Single Phase Transformer

Electrical power transformer is a static device which transforms electrical energy from one circuit to another without any direct electrical connection and with the help of mutual induction between two windings. It transforms power from one circuit to another without changing its frequency but may be in different voltage level.
A single-phase transformer is a type of power transformer that utilizes single-phase alternating current, meaning the transformer relies on a voltage cycle that operates in a unified time phase.
The working principle of the single phase transformer is based on the Faraday's law of electromagnetic induction. Basically, mutual induction between two or more windings is responsible for transformation action in an electrical transformer.

Faraday's law of electromagnetic induction

According to Faraday’s law, “Rate of change of flux linkage with respect to time is directly proportional to the induced EMF in a conductor or coil”.
The principle of operation of a transformer has been explained in the following simple steps:

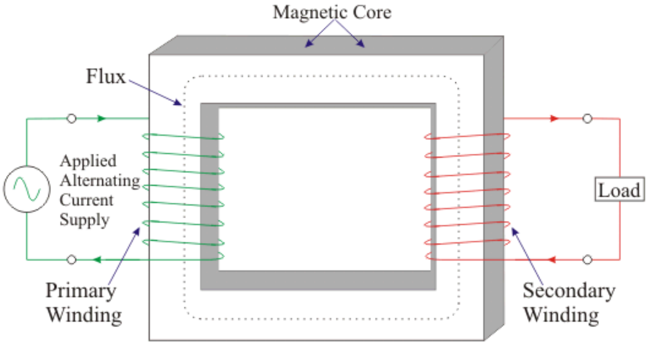
- As soon as the primary winding is connected to a single–phase supply, an AC current starts flowing through it.
- An alternating flux is produced in the core by the AC primary current.
- The alternating flux gets linked with the secondary winding through the core.
- Now, according to Faraday’s laws of electromagnetic induction this varying flux will induce voltage into the secondary winding.

Construction

The three main parts of a transformer are:

- **Primary Winding**: The winding that takes electrical power and produces magnetic flux when it is connected to an electrical source.
- **Magnetic Core**: This refers to the magnetic flux produced by the primary winding. The flux passes through a low reluctance path linked with secondary winding creating a closed magnetic circuit.
- **Secondary Winding**: The winding that provides the desired output voltage due to mutual induction in the transformer.

The primary winding is supplied an alternating electrical source. The alternating current through the primary winding produces an alternating flux that surrounds the winding. Another winding, also known as the secondary winding, is brought close to the primary winding. Eventually, some portion of the flux in the primary will link with the secondary. As this flux is continually changing in amplitude and direction, there is a change in flux linkage in the second winding as well. According to Faraday’s law of electromagnetic induction, an electromotive force (emf) is induced in the secondary winding which is called as induced emf. If the circuit of the secondary winding is closed an induced current will flow through it. This is the simplest form of electrical power transformation; this is the most basic working principle of a transformer.



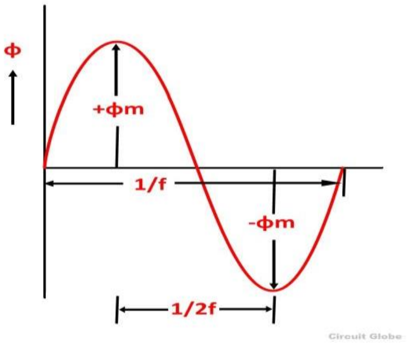
Single Phase Transformer

It consists of two coils of electrical wire called inner and outer windings. The primary is usually known to have the higher amount of voltage. Both coils are wrapped around a common closed magnetic iron circuit which is referred to as the core. The core is made up of several layers of iron, laminated together to decrease losses. Being linked at the common core allows power to be transferred from one coil to the other without an electrical connection. When current passes through the primary coil, a magnetic field is created which induces a voltage in the secondary coil. Usually, the primary coil is where the high voltage comes in and then is transformed to create a magnetic field. The job of the secondary coil is to transform the alternating magnetic field into electric power, supplying the required voltage output.

EMF equation for 1ø transformer: -

When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux ϕ_m sets up in the iron core of the transformer. This sinusoidal flux links with both primary and secondary winding. The function of flux is a sine function. The rate of change of flux with respect to time is derived mathematically.
The derivation of **EMF Equation** of the transformer is shown below. Let

- ϕ_m be the maximum value of flux in Weber
- f be the supply frequency in Hz
- N_1 is the number of turns in the primary winding
- N_2 is the number of turns in the secondary winding
- Φ is the flux per turn in Weber



As shown in the above figure that the flux changes from + ϕ_m to – ϕ_m in half a cycle of 1/2f seconds.

By Faraday's Law

Let E_1 is the emf induced in the primary winding

$$E_1 = -\frac{d\psi}{dt} \ldots \ldots \ldots (1)$$

Where $\Psi = N_1\phi$

$$\text{Therefore, } E_1 = -N_1\frac{d\varphi}{dt} \quad \ldots\ldots\ldots(2)$$

Since ϕ is due to AC supply $\phi = \phi_m \, \mathrm{Sin}(wt)$

$$E_1 = -N_1\frac{d}{dt}(\varphi_m \, \mathrm{Sinwt})$$

$$E_1 = -N_1 \, w\varphi_m \, \mathrm{Coswt}$$

$$E_1 = N_1 w\varphi_m \, \mathrm{Sin}(wt - \pi/2) \ldots \ldots \ldots . (3)$$

So, the induced emf lags flux by 90 degrees.

Maximum valve of emf

$$E_1 \mathrm{max} = N_1 w\varphi_m \ldots \ldots \ldots . (4)$$

But w = 2πf

$$E_1 \mathrm{max} = 2\pi f N_1 \varphi_m \ldots \ldots \ldots . (5)$$

Root mean square RMS value is

$$E_1 = \frac{E_{1max}}{\sqrt{2}} \dots \dots \dots \dots (6)$$

Putting the value of E_1max in equation (6) we get

$$E_1 = \sqrt{2}\pi f N_1 \varphi_m \dots\dots (7)$$

Putting the value of $\pi = 3.14$ in the equation (7) we will get the value of E_1 as

$$E_1 = 4.44 f N_1 \varphi_m \dots \dots \dots (8)$$

Similarly,

$$E_2 = \sqrt{2}\pi f N_2 \varphi_m$$

Or

$$E_2 = 4.44 f N_2 \varphi_m \dots \dots \dots (9)$$

Now, equating the equation (8) and (9) we get

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

Or

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

The above equation is called the turn ratio where K is known as transformation ratio.

The equation (8) and (9) can also be written as shown below using the relation

($\phi m = B_m$ x A_i) where A_i is the iron area and B_m is the maximum value of flux density.

$$E_1 = 4.44 N_1 f B_m A_i \text{ Volts} \quad \text{and} \quad E_2 = 4.44 N_2 f B_m A_i \text{ Volts}$$

For a sinusoidal wave

$$\frac{\text{R.M.S value}}{\text{Average value}} = \text{Form factor} = 1.11$$

Losses in Transformer

In any electrical machine, 'loss' can be defined as the difference between input power and output power. An electrical transformer is an static device, hence mechanical losses (like windage or friction losses) are absent in it. A transformer only consists of electrical losses (iron losses and copper losses). Transformer losses are similar to losses in a DC machine, except that transformers do not have mechanical losses. **Losses in transformer** are explained below -

(I) Core Losses or Iron Losses

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

- **Hysteresis loss in transformer**: Hysteresis loss is due to reversal of magnetization in the transformer core. This loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. It can be given by, Steinmetz formula:
  $W_h = \eta B_{max}^{1.6} f V$ (watts)
  where,

η = Steinmetz hysteresis constant
V = volume of the core in m^3

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

(II) Copper Loss in Transformer

Copper loss is due to ohmic resistance of the transformer windings. Copper loss for the primary winding is $I_1^2R_1$ and for secondary winding is $I_2^2R_2$. Where, I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively. Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load.

Efficiency of Transformer

Just like any other electrical machine, **efficiency of a transformer** can be defined as the output power divided by the input power. That is efficiency = output / input.

Transformers are the most highly efficient electrical devices. Most of the transformers have full load efficiency between 95% to 98.5%. As a transformer being highly efficient, output and input are having nearly same value, and hence it is impractical to measure the efficiency of transformer by using output / input. A better method to find efficiency of a transformer is using,

efficiency = (input - losses) / input = 1 - (losses / input).

Condition for Maximum Efficiency

Let, Copper loss = I12R1, Iron loss = Wi

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2R_1 + W_i}{V_1I_1\cos\Phi_1}$$

$$\eta = 1 - \frac{I_1R_1}{V_1\cos\Phi_1} - \frac{W_i}{V_1I_1\cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1\cos\Phi_1} + \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

η will be maximum at $\frac{d\eta}{dI_1} = 0$

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\frac{I_1^2R_1}{V_1I_1^2\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$I_1^2R_1 = W_i$$

Hence, **efficiency of a transformer** will be maximum when copper loss and iron losses are equal. That is Copper loss = Iron loss.

All Day Efficiency of Transformer

As we have seen above, ordinary or commercial efficiency of a transformer can be given as

$$\text{ordinary efficiency} = \frac{\text{output (in watts)}}{\text{input (in watts)}}$$

But in some types of transformers, their performance cannot be judged by this efficiency. For example, distribution transformers have their primaries energized all the time. But, their secondaries supply little load all no-load most of the time during day (as residential use of electricity is observed mostly during evening till midnight). That is, when secondaries of transformer are not supplying any load (or supplying only little load), then only core losses of transformer are considerable and copper losses are absent (or very little). Copper losses are considerable only when transformers are loaded. Thus, for such transformers copper losses are relatively less important. The performance of such transformers is compared based on energy consumed in one day.

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

All day efficiency of a transformer is always less than ordinary efficiency of it.

Auto Transformer

An A**uto Transformer** is a transformer with only one winding wound on a laminated core. An auto transformer is like 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.**

Explanation of Auto Transformer with Circuit Diagram

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 and 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.

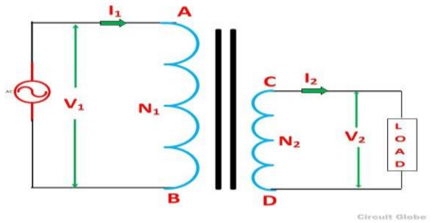


Figure A: Ordinary Two Winding Transformer

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 desired secondary voltage and 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.

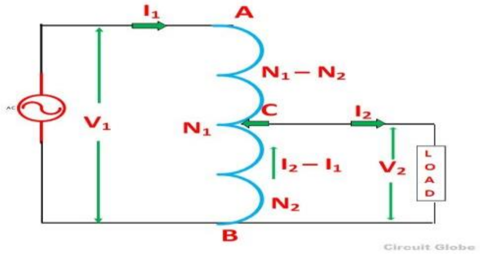


Figure B: Auto – Transformer

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,

$$V_1 = E_1 \text{ and } V_2 = E_2$$

Therefore, the transformation ratio

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

Transformer Inrush Current

Definition: The transformer inrush current is the maximum instantaneous current drawn by the primary of the transformer when their secondary is open circuit. The inrush current does not create any permanent fault, but it causes an unwanted switching in the circuit breaker of the transformer. During the inrush current, the maximum value attained by the flux is over twice the normal flux.