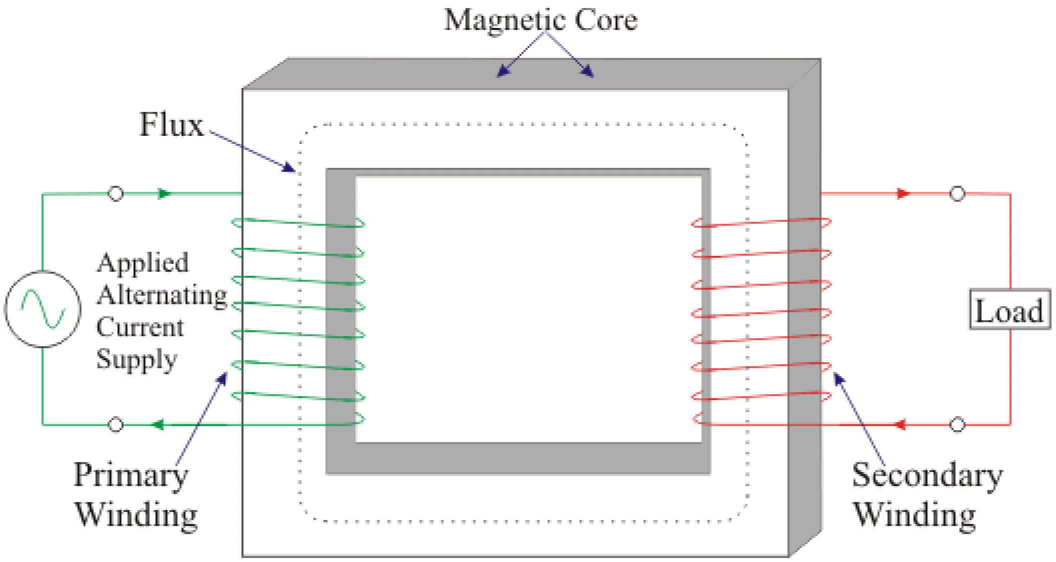
UNIT-II
TRANSFORMERS

Single Phase Transformer and Applications of Single Phase Transformer



Single Phase Transformer

$$E_{rms} = 4,44 \times f \times N \times \Phi_{max}$$

Transformer is electromagnetic static electrical equipment (with no moving parts) which transforms magnetic energy to electrical energy. It consists of a magnetic iron core serving as a magnetic transformer part and transformer cooper winding serving as electrical part. The transformer is high-efficiency equipment, and its losses are very low because there isn't any mechanical friction inside. Transformers are used in almost all electrical systems from low voltage up to the highest voltage level. It operates only with alternating current (AC), because the direct current (DC) does not create any electromagnetic induction. Depending on the electrical network where the transformer is installed, there are two transformer types, three-phase transformers and **single phase transformers**. The operation principle of the single-phase transformer is: the AC voltage source injects the AC current through the transformer primary winding.

The AC current generates the alternating electromagnetic field. The magnetic field lines are moving through iron transformer core and comprise the transformer secondary circuit. Thus the voltage is induced in the secondary winding with the same frequency as the voltage of the primary side. The induced voltage value is determine by Faraday's Law.

Where,
f → frequency Hz
N → number of winding turns
Φ → flux density Wb

If the load is connected on the secondary transformer side the current will flow through secondary winding. Basically, the **single phase transformers** can operate as step up transformer or step down transformers.

The main parts of a transformer are windings, core, and isolation. The windings should have small resistance value and usually they are made of copper (rarely of aluminum). They are wound around the core and must be isolated from it. Also, the windings turns have to be isolated from each other. The transformer core is made from very thin steel laminations which have high permeability. The laminations have to be thin (between 0.25 mm and 0.5 mm) because of decreasing power losses (known as eddy current losses). They have to be isolated from each other, and usually, the insulating varnish is used for that purpose. The transformer insulation can be provided as dry or as liquid-filled type. The dry-type insulation is provided by synthetic resins, air, gas or vacuum. It is used only for small size transformers (below 500 kVA). The liquid insulation type usually means using mineral oils. The oil has a long life cycle, good isolation characteristics, overload capability and also provides transformer cooling. Oil insulation is always used for big transformers.

The **single phase transformer** contains two windings, one on primary and the other on the secondary side. They are mostly used in the single-phase electrical power system. The three-phase system application means using three single phase units connected in the three-phase system. This is a more expensive solution, and it is used in the high voltage power system.

Applications of Single Phase Transformer

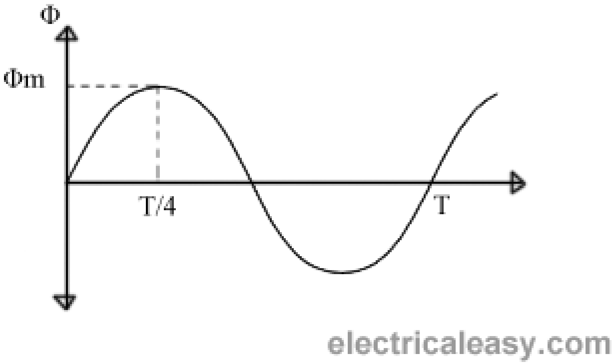
The advantages of three single-phase units are transportation, maintenance, and spare unit availability. The single-phase transformers are widely used in commercial low voltage application as electronic devices. They operate as a step-down voltage transformer and decrease the home voltage value to the value suitable for electronics supplying. On the secondary side, rectifier is usually connected to convert a AC voltage to the DC voltage which is used in electronics application

EMF equation of a transformer and Voltage Transformation Ratio

In a transformer, source of alternating current is applied to the primary winding. Due to this, the current in the primary winding (called as magnetizing current) produces alternating flux in the core of transformer. This alternating flux gets linked with the secondary winding, and because of the phenomenon of mutual induction an emf gets induced in the secondary winding. Magnitude of this induced emf can be found by using the following **EMF equation of the transformer**.

EMF equation of the Transformer

Let,
N_1 = Number of turns in primary winding
N_2 = Number of turns in secondary winding
Φ_m = Maximum flux in the core (in Wb) = (B_m x A)
f = frequency of the AC supply (in Hz)



As, shown in the fig., the flux rises sinusoidally to its maximum value Φ_m from 0. It reaches to the maximum value in one quarter of the cycle i.e in T/4 sec (where, T is time period of the sin wave of the supply = 1/f).
Therefore,
average rate of change of flux = $\Phi_m /_{(T/4)}$ = $\Phi_m /_{(1/4f)}$
Therefore,
average rate of change of flux = 4f Φ_m .... (Wb/s).
Now,
Induced emf per turn = rate of change of flux per turn

Therefore, average emf per turn = 4f Φ_m ....(Volts).

Now, we know, Form factor = RMS value / average value
Therefore, RMS value of emf per turn = Form factor X average emf per turn.

As, the flux Φ varies sinusoidally, form factor of a sine wave is 1.11

Therefore, RMS value of emf per turn = 1.11 x 4f Φ_m = 4.44f Φ_m.

RMS value of induced emf in whole primary winding (E_1) = RMS value of emf per turn X Number of turns in primary winding

$E_1 = 4.44f\ N_1\ \Phi_m$ .... eq 1

Similarly, RMS induced emf in secondary winding (E_2) can be given as

$E_2 = 4.44f\ N_2\ \Phi_m$. .... eq 2

from the above equations 1 and 2,

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

This is called the **emf equation of transformer**, which shows, emf / number of turns is same for both primary and secondary winding.

For an ideal transformer on no load, $E_1 = V_1$ and $E_2 = V_2$.

where, V_1 = supply voltage of primary winding

V_2 = terminal voltage of secondary winding

Voltage Transformation Ratio (K)

As derived above,

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

Where, K = constant

This constant K is known as **voltage transformation ratio**.

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

Transformer - Losses and Efficiency

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**

(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. It is clear that 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

$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2 R_1 + W_i}{V_1 I_1 \cos\Phi_1}$$

$$\eta = 1 - \frac{I_1 R_1}{V_1 \cos\Phi_1} - \frac{W_i}{V_1 I_1 \cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1 \cos\Phi_1} + \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

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

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1 \cos\Phi_1} = \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

$$\frac{I_1^2 R_1}{V_1 I_1^2 \cos\Phi_1} = \frac{W_i}{V_1 I_1^2 \cos\Phi_1}$$

$$I_1^2 R_1 = W_i$$

electricaleasy.com

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 can not 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 on the basis of energy consumed in one day.

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

Voltage Regulation of Transformer

What is Voltage Regulation?

Voltage regulation is a measure of change in the voltage magnitude between the sending and receiving end of a component. It is commonly used in power engineering to describe the percentage voltage difference between no load and full load voltages distribution lines, transmission lines, and transformers.

Explanation of Voltage Regulation of Transformer

Say an electrical power transformer is open circuited, meaning that the load is not connected to the secondary terminals. In this situation, the secondary terminal voltage of the transformer will be its secondary induced emf E_2.

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.

Now if at this loading condition, any one measures the voltage between secondary terminals, he or she will get voltage V_2 across load terminals which is obviously less than no load secondary voltage E_2 and this is because of I_2Z_2 voltage drop in the transformer.

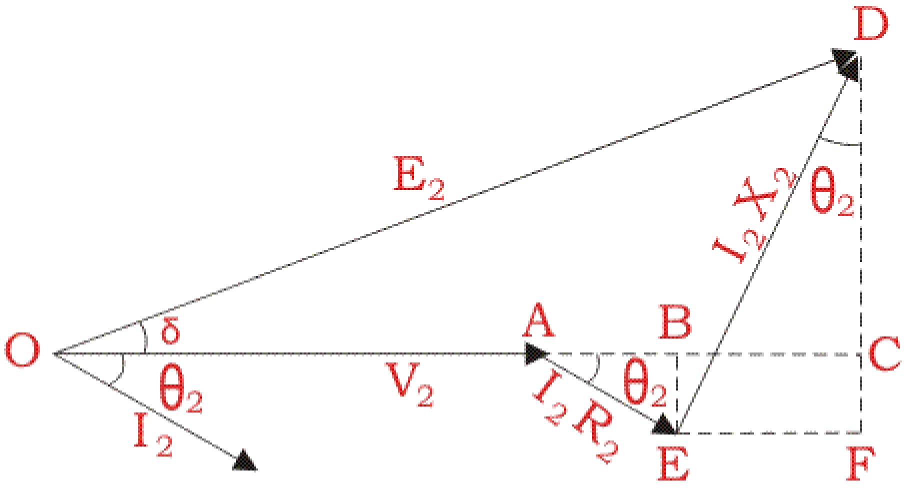
Expression of Voltage Regulation of Transformer

The equation for the **voltage regulation of transformer**, represented in percentage, is

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

Voltage Regulation of Transformer for Lagging Power Factor

Now we will derive the expression of voltage regulation in detail. Say lagging power factor of the load is $\cos\theta_2$, that means angle between secondary current and voltage is θ_2.



Voltage Regulation at Lagging Power Factor

Here, from the above 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.

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

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

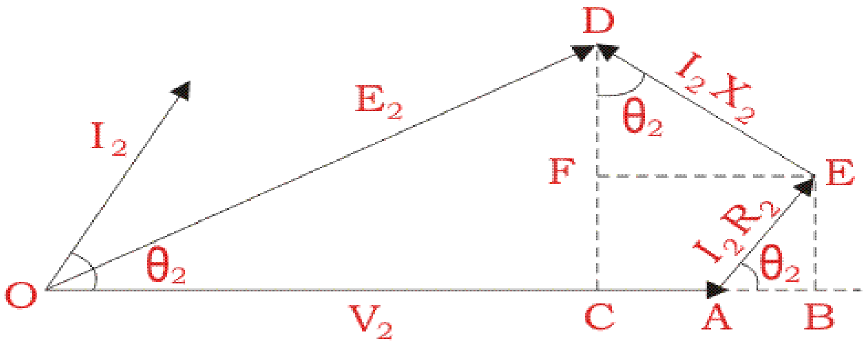
Voltage regulation of transformer at lagging power factor,

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

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

Voltage Regulation of Transformer for Leading Power Factor

Let's derive the expression of voltage regulation with leading current, say 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 above 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 theorectically possible in the case for an ideal transformer.

Open and Short Circuit Test of Transformer

Open and short circuit tests are performed on a transformer to determine the:

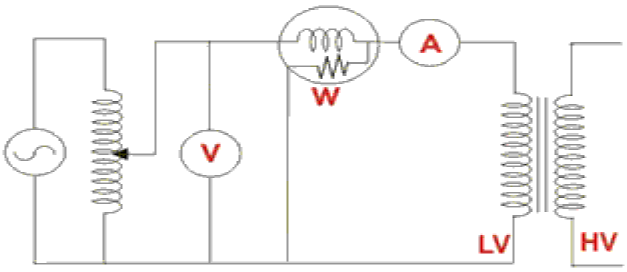
1. Equivalent circuit of transformer
2. Voltage regulation of transformer
3. Efficiency of transformer

The power required for **open circuit tests and short circuit tests on a transformer** is equal to the power loss occurring in the transformer.

Open Circuit Test on Transformer

The connection diagram for **open circuit test on transformer** is shown in the figure. A voltmeter, wattmeter, and an ammeter are connected in LV side of the transformer as shown. The voltage at rated frequency is applied to that LV side with the help of a variac of variable ratio auto transformer.

The HV side of the transformer is kept open. Now with the help of variac, applied voltage gets slowly increased until the voltmeter gives reading equal to the rated voltage of the LV side. After reaching rated LV side voltage, we record all the three instruments reading (Voltmeter, Ammeter and Wattmeter readings).



Open Circuit Test on Transformer

The ammeter reading gives the no load current I_e. As no load current I_e is quite small compared to rated current of the transformer, the voltage drops due to this current that can be taken as negligible.
Since voltmeter reading V_1 can be considered equal to the secondary induced voltage of the transformer, wattmeter reading indicates the input power during the test. As the transformer is open circuited, there is no output, hence the input power here consists of core losses in transformer and copper loss in transformer during no load condition. But as said earlier, the no-load current in the transformer is quite small compared to the full load current so, we can neglect the copper loss due to the no-load current. Hence, can take the wattmeter reading as equal to the core losses in the transformer.
Let us consider wattmeter reading is P_o.

$$P_o = \frac{V_1^2}{R_m}$$

Where, R_m is shunt branch resistance of transformer.
If, Z_m is shunt branch impedance of transformer.

$$Then,\ Z_m = \frac{V_1}{I_e}$$

Therefore, if shunt branch reactance of transformer is X_m,

$$Then,\ \left(\frac{1}{X_m}\right)^2 = \left(\frac{1}{Z_m}\right)^2 - \left(\frac{1}{R_m}\right)^2$$

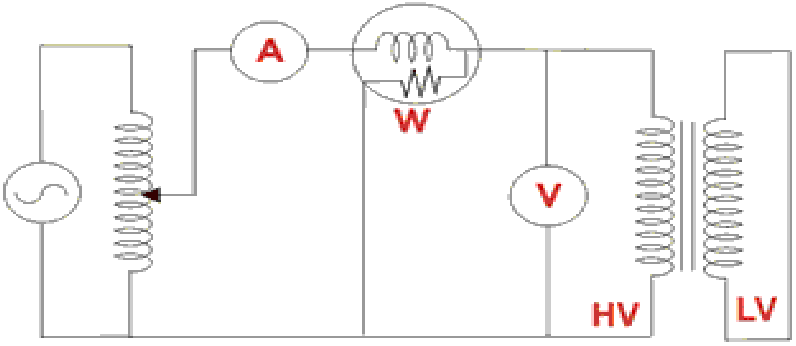
These values are referred to the LV side of the transformer due to the tests being conducted on the LV side of transformer. These values could easily be referred to HV side by multiplying these values with square of transformation ratio.

Therefore it is seen that the **open circuit test on transformer** is used to determine core losses in transformer and parameters of the shunt branch of the equivalent circuit of the transformer.

Short Circuit Test on Transformer

The connection diagram for the short circuit test on the **transformer** is shown in the figure below. A voltmeter, wattmeter, and an ammeter are connected in HV side of the transformer as shown. A low voltage of around 5-10% is applied to that HV side with the help of a variac (i.e. a variable ratio auto transformer). We short-circuit the LV side of the transformer. Now with the help of variac applied voltage is slowly increased until the wattmeter, and an ammeter gives reading equal to the rated current of the HV side.

After reaching the rated current of the HV side, we record all the three instrument readings (Voltmeter, Ammeter and Watt-meter readings). The ammeter reading gives the primary equivalent of full load current IL. As the voltage applied for full load current in a short circuit test on the transformer is quite small compared to the rated primary voltage of the transformer, the core losses in the transformer can be taken as negligible here.



Short Circuit Test on Transformer

Let's say, voltmeter reading is V_{sc}. The watt-meter reading indicates the input power during the test. As we have short-circuited the transformer, there is no output; hence the input power here consists of copper losses in the transformer. Since the applied voltage V_{sc} is short circuit voltage in the transformer and hence it is quite small compared to the rated voltage, so, we can neglect the core loss due to the small applied voltage. Hence the wattmeter reading can be taken as equal to copper losses in the transformer. Let us consider wattmeter reading is P_{sc}.

$$P_{sc} = R_e I_L^2$$

Where, R_e is equivalent resistance of transformer.

If, Z_e is equivalent impedance of transformer.

$$Then,\ Z_e = \frac{V_{sc}}{I_L}$$

Therefore, if equivalent reactance of transformer is X_e.

$$Then,\ X_e^2 = Z_e^2 - R_e^2$$

These values are referred to the HV side of the transformer as the test is conducted on the HV side of the transformer. These values could easily be converted to the LV side by dividing these values with the square of transformation ratio.

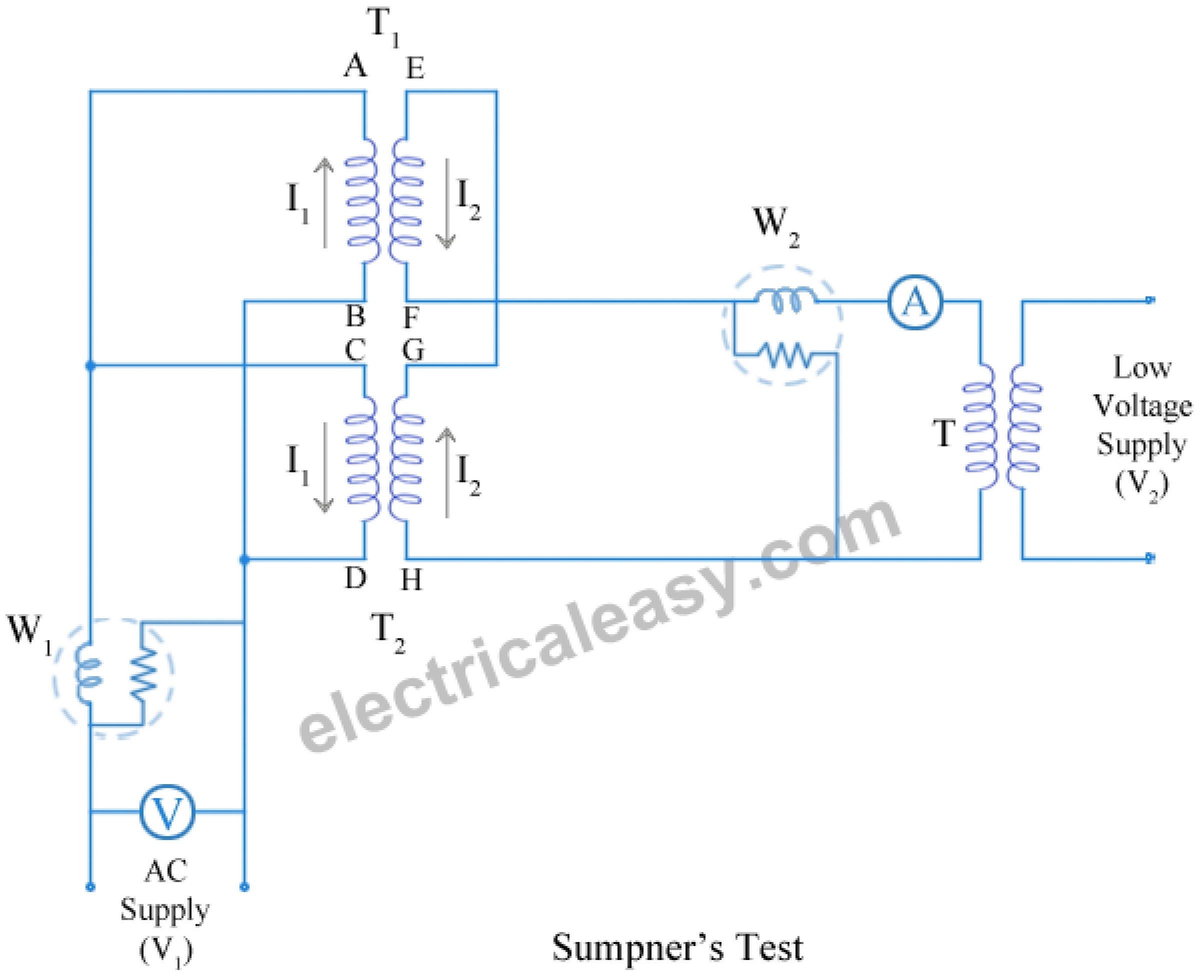
Hence the **short-circuit test of a transformer** is used to determine copper losses in the transformer at full load. It is also used to obtain the parameters to approximate the equivalent circuit of a transformer.

Sumpner's test or Back-to-Back test on Transformer

Sumpner's test or back to back test on transformer is another method for determining transformer efficiency, voltage regulation and heating under loaded conditions. Short circuit and open circuit tests on transformer can give us parameters of equivalent circuit of transformer, but they can not help us in finding the heating information. Unlike O.C. and S.C. tests, actual loading is simulated in Sumpner's test. Thus the Sumpner's test give more accurate results of regulation and efficiency than O.C. and S.C. tests.

Sumpner’s test

Both transformers are connected to supply such that one transformer is loaded on another. Primaries of the two identical transformers are connected in parallel across a supply. Secondaries are connected in series such that emf's of them are opposite to each other. Another low voltage supply Sumpner's test or back to back test can be employed only when two identical transformers are is connected in series with secondaries to get the readings, as shown in the circuit diagram shown below.



electricaleasy.com

Sumpner's Test

In above diagram, T_1 and T_2 are identical transformers. Secondaries of them are connected in voltage opposition, i.e. E_{EF} and E_{GH}. Both the emf's cancel each other, as transformers are identical. In this case, as per superposition theorem, no current flows through secondary. And thus the no load test is simulated. The current drawn from V_1 is $2I_0$, where I_0 is equal to no load current of each transformer. Thus input power measured by wattmeter W_1 is equal to iron losses of both transformers.
i.e. iron loss per transformer $Pi = W_1/2$.

Now, a small voltage V_2 is injected into secondary with the help of a low voltage transformer. The voltage V_2 is adjusted so that, the rated current

I_2 flows through the secondary. In this case, both primaries and secondaries carry rated current. Thus short circuit test is simulated and wattmeter W_2 shows total full load copper losses of both transformers.
i.e. copper loss per transformer $P_{Cu} = W_2/2$.

From above test results, the **full load efficiency of each transformer** can be given as -

$$\begin{array}{c}\text{% full load efficiency}\\ \text{of each transformer}\end{array} = \frac{\text{output}}{\text{output} + \frac{W_1}{2} + \frac{W_2}{2}} \times 100$$