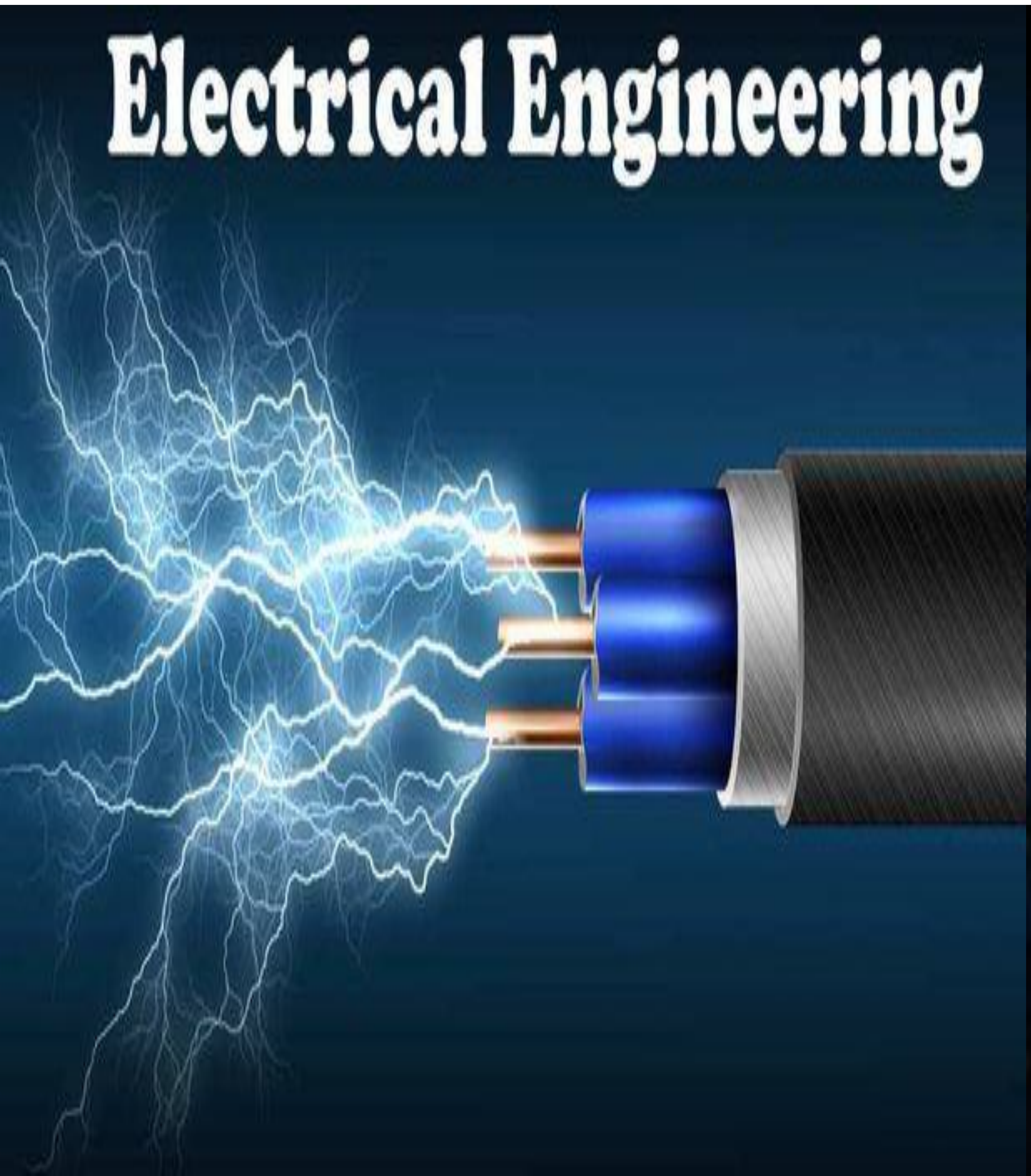
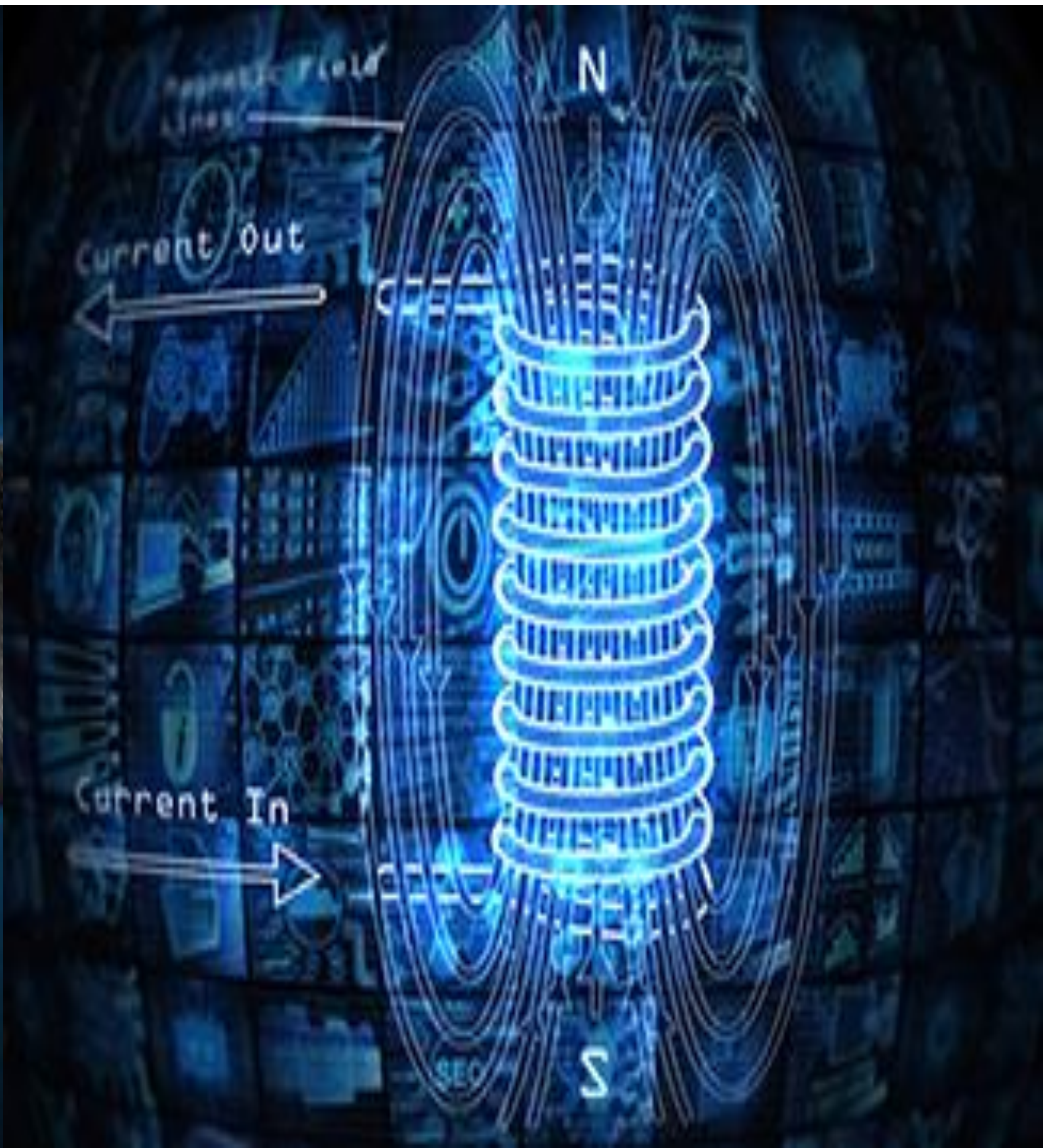

Electrical Engineering

N
Current Out
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S

LECTURE 19

Transformer

Introduction

- The transformer as shown in **Fig. 8.1** is a device or a machine that transfers electrical energy from one electrical circuit to another electrical circuit through the medium of magnetic field and without a change in the frequency.

Fig. 8.1

- The electric circuit of the transformer is shown in **Fig. 8.2.** The winding which receives energy from the supply mains is called primary winding and the winding which delivers electric energy to the load is called the secondary winding.

- The transformer is an electromagnetic energy conversion device, since the energy received by the primary is first converted to magnetic energy and it is then reconverted to useful electrical energy in the other circuits.

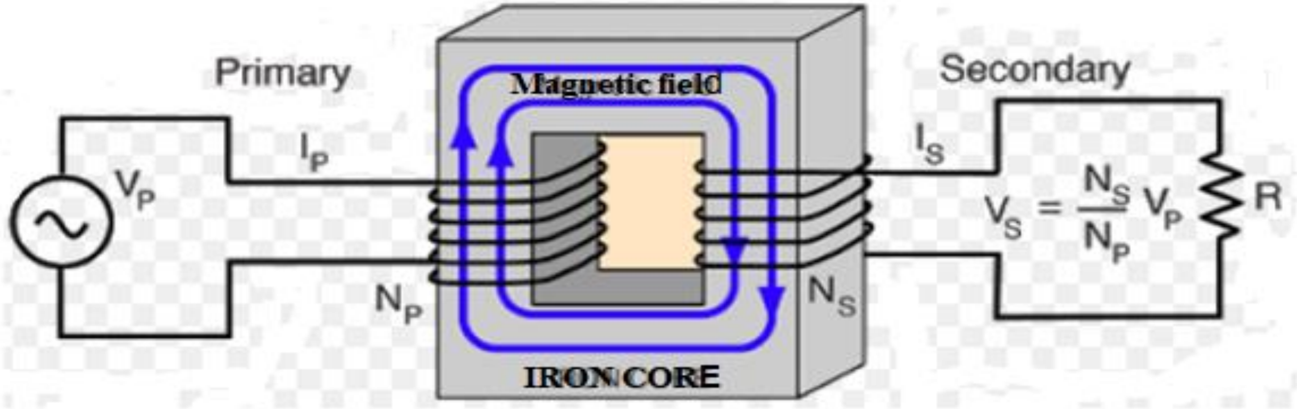


Fig. 8.2

Transformer

➢ Introduction

- ✓ The coupling magnetic field allows the transfer of energy in either direction, from high-voltage to low-voltage circuits or from low-voltage to high-voltage circuits as shown in **Fig. 8.3**.
- ✓ If the transfer of energy occurs at the same voltage, the purpose of the transformer is merely to isolate the two electric circuits.
- ✓ If the secondary winding has more turns than the primary winding, then the secondary voltage is higher than the primary voltage and the transformer is called a step-up transformer.
- ✓ If the secondary winding has less turns than the primary winding, then the secondary voltage is lower than the primary voltage and the transformer is called a step-down transformer.

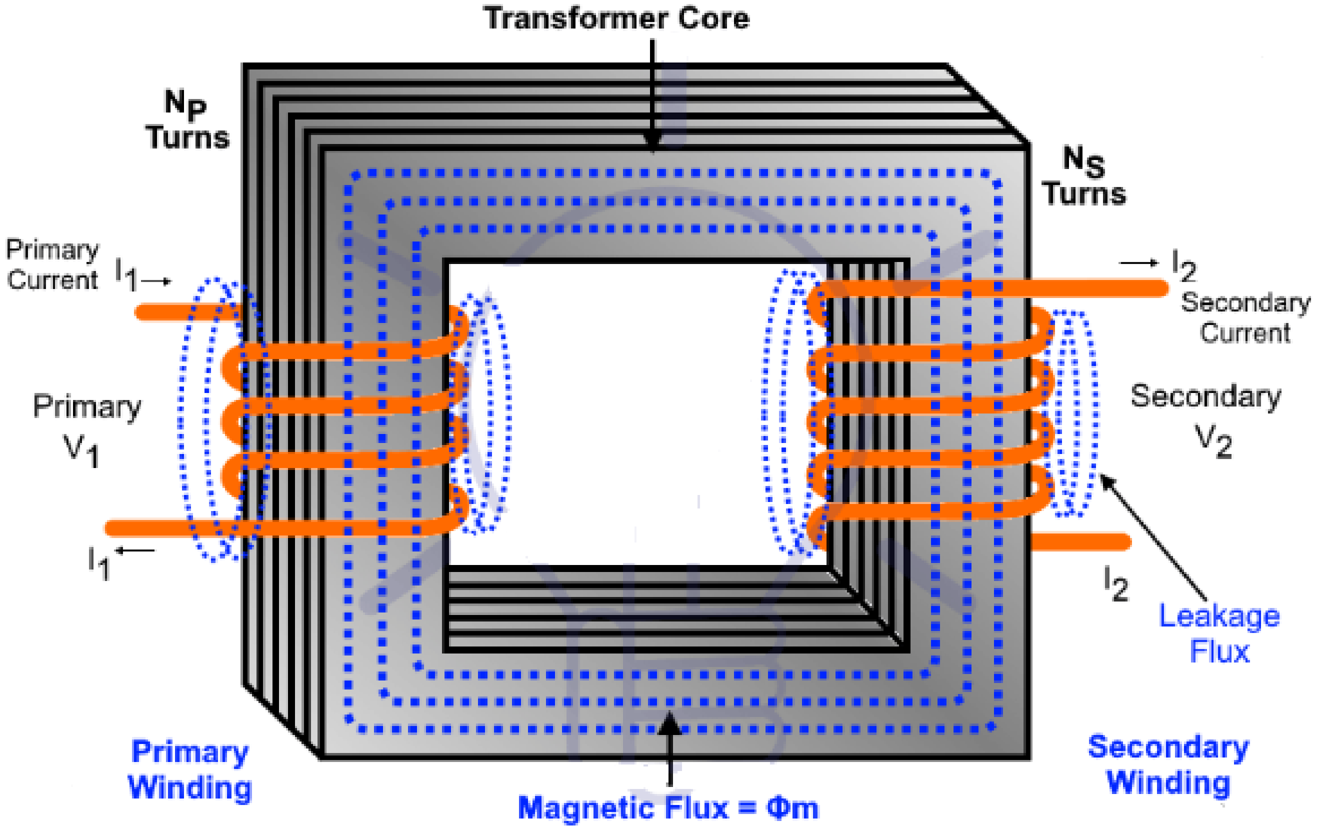


Fig. 8.3

Transformer

- **Introduction**
  - ✓ The secondary of step-up transformer becomes the primary of step-down transformer.
  - ✓ A transformer can be termed as a step-up or step-down transformer only after it has been put into service.
  - ✓ Therefore, the windings of a transformer should be used high-voltage winding and low-voltage winding instead of primary and secondary windings.
  - ✓ In general, important tasks performed by transformers are:
    1) For decreasing or increasing voltage and current levels from one circuit to another circuit (or circuits when there are 2 or more output windings) in low and high current circuits.
    2) For matching the impedance of source and its load for maximum power transfer in electronic and control circuits, and
    3) For isolating d.c. while permitting the flow of a.c. between two circuits or for isolating one circuit from another.
  - ✓ Therefore, the transformer is an essential piece of apparatus both for high and low current circuits.

Transformer

- **Introduction**
  - ✓ Insulation considerations limit the generation of alternator voltages from about 11 to 22 kV.
  - ✓ The voltage is stepped up to higher economical transmission voltage, 400 kV or even higher by means of transformers, in order to reduce the transmission losses.
  - ✓ Transformers are installed to step down the voltage suitable for its utilization for motors, illumination purposes etc.
  - ✓ Transformers are widely employed in electronic and control circuits in addition to power systems.

    Filament transformers are used to supply heating power to filaments of vacuum tubes.

    Pulse transformers are used in radar, television and digital computers.
  - ✓ Transformers are built in an amazing range of sizes. In electronic, measurement and control circuits, transformer size may be so small that it weighs only a few tens of grams whereas in high voltage power circuits, it may weigh hundreds of tonnes.
  - ✓ The energy transfer in the transformer takes place without use of moving parts. So, it has the highest possible efficiency out of all the electrical machines and requires almost negligible maintenance and supervision.

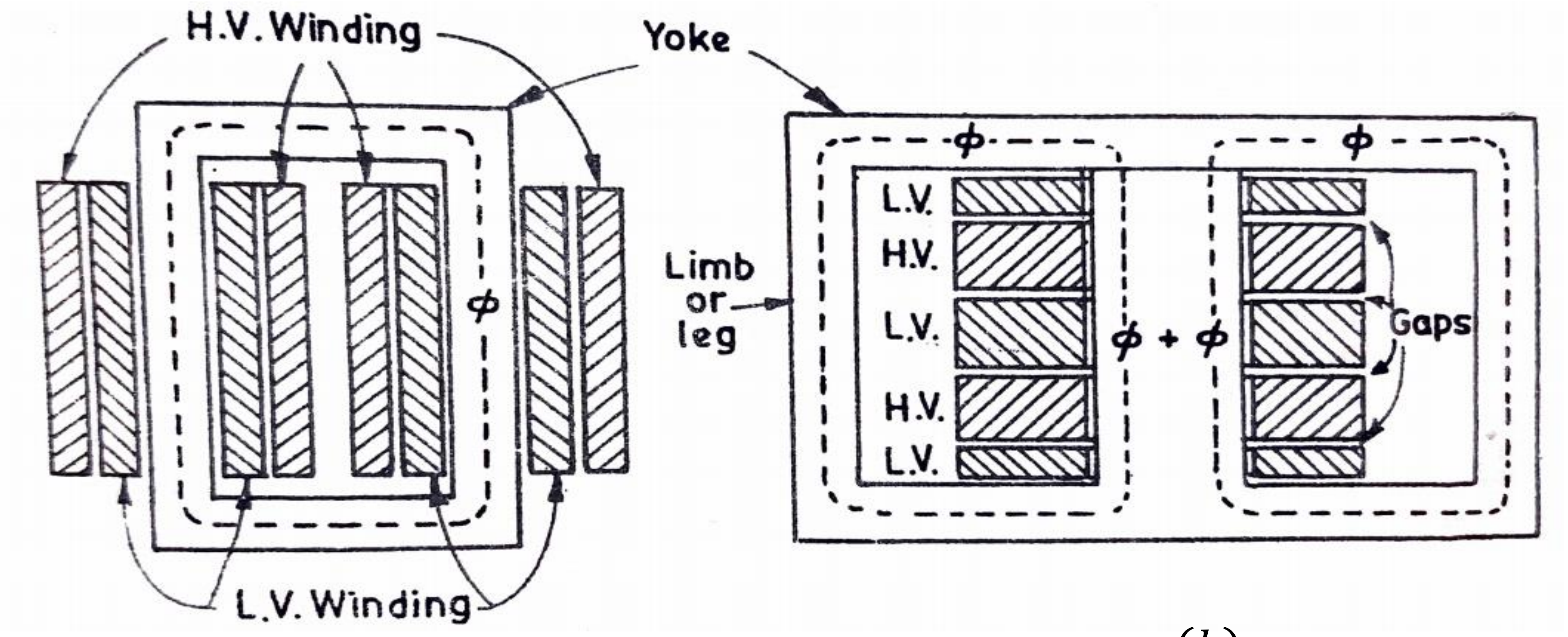
Transformer

- **Transformer Construction**

  - ✓ There are two general types of transformers and these are as follows:

    1. the core type and
    2. the shell type.

  - ✓ The core and shell type of transformers are shown in **Fig. 8.4** (a) and (b) respectively.



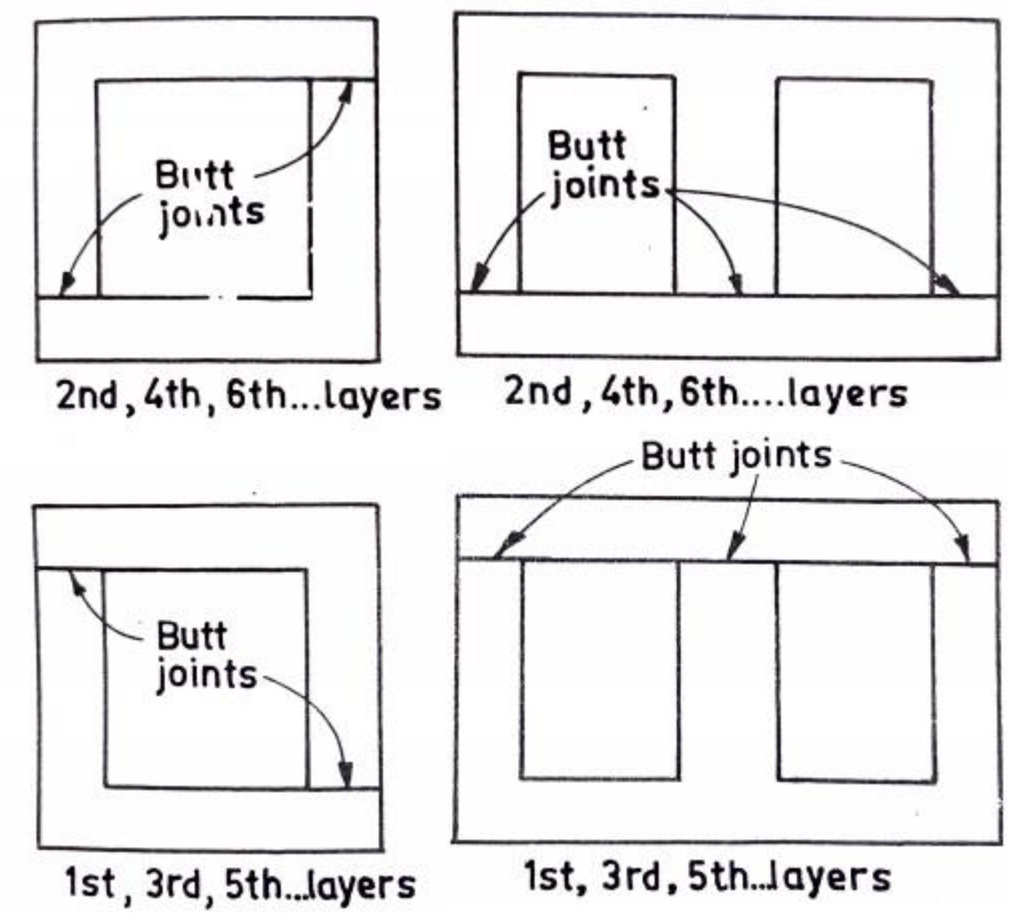
(a) (b)

Fig. 8.4

Transformer

- **Transformer Construction**

  - ✓ Most of the transformers have magnetic core made from cold-rolled grain-oriented sheet-steel (C.R.G.O.) in order to reduce the core losses.
  - ✓ This material has low core loss and high permeability when magnetized in the rolling direction.
  - ✓ The magnetic core is a stack of thin silicon-steel laminations about 0.35 mm thick for 50 Hz transformers.
  - ✓ These laminations are insulated from one another by thin layers of varnish in order to reduce the eddy current losses.
  - ✓ One type of laminations for the core and shell type of transformers is shown in **Fig. 8.5** (a) and (b) respectively.



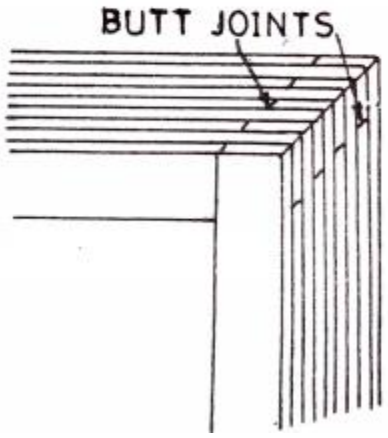
(a) (b)

Fig. 8.5

Transformer

- **Transformer Construction**

  - ✓ The steel core is assembled in such a manner that the butt joints in adjacent layers are staggered as shown in **Fig. 8.5** (c).
  - ✓ The staggering of the butt joints is essential because the staggering of the butt joints avoid continuous air gap so that
    - the reluctance of the magnetic circuit is not increased.
    - the mechanical strength of the core is not reduced.
  - ✓ The vertical portions of the core are called limbs or legs and the top and bottom portions are called the yoke as shown in **Fig. 8.4** (a) and (b) respectively.
  - ✓ For single phase transformers, core-type has two-legged core whereas shell-type has three-legged core as shown in **Fig. 8.4** (a) and (b) respectively.



(c)

Fig. 8.5

Transformer

➢ Transformer Construction

- ✓ There are two types of windings employed for transformers.
- ✓ The concentric coils are used for core-type of transformers. The windings surround a considerable part of steel core as shown in **Fig. 8.4** (a) and **Fig. 8.6** (a).
- ✓ The interleaved (or sandwiched) coils are used for shell-type of transformers. The steel core surrounds a major part of the windings as shown in **Fig. 8.4** (b) and **Fig. 8.6** (b).
- ✓ Core-type of transformer requires less iron but more conductor material as compared to a shell-type transformer for a given output and voltage rating.

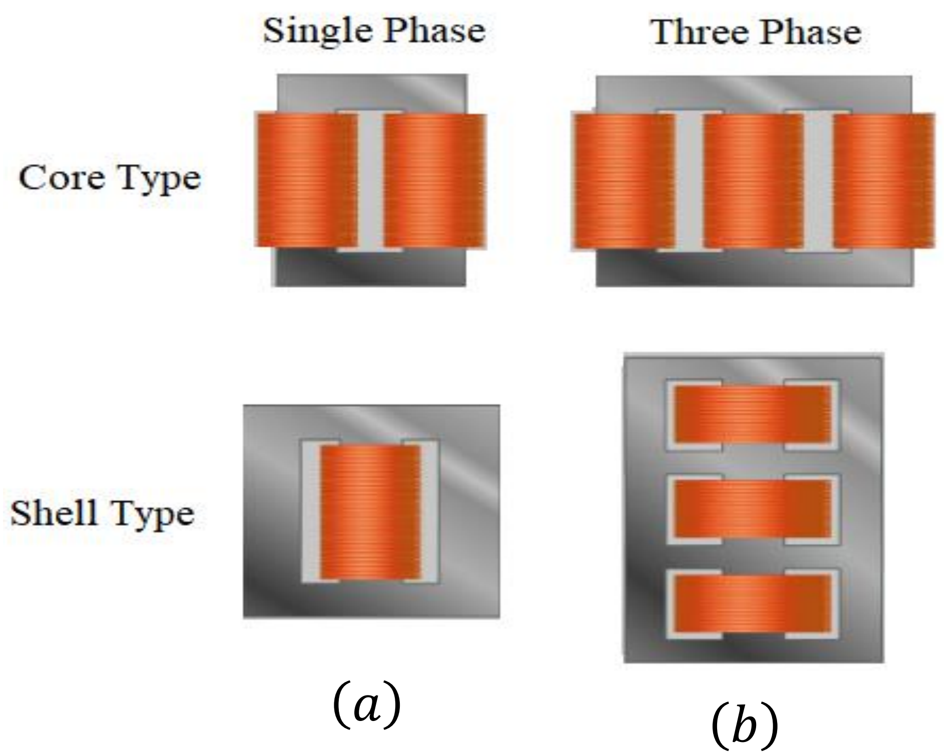


Fig. 8.6

- ✓ In core-type transformer, the flux has a single path around the legs or yokes as shown in **Fig. 8.4** (a). In shell-type transformer, the flux in the central limb divides equally and returns through the outer two legs as shown in **Fig. 8.4** (b).

Transformer

- **Transformer Construction**
  - ✓ In iron-core transformers, most of the flux is confined to high permeability core.
  - ✓ There is some flux that leaks through the core legs and non-magnetic material surrounding the core. This flux is called leakage flux and it links only one winding and not the other.
  - ✓ A reduction in this leakage flux is desirable as it improves the transformer performance considerably.
  - ✓ In the core-type transformer, this is achieved by placing half of the low voltage (L.V.) winding over one leg and other half over the second leg or limb.
  - ✓ For the high voltage winding also, half of the winding is over one leg and the other half over the second leg as shown in **Fig. 8.4** (a).
  - ✓ L.V. winding is placed adjacent to the steel core and H.V. winding outside in order to minimise the amount of insulation required.
  - ✓ In the shell-type transformer, the L.V. and H.V. windings are wound over the central limb and are interleaved or sandwiched as shown in **Fig. 8.4** (b).
  - ✓ The bottom and top of L.V. coils are half the size of other L.V. coils.

Transformer

- **Transformer Construction**
  - ✓ During the transformer construction, first the primary and secondary windings are wound, then the laminations are pushed through the coil openings, layer by layer and the steel core is prepared.
  - ✓ The laminations are then tightened by means of clamps and bolts.
  - ✓ Low power transformers are air-cooled whereas large power transformers are immersed in oil for better cooling. In oil-cooled transformers, the oil serves as a coolant and also as an insulating medium.
  - ✓ For power frequency range of 25 to 400 Hz, transformers are constructed with 0.35 mm thick silicon-steel laminations.
  - ✓ For audio-frequency range of 20 to 20,000 Hz, iron core with suitable refinements is used.
  - ✓ For high frequencies in communication circuits, core is made up of powdered ferromagnetic alloy.
  - ✓ The magnetic circuit of a transformer may be made of non-magnetic material and the transformer is referred to as an air-core transformer. The air-core transformer is primarily used in radio devices and in certain types of measuring and testing instruments.
  - ✓ Cores made of soft ferrites are also used for pulse transformers as well as for high frequency electronic transformers.

Transformer

- **Principle of Transformer Action**
  - ✓ The schematic diagram for both core and shell types of transformers is as shown in **Fig. 7**.
  - ✓ The primary winding P is connected to an alternating voltage source. So, an alternating current $I_{\emptyset}$ starts flowing through N_1 turns.
  - ✓ The alternating mmf $N_1 I_{\emptyset}$ sets up alternating flux $\emptyset$ which is confined to the high permeability iron path as indicated in **Fig. 8.7**.

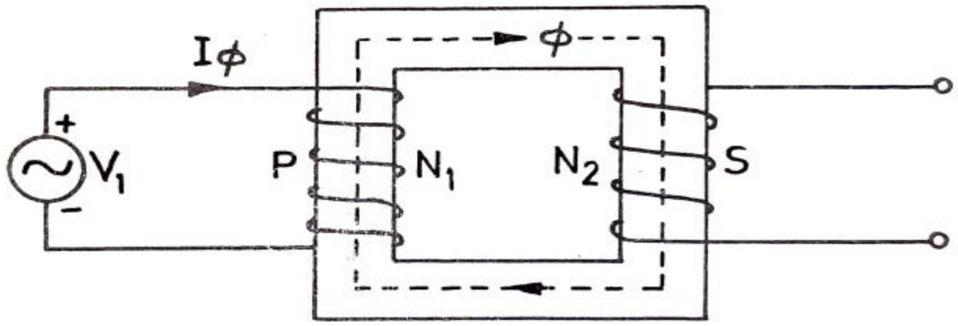


Fig. 8.7

  - ✓ An e.m.f. is induced in a coil if it links a changing flux according to the principle of electromagnetic induction.
  - ✓ The alternating flux induces voltage E_1 in the primary P and E_2 in the secondary S.
  - ✓ A load current starts flowing if the load is connected across the secondary.
  - ✓ There may be a third (or tertiary) winding on the same iron core in addition to the secondary winding. The emf induced in the secondary or tertiary winding is usually referred to as the emf due to transformer action.

Transformer

- **Principle of Transformer Action**
  - **Ideal Two-winding Transformer**
    - The various assumptions for an ideal transformer are as follows:
      1. Winding resistances are negligible.
      2. All the flux set up by the primary links the secondary windings, i.e. all the flux is confined to the magnetic core.
      3. The core losses (hysteresis and eddy current losses) are negligible.
      4. The core has constant permeability, i.e. the magnetization curve for the core is linear.
    - The effect of these assumptions are to be considered one by one.

Transformer

- **Principle of Transformer Action**
  - ✓ Let the sinusoidal voltage V_1 is applied to the primary of a transformer with secondary open-circuited. The sub-scripts 1 and 2 are associated with the primary and secondary windings of a transformer respectively.
  - ✓ Then the current $I_\emptyset$ is flowing through the primary winding due to applied voltage V_1. The current is also a sine wave.
  - ✓ The core flux $\emptyset$ is produced due to mmf $N_1 I_\emptyset$ and it follows the variations of $I_\emptyset$ very closely.
  - ✓ So, the flux $\emptyset$ is in time phase with the current $I_\emptyset$ and varies sinusoidally (i.e. if $I_\emptyset$ is zero, $\emptyset$ is zero and if $I_\emptyset$ is maximum positive, $\emptyset$ is also maximum positive and so on).
  - ✓ Therefore, if the applied voltage V_1 has sine waveform, the flux $\emptyset$ must also have a sine waveform.
  - ✓ Let the sinusoidal variation of flux $\emptyset$ be expressed as

$$\emptyset = \emptyset_{max} \sin \omega t$$

where $\emptyset_{max}$ is the maximum value of the magnetic flux in webers and $\omega = 2\pi f$, is the angular frequency in rad/sec and f is the supply frequency in Hz.

Transformer

- **Principle of Transformer Action**
  - ✓ The emf e_1 in volts, induced in the primary N_1 turns by the alternating flux is given by

$$e_1 = -N_1 \frac{d\emptyset}{dt}$$
$$= N_1 \omega \, \emptyset_{max} \cos \omega t$$
$$= N_1 \omega \emptyset_{max} \sin\left(\omega t - \frac{\pi}{2}\right)$$

Its maximum value, E_{1max} occurs when $\sin\left(\omega t - \frac{\pi}{2}\right)$ is equal to 1

$$\therefore \quad E_{1max} = N_1 \omega \emptyset_{max}$$

$$e_1 = E_{1max} \sin\left(\omega t - \frac{\pi}{2}\right)$$

$\therefore$ RMS value of emf E_1 induced in primary winding is given by

$$E_1 = \frac{E_{1max}}{\sqrt{2}} = \frac{2\pi}{\sqrt{2}} f N_1 \emptyset_{max} = \sqrt{2} \pi f N_1 \emptyset_{max}$$

Transformer

- **Principle of Transformer Action**
  - The current $I_\emptyset$ in the primary is assumed to flow along the path $abcda$ in **Fig. 8.8.**

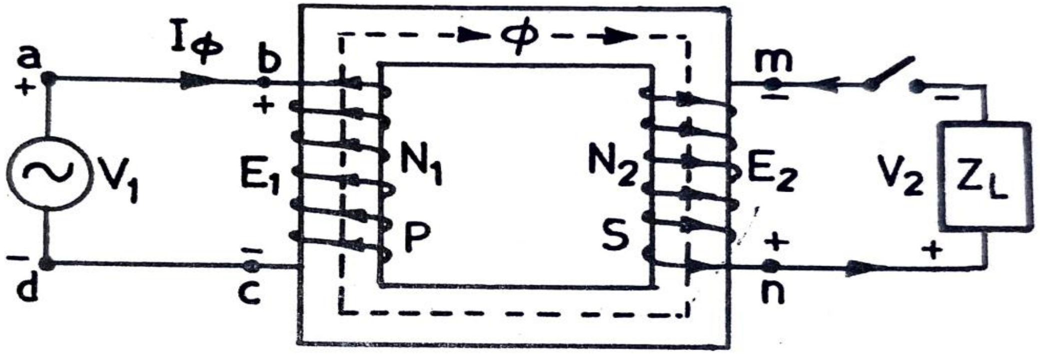


Fig. 8.8.

  - The emf e_1 induced in N_1 turns must be in such a direction as to oppose the cause, i.e. $I_\emptyset$; as per Lenz's law.
  - Therefore, the direction of e_1 as shown by the arrow in the primary N_1 turns oppose v_1.
  - Since primary winding resistance is negligible, e_1 at every instant, must be equal and opposite to v_1

$$v_1 = -e_1 = N_1 \frac{d\emptyset}{dt}$$

or $$V_1 = -E_1$$

Transformer

- **Principle of Transformer Action**
  - ✓ The emf induced in the secondary is

$$e_2 = -N_2 \frac{d\emptyset}{dt} = -N_2 \omega \emptyset_{max} \cos \omega t$$

$$= N_2 \omega \emptyset_{max} \sin\left(\omega t - \frac{\pi}{2}\right)$$

$$= E_{2max} \sin\left(\omega t - \frac{\pi}{2}\right)$$

∴ RMS value of emf E_2 induced in secondary winding is given by

$$E_2 = \frac{E_{2max}}{\sqrt{2}} = \sqrt{2}\pi f N_2 \emptyset_{max}$$

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

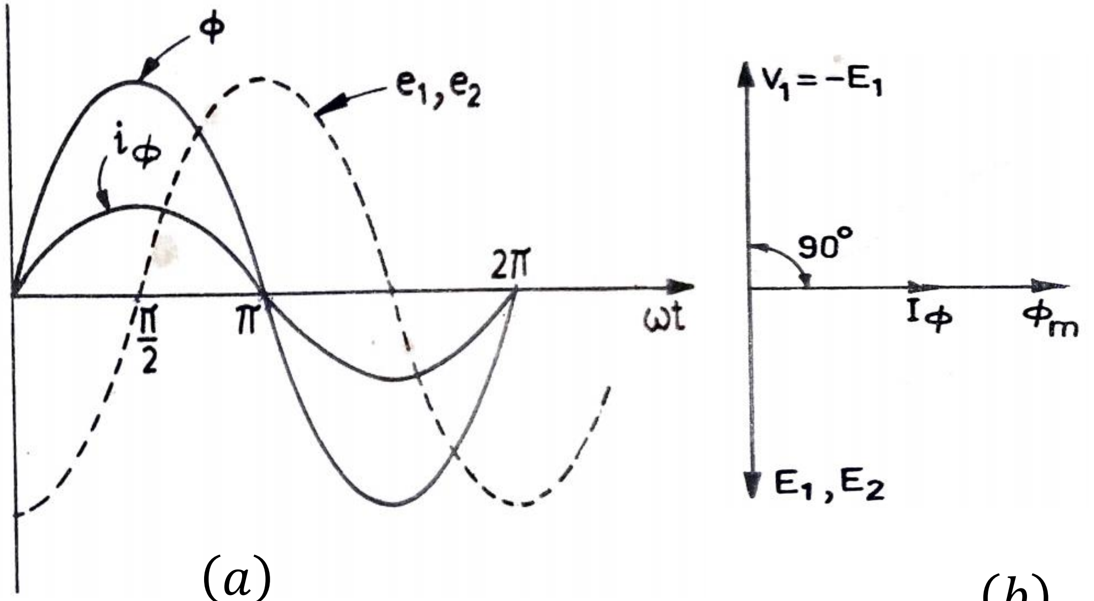
or, $$\frac{E_1}{N_1} = \frac{E_2}{N_2} = \sqrt{2}\pi f \emptyset_{max}$$

i.e. emf per turn in primary = emf per turn in the secondary.

Transformer

- **Principle of Transformer Action**

  - The waveforms of $\emptyset, I_{\emptyset},\ e_1$ and e_2 are drawn in **Fig. 8.9** (a). The phasor diagram of an ideal transformer at no load is drawn in **Fig. 8.9** (b).
  - At time $t = 0$, the flux is zero, therefore, it is drawn horizontally in **Fig. 8.9** (b).
  - The vertical projection of a phasor in the phasor diagram is equal to its value in the time diagram.
  - The values of e_1 and e_2 are maximum negative at $t = 0$, these are therefore, drawn downward along the vertical axis.



(a) (b)

Fig. 8.9

  - Here N_1 and N_2 are assumed equal and, therefore, $E_1 = E_2$.
  - The applied voltage V_1 is equal and opposite to E_1 and it is accordingly drawn opposing E_1.
  - It is seen from **Fig. 8.9** that e.m.fs. E_1 and E_2 lag by 90^0 the mutual flux $\emptyset_m$ that induces them. The applied voltage V_1 leads the flux $\emptyset_m$ by 90^0.

Transformer

- **Principle of Transformer Action**
  - ✓ A load impedance Z_L gets connected across the secondary terminal if the switch S is closed in **Fig. 8.8**.
  - ✓ Since the secondary winding resistance is zero, $V_2 = E_2$.
  - ✓ According to Lenz's law, the direction of secondary current I_2 should be such that the secondary mmf F_2 $(= I_2 N_2)$ is opposite to mutual flux $\emptyset_m$ in the core.
  - ✓ As F_2 to be directed against $\emptyset_m$, the current I_2 must leave the terminal n, pass through the load and enter the terminal m in **Fig. 8.8**.
  - ✓ The secondary winding behaves like a voltage source. Therefore, terminal n must be treated as positive and terminal m as negative
  - ✓ When terminal b is positive with respect to c in **Fig. 8.8**, terminal n is positive with respect to m at the same time. This forms the basis for polarity markings in transformers.
  - ✓ If secondary winding is wound in a manner opposite to that shown in **Fig. 8.8**, terminal m would be positive with respect to terminal n.
  - ✓ This shows that polarity markings of the windings in transformers depend upon the manner in which the windings are wound around the legs with respect to each other.

Transformer

- **Principle of Transformer Action**

  - ✓ The secondary mmf F_2 being opposite to $\emptyset_{m,}$ tends to reduce the alternating mutual flux $\emptyset_m$.
  - ✓ Any reduction in $\emptyset_m$ would reduce E_1.
  - ✓ In an ideal transformer, $V_1 = -E_1$.
  - ✓ If the applied voltage V_1 is constant, E_1 and, therefore, mutual flux $\emptyset_m$ in the core must remain constant.
  - ✓ This can happen only if the primary draws more current I_1' from the source, in order to neutralize the demagnetizing effect of F_2.
  - ✓ So, I_2 causes the primary to take more current, I_1', in addition to $I_\emptyset$ such that

$$I_1' N_1 = I_2 N_2$$

Compensating primary mmf, F_1 = Secondary mmf, F_2

Here I_1' is called the load component of primary current I_1.

  - ✓ It is seen that core flux in an ideal transformer remains constant and is independent of the load current.

Transformer

- **Principle of Transformer Action**

  - ✓ Assume I_2 lag behind V_2 by an angle θ_2, the phasor diagram under load for an ideal transformer is drawn in **Fig. 8.10**.
  - ✓ Since mmfs F_1 and F_2 tend to magnetize the core in opposite directions, they are shown in phase opposition in **Fig. 8.10**.
  - ✓ The total primary current I_1 is the phasor sum of I_1' and $I_\emptyset$,

    i.e., $\overline{I_1} = \overline{I_2'} + \overline{I_\emptyset}$

  - ✓ The power factor on the primary side of the ideal transformer is $\cos\theta_1$.
  - ✓ If the magnetizing current $I_\emptyset$ is neglected, then

$$I_1 N_1 = I_2 N_2$$

i.e. Primary ampere-turns = Secondary ampere-turns.

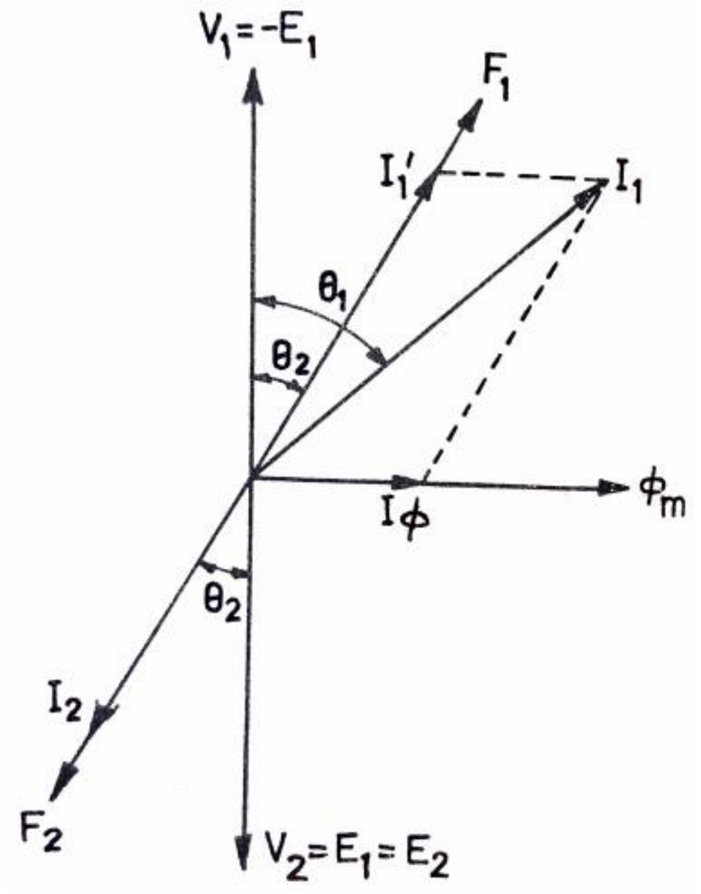


Fig. 8.10

Transformer

- **Principle of Transformer Action**
  - ✓ Thus for an ideal transformer with $I_{\emptyset} = 0,$ we have

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

∴ $$E_1 I_1 = E_2 I_2$$

or $V_1 I_1 = V_2 I_2;$ V_1, V_2, I_1, I_2 are rms values.

i.e. Primary volt-amperes = Secondary volt-amperes.

We know, $v_1 = N_1 \dfrac{d\emptyset}{dt}$ and $v_2 = N_2 \dfrac{d\emptyset}{dt}$

∴ $$\frac{v_1}{N_1} = \frac{v_2}{N_2}$$

Also, $i_1 N_1 = i_2 N_2$

∴ $v_1\, i_1 = v_2 i_2$

- ✓ The instantaneous power input into primary equals the instantaneous power output from the secondary.

Transformer

- **Principle of Transformer Action**

  - ✓ The terminal b of **Fig. 8.8** is positive with respect to terminal c, since current $I_{\emptyset}$ flow from a high potential to a lower potential only.

  - ✓ The application of Kirchhoff's voltage law to the primary winding circuit $abcda$ gives,

$$v_1 - e_1 = 0$$

$$\text{or,} \quad v_1 = e_1$$

We know,

$$v_1 = N_1 \frac{d\emptyset}{dt} \qquad \therefore \quad e_1 = N_1 \frac{d\emptyset}{dt}$$

The relation is referred to as the circuit view point.

  - ✓ The e.m.f. e_1 is treated as a voltage drop in the direction of current $I_{\emptyset}$

  - ✓ This physical fact is also written in mathematical form as

$$v_1 = -e_1 = N_1 \frac{d\emptyset}{dt}$$

The relation is referred to as the field or flux view point.

where e_1 is treated as a reaction e.m.f., counter e.m.f. or generated e.m.f.

  - ✓ The field view-point gives better physical concepts of the internal behaviour of a transformer

Transformer

Example – P 8.1

The emf per turn for a single phase, 2310/220 V, 50 Hz transformer is approximately 13 volts. Calculate (a) the number of primary and secondary turns and (b) the net cross-sectional area of the core, for a maximum flux density of 1.4 T.

Transformer

Solution of Example – P 8.1

Emf per turn $E_t = 13$ volts

(a) Number of secondary turns = $\dfrac{\text{Secondary voltage}}{E_t}$

$$\therefore \qquad N_2 = \frac{220}{13} = 16.92$$

Now the number of turns can't be a fraction, therefore, $N_2 = 17$ (nearest whole number).

For $N_2 = 17,$ Number of primary turns

$$N_1 = N_2\left(\frac{V_1}{V_2}\right) = 17\left(\frac{2310}{220}\right) = 178.5$$

N_2 can't be equal to 17 turns. The nearest integers are 16 or 18. It is preferable to take $N_2 = 18$.

$$\therefore \qquad N_1 = 18 \times 10.5 = 189 \text{ turns.}$$

Thus the required values of N_1 and N_2 are 189 and 18 turns respectively.

Solution of Example – P 8.1

(b) New value of e.m.f. per turn

$$E_t = \frac{220}{18} \text{ volts.}$$

The net core area can be obtained from the relation,

$$\sqrt{2}\pi f \emptyset_{max} = E_t$$

or, $$\sqrt{2}\pi f B_m A_i = E_t = \frac{220}{18}$$

Here $B_m =$ maximum value of flux density in Wb/m^2 or tesla and $A_i =$ Net core area.

$$\therefore \quad \sqrt{2}\pi(50)(1.4)A_i = \frac{220}{18} = 393 \text{ cm}^2$$

if N_2 is taken equal to 16, the emf per turn increases and net core area is more, which is not desirable.

Transformer

Example – P 8.2

A 50 Hz single phase transformer, has one primary winding and two secondary windings. The primary is rated at 220 V and the secondaries are rated at 22 volts with a centre tapping and 600 V without any tapping. For a net core area of 75 cm^2, calculate the number of turns of the three windings. The maximum value of flux density is 1.2 T.

Transformer

Solution of Example – P 8.2

Emf per turn

$$E_t = \sqrt{2}\pi f B_m A_i$$

$$= \sqrt{2}\pi f(50)(1.2)(75) \times 10^{-4}$$

$$= 2.00 \text{ volts}$$

$\therefore$ Number of turns in the 22 V winding

$$= \frac{22}{2} = 11 \text{ turns}$$

A centre tapping is possible only if there are even number of turns. Thus the 22 V winding must have 12 turns.

$\therefore$ Turns in the 600 V secondary winding

$$= 600 \times \frac{12}{22} = 327.$$

and turns in the 220 V primary winding

$$= \frac{220 \times 12}{22} = 120.$$

Transformer

Example – P 8.3

(a) A 2200/220 V, 50 Hz, single-phase transformer has exciting current of 0.6 A and a core loss of 361 watts, when its h.v. side is energised at rated voltage. Calculate the two components of the exciting current.

(b) If the transformer of part (a), supplies a load current of 60 A at 0.8 $p.f$. lag on its $l.v$. side, then calculate the primary current and its power factor. Ignore leakage impedance drops.

Solution of Example – P 8.3

(a) Exciting current $I_e = 0.6$ A

Supply voltage $V_1' = 2200\ V$; Core loss $P_c = 361$ watts.

∴ Core loss component

$$I_c = \frac{P_c}{V_1'} = \frac{361}{2200} = 0.164 \text{ A}$$

Magnetising component $I_\emptyset = \sqrt{I_e^2 - I_c^2} = \sqrt{(0.60)^2 - (0.164)^2} = 0.574$ A

(b) The primary current component I_1', required to neutralise the effect of secondary current $I_2 = 60$ A, is given by

$$I_1' N_1 = I_2 N_2$$

or $$I_1' = \frac{220}{2200}(60) = 6 \text{ A}$$

Solution of Example – P 8.3

(b) The vertical component of $I_e = I_c = 0.164$ A

The horizontal component of $I_e = I_\emptyset = 0.577$ A

$\therefore$ Vertical component of $I_1 = I_1 \cos\theta_1 = I_1' \cos\theta_2 + I_e = 6 \times 0.8 + 0.164 = 4.964$ A

and horizontal component of $I_1 = I_1 \sin\theta_1 = I_1' \sin\theta_2 + I_\emptyset = 6 \times 0.6 + 0.577 = 4.177$ A

$\therefore$ Primar current $I_1 = \sqrt{(I_1 \cos\theta_1)^2 + (I_1 \sin\theta_1)^2} = \sqrt{(4.964)^2 + (4.177)^2} = 6.488$ A

Primary power factor

$$= \cos\theta_1 = \frac{I_1 \cos\theta_1}{I_1} = \frac{4.964}{6.47} = 0.766 \text{ lagging.}$$

LECTURE 20

Transformer

- **Transformer Phasor Diagrams**
  - ✓ The phasor diagram shows the insight of transformer.
  - ✓ An ideal transformer never exists. So, the phasor diagram of real transformer is to be drawn considering various imperfections.
  - ✓ Magnetization curve of the actual transformer core is non-linear. It's effect is to introduce higher order harmonics in the magnetizing current.
  - ✓ Since all the quantities in a phasor diagram must be of the same frequency, these higher order harmonics (whose frequencies are odd multiples of fundamental frequency) can't be represented in the phasor diagram.
  - ✓ So a linear magnetization curve for the transformer core is assumed.
  - ✓ The phasor diagram of a transformer is developed, first at no load and then under load.

Transformer

- **Transformer phasor diagram at no load.**

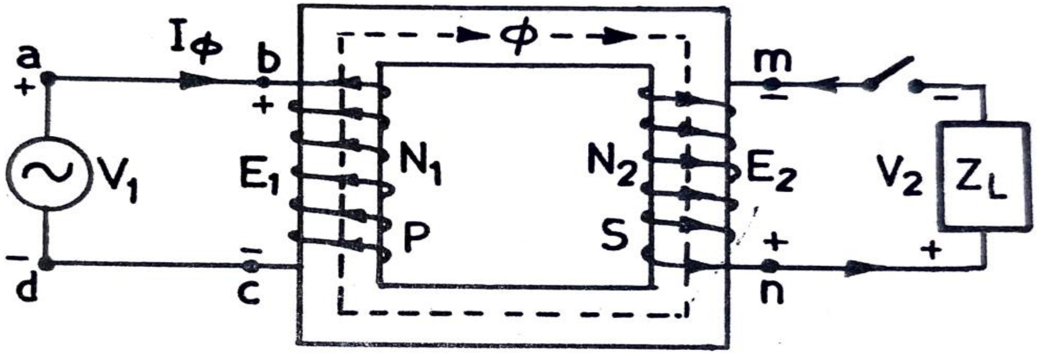
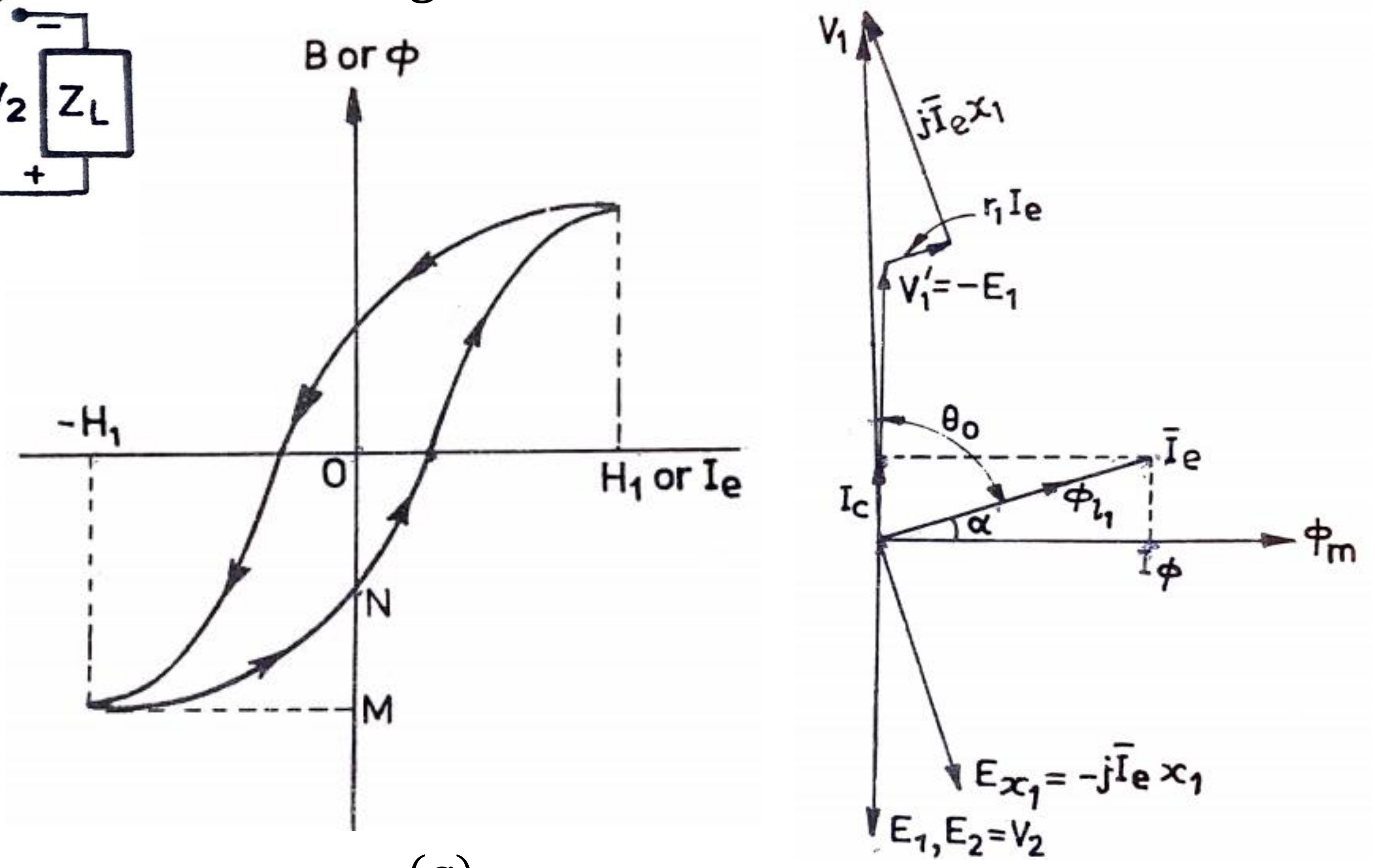


Fig. 8.8.

... s shown in **Fig. 8.11**.

- ✓ The induced emfs E_1 and E_2 lag ϕ_m by 90°.
- ✓ The voltage $-E_1$ is being replaced by V_1' and the voltage V_1' is treated as a voltage drop in the primary in the direction of flow of primary current.
- ✓ The various imperfections in a real transformer are now considered one by one.



$(\boldsymbol{a})$

Fig. 11

$(\boldsymbol{b})$

Transformer

- **Transformer phasor diagram at no load.**

  (a) **Effect of transformer core loss.**

  - The core loss (or iron loss) consist of hysteresis loss and eddy current loss.
  - These losses are always present in the ferromagnetic core of the transformer, since the transformer is an ac-operated magnetic device.
  - The hysteresis loss in the core is minimized by using high grade material such as cold-rolled-grain oriented (CRGO) steel and

    the eddy current loss is minimised by using thin laminations for the core.

Transformer

- **Transformer phasor diagram at no load.**
  - The current in the primary is alternating. Therefore, the magnetizing force H is cyclically varying from one position value say H_1 to a corresponding negative value $-H_1$ as shown in **Fig. 8.11** (a).
  - When the magnetizing force is $-H_1$, the flux density is maximum negative equal to OM.
  - As the magnetizing force decreases from $-H_1$, the current I_e decreases and becomes zero for a flux density, or flux, equal to ON.
  - When the current I_e becomes positive and equal OP, the flux is reduced to zero but it is going to become positive.
  - The traverse of the loop along the arrows involves time.
  - Since I_e is crossing zero positive (passing through zero and becoming positive) when flux is negative (=ON), and I_e is positive (=OP) with flux crossing zero positive, I_e leads $\emptyset_m$, or $\emptyset_m$ lags I_e, by some time angle.
  - This angle of lead or lag, being dependent upon the hysteresis loop, is called hysteretic angle.
  - In **Fig. 8.11** (b), e_1 is showing leading $\emptyset_m$, or $\emptyset_m$ is shown lagging I_e, by hysteretic angle α.

Transformer

- **Transformer phasor diagram at no load.**

  - ✓ The no-load primary current I_e is called the exciting current of the transformer and can be resolved into two components.

    1) The components $I_\emptyset$ along $\emptyset_m$ is called the reactive or magnetizing current, since its function is to provide the required magnetic flux $\emptyset_m$.

    2) The second component, or power component, of I_e; since I_c when multiplied by V_1' gives the total core loss P_c.

$$\therefore \qquad V_1' \, I_c = P_c \;\; or \;\; I_c = \frac{P_c}{V_1'} \text{ Amp.}$$

  - ✓ From **Fig. 8.11** (b), it is seen that

$$I_e = \sqrt{I_\emptyset^2 + I_c^2}$$

Transformer

- **Transformer phasor diagram at no load.**

(b) Effect of transformer resistance.

- The effect of primary resistance r_1 is accounted by adding a voltage drop equal to $r_1 I_e$ to V_1' as shown **Fig. 8.11** (b).
- The voltage drop, $r_1 I_e$ is in phase with I_e and is drawn in parallel to I_e in the phasor diagram.

(c) Effect of leakage flux.

- The magnetic potential difference is necessary for the establishment of flux in a magnetic circuit.
- The point A is at a higher magnetic potential than point B in **Fig. 8.12** for the direction of current I_e in the primary.
- This magnetic potential difference establishes:
  - (i) the mutual flux $\emptyset_m$ linking both the windings and
  - (ii) the primary leakage flux $\emptyset_{l1}$, which links only the primary winding.

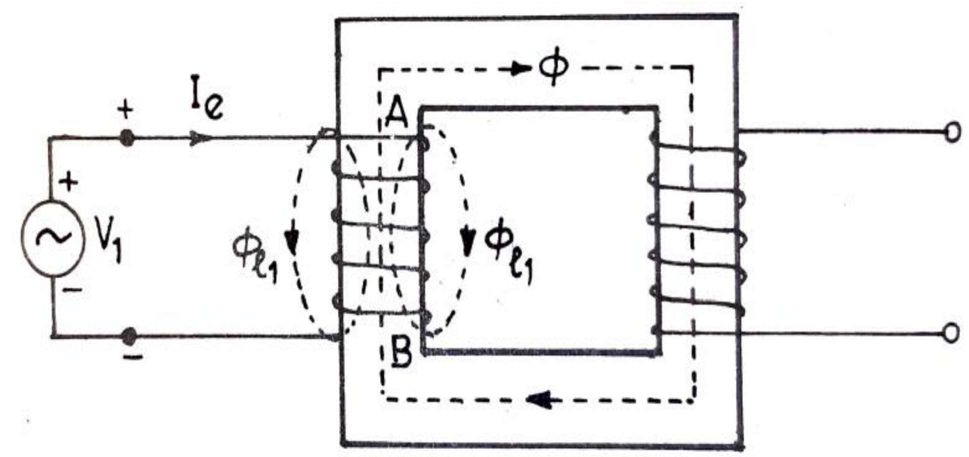


Fig. 8.12

Transformer

- **Transformer phasor diagram at no load.**
  - ✓ The mutual flux $\emptyset_m$ exists entirely in the ferromagnetic core and therefore, involves hysteresis loop.
  - ✓ The current I_e that establishes $\emptyset_m$ must lead it by some hysteretic angle.
  - ✓ The primary leakage flux $\emptyset_{l1}$ exists largely in air. Although $\emptyset_{l1}$ pass through some iron, the reluctance offered to $\emptyset_{l1}$ is mainly due to air. Consequently $\emptyset_{l1}$ does not involve any hysteresis loop.
  - ✓ The flux $\emptyset_{l1}$ as shown in **Fig. 8.11** (b) is in phase with the current I_e which produces it.
  - ✓ The primary leakage flux $\emptyset_{l1}$ induces an emf E_{x1} in the primary winding. The emf E_{x1} lagg the flux $\emptyset_{l1}$ by 90°.
  - ✓ Since I_e leads E_{x1} by 90°, $\overline{E_{x1}} = -j\overline{I_e}x_1$.
  - ✓ The primary applied voltage V_1 must have a component $j\overline{I_e}x_1$, equal and opposite to E_{x1}.
  - ✓ Here x_1 has the nature of reactance and is referred to as the primary leakage reactance in ohms. x_1 is a fictitious quantity merely introduced to represent the effects of primary leakage flux.

Transformer

- **Transformer phasor diagram at no load.**
  - The total voltage drop in primary at no load is $I_e(r_1 + jx_1) = I_e z_1$, where z_1 is the primary leakage impedance.
  - N_1 is assumed to be equal to N_2 for the phasor diagram as shown in **Fig. 8.11**.
  - The primary voltage equation at no load can be written as

$$\overline{V_1} = \overline{V'_1} + \overline{I_e}(r_1 + jx_1)$$

  - At no load V_1' or V_1 are very nearly equal.
  - Even at full load, primary leakage impedance drop in power transformers, is about 2 to 5% of V_1,
  - The magnitude of V_1' or E_1 and therefore, $\emptyset_m$ does not change appreciably from no load to full load.
  - The total primary flux is the phasor sum of $\emptyset_{l1}$ and $\emptyset_m$, therefore, its phasor is a little ahead of $\emptyset_m$.

Transformer

- **Transformer phasor diagram under load.**
  - ✓ When switch S of the circuit as shown in **Fig. 8.13** is closed, secondary current I_2 starts flowing from terminal n to the load.

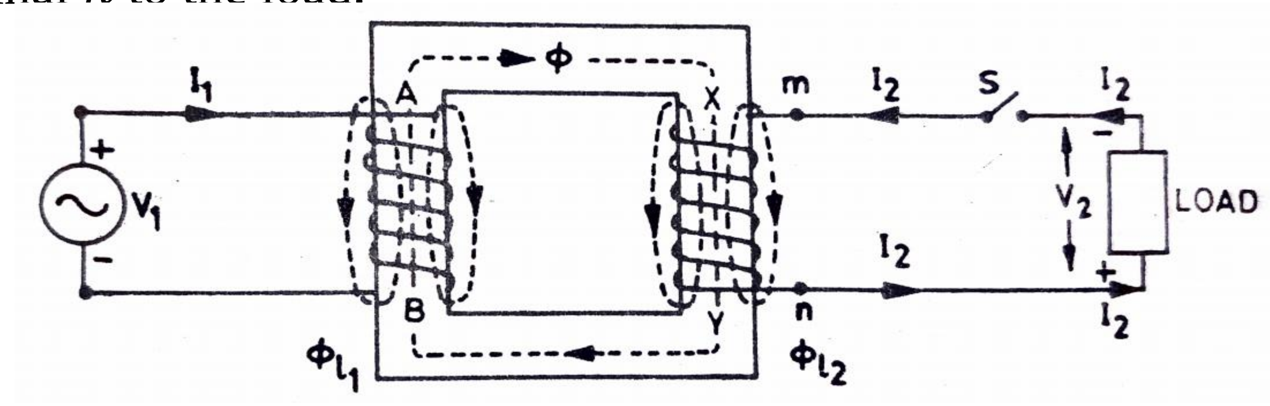


Fig. 8.13

  - ✓ The transformer phasor diagram under lagging load is shown in **Fig. 8.14 (**a).
  - ✓ Assume the load to have a lagging power factor so that the secondary current I_2 lags secondary load voltage V_2 by an p.f. angle θ_2.
  - ✓ The secondary resistance drop, $r_2 I_2$ is drawn parallel to I_2.

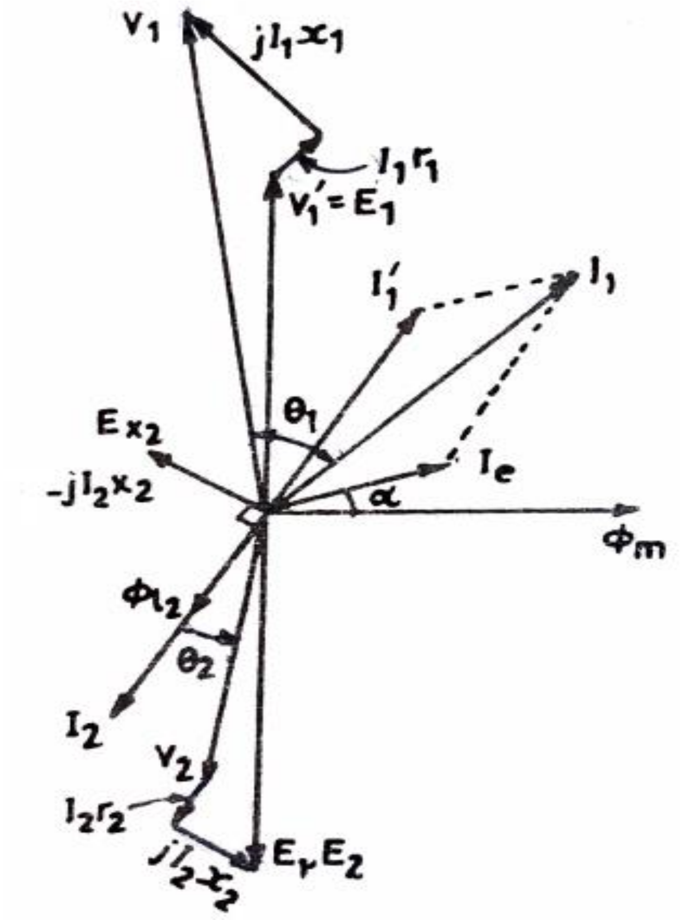


Fig. 8.14 $(\boldsymbol{a})$

Transformer

- **Transformer phasor diagram under load.**
  - The secondary m.m.f. I_2N_2 gives rise to a leakage flux $\emptyset_{l2}$ which links only the secondary and not the primary.
  - The flux $\emptyset_{l2}$ is called the secondary leakage flux and it is in phase with $I_{2.}$. Similarly, the primary leakage flux $\emptyset_{l1}$ is in phase with I_e.
  - The secondary leakage flux induces e.m.f. E_{x2} in the secondary winding. The e.m.f. E_{x2} lags $\emptyset_{l2}$ by 90^0.
  - The secondary no load voltage E_2 have a component equal and opposite to $-jx_2I_2$.
  - Thus, the phasor sum of $\overline{V_2}$, $\overline{I_2}r_2$ and $j\overline{I_2}x_2$ gives the secondary induced e.m.f. E_2 as shown in **Fig. 8.14** (a).
  - The voltage equation for the secondary circuit is written as

$$\overline{E_2} = \overline{V_2} + \overline{I_2}(r_2 + jx_2) = \overline{V_2} + \overline{I_2}z_2$$

where z_2 is the secondary leakage impedance of the transformer.

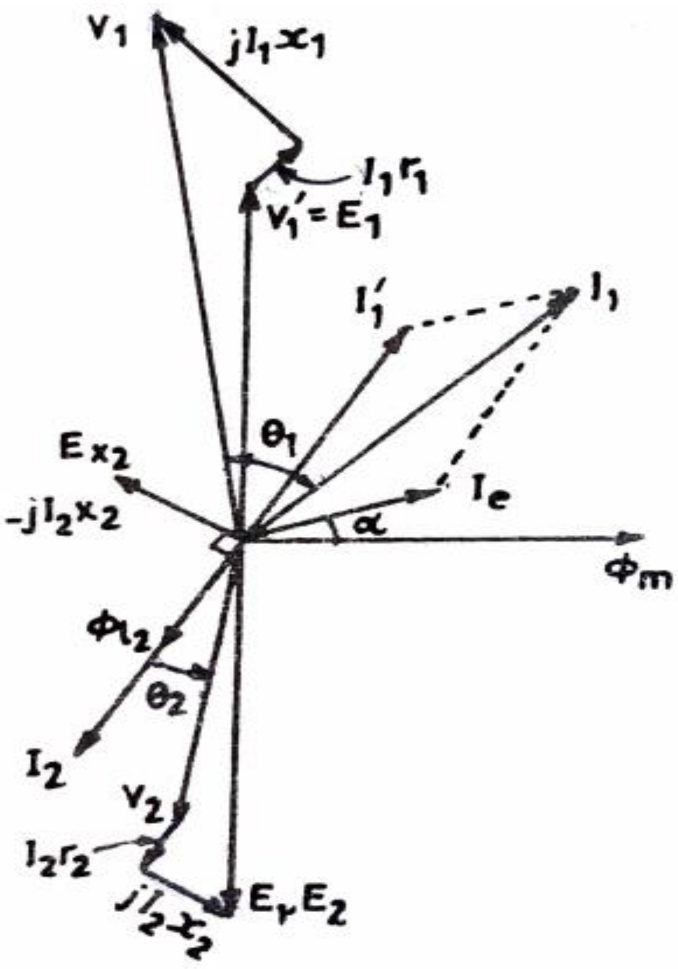


Fig. 8.14 (a)

Transformer

- **Transformer phasor diagram under load.**
  - The mutual flux $\emptyset_m$ lead E_2 by 90^0 and exciting current I_e leads $\emptyset_m$ by the hysteretic angle α.
  - The phasor V_2 is drawn to the left of vertical line, so that E_2 is vertically downward and the flux $\emptyset_m$ is in horizontal.
  - The component of the primary current which neutralises the demagnetizing effect of I_2 is I_1' $(I_1' N_1 = I_2 N_2)$. It is drawn opposite to I_2.
  - The phasor sum of I_1' and I_e gives the total primary current I_1.
  - The voltage equation for the primary circuit under load is written as

$$\overline{V_1} = \overline{V_1'} + \overline{I_1}(r_1 + jx_1) = \overline{V_1'} + \overline{I_1} z_1$$

where z_1 is the primary leakage impedance of the transformer.

  - The angle θ_1 between V_1 and I_1 is the primary power-factor angle under load.

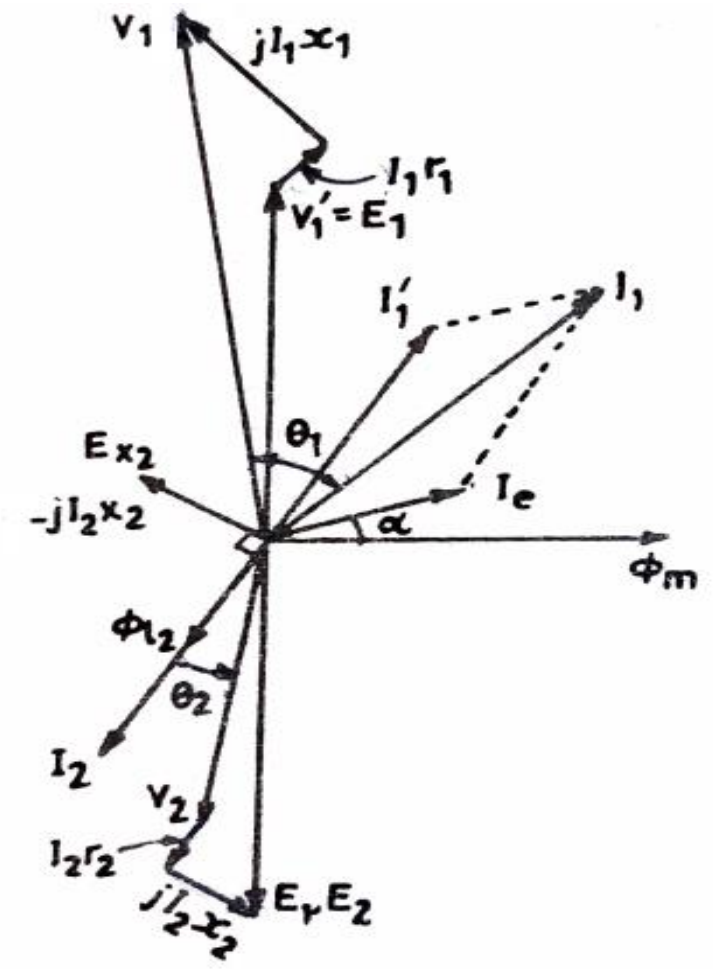


Fig. 8.14 (a)

Transformer

➢ **Transformer phasor diagram under load.**

- ✓ If the secondary load current I_2 leads the voltage V_2 (i.e. load p.f. is leading), then the phasor diagram of the transformer is shown in **Fig. 8.14** (b).
- ✓ The entire procedure for drawing the phasor diagram is the same as explained for **Fig. 8.14** (a).
- ✓ The transformer phasor diagram gives a better physical picture of what happens in the primary and secondary windings of a transformer and its core.
- ✓ The phasor diagram is helpful only (i) when a transformer is to be studied alone and (ii) when the internal behaviour of the transformer is to be understood.
- ✓ When the transformer is a part of the large power system network, the transformer equivalent circuit is used instead of phasor diagram.

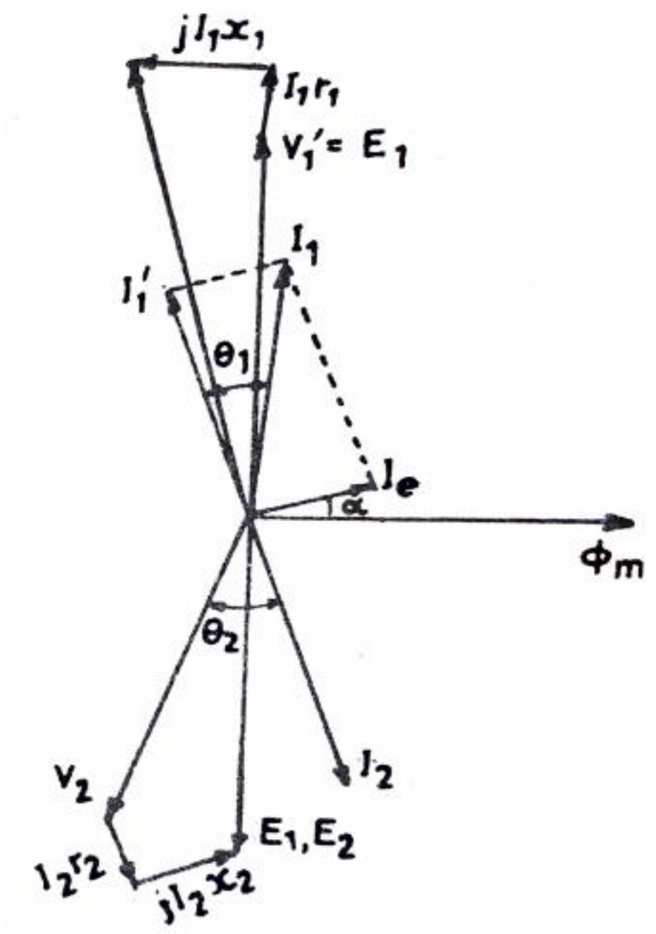


Fig. 8.14 $(\boldsymbol{b})$

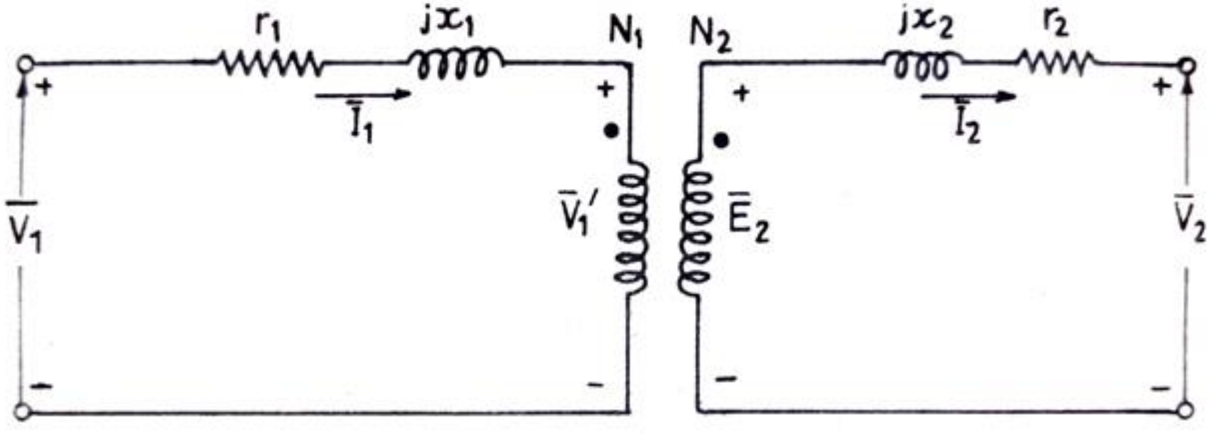
Transformer

- **Equivalent Circuit of a Transformers**

  - ✓ Equivalent circuit is simply a circuit representation of the equations describing the performance of the device.
  - ✓ The equivalent circuit of any electrical device is necessary for analysis and investigation of the device.
  - ✓ The equivalent circuit for electromagnetic devices consists of a combination of resistances, inductances, capacitances, voltages etc.
  - ✓ The transformer equivalent circuit is drawn in **Fig. 8.15** (a) by using the following equations describe the behavior of the transformer under load.

$$\overline{V_1} = \overline{V_1'} + \overline{I_1}(r_1 + jx_1) = \overline{V_1'} + \overline{I_1} z_1$$

$$\overline{E_2} = \overline{V_2} + \overline{I_2}(r_2 + jx_2) = \overline{V_2} + \overline{I_2} z_2$$

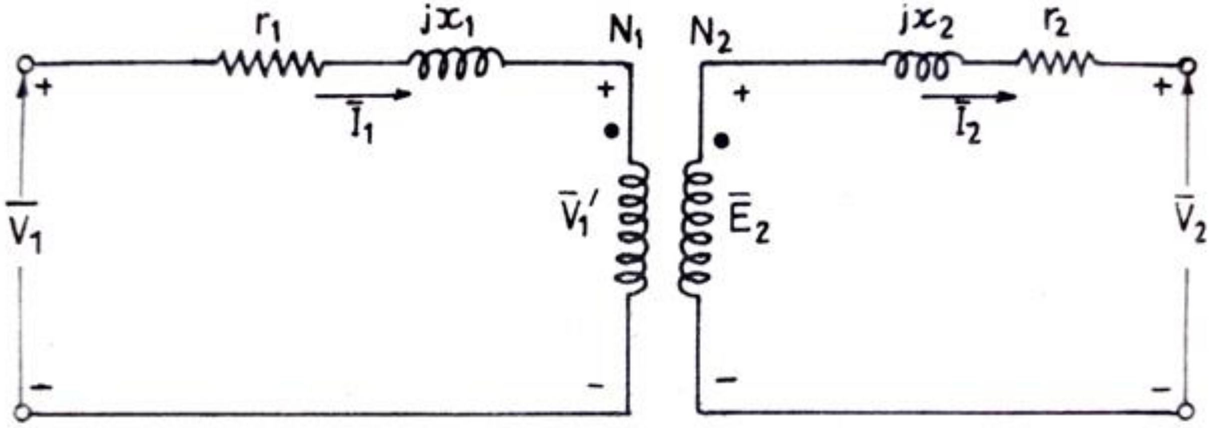


$(\boldsymbol{a})$

Fig. 8.15

Transformer

- **Equivalent Circuit of a Transformers**



$(\boldsymbol{a})$

Fig. 8.15

- ✓ In this equivalent circuit, $(r_1 + jx_1)$ and $(r_2 + jx_2)$ are the leakage impedances of the primary and secondary windings respectively.
- ✓ The voltage V_1' is treated as a voltage drop in the direction of I_1.
- ✓ The magnitude of V_1' does not change appreciably from no load to full load in large transformers.
- ✓ The magnitude of V_1' depends on f, N_1 and $\emptyset_m$ as $|V_1'| = |E_1|$.
- ✓ The primary current I_1 consists of two components as shown in **Fig. 8.15** (a).

  (i) One component I_1' is the load component and counteracts the secondary m.m.f. I_2N_2 completely.

  (ii) The other component is the exciting current I_e which is composed of I_c and $I_\emptyset$.

Transformer

- **Equivalent Circuit of a Transformers**
  - ✓ The current I_c is in phase with V_1' as shown in **Fig. 8.11** and the product $V_1' I_c$ gives core loss.
  - ✓ The resistance R_c is in parallel with V_1' and it represents the core loss P_c.

$$\left.\begin{aligned} P_c &= I_c^2 R_c = V_1' I_c = \frac{(V_1')^2}{R_c} \\ R_c &= \frac{V_1'}{I_c} \end{aligned}\right\}$$

  - ✓ The current $I_\emptyset$ lags V_1' by 90^0 as shown in **Fig. 8.11** and this is represented in the equivalent circuit by a reactance $X_\emptyset$ such that

$$X_\emptyset = \frac{V_1'}{I_\emptyset}$$

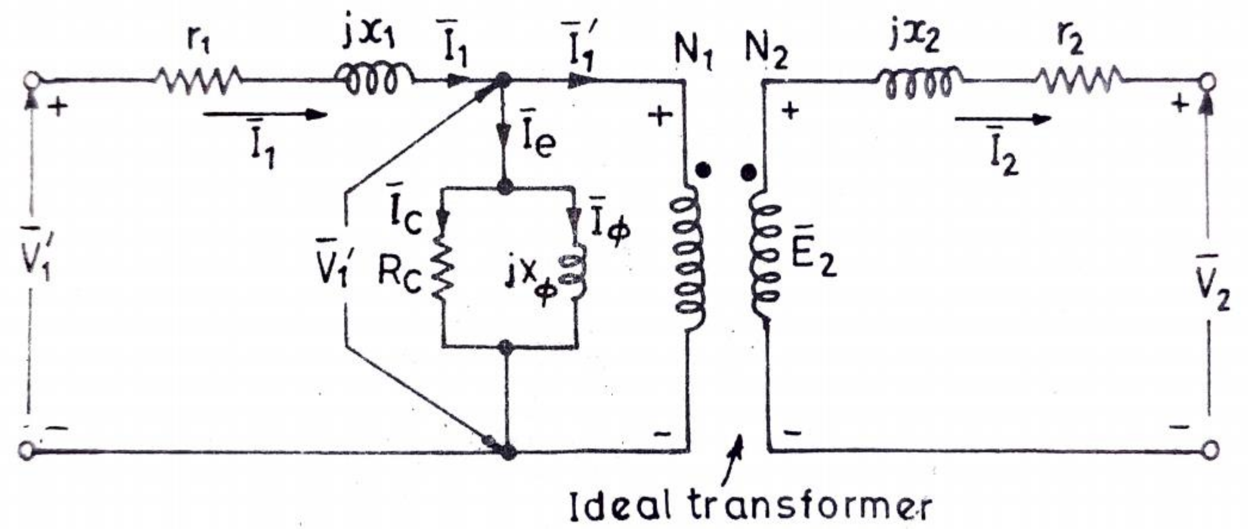
The resistance R_c and reactance $x_\emptyset$ are called core-loss resistance and magnetising reactance respectively.

They are treated constant for minor changes in supply voltage and frequency which is common under normal operation.

Transformer

➢ Equivalent Circuit of a Transformers

- ✓ The resistance R_c and reactance $x_\emptyset$ are shown in the circuit of **Fig. 8.15** (b).
- ✓ This circuit is the exact equivalent circuit of a transformer.
- ✓ In **Fig. 8.15** (a) and (b), the ideal transformer is introduced to show the transformation of voltage and current between primary and secondary windings.



$(\boldsymbol{b})$

Fig. 8.15

- ✓ The transformer magnetization curve is assumed linear, since the effect of higher order harmonics can’t be represented in the equivalent circuit.
- ✓ In transformer analysis, it is useful to transfer the secondary quantities to primary side or primary quantities to secondary side.

Transformer

- **Equivalent Circuit of a Transformers**
  - ✓ Secondary resistance drop $I_2 r_2$ when transferred to primary side is multiplied by the turns ratio N_1/N_2.

∴ Secondary resistance drop, when transferred to primary

$$= (I_2 r_2)\frac{N_1}{N_2}$$

$$= \left(I_1 . \frac{N_1}{N_2} . r_2\right)\frac{N_1}{N_2} \qquad \left[\text{Putting } I_2 = I_1 \frac{N_1}{N_2}\right]$$

$$= I_1 \left[\left(\frac{N_1}{N_2}\right)^2 r_2\right] = I_1 r_2'$$

where $\quad r_2' = r_2 \left(\frac{N_1}{N_2}\right)^2$

Transformer

- **Equivalent Circuit of a Transformers**

  - Secondary leakage reactance drop $I_2 x_2$, when transferred to primary is

$$I_2 x_2 \left(\frac{N_1}{N_2}\right) = I_1 \left(\frac{N_1}{N_2}\right)^2 x_2 = I_1 x_2'$$

  The quantity x_2' is called the secondary leakage reactance referred to primary.

  - Total primary leakage reactance is

$$x_{e1} = x_1 + x_2 \left(\frac{N_1}{N_2}\right)^2 = x_1 + x_2'$$

  where x_{e1} is called the equivalent or total leakage reactance referred to primary.

  - The equivalent or total leakage reactance referred to secondary is

$$x_{e2} = x_2 + x_1 \left(\frac{N_2}{N_1}\right)^2 = x_2 + x_1'$$

Transformer

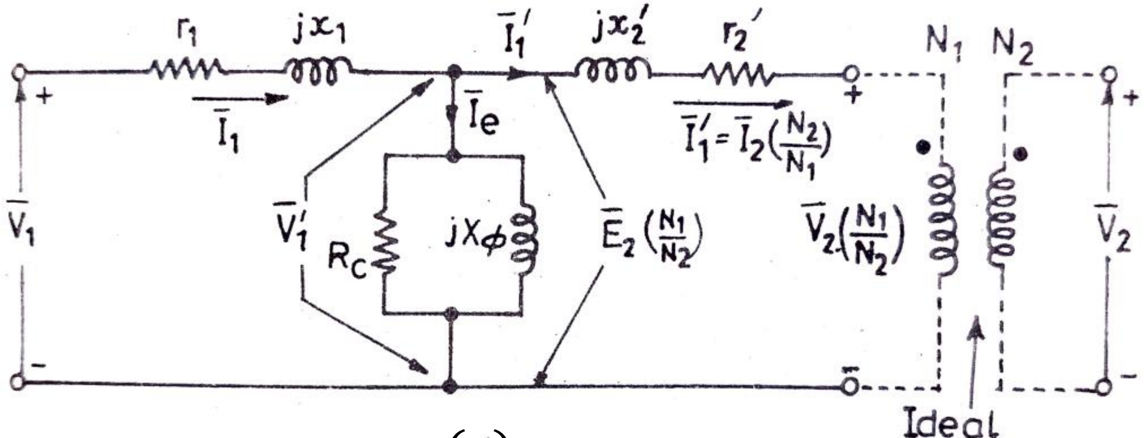
- **Equivalent Circuit of a Transformers**

  - ✓ The equivalent (or total) leakage impedance referred to primary is $z_{e1} = r_{e1} + jx_{e1}$
  - ✓ The equivalent (or total) leakage impedance referred to secondary is $z_{e2} = r_{e2} + jx_{e2}$
  - ✓ So,

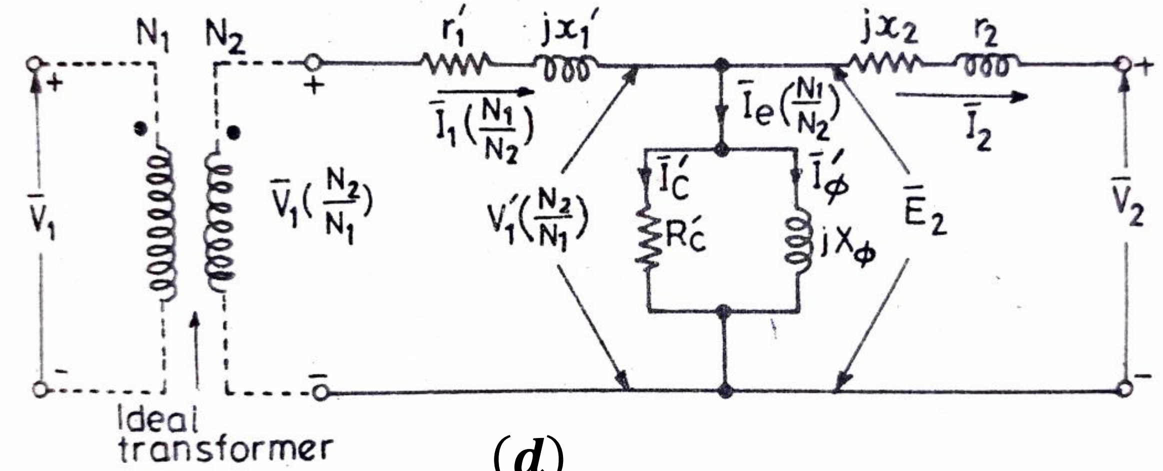
$$z_{e1} = \left(\frac{N_1}{N_2}\right)^2 z_{e2}$$

$$z_{e2} = \left(\frac{N_2}{N_1}\right)^2 z_{e1}$$

- **Simplification of the Exact Equivalent Circuit of a Transformers**
  - ✓ The equivalent circuit of **Fig. 8.15** (b) is simplified by referring all the quantities to primary or secondary and at the same time, moving the ideal transformer to one side.
  - ✓ If the secondary quantities are referred to primary, the equivalent circuit of **Fig. 8.15** (c) is obtained.
  - ✓ Since it is usual to omit the ideal transformer, it is shown dotted in **Fig. 8.15** (c) for the sake of completeness.
  - ✓ When the primary quantities are referred to the secondary side, the equivalent circuit of **Fig. 8.15** (d) is obtained.



(*c*)



(*d*)

Fig. 8.15

Transformer

- **Equivalent Circuit of a Transformers**

We know,

$$R_c' = R_c\left(\frac{N_2}{N_1}\right)^2$$

$$X_\emptyset' = X_\emptyset\left(\frac{N_2}{N_1}\right)^2$$

- ✓ The exact equivalent circuits of **Fig. 8.15** (c) and (d) are known as T-circuits for a transformer referred to primary and secondary windings respectively.
- ✓ In the equivalent circuits of **Fig. 8.15** (c) and (d), the referred quantities with suitable notation are used.

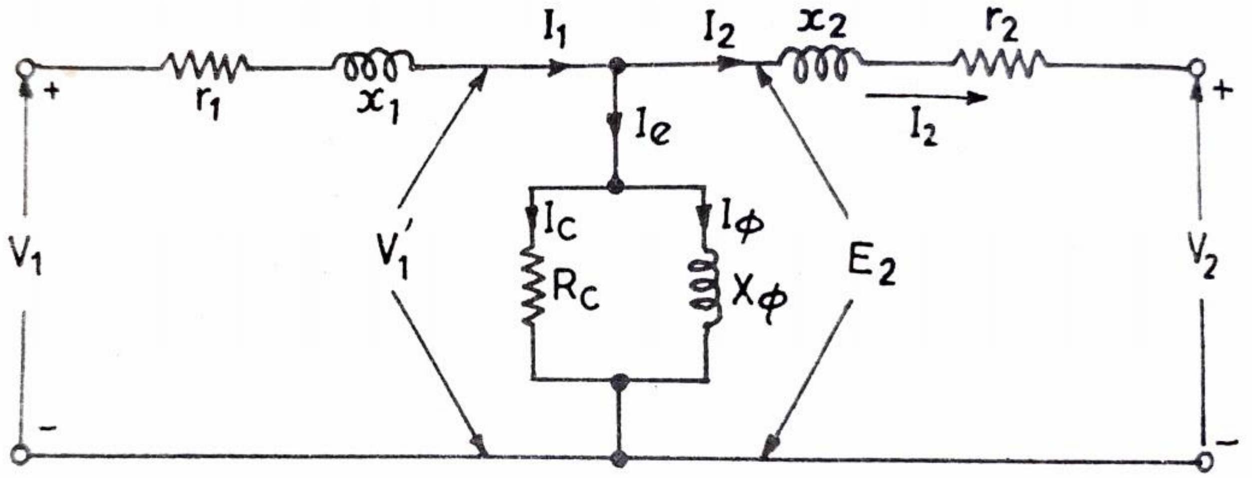
Transformer

- **Equivalent Circuit of a Transformers**
  - ✓ A more general equivalent circuit is drawn in **Fig. 8.15** (e), where for simplicity,

    (i) a particular notation for referred quantities has been dropped

    (ii) the complex notation (bar over I, j with reactances etc.) has been given up and

    (iii) the ideal transformer is not shown.



$(\boldsymbol{e})$

Fig. 8.15

  - ✓ In the general equivalent circuit of a transformer, one has merely to keep in mind about the side to which all the quantities have been referred.

Transformer

- **Equivalent Circuit of a Transformers**
  - ✓ The phasor diagram for the equivalent circuit of **Fig. 8.15** (e) is drawn in **Fig. 8.16.**
  - ✓ The current $\overline{I_2}$ lags $\overline{V_2}$ by an angle θ_2 and then add $\overline{I_2}(r_2 + jx_2)$ to $\overline{V_2}$ to obtain $\overline{E_2}$ or $\overline{V_1'}$.
  - ✓ The current $\overline{I_\emptyset}$ lag the voltage $\overline{E_2}$ or $\overline{V_1'}$ by 90^0 and $\overline{I_c}$ is in phase with $\overline{E_2}$ or $\overline{V_1'}$.
  - ✓ The phasor sum of $\overline{I_c}$ and $\overline{I_\emptyset}$ gives $\overline{I_e}$ and phasor sum of $\overline{I_2}$ and $\overline{I_e}$ gives $\overline{I_1}$.
  - ✓ The voltage drop $\overline{I_2}(r_2 + jx_2)$ is added to $\overline{V_2}$ to obtain $\overline{V_1'}$
  - ✓ The voltage drop $\overline{I_1}(r_1 + jx_1)$ is added to $\overline{V_1'}$ to obtain $\overline{V_1}$.
  - ✓ The secondary p.f. is $\cos\theta_2$ lagging and the primary p.f. is $\cos\theta_1$ lagging.

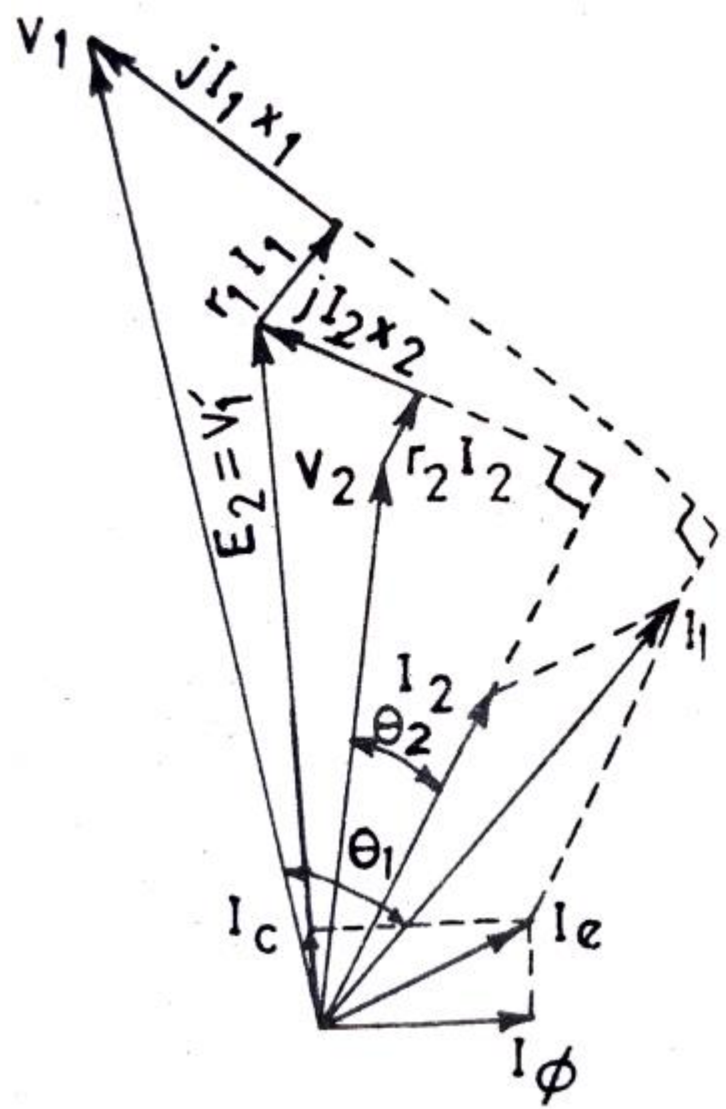


Fig. 8.16

Transformer

- **Approximate Equivalent Circuit of a Transformers**

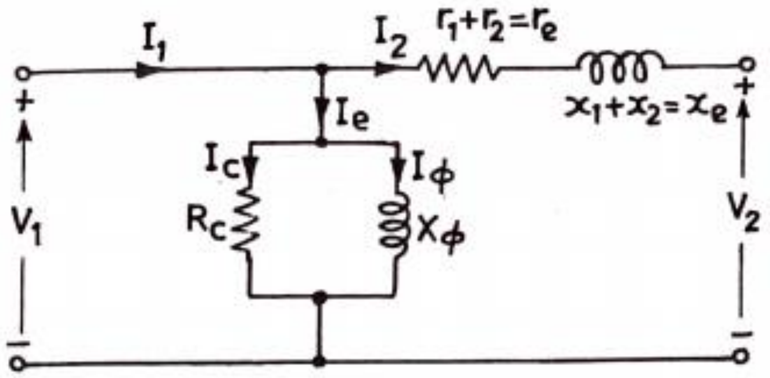
  - Approximate equivalent circuit is obtained from the exact equivalent circuit of **Fig. 8.15** (e), if the shunt branch (R_c and $X_\emptyset$ in parallel) is moved to the primary or secondary terminals as shown in **Fig. 8.17** (a) and (b) respectively.

  - It is seen from **Fig. 8.17** (a) that the exciting current I_e does not flow through r_1 and x_1, whereas I_e does flow through r_1 and x_1 in the exact equivalent circuit.

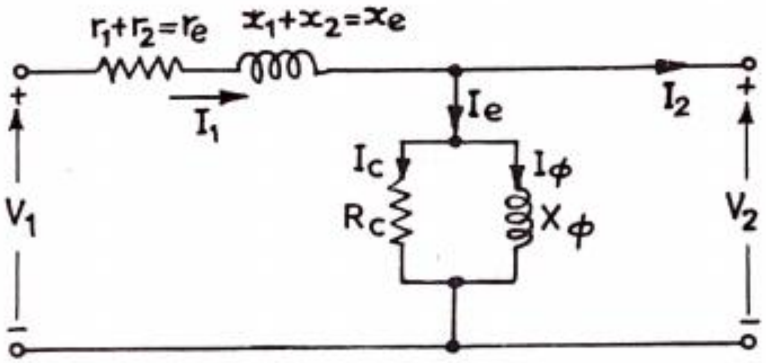
  - Thus the primary leakage impedance drop due to the exciting current, $i.e.$, $I_e(r_1 + jx_1)$ is neglected in **Fig. 8.17** (a), though it is not so actually.

  - It is also be seen from **Fig. 8.17** (b) that I_e flows through r_2 and x_2, whereas I_e does flow through r_2 and x_2 in the exact equivalent circuit.

  - Thus the secondary leakage impedance drop due to I_e, $i.e.$ $I_e(r_2 + jx_2)$ has been included, though $I_e(r_2 + jx_2)$ is actually zero.



$(\boldsymbol{a})$



$(\boldsymbol{b})$

Fig. 8.17

Transformer

- **Approximate Equivalent Circuit of a Transformers**

  - Since the exciting current is only about 2 to 6 percent of the rated winding current in power and distribution transformers, the error introduced by neglecting $I_e(r_1 + jx_1)$ or including $I_e(r_2 + jx_2)$ is insignificant.
  - However, the computational labour involved is reduced considerably by the use of approximate equivalent circuits of **Fig. 8.17** (a) and (b).
  - One must keep in mind about the side to which all the equivalent circuit quantities are referred.
  - Further simplification is achieved by neglecting the shunt branch R_c and $X_\emptyset$ in **Fig. 8.17** (a) and (b) and get the equivalent circuit of **Fig. 8.17** (c).
  - The simplification of neglecting exciting current I_e in comparison with rated currents is almost justifiable in large transformers, say over 100 kVA or so.

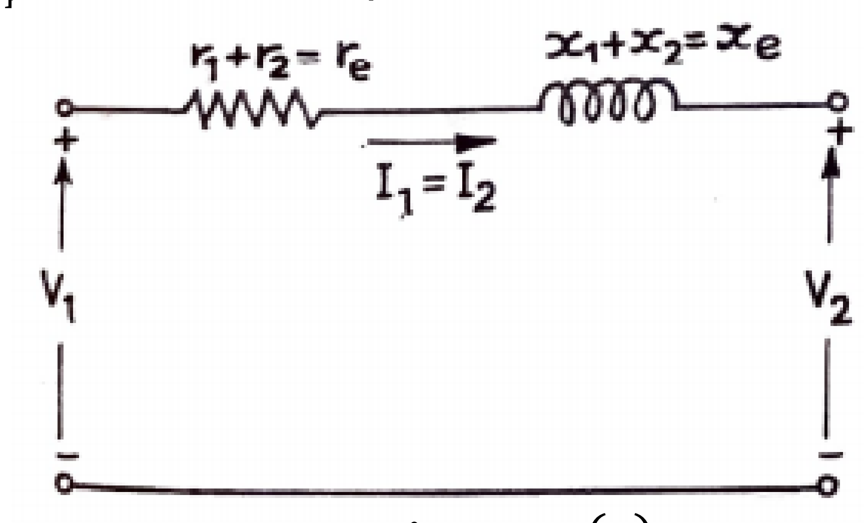


Fig. 8.17 (c)

Transformer

➢ Approximate Equivalent Circuit of a Transformers

- ✓ For transformers having ratings near 500 kVA or more, the equivalent resistance r_e is quite small as compared with equivalent leakage reactance x_e.
- ✓ So, r_e is neglected and lead to the equivalent circuit of **Fig. 8.17** (d).
- ✓ Thus, when a large power system is studied, a transformer is usually replaced by its equivalent circuit of the form shown in **Fig. 8.17** (d).
- ✓ The equivalent circuit of **Fig. 8.15** (e) is used only when the exciting current is a large percentage of the rated current.

  e.g., in audio-frequency transformers used in electronic circuits, in transformers used for relaying and measurement purposes etc.

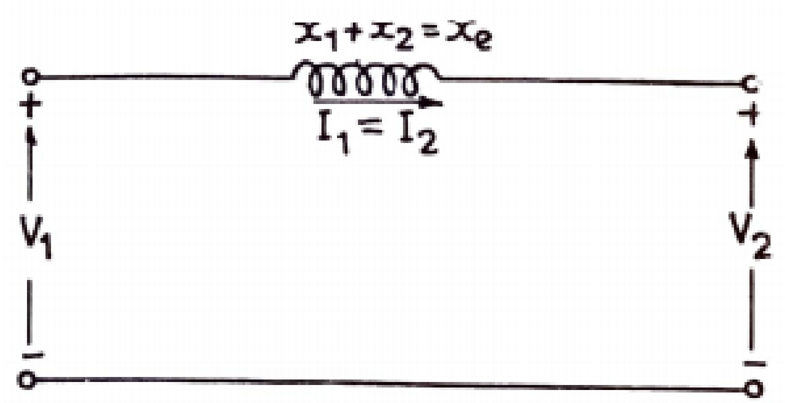


Fig. 8.17 $(\boldsymbol{d})$

- ✓ For high voltage surge investigations, the transformer equivalent circuit must be modified to include the effects of inter-turn and turn to earth capacitances.

LECTURE 21

Transformer

- **Rating of Transformers**

  - ✓ The manufacturer of transformer fixes a name plate on the transformer on which are recorded the rated output, the rated voltages, the rated frequency etc. of a particular transformer.
  - ✓ A typical name plate rating of a single phase transformer is as follows: 20 kVA, 3300/220 V, 50 Hz.
  - ✓ Here, 20 kVA is the rated output, at the secondary terminals. The rated output is expressed in kilo-volt-amperes (kVA) rather than in kilowatts (kW). The rated transformer output is limited by heating and hence by the losses in the transformer.
  - ✓ These losses depend on transformer voltage (core loss) and current (I^2r loss) and are almost unaffected by the load power factor. So, the transformer rated output is expressed in kVA and not in kW.
  - ✓ At zero p.f. load, a transformer is made to operate at rated kVA output while delivering zero power.
  - ✓ For any transformer :

$$\left\{\begin{array}{c}\text{(Rated input in kVA at}\\ \text{the primary terminals)}\\ (\cos\theta_1)\end{array}\right\} = \left\{\begin{array}{c}\text{(Rated output in kVA at}\\ \text{the secondary terminals)}\\ (\cos\theta_2)\end{array}\right\} + \text{Losses}$$

Transformer

- **Rating of Transformers**
  - Since the transformer operates at a very high efficiency, losses may be ignored.
  - The primary p.f. $\cos\theta_1$ and the secondary p.f. $\cos\theta_2$ are nearly equal.
  - Therefore, the rated kVA marked on the nameplate of a transformer, refers to both the windings, i.e. the rated kVA of the primary winding and the secondary winding are equal.
  - The voltage 3300/220 V refers to the design voltages of the two windings. Either of the two may serve as primary or secondary.
  - If it is a step down transformer, then 3300 V is the rated primary voltage and refers to the voltage applied to the primary winding.
  - The voltage of 220 V is the rated secondary voltage and refers to the voltage developed between output terminals at no load, with rated voltage applied to the primary terminals.

Transformer

- **Rating of Transformers**
  - Rated primary and secondary currents are calculated from the rated kVA and the rated voltages.
  - Rated (or full-load) primary current $= 20{,}000/3300 = 6.06$ A.
  - Rated (or full-load) secondary current $= 20{,}000/220 = 90.91$ A.
  - Rated frequency refers to the frequency for which the transformer is designed to operate.
  - The ratios E_1/E_2 and N_1/N_2 are called the voltage ratio and turns ratio respectively.
  - At no load, V_1 and E_1 are nearly equal in magnitude for large transformers, therefore, their no-load voltage ratio is

$$\frac{V_1}{E_2} = \frac{N_1}{N_2}, \qquad i.e. \ \frac{\text{Rated primary voltage}}{\text{Rated secondary voltage}} = \frac{N_1}{N_2}$$

Transformer

- **Open-circuit and Short-circuit Tests**
  - ✓ The open-circuit and short-circuit tests on a transformer are performed to determe

    (i) the parameters of the equivalent circuit of **Fig. 8.17**.

    (ii) the voltage regulation and

    (iii) the efficiency.
  - ✓ The equivalent circuit parameters can also be obtained from the physical dimensions of the transformer core and its winding details.
  - ✓ Complete analysis of the transformer can be carried out, once its equivalent circuit parameters are known.
  - ✓ The power required during these two tests is equal to the appropriate power loss occurring in the transformer.

Transformer

- ✓ Consider a 3300/220 V, 33 kVA, single-phase transformer.
- ✓ For open-circuit test on low voltage side, the ranges of voltmeter, ammeter and wattmeter are 220 V (rated value), 6 A (2 to 6% of rated current of 150 A) and 6 A, 220 V respectively.
- ✓ These are the standard ranges for ordinary instruments and, therefore, more accurate readings can be obtained.
- ✓ If the open circuit test is performed on the h.v. side, a source of 3300 V may not be readily available.
- ✓ At the same time, the instrument ranges are 3300 V, 0.4 A and 0.4, 3300 V which are not within the range of ordinary instruments and the results obtained may not be so accurate. Also it may not be safe to work on the high voltage side.
- ✓ For a short-circuit test on the h.v. side, the instrument ranges are 165 V (2 to 12% of rated voltage of 3300 V), 10 A (rated current) and 10 A, 165 V, which are well within the range of the ordinary instruments.
- ✓ On the other hand, instrument ranges, for a short-circuit test on l.v. side are 11 V, 150 A, and 150 A, 11 V.
- ✓ Instruments of such ranges and auto-transformer capable of handling 150 A, may not be readily available and at the same time, the results may not be so accurate.
- ✓ Thus, open-circuit and short-circuit tests are performed on the l.v. side and h.v. side respectively.

Transformer

- **Open-circuit (or No-load) Test**

  - The circuit diagram for performing open circuit test on a single phase transformer is shown in **Fig. 8.18** (a).
  - A voltmeter, wattmeter and an ammeter are connected on the low voltage side of the transformer in the circuit.
  - The high voltage side is left open circuited.
  - The voltage of rated frequency is applied to the primary, $i.e.$ low voltage side winding.
  - This voltage is varied with the help of a variable ratio auto-transform.

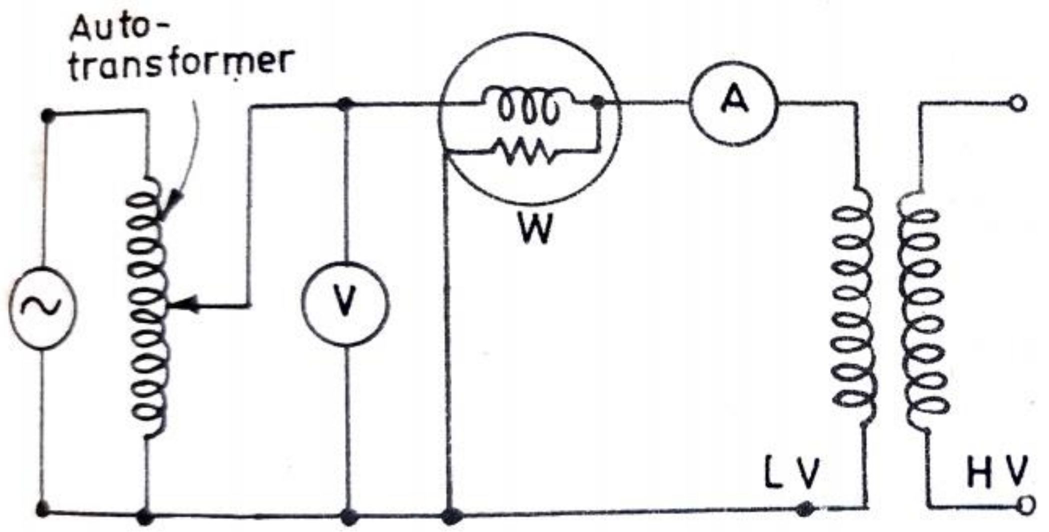


Fig. 8.18 (a).

  - When the voltmeter reading is equal to that rated voltage of the l.v. winding, all the three instrument readings are recorded.
  - The ammeter records the no-load current or exciting current I_e.
  - Since I_e is quite small (2 to 6% of rated current), the primary leakage impedance drop is almost negligible, and for all practical purposes, the applied voltage V_1 is equal to the induced e.m.f. V_1'.

Transformer

- **Open-circuit (or No-load) Test**
  - The equivalent circuit of **Fig. 8.15** (e) gets modified and is shown in **Fig. 8.18** (b).
  - The input power given by the wattmeter reading consists of core loss and ohmic loss.
  - The exciting current is about 2 to 6 percent of the full load current.
  - The ohmic loss in the primary $(= I_e^2 r_1)$ varies from 0.04 percent to 0.36 percent of the full-load primary ohmic loss.
  - So, the ohmic loss during open circuit test is negligible in comparison with the normal core loss.
  - Hence the wattmeter reading can be taken as equal to transformer core loss.
  - A negligible amount of dielectric loss may also exist.
  - Error in the instrument readings is to be eliminated if required.

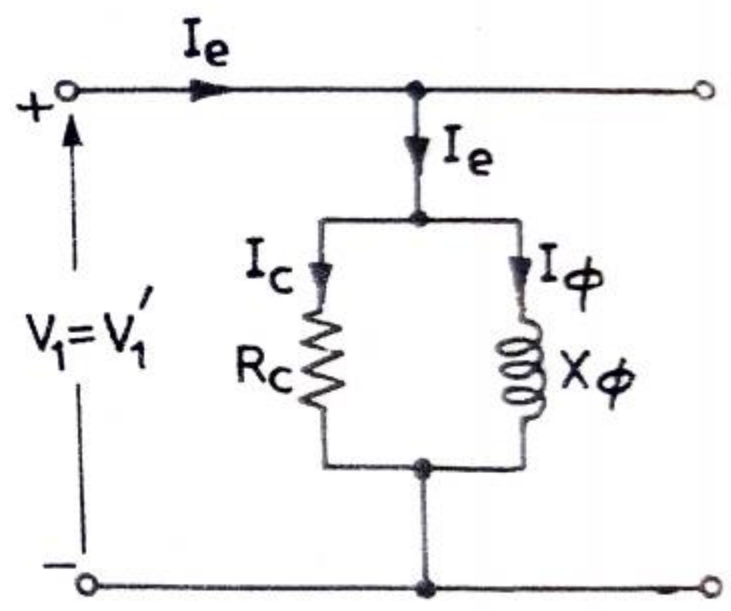


Fig. 8.18 (b).

Transformer

- **Open-circuit (or No-load) Test**

  - Let

V_1= applied rated voltage on l.t. side,

I_e= exciting current (or no-load current),

and P_c = Core loss.

Then $$P_c = V_1 I_e \cos\theta_0$$

$$\therefore \text{ No load p.f., } \cos\theta_0 = P_c / V_1 I_e$$

  - From the phasor diagram of **Fig. 1**2 (b), it is seen that

$$I_c = I_e \cos\theta_0 \quad \text{and} \quad I_\emptyset = I_e \sin\theta_0$$

  - From **Fig. 19** (b), it is seen that

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

Transformer

- **Open-circuit (or No-load) Test**

$\therefore$ Core loss resistance

$$R_{CL} = \frac{V_1}{I_c} = \frac{V_1}{I_e \cos\theta_0}$$

$$= \frac{V_1^2}{V_1 I_e \cos\theta_0} = \frac{V_1^2}{P_c}$$

Also

$$I_c^2 R_{CL} = P_c$$

$$R_{CL} = \frac{P_c}{I_c^2} = \frac{P_c}{(I_e \cos\theta_0)^2}$$

Magnetizing reactance,

$$X_{\emptyset L} = \frac{V_1}{I_\emptyset} = \frac{V_1}{I_e \sin\theta_0}$$

The subscript L with R_C and $X_\emptyset$ is used merely to emphasize that these values are for l.t. side.

Transformer

- **Open-circuit (or No-load) Test**
  - A voltmeter is sometimes used at the open-circuited secondary terminals, in order to determine the turns ratio.
  - Thus the open-circuit test gives the following information:

    (i) core loss at rated voltage and frequency,

    (ii) the shunt branch parameters of the equivalent circuit, $i.e.\ R_C$ and $X_\emptyset$ and

    (iii) turns ratio of the transformer.

Transformer

- **Short-circuit Test**
  - The low voltage side of the transformer is short-circuited and the instruments are placed on the high voltage side, as shown in **Fig. 8.19** (a).
  - The applied voltage is adjusted by auto-transformer to circulate rated current in the high voltage side.
  - In a transformer, the primary m.m.f. is almost equal to the secondary m.m.f., therefore, a rated current in the h.v. winding causes rated current to flow in the l.v. winding.
  - A primary voltage of 2 to 12% of its rated value is sufficient to circulate rated currents in both primary and secondary windings.
  - It is clear from **Fig. 8.19** (b) that the secondary leakage impedance drop appears across the exciting branch (R_C and $X_\emptyset$ in parallel).

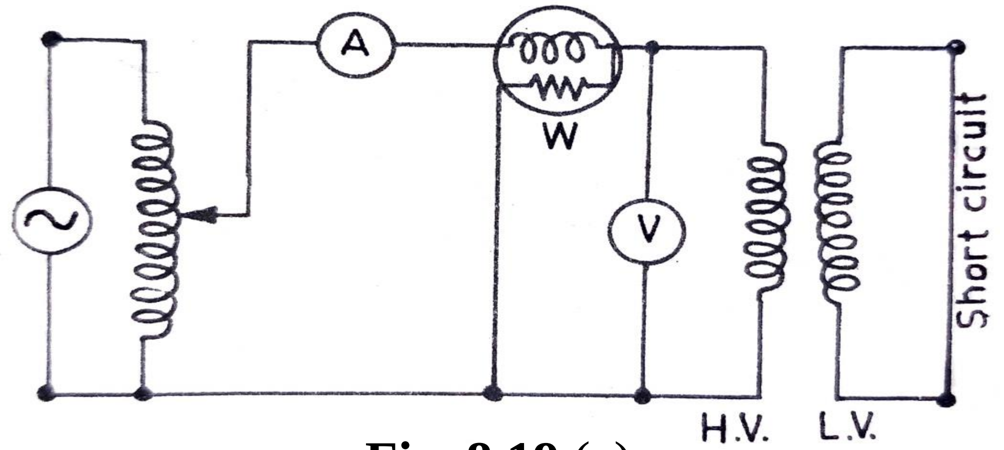


Fig. 8.19 (a)

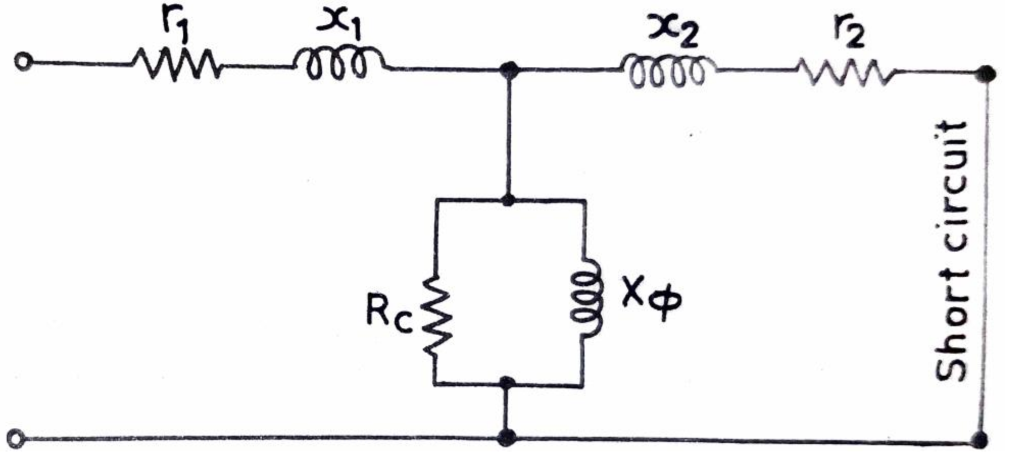


Fig. 8.19 (b)

Transformer

- **Short-circuit Test**

  - ✓ About half (1 to 6%) of the applied voltage appears across the secondary leakage impedance and, therefore, across the exciting branch.
  - ✓ The core flux induces the voltage across the exciting branch.
  - ✓ Since the voltage across the exciting branch is (1 to 6) % of rated voltage, the core flux is also 1 to 6% of its rated value.

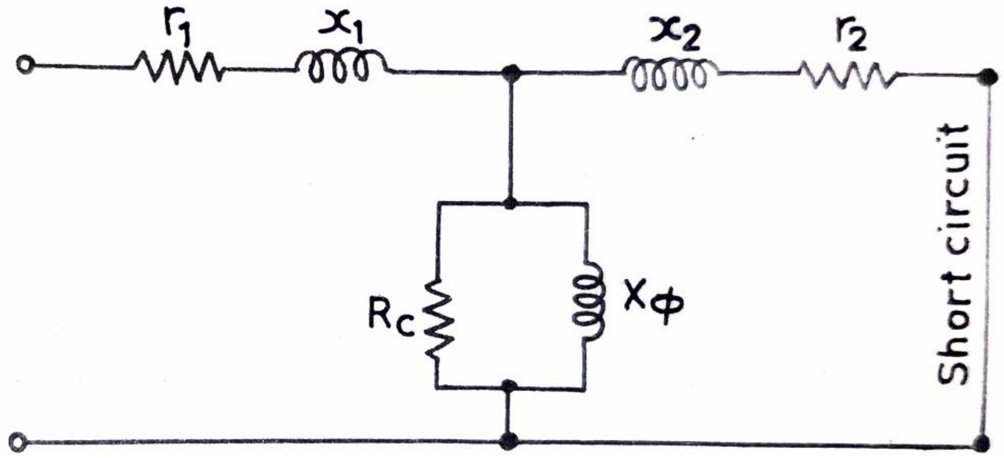


Fig. 8.19 (b)

  - ✓ Hence the core loss, being approximately proportional to the square of the core flux, is 0.01 to 0.36% of its value at rated voltage.
  - ✓ The wattmeter, in short circuit test, records the core loss and the ohmic loss in both the windings.
  - ✓ Since the core loss has been proved to be almost negligible in comparison with the rated-voltage core loss, the wattmeter can be taken to register only the ohmic losses in both the windings.

Transformer

- **Short-circuit Test**
  - ✓ At rated voltage, the exciting current is 2 to 6% of full load current.
  - ✓ When the voltage across the exciting branch is 1 to 6% of rated voltage, the exciting current may be 0.02 to 0.36 of its full-load current.
  - ✓ Therefore, it can be safely ignored and as a result of this, the equivalent circuit of a transformer with the secondary short-circuited gets modified and shown in **Fig. 8.19** (c).

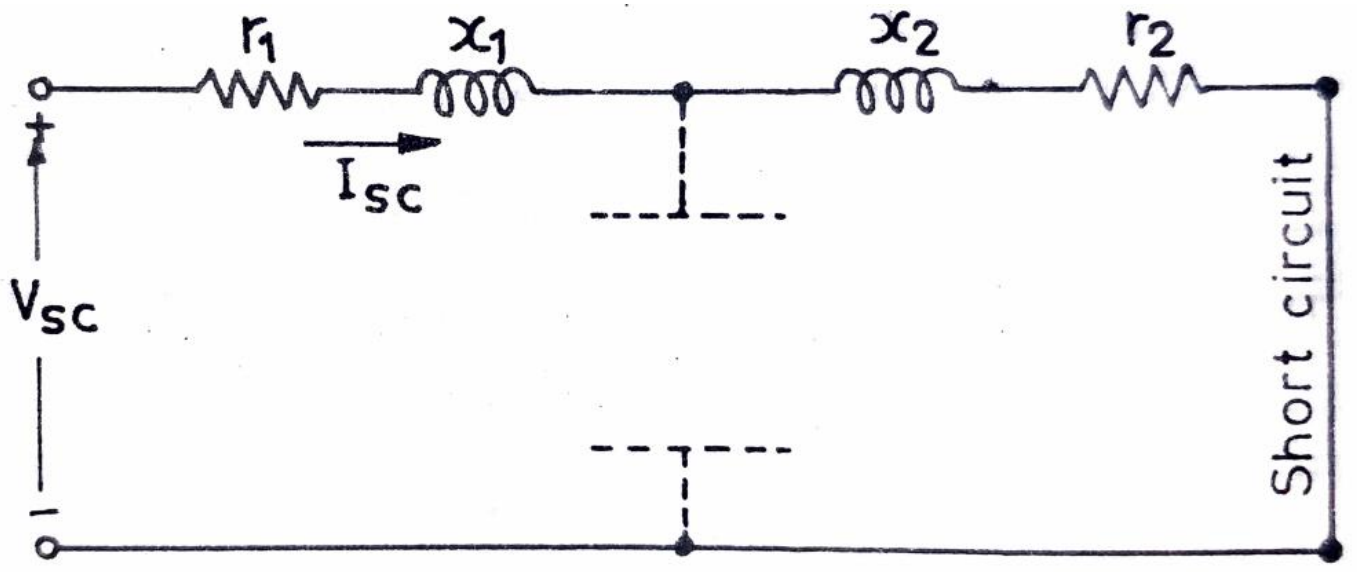


Fig. 8.19 (c)

Transformer

- **Short-circuit Test**

  - The instrument readings may be corrected, if required.
  - Let V_{sc}, I_{sc} and P_{sc} be the voltmeter, ammeter and wattmeter readings. Then it is seen from **Fig. 8.19** (c) that

$$Z_{eH} = \frac{V_{sc}}{I_{sc}}; \qquad r_{eH} = \frac{P_{sc}}{I_{sc}^2}; \qquad x_{eH} = \sqrt{Z_{eH}^2 - r_{eH}^2}$$

    Here r_{eH}, x_{eH} and Z_{eH} are the equivalent resistance, equivalent leakage reactance and equivalent leakage impedance, referred to the h.v. side respectively.

  - These parameters can be referred to the l.v. side, if required.
  - In the analysis of transformer equivalent circuit, the values of equivalent resistance and equivalent leakage reactance referred to either side, are used.
  - However, if the leakage impedance parameters for both primary and secondary are required separately, then it is usual to take $r_1 = r_2 = 1/2r_e$ and $x_1 = x_2 = 1/2x_e$, referred to the same side.

Transformer

Example – P 8.4

A 20 kVA, 2500/250 V, 50 Hz, single-phase transformer gave the following test result:

Open-circuit test (on l.v. side) — 250 V, 1.4 A, 105 watts

Short-circuit test (on h.v. side) — 104 V, 8 A, 320 watts

Compute the parameters of the approximate equivalent circuit referred to high-voltage and low-voltage sides. Also draw the exact equivalent circuit referred to the low-voltage side.

Solution of Example – P 8.4

From open-circuit test:

$$\text{No-load power factor} = \cos\theta_0 = \frac{105}{250 \times 1.4} = 0.3$$

$$\therefore \qquad \theta_0 = 72.55^0$$

$$\therefore \qquad \sin\theta_0 = 0.954$$

$$\therefore \qquad I_c = I_e \cos\theta_0 = 1.4 \times 0.3 = 0.42 \text{ A}$$

and

$$I_\emptyset = I_e \sin\theta_0 = 1.4 \times 0.954 = 1.336 \text{ A}$$

Hence

$$R_{CL} = \frac{V_1}{I_c} = \frac{250}{0.42} = 595\ \Omega$$

$$X_{\emptyset L} = \frac{V_1}{I_\emptyset} = \frac{250}{1.336} = 187\ \Omega$$

Transformer

Solution of Example – P 8.4

Alternatively, the value of R_{CL} and $X_{\emptyset L}$can be determined as follows:

$$R_{CL} = \frac{V_1^2}{P_c} = \frac{(250)^2}{105} = 595\ \Omega$$

Now,

$$I_c = \frac{V_1}{R_{CL}} = \frac{250}{595} = 0.42\ \text{A}$$

and $$I_\emptyset = \sqrt{I_e^2 - I_c^2} = \sqrt{(1.4)^2 - (0.42)^2} = 1.336\ \text{A}$$

$$\therefore \qquad X_{\emptyset L} = \frac{V_1}{I_\emptyset} = \frac{250}{1.336} = 187\ \Omega$$

Transformer

Solution of Example – P 8.4

From short-circuit test:

$$Z_{eH} = \frac{V_{sc}}{I_{sc}} = \frac{104}{8} = 13\ \Omega$$

$$r_{eH} = \frac{P_{sc}}{I_{sc}^2} = \frac{320}{(8)^2} = 5\ \Omega$$

$$x_{eH} = \sqrt{Z_{eH}^2 - r_{eH}^2} = \sqrt{(13)^2 - 5^2} = 12\ \Omega$$

Equivalent circuit parameters referred to l.v. side are

$$R_{cL} = 595\ \Omega \qquad\qquad X_{\emptyset L} = 187\ \Omega$$

$$r_{cL} = 5\left(\frac{1}{10}\right)^2 = 0.05\ \Omega; \qquad\qquad x_{eL} = 12\left(\frac{1}{10}\right)^2 = 0.12\ \Omega$$

Solution of Example – P 8.4

The equivalent circuit is shown in **Fig. 21** (a)

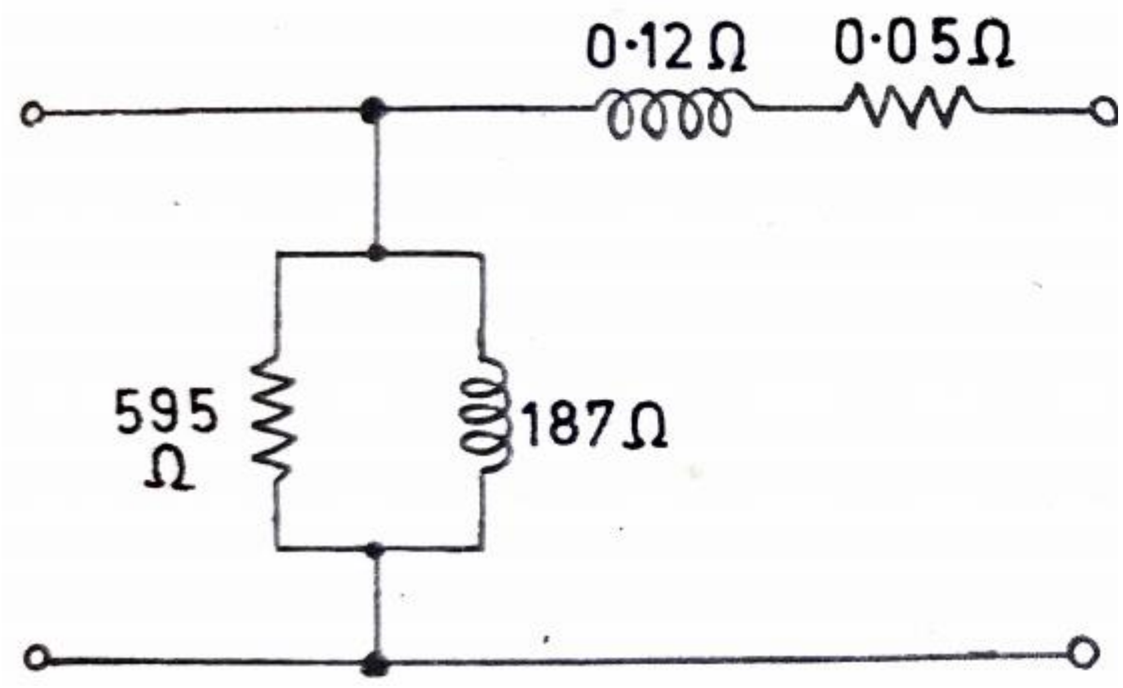


Fig. 21 (a)

Solution of Example – P 8.4

Equivalent circuit parameters referred to h.v. side are

$$R_{cH} = 595(10)^2 = 59{,}500\ \Omega$$

$$X_{\emptyset H} = 187(10)^2 = 18{,}700\ \Omega$$

$$r_{eH} = 5\ \Omega; \qquad x_{eH} = 12\ \Omega.$$

Exact equivalent circuit parameters referred to l.v. side are

$$r_{1L} = {r'_1}_H = \frac{1}{2} r_{eL} = \frac{1}{2}(0.05) = 0.025\ \Omega$$

$$x_{1L} = {x'_1}_H = \frac{1}{2} x_{eL} = \frac{1}{2}(0.12) = 0.06\ \Omega$$

$$R_{eL} = 595\ \Omega \quad \text{and} \quad X_{\emptyset L} = 187\ \Omega$$

Solution of Example – P 8.4

The exact equivalent circuit is shown in **Fig. 21** (b)

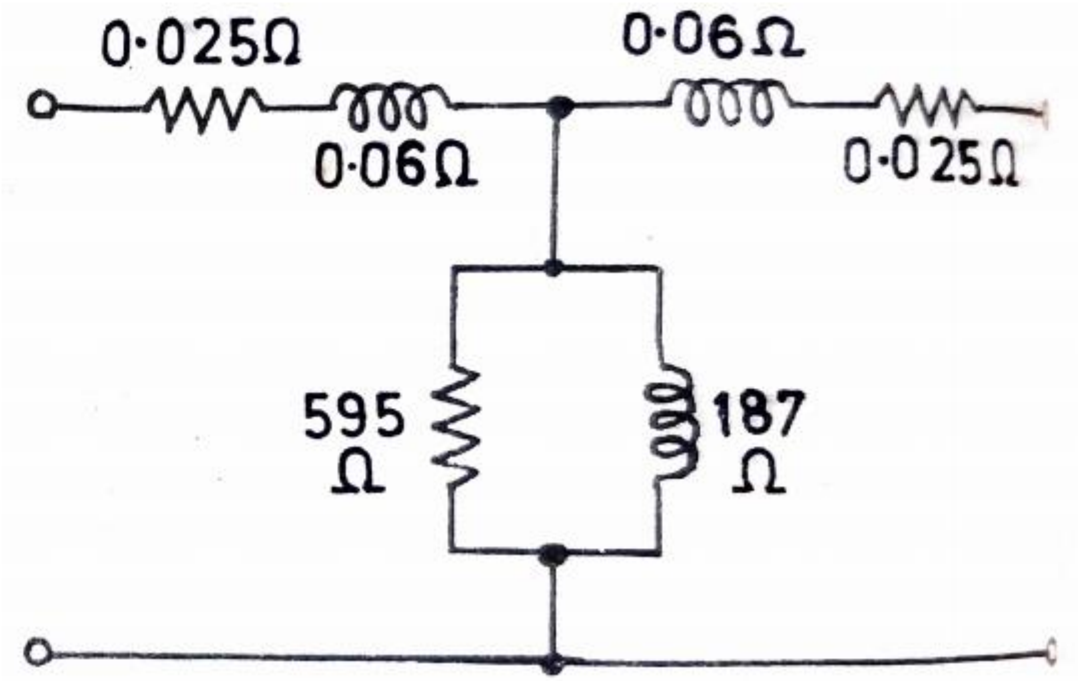


Fig. 21 (b)

Transformer

Example – P 8.5

A 200 kVA, 1100/400 V, delta-star distribution transformer gave the following test results:

Open circuit test—400 V, 9 A, 1.50 kW.

Short circuit test—350 V, rated current, 2.1 kW.

Calculate the equivalent circuit parameters referred to the h.v. side and its efficiency at half full load of unity power factor.

Solution of Example – P 8.5

At first, all the quantities are reduced to per phase values.

Open-circuit test.

The applied voltage for this test is equal to the rated voltage on the l.v. side, which is star connected.

$\therefore$ Per phase applied voltage $V_1 = \dfrac{400}{\sqrt{3}} = 231\text{V}$

Per phase exciting current $I_e = 9$ A

and per phase core loss $P_c = \dfrac{1500}{3} = 500$ W

Now $V_1 I_e \cos\theta_0 = P_c$

$\therefore$ Core loss current $= I_e \cos\theta_0 = I_c = \dfrac{P_c}{V_1} = \dfrac{500}{231} = 2.165$ A

Transformer

Solution of Example – P 8.5

Magnetizing current, $$I_{\emptyset} = \sqrt{I_e^2 - I_c^2} = \sqrt{9^2 - (2.165)^2} = 8.73 \text{ A}$$

$$R_{cL} = \frac{V_1}{I_c} = \frac{231}{2.165} = 106.8\ \Omega$$

$$X_{\emptyset L} = \frac{V_1}{I_{\emptyset}} = \frac{231}{8.73} = 26.47\ \Omega$$

Core loss resistance referred to h.v. side

$$R_{cH} = R_{cL}\left(\frac{\text{Per phase voltage on h.v. side}}{\text{Per phase voltage on l.v. side}}\right)^2 = 106.8\left(\frac{11{,}000}{231}\right)^2 = 242.2\ \text{k}\Omega$$

$$X_{\emptyset H} = X_{\emptyset L}\left(\frac{\text{Per phase voltage on h.v. side}}{\text{Per phase voltage on l.v. side}}\right)^2 = 26.47\left(\frac{11{,}000}{231}\right)^2 = 60.02\ \text{k}\Omega$$

Solution of Example – P 8.5

Short-circuit test

This test is performed on h.v. side, which is in delta.

$\therefore$ Applied voltage/phase $V_{sc} = 350$ V

Current/phase $I_{sc} =$ Rated current $= \dfrac{200{,}000}{3 \times 11{,}000} = 6.06$ A

Ohmic loss per phase $P_{sc} = \dfrac{2100}{3} = 700$ W

$$Z_{eH} = \frac{V_{sc}}{I_{sc}} = \frac{350}{6.06} = 57.8\ \Omega$$

$$r_{eH} = \frac{P_{sc}}{I_{sc}^2} = \frac{700}{(6.06)^2} = 19.06\ \Omega$$

$$x_{eH} = \sqrt{(57.8)^2 - (19.06)^2} = 54.6\ \Omega$$

Transformer

Solution of Example – P 8.5

Efficiency at half full load

$$\eta = 1 - \frac{\text{Per phase losses}}{\text{Per phase output} + \text{Per phase losses}}$$

$$= 1 - \frac{500 + \left(\frac{1}{2}\right)^2 \times 700}{\frac{1}{2}\left(\frac{200}{3} \times 1000 \times 1\right) + 500 + \left(\frac{1}{2}\right)^2 \times 700}$$

$$= 1 - \frac{675}{34{,}008}$$

$$= 0.9802 \text{ p.u.} \quad \text{or } 98.02\%$$


Thank you