6.1.1 TRANSFORMER

State and illustrate the working principle of the transformer.

A transformer works on the principle of Faraday's Laws of Electromagnetic Induction. As the transformer is a static device and has no rotating part, so the type of induction is also static induction that is mutual induction. “Whenever a conductor links the changing flux an e.m.f. is induced in that conductor”. This induced e.m.f. is proportional to the rate of change of flux and the number of turns.
Consider there are two coils ‘A’ and ‘B’ wound on the iron cores as shown in. Coil A. is connected across the supply i.e. it is the primary winding and coil B, where load is connected is known as secondary winding. If the coil ‘A’ is energised by ac. mains the magnetic flux of alternating nature will be produced. This changing flux is also realised by the iron cores. The coil ‘B’ which is wound on the cores will also link this changing flux, through iron cores which is a path of low reluctance. A result e.m.f. is induced in coil B.

6.1.2 CONCEPT OF MUTUAL INDUCTANCE

When the flux from one coil links another coil, an e.m.f. (known as mutually induced e.m.f.) is induced in the second coil. By Lenz’s law this mutually induced e.m.f. is also a counter e.m.f.
This inductive effect is called mutual inductance (symbol $M$). The first and the second coils are called the primary and the secondary coils. The mutually induced e.m.f. can be written as

$$e = M$$

Where $e$ is the e.m.f. induced in the secondary coil (in volts), $i$ is the rate of change of current in the primary coil and $M$ is the coefficient of mutual inductance or simply mutual inductance. The unit of mutual inductance is also henry (H). The mutual inductance between two coils is $IH$ if current changing at the rate of 1 ampere per second in one coil induces a voltage of 1 volt in the second coil.

### 6.1.3 COEFFICIENT OF MUTUAL INDUCTION

It is denoted by the letter $M$.

If there are two coils having $N_1$ and $N_2$ number of turns; than the coefficient of mutual inductance between the two coils is defined as the weber turns in one coil due to one ampere current in the other neighbouring coil.
Let there be I, ampere current flowing in one coil produces $\phi_1$ Wb flux. Now this flux links with the second coil without loss of any flux.

Now the flux linkage (Wb-turns) in the second coil for unit current in the first coil are

\[ M = \frac{N_2\phi_1}{I} \]

If $N_2\phi_1 = 1$ and $I = IA$ in that case $M = 1$, which can be defined as the two coils are said to have a mutual inductance of IH if one ampere current.

When flowing in one produces a flux linkage of one Wb-turns in the other neighbouring coil.

It can otherwise be defined as two coil will have a mutual inductance of one henry if a current changing at the rate of one ampere per second in one coil induces an e.m.f. of one volt in the other coil.
6.1.4 DEFINE THE TRANSFORMATION RATIOS

There are the following types of transformation ratios of a transformer:

i) Voltage transformation ratio,
ii) Turn transformation ratio.
iii) Current transformation ratio and
iv) Impedance transformation ratio

Let the primary winding has got $N_1$ turns and secondary winding $N_2$ turns then the voltage induced can be given as:

$$E_1 = 4.44 \phi_m . f . N_1 \text{ Volts}$$

and

$$E_2 = 4.44 \phi_m . f . N_2 \text{ Volts}$$

Now the ratio of secondary voltage to primary voltage is defined and the voltage transformer ratio i.e.

$$= \frac{E_2}{E_1}$$
Now if both the voltages are represented in the form of transformer e.m.f. then,

\[ = \]

\[ \therefore = \]

The ratio of secondary number of turns to primary number of turns is defined as the turn transformation ratio.

6.1.5 CONSTRUCTION

The transformer is a very simple device. It consists of a magnetic circuit lining with two distinct windings i.e. the primary and the secondary/ the magnetic circuit is formed by an iron core. The presence of iron introduces iron losses but ensures a high permeability of the magnetic circuit. Because of high permeability the magnitude of the exiting current, necessary to set up the required flux in the core, in the core, is small. The presence of iron core causes almost 100% of the magnetic flux generated by the primary to be linked with the secondary. The core is built up of thin sheets of silicon steel, an
alloy of iron containing about 4 to 5% silicon. To reduce eddy current loss the core is laminated, the usual thickness of limitations being about 0.5mm. Depending on the relative positions of the core and the windings, a single phase transformer may be a core type transformer or a shell type transformer.

A core type transformer has the high and low voltage windings divided into two parts each and placed on the core. Thus each limb carries one half of the primary and one half of the secondary winding thus ensuring a close coupling between the two windings. The low voltage winding is placed nearest to the core to reduce the amount of the insulating material.
It shows a shell type transformer. As seen in this figure the core surrounds the windings (in contrast with the core). Another difference between the core type and the shell type is that in core type transformers ‘cylindrical windings type construction is more economical for low voltage transformers and the core type construction is more suitable for high voltage transformers.

6.1.6 TYPES OF TRANSFORMERS

According to core construction there are three main types of transformers namely (i) core type ii) shell type and iii) berry type.

i) Core Type Transformers:
Core type transformer with arrangement of core and coils, in this type of transformer the winding surround the iron care. Both the windings are divided and half of each winding is placed on each limb to make the leakage flux as small as possible Since insulation of low voltage winding
Transformer

is easy so low voltage winding is placed next to core and then high voltage winding is placed around the low voltage coils. In such an arrangement only one layer of high voltage insulation is required and removal or repair of the high voltage winding, which is more liable to faults than the low voltage winding, is easy arid convenient.
(ii) **Shell-Type Transformers:**
The shell type transformer, in this type of transformer the iron core surrounds the copper windings. The core is in the form of a figure. The entire flux passes through the central part of iron core, but outside this central core it divides into two Paris half going in each direction. Sandwich type winding is used in which the sections of the primary winding are sand-witched in between the section of the secondary winding.
In this manner the leakage flux is reduced to try small value. To minimise the amount of high voltage insulation low voltage coils are placed adjacent to the iron core.

If the core type and shell type transformers are compared, then se conclude that the core type transformer has a longer mean length of iron core and a shorter mean length of turn. The core type transformer has lessor cross-section of iron and, therefore, a greater iber of turns.
Since core type transformer has more space for insulation so it is preferred for high voltage.

In the shell type the coils are better braced mechanically so that they are less easily displaced by the high electro-mechanical forces that frequently develop during short circuits.

iii) **Berry Type Transformers:**

   The Berry type transformer consists of a divided core and has circular shell type construction.
Concentric circular coils are wound on the central limb. The magnetic flux path a completed through a number of radially projecting sections connected with outer iron cores. This type of transformers gives rugged construction and provides better cooling.

6.1.7 CORE OF TRANSFORMER
In all type of transformers, the core is made of CRGO sheet steel laminations of about 0.35mm thickness. It provides high permeability and low hysteresis loss at the usual operating flux densities and frequency. To minimise eddy currents and eddy current loss, the laminations are insulated from each other by a light coat of core plate varnish or by an silicon oxide layer on the surface. The lamination are assembled so as to provide a continuous magnetic path with minimum air gap.
6.1.8 AUTO TRANSFORMER

The operating principle and general construction of an auto-transformer is same as that of conventional two winding transformer. The auto-transformer differs from a conventional two winding transformer in the way in which the primary and secondary are inter-related. In the conventional transformer, the primary and secondary windings are completely insulated from each other but are magnetically linked by a common core. In the auto-transformer, the two windings primary and secondary are connected electrically as well as magnetically, in fact, a part of the single continuous winding is common to both primary and secondary.

The auto-transformers are of two types in construction. In one type of auto-transformers, there is a continuous winding with taps brought out at convenient points determined by the desired secondary voltages, and in the other type of auto-transformers there are two or more distinct coils which are electrically connected to form a continuous winding. In either case, the same laws governing conventional two winding
transformers apply equally well to auto-transformers.

In the auto-transformer the primary winding is AB consisting of whole turns between terminals A and B, let it be N1. Voltage V1 is applied across primary terminals A and B. To obtain secondary winding, the winding AB is tapped at C and, therefore, secondary winding consists of turns between terminals Band C, let it be N, and secondary voltage is available across terminals B and C.
As in ordinary transformer, transformation ratio is equal to turn ratio.

\[ i.e. \quad = \quad = \quad = \quad K \text{ (Transformation ratio)} \]

The current flowing in section AC of winding is primary current \( I_1 \) flowing downwards, current...
supplied to load is \( I_2 \) and current in section BC will be \((I_2-I_1)\) flowing upward.

\[
\text{Power delivered to load} = V_2 I_2 \\
\text{Power in winding, AC} = E_{AC} x I_1 = (V_1 = V_2) \times I_1 \\
\text{Power transformed} = \text{Power in winding BC} \\
= V_2 (I_2-I_1) = V_2 I_2 (1-) = V_2 I_2 (1-K)
\]

Ratio of Power transformed to the total power delivered

\[
= 1 - K
\]

Power conducted directly = Power delivered to load – Power transferred by transformer action

\[
= V_2 I_2 - V_2 I_2 (1-K) = KV_2 I_2 = K \times \text{Power output}
\]
**Advantages**
1. Continuously varying voltage can be obtained.
2. Since the section of the winding that is common to both primary and secondary circuits carries only the difference of primary and secondary currents, therefore, an auto-transformer requires less copper and is more efficient than a two-winding transformer of a similar rating.

**Practical Applications**
(i) The auto-transformer is used as balance coil to give neutral in a 3-wire ac distribution system.
(ii) Auto-transformers with a number of tappings are used for starting induction motors and synchronous motors. When auto-transformers are used for this purpose, these are known as auto-starters.
(iii) A continuously variable auto-transformer finds useful application in electrical testing laboratory.
(iv) Auto-transformers have the biggest sphere of usefulness as regulating transformers.
(v) Auto-transformers are also used as boosters to raise the voltage in ac feeders.
As furnace transformers for getting convenient supply to suit the furnace winding from 230 V ac supply.

Since in distribution transformers, the transformation ratio is low and auto-transformers lose much of their advantage when the ratio of transformation is low, so it is not advantageous to use auto-transformer as distribution transformer. There is another disadvantage also, that the primary and secondary are conductively connected.

6.1.9 What is meant by the three phase transformer? Write the advantages and disadvantages of star and delta connections?
A three phase three transformer is that which operator in the three phases supply. The voltage may be 440 V, 6. kV, 11 kV, 66 kV, 132 kW, 200 kV, 400Kv and even more. Generally the core type construction is used. The winding is one only on the internal three limbs. Each limb carried the primary and secondary both. So there are three sets of primary winding and three sets of secondary Windings. The windings can have either cylindrical or sandwiched type of coils.
They can either be connected in star or in delta. These are the possible connections.
ADVANTAGES OF STAR CONNECTIONS

i) In start connections the line voltage is equal to the phase voltage. Therefore the insulation required for phase winding will be of less dielectric strength.

ii) Less phase voltage means less number of turns i.e. less copper is required i.e. cost in less.

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iii) In star the neutral point is obtained, so three phase four wire supply can be taken to distribute the lighting and power load simultaneously. The secondary of the distribution transformer is connected in star.

ADVANTAGES OF DELTA CONNECTIONS
i) In delta connections if one phase fails the three phase supply will be continued to the load but with a reduced efficiency.

ii) In open delta connections the efficiency decreases to 57.7% of the full load output of the transformer.

iii) These connections are efficiently used for transformation, transformer only three wires are required to transmit the power thus reducing the cost of the transmission lines.

Delta-Delta Connection
It 3 phases transformer connected in Y—Y on a typical 3 phase 4 wire system. 11 this arrangement is used for a step down distribution transformer, say 11000/400 volts, then on the secondary side a 400 volt supply between the phases is available for three phase motors and a 230 volt supply is available.
between each phase and neutral for lamps and other single phase loads. It shows the arrangement which does not produce any phase displacement between primary and secondary voltages as seen from the phasor. If the three terminals, \( a_2, b_2, c_2 \) are connected to neutral \( n \) and \( a_1, b_1, c_1 \) are brought out as phase terminals, an arrangement give the same performance. However, when two such transformers have to be put in parallel, both should be connected either for zero phase displacement or \( 180^0 \) phase displacement.

The use of star-star connection on a 3 phase 3 wires system is considered undesirable. Even if a sine wave
voltage is impressed on the primary winding, the exciting current is not a pure sine wave but contains a third harmonic component. Consequently the three exciting currents do not add upto zero and the neutral is needed to carry the resultant current. If the neutral is not present, the three currents are forced to add up to zero. As a result of this the flux is not purely sinusoidal and therefore the secondary voltages are distorted from the sine wave.

The star—star connection is the most economical connection for small high voltage transformers as the number of turns per phase and the amount of insulation is a minimum.

**Delta-Star Connection**

It shows a delta-star arrangement. This arrangement also produces a 300 phase displacement between primary and secondary voltages. If the line voltages are $V_1$ and $V_2$, the phase windings must be designed for voltages $V_1$ and $V_2$. The presence of a delta winding helps in stabilizing the potential of star point as in a star-delta connection. This connection is very commonly used for step up power transformers at generating stations and step down distribution.
transformers. At the generating stations, the generator terminals are connected to the delta winding while the star terminals are connected to the star winding so that a 3 phase 4 wire supply transmission lines. In the case of distribution transformers, the low voltage distributors are connected to the star winding so that a 3 phase 4 wires supply is available for distribution.
6.1.10 LINE VOLTAGE AND PHASE VOLTAGE

The delta connection is a balanced system and moreover only one phase winding is included between any pair of line terminals or line conductors. Therefore line voltage between any pair of lines is equal to phase voltage of the phase winding connected between the two considered lines. Hence line voltage $V_L$ is same as phase voltage, $V_{ph}$.

As phase sequence is RYB, the voltage having its positive direction from R and Y leads by $120^\circ$ or that having its positive direction from Y and
B. Hence calling the voltage between line R and Y as \( V_{RY} \) and that between Y and B as \( V_{YB} \). It is seen that \( V_{RY} \) leads \( V_{YB} \) BY 120\(^0\).

### 6.1.11 LINE CURRENT AND PHASE CURRENTS

Where it is seen that the current flowing in each line vector is difference of the two phases currents. Therefore current in line R is 
\[
I_R = I_{RY} - I_{YB} ; I_Y = I_{RY} - I_{YB} \text{ and } I_B = I_{BR} - I_{YB}.
\]

Hence, \( I_{RY} - I_{YB} \); \( I_{YB} = I_{PH} \) as the system is balanced. (Three phase currents are equal).

It is seen that the current in any line conductor is divided between the two phases connected to that conductor. Now as per Kirchhoff’s Law, the sum of the currents leaving a junction is equal to the sum of currents approaching it.

Hence, 
\[
I_{RY} = I_{ER} + I_{YB} \quad \therefore I_R = I_{RY} - I_{YB}
\]

\[\therefore \] To find the line current \( I_R \) the vector sum of \( I_{RY} \) and \((-I_{YB})\) is to be found. Therefore with vector \( I_{YB} \) is reversed and vectorically sum it up.
with the vector $I_{RY}$ and $I_{BR}$ reversed (i.e. $-I_B$) is $60^0$. It is also seen that $I_{RY} = I_{BR} = I_{PH}$.

$\therefore I_R =$
(as $I_{RY} = I_{BR} = I_{ph}$)
Similarly it can be found

$$I_Y = I_{YB} - I_{RY} \text{ (Vector difference)}$$
Line current $$I_B = I_{BR} - I_{YB} \text{ (Vector difference)}$$

$= I_{Ph}$
$\therefore$ In delta connection

Line current $= I_{Ph} = $ Phase Current.
1. Line Current are $120^0$ apart.
2. Line Currents are $30^0$ behind the respective phase currents.
3. The angle between the line current and the corresponding the voltage is $(30^0 + \phi)$ with the current lagging.

6.1.12 **APPLICATION OF TRANSFORMER**
i) To setup or step down voltages in the case of power transformers. This is of great advantage in power transmission and distribution. Power transmission and distribution is very economical at high voltages. Power transformers work nearly at full load. So it should have maximum efficiency near the full load. Thus the copper loss be equal to iron loss at full load. These transformers work at large flux density. The distribution transformer must have maximum all day efficiency. So they should have low iron loss and must work at lower value of flux density.

ii) To isolate two electrical circuits from each other.

iii) To provide corrections to customer’s voltage either the help of tappings in the windings.

iv) To provide corrections to customer’s voltage with the help of tappings in the windings.

v) To convert into a high voltage a.c. with rectifiers. This is needed in many application of daily use like ratio and television.

vi) To melt cores such as in induction furnace.

vii) As an auto transformer, it provides continuously variable voltage supply required in laboratories and else where.
As instrument transformers, they are used to increase the range of instruments and also to provide system of protection in electrical systems.

6.1.13 TRANSFORMERS LOSSES

The losses in a transformer consist of copper losses and iron losses. The iron losses (or core losses) are hysteresis loss and eddy current loss. The iron losses vary with the flux but are independent of load current. Under normal conditions the flux remains approximately constant so that the iron losses are termed as constant losses and denoted by $p_i$.

LOSES, TESTING AND EFFICIENCY

Since the transformer is a static machine so there is no friction and windage losses. Hence the losses occurring in a transformer are (i) iron loss and (ii) copper loss).

i) Core losses or Iron Losses

These losses consist of hysteresis and eddy current losses, which occur due to pulsation of flux in the core. These losses depend upon the
maximum flux density in the core and frequency. Since from no load to full load the flux linkage with core and frequency remains constant so these losses remain constant i.e. these losses are independent of load.

6.1.14 a) COPPER LOSSES
The copper losses have two components, the primary winding copper loss and the secondary winding copper loss.

\[
\text{Copper} = I_1^2r_1 + I_2^2r_2
= I_1^2r_1 + I_2^2r_2 = r_1R_1
= I_2^2r_2 + I_1^2r_1 = I_2^2R_2
\]

For correct determination of copper loss the winding resistances should be determined at the operating temperature of the windings.

b) HYSTERESIS LOSS
Since the flux in a transformer core is alternating, power is required for the continuous reversals of the elementary magnets of which the iron is composed. This loss is known as hysteresis loss.
Hysteresis loss = $K_h f B_m^{1.6}$

When $f$ is the frequency in Hz, $B_m$ is the maximum flux density in core and $K_h$ is a constant.

c) EDDY CURRENT LOSS
This is due to the flow of eddy current in the core. Thin laminations, insulated from each other, reduce the eddy current loss to small proportion.

Eddy current loss = $K_e f^2 B_m^2$

Where $K_e$ is a constant.
Fill in the blanks

(1) A transformer have all parts __________.
(2) Transformer works on the principle of __________.
(3) The two coils in transformer magnetically __________ with each other.
(4) An auto transformer has only __________ winding.
(5) A transformer cannot increase __________.
(6) The unit of inductance is __________.
(7) In step up transformer the number of turns in primary side is __________ the secondary side.
(8) Primary and secondary winding losses are called __________ loss.
(9) The basic formula for coefficient of coupling is K= __________.
(10) A transformer does not respond to constant __________.

**Answers**

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<td>One</td>
<td>v</td>
<td>Power</td>
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<td>vii</td>
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<td>viii</td>
<td>Copper</td>
<td>ix</td>
<td>( \frac{M}{\sqrt{L_1L_2}} )</td>
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True or False

(1) Working principle of transformer is Lenz’s law.
(2) Step up transformer reduces the secondary voltage.
(3) Auto transformer has two types of winding.
(4) Henry is the unit of charge.
(5) Transformer increase and transfer power.
(6) Copper losses are the losses in windings.
(7) A transformer converts mechanical power into electrical power.
(8) Greater the number of turn of coil higher the inductance.
(9) Primary and secondary coil in transformer electrically linked.
(10) $V_P/V_S = N_P/N_S = I_S/I_P$ is convert transformer ratio.

**Answers**

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Multiple Choice Questions

(1) A step up transformer is one which steps up.
   a) Current    b) Voltage
   c) Power

(2) A step down transformer always step up.
   a) Reactive   b) Power
   c) Current

(3) The purpose of lamination of transformer core is to
   a) Increase eddy current  b) Decrease current
   c) Decrease eddy current

(4) A transformer is used for
   a) DC voltage    b) AC voltage
   c) Both AC and DC

(5) The turn’s ratio to 50 Ω source to 200 load is
   a) 0.25    b) 0.5
   c) 2
(6) A transformer has 100 primary turns, 500 secondary turns and 200 V primary voltage then secondary voltage is
   a) 100 V          b) 400 V          c) 50 V

(7) If transformer has works on
   a) Self inductance    b) Faraday’s law
   c) Mutual inductance

(8) To find power in 1\phi transformer we use formula
   a) \sqrt{3} VI \cos\phi     b) V \times I
   c) VI \cos\phi

(9) The unit of power is
    a) Ohm        b) Joule        c) Watt

(10) If the area of the cross section of the core is more than higher the
     a) Capacitance b) Resistance c) Inductance

**Answers**

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