UNIT: V

TESTING OF SINGLE PHASE TRANSFORMERS AND AUTOTRANSFORMERS

O.C. and S.C. Tests on Single Phase Transformer :-

The efficiency and regulation of a ***Transformer*** on any load condition and at any power factor condition can be predetermined by indirect loading method. In this method, the actual load is not used on transformer. But the equivalent circuit parameters of a transformer are determined by conducting two tests on a transformer which are,

1. Open circuit test (O.C. Test)

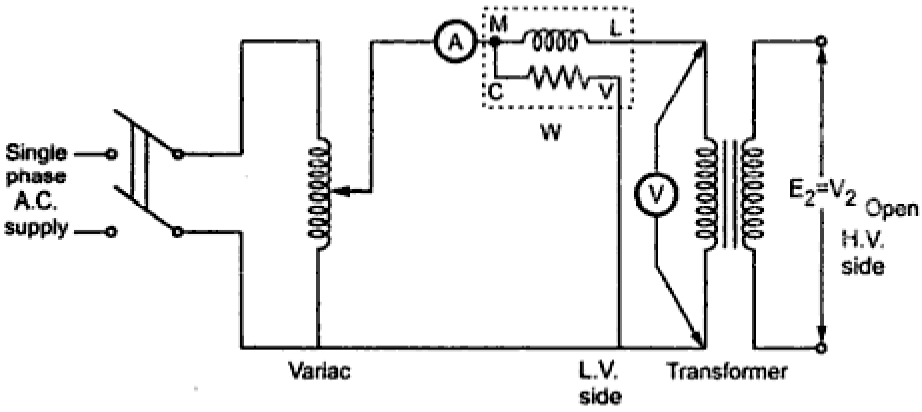
2. Short circuit test (S.C. Test)

The parameters calculated from these test results are effective in determining the regulation and efficiency of a transformer at any load and power factor condition, without actually loading the transformer.

The advantage of this method is that without much power loss the tests can be performed and results can be obtained. Let us discuss in detail how to perform these tests and how to use the results to calculate equivalent circuit parameters.

1. Open Circuit Test (O.C. Test) :-

The experimental circuit to conduct O.C. test is shown in the Fig.



The transformer primary is connected to a.c. supply through ammeter, wattmeter and variac. The secondary of transformer is kept open. Usually low voltage side is used as primary and high voltage side as secondary to conduct O.C. test.

The primary is excited by rated voltage, which is adjusted precisely with the help of a variac. The wattmeter measures input power. The ammeter measures input current. The voltmeter gives the value of rated primary voltage applied at rated frequency.

Sometimes a voltmeter may be connected across secondary to measure secondary voltage which is $\mathbf{V_2= E_2}$ when primary is supplied with rated voltage. As voltmeter resistant, is very high, though voltmeter is connected, secondary is treated to be open circuit as voltmeter current is always negligibly small.

When the primary voltage is adjusted to its rated value with the help of variac, readings of ammeter and wattmeter are to be recorded.

The observation table is as follows

Vo(volts)	Io(Amp)	Wo(watts)
rated		

V_o =Rated voltage
W_o =Input power
I_o=Input current = no load current

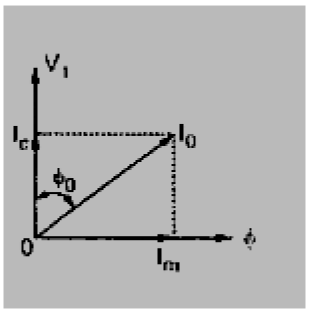
As transformer secondary is open, it is on no load. So current drawn by the primary is no load current **I_o**. The two components of this no load current are,

$$\boxed{\begin{array}{c} I_m = I_o \sin \Phi_o \\ I_c = I_o \cos \Phi_o \end{array}}$$

Where **$\cos \Phi_o$=**no load power factor.

And hence power input can be written as, **$W_o = V_o I_o \cos \Phi_o$**

The phasor diagram is shown in the Fig.



As secondary is open,**I_2=0**.Thus its reflected current on primary **I_2'** is also zero. So we have primary current **$I_1 = I_o$.** The transformer no load current is always very small, hardly 2 to 4 % of its full load value. As **I_2=0**, secondary copper losses are zero. And **I_1=I_o** is very low hence copper losses on primary are also very very low. Thus the total copper losses in O.C. test are negligibly small.

As against this the input voltage is rated at rated frequency hence flux density in the core is at its maximum value. Hence iron losses are at rated voltage. As output power is zero and copper losses are very low, the total input power is used to supply iron losses. This power is measured by the wattmeter i.e. **W_o**.

Hence the wattmeter in O.C. test gives iron losses which remain constant for all the loads.

W_o=P_i=Iron losses

We now that,

$$W_o = V_o I_o \cos \Phi_o$$

$$\cos \Phi_o = \frac{W_o}{V_o I_o} = \text{no load power factor}$$

therefore we can obtain…..

$$I_m = I_o \sin \Phi_o$$
$$I_c = I_o \cos \Phi_o$$

Once I_c and I_m are known we can determine exciting circuit parameters as,

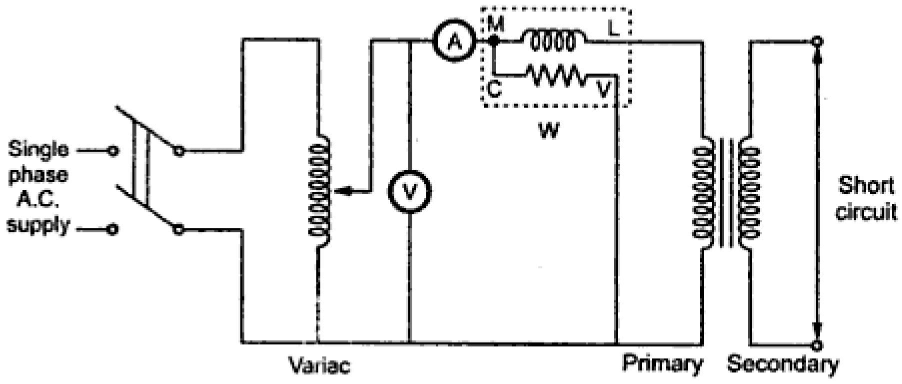
$$R_o = \frac{V_o}{I_c}\ \Omega \quad \text{and} \quad X_o = \frac{V_o}{I_m}\ \Omega$$

*The no load power factor **cos Φ_o** is very low hence wattmeter used must be low power factor type otherwise there might be error in the results. If the meters are connected on secondary and primary is kept open then from O.C test we get R_o' and X_o' with which we can obtain X_o and R_o knowing the transformation ratio K.

2. Short circuit test (S.C. Test):-

In this test, primary is connected to a.c. supply through variac, ammeter and voltmeter as shown in the Fig:

Short Circuit Test (S.C. Test)



The secondary is short circuited with the help of thick copper wire or solid link. As high voltage side is always low current side, it is convenient to connect high voltage side to supply and shorting the low voltage side.

As secondary is shorted, its resistance is very very small and on rated voltage it may draw very large current. Such large current can cause overheating and burning of the transformer. To limit this short circuit current, primary is supplied with low voltage which is just enough to cause rated current to flow through primary which can be observed on an ammeter.

The low voltage can be adjusted with the help of variac. Hence this test is also called low voltage test or reduced voltage test. The wattmeter reading as well as voltmeter, ammeter readings are recorded.

The observation table is as follows:

Vsc(volts)	Isc(Amp)	Wsc(watts)
	rated	

Now the currents flowing through the windings are rated currents hence the total copper loss is full load copper loss. Now the voltage applied is low which, is a small fraction of the rated voltage. The iron losses are function of applied voltage. So the iron losses in reduced voltage test are very small. Hence the wattmeter reading is the power loss which is equal to full load copper losses as iron losses are very low.

$W_{sc}=P_{cu}$=Full load copper loss

We now that,

$$W_{sc}= V_{sc}\, I_{sc} \cos \Phi_{sc}$$

$$\cos \Phi_{sc}=\frac{V_{sc} I_{sc}}{W_{sc}} = \text{short circuit power factor}$$

$$W_{sc}= I_{sc}^2 R_{1e}= \text{copper loss}$$

$$\therefore R_{1e}=\frac{Wsc}{I_{sc}^2}$$

While $Z_{1e}=\frac{V_{sc}}{I_{sc}}=\sqrt{R_{1e}^2 + X_{1e}^2}$

$\therefore X_{1e} =\sqrt{Z_{1e}^2 - R_{1e}^2}$

Thus we get the equivalent circuit parameters R_{1e} , X_{1e} and Z_{1e} knowing the transformation ratio K, the equivalent circuit parameters referred to secondary also can be obtained.

*If the transformer is step tip transformer, its primary is L.V. while secondary is H.V. winding. In S.C. test, supply is given to H.V. winding and L.V. is shorted. In such case we connect meters on H.V. side which is transformer secondary though for S.C. test purpose

H.V. side acts as primary. In such case the parameters calculated from S.C. test readings are referred to secondary which are $\mathbf{R_{2e}}$, and $\mathbf{X_{2e}}$ and $\mathbf{Z_{2e}}$. So before doing calculations it is necessary to find out where the readings are recorded on transformer primary or secondary and accordingly the parameters are to be determined. In step down transformer, primary is high voltage itself to which supply is given in S.C. test. So in such case test results give us parameters- referred to primary i.e. $\mathbf{R_{1e}}$, $\mathbf{Z_{1e}}$, and $\mathbf{X_{1e}}$.

- ***Calculation of efficiency from O.C and S.C tests*:-**

We know that

From OC test $W_o= P_i$

From sc test $W_{sc}=P_{cu}$

$$\%\eta \text{ on full load} = \frac{V_2(I_2)F.L.COS\Phi}{V_2(I_2)F.L.COS\Phi + Wo + Wsc}$$

Thus for any p.f. cos **Φ**2 the efficiency can be predetermined. Similarly at any load which is fraction of full load then also efficiency can be predetermined as,

$$\%\ \eta \text{ at any load} = \frac{n\ (\text{VA Rating}) \times \cos\Phi}{n(\text{VA Rating})\times\cos\Phi + Wo + n^2 Wsc} \times 100$$

where n = Fraction of full load

$$\%\eta = \frac{n\,V_2I_2\mathrm{COS}\Phi}{nV_2I_2\mathrm{COS}\Phi + W_o + W_{sc}} \times 100$$

where $I_2 = n(I_2)$F.L.

Calculation of Regulation

From S.C. test we get the equivalent circuit parameters referred to primary or secondary.

The rated voltages V_1, V_2 and rated currents (I_1) F.L. and (1_2) F.L. are known for the given transformer. Hence the regulation can be determined as,

$$\%\ R = \frac{I_2R_{2e}\cos\Phi \pm I_2X_{2e}\sin\Phi}{V_2} \times 100$$

$$\%\ R = \frac{I_1R_{1e}\cos\Phi \pm I_1X_{1e}\sin\Phi}{V_1} \times 100$$

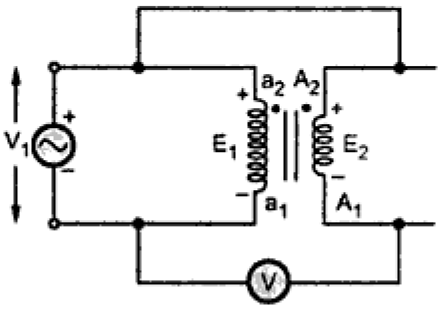
where I_1, I_2 are rated currents for full load regulation
For any other load the currents I_1, I_2 must be changed by fraction n .

I_1, I_2 at any other load = $n(I_1)$F.L , $n(I_2)$F.L

Polarity Test :-

When the primary winding of a transformer is excited with suitable rated voltage then e.m.f. gets induced in both the windings. The polarities of this e.m.fs depend on how the windings are wound on the core. It is usual practice to determine which ends of the two windings acquire simultaneously positive or negative polarity. This polarity determination is carried out by conducting the polarity test on a transformer.

Consider a transformer shown in the Fig. Usually the ends of the L.V. winding are labeled with small letters as a_1, a_2 while the ends of the H.V. windings are labeled with capital letters as A_1, A_2.



In determining the relative polarity of the two windings of a transformer using polarity test, the two windings are connected in series across a voltmeter. The voltmeter is connected across $a_1 - A_1$.

One of the windings is excited by suitable voltage source. So a_1- a_2 is excited by voltage V_1. Let E_l and E_2 are the induced e.m.f.s.

<u>Key Point</u>: If the voltmeter reads $\mathbf{E_{1\sim}}$ $\mathbf{E_2}$***, thus voltmeter reading is less than*** V_1***, and then the polarities are called subtractive in nature.***

The net voltage acting around the local circuit consisting the voltmeter is $\mathbf{E_{1\sim}}$ $\mathbf{E_2}$. In such case the ends a_2, A_2 are simultaneously positive or negative. This is indicated by dots, as shown in the Fig.

<u>Key Point</u>: But if the windings are wound in such a way that the voltmeter reads $E_1 + E_2$***, the polarities are said to be additive.***

In such case the voltmeter reading is more than V_1. This confirms that if a_2 is positive, terminal A_2 is negative and vice-versa. In such case, the polarity markings of one of the windings must be interchanged.

<u>Key Point</u>: In practice the transformer windings are wound in such a way that the relative polarities are subtractive which is indicated by dots, as per the dot convention.

<u>Sumpner's Test (Back to Back Test) :-</u>

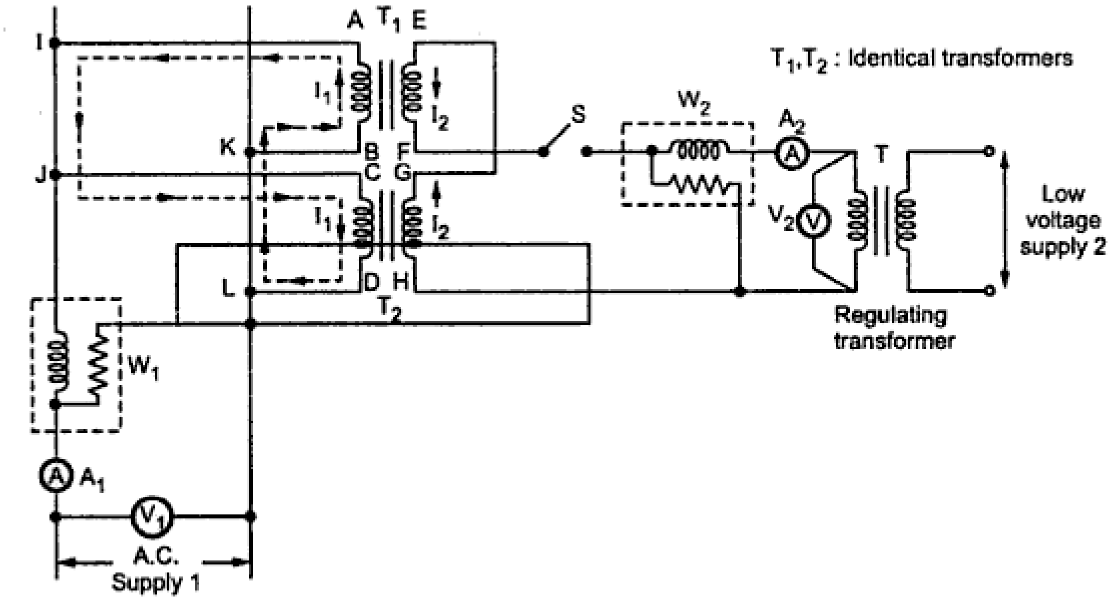
The Sumpner's test is another method of determining efficiency, regulation and heating under load conditions. The O.C. and S.C. tests give us the equivalent circuit parameters but cannot give heating information under various load conditions. The Sumpners test

gives heating information also. In O.C. test, there is no load on the transformer while in S.C. test also only fractional load gets applied. In all in O.C. and S.C. tests, the loading conditions are absent.

Hence the results are in accurate. In Sumpner's test, actual loading conditions are simulated hence the results obtained are much more accurate. Thus Sumpner's test is much improved method of predetermining regulation and efficiency than O.C. and S.C. tests.

The Sumpner's test requires two identical transformers. Both the transformers are connected to the supply such that one transformer is loaded on the other. Thus power taken from the supply is that much necessary for supplying the losses of both the transformers and there is very small loss in the control circuit.

While conducting this test, the primaries of the two identical transformers are connected in parallel across the supply V1. While the secondary's are connected in series opposition so that induced e.m.f.s in the two secondary's oppose each other. The secondary's are supplied from another low voltage supply are connected in each circuit to get the readings. The connection diagram is shown in the Fig



T_1 and T_2 are two identical transformers. The secondaries of T_1 and T_2 are connected in series opposition. So $\mathbf{E_{EF} = E_{GH}}$ i.e. induced in two secondary's are equal but the secondaries are connected such that E is connected to G and F is connected to H. Due to such series opposition, two e.m.f.s act in opposite direction to each other and cancel each other. So net voltage in the local circuit of secondaries is zero, when primaries are excited by supply 1 of rated voltage and frequency. So there is no current flowing in the loop formed by two secondaries. The series opposition can be checked by another voltmeter connected in the secondary circuit as per polarity test. If it reads zero, the secondary's are in series opposition and if it reads double the induced e.m.f. in each secondary, it is necessary to reverse the connections of one of the secondaries.

As per superposition theorem, if V_2 is assumed zero then due to phase opposition no current flows through secondary and both the transformers T_1, T_2 are as good as on no load. So O.C. test gets simulated. The current drawn from source V_1 in such case is 2 I_o where I_o is no load current of each transformer. The input power as measured by wattmeter W_1 thus reads the iron losses of both the transformers.

P_i per transformer = $\frac{W_1}{2}$ as T_1 and T_2 are identical

Then a small voltage V_2 is injected into the secondary with the help of low voltage transformer, by closing the switch S. With regulating mechanism, the voltage V, is adjusted so that the rated secondary current I_2 flows through the secondaries as shown. I_2 flows from E to F and then from H to G. The flow of I_1 is restricted to the loop B A I J C D L K B and it does not pass through W_1.

Hence W_1 continues to read core losses. Both primaries and secondary's carry rated current so S.C. test condition gets simulated. Thus the wattmeter W, reads the total full load copper losses of both the transformers.

(P_{cu})per transformer = $\frac{W_2}{2}$

Key Point: ***Thus in the Sumpner's test without supplying the load, full iron loss occurs in the core while full copper loss occurs in the windings simultaneously. Hence heat run test can be conducted on the two transformers. In O.C. and S.C. test, both the losses do not***
occur simultaneously hence heat run lest cannot be conducted. This is the advantage of Sumpner's test.

From the test results the full load efficiency of each transformer can be calculated as,

$\%\acute{\eta}_{FL}$ of each transformer=$\frac{output}{output+\frac{W_1}{2}+\frac{W_2}{2}}\times100$

Where output=VA rating$\times cos\Phi_2$

The only limitation is that two identical transformers are required. In practice exact identical transformers cannot be obtained. As two transformers are required, the test is not
economical.

□ *Separation of Core Losses Test*

It is seen that the core losses of transformer includes,

1. Hysteresis loss
2. Eddy current loss

For a given volume and thickeners of laminations, these losses depend on the operating frequency, maximum flux density in the core and the voltage.

The hysteresis loss is given by **Steinmet'z relation**,

$$\mathbf{P_h=K_hB_m^{1.67}fV} \text{ watts}$$

$$\text{i.e } \mathbf{P_h=AB_m^{1.67}f} \text{ watts}$$

Where A = constant assuming constant voltage.

The eddy current loss is given by,

$$\mathbf{P_e=K_eB_m^{2}f^2t^2} \text{ watts}$$

$$\text{i.e } \mathbf{P_e=BB_m^{2}f^2} \text{ watts}$$

Where B= constant for given thickness t of core

Thus the total core loss becomes,

$$\mathbf{P_i = P_h + P_e = AB_m^{1.67}f + BB_m^{2}f^2}$$

Practically conduct two tests on transformers at two different frequencies f_1 and f_2, keeping maximum flux density B . in the core same. The results are to be used in the equations (1), (2) and (3) to obtain the constants A and B. Thus the core losses i.e. iron losses can be separated into hysteresis and eddy current losses.

Autotransformer :-

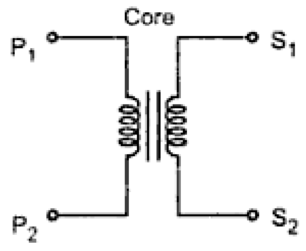
Construction :-

In an autotransformer only one winding is wound on a laminated magnetic core while in 2 winding transformer, two windings are wound. The single winding of the autotransformer is used as primary and secondary. The part of the winding is common to both primary and secondary. The voltage can be stepped down or stepped up using an autotransformer. Accordingly the autotransformers are classified as step up autotransformer and step down autotransformer.

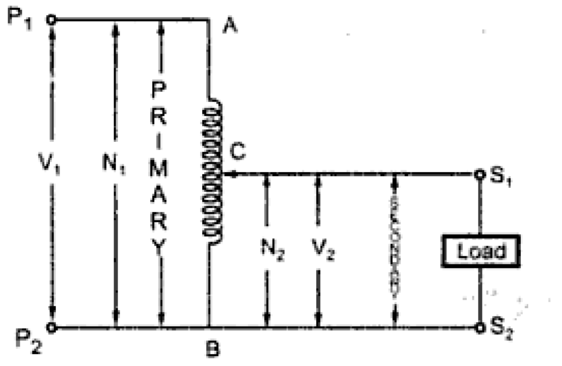
The Fig.(a) shows the conventional two winding transformer while the Fig.(b)and (c) show the step down and step up autotransformers respectively.

In step down autotransformer shown in the Fig. (b), the entire winding acts as a primary while the part of the winding is used common to both primary and secondary. Thus AB forms the primary having N_1 turns while BC forms the secondary with N_2 turns.

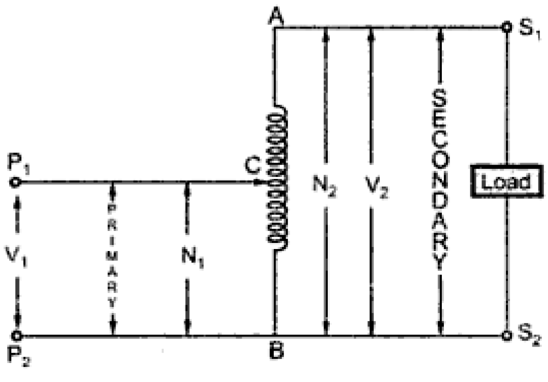
As $N_2 < N_1$ the output voltage $V_2 < V_1$ and it acts as a step down auto transformer. In step up autotransformer shown in the Fig. (c), the entire winding acts as secondary while the part of the winding is used common to both primary and secondary. Thus AB form-, the secondary having N_2 turns while BC forms the primary with Na turns. As $N_2>N_1$, the output voltage $V_2>V_1$ and it acts as a step up autotransformer.



(a) 2 winding transformer

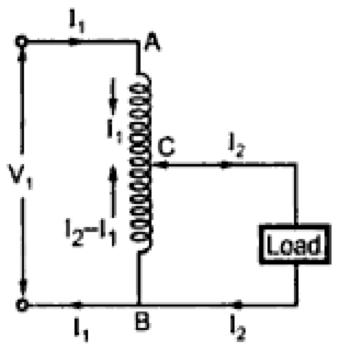


(b) Step down autotransformer

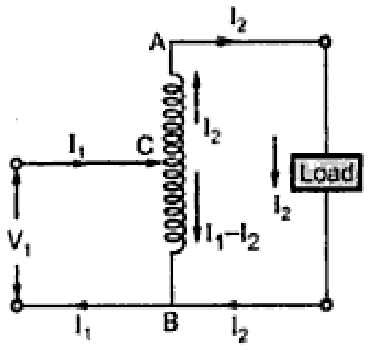


(c) Step up autotransformer

The current distribution in the step down and step up autotransformers is shown in the Fig. (a) and (b) respectively



(a) Step down autotransformer



(b) Step up autotransformer

Transformation Ratio of an Autotransformer:-

Neglecting the losses, the leakage reactance and the magnetizing current, the transformation ratio of an autotransformer can be obtained as,

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

K is greater than unity for step up autotransformer while K is less than unity for step down autotransformer.

Due to the use of single winding, compared to the normal two winding transformer, for the same capacity and voltage ratio, there is substantial saving in copper in case of
Autotransformers.

Advantages of Autotransformer :-

The various advantages of an autotransformer are,

1. Copper required is very less.
2. The efficiency is higher compared to two winding transformer.
3. The size and hence cost is less compared to two winding transformer.
4. The resistance and leakage reactance is less compared to two winding transformer.
5. The copper losses I^2R, are less.
6. Due to less resistance and leakage reactance, the voltage regulation is superior than the two winding transformer.
7. VA rating is more compared to two winding version.
8. A smooth and continuous variation of voltage is possible.

Limitations of Autotransformer :-

Apart from its advantages, an autotransformer suffers from following limitations,

1. Low impedance hence high short circuit currents for short circuits on secondary side.
2. If a section of winding common to primary and secondary is opened, full primary voltage appears across the secondary resulting in higher voltages on secondary and danger of accidents.
3. No electrical separation between primary and secondary which is risky in case of high voltage levels.
4. Economical only where the voltage ratio is less than 2.

Applications of Autotransformer:-

The various application-, of an autotransformer are,

1. For safely starting the machines like induction motors, synchronous motors i.e. as a startor.

2. To give a small boost to a distribution cable to compensate for a voltage drop i.e. as a booster.

3. As a furnace transformer to supply power to the furnaces at the required supply voltage.

4. For interconnecting the systems which are operating roughly at same voltage level.

5. It can be used to vary the voltage to the load, smoothly from zero to the rated voltage. Such a device giving smooth and continuous supply using an autotransformer is called variac. A single phase autotransformer used as variac is shown in the Fig.

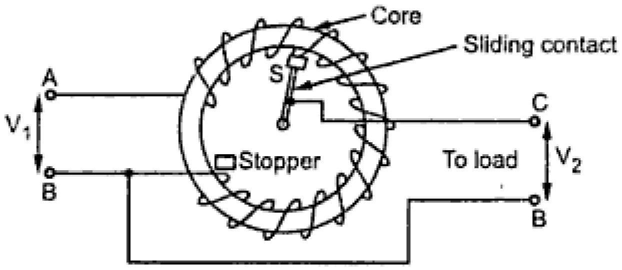


Fig. Autotransformer as variac

The portion Ala forms primary while with the help of sliding contacts, the secondary turns can be changed. Thus by rotating sliding contact smooth variable voltage can be obtained. Such variacs are commonly used for dimming the lights in the cinema halls. Hence the variacs are also called dimmerstats.

6. In various control systems as well as appliances.