LNCT GROUP OF COLLEGES

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Department: EX

Subject: BEEE

Unit: III

Topic: TRANSFORMER

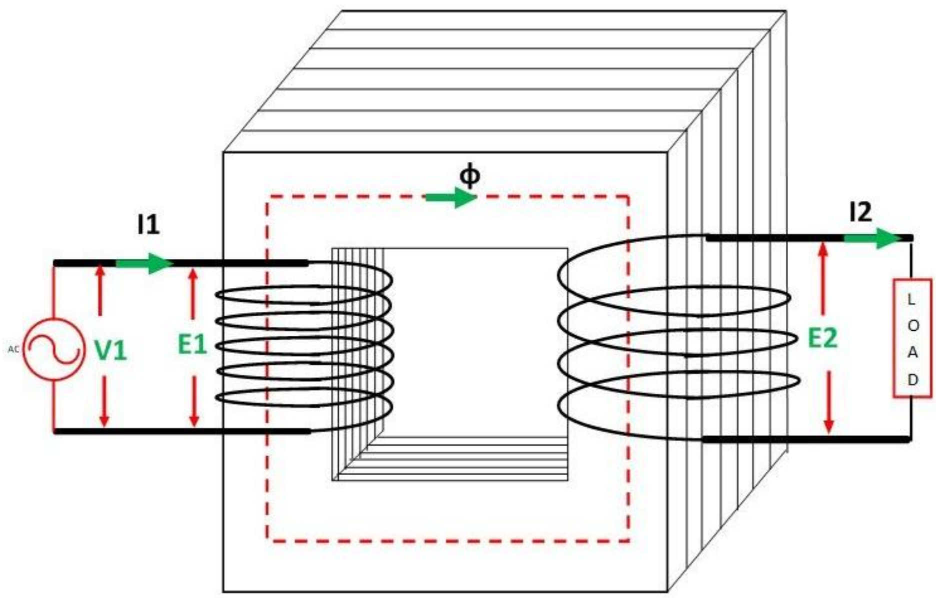
DEFINITION OF TRANSFORMER

A **transformer** is a static device which transfers A.C. Electrical Power from one circuit to another circuit at the same frequency but the voltage level is usually changed. It is most commonly used to increase ('step up') or decrease ('step down') voltage levels between circuits.

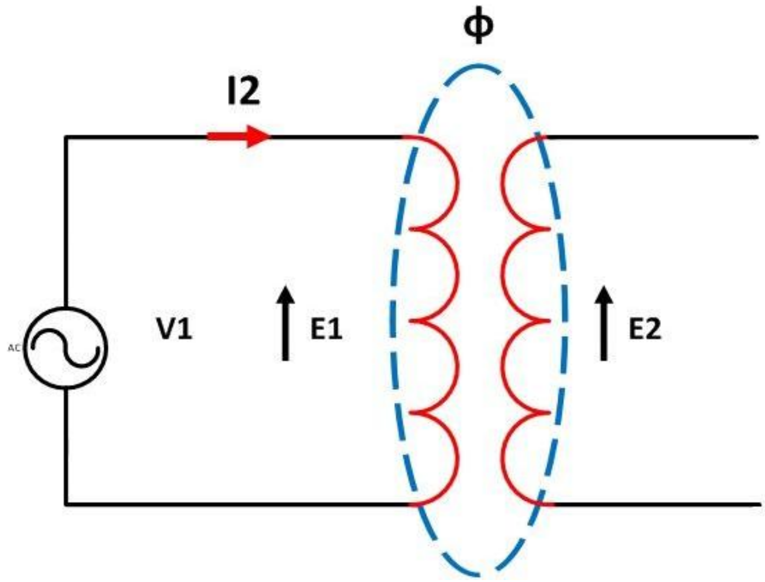
WORKING PRINCIPLE OF TRANSFORMER

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 shown in the figure below:



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 dϕ/dt).

dϕ/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 ($E_1 \infty N_1$). Similarly induced emf in the secondary winding is proportional to the number of turns on the secondary side. ($E_2 \infty N_2$).

Transformation ratio

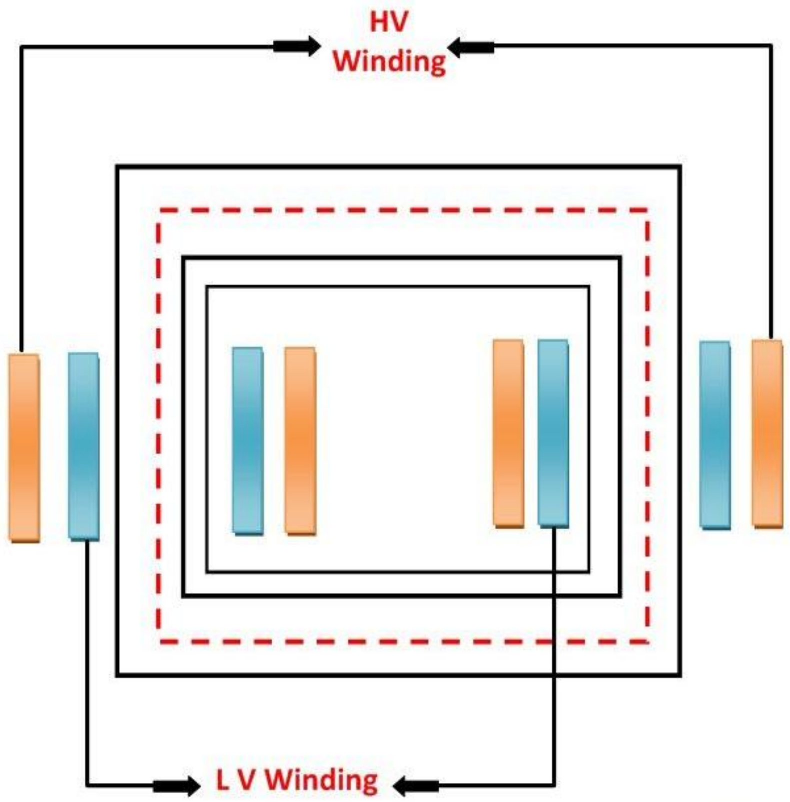
$$E_2/E_1=N_2/N_1=I_1/I_2=K$$

K=TRANSFORMATION RATIO

CONSTRUCTION OF SINGLE PHASE TRANSFORMER

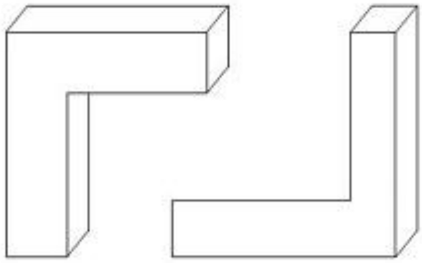
The transformer mainly consists of the Magnetic circuit, electric circuit, dielectric circuit, tanks, and accessories. The main elements of the transformer are the **primary and secondary windings** and the **steel core**. The core of the transformer is made up of silicon steel in order to provide a continuous magnetic path. Usually, the core of the transformer is laminated for minimizing the eddy current loss.

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**.

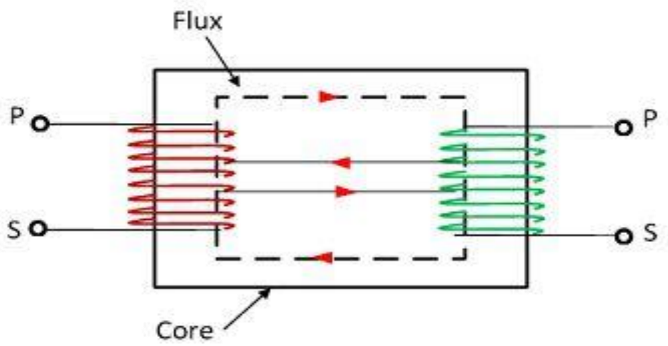


Core Type Transformer

In a simple core type construction of the transformer, 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 secondary windings are interleaved to reduce the leakage flux. Half of each winding is placed side by side or concentrically on the leg of the core as shown in the figure below. For simplicity, the primary and secondary winding is located on the separate limbs of the core.

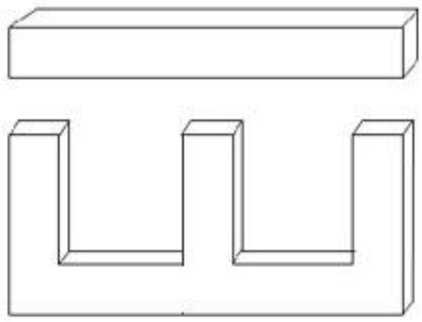


Core Type Transformer

The insulation layer is provided between the core and lower winding and between the primary and the secondary winding. For reducing the insulation, the low winding is always placed near to the core. The winding is cylindrical, and the lamination is inserted later on it.

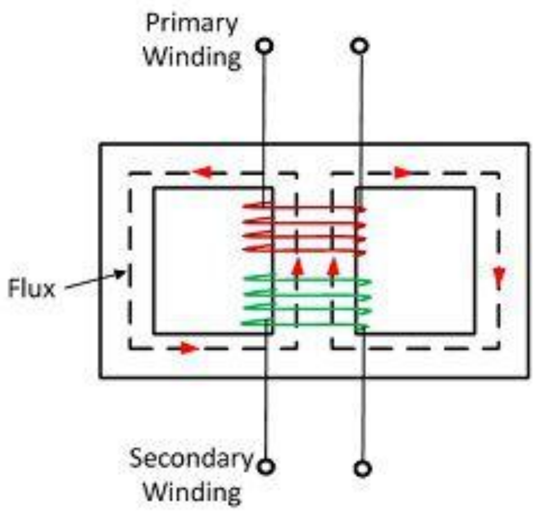
Shell Type Transformer

The laminations are cut in the form of a long strip of E's, and I's as shown in the figure below. To reduce the high reluctance at the joints where the lamination are butted against each other, the alternate layers are stacked differently to eliminate continuous joint.



Shell Type Transformer

The shell type transformer has three limbs or legs. The central limb carries the whole of the flux, and the side limb carries the half of the flux. Hence the width of the central limb is about to double to that of the outer limbs.



Shell Type Transformer

The primary and secondary both the windings are placed on the central limbs. The low voltage winding is placed near the core, and the high voltage winding is placed outside the low voltage winding to reducing the cost of insulation placed between the core and the low voltage winding. The windings are cylindrical, and the core laminations are inserted on it.

Differences Between Core Type and Shell Type Transformer

1. In core type transformer the core surrounds the windings whereas in shell type transformer the winding surrounds the core of the transformer.

2. In core type transformer the lamination is cut in the form of L-shape whereas, in shell type transformer, the laminations are cut in the E and L shapes.

3. The cross-section area of the core type transformer is rectangular, whereas the cross-section area of the shell type transformer is square, cruciform two slipped, or three stepped in shapes.

4. The core type transformer requires more copper conductor as compared to shell type transformer because in core type transformer the winding is placed on the separate limbs or legs.

5. The core type transformer is also called cylindrical or core winding transformer because their windings are arranged as the concentric coil. In shell type transformer, the low voltage winding and the high voltage winding are put in the form of the sandwich, and hence it is called the sandwich or disc winding transformer.

6. The core type transformer has two limbs, whereas the shell type transformer has three limbs.

7. The mechanical strength of the core type transformer is low as compared to shell type transformer because the shell type transformer has bracings.

8. The core type transformer required less insulation as compared to shell type transformer because shell type transformer has three limbs.

9. In core type transformer the flux is equally distributed to the side limb of the transformer whereas, in shell type transformer, the central limb carries the whole of the flux and the side limbs carry the half of the flux.

10. In core type transformer both the primary and the secondary windings are placed on the side limbs whereas, in shell type transformer, the windings are placed on the central limbs of the transformer.

11. The core type transformer has two magnetic circuits whereas the shell type transformer has one magnetic circuit.

12. The losses in a core type transformer are more as compared to shell type transformer because the core type transformer consists two magnetic circuits.

13. In core type transformer few windings are removed for maintenance. In shell type transformer numbers of the winding are required to remove for the maintenance.

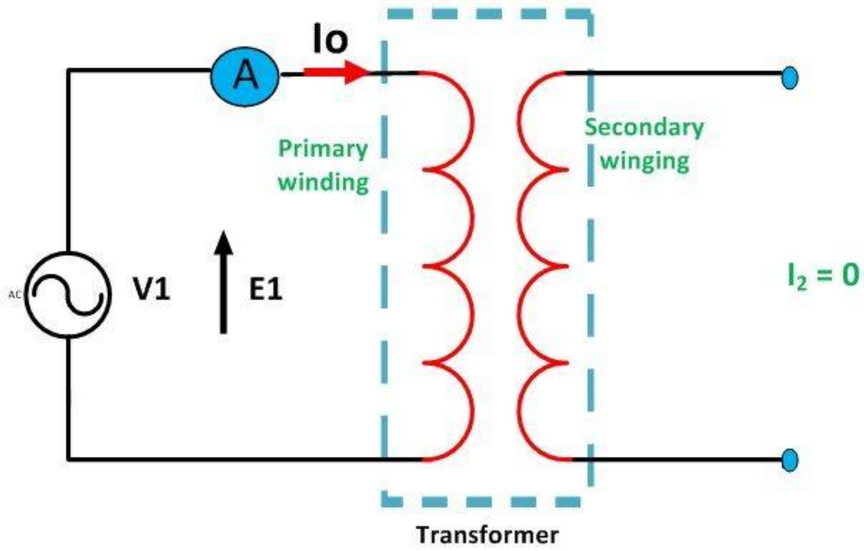
14. The output of the core type transformer is less because it has more losses as compared to the shell-type transformer.

15. The winding of the shell type transformer is distributed type, and hence heat is dissipated naturally, whereas, in core type transformer, the natural cooling is not possible.

The laminations of both the transformer are made up of high-grade silicon steel. The lamination reduces the eddy-current loss, and silicon steel reduces the hysteresis loss. The laminations are insulated from each other by using the enamel insulation coating.

Transformer on No Load: 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. varies from 0.1 to 0.15.



The no-load current consists of two components:

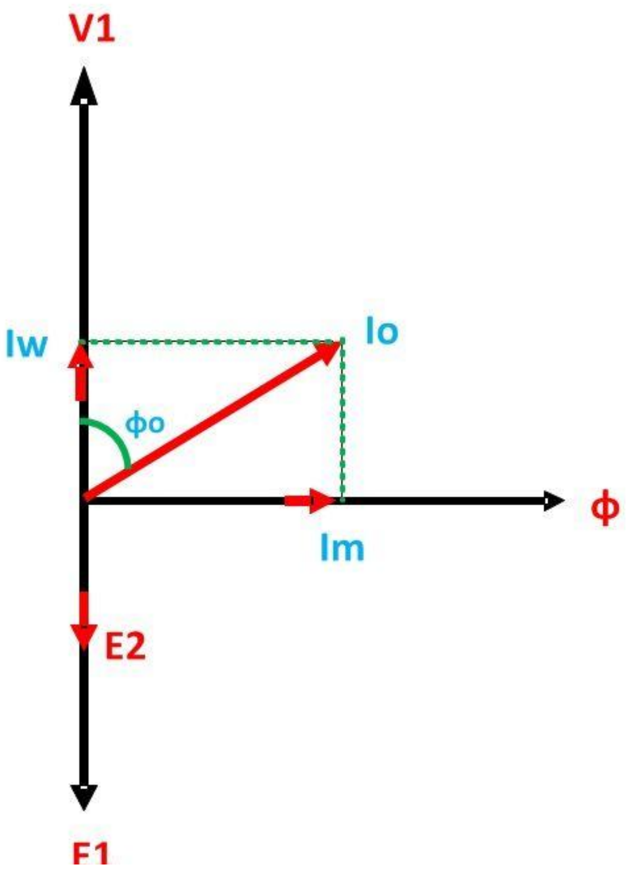
- **Reactive or magnetizing component I_m**

(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 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 . 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.



Working component $I_w = I_0 \cos\varphi_0$

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

Magnetizing component $I_m = I_0 \sin\varphi_0$

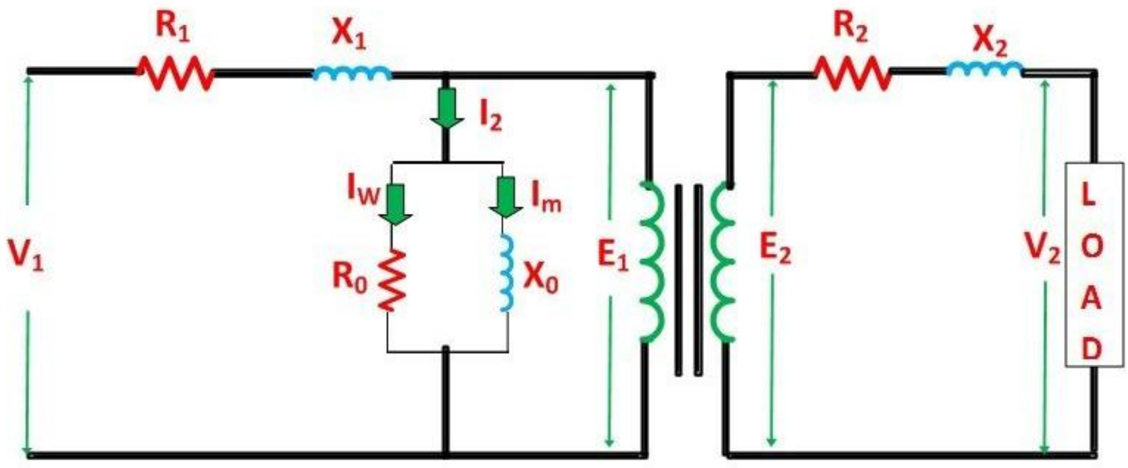
Power factor $\cos\varphi_0 = \frac{I_w}{I_0}$

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

EQUIVALENT CIRCUIT

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.

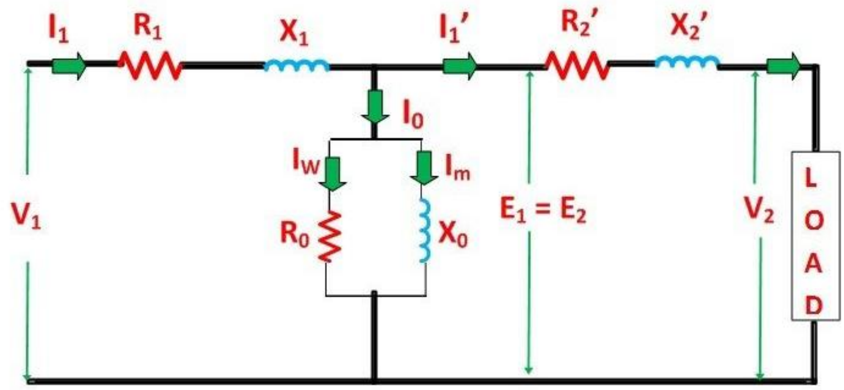
The simplified equivalent circuit of a transformer is drawn by representing all the parameters of the transformer either on the secondary side or on the primary side. The equivalent circuit diagram of the transformer is shown below:



EXACT EQUIVALENT CIRCUIT DIAGRAM OF A TRANSFORMER

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:



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:

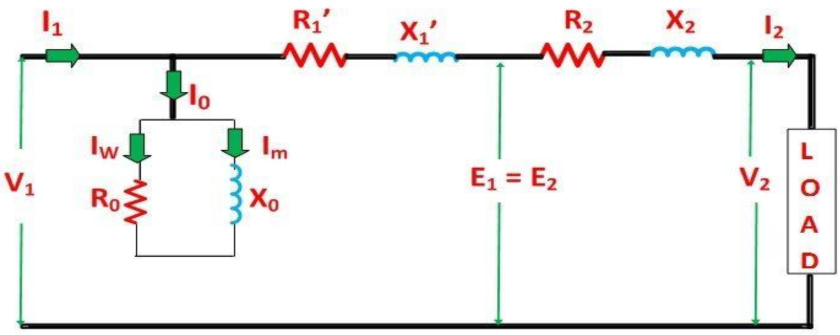
$$X_2' = \frac{X_2}{K^2}$$

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

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

$$X_1' = K^2 X_1$$

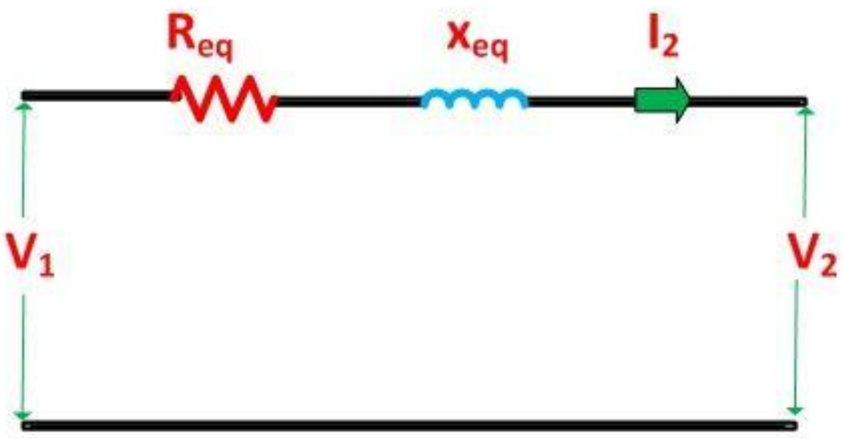
The equivalent reactance referred to the secondary side is given as

$$X_{eq} = X_2 + X_I'$$

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.

The simplified Approximate Equivalent circuit diagram of the transformer is shown below:



Simplified Equivalent Circuit Diagram of a Trans

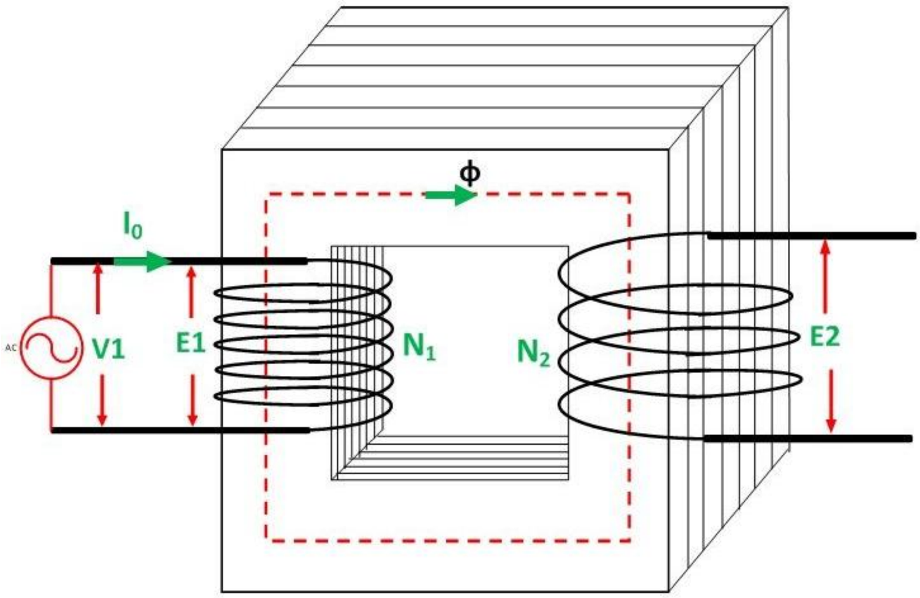
Transformer On Load Condition

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 I2 flows through the secondary winding of the transformer. The magnitude of the secondary current depends on the terminal voltage V2 and the load impedance. The phase angle between the secondary current and voltage depends on the nature of the load.

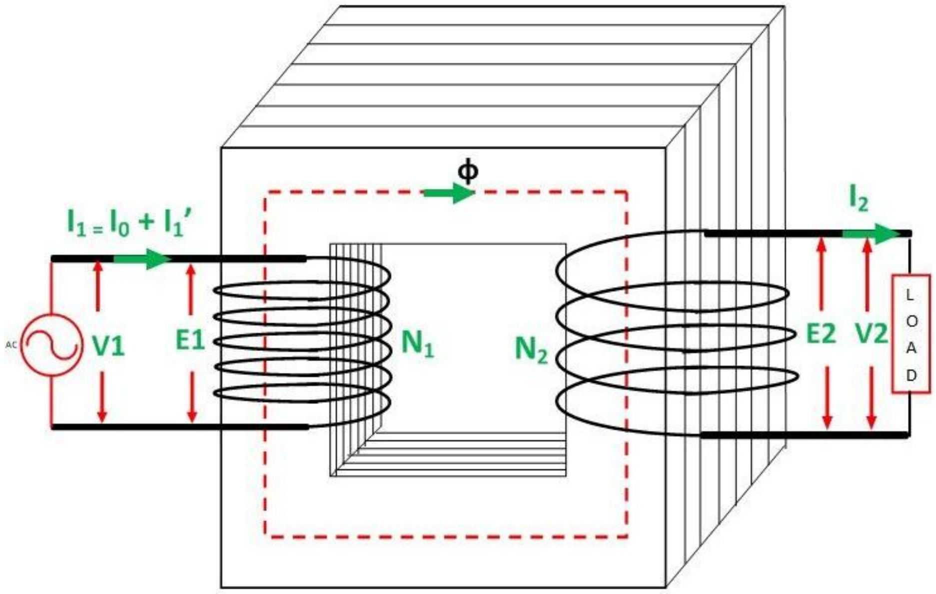
Operation of the Transformer on Load Condition

The Operation of the Transformer on Load Condition is explained below:

- 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_{0I0} and this force set up the flux Φ in the core of the transformer. The circuit of the transformer at no load condition is shown in the figure below:



  - 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 φ2 in the transformer core. The flux φ_2 opposes the flux φ, according to Lenz's law.



- As the flux φ2 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 I2. 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 φ2 which induces because of the MMF N_2I_2

Now, $N_1I_{1'} = N_2I_2$

Therefore,

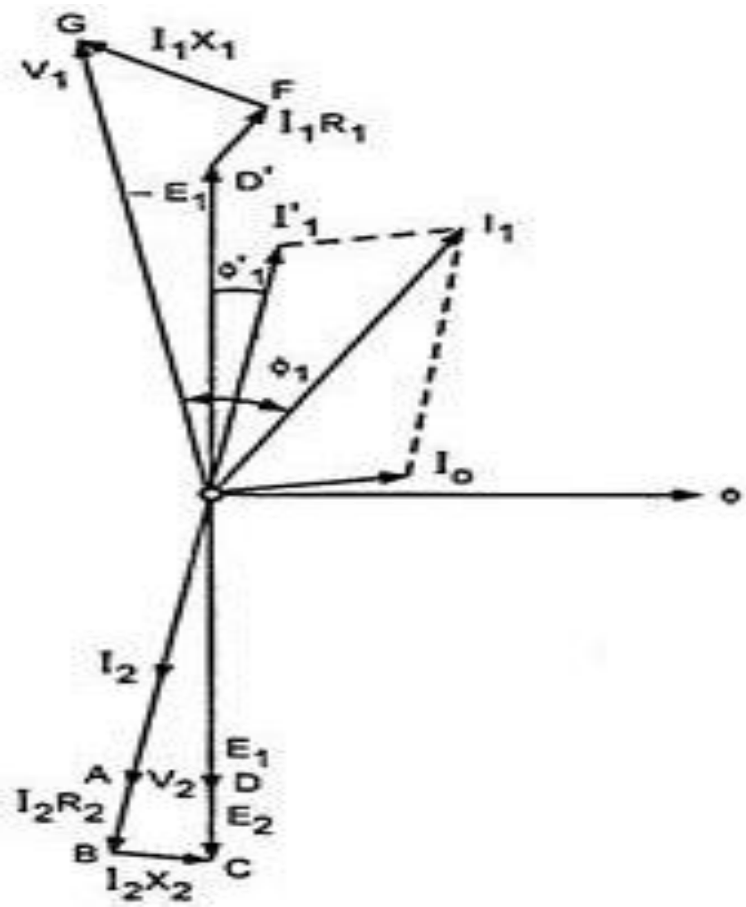
$$I_1' = \left(\frac{N_2}{N_1}\right) I_2 = KI_2$$

- The phase difference between V1 and I1 gives the power factor angle ϕ1 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 I1 is the vector sum of the currents I0 and I1'. i.e

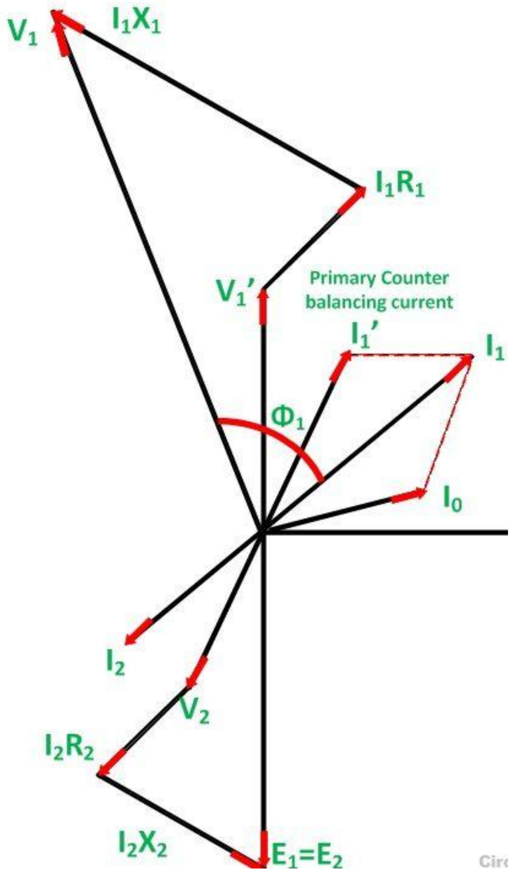
$$\overline{I_1} = \overline{I_0} + \overline{I_1'}$$

<u>Phasor Diagram of Transformer for pure Resistive Load</u>



Phasor Diagram of Transformer for Inductive Load

The phasor diagram of the actual transformer when it is loaded inductively is shown below:



Phasor Diagram of the Transformer on Inductive Load

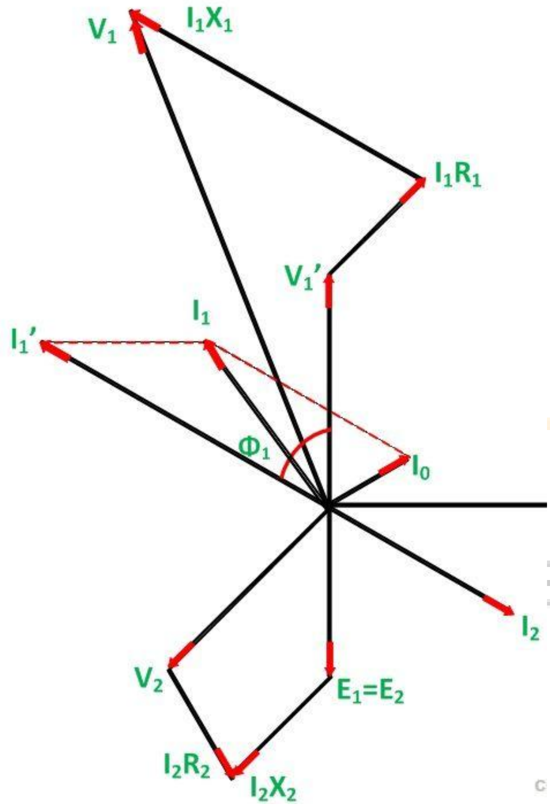
Steps to draw the phasor diagram

- Take flux ϕ, a reference
- Induces emf E1 and E2 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. E1 is represented by V1'.
- Current I0 lags the voltage V1' by 90 degrees.
- The power factor of the load is lagging. Therefore current I2 is drawn lagging E2 by an angle ϕ2.

- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V2 is the phase difference of E2 and voltage drop.

Phasor Diagram of Transformer on Capacitive Load

The Transformer on the Capacitive load (leading power factor load) is shown below in the phasor diagram.



Phasor Diagram of the Transformer on Capacitive Load

Steps to draw the phasor diagram at capacitive load

- Take flux ϕ a reference
- Induces emf E1 and E2 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. E1 is represented by V1'.
- Current I0 lags the voltage V1' by 90 degrees.

- The power factor of the load is leading. Therefore current I2 is drawn leading E2
- The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V2 is the phasor difference of E2 and voltage drop.

V2 = E2 – voltage drops

I2 R2 is in phase with I2 and I2X2 is in quadrature with I2.

- Current I1' is drawn equal and opposite to the current I2
- The total current I1 flowing in the primary winding is the phasor sum of I1' and I0.
- Primary applied voltage V1 is the phasor sum of V1' and the voltage drop in the primary winding.

V1 = V1' + voltage drop

I1R1 is in phase with I1 and I1XI is in quadrature with I1.

- The phasor difference between V1 and I1 gives the power factor angle ϕ1 of the primary side of the transformer.
- The power factor of the secondary side depends upon the type of load connected to the transformer.

This is all about the phasor diagram on various loads.

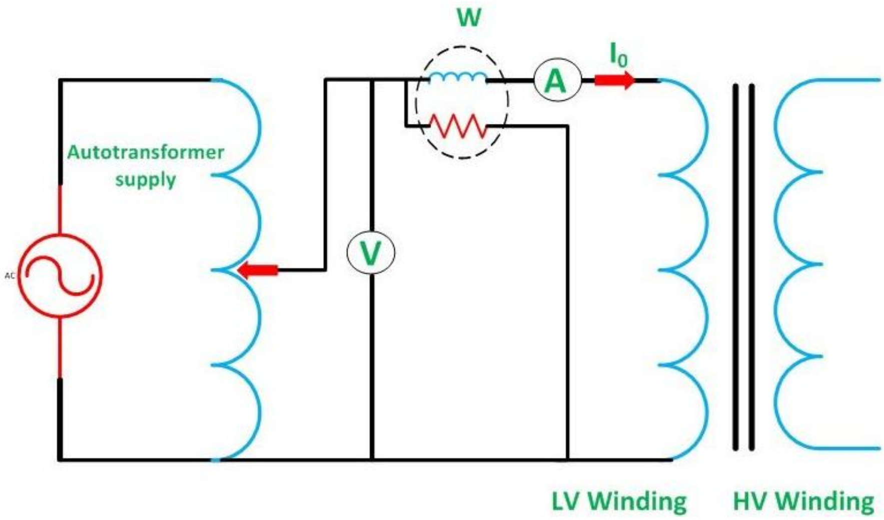
Testing of Transformer:

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 the 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 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.



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 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

$$W_0 = V_1 I_0 \cos\varphi_0 \quad \text{.............}(1)$$

The no-load power factor is

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

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

$$I_w = I_0 \cos\varphi_0$$

Magnetizing component is

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

No load parameters are given below

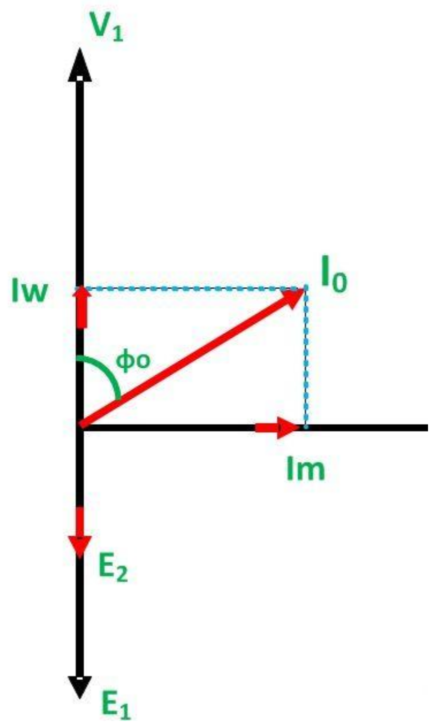
Equivalent exciting resistance is

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

Equivalent exciting reactance is

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

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



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

Short Circuit Test

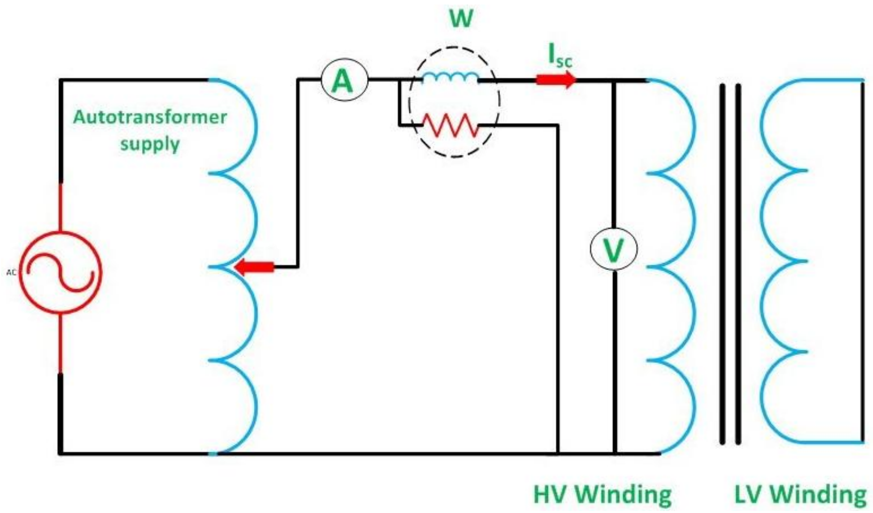
The short circuit test is performed for determining the below mention parameter of the transformer.

- 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 shortcircuited 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 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 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

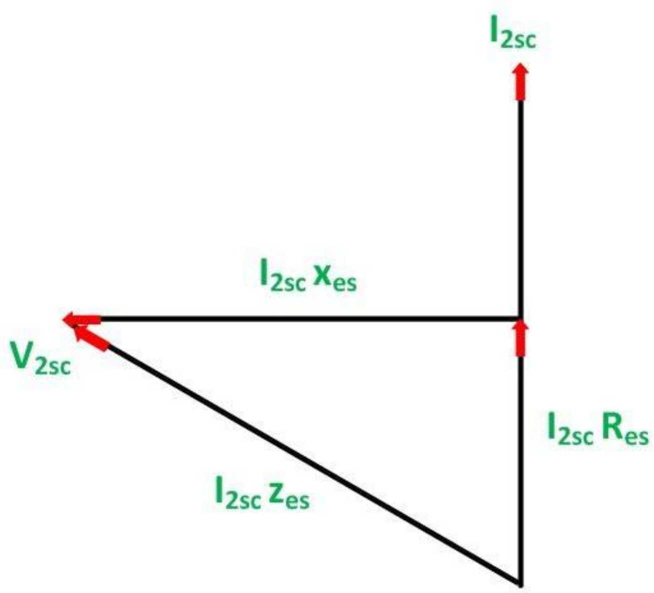
Then the full load copper loss of the transformer is given by

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

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



Phasor Diagram of Short Circuit Test

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.