SRI MANAKULA VINAYAGAR ENGINEERING COLLEGE
(Approved by AICTE, New Delhi & Affiliated to Pondicherry University)
(Accredited by NBA-AICTE, New Delhi, ISO 9001:2000 Certified Institution & Accredited by NAAC with "A" Grade)
Madagadipet, Puducherry - 605 107

Department of Electrical and Electronics Engineering

Subject Name: Electrical Machines - I **Subject Code: EE T33**

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UNIT IV
TRANSFORMERS

Single phase transformers – Principle-Construction – No load operation – Ideal transformer-Vector diagram- no load and on load -Equivalent circuit – Parallel operation and load sharing of single phase transformers – Testing – Losses –– Efficiency, voltage regulation and all day efficiency Applications

Two Marks

1. **Define a transformer?**

   A transformer is a static device which transfers electrical energy from one circuit to another circuit without changing frequency.

2. **Mention the difference between core and shell type transformers?** April 2015

   Core type transformer

   The coils are wound around the two limbs of a rectangular magnetic core.
   The winding surrounds the core
   Single magnetic path

   Shell type transformer

   The coils are wound on the central limb of a three limb core.
   The core surrounds the winding
   Two magnetic paths

3. **What is the function of transformer oil in a transformer?**

   1. It provides good insulation
   2. Cooling.

4. **Why are breathers used in transformers?**

   Breathers are used to entrap the atmospheric moisture and thereby not allowing it to pass on to the transformer oil. Also to permit the oil inside the tank to expand and contract as its temperature increases and decreases.

5. **Give the emf equation of a transformer and define each term?**

   EMF induced in primary coil $E_1 = 4.44\ f\Phi_m N_1$ Volts
   EMF induced in secondary Coil $E_2 = 4.44\ f\Phi_m N_2$ Volts
   Where,

E_1, E_2 – EMF induced in primary coil and secondary coil
f – frequency of AC input
Φ_m – maximum value of flux in the core
N_1, N_2 – Number of primary & secondary turns.

6. Define the term transformation ratio?

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

The constant k is called transformation ratio.
(i). K>1 then the transformer is called step up transformer
(ii). K<1 then the transformer is called step down transformer

7. Define Ideal Transformer? Nov'2014

An ideal transformer is one that has,
(i). No winding resistance
(ii). No leakage flux
(iii). No Iron loss (Hysteresis loss and eddy current loss)

8. Define power factor?

The power factor is the cosine of phase angle between voltage and current.
Power Factor (P.F) = cosΦ
The power factor is defined as the ratio of the real power flowing to the load to the apparent power in the circuit.

$$Powerfactor = \frac{\text{Re}\ alpower(W)}{Apparentpower(VA)}$$

9. Why transformers are rated in kVA? April 2014, Nov' 2013

Copper loss of a transformer depends on current & iron loss on voltage. Hence total losses depend on Volt-Ampere and not on PF. That is why the rating of transformers are in kVA and not in kW.

10. What are the necessary tests to determine the equivalent circuit of the transformer?

1. Open circuit test
2. Short circuit test

11. Define all day efficiency of a transformer? April 2015, april 2012, Nov'2014

It is computed on the basis of energy consumed during a certain period, usually a day of 24 hrs. all day efficiency=output in kWh/input in kWh for 24 hrs.

12. How does change in frequency affect the operation of a given transformer?

With a change in frequency, iron and copper loss, regulation, efficiency & heating varies so the operation of transformer is highly affected.

13. Define regulation and efficiency of the transformer?

The regulation of the transformer is defined as the reduction in magnitude of the terminal voltage due to load, with respect to the no-load terminal voltage.
% regulation up = (V_2 on no-load- V_2 when loaded/ V_2 on no-load) x 100
% regulation down = (V_2 on no-load- V_2 when loaded/ V_2 when loaded) x 100
Transformer efficiency η= (output power/input power) x 100

14. What is the condition for maximum efficiency of a transformer? Nov'2013

When Copper loss is equal to Iron loss we will get maximum efficiency in a transformer.

15. Why the efficiency of a transformer is higher than that of motors?

Motors has moving parts so there is always a loss, but transformer has no moving parts so more efficiency.

16. List out the applications of a transformer.

- It can rise or lower the level of Voltage or Current in an AC circuit.
- It can increase or decrease the value of capacitor, an inductor or resistance in an AC circuit.
- It can be used to prevent DC from passing from one circuit to the other.
- It can isolate two circuits electrically.

17. What are losses in transformer? April 2013

(i). Core loss or iron loss – It depends on voltage

It includes both hysteresis loss and eddy current loss

(ii). Copper loss – It depends on current

18. Why the transformer core is laminated?

The eddy current and hysteresis losses are minimized by using silicon steel laminations. The core is laminated to reduce core loss.

19. Define eddy current loss and hysteresis loss and how to minimize it? April 2012,

Eddy current losses are caused due to conduction of core and are reduced by laminating the core. Hysteresis loss is due to reversal of magnetization and depends on core. In general this loss increases as frequency is increased. These losses are minimized by choosing silicon steel material.

Hysteresis loss in transformer is denoted as,

$W_h = K_h f B_m^{1.6}$ watts

Eddy Current loss in transformer is denoted as,

$W_e = K_e f^2 K_f^2 B_m^2$ watts

Where, K_h = Hysteresis Constant.

K_e = Eddy Current Constant.

K_f = form Constant.

20. What are conditions for parallel operation in single phase transformer? April 2015.

i) Primary windings of the transformer should be suitable for the supply system voltage and frequency.

ii) The transformer should be properly connected with regard to polarity.

iii) The voltage rating of both transformers is identical.

iv)The percentage impedance should be equal in magnitude and have the same X/R ratio in order to avoid circulating current and operation at different power factor.

21. Write the properties of ideal transformer April 2015

a. Zero winding resistance: It is assumed that, resistance of primary as well as secondary winding of an ideal transformer is zero. That is, both the coils are purely inductive in nature.

b. Infinite permeability of the core: Higher the permeability, lesser the mmf required for flux establishment. That means, if permeability is high, less magnetizing current is required to magnetize the transformer core.

c. No leakage flux: Leakage flux is a part of magnetic flux which does not get linked with secondary winding. In an ideal transformer, it is assumed that entire amount of flux get linked with secondary winding (that is, no leakage flux).

d. 100% efficiency: An ideal transformer does not have any losses like hysteresis loss, eddy current loss etc. So, the output power of an ideal transformer is exactly equal to the input power. Hence, 100% efficiency.

22. What are the different types of transformer? April 2013

(A) On the basis of construction, transformers can be classified into two types as;

(i) Core type transformer and (ii) Shell type transformer

(B) On the basis of their purpose

1. Step up transformer: Voltage increases (with subsequent decrease in current) at secondary.
2. Step down transformer: Voltage decreases (with subsequent increase in current) at secondary.

(C) On the basis of type of supply

1. Single phase transformer
2. Three phase transformer

(D) On the basis of their use

1. Power transformer: Used in transmission network, high rating
2. Distribution transformer: Used in distribution network, comparatively lower rating than that of power transformers.
3. Instrument transformer: Used in relay and protection purpose in different instruments in industries
   - Current transformer (CT)
   - Potential transformer (PT)

(E) On the basis of cooling employed

1. Oil-filled self cooled type
2. Oil-filled water cooled type
3. Air blast type (air cooled)

23. Write the significance of all day efficiency of transformer Nov'2012

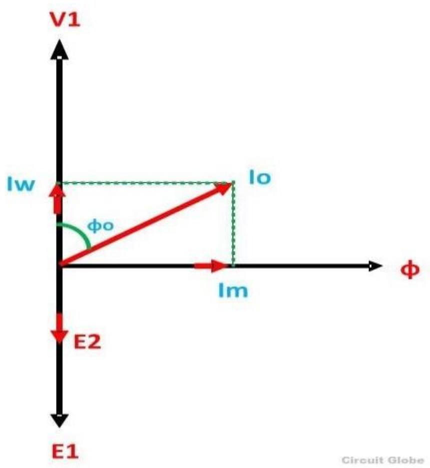
All Day Efficiency (Energy Efficiency)

In electrical power system, we are interested to find out the all-day efficiency of any transformer because the load at transformer is varying in the different time duration of the day. So all day efficiency is defined as the ratio of total energy output of transformer to the total energy input in 24 hours.

$$\text{All day efficiency} = \frac{\text{kWh output during a day}}{\text{kWh input during the day}}$$

Here, kWh is kilowatt hour.

24. Draw the noload vector diagram of a transformer April 2014



11 MARKS

1. **Explain the construction and principle of operations of single phase transformer.** April 2013

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. It consists of two windings insulated from each other and wound on a common core made up of magnetic material.

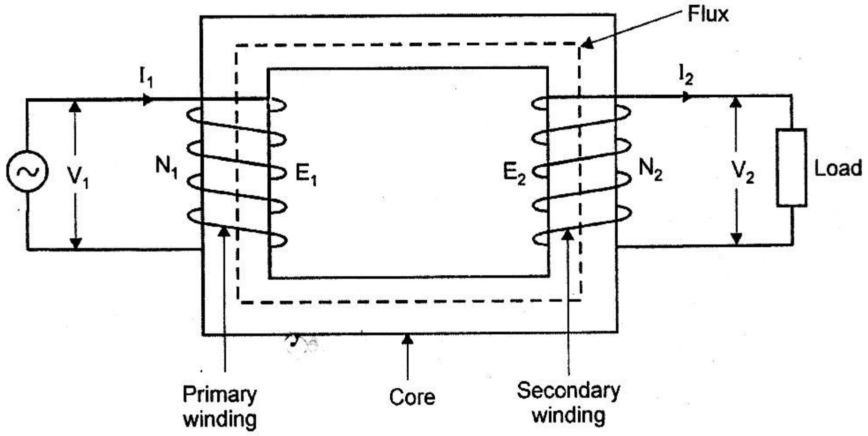


Fig. 4.1

Alternating voltage is connected across one ofthe windings called the primary winding. In both the windings emf is induced by electromagnetic induction. The second winding is called the secondary winding. It is shown in figure 4.1.

WORKING PRINCIPLE OF A TRANSFORMER

When the primary winding is connected to an ac source an exciting current flows through the winding. 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 (El) is almost equal to the applied voltage V1 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.

ln 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 4.2(b)), when the number of turns in the secondary winding is higher than the primary winding, it is called a step-up transformer (Figure 4.2(a)).

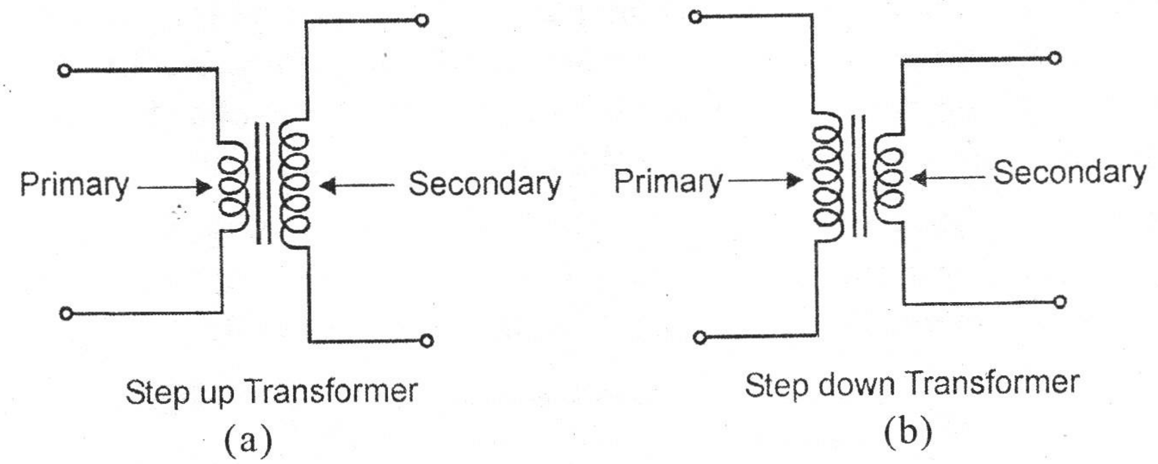


Fig. 4.2

CLASSIFICATION OF TRANSFORMERS

Transformers are classified on the basis of

i) Duty they perform

1. Power transformer - for transmission and distribution purposes
2. Current transformer - instrument transformers
3. Potential transformer - instrument transformer

(ii) Construction

1. Core type transformer 2. Shell type transformer 3. Berry type transformer

(iii) Voltage output

1. Step down transformer (Higher to Lower)
2. Step up transformer (Lower to Higher)
3. Auto Transformer (Variable from '0' to rated value)

(iv) Application

1. Welding transformer 2. Furnace transformer

(V) Cooling

1. Air cooled 2. Oil immersed

(vi) Input supply

1. Single phase transformer
2.Three phase transformer

a. Star – Star b. Star – Delta c. Delta- Delta d. Delta – Star
e. Open – Delta f. Scott connection

CONSTRUCTIONAL DETAILS

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

i) The magnetic core.

ii) Primary and secondary windings.
iii) Insulation of windings.
iv) Expansion tank or conservator.
v) Lead and tappings for coils with their supports, terminals and terminal insulators.
vi) Tank, oil, cooling arrangement, temperature gauge, oil gauge.
vii) Buchholz relay.
viii) 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 thickness of 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.

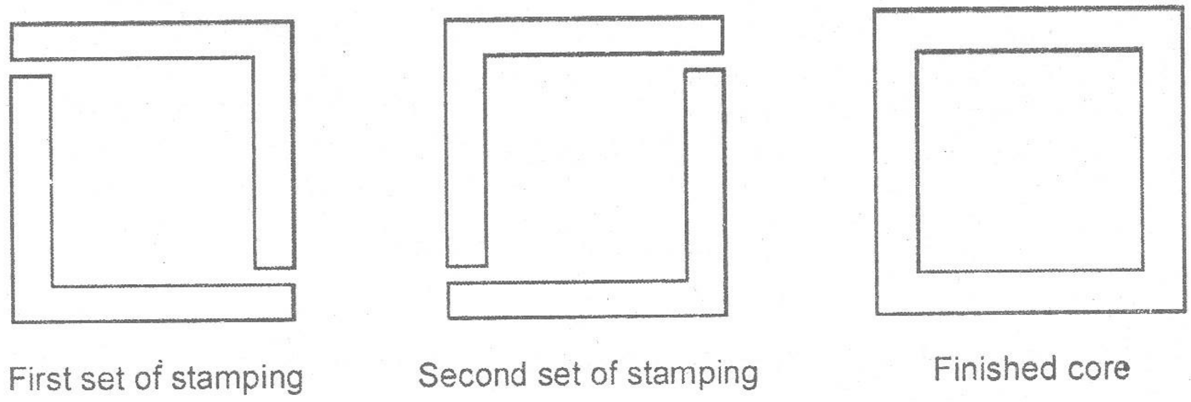


Fig. 4.3

Various types of samplings and laminations employed in the construction of transformers are shown in figure 4.3. Here the core surrounds the considerable part of

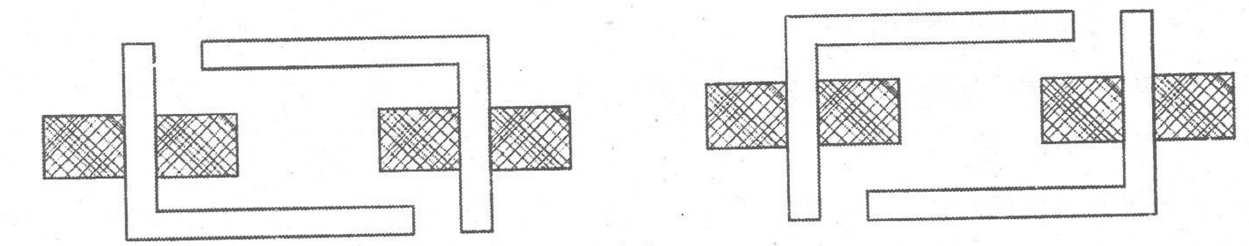
The joints are staggered to avoid continuous gap causing increase in magnetising current. If the joints are not staggered, the core will have less mechanical strength and during operation there would be undue humming noise. After arranging the laminations they are bolted together.

The two types of transformer cores are:

a. Core type b. Shell type

a) Core type transformer

Here the windings surround a considerable part of core as shown in figure 4.4 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 figure 3.4(a). The coils used usually are of cylindrical type and are usually wound. For transformers of hi gher rating stepped core with circular cylindrical coils are used. For transformers of smaller rating, rectangular coils with core of square or rectangular cross section is used. Insulating cylinders are used to separate windings from the core and from each other.



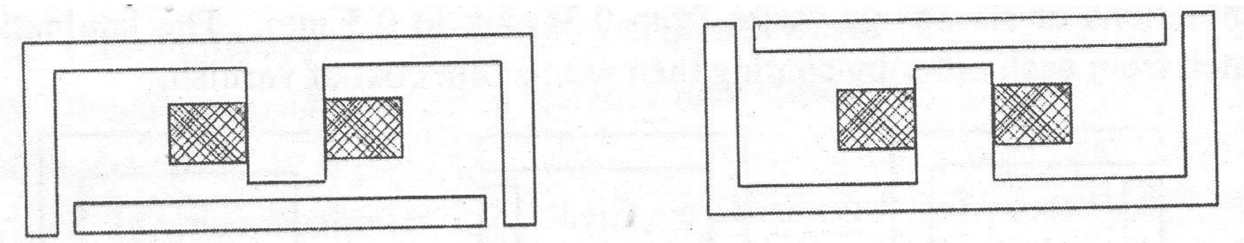
(a)

Fig. 4.4

b) Shell type transformer

Here the core surrounds the considerable part of windings as shown in figure 4.4(b). The two windings are carried by central limb. The core is made up of E and I stamping (figure 4.4(b)) and has three limbs. lt has two parallel paths for magnetic flux.

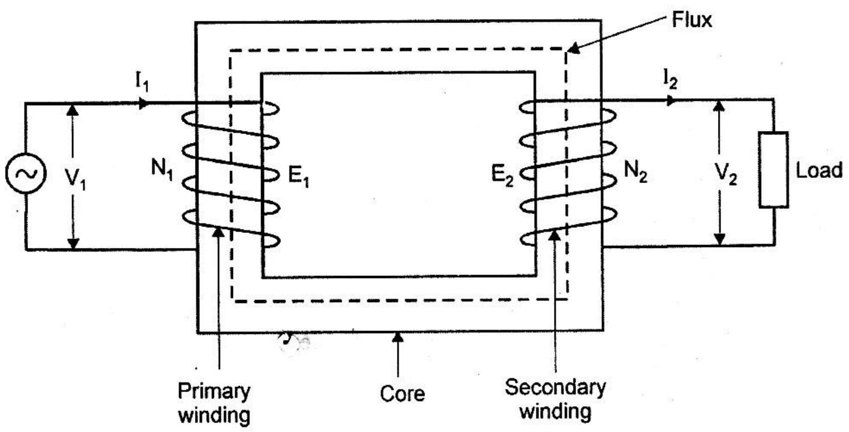
The coils used are of multilayer disc type and are former wound in the form of pan-cakes. Each layer is insulated from each other by paper.



(b)

2. **Explain the principle of a single phase transformer and derive its emf equation.** April 2015
3. **Derive the emf equation of of a transformer and explain the working.** Nov'2014
4. **(a) Discuss about the working principle of single phase transformer** April 2012
   (b) Derive the emf equation of of 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. It consists of two windings insulated from each other and wound on a common core made up of magnetic material.



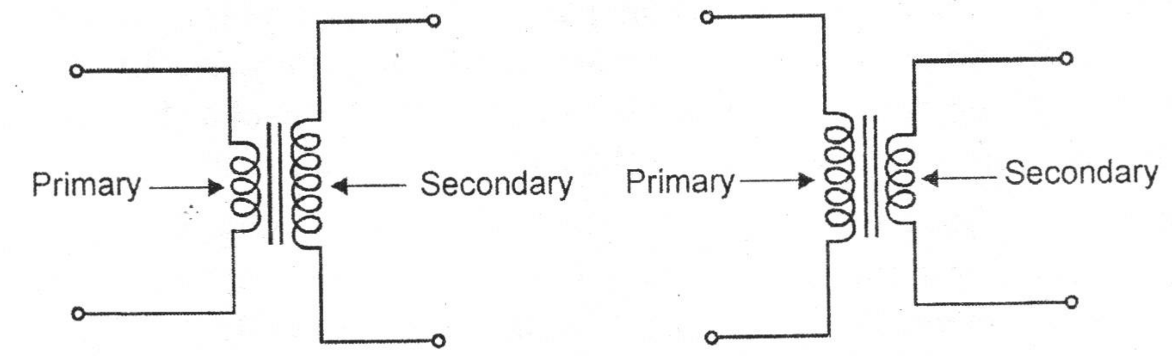
Alternating voltage is connected across one ofthe windings called the primary winding. In both the windings emf is induced by electromagnetic induction. The second winding is called the secondary winding. It is shown in figure 4.1.

WORKING PRINCIPLE OF A TRANSFORMER

When the primary winding is connected to an ac source an exciting current flows through the winding. 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 (El) is almost equal to the applied voltage V1 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.

ln 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 4.2(b)), when the number of turns in the secondary winding is higher than the primary winding, it is called a step-up transformer (Figure 4.2(a)).



Step up Transformer (a) Step down Transformer (b)

E.M.F. EQUATION OF A TRANSFORMER

Consider that an alternating voltage V_1 of frequency f is applied to the primary as shown in Fig.

The sinusoidal flux Φ produced by the primary can be represented as:

$$V1 = Vm \sin wt$$

The instantaneous e.m.f. e_1 induced in the primary is

$$e_1 = -N_1 \frac{d\Phi}{dt} = -N_1 \frac{d}{dt}(\Phi_m \sin wt)$$

$$= -w N_1 \Phi_m \cos wt$$

$$= -2\pi f N_1 \Phi_m \cos wt$$

$$= 2\pi f N_1 \Phi_m \sin(wt - 90^\circ) \quad \ldots\ldots(i)$$

It is clear from the above equation that maximum value of induced e.m.f. in the primary is

$$E_{m1} = 2\pi f N_1 \Phi_m$$

The r.m.s. value E_{rms} of the primary e.m.f. is

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \Phi_m}{\sqrt{2}}$$

or $E_1 = 4.44 \text{ f } N_1 \Phi_m$

Similarly $E_2 = 4.44 \text{ f } N_2 \Phi_m$

In an ideal transformer, $E_1 = V_1$ and $E_2 = V_2$.

Note. It is clear from exp. (i) above that e.m.f. E_1 induced in the primary lags behind the flux Φ by 90°. Likewise, e.m.f. E_2 induced in the secondary lags behind flux Φ by 90°.

4.6 TRANSFORMATION RATIO (K)

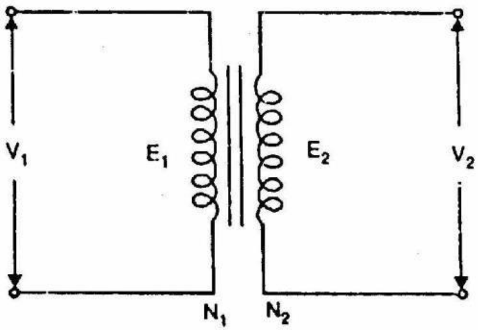


Fig. 4.6

From the above equations of induced e.m.f., we have

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

The constant K is called *voltage transformation ratio*. Thus if K = 5 (i.e. $N_2/N_1 = 5$), then $E_2 = 5\ E_1$.

For an ideal transformer;

(i) $E_1 = V_1$ and $E_2 = V_2$ as there is no voltage drop in the windings.

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

(ii) there are no losses. Therefore, volt-amperes input to the primary are equal to the output volt-amperes i.e.

$$V_1 I_1 = V_2 I_2$$

(or) $$\frac{I_2}{I_1} = \frac{V_1}{V_2} = K$$

$\therefore \frac{I_2}{I_1} = K$, this is called *current transformation ratio*.

Hence, currents are in the inverse ratio of voltage transformation ratio. This simply means that if we raise the voltage, there is a corresponding decrease of current.

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 enameled 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 tank. and 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 or
hottest 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 rigion 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 alarm
the 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.

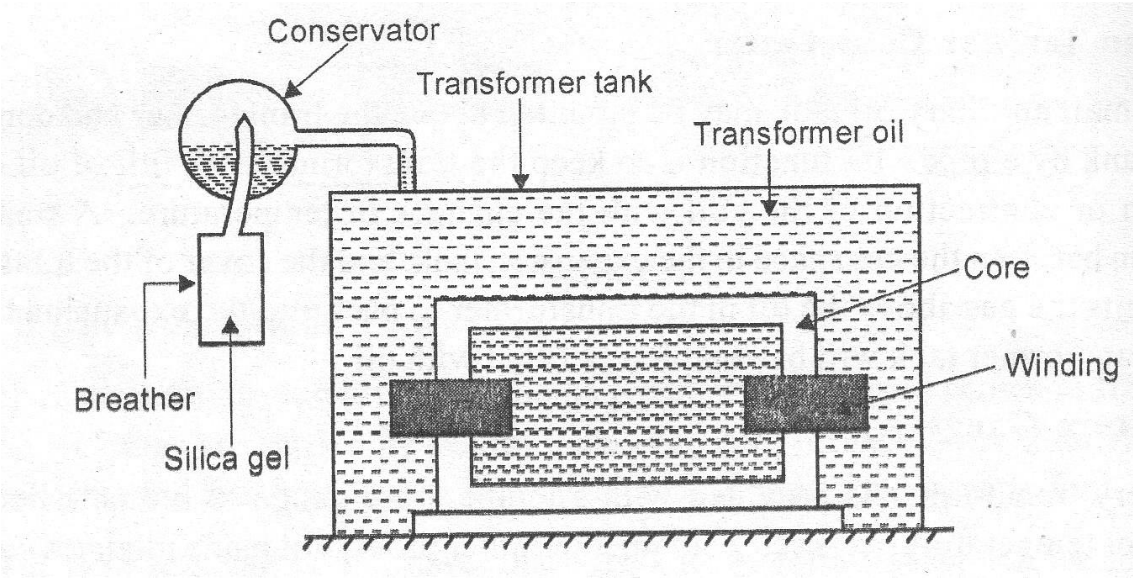


Fig. 4.5

Cooling Arrangement in Transformers

The various methods of cooling employed in a transformer are

a) Oil immersed natural cooled transformers
b) Oil immersed forced air cooled transformers
c) Oil immersed water cooled transformers
d) Oil immersed forced oil cooled transformers
e) Air blast transformers

a) Oil immersed Natural Cooled Transformers

In this type, the core and coils are immersed in insulating oil contained in an iron tank. The heat produced in the core and windings is conduct by the circulation of oil to the surface which dissipates heat to surroundings. In transformers of larger output, the dissipation surface is increased by providing large number of tubes on its sides. The oil only keeps the windings cool but also provides additional insulation.

b) Oil Immersed Forced Air Cooled Transformers

In this type, the core and windings are immersed in oil and cooling is increased by forced air over the cooling surfaces. The air is forced over external surfaces such as tank, tubes and radiators by means of fan mounted external to the transformer.

c) Oil immersed Water Cooled Transformers

In this type, the core and windings are immersed in oil and cooling is increased by circulation of cold water through the tubes immersed in oil.

d) Oil immersed Fdrced Oil Cooled Transformers

In this type, the core and windings are immersed in oil and cooling is achieved by forced oil circulation. ln this method of cooling forced oil circulation is obtained by a centrifugal pump which -is located at either the oil inlet or outlet. The pump motor used for cooling is designed to operate totally immersed in the cooling oil being circulated.

e) Air Blast Transformers

Here the transformer is cooled by a forced circulation of air through core and windings. It is used in substations located in thickly populated places where oil is considered a fire hazard. The air supplied is filtered to avoid dust entering the ventilating ducts.

5. **Draw and explain the working of ideal single phase transformer no load and load vector diagram.** Nov'2014

THEORY OF AN IDEAL TRANSFORMER ON NO-LOAD

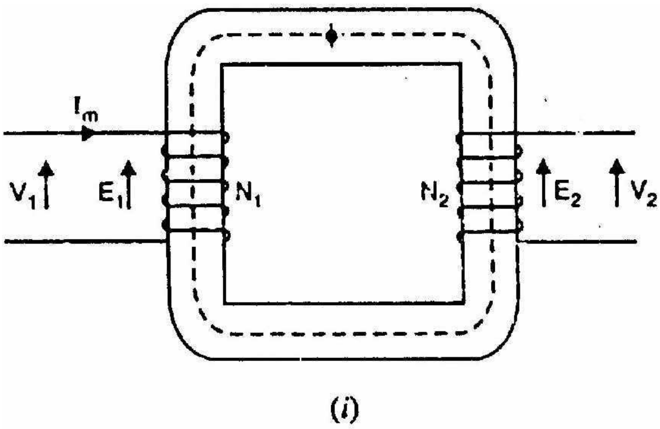
An ideal transformer is one that has

(i) no winding resistance

(ii) no leakage flux i.e., the same flux links both the windings

(iii) no iron losses (i.e., eddy current and hysteresis losses) in the core

Although ideal transformer cannot be physically realized, yet its study provides a very powerful tool in the analysis of a practical transformer. In fact, practical transformers have properties that approach very close to an ideal transformer.



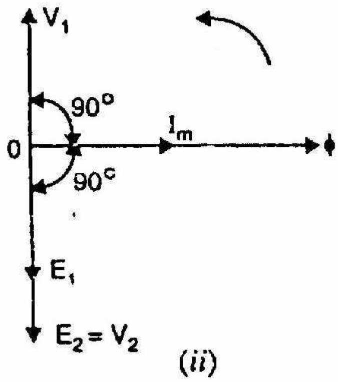


Fig. 4.7

Consider an ideal transformer on no load i.e., secondary is open-circuited as shown in Fig. (4.7 (i)). Under such conditions, the primary is simply a coil of pure inductance. When an alternating voltage V1 is applied to the primary, it draws a small magnetizing current Im which lags behind the applied voltage by 90°. This alternating current Im produces an alternating flux f which is proportional to and in phase with it. The alternating flux f links both the windings and induces e.m.f. E1 in the primary and e.m.f. E2 in the secondary. The primary e.m.f. E1 is, at every instant, equal to and in opposition to V1 (Lenz's law). Both e.m.f.s E1 and E2 lag behind flux f by 90° (See Sec. 7.3). However, their magnitudes depend upon the number of primary and secondary turns.

Fig. (4.7 (ii)) shows the phasor diagram of an ideal transformer on no load.

Since flux f is common to both the windings, it has been taken as the reference phasor. As seen in e.m.f equation of transformer, the primary e.m.f. E1 and secondary e.m.f. E2 lag behind the flux f by 90°. Note that E1 and E2 are in phase. But E1 is equal to V1 and 180° out of phase with it.

PRACTICAL TRANSFORMER

A practical transformer differs from the ideal transformer in many respects. The practical transformer has (i) iron losses (ii) winding resistances and (iii) magnetic leakage, giving rise to leakage reactances.

(i) **Iron losses**. Since the iron core is subjected to alternating flux, there occurs eddy current and hysteresis loss in it. These two losses together are known as iron losses or core losses. The iron losses depend upon the supply frequency, maximum flux density in the core, volume of the core etc. It may be noted that magnitude of iron losses is quite small in a practical transformer.

(ii) **Winding resistances**. Since the windings consist of copper conductors, it immediately follows that both primary and secondary will have winding resistance. The primary resistance R1 and secondary resistance R2 act in series with the respective windings as shown in Fig. (4.8). When current flows through the windings, there will be power loss as well as a loss in voltage due to IR drop. This will affect the power factor and E1 will be less than V1 while V2 will be less than E2.

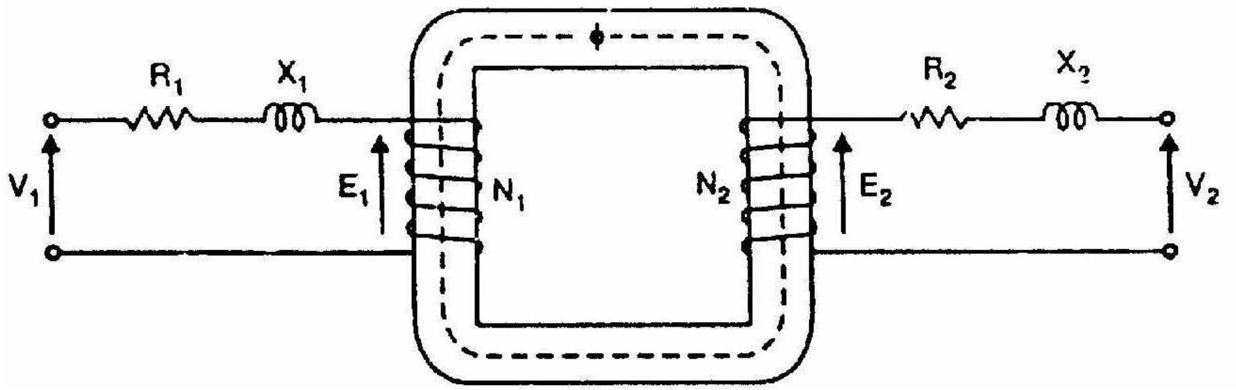


Fig. 4.8

(iii) **Leakage reactances**. Both primary and secondary currents produce flux. The flux Φ which links both the windings is the useful flux and is called mutual flux. However, primary current would produce some flux Φ which would not link the secondary winding (See Fig. 4.9). Similarly, secondary current would produce some flux f that would not link the primary winding. The flux such as Φ_1 or Φ_2 which links only one winding is called leakage flux. The leakage flux paths are mainly through the air. The effect of these leakage fluxes would be the same as though inductive reactance were connected in series with each winding of transformer that had no leakage flux as shown in Fig. (4.8). In other words, the effect of primary leakage flux Φ_1 is to introduce an inductive reactance X1 in series with the primary winding as shown in Fig. (4.8). Similarly, the secondary leakage flux Φ_2 introduces an inductive reactance X2 in series with the secondary winding. There will be no power loss due to leakage reactance. However, the presence of leakage reactance in the windings changes the power factor as well as there is voltage loss due to IX drop.

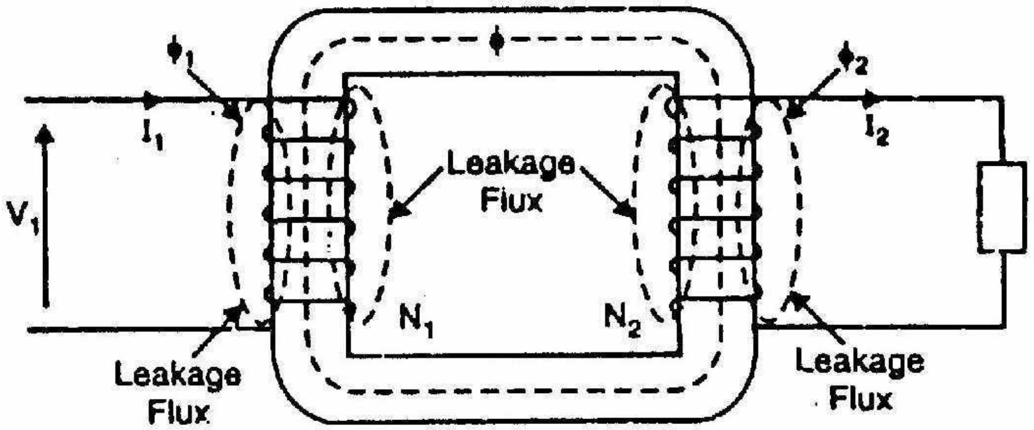


Fig. 4.9

Note. Although leakage flux in a transformer is quite small (about 5% of f) compared to the mutual flux Φ, yet it cannot be ignored. It is because leakage flux paths are through air of high reluctance and hence require considerable e.m.f. It may be noted that energy is conveyed from the primary winding to the secondary winding by mutual flux Φ which links both the windings.

PRACTICAL TRANSFORMER ON NO LOAD

Consider a practical transformer on no load i.e., secondary on open-circuit as shown in Fig. (4.10 (i)). The primary will draw a small current I_0 to supply (i) the iron losses and (ii) a very small amount of copper loss in the primary. Hence the primary no load current I_0 is not 90° behind the applied voltage V_1 but lags it by an angle $\Phi_0 < 90°$ as shown in the phasor diagram in Fig. (4.10 (ii)).

No load input power, $W_0 = V_1 I_0 \cos \Phi_0$

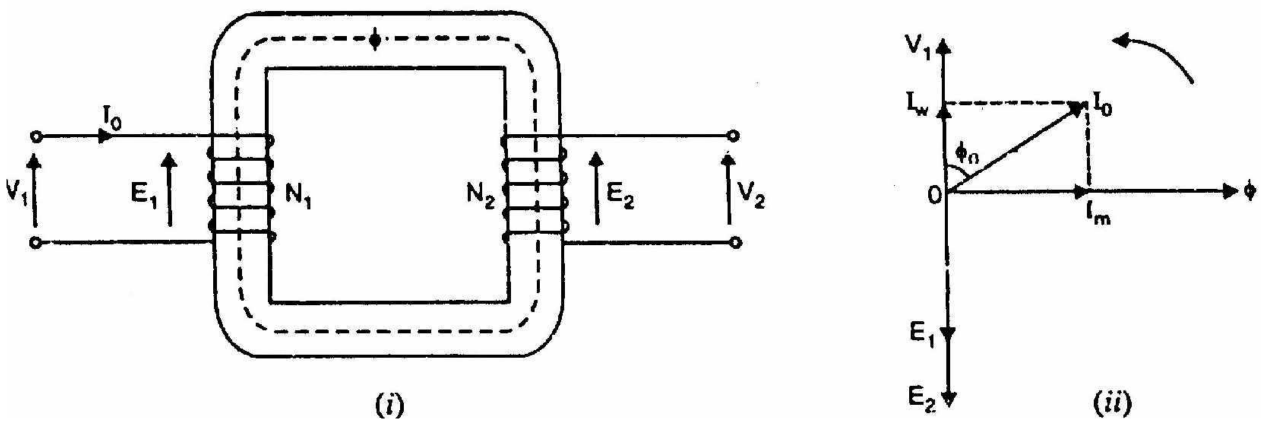


Fig. 4.10

As seen from the phasor diagram in Fig. (4.10 (ii)), the no-load primary current I0 can be resolved into two rectangular components viz.

(i) The component I_W in phase with the applied voltage V_1. This is known as active or working or iron loss component and supplies the iron loss and a very small primary copper loss.

$I_W = I_0 \cos \Phi_0$

(b) The component Im lagging behind V_1 by 90° and is known as magnetizing component. It is this component which produces the mutual flux f in the core.

$I_m = I_0 \sin \Phi_0$

Clearly, I_0 is phasor sum of I_m and I_W,

$$\square I_0 \sqrt{I_m^2 + I_W^2}$$

No load p.f., $\cos \Phi_0 = \frac{I_W}{I_0}$

It is emphasized here that no load primary copper loss (i.e. $I_0{}^2 R_1$) is very small and may be neglected. Therefore, the no load primary input power is practically equal to the iron loss in the transformer i.e.,

No load input power, W_0 = Iron loss

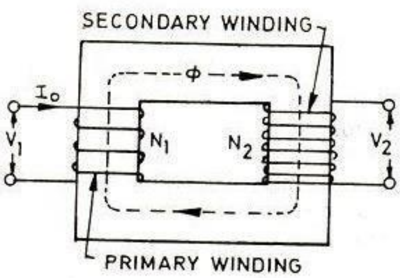
Note. At no load, there is no current in the secondary so that $V_2 = E_2$. On the primary side, the drops in R1 and X1, due to I_0 are also very small because of the smallness of I_0. Hence, we can say that at no load, $V_1 = E_1$.

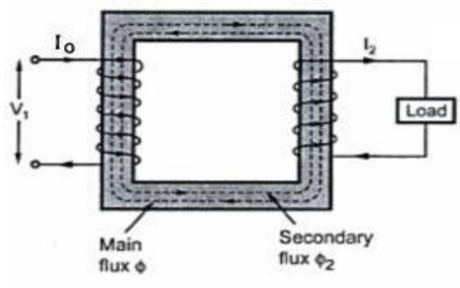
6. **(a) Explain the operations of single phase transformer under loaded condition and hence draw the vector diagram of the transformer under lagging power factor load. April 2015.**

When the transformer is loaded, the current I_2 flows through the secondary winding. The magnitude and phase of I_2 is determined by the load. If load is inductive, I_2 lags V_2. If load is capacitive, I_2 leads V_2 while for resistive load, I_2 is in phase with V_2.

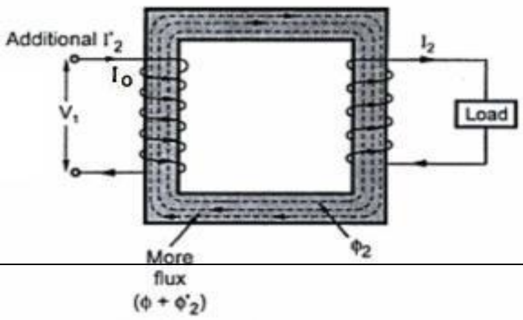
There exists a secondary m.m.f. $N_2 I_2$ due to which secondary current sets up its own flux ϕ_2. This flux opposes the main flux ϕ which is produced in the core due to magnetising component of no load current. Hence the m.m.f. $N_2 I_2$ is called **demagnetising ampere-turns**. This is shown in the Fig.

The flux ϕ_2 momentarily reduces the main flux ϕ, due to which the primary induced e.m.f. E_1 also reduces. Hence the vector difference $\bar{V}_1 - \bar{E}_1$ increases due to which **primary draws more current from the supply.** This additional current drawn by primary is due to the load hence called load component of primary current denoted as I_2' as shown in the Fig.





ϕ_2 opposes ϕ



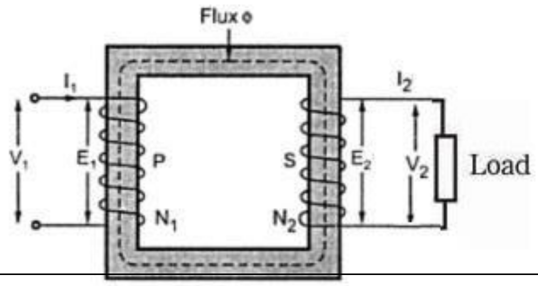


Fig. 1.16 Transformer on load

This current I_2' is in antiphase with I_2. The current I_2' sets up its own flux ϕ_2' which opposes the flux ϕ_2 and helps the main flux ϕ. This flux ϕ_2' neutralises the flux ϕ_2 produced by I_2. The m.m.f. i.e. ampere turns $N_1 I_2'$ balances the ampere turns $N_2 I_2$. Hence the net flux in the core is again maintained at constant level.

Key Point: *Thus for any load condition, no load to full load the flux in the core is practically constant.*

The load component current I_2' always neutralises the changes in the load. As practically flux in core is constant, the core loss is also constant for all the loads. Hence the transformer is called **constant flux machine**.

As the ampere turns are balanced we can write,

$$N_2 I_2 = N_1 I_2'$$

$$\therefore \quad I_2' = \frac{N_2}{N_1} I_2 = K\, I_2 \qquad \text{... (1)}$$

Thus when transformer is loaded, the primary current I_1 has two components :

1. The no load current I_o which lags V_1 by angle ϕ_o. It has two components I_m and I_c.
2. The load component I_2' which is in antiphase with I_2. And phase of I_2 is decided by the load.

Hence primary current I_1 is vector sum of I_0 and I_2'.

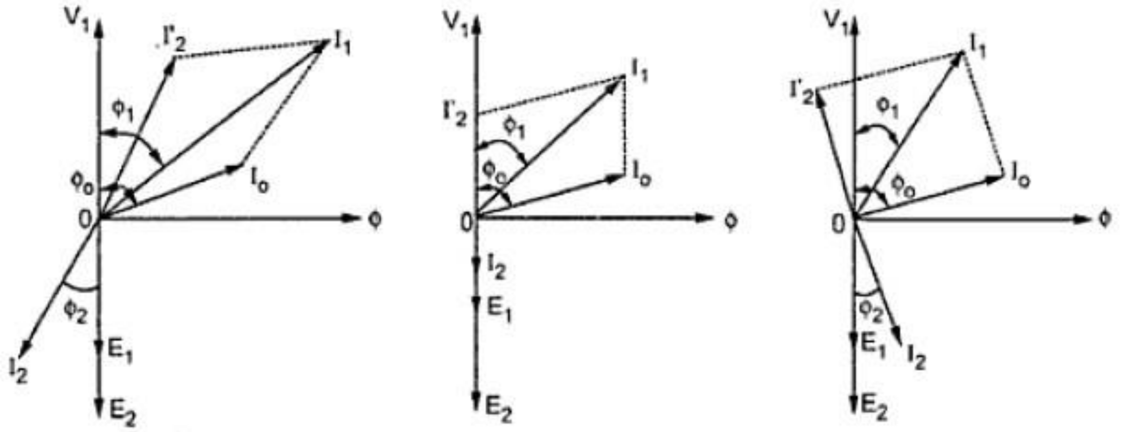
$$\therefore \quad \bar{I}_1 = \bar{I}_o + \bar{I}_2' \qquad \text{... (2)}$$

Assume inductive load, I_2 lags E_2 by ϕ_2, the phasor diagram is shown in the Fig. 1.17 (a).

Assume purely resistive load, I_2 in phase with E_2, the phasor diagram is shown in the Fig. 1.17 (b).

Assume capacitive load, I_2 leads E_2 by ϕ_2, the phasor diagram is shown in the Fig. 1.17 (c).

Note that I_2' is always in antiphase with I_2.



(a) Inductive load (b) Resistive load (c) Capacitive load

Fig. 1.17

Actually the phase of I_2 is with respect to V_2 i.e. angle ϕ_2 is angle between I_2 and V_2. For the ideal case, E_2 is assumed equal to V_2 neglecting various drops.

The current ratio can be verified from this discussion. As the no load current I_o is very small, neglecting I_o we can write,

$$I_1 \cong I_2'$$

Balancing the ampere-turns,

$$N_1 I_2' = N_1 I_1 = N_2 I_2$$

$$\therefore \quad \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$$

Under full load conditions when I_o is very small compared to full load currents, the ratio of primary and secondary current is constant.

Describe the method of drawing equivalent circuit of single phase transformer and explain how to reduce the equivalent circuit. **April 2013**

(b) From the first principles, obtain the approximate equivalent circuit of a transformer referred to secondary. **April 2015, nov'2012**

Equivalent Circuit of Transformer

The term equivalent circuit of a machine means the combination of fixed and variable resistances and reactances, which exactly simulates performance and working of the machine.

For a transformer, no load primary current I_o has two components,

$$I_m = I_o \sin \phi_o = \text{Magnetising component}$$

$$I_c = I_o \cos \phi_o = \text{Active component}$$

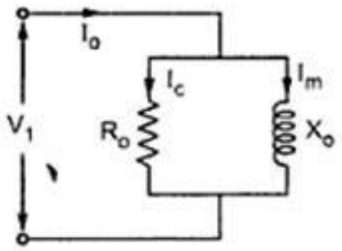


Fig. No load equivalent circuit

I_m produces the flux and is assumed to flow through reactance X_o called no load reactance while I_c is active component representing core losses hence is assumed to flow through the resistance R_o. Hence equivalent circuit on no load can be shown as in the Fig. 1.27. This circuit consisting of R_o and X_o in parallel is called exciting circuit. From the equivalent circuit we can write,

$$R_o = \frac{V_1}{I_c}$$

and $$X_o = \frac{V_1}{I_m}$$

When the load is connected to the transformer then secondary current I_2 flows. This causes voltage drop across R_2 and X_2. Due to I_2, primary draws an additional current $I_2' = I_2 / K$. Now I_1 is the phasor addition of I_o and I_2'. This I_1 causes the voltage drop across primary resistance R_1 and reactance X_1.

Hence the equivalent circuit can be shown as in the Fig. 4.12.

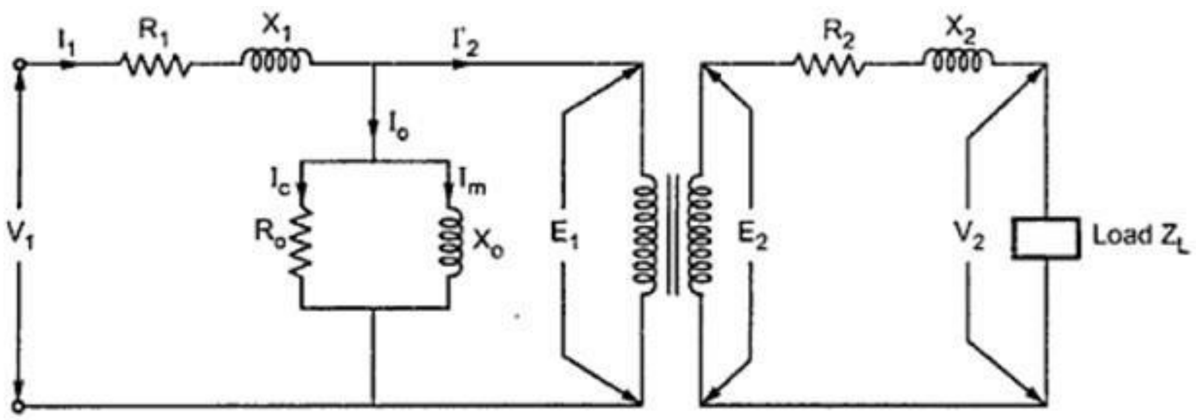


Fig. 4.12

But in the equivalent circuit, windings are not shown and it is further simplified by transferring all the values to the primary or secondary. This makes the transformer calculations much easy.

So transferring secondary parameters to primary we get,

$$R_2' = \frac{R_2}{K^2}, \quad X_2' = \frac{X_2}{K^2}, \quad Z_2' = \frac{Z_2}{K^2}$$

while $$E_2' = \frac{E_2}{K}, \quad I_2' = KI_2$$

where $$K = \frac{N_2}{N_1}$$

While transferring the values remember the rule that

Low voltage winding → High current → Low impedance

High voltage winding → Low current → High impedance

Thus the exact equivalent circuit referred to primary can be shown as in the Fig. 4.13

Similarly all the primary value can be referred to secondary and we can obtain the equivalent circuit referred to secondary.

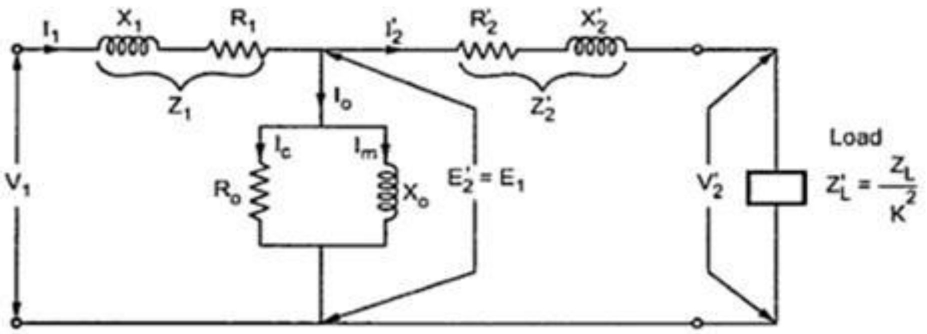


Fig. 4.13 Exact equivalent circuit referred to primary

Now as long as no load branch i.e. exciting branch is in between Z_1 and Z_2', the impedances cannot be combined. So further simplification of the circuit can be done. Such circuit is called approximate equivalent circuit.

To get approximate equivalent circuit, shift the no load branch containing R_o and X_o to the left of R_1 and X_1. By doing this we are creating an error that the drop across R_1 and X_1 due to I_o is neglected. Hence such an equivalent circuit is called **approximate equivalent circuit.**

So approximate equivalent circuit referred to primary can be as shown in the Fig. 4.14

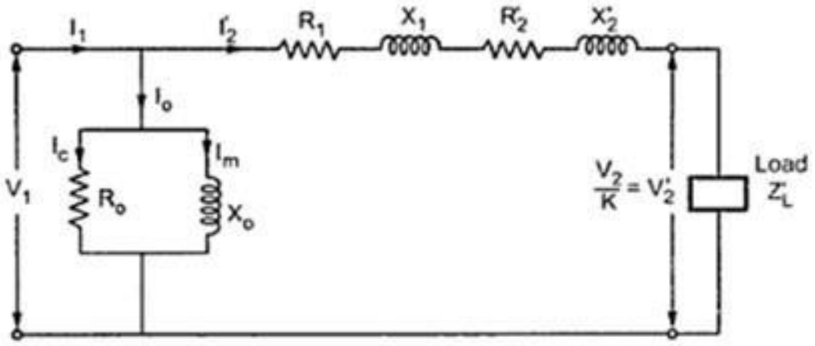


Fig. 4.14 Approximate equivalent circuit referred to primary

In this circuit now R_1 and R_2' can be combined to get equivalent resistance referred to primary R_{1e} as discussed earlier. Similarly X_1 and X_2' can be combined to get X_{1e}. And equivalent circuit can be simplified as shown in the Fig. 4.15

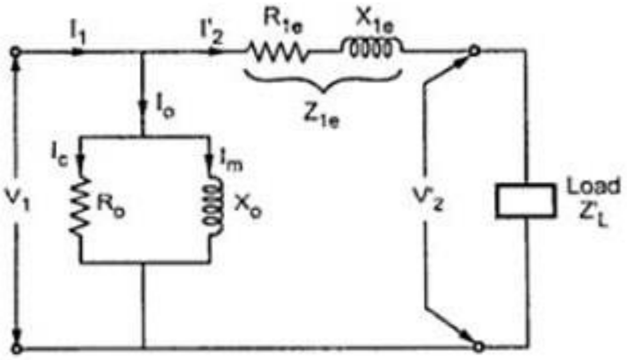


Fig. 4.15

We know that, $R_{1e} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}$

$$X_{1e} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

$$Z_{1e} = R_{1e} + j\,X_{1e}$$

$$R_o = \frac{V_1}{I_c} \quad \text{and} \quad X_o = \frac{V_1}{I_m}$$

and $I_c = I_o \cos\phi_o$ and $I_m = I_o \sin\phi_0$

In the similar fashion, the approximate equivalent circuit referred to secondary also can be obtained.

4.10.1 Equivalent circuit referred to secondary

If all the primary quantities are referred to secondary, we get the equivalentcircuit of the transformer referred to secondary.

$$R_1' = K^2 R_1, \quad X_1' = K^2 X_1, \quad Z_1' = K^2 Z_1$$

$$E_1' = K E_1, \quad I_1' = \frac{I_1}{K}, \quad I_o' = \frac{I_o}{K}$$

Similarly the exciting circuit parameters also gets transferred to secondary as R_o' and X_o'. The circuit is shown in the Fig. 4.16

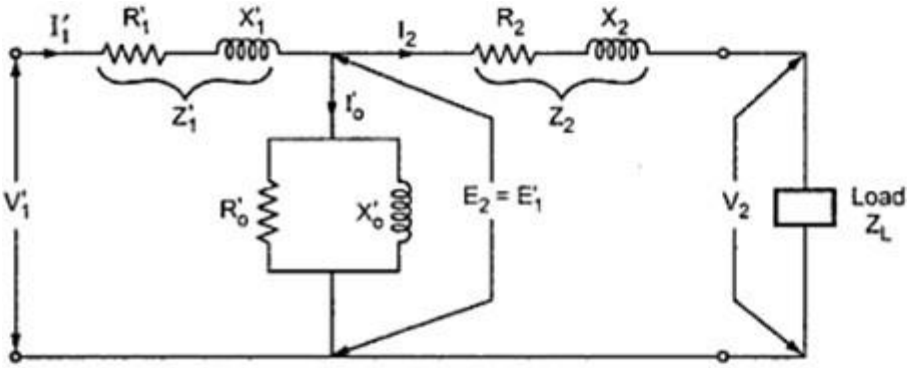


Fig.4.16 Exact equivalent circuit referred to secondary

To get approximate equivalent circuit, shift the no load branch containing R_o' and X_o' to the left of R_1' and X_1'. By doing this we are creating an error that the drop across R_1' and X_1' due to I_o' is neglected. Hence such an equivalent circuit is called **approximate equivalent circuit.**

So approximate equivalent circuit referred to primary can be as shown in the Fig. 4.17

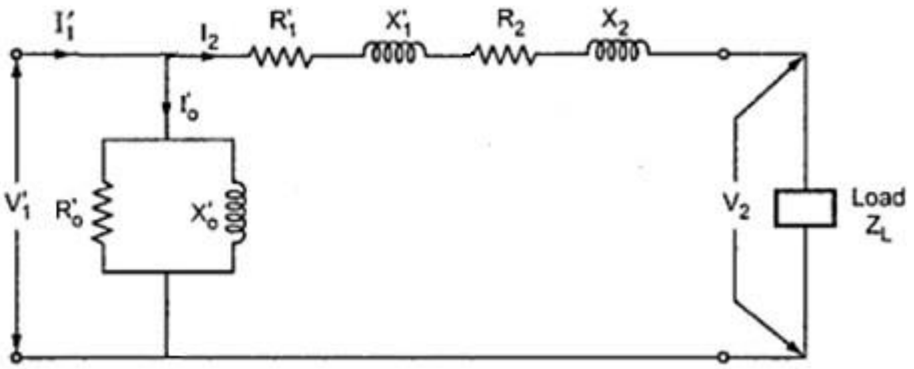


Fig. 4.17. Approximate equivalent circuit referred to secondary

The equivalent circuit can be simplified as shown in the Fig. 4.18

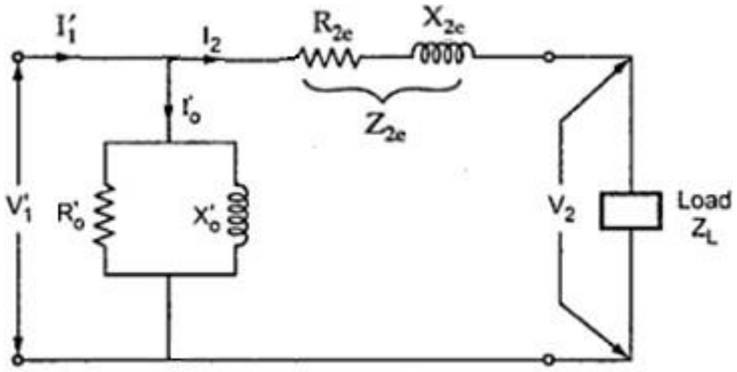


Fig. 4.18.

We know that, $Z_{2e} = R_{2e} + j X_{2e}$

4.11 TESTING OF TRANSFORMERS

INDIRECT LOADING TESTS OF TRANSFORMERS

4.11.1 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.

4.11.2 Open Circuit Test (O.C. Test)

The experimental circuit to conduct O.C. test is shown in the Fig.4.19

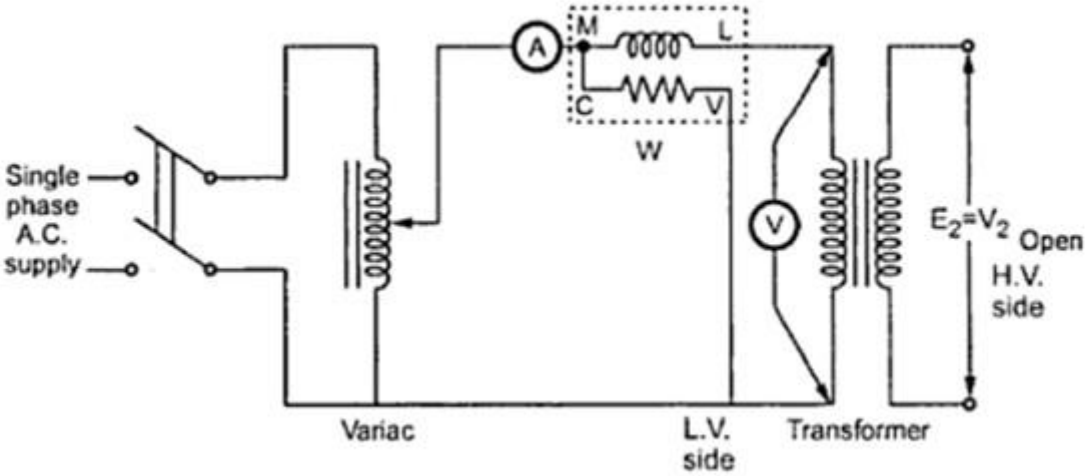


Fig.4.19 Experimental circuit for O.C. test

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 $V_2 = E_2$ when primary is supplied with rated voltage. As voltmeter resistance 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.

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,

$$I_m = I_o \sin \phi_o$$

$$I_c = I_o \cos \phi_o$$

where $\cos \phi_o$ = No load power factor

And hence power input can be written as,

$$W_o = V_o I_o \cos \phi_o$$

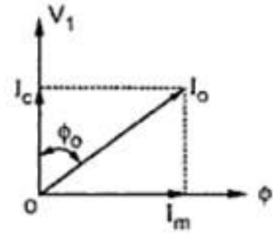


Fig. 4.20

The phasor diagram is shown in the Fig. 4.20

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.

$$\therefore \quad W_o = P_i = \text{Iron losses}$$

Calculations : We know that,

$$W_o = V_o I_o \cos \phi$$

$$\therefore \quad \cos \phi_o = \frac{W_o}{V_o I_o} = \text{no load power factor}$$

Once $\cos \phi_o$ is known we can obtain,

$$I_c = I_o \cos \phi_o$$

and

$$I_m = I_o \sin \phi_o$$

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

$$R_o = \frac{V_o}{I_c} \quad \Omega$$

and

$$X_o = \frac{V_o}{I_m} \quad \Omega$$

Key Point : *The no load power factor $\cos \phi_o$ is very low hence wattmeter used must be low power factor type otherwise there might be error in the results.*

4.11.3 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. 4.21

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.

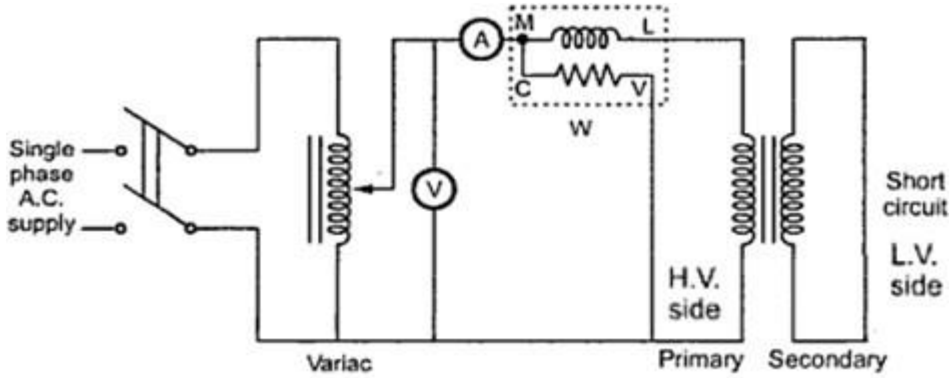


Fig. 4.21 Experimental circuit for S.C. test

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.

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

Calculations : From S.C. test readings we can write,

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

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

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

$$\therefore \quad \boxed{R_{1e} = \frac{W_{sc}}{I_{sc}^2}}$$

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

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

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.

LOAD TEST ON TRANSFORMER

In this method the required load is directly connected to the secondary of the transformer. Hence this method is also called **direct loading test** on transformer. The various meters are connected on primary and secondary side of the transformer. Then the load is varied from no load to full load and the readings on the various meters are recorded,

The Fig. 4.22 shows the experiment set up for the load test on transformer. An ammeter, voltmeter and a wattmeter is connected on primary as well as secondary side of the transformer. The primary is connected to the supply through variac which is used to adjust primary voltage to its rated value at each load condition.

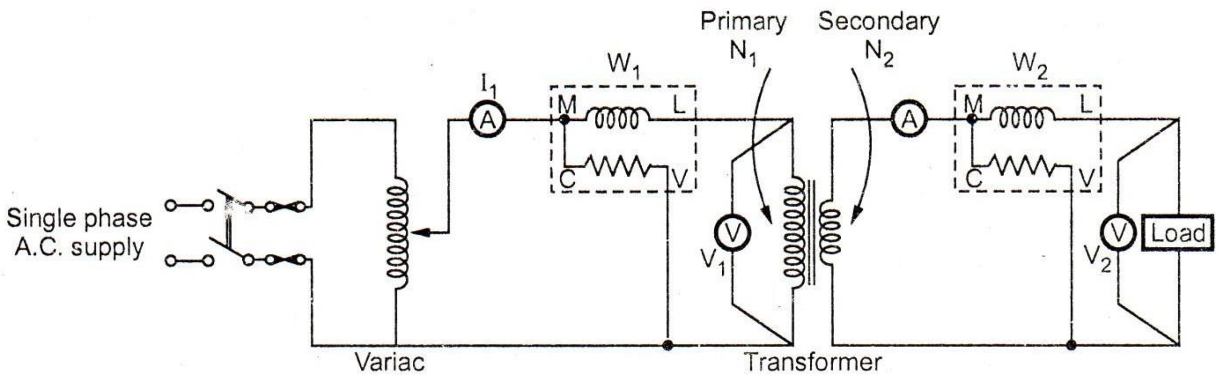


Fig. 4.22 Load test on transformer

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

No.	Primary side			Secondary side		
	V_1 V	I_1 A	W_1 W	V_2 V	I_2 A	W_2 W
1	Rated			E_2	0	0
2 ⋮						

This first reading is to be noted on load for which I_2 = 0 A and W_2=0 W

Calculations

From the observation table,

W_1 = Input power to the transformer

W_2 = Output power delivered to the load

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

The first reading is on no load for which,

$$V_2 = E_2$$

Thus at any other load, regulation can be obtained as

% R = $\frac{E_2 - V_2}{V_2}$ × 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 is plotted as shown in the Fig. 4.23.

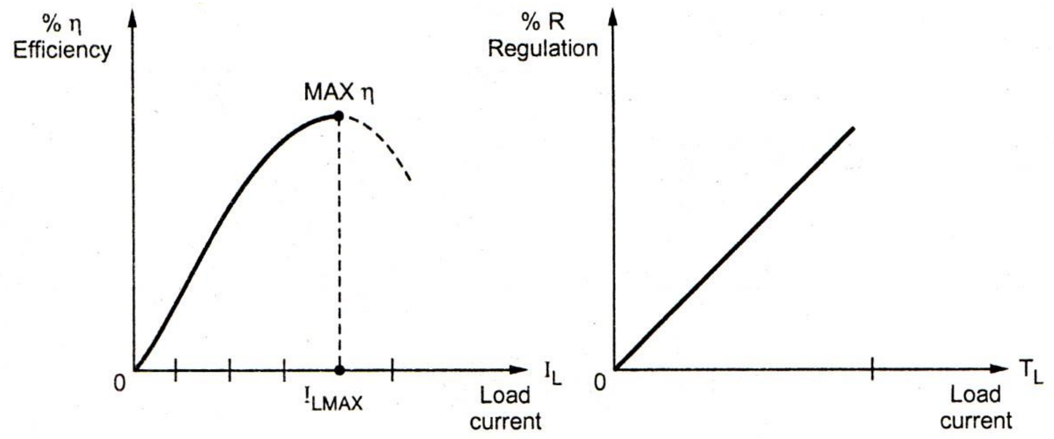


Fig. 4.23 Efficiency and regulation characteristics

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_2 keeps 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. l. 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.

Key Point : Hence this method is suitable for small transformers and rarely used.

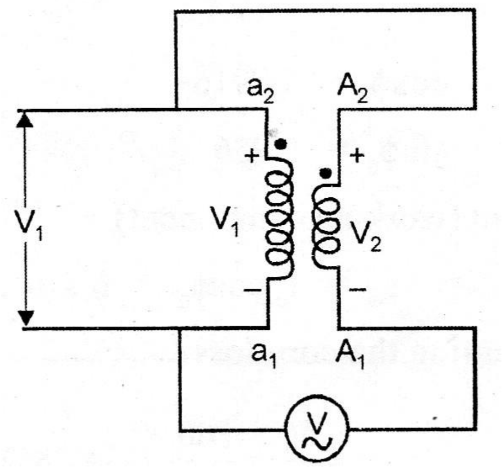
POLARITY TEST

Figure 4.24 shows polarity test on two winding transformer. A polarity test is carried out to find out the terminal having the same instantaneous polarity assuming that the terminals are not marked.

Similar polarity ends of the two windings of a transformer are those ends acquire simultaneously positive or negative polarity of emf's induced in them. are indicated by the dot convention.

Usually the ends ofthe LV winding are labelled with small letter ofthe with suffix l and 2, while the HV winding are labelled by the corresponding letter with suffix 1 and 2.

ln determining the relative polarity of the two windings of a two windings are connected in series across a voltmeter, while one of the excited from a suitable voltage source. If the polarities ofthe windings are as on the diagram, the voltmeter should read V= VI ~ V2 _ If it reads V= VI +V? polarity marking of one of the windings must be interchanged. _



7. Explain the sumpner's test withwith its circuit diagram of single phase transformer. April 2013

4.14 Sumpner's Test (Back to Back Test)

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 Sumpner's 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 O.C. and S.C. tests, the loading conditions are absent. Hence the results are inaccurate. 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 V_1. While the secondaries are connected in series opposition so that induced e.m.f.s in the two secondaries oppose each other. The secondaries are supplied from another low voltage supply, meters are connected in each circuit to get the readings. The connection diagram is shown in the Fig. 4.25.

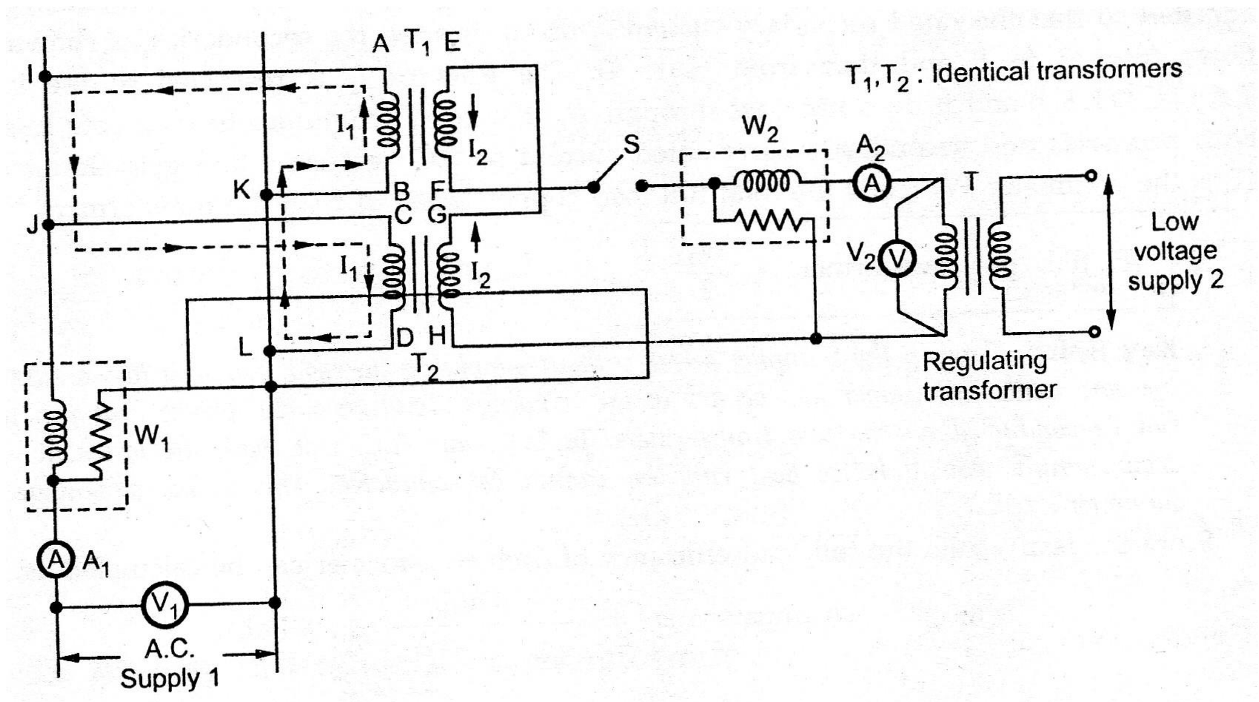


Fig. 4.25. Connection diagram for sumpner's test

T1 and T2 are two identical transformers. The secondaries of T1 and T2 are connected in series opposition. So E_{EF} = E_{GH} i.e. induced e.m.f in two secondaries 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 secondaries 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.

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 $2 I_0$. Where I_0 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.

$\therefore P_i$ per transformer = $\frac{W_1}{2}$ As T_1 , 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_2 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 secondaries carry rated current so S.C. test condition gets simulated.
Thus the wattrneter W_2 reads the total full load copper losses of both the transformers.

$\therefore (P_{cu})$F.L 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 test 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,

$$\% \, \eta_{F.L} \text{ of each transformer} = \frac{Output}{Output + \frac{W_1}{2} + \frac{W_2}{2}} \times 100$$

Where Output = VA rating × cos Φ_2

Key Point: As all the voltages, currents and powers are measured during the test, the equivalent circuit parameters also can be determined. Hence the regulation at any load and load power factor condition can be predetermined.

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.

Problem: 2 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 $\cos \Phi_o = \frac{P_o}{V_1 I_o} = \frac{55}{(1100 \times 0.5)} = 0.1$

$\cos \Phi_o$=0.1

$\sin \Phi_o$= 0.9949

Wattfull component (working component)

$I_w = I_o \cos \Phi_o = 0.5 \times 0.1 = 0.05$ A

Wattless component (magnetizing component)

$I_m = I_o \sin \Phi_o = 0.5 \times 0.9949 = 0.4974$

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

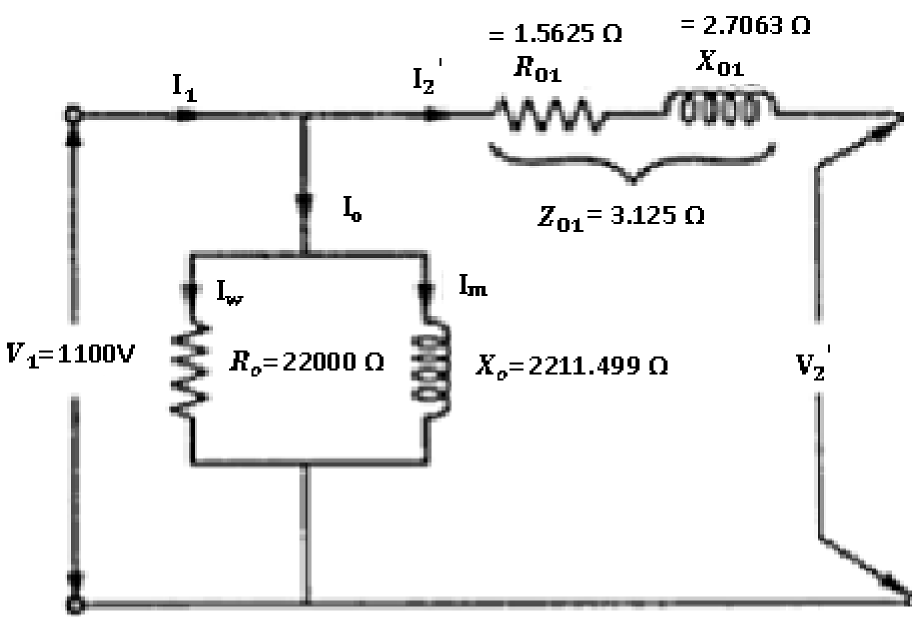
Parameters referred to 1100 V (H.V) side

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

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

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

Equivalent circuit is shown below (referred to primary)



Problem 3: 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%

PARALLEL OPERATION OF TRANSFORMERS:

It is economical to install numbers of smaller rated **transformers in parallel** than installing a bigger rated electrical power transformers. This has mainly the following advantages,

1. To maximize electrical power system efficiency:

Generally electrical power transformers gives the maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on only those transformers which will give the total demand by running nearer to its full load rating for that time. When load increases, we can switch none by one other transformer connected in parallel to fulfill the total demand. In this way we can run the system with maximum efficiency.

2. To maximize electrical power system availability:

If numbers of transformers run in parallel, we can shutdown any one of them for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.

3. To maximize power system reliability:

if any one of the transformers running in parallel, is tripped due to fault. The system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.

4. To maximize electrical power system flexibility:

There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfill the extra demand because, it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.

From the Fig. 4.22 it can be seen that the primary windings are connected to the supply bus bars while the secondary windings are connected to load bus bars.

Two or more transformers are connected in parallel to carry common load. If a given transformer is insufficient in capacity to deliver a particular load it may either be taken out of the circuit and replaced with a larger unit or an additional unit may be added to the circuit by connecting its primary side to the same source of supply and its secondary side to the same load circuit. The second unit is then said to be operating in parallel with the first unit. For satisfactory parallel operation of transformers there are conditions that must be satisfied.

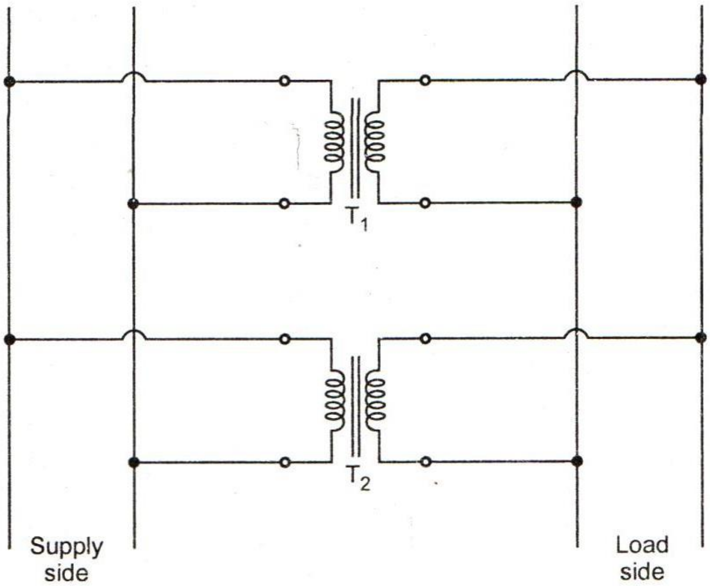


Fig. 4.22 Parallel operation

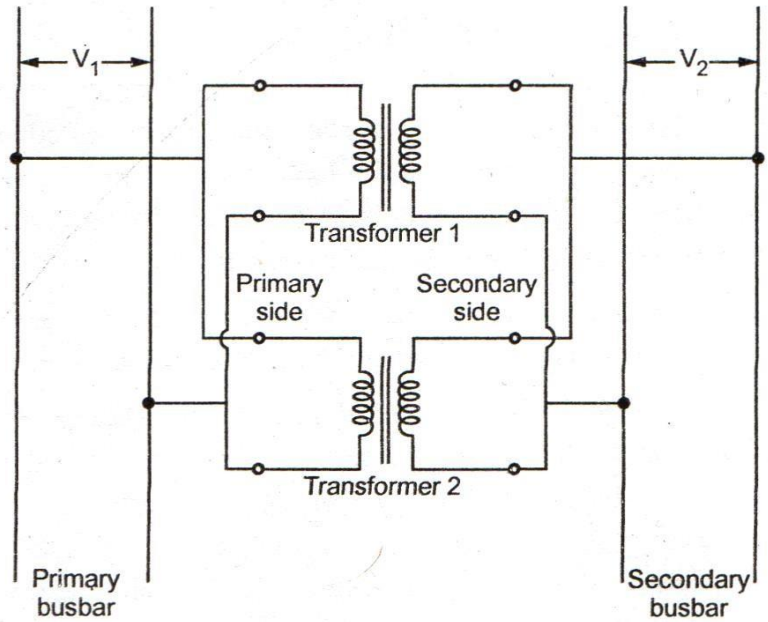


Fig. 4.23 Alternative connection of parallel transformer

Key point: Satisfactory parallel operation of the transformer implies that the transformers connected in parallel share common load approximately in proportion to their ratings. The most satisfactory condition is achieved when the load shared by the transformers is in exact proportion with their ratings.

Conditions for* Parallel *Operation of Transformers

When two or more transformers run in parallel, they must satisfy the following conditions for satisfactory performance. These are the conditions for **parallel operation of transformers**

1) The supply system voltage and frequency must suit the primary windings of the transformers.
2) The transformers that are connected must have same polarity. In case of three phase transformers the transformers should have same angular displacement and same phase sequence.
3) The voltage ratios of the primaries and secondaries of the transformers must be same.
4) The percentage impedance must be equal in magnitude and have same $\frac{X}{R}$ ratio in order to avoid circulating currents and operating at different power factors.
5) If the transformers have the different KVA ratings, the equivalent impedances should be inversely proportional to individual KVA rating to avoid circulating currents.

6) **State the various losses in a transformer. Define efficiency of a transformer and hence deduce the condition for maximum efficiency. (April – 2015)**

LOSSES IN A TRANSFORMER

1) In a transformer, there exists two types of losses.
2) i) The core gets subjected to an alternating flux, causing **core losses**.
3) ii) The windings carry currents when transformer is loaded, causing **copper losses.**

Copper Loss

Copper loss is I^2R loss, in primary side it is $I_1^2R_1$ and in secondary side it is $I_2^2R_2$ loss, where I_1 & I_2 are primary & secondary current of transformer and R_1 & R_2 are resistances of primary & secondary winding. As the both primary & secondary currents depend upon load of transformer, **copper loss in transformer** vary with load.

Copper loss can simply be denoted as,

$$\text{Copper loss} = I_L^2R_2' + \text{Stray loss}$$

Where, $I_L = I_2$ = load current of transformer

R_2' is the resistance of transformer referred to secondary.

❖ Copper losses can be minimized by using conductors of large diameters in order to reduce the resistance per unit length of the conducting windings of the electrical device. The value of Cu loss is found from the short-circuit test.

Core or Iron Loss

Hysteresis loss and eddy current loss, both depend upon magnetic properties of the materials used to construct the core of transformer. So these losses in transformer are fixed and do not depend upon the load current. So **core loss in transformer** which is alternatively known as **iron loss in transformer** can be considered as constant for all range of load.

Hysteresis loss in transformer is denoted as,

$$W_h = K_h f (B_m)^{1.6} \ watts$$

Eddy current loss in transformer is denoted as,

$$W_e = K_e f^2 K_f^2 B_m^2 \ watts$$

Where, K_h = Hysteresis constant.

K_e = Eddy current constant.

K_f = Form constant.

B_m=Maximum flux density, wb/m^2

f = Frequency,Hz

❖ These losses are minimized by using steel of high silicon content for the core and by using very thin laminations. Iron or core loss is found from the O.C. test. The input of the transformer when on no-load measures the core loss.

Efficiency

The efficiency of a transformer at a particular load and power factor is defined as the output divided by the input.

$$Efficiency = \frac{Output}{input}$$

But a transformer being a highly efficient piece of equipment, has very small loss, hence it is impractical to try to measure transformer efficiency by measuring input and output. These quantities are nearly of the same size. A better method is to determine the losses and then to calculate the efficiency from,

$$Efficiency = \frac{Output}{Output + Losses} = \frac{Output}{Output + Culoss + ironloss}$$

$$Efficiency = \frac{input - losses}{input} = 1 - \frac{losses}{input}$$

➢ It may be noted here that efficiency is based on power output in watts and not in volt-amperes, although losses are proportional to VA. Hence, at any volt-ampere load, the efficiency depends on power factor, being maximum at a power factor of unity.

➢ Efficiency can be computed by determining core loss from no-load or open-circuit test and Cu loss from the short-circuit test.

Condition for Maximum Efficiency

Cu loss = $I_1^2 R_{01}$ or $I_2^2 R_{02} = W_{cu}$

Iron loss = Hysteresis loss + Eddy current loss = $W_h + W_e = W_i$

Considering primary side,

Primary input = $V_1 I_1 \cos \varphi_1$

$$Efficiency = \frac{input - losses}{input} = \frac{input - (culoss + ironloss)}{input}$$

$$Efficiency = \frac{V_1 I_1 \cos\varphi_1 - \left(I_1^2 R_{01} + W_i\right)}{V_1 I_1 \cos\varphi_1}$$

$$= \frac{V_1 I_1 \cos\varphi_1}{V_1 I_1 \cos\varphi_1} - \frac{I_1^2 R_{01}}{V_1 I_1 \cos\varphi_1} - \frac{W_i}{V_1 I_1 \cos\varphi_1}$$

$$\eta = 1 - \frac{I_1 R_{01}}{V_1 \cos\varphi_1} - \frac{W_i}{V_1 I_1 \cos\varphi_1}$$

Differentiating both sides with respect to I_1, we get

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\varphi_1} + \frac{W_i}{V_1 I_1^2 \cos\varphi_1}$$

For η to be maximum,

$$\frac{d\eta}{dI_1} = 0$$

Hence the above equation becomes,

$$0 = -\frac{R_{01}}{V_1 \cos\varphi_1} + \frac{W_i}{V_1 I_1^2 \cos\varphi_1}$$

$$\frac{R_{01}}{V_1 \cos\varphi_1} = \frac{W_i}{V_1 I_1^2 \cos\varphi_1}$$

$$W_i = \frac{R_{01} V_1 I_1^2 \cos\varphi_1}{V_1 \cos\varphi_1}$$

$$W_i = I_1^2 R_{01}$$

Cu.loss = Iron loss

The output current corresponding to maximum efficiency is $I^2 = \sqrt{\frac{W_i}{R_{01}}}$

It is this value of the output current which will make the Cu loss equal to the iron loss. By proper design, it is possible to make the maximum efficiency occur at any desired load.

Note:

1. If we are given iron loss and full load Cu loss, then the load at which two losses would be equal (*i.e.* corresponding to maximum efficiency) is given by

$$\eta = \text{Full load KVA} \times \sqrt{\frac{Ironloss}{F.L.Culoss}}$$

2.The efficiency at any load is given by,

$$\eta = \frac{x \times F.L.load.KVA \times p.f}{\left(x \times F.L.load.KVA \times p.f\right) + W_i + W_{cu}} \times 100$$

where, x= ratio of actual to full load KVA