SRI MANAKULA VINAYAGAR ENGINEERING COLLEGE
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Madagadipet, Puducherry - 605 107

DEPARTMENT OF MECHANICAL ENGINEERING

Subject Name: Electrical and Electronics Engineering **Subject Code:**MET35

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1. TRANSFORMER

EMF Equation – Equivalent circuit – Voltage regulation - OC and SC Test – Efficiency – condition for maximum efficiency – All day efficiency – Autotransformer –Introduction to three phase Transformer

Part-A (2 Marks)

1. Why transformer rating is expressed in terms of KVA (NOV/2014)

Copper loss depends on current and iron loss depends upon voltage. Hence the total loss in a transformer depends upon volt-ampere (VA) only and not on the phase angle between voltage and current i.e. it is independent of load power factor. That is why the rating the transformer is KVA and not in KW.

2. What are the losses in single phase transformer?

- Core (or) iron losses
  (a) Hysteresis loss (b) Eddy current loss
- Copper loss

3. What are turns ratio and transformation ratio of transformer?

Turns ratio = $\frac{N_2}{N_1}$

Transformation ratio = $\frac{E_2}{E_1} = \frac{I_1}{I_2}$ = K

4. Define "All day Efficiency" of a transformer.

The ratio of output in kWh to input in Kwh of a transformer over a 24 hour period is known as all-day efficiency.

All day Efficiency=$\frac{\text{kwh output in 24 hours}}{\text{kwh input in 24 hours}}$

5. How can the iron loss are minimized in a transformer.

The iron loss in a transformer is made up of hysteresis loss and eddy current loss. Hysteresis loss can be minimized by using steel of high silicon content for the transformer core. The eddy current loss can be minimized by using very thin laminations of transformer core.

6. What are the advantages of OC and SC tests on the transformers?

- The power required to carry out these test is very small as compared to the full load output of the transformer.
- These tests enable us to determine the efficiency of the transformer accurately at any load and power factor without actually loading the transformer.
- The short circuit test is used to determine$R_{o1} and\ X_{o1}(or\ R_{o2} and\ X_{o2})$. By using this data, we can find out voltage drop and voltage regulation of the transformer.

7. Does transformer draw any current when secondary is open? Why? (NOV-2014)

The transformer draws no- load current when secondary is open. The transformer works on the principle of electromagnetic induction, since both primary and secondary windings are wound on the same core, the primary is connected to the ac supply, it forms a closed path that ensures no-load current that establish flux in the core.

8. The no-load ratio of a 50HZ, single phase transformer is 6000/250V. Estimate the number of turns in each winding if maximum flux is 0.06Wb in the core.(APRIL-2014)

$E_1=4.44f\phi_m N_1$ and $E_2=4.44f\phi_m N_2$

$N_1= (6000)/ (4.44\times50\times0.06)= 450$

$N_2= (250)/ (4.44\times50\times0.06) = 19$

9. Define voltage regulation of a transformer.(APRIL-2014)

Because of the voltage drop across the primary and secondary impedances it is observed that the secondary terminal voltage drops from it's no load value (E_2) to load value (V_2) as load and load current increases. This decrease in the secondary terminal voltage expressed as a fraction of the no load secondary terminal voltage is called regulation of a transformer.

10. A 220/110 V, 50 Hz ideal transformer has 166 turns in its primary. What is the peak value of flux (NOV/2013)

$E_1=4.44f\phi_m N_1$

$\phi_m= E_1/(4.44fN_1)$

$\phi_m= (220)/ (4.44\times50\times166)= 0.006\text{Wb}$

11. Write down the condition for maximum efficiency of the transformer(APRIL/2013) (NOV/2013)

The condition for maximum efficiency of the transformer is core loss equal to copper loss.

12. Define transformation ratio. (APRIL/2013)

The voltage transformation ratio is

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

13. Classify the transformer according to the construction (NOV/2012)

- Core type transformer
- Shell type transformer
- Berry type transformer

14. Define a transformer. (APRIL/2012)

The transformer works on the principle of electromagnetic induction. A transformer is an electrical device, having no moving parts, which by mutual induction transfers electric energy from one circuit to another at the same frequency, usually with changed values of voltage and current.

15. What are the advantages of three phase transformer? (NOV/2012)

- The cost of three phase transformer is around 15% less than single phase transformer bank
- It is weightless and occupies less space
- The bus bar structure, switch gear and other wiring for a three phase installation are simple
- It can be more easily transported
- The amount core material required is less.

16. What is an autotransformer?

Autotransformer is one in which one winding acts as both primary and secondary and energy transformation is carried out both electrically and magnetically.

17. What are the advantages of autotransformer?

- It has only one winding, so saving is in conductor material and cost.
- Continuously varying voltage can be obtained.
- Better voltage regulation.
- Higher efficiency and smaller in size.

18. Mention some applications of an auto transformer. (APRIL/2012)

- Used for starting of induction motors and synchronous motors
- Used in electrical testing laboratory
- Used as booster to raise the voltage in AC feeders

19. What happens, if dc supply applied to the transformer?

DC supply has no frequency, if frequency is zero, inductive reactance 2πfL is zero. Total impedance becomes very low. Thus winding will draw very high current; this may cause the burning of the winding.

20. Why all day efficiency is lower than commercial efficiency?

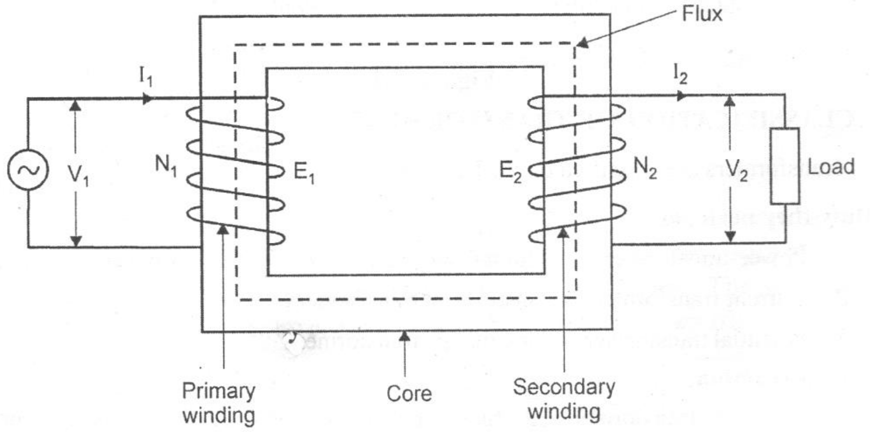
All day efficiency is based on energy, but the commercial efficiency is based on power. Time is involved in all day efficiency. So the efficiency is less than commercial efficiency.

Part –B (11 Marks)

1. State and explain the operating principle of a transformer.

(i) Transformer

Thetransformer works on the principle of electromagnetic induction. A transformer is an electrical device, having no moving parts, which by mutual induction transfers electric energy from one circuit to another at the same frequency, usually with changed values of voltage and current. It consists of two windings insulated from each other and wound on a common core made up of magnetic material.



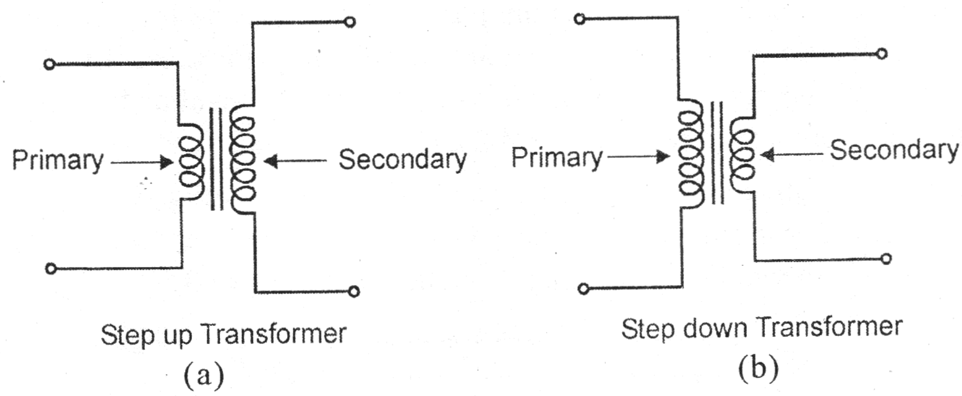
Alternating voltage is connected across one ofthe windings called the primary winding. In both the windings emfis induced by electromagnetic induction. The second winding is called the secondary winding. It is shown in the above figure.

(ii) WORKING PRINCIPLE OF A TRANSFORMER

The primary winding is connected to an AC source, an exciting current flows through it. As the current is alternating, it will produce an alternating flux in the core which will be linked by both the primary and secondary windings. The induce emf in the primary winding (E_l) is almost equal to the applied voltage $V_1$and will oppose the applied voltage. The emf induced in the secondary winding (EZ) can be utilized to deliver power to any load connected across the secondary. Thus power is transferred from the primary to the secondary circuit by electromagnetic induction.

The flux in the core will alternate at the same frequency as the frequency of the supply voltage. The frequency of induced emf in secondary is the same as that of the supply, voltage. The magnitude of the emf induced in the secondary winding will depend upon its number of turns.

In a transformer, if the number of turns in the secondary winding is less than those in the primary winding, it is called a step-down transformer (Figure (b)), when the number of turns in the secondary winding is higher than the primary winding, it is called a step-up transformer (Figure (a)).



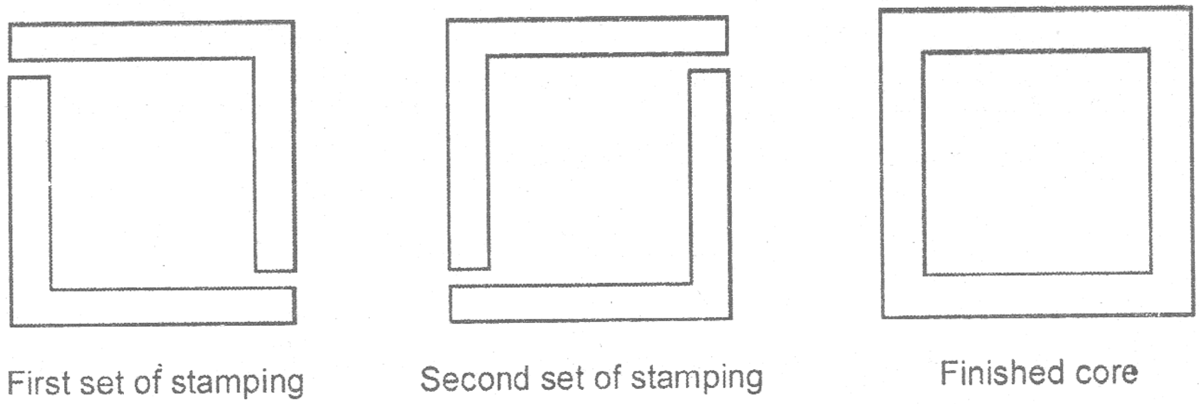
2. Describe the construction details of transformer and also explain the principle of operation with necessary diagram (11) (NOV/2014)

A transformer is a static device and its construction is simple as there are no moving parts. The main components of a transformer are

- The magnetic core.
- Primary and secondary windings.
- Insulation of windings.
- Expansion tank or conservator.
- Lead and tappings for coils with their supports, terminals and terminal insulators.
- Tank, oil, cooling arrangement, temperature gauge, oil gauge.
- Buchholz relay.
- Silica gel breather.

Magnetic Core

Magnetic circuit consists of an iron core. The transformer core is generally laminated and is made out of a good magnetic material like silicon steel. The thicknessof laminations or stampings varies from 0.35 mm to 0.5 mm. The laminations are insulated from each other by coating then with a thin coat of varnish.



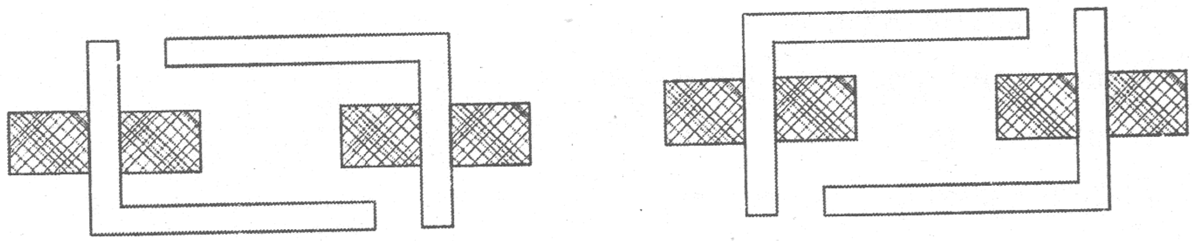
Various types of samplings and laminations employed in the construction of transformers are shown in above figure. Here the core surrounds the considerable part of coil. The joints are staggered to avoid continuous gap causing increase in magnetising current. If the joints are not staggered, the core will have less mechanical strength and during operation there would be undue humming noise. After arranging the laminations they are bolted together.

The two types of transformer cores are:

- Core type
- Shell type

a) Core type transformer

Here the windings surround a considerable part of core as shown in the below figure and has only one magnetic path. It has two limbs for the two windings and is made up of two L-type stampings as shown in below figure (a). The coils used usually are of cylindrical type and are usually wound. For transformers of higher rating stepped core with circular cylindrical coils are used. For transformers of smaller rating, a rectangular coil with core of square or rectangular cross section is used. Insulating cylinders are used to separate windings from the core and from each other.

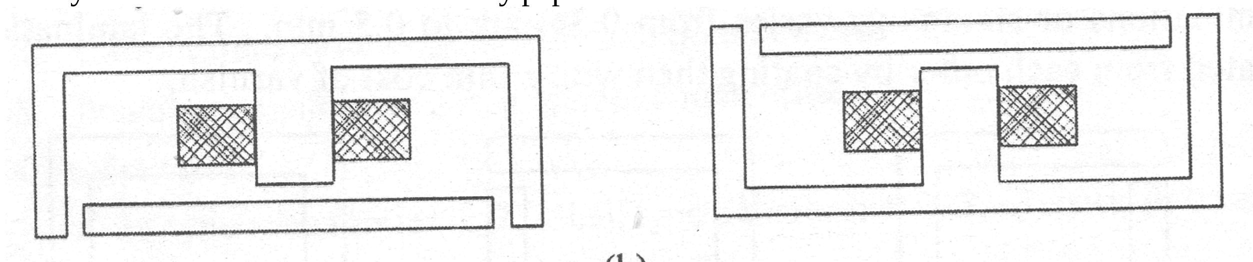


(a)

b) Shell type transformer

Here the core surrounds the considerable part of windings as shown in the below figure (b). The two windings are carried by central limb. The core is made up of E and I stamping (figure (b)) and has three limbs. It has two parallel paths for magnetic flux.

The coils used are of multilayer disc type and are former wound in the form of pan-cakes. Each layer is insulated from each other by paper.



(b)

Winding

There are two windings in a transformer. They are called primary and secondary windings. Generally the windings are made of copper.

Insulation

Paper is still used as the basic conductor insulation. Enamel insulation is used as the inter-turn insulation of low voltage transformers. For power transformers enamelled copper with paper insulation is also used.

Insulating Oil

The oil used in transformer protects the paper from dirt and moisture and removes the heat produced in the core and coils. It also acts as insulating medium. The oil must possess the following properties.

i) High dielectric strength.
ii) Free from inorganic acid, alkali and corrosive sulphur to prevent injury to the conductor or insulation.
iii) Low viscosity to provide good heat transfer.
iv) Free from sludging under normal operating conditions.
v) Good resistance to emulsion so that the oil may throw down any moisture entering the tank instead of holding it in suspense.

Expansion Tank or Conservator

A small auxiliary oil tank may be mounted above the transformer and connected to main tank by a pipe. Its function is to keep the transformer tank full of oil despite expansion or contraction of the coil with the changes in temperature. A small pipe connection between the gas space in the expansion tankand the cover of the transformer tank permits the gas above the oil in the transformer to pass into the expansion tank, so that the transformer tank will be completely filled with oil.

Temperature Gauge

Every transformer is provided with a temperature gauge to indicate hot oil orhottest spot temperature. It is self-contained weather proof unit made of alarm contacts. It is dial operated by bourdon gauge connected to a thermometer bulb located in the region of hottest oil.

Gauge

Every transformer is fitted with an oil gauge to indicate the oil level present inside tank. The oil gauge may be provided with an alarm contact with gives an alarmthe oil level has dropped beyond permissible height due to oil leak or due to any other reason.

Relay

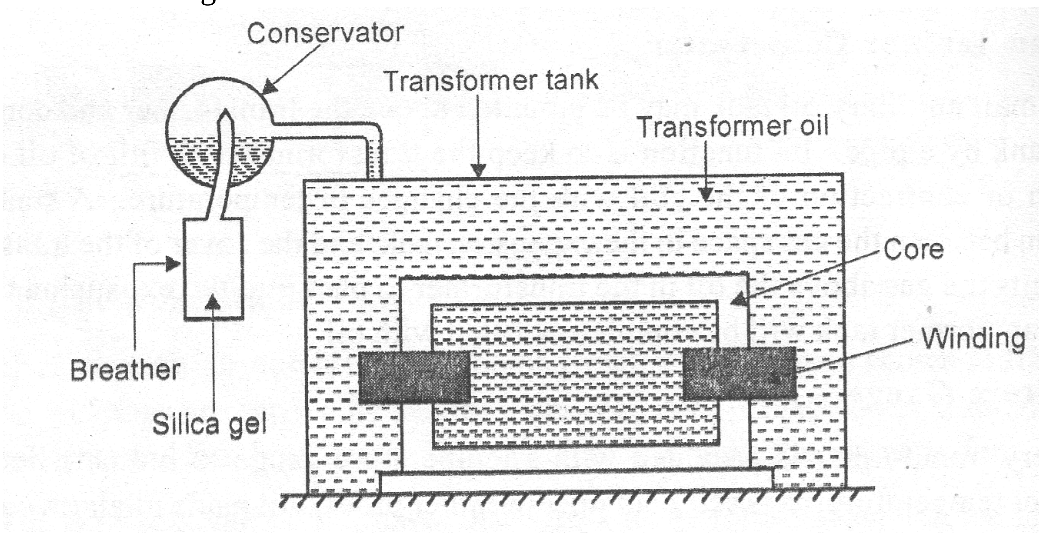
The first warning that a fault is present may be given by the presence of bubbles in the oil. If the transformer is fitted with a conservator and there are no pockets in which gas can collect, the gas bubbles will rise up the pipe joining the conservator to the tank. It is possible to mount gas operated relay in this pipe to give an alarm in case of minor fault and to disconnect the transformer from the supply mains in case of severe faults.

Breather

The simplest method to prevent the entry of the moisture inside the transformer tank is to provide chambers known as breather. The breather is filled with some drying agent, such as calcium chloride or silica gel. Silica gel or calcium chloride absorbs moisture and allows dry air to enter the transformer tank. The drying agent is replaced periodically as routine maintenance. The whole ofthe transformer tank and portion of conservator used filled with oil. The breather is connected on one side of the conservator. Thus a small surface area of transformer oil is exposed to the atmosphere through the breather.

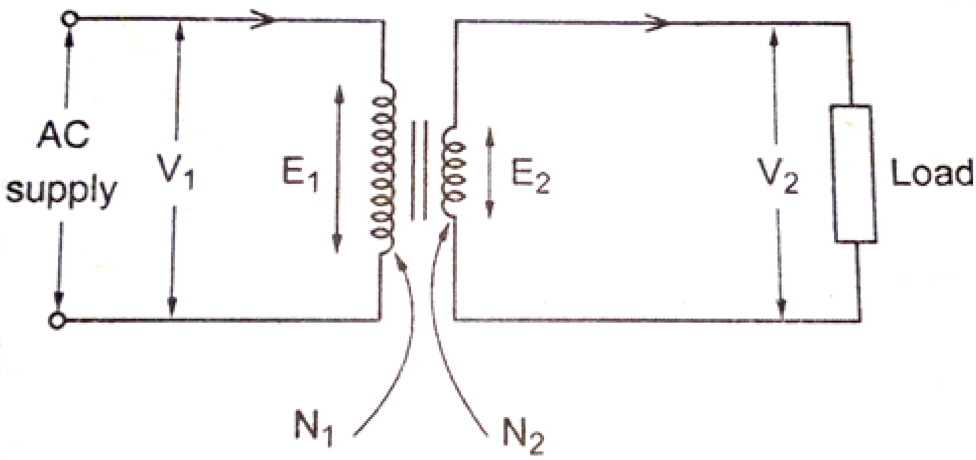
Bushings

Connections from the transformer windings are brought out by means bushings. Ordinary porcelain insulators can be used upto a voltage of 33kV. Above 33kV, capacitor and oil filled type of bushings are used. Bushings are fixed on the transformer tank.



3. Derive the emf equation of a transformer (5) (APRIL 2012/APRIL/NOV/2014)

Consider an alternating voltage (V_1) of frequency (f) is applied to primary winding of the transformer

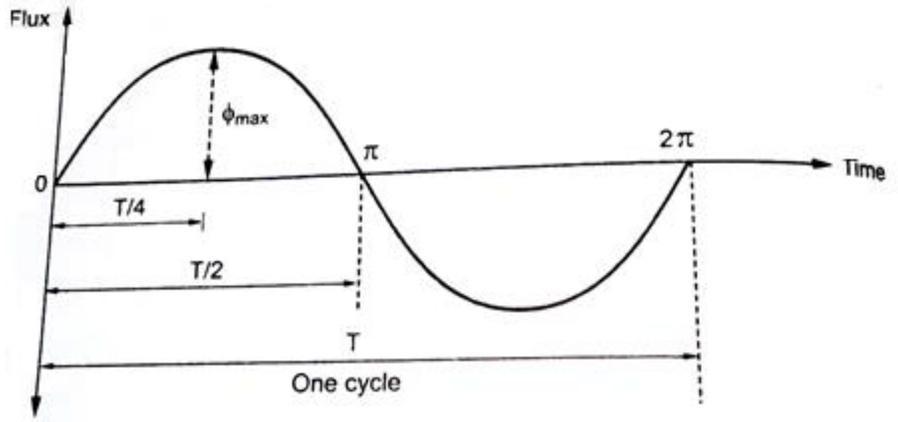


Let

- ✓ 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
- ✓ A be the area of core in m^2
- ✓ B_m be the maximum value of flux density in (wb/m^2)
- ✓ V_1 be the supply voltage across primary in volts
- ✓ V_2 be the terminal voltage across secondary in volts
- ✓ I_1 be the primary current in amps
- ✓ I_2 be the secondary current in amps

- ✓ E_1 be the EMF induced in primary winding in volts
- ✓ E_2 be the EMF induced in secondary winding in volts

Since the applied voltage is alternating in nature, the flux established is also an alternating one. From the figure given below, it is clear that the flux is attaining its maximum value in one quarter of the cycle (T/4), where T is the time in seconds.



We know that, T= 1/f, where f is the supply frequency

$$\text{Average EMF } (e) = \frac{d\varphi}{dt}$$

Where $d\phi = \phi_m$

$$dt = \frac{1}{4f}$$

$$\text{Average rate of change of flux} = \frac{\varphi_m}{\frac{1}{4f}} = 4f\,\phi_m \text{ volts}$$

Average EMF induced per turn= average rate of change of flux= $4f\,\phi_m$ volts
RMS value= Form Factor × Average Value= 1.11 × Average Value
The RMS value of EMF induced/turn= 1.11 × $4f\,\phi_m$ = $4.44f\,\phi_m$ volts
The primary and secondary winding having N_1 and N_2 turns respectively
RMS value of EMF induced in primary winding

$$E_1 = 4.44f\,\phi_m N_1 \text{ volts}$$

RMS value of EMF induced in secondary winding

$$E_2 = 4.44f\,\phi_m N_2 \text{ volts}$$

EMF equation in terms of flux density is given by

$$E_1 = 4.44f\;N_1 B_m A \;\text{ Volts and }\; E_2 = 4.44f\;N_2 B_m A \;\text{ volts}$$

<u>Transformation Ratio</u>

For an ideal transformer, $E_1 = V_1$ and $E_2 = V_2$
There is no voltage drop in the windings, $V_1 I_1 = V_2 I_2$

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

$$\frac{V_2}{V_1} = K \text{ ----- Voltage ratio}$$

$$\frac{E_2}{E_1} = K \text{ ----- Transformation ratio}$$

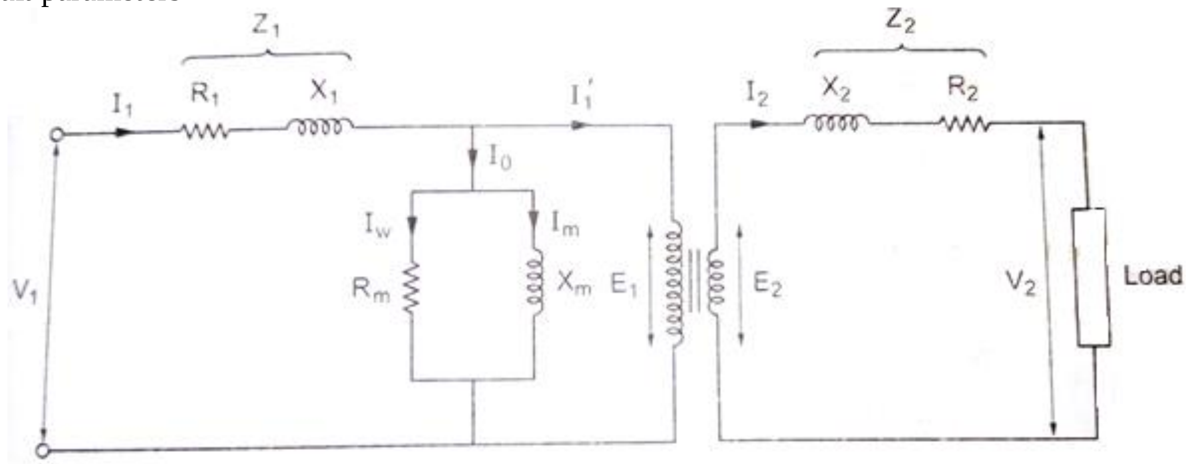
$$\frac{N_2}{N_1} = K \text{ ----- Turns ratio}$$

$$\frac{I_1}{I_2} = K \text{ ------ Current ratio}$$

4. Obtain the equivalent circuit of a transformer. (NOV/2012/APRIL/2014)

The equivalent circuit of any device can be helpful in predetermination of the behavior of the device under varying conditions of operation. The equivalent circuit for electromagnetic devices consists of a combination of resistances, inductances and capacitances. An actual transformer represented by two windings linked by a magnetic circuit. To estimate the performance of a transformer and to do simple calculation, a transformer is often represented by its equivalent circuit.

In this equivalent, the effects of the core and the windings are represented by equivalent circuit parameters



Representation of core by its electrical equivalent

- ✓ The core forms the path for the magnetic flux (ϕ_m), set up by a current (I_m) lagging E_1 by 90°. Hence the magnetizing component of the core is represented by a pure inductive reactance (X_m) connected across the EMF (E_1)
- ✓ Core loss is accounted by a current I_w in phase with E_1 which is represented by a resistance R_m connected across E_1

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

No-load primary current $\overline{I_0} = \overline{I_w} + \overline{I_m}$

Supply voltage= V_1

EMF induced in primary winding due to flux (ϕ_m) = E_1

The core loss component-= I_w

The magnetizing component= I_m

The magnetic loss components are R_m and X_m

- ✓ From no-load to full load, the core loss occurs in the transformer, so the magnetic loss components are connected in parallel

Representation of primary winding

The primary winding of a transformer is represented by its equivalent resistance (R_1) and leakage reactance (X_1)

Primary winding resistance= R_1 Ω

Primary leakage reactance= X_1 Ω

Primary winding impedance $Z_1 = \sqrt{R_1^{\,2} + X_1^{\,2}}$ Ω

The difference between V_1 and E_1= $I_1 Z_1$ Ω

Representation of secondary winding

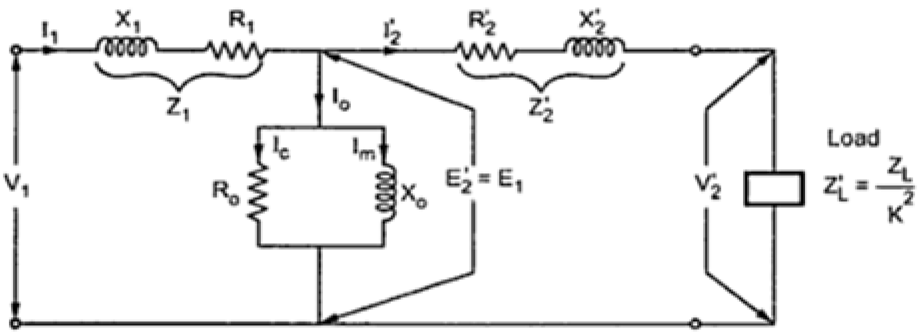
The secondary winding of a transformer is represented by its equivalent resistance (R_2) and leakage reactance (X_2)

Secondary winding resistance= R_2 Ω

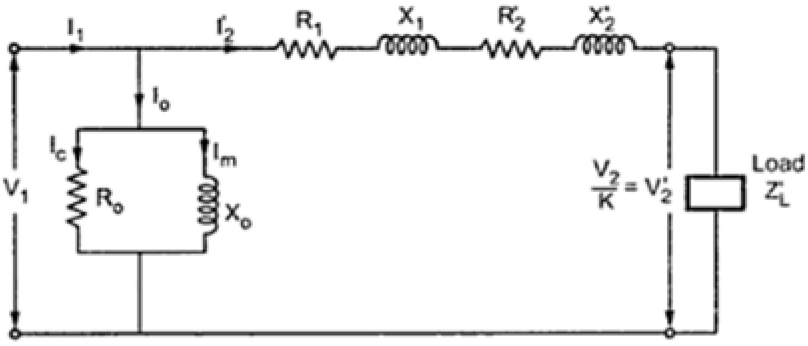
Secondary leakage reactance= X_2 Ω

Secondary winding impedance $Z_2 = \sqrt{R_2^{\,2} + X_2^{\,2}}$ Ω

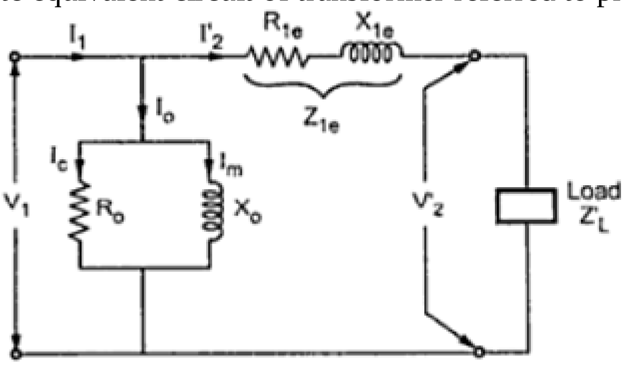
The difference between V_2 and E_2= $I_2 Z_2$ Ω



Exact equivalent circuit of transformer with secondary quantities referred to primary side



Approximate equivalent circuit of transformer referred to primary side



$R_2^{'} = \frac{R_2}{K^2}$ --- The secondary resistance referred to primary side

$X_2^{'} = \frac{X_2}{K^2}$ --- The secondary reactance referred to primary side

$Z_2 = \frac{Z_2}{K^2}$ --- The secondary impedance referred to primary side

$I_2^{'} = KI_2$ --- The secondary current referred to primary side

$E_2^{'} = \frac{E_2}{K}$ --- The secondary induced EMF referred to primary side

$V_2^{'} = \frac{V_2}{K}$ --- The secondary voltage referred to primary side

✓ The voltage drop due to primary and secondary winding resistance and reactance always vary with load current. Therefore it is connected in series

5. **Explain OC and SC tests on single phase transformer. (APRIL/2012)**

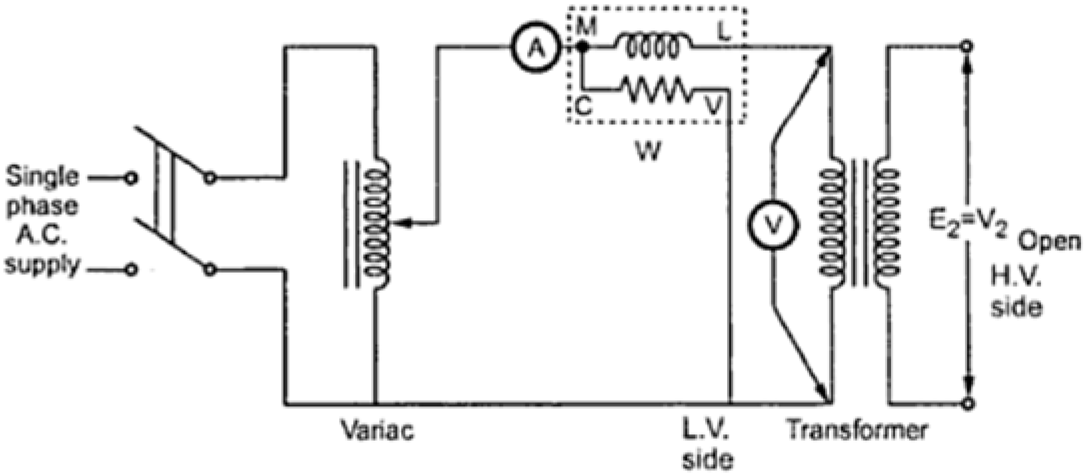
INDIRECT LOADING TESTS OF TRANSFORMERS

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 transormer by conducting two tests on a transformer which are (i) open circuit test (ii) short circuit test

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

The advantage of this method is that without much power loss the tests can be performed and results can be obtained.

(i) Open circuit Test



The transformer primary is connected to ac 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 OC 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 voltage applied at rated frequency. Sometimes a voltmeter may be connected across secondary to measure the secondary voltage which is $V_2= E_2$ when primary is supplied with rated voltage. As voltmeter resisitance is very high, though voltmeter is connected, secondary is treated to be open circuit as voltmeter current is always neglibibly 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.

V_0 = Rated voltage
W_0= Input power
I_0= 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_0. The two components of this no load current are,

$$I_m= I_0 \sin\phi_0$$
$$I_0= I_0 \cos\phi_0$$

Where $\cos\phi_0$= No load power factor

Hence power input can be written as $W_0= V_0 I_0 \cos\phi_0$

As secondary is open, I_2=0. Thus it's reflected current on primary $I_2$is also zero. So we have primary current $I_1= I_0$. The transformer no load current is very small, hardly 2 to 4% of its full load value. As I_2=0, secondary copper losses are zero. And $I_1=I_0$ is very low hence copper losses on primary are also very low. Thus the total copper losses in OC test are negligibly small. As against this the input voltage is at rated frequency, hence flux density in the core is at its maximum value. Hence iron losses 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 (W_0). Hence the wattmeter in OC test gives iron losses which remain constant for all loads.

$$W_0= P_i = \text{Iron losses}$$
$$W_0= V_0 I_0 \cos\phi$$
$$\cos\varphi_0 = \frac{W_0}{V_0 I_0} \text{ -No Load Power Factor}$$

Once $\cos\phi_0$ is known we can obtain

$$I_c=I_0 \cos\phi_0$$
$$I_m=I_0 \sin\phi_0$$

Once I_c and I_m are known

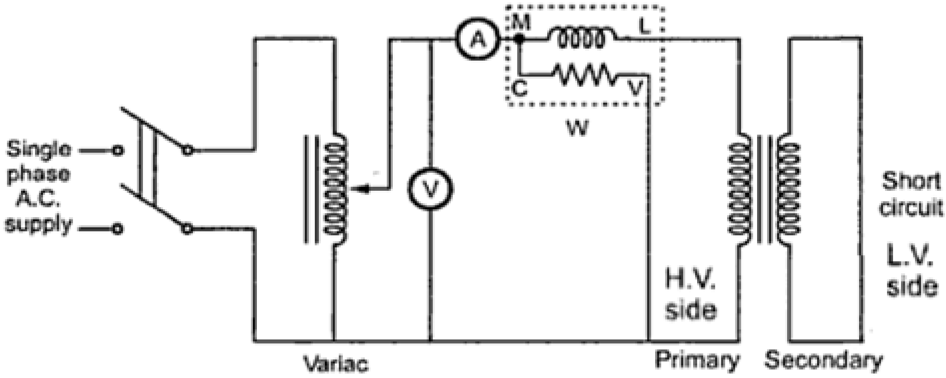
$$R_0 = \frac{V_0}{I_c}$$

$$X_0 = \frac{V_0}{Im}$$

The no load power factor $\cos\phi_0$ is very low, hence wattmeter used is low power factor meter type.

Short Circuit test (SC test)

In this test, primary is connected to ac supply through variac, ammeter and voltmeter. 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 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 ammeter.



Now the currents flowing through the windings are rated currents hence the total copper loss. Now the voltage applied is low which a small fraction of the rated voltage is. 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.

$W_{sc} = (P_{cu})$ F.L= Full load copper loss

From SC test readings

$W_{sc} = V_{sc} I_{sc} \cos\phi_{sc}$

$$\cos\varphi_{sc} = \frac{W_{sc}}{V_{sc} I_{sc}}$$ ----Short circuit power factor

$W_{sc} = I_{sc}^2 R_{01}$ = copper loss

$$R_{01} = \frac{W_{sc}}{I_{sc}^2}$$

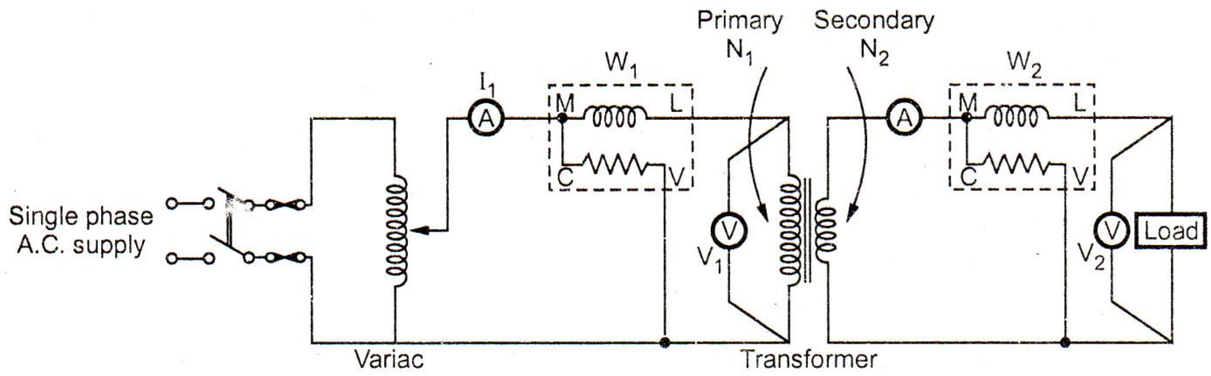
$$Z_{01} = \frac{V_{sc}}{I_{sc}} = \sqrt{R_{01}^2 + X_{01}^2}$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

Thus we get the equivalent circuit parameters R_{01}, X_{01} and Z_{01}. Knowing the transformation ration K, the equivalent circuit parameters refereed to secondary also can be obtained.

6. Explain load test on transformer

In this method the required load is directly connected to the secondary of thetransformer. Hence this method is also called **direct loading test** on transformer. Thevarious meters are connected on primary and secondary side of the transformer. Then theload is varied from no load to full load and the readings on the various meters arerecorded. Anammeter, voltmeter and a wattmeter is connected on primary as well as secondary side ofthe transformer. The primary is connected to the supply through variac which is used toadjust primary voltage to its rated value at each load condition.



The load is to be varied from no load to full load in desired steps. At all time, keepprimary voltage V_1 constant at its rated value with the help of variac. The followingobservation table is prepared.

W_1 = Input power to the transformer

W_2 = Output power delivered to the load

∴ $\% \eta = \frac{W_2}{W_1} \times 100$

The first reading is on no load for which $V_2 = E_2$

Thus at any other load, regulation can be obtained as

$\% R = \frac{E_2 - V_2}{V_2} \times 100$

Where V_2 is secondary terminal voltage at corresponding load. The graph of % η and % R on each load against load current $I_L$can be plotted.

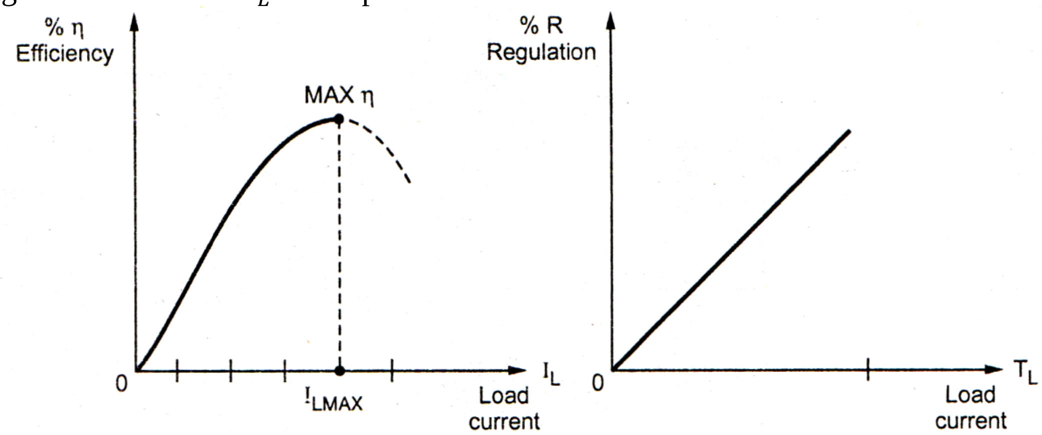


Fig. 4.23 Efficiency and regulation characteristics

The efficiency increases as load increases upto particular load. After that load,efficiency decreases as load increases. The regulation increases as the load increases as V_2keeps on decreasing as the load increases.

Advantages and Disadvantages of Direct Loading

The important advantage of this method is that the results are accurate as load is directly used,

The **disadvantages** of this method are,

1. For large rating transformers, suitable load is difficult to obtain in the laboratory. It cannot be loaded upto its full load capacity in the laboratory.
2. There are large power losses during the test.

7. *Problem 1:* **Draw the equivalent circuit of a single phase 1100/220 v transformer on which the following results were obtained.**
   (a) 1100 V, 0.5A, 55W on primary, secondary being open circuit.
   (b) 10v, 80A,400W on low voltage side, HV short circuited.

Given data:

Primary voltage V_1= 1100V, Secondary voltage V_2= 220V

Solution:

O.C test:

Primary voltage V_1= 1100V No-load input current I_o= 0.5 A

No-load input Power P_o= 55w

$$P_o = V_1 I_o \cos\Phi_o$$

No-load input power factor $\cos\Phi_o = \frac{P_o}{V_1 I_o} = \frac{55}{(1100\times0.5)} = 0.1$

$\cos\Phi_o$=0.1

$\sin\Phi_o$= 0.9949

Wattfull component (working component)

$$I_w = I_o \cos\Phi_o = 0.5\times0.1 = 0.05\text{ A}$$

Wattless component (magnetizing component)

$$Im = I_o \sin\Phi_o = 0.5\times0.9949 = 0.4974$$

Resistance representing the core loss

$$R_o = \frac{V_1}{I_w} = \frac{1100}{0.05} = 22000\ \Omega$$

Magnetizing reactance

$$X_o = \frac{V_1}{Im} = \frac{1100}{0.4974} = 2211.499\ \Omega$$

S.C test:

Short circuit voltage V_{sc}= 10V Short circuit current I_{sc}= 80 A

Losses W_{sc}= 400 W

Impedance of transformer referred to secondary

$$Z_{02} = \frac{V_{sc}}{I_{sc}} = \frac{10}{80} = 0.125\ \Omega$$

$$R_{02} = \frac{W_{sc}}{{I_{sc}}^2} = \frac{400}{80^2} = 0.0625\ \Omega$$

$$X_{02} = \sqrt{{Z_{02}}^2 - {R_{02}}^2} = \sqrt{(0.125^2 - 0.0625^2)} = 0.1082\ \Omega$$

Transformation ratio K = $\frac{V_2}{V_1} = \frac{220}{1100} = 0.2$

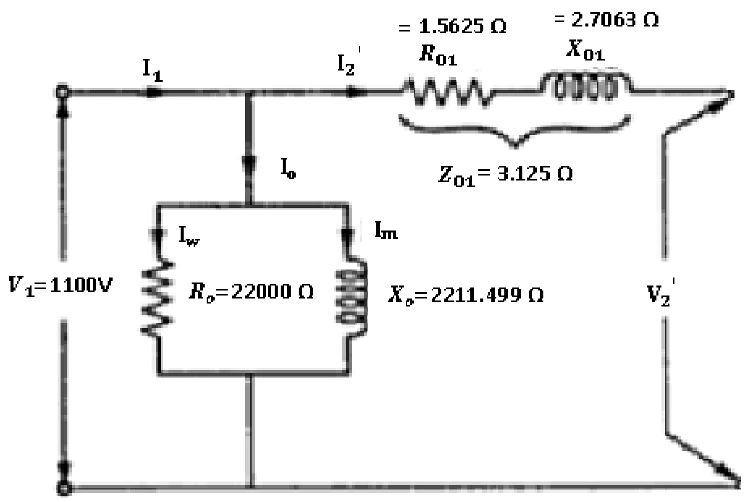
Parameters referred to 1100 V (H.V) side

$$Z_{01} = \frac{Z_{02}}{K^2} = \frac{0.125}{0.2^2} = 3.125\ \Omega$$

$$R_{01} = \frac{R_{02}}{K^2} = \frac{0.0625}{0.2^2} = 1.5625\ \Omega$$

$$X_{01} = \sqrt{{Z_{01}}^2 - {R_{01}}^2} = \sqrt{(3.125^2 - 1.5625^2)} = 2.7063\ \Omega$$

Equivalent circuit is shown below (referred to primary)



8. *Problem 2:* **In a 50 KVA Transformer, the iron loss is 500 W and full load copper loss is 800 W. Find the efficiency at full and half loads at 0.8 p.f. lagging.**

Given data:

Transformer rating = 50KVA, Iron loss P_i= 500w,

Full load copper loss P_{cu} = 800w

Power factor cos Φ = 0.8

To find:

Efficiency at (i) Full load (ii) At half load

Solution:

(i) At full load:

$$\text{Efficiency} = \frac{(n)KVA\ Cos\Phi}{(n)KVA\ Cos\Phi + P_i + (n)^2 P_{cu}} \times 100$$

$$= \frac{50\times10^3\times0.8}{(50\times10^3\times0.8)+500+800} \times 100$$

= 96.85%

(ii) At half load:

$$\text{Efficiency} = \frac{(n)KVA\ Cos\Phi}{(n)KVA\ Cos\Phi + P_i + (n)^2 P_{cu}} \times 100$$

$$= \frac{\left(\frac{1}{2}\right)50\times10^3\times0.8}{\left(\frac{1}{2}\right)(50\times10^3\times0.8)+500+\left(\frac{1}{2}\right)^2 800} \times 100$$

= 96.61%

9. Derive the efficiency of a transformer

Due to losses in a transformer, the output power of a transformer is less than the input power supplied.

Power output = Power input – Total losses

Power input = Power output + Total losses

= Power output + $P_i + P_{cu}$

The efficiency of any device is defined as the ratio of the power output to power input. So for a transformer the efficiency can be expressed as,

$$\eta = \frac{\text{Power output}}{\text{Power input}}$$

$$\eta = \frac{\text{Power output}}{\text{Power output} + P_i + P_{cu}}$$

Now power output = $V_2 I_2 \cos\Phi$

Where Cos Φ = Load power factor

The transformer supplies full load of current I_2 and with termainal voltage V_2.

P_{cu}= Copper loss on full load = ${I_2}^2 R_{2e}$

$$\eta = \frac{V_2 I_2 \cos\Phi}{V_2 I_2 \cos\Phi + P_i + {I_2}^2 R_{2e}}$$

But $V_2 I_2$ = VA rating of a transformer

$$\eta = \frac{(\text{VA rating})\times\cos\Phi}{(\text{VA rating})\times\cos\Phi + P_i + {I_2}^2 R_{2e}}$$

This is the full load percentage efficiency with,

I_2= Full load secondary current

But if the transformer is subjected to fractional load then based on the appropriate values of various quantities, the efficiency can be obtained.

Let n = Fraction by which load is less than full load = $\frac{Actual\ load}{Full\ load}$

For example, if transformer is subjected to half load then,

$$n = \frac{Half\ load}{Full\ load} = \frac{(1/2)}{1} = 0.5$$

When load changes, the load current changes by same proportion as

New I_2= n (I_2)F.L

Similarly the output $V_2 I_2$ cos Φ also reduces by the same fraction. Thus fraction of VA rating is available at the output. Similarly as copper losses are proportional to square of current then,

New $P_{cu} = n^2(P_{cu})$ F.L.

So copper losses get reduced by n^2.

In general for fractional load, the efficiency is given by,

$$\%\eta = \frac{n(\text{VA rating})\times\cos\Phi}{n(\text{VA rating})\times\cos\Phi + P_i + n^2(P_{cu})F.L}$$

Where n = *Fraction by which load is less than full load*

For all types of load power factors lagging, leading and unity the efficiency expression does not change, and remains same.

10. Derive the condition for maximum efficiency and explain about the All day efficiency of a transformer

To determine at which load the efficiency will be maximum

Differentiate the denominator with respect to load current I_2 and equate to zero, thus

$$\frac{d}{dI_2}\left[V_2\cos\phi_2 + \frac{P_i}{I_2} + I_2R_{02}\right] = 0$$

$$-\frac{P_i}{I_2^{\ 2}} + R_{02} = 0$$

$$-\frac{P_i}{I_2^{\ 2}} = -R_{02}$$

$$P_i = I_2^{\ 2}R_{02}$$

Core loss= copper loss

Thus the efficiency of a transformer is maximum at that load which makes copper loss equal to core loss.Constant losses= variable losses

ALL DAY EFFICIENCY

For a transformer, the efficiency is defined as the ratio of output power to input power. This is its power efficiency. But power efficiency is not the true measure of the performance of some special types of transformers such as distribution transformers. Distribution transformers serve residential and commercial loads. The load on such transformers vary considerably during the period of the day. The primary of the transformers is energized at its rated voltage for 24 hours, to provide continuous supply to the consumer. The core loss which depends on voltage, continuously for all the loads. But copper loss depends on the load condition. For no load, copper loss is negligibly small while on full load it is at its rated value. Hence power efficiency cannot give the measure of true efficiency of such transformers. In such case, the energy output is calculated in kilowatt hours (kWh). Then the ratio of total energy output to total energy input (output+losses) is calculated. Such ratio is called energy efficiency or all day efficiency of a transformer. Based on this efficiency,

$$\%\ \text{All day}\ \eta = \frac{\text{Output energy in kWh during a day}}{\text{Input energy in kWh during a day}} \times 100$$

$$= \frac{\text{Output energy in kWh during a day}}{\text{Output energy + Energy spent for total losses}} \times 100$$

While calculating energies, all energies can be expressed in watt hour (Wh) instead of kilo watt hour (kWh).

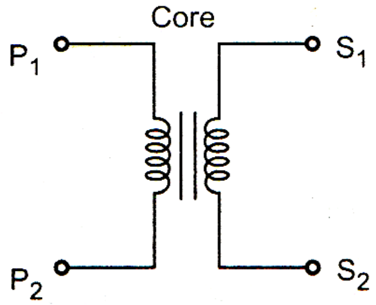
11. Write short notes on autotransformer

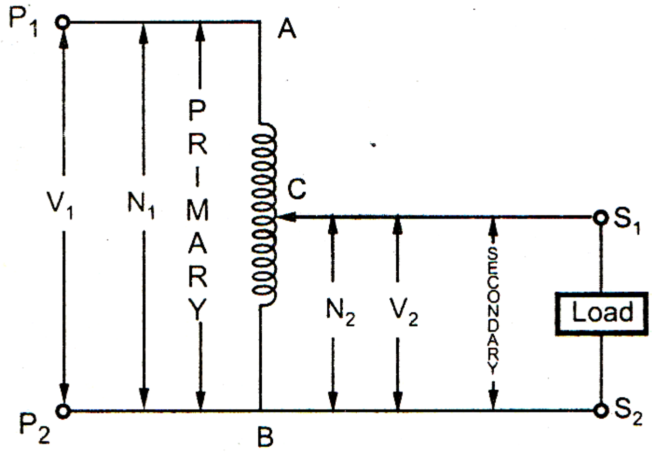
Transformers are discussed in which the windings are electrically isolated and the e.m.f. in secondary gets induced due to induction. In practice it is possible to use only one winding for the transformer so that part of this winding is common to the primary and secondary. Such a special type of transformer having only one winding such that part of the winding is common to the primary and secondary is called autotransformer. Obviously the two windings are electrically connected and it works on the principle of conduction as well as induction. Such an autotransformer is very much economical where the voltage ratio is less than 2 and the electrical isolation of the two windings is not necessary. The power transfer in 2 winding transformer is fully inductively while in autotransformer the power is transferred from primary to secondary by both inductively as well as conductively.

(i) Construction

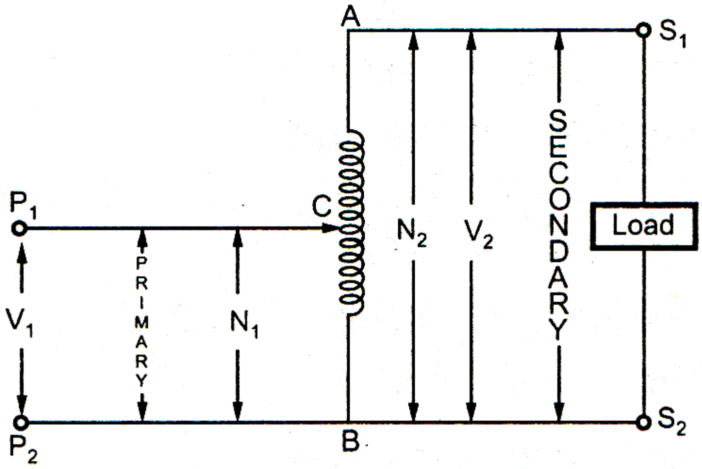
In an autotransformer only one winding is wound on a laminated magnetic core while in 2 winding transformer, two windings are wound. The single winding of the autotransformer is used as primary and secondary. The part of the winding is common to both primary and secondary. The voltage can be stepped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





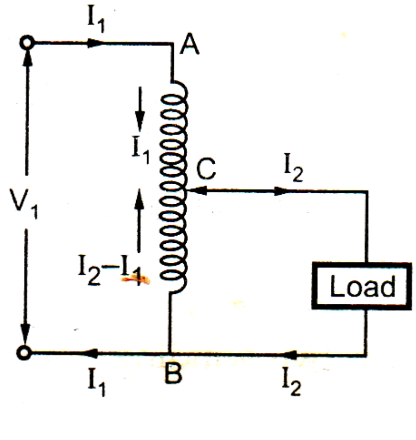
(a) 2 winding transformer (b) step-down autotransformer

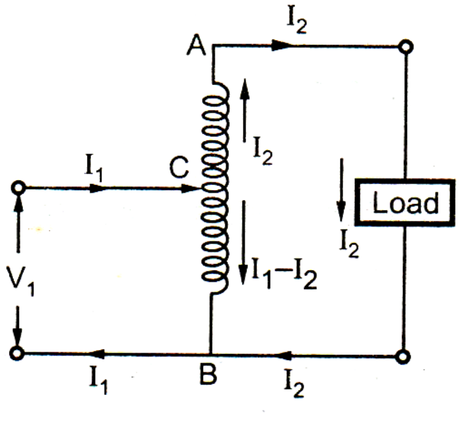


(c) Step up autotransformer

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 N1 turns while BC forms the secondary with N2 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 forms the secondary having N_2 turns while BC forms the primary with N_1 turns. As $N_2 > N_l$, the output voltage $V_2 > V_1$ and it acts as a step-up autotransformer.

The current distribution in the step down and step up autotransformers is shown in the Fig. d and e respectively.





(d) step-down autotransformer

(e) step up autotransformer

(ii) Transformation Ratio of An Autotransformer

Neglecting the losses, the leakage reactance and the magnetising 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.

Let us obtain the expression for the copper saving in the autotransformers.

(iii)Copper Saving in Autotransformer

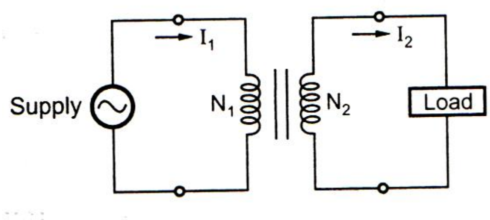
For any winding, the cross-section of winding is proportional to the current I. While the total length of the winding is proportional to the number of turns N. Hence the weight of copper is proportional to the product of N and I.

Weight of copper α NI

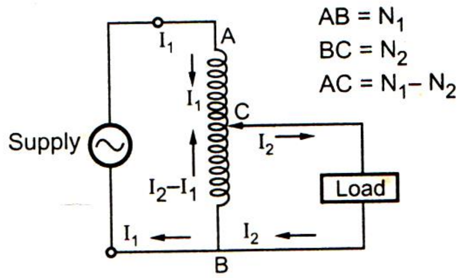
Where I = current in the winding

and N = number of turns of the winding

Consider a two winding transformer and step-down autotransformer as shown in Fig. f and g.



(f) Two winding transformer



(g) Step down transformer

Let W_{TW} = total weight of copper in two winding transformer

W_{AT} = weight of copper in autotransformer

In two winding transformer,

Weight of copper of primary $\alpha\ N_1 I_1$

Weight of copper of secondary $\alpha\ N_2 I_2$

$W_{TW}\ \alpha\ N_1I_1 + N_2 I_2$ ….. total weight of Cu

In case of step-down autotransformer.

Weight of copper of section AC $\alpha\ (N_1 - N_2) I_1$

Weight of copper of section BC $\alpha\ N_2 (I_2 - I_1)$

$W_{AT}\ \alpha\ (N_1 - N_2) I_1 + N_2 (I_2 - I_1)$ …..total weight of Cu

Taking ratio of the two Weights,

$$\frac{W_{TW}}{W_{AT}} = \frac{N_1I_1+N_2I_2}{(N_1-N_2)I_1+N_2(I_2-I_1)}$$

$$= \frac{N_1I_1+N_2I_2}{N_1I_1- N_2I_1+N_2I_2-N_2I_1}$$

$$= \frac{N_1I_1+N_2I_2}{N_1I_1+N_2I_2-2N_2I_1}$$

But $K = \frac{N_2}{N_1} = \frac{I_1}{I_2}$

$$\frac{W_{TW}}{W_{AT}} = \frac{N_1I_1+KN_1(\frac{I_1}{K})}{N_1I_1+KN_1(\frac{I_1}{K})-2KN_1I_1}$$

$$= \frac{2N_1I_1}{2N_1I_1-2kN_1I_1} = \frac{1}{1-K}$$

$$W_{AT} = (1-K)\ W_{TW}$$

Saving of copper $= W_{TW} - W_{AT} = W_{TW} - (1-K)\ W_{TW}$

Saving of copper $= K\ W_{TW}$ ….. For step down autotransformer

Thus saving of copper is K times the total weight of copper in two winding transformer.

And Saving of copper $= \frac{1}{K} W_{TW}$ ….. For step up autotransformer

12. **Discuss the constructional details and various connections, operation of three phase transformer**

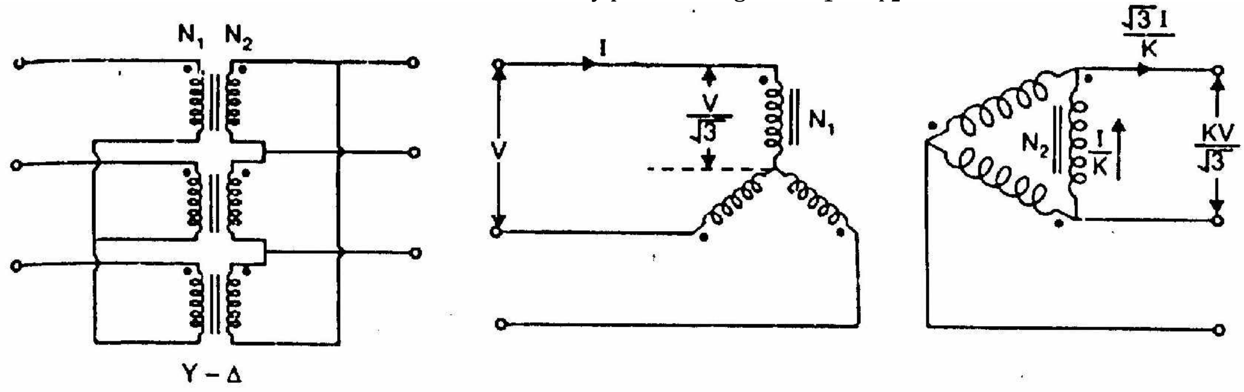
THREE-PHASE TRANSFORMER

Three phase voltages are raised or lowered by means of three-phase transformers. A three-phase transformer can be built in two ways viz., (i) by suitably connecting a bank of three single-phase transformers or (ii) by constructing a three-phase transformer on a common magnetic structure. In either case, the windings may be connected in Y – Y, Δ – Δ, Y – Δ or Δ – Y.

(i) BANK OF THREE SINGLE-PHASE TRANSFORMERS

Three similar single-phase transformers can be connected to form a three-phase transformer. The primary and secondary windings may be connected in star (Y) or delta (Δ) arrangement. The below Figure (i) shows a Y - Δ connection of a three phase transformer. The primary windings are connected in star and the secondary windings are connected in delta. A more convenient way of showing this connection is illustrated in the below figure (ii)The ratio of secondary phase voltage to primary phase voltage is the phase transformation ratio K.

Phase transformation ratio, $K = \frac{\text{Secondary phase voltage}}{\text{Primary phase voltage}} = \frac{N_2}{N_1} = \frac{I_{P1}}{I_{P2}}$



(i) (ii)

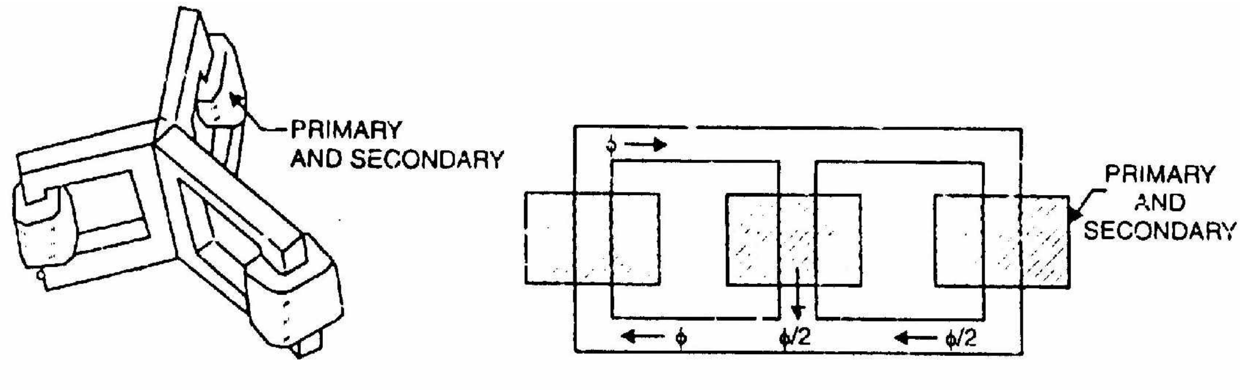
Referring to the above figure (ii), primary line-to-line voltage is V and the primary line current is I. The phase transformation ratio is K (= N_2/N_1). The secondary line voltage and line current are also shown in the above figure.

(ii) THREE-PHASE TRANSFORMER

A three-phase transformer can be constructed by having three primary and three secondary windings on a common magnetic circuit. The basic principle of a three phase transformer is illustrated in figure(i) The three single-phase core typetransformers, each with windings (primary and secondary) on only one leg have their unwound legs combined to provide a path for the returning flux.

The primaries as well as secondary may be connected in star or delta. If the primary is energized from a 3-phase supply, the central limb (i.e., unwound limb) carries the fluxes produced by the 3-phase primary windings. Since the phasor sum of three primary currents at any instant is zero, the sum of three fluxes passing through the central limb must be zero. Hence no flux exists in the central limb and it may, therefore, be eliminated.

This modification gives a three leg core type 3-phase transformer. In this case, any two legs will act as a return path for the flux in the third leg. For example, if flux is ϕ in one leg at some instant, then flux is ϕ /2 in the opposite direction through the other two legs at the same instant. All the connections of a 3-phase transformer are made inside the case and for delta-connected winding three leads are brought out while for star connected winding four leads are brought out.



(*i*) (*ii*)

For the same capacity, a 3-phase transformer weighs less, occupies less space and costs about 20% less than a bank of three single-phase transformers.

Because of these advantages, 3-phase transformers are in common use, especially for large power transformations.

A disadvantage of the three-phase transformer lies in the fact that when onephase becomes defective, the entire three-phase unit must be removed from service. When one transformer in a bank of three single-phase transformersbecomes defective, it may be removed from service and the other two transformers may be reconnected to supply service on an emergency basis until repairs can be made.

(iii) THREE-PHASE TRANSFORMER CONNECTIONS

A three-phase transformer can be built by suitably connecting a bank of three single-phase transformers or by one three-phase transformer. The primary orsecondary windings may be connected in either star (Y) or delta (Δ) arrangement. The four most common connections are (i) Y-Y (ii) Δ-Δ (iii) Y-Δ and (iv) Δ-Y.

$$K = \frac{\text{Secondary phase voltage}}{\text{Primary phase voltage}} = \frac{V_{Ph2}}{V_{Ph1}} = \frac{N_2}{N_1}$$

Reference:

- *B. L. Theraja& A. K. Theraja, A Textbook of Electrical Technology: AC and DC Machines, Volume - II, 23rd Edition, S. Chand & Company, New Delhi, 2012*
- *U. A. Bakshi, M. V. Bakshi, Electrical Machines-I, Second Edition, Technical Publications*