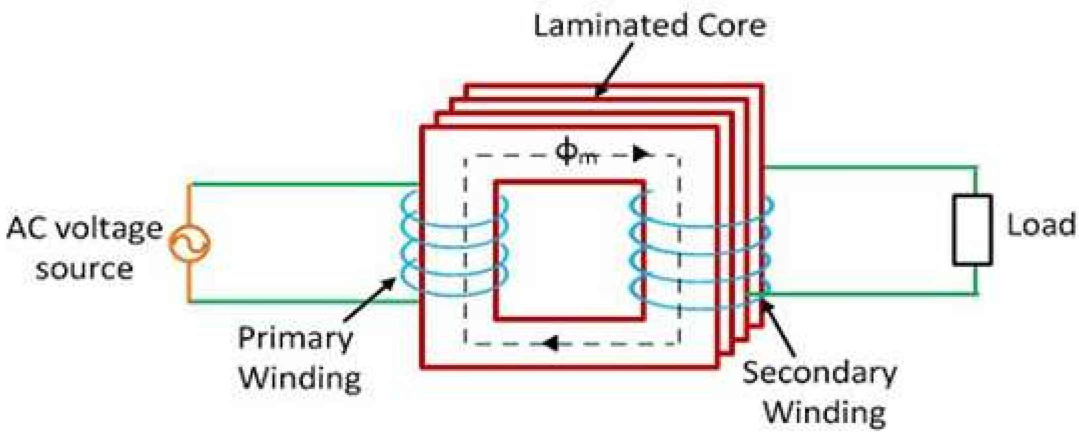
Transformer

The transformer is the static device which works on the principle of electromagnetic induction. It is used for transferring the electrical power from one circuit to another without any variation in their frequency. In electromagnetic induction, the transfer of energy from one circuit to another takes places by the help of the mutual induction. i.e. the flux induced in the primary winding is linked with the secondary winding.

Construction of an Electrical Transformer

The primary winding, secondary winding and the magnetic core are the three important of the transformer. These coils are insulated from each other. The main flux is induced in the primary winding of the transformer. This flux passes through the low reluctance path of the magnetic core and linked with the secondary winding of the transformer.



Transformer Working

The main principle of operation of a transformer is electromagnetic induction.

Consider the N1 and N2 are the numbers of the turn on the primary and the secondary winding of the transformer shown in the figure above. The voltage is applied to the primary winding of the transformer because of which the current is induced in it. The current causes the magnetic flux which is represented by the dotted line in the above figure.

The flux induces in the primary winding because of self-induction. This flux is linked with the secondary winding because of mutual induction. Thus, the emf is induced in the secondary winding of the transformer. The power is transferred from the primary winding to the secondary winding. The frequency of the transferred energy also remains same.

The produced electro-motive force can be explained with the help of Faraday's laws of Electromagnetic Induction as

$$e=N*d\Phi/dt$$

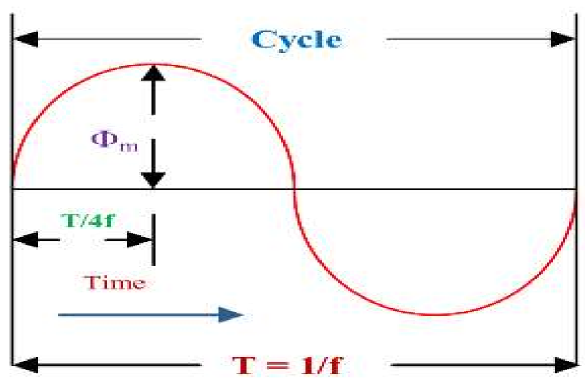
The induced emf in primary and secondary windings depends upon rate of change of flux linkages. The rate of change of flux is same for both primary and secondary; therefore induced emf in primary is proportional to number of turns of primary windings and in secondary is proportional to number of turns of secondary winding.

E.M.F. Equation of transformer

Suppose N_1 = No. of turns of primary coil & N_2 = No. of turns of secondary coil of a transformer.

Φ_m = Maximum flux in core (Webers)

$= B_m \times A$



f= frequency of alternating current in Hz

From the figure, it has been seen that the flux Φ increases from its zero value to maximum value Φm in one quarter of the cycle i.e in 1/4 f second

$$\therefore average\ rate\ of\ change\ of\ flux = \frac{\Phi m}{1/4f}$$

$$=4\ f\ \Phi_m \text{ Wb/s or volt}$$

Now, rate of change of flux per turn means induced e.m.f in volts.

$\therefore$ average e.m.f/ turn = 4 f Φ_m volt

If the magnitude of flux Φ varies sinusoidally, then the r.m.s value of induced e.m.f is obtained by multiplying the average value with from factor.

$$\therefore \text{ From factor } = \frac{r.m.s\ value}{average\ value} = 1.11$$

$\therefore$ r.m.s value of e.m.f./turn = 1.11 x $4f\Phi_m = 4.44\ f\Phi_m$ volt

Now, r.m.s value of the induced e.m.f in the primary winding

$\therefore E_1$ = (induced e.m.f/turn) x No. of primary turns

$\therefore E_1 = 4.44\ f\ \Phi_m\ N_1$ (As $\Phi_m = B_m \times A$)

$\therefore E_1 = 4.44\ f\ N_1 B_m\ A$ .... (i)

Similarly, r.m.s value of the e.m.f. induced in secondary is,

$\therefore E_2$ = (induced e.m.f/turn) x No. of Secondary turns

$= 4.44\ f\ \Phi_m\ N_2$ (As $\Phi_m = B_m \times A$)

$\Rightarrow E_2 = 4.44\ f\ N_2\ B_m\ A$ ....(ii)

It is seen from equation (i) and (ii) that $E_1 / N_1 = E_2 / N_2 = 4.44\ f\ \Phi_m$.

From the above equation it is seen that the e.m.f/ turn is the same in both primary and secondary windings.

Voltage Transformation Ratio
.From equation (i) and (ii), we get

$\therefore E_1 / N_1 = E_2 / N_2 = 4.44\ f\ \Phi_m = K$

Constant K is known as voltage transformation ratio.

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

ii) If $N_2 < N_1$ i.e $K < 1$, then transformer is

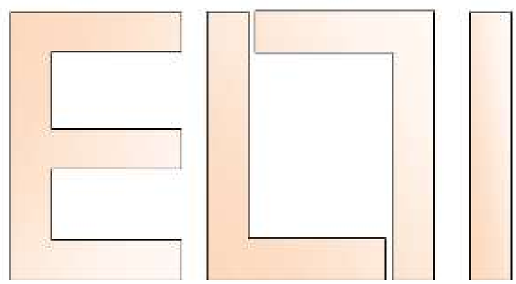
called step-down transformer.

Transformer types on basis of construction

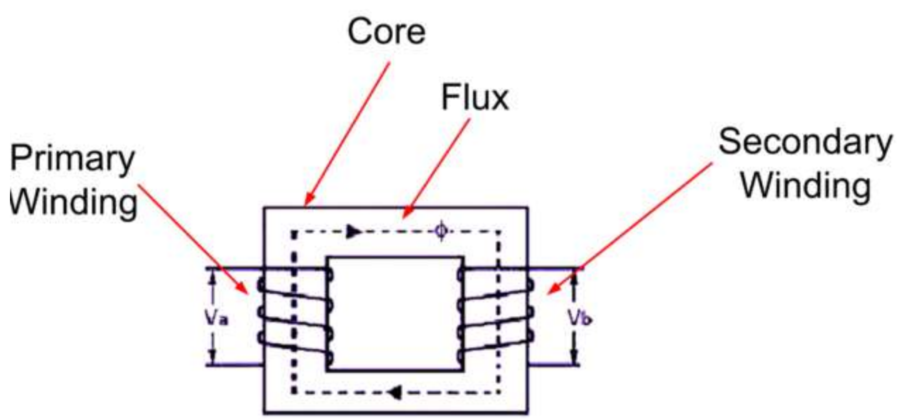
According to core construction and manner in which primary and secondary windings are placed around it, transformer can be categorized in two types:

a) Core type
b) Shell type

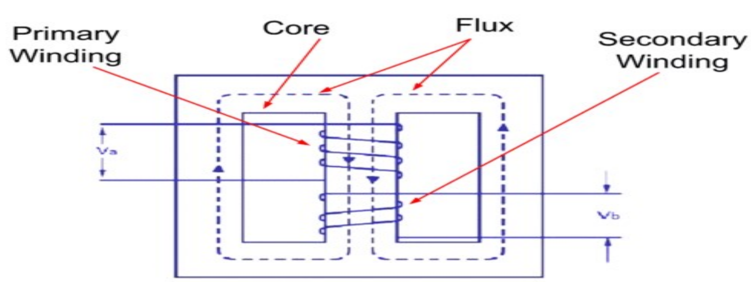
In core and shell-type transformer, the laminations are in the following types i.e. L, E, &I types respectively, which are shown in fig. To avoid high reluctance at joints, the laminations are butted each other which is shown in fig.



Core Type transformer: In **core** type transformers, winding is positioned on two limbs of the core and there is only one flux path and windings are circumventing the core.



Shell Type transformer: In shell type transformers, winding is positioned on the middle limb of the core while other limbs are utilized as the mechanical support.



<u>**Ideal transformer**</u>

An ideal transformer is an imaginary transformer which has. - no copper losses (no winding resistance) - no iron loss in core. - no leakage flux. In other words, an ideal transformer gives output power exactly equal to the input power.
In an ideal transformer, there is no power loss. Therefore, the output power is equal to the input power.

$$E_2 I_2 \cos\varphi = E_1 I_1 \cos\varphi \quad \text{or} \quad E_2 I_2 = E_1 I_1$$

OR

$$\frac{E_2}{E_1} = \frac{I_1}{I_2}$$

Since $E_1 \infty N_2$ and $E_1 \infty N_1$, also E_1 is similar to V_1 and E_2 is similar to V_2

Therefore, the transformation ratio will be given by the equation shown below

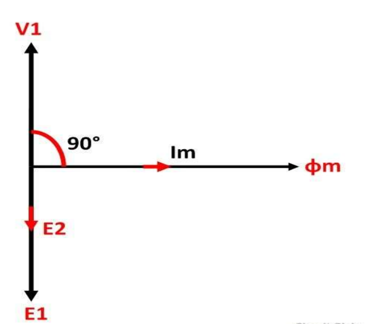
$$\frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$$

The primary and the secondary currents are inversely proportional to their respective turns.

Phasor diagram:

The phasor diagram of the ideal transformer is shown in the figure below. As the coil of the primary transformer is purely inductive the magnetizing current induces in the transformer lag 90º by the input voltage V_1.

The E_1 and E_2 are the emf induced in the primary and secondary winding of the transformer. The direction of the induced emf is inversely proportional to the applied voltage.



Losses in Transformer

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

1. 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.
   (a) 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.

(b) 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 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 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 – co-efficient of eddy current. Its value depends upon the nature of magnetic material like volume and resistivity of core material, thickness of laminations, where

- B_m – maximum value of flux density in wb/m^2
- T – thickness of lamination in meters
- F – frequency of reversal of magnetic field in Hz
- V – volume of magnetic material in m^3

2. 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.

Efficiency of transformer

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 Ƞ.

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

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

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

Where,

V_2 – Secondary terminal voltage
I_2 – Full load secondary current
$\cos\phi_2$ – power factor of the load
Pi – Iron losses = hysteresis losses + eddy current losses
Pc – Full load copper losses = I_2^2Res

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

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

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The value of the terminal voltage V2 is approximately constant. Thus, for a given power factor the Transformer efficiency depends upon the load current I2. In equation (1), the numerator is constant and the transformer efficiency will be maximum if the denominator with respect to the variable I2 is equated to zero.

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

Or

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

i.e Copper losses = Iron losses

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

From equation (2) the value of output current I2 at which the transformer efficiency will be maximum is given as

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