 - I_1)N_2$$

$$W_a \propto I_1N_1 + I_2N_2 - 2I_1N_2$$

If the same duty is performed with an ordinary two winding transformer shown above in the figure (A), the total weight of the copper required in the ordinary transformer,

W_0 = weight of copper on its primary winding + weight of copper on its secondary winding

Therefore,

$$W_o \propto I_1N_1 + I_2N_2$$

Now, the ratio of the weight of the copper in an auto transformer to the weight of copper in an ordinary transformer is given as

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$$\frac{W_a}{W_o} = \frac{I_1N_1 + I_2N_2 - 2I_1N_2}{I_1N_1 + I_2N_2}$$

OR

$$\frac{W_a}{W_o} = \frac{I_1N_1 + I_2N_2}{I_1N_1 + I_2N_2} - \frac{2I_1N_2}{I_1N_1 + I_2N_2}$$

$$\frac{W_a}{W_o} = 1 - \frac{2\,I_1N_2/I_1N_1}{I_1N_1/I_1N_1 + I_2N_2/I_1N_1} = 1 - K$$

OR

$$W_a = (1 - K)W_o$$

Saving of copper affected by using an auto transformer = weight of copper required in an ordinary transformer – weight of copper required in an auto transformer.

Saving of copper = $W_O - W_a = W_o - (1 - K)W_o = KW_O$

Therefore,

Saving of copper = K x weight of copper required for two windings of the transformer

Hence, saving in copper increases as the transformation ratio approaches unity. Hence the auto transformer is used when the value of K is nearly equal to unity.

Advantages of Auto transformer

- Less costly
- Better regulation
- Low losses as compared to ordinary two winding transformer of the same rating.

Disadvantages of Auto transformer

There are various advantages of the auto transformer, but then also one major disadvantage, why auto transformer is not widely used, is that

- The secondary winding is not insulated from the primary winding.
  If an auto transformer is used to supply low voltage from a high voltage and there is a break in the secondary winding, the full primary voltage comes across the secondary terminal which is dangerous to the operator and the equipment. So the auto transformer should not be used for interconnecting high voltage and low voltage systems.
- Used only in the limited places where a slight variation of the output voltage from input voltage is required.

Applications of Auto transformer

- It is used as a starter to give up to **50 to 60%** of full voltage to the stator of a squirrel cage induction motor during starting.
- It is used to give a small boost to a distribution cable, to correct the voltage drop.
- It is also used as a voltage regulator
- Used in power transmission and distribution system and also in the audio system and railways.

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ASSIGNMENT

Q.1 Explain the working principle of a transformer with constructional details.

Q.2 Develop the e.m.f. equation of transformer and hence show that,

$$E_2 / E_1 = V_2 / V_1 = I_1 / I_2 = K$$

Q.3 Explain the behavior of transformer on no load and full load with phasor diagrams.

Q.4 Draw and explain the equivalent circuit of single phase transformer at lagging power factor load.

Q.5 What are the different losses in a transformer? Distinguish between constant losses and variable losses.

Q.6 Show that when the efficiency of a transformer is maximum, the output current becomes equal to the square root of the ratio of iron loss and the equivalent resistance of the transformer referred to secondary.

Q.7 What do you mean by all day efficiency? Why the rating of transformer is express in KVA not in KW?

Q.8 Define voltage regulation of transformer. Derive the expression for it explain how it depends on the load power factor.

Q.9 A 6600/440V Single phase 600 KVA transformer has 1200 primary turns. Find (i) Transformation ratio,(ii) Secondary turns,(iii) Voltage per turn, (iv) Secondary current, when it supplies a load of 400 KW at 0.8 P.F. Lagging.

Q.10 The following reading were obtained for O.C. and S.C. test on 8 KVA,400/120 V, single phase transformer :

O.C. (L.V. Side) :	**120V**	**4A**	**75W**
S.C. (H.V. Side) :	**9.5V**	**20A**	**110W**

(i) The equivalent circuit constants, referred to high voltage side.
(ii) Voltage regulation and efficiency for 0.8 Lagging P.F. at full load.
(iii) The efficiency at half full load and 0.8 power factor lagging load.

Q.11 A 5 KVA transformer has 34 W core loss and 40W copper loss at full load. If operated at rated KVA and 0.8 power factor lagging for 6 Hours. One half rated KVA and 0.5 power factor lagging for 12 hours and no load for 6 hour. What is its all day efficiency?

Q.12 The maximum efficiency of a 500 KVA 3000/500V, 50Hz, 1-Phase transformer is 98% and occurs at ¾ th of full load at unity power factor. If the impedance is 10% calculate the regulation at full load 0.8 p.f. lagging.

Q.13 A 200KVA, 1000/250V,50Hz 1-Phase transformer gave the following results

No load test	**250V**	**18A**	**1300W**
Short circuit test	**80V**	**200A**	**2400W**

Calculate the all day efficiency if the transformer is loaded as follows during a day:

8 Hours Full load at 0.8 p.f. Lagging

10 Hours Half load at unity p.f.

6 Hours at no load

Q.14 The primary and secondary voltage of an auto transformer are 500V and 400V respectively. Show with the aid of diagram the current distribution in the winding. When the secondary current is 100 A and calculate the economy of copper in this particular case.

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