NATIONAL INSTITUTE OF TECHNOLOGY JAMSHEDPUR

# Electrical Engineering and Measurement (EE1101) (Transformer)

Presented

by

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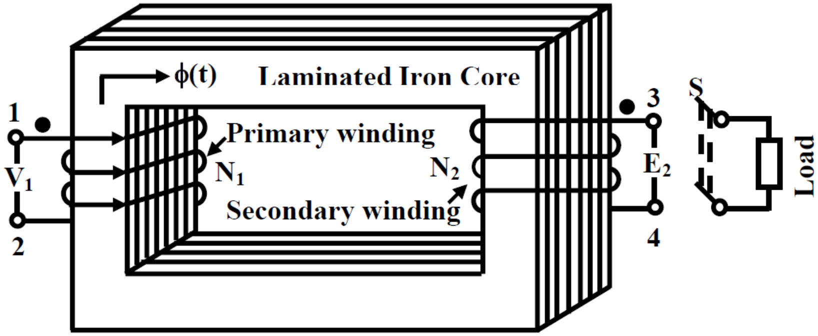
# Introduction on Transformer

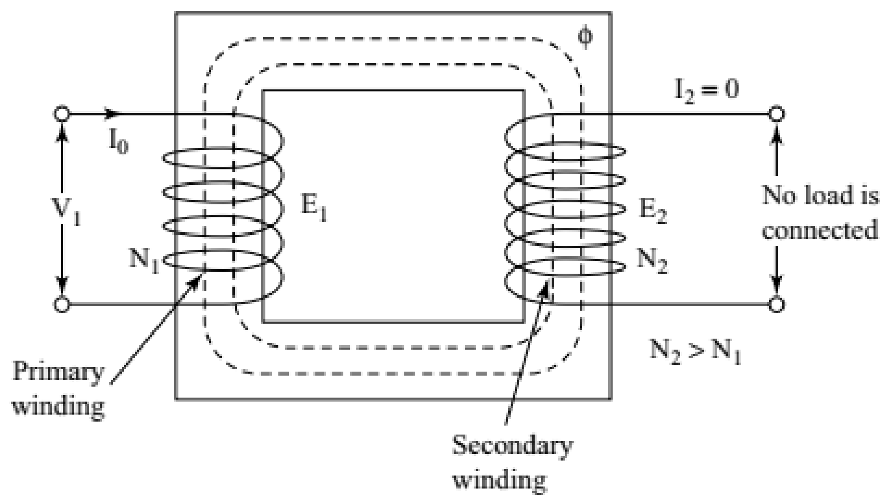
- A transformer is a static electrical device that is used to convert AC voltage (or current) from one value to the other without changing the frequency using the principles of electromagnetic induction.
- A transfer is a static device which consists of two or more stationary electric circuits interlinked by a common magnetic circuit for the purpose of transferring electrical energy between them. The transfer of energy from one circuit to another takes place without a change in frequency.
- The transformer action is based on the laws of electromagnetic induction.
- There is no electrical connection between the primary and secondary. The a.c. power is transferred from primary to secondary through magnetic flux.
- There is no change in frequency i.e., output power has the same frequency as the input power.
- Transformer will not change the power, it changes either voltage or current.



# Brief Working Principle

1) A simple form of a transformer consists essentially of two insulated windings interlinked by a common or mutual magnetic field established in a core of magnetic material.

2) When one of the windings, termed the ***primary***, is connected to an alternating-voltage source (say $V_1$) as shown in the following figure, an alternating flux is produced in the core with an amplitude depending on the primary voltage, frequency and number of turns of the primary ($N_1$).



# Brief Working Principle

3) The flux links the turns $N_1$ of primary winding and induces in them an alternating voltage $E_1$ by self induction.
4) The flux links the other winding, called the ***secondary winding*** with turns $N_2$**.** A voltage $E_2$ is induced in this secondary of the same frequency as the primary voltage but its magnitude depends on the number of secondary turns ($N_2$) by mutual induction.
5) When the number of primary and secondary turns are properly proportioned, almost any desired voltage ratio, or ***ratio of transformation*** can be achieved.
6) There is no relative motion between the coils, the frequency of the induced voltage in coil 2 is exactly the same as the frequency of the applied voltage to coil 1.

# Applications of Transformers

Transformers are built in an astonishing range of sizes from the tiny units used in communication systems to monsters used in high-voltage transmission systems, weighing hundreds of tons.

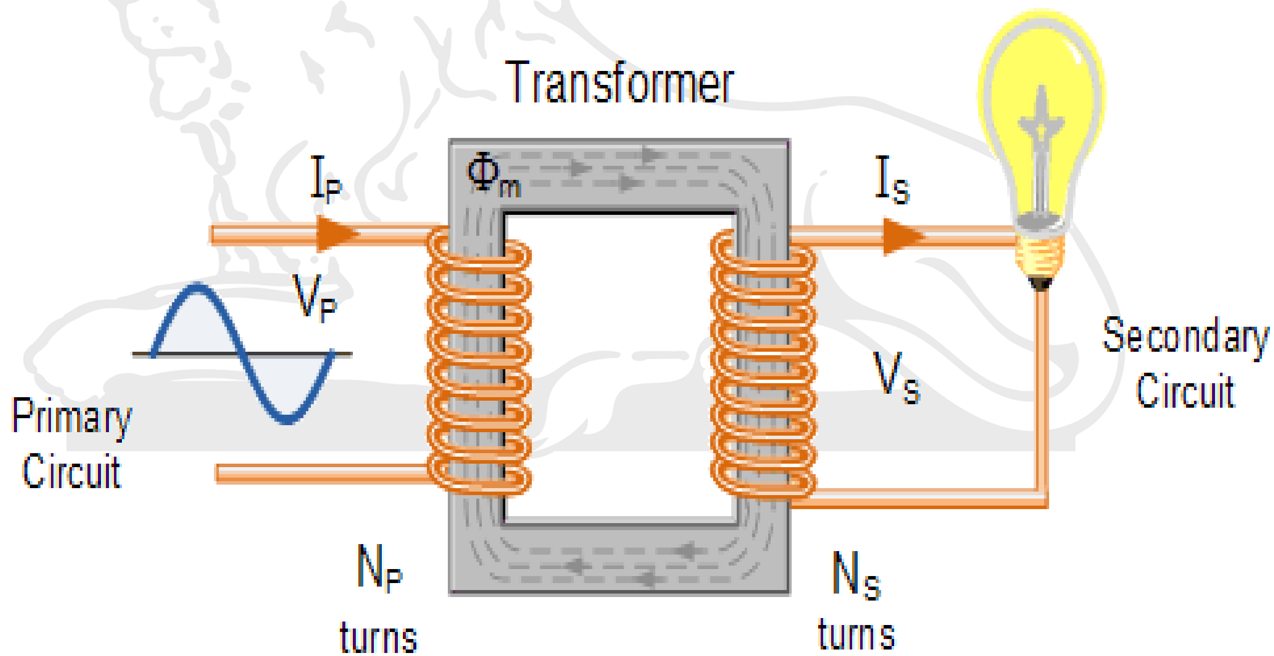
1. Changing voltage and current levels in electric power systems. For example, transformers are used extensively in ac power systems in distribution of voltages (240/415 V) for domestic purposes from a transmission voltage as high as 400-11kV.
2. Matching source and load impedances for maximum power transfer in electronic and control circuitry.
3. In communication and electronic systems where frequency ranges from audio to radio and video, transformers are used as at input/output to connect the microphone to the first amplifying stage/to connect the last amplifying stage to the loudspeaker.
4. Electrical isolation (isolating one circuit from another or isolating dc while maintaining ac continuity between two circuits).

# Can the transformer operate on DC?

- Answer: **NO**
- The transformer action does not take place with a direct current of constant magnitude.
- Because with a DC primary current, the flux produced in the core is not alternating but it is of constant value.
- As there is no change in the flux linkage with the secondary winding, the induced emf in the secondary is zero.
- If DC is applied to the primary then there is a possibility of transformer core saturation.
- If core saturates the primary will draw excessively large current. Therefore application of DC should be avoided.

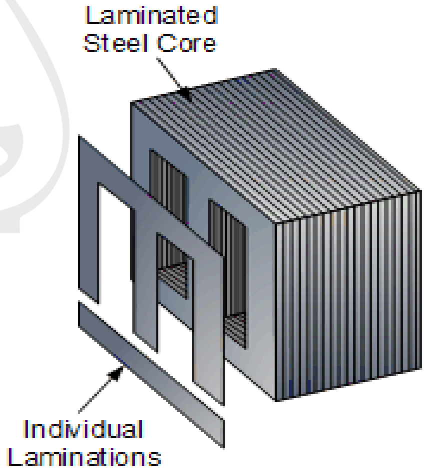
# Single Phase Transformer

- A transformer is represented in Figure below, as consisting of two electrical circuits linked by a common ferromagnetic core.
- One coil is termed the primary winding which is connected to the supply of electricity, and the other the secondary winding, which may be connected to a load.



# Construction of Transformer

- The three main parts of a transformer are:
  1. Primary Winding: The winding that takes electrical power, and produces magnetic flux when it is connected to an electrical source.
  2. Magnetic Core: Provides a path for the magnetic lines of flux produced by the primary winding. The flux passes through a low reluctance path linked with secondary winding creating a closed magnetic circuit.
  3. Secondary Winding: The winding that provides the desired output voltage due to Faraday's law of electromagnetic induction.



# Types of Transformers

The different types of transformers are required for different applications. The following section describes the type of transformers:

**1) Based on Voltage Level**

**(a) Step up transformer**

**(b) Step down transformer**

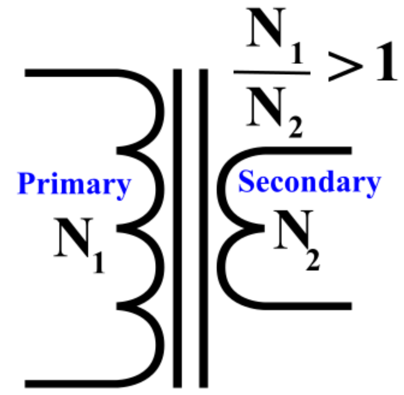
**(c) One to one transformer**

A transformer may receive energy at one voltage and deliver it at the same voltage. Such transformer is called **one to one transformer. It is used to isolate two circuits.**

# Types of Transformers

***Step-Down Transformer:***

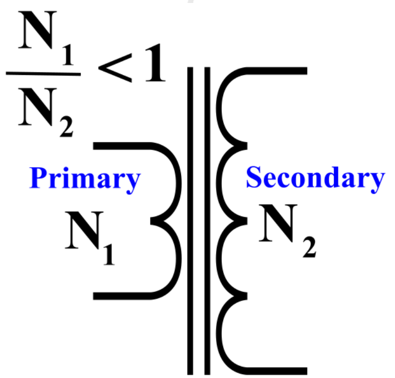
- A transformer in which the output (secondary) voltage is less than its input (primary) voltage is called a step-down transformer.
- A step-down transformer is designed such that the number of windings on the primary side ($N_1$) is greater than the windings on the secondary side ($N_2$).
- In this type of transformer, the overall winding ratio ($N_1/N_2$) of primary and secondary always remains more than 1.



# Types of Transformers

***Step-Up Transformer:***

- A transformer in which the output (secondary) voltage is greater than its input (primary) voltage is called a step-up transformer.
- Step-up transformer increases the low primary voltage ($V_1$) to a high secondary voltage ($V_2$).
- It is achieved by choosing the ratio of primary and secondary winding ratio as less than 1. This means the number turns in secondary winding is higher than the primary winding.

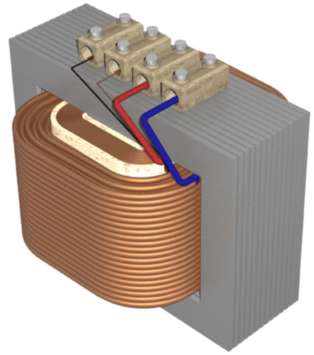


# Types of Transformers

**2) Based on Core Material**

***(i) Iron core transformer***:

- In order to ensure the largest and most effective magnetic linkage of the two windings, the core, which supports them mechanically and conducts their mutual flux, is normally made of highly permeable iron or steel alloy (cold-rolled, grain-oriented sheet steel).
- Such a transformer is generally called an ***iron-core transformer.*** This type of transformer uses multiple soft iron plates as the core material.
- Due to the excellent magnetic properties of iron, the flux linkage of the iron core transformer is very high.
- Thus, the efficiency of the iron core transformer is also high. Transformers operated from 25–400 Hz are invariably of iron-core construction.



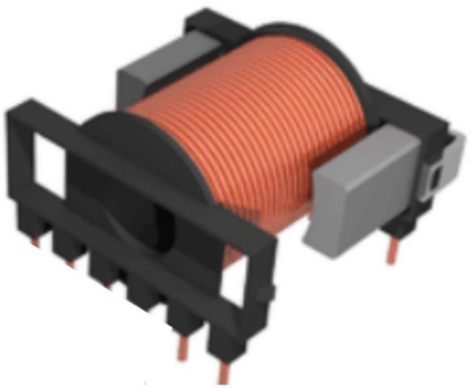
# Types of Transformers

***ii. Air core transformer:***

- When the magnetic circuit linking the windings is made of nonmagnetic material, the transformer is referred to as an ***air-core transformer*.**
- The air-core transformer is of interest mainly in radio devices and in certain types of measuring and testing instruments.

(iii) ***Ferrite core transformer:***

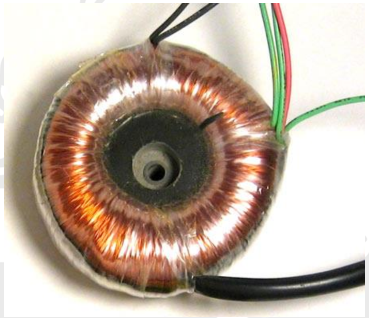
- A ferrite core transformer uses a ferrite core due to high magnetic permeability.
- Ferrite core transformers are used in high-frequency application such as in switch mode power supply (SMPS), RF related applications, etc. because this transformer offers very low losses in the high-frequency application.



# Types of Transformers

*(iv)* ***Toroidal core transformer***

- Toroidal core transformer uses toroid shaped core material, such as **iron core or ferrite core**.
- Toroids are ring or donut shaped core material, which are widely used for superior electrical performance.
- Due to the ring shape, the leakage inductance is very low and offers very high inductance and Q (quality factor) factors.



# Types of Transformers

**3) Based on Applications**

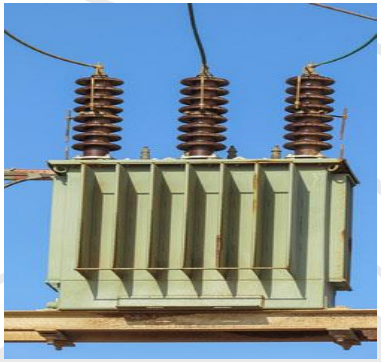
***(i) Power transformer***

- This transformer acts as a bridge between the power generator and the primary distribution grid.
- The main principle of the power transformer is to convert the low voltage high current to a high voltage low current.
- This is required to minimize the power loss in the power distribution system. Depending on the power rating and specification, power transformers can further be classified into three categories: ***Small power transformer, Medium power transformers, and the large power transformers.*** The rating of these transformers can vary from 30 KVA to 100 MVA.

# Types of Transformers

***(ii) Distribution transformer***

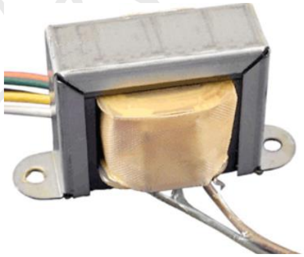
- This is used in the last phase of the power system.
- Distribution transformers are step down transformers, which converts high grid voltage to the end customer required voltage, i.e. 110V or 230V.
- The transformer is generally mounted on a utility pole as shown in following figure.
- Generally, distribution transformers have a rating of less than 200kVA.



# Types of Transformers

**(iii) *Audio Transformer*:**

- This kind of transformer is used in the electronics for audio applications where impedance matching is required.
- Audio transformer balances the amplifier circuit and loads (for example a loudspeaker). An audio transformer is shown in following figure.



# Types of Transformers

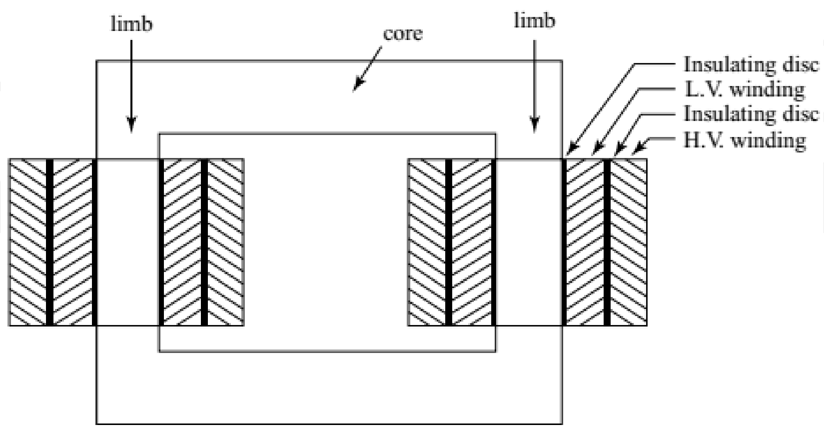
**4) Based on the manner in which the primary and secondary winding are wound on the core**

(i) core-type transformer

(ii) shell-type transformer

(i) **Core-type transformer**.

- In a core-type transformer, half of the primary winding and half of the secondary winding are placed round each limb as shown in the following figure. This reduces the leakage flux.
- It is a usual practice to place the low-voltage winding below the high-voltage winding for avoiding the insulation problem and mechanical considerations.

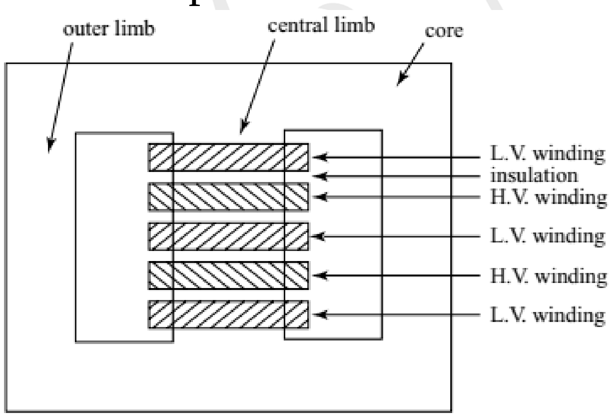



(a) Core-type construction

# Types of Transformers

(ii) **Shell-type transformer**.

- This method of construction involves the use of a double magnetic circuit. Both the windings are placed round the central limb, the other two limbs acting simply as a low-reluctance flux path.
- The windings are wound in the form of a number of circular discs, and are placed one above the other. The extreme two discs on the central limb are low-voltage winding sections.
- The width of the central limb is twice the width of the outer limbs so that the flux density is the same in all the limbs
- The choice of type (whether core or shell) will not greatly affect the efficiency of the transformer.
- In power transformers, in general, the core-type construction is preferred while for distribution transformers, the shell-type construction is preferred.



(b) Shell-type construction

# Ideal Transformers

A transformer which has 100% efficiency and does not have any losses. Such a transformer is called as an **ideal transformer.**

***Properties of an ideal transformer***

1) The primary and secondary windings have zero resistance.
2) All the flux produced by the primary links the secondary winding i.e., there is no leakage flux.
3) Core loss comprising of eddy current and hysteresis losses are neglected. (These losses are discussed in detail in later).
4) Permeability $\mu_r$ of the core is infinitely large. In other words, very small (or zero) current is required to establish flux in the core .

# IDEAL Transformers

- Ideal transformer is a transformer which does not have any loss.
- In other words, an ideal transformer gives output power exactly equal to the input power.
- An ideal transformer is one that has
  1. No winding resistance (i.e. no copper losses)
  2. No leakage flux
  3. No iron losses (i.e. eddy current and hysteresis losses) in the core.

# EMF Equation of a Transformer

The supplying current establishes flux $\phi$ in the core (positive direction marked on diagram) all of which is assumed confined to the core i.e., there is no leakage of flux. Let the flux at any instant be given by

$$\emptyset = \phi_{max}\, sin\omega t \qquad (1)$$

The emf induced in the coil of N turns is given by Faraday's law as

$$e = -N\frac{d\phi}{dt} = -N\phi_{max}\omega cos\,\omega t = N\phi_{max}\omega sin\,(\omega t - \pi/2) \qquad (2)$$

From equations (1) and (2), it is clear that the induced emf lags the flux by 90°. The equation (2) may be written as

$$e = E_{max} sin\,(\omega t - \pi/2) \qquad (3)$$

Where, $E_{max} = N\phi_{max}\omega$ =maximum value of e.

The rms value of the induced emf is given by

$$E_{rms} = E = \frac{E_{max}}{\sqrt{2}} = \frac{N\phi_{max}\omega}{\sqrt{2}} = \frac{N\phi_{max}2\pi f}{\sqrt{2}}$$

$$E_{rms} = E = 4.44\ \phi_{max} f N \qquad (4)$$

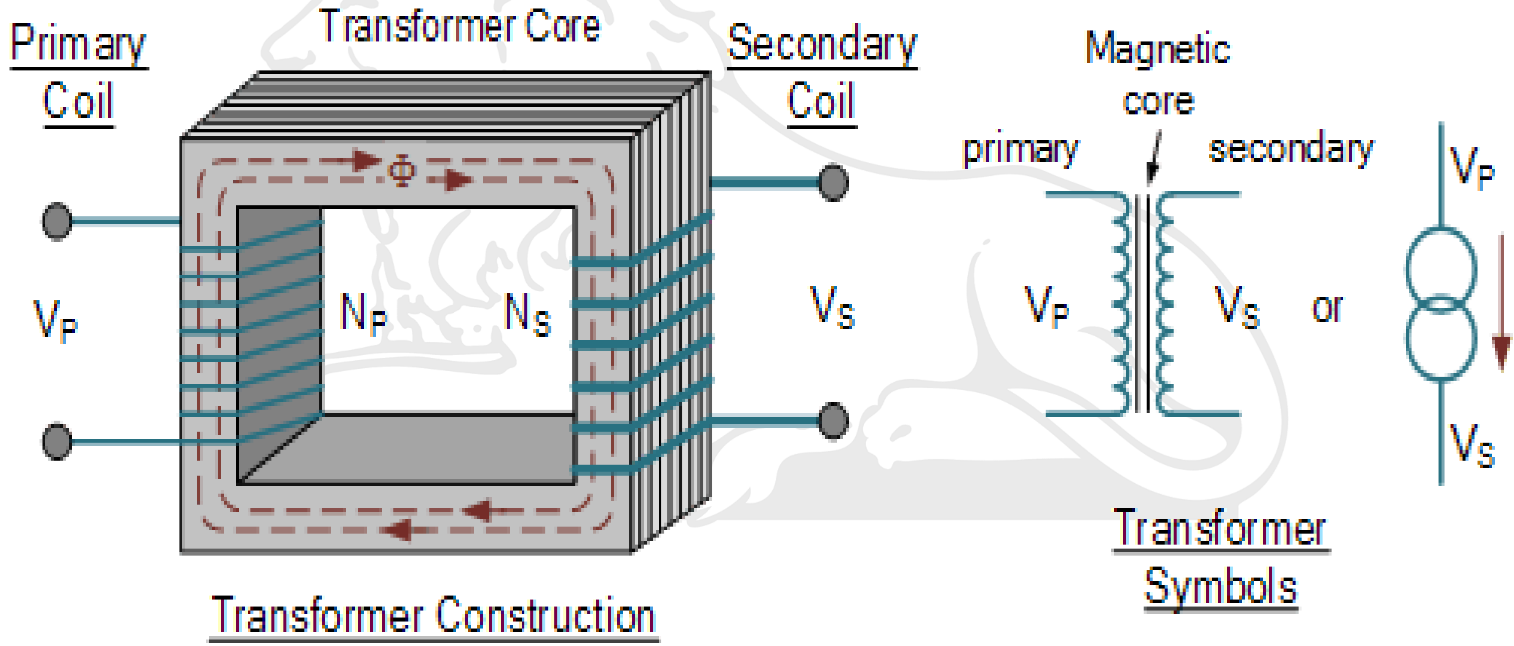
# EMF Equation of a Transformer

From equation (4), the rms value of the induced emf in primary winding is given by

$$E_{1rms} = E_1 = 4.44\ \phi_{max} f N_1 \tag{5}$$

Similarly, the rms value of the induced emf in secondary winding is given by

$$E_{2rms} = E_2 = 4.44\ \phi_{max} f N_2 \tag{6}$$



# Voltage Ratio and Turn Ratio

From equation (5), voltage per turn in primary winding is given by

$$\frac{E_1}{N_1} = 4.44\ \phi_{max} f \tag{7}$$

Similarly from equation (6), voltage per turn in secondary winding is given by

$$\frac{E_2}{N_2} = 4.44\ \phi_{max} f \tag{8}$$

Equations (7) and (8) show that the voltage per turn in both the windings is the same. That is,

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} \tag{9}$$

Also,

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = a \tag{9}$$

The turn ratio, or induced voltage ratio, is called the transformation ratio and is denoted by symbol a. In a transformer, the mmf of primary winding is same as the mmf of secondary winding

$$N_1 I_1 = N_2 I_2 \rightarrow \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

Hence,

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

# Problems

1. A transformer has 500 primary turns and 3000 secondary turns. If the primary voltage is 240 V, determine the secondary voltage, assuming an ideal transformer.
2. An ideal transformer with a turns ratio of 2:7 is fed from a 240 V supply. Determine its output voltage.
3. An ideal transformer has a turns ratio of 8:1 and the primary current is 3 A when it is supplied at 240 V. Calculate the secondary voltage and current.
4. An ideal transformer, connected to a 240 V mains, supplies a 12 V, 150 W lamp. Calculate the transformer turns ratio and the current taken from the supply.

# Problems

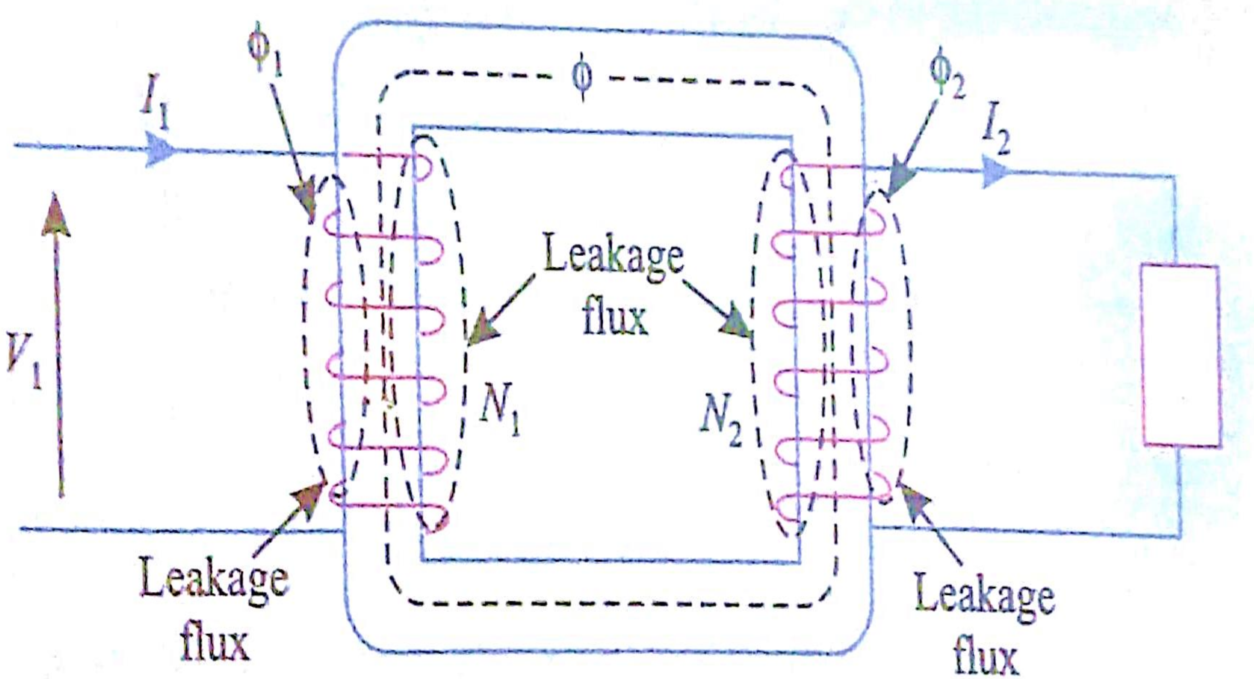
5. A 100 kVA, 4000 V/200 V, 50 Hz single-phase transformer has 100 secondary turns. Determine (a) the primary and secondary current, (b) the number of primary turns, and (c) the maximum value of the flux.
6. A single-phase, 50 Hz transformer has 25 primary turns and 300 secondary turns. The cross-sectional area of the core is 300 $cm^2$. When the primary winding is connected to a 250 V supply, determine (a) the maximum value of the flux density in the core, and (b) the voltage induced in the secondary winding.
7. A single-phase 500 V/100 V, 50 Hz transformer has a maximum core flux density of 1.5 T and an effective core cross-sectional area of 50 cm2. Determine the number of primary and secondary turns.

# Problems

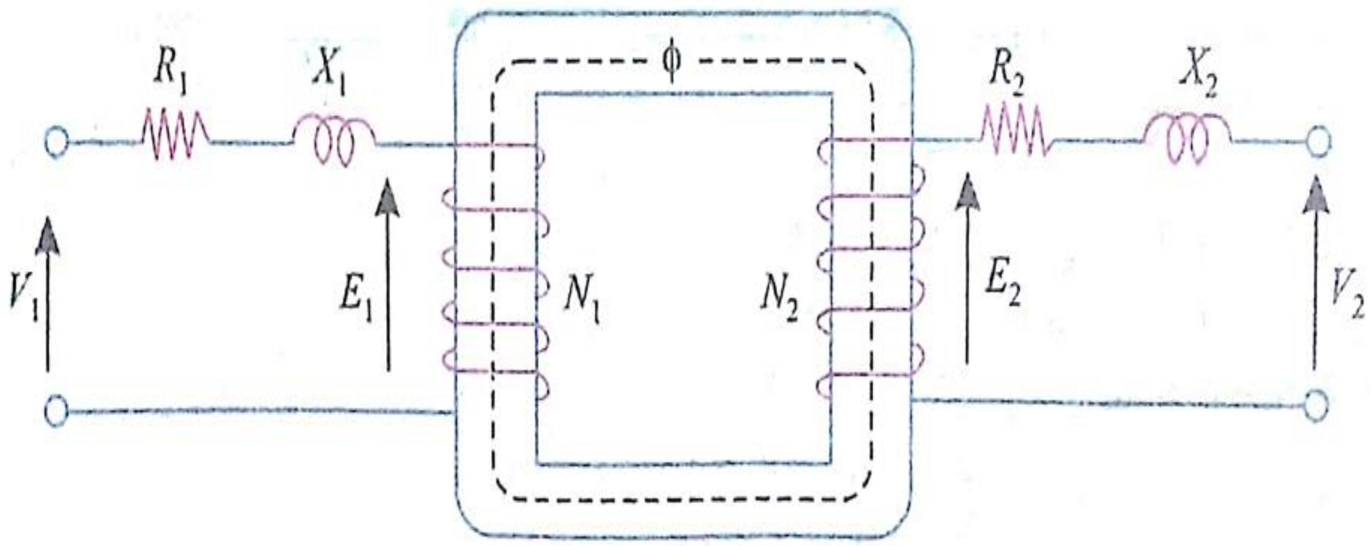
8. A 4500 V/225 V, 50 Hz single-phase transformer is to have an approximate e.m.f. per turn of 15 V and operate with a maximum flux density of 1.4 T. Calculate (a) the number of primary and secondary turns and (b) the cross-sectional area of the core.
9. A 3.3 kV/110 V, 50 Hz, single-phase transformer is to have an approximate e.m.f. per turn of 22 V and operate with a maximum flux of 1.25 T. Calculate (a) the number of primary and secondary turns, and (b) the cross-sectional area of the core.

# Non-Ideal Transformer or Practical Transformer

- The Practical transformer has:
  1. winding resistance (i.e. copper losses)
  2. Leakage reactance
  3. Iron losses (i.e. eddy current and hysteresis losses)



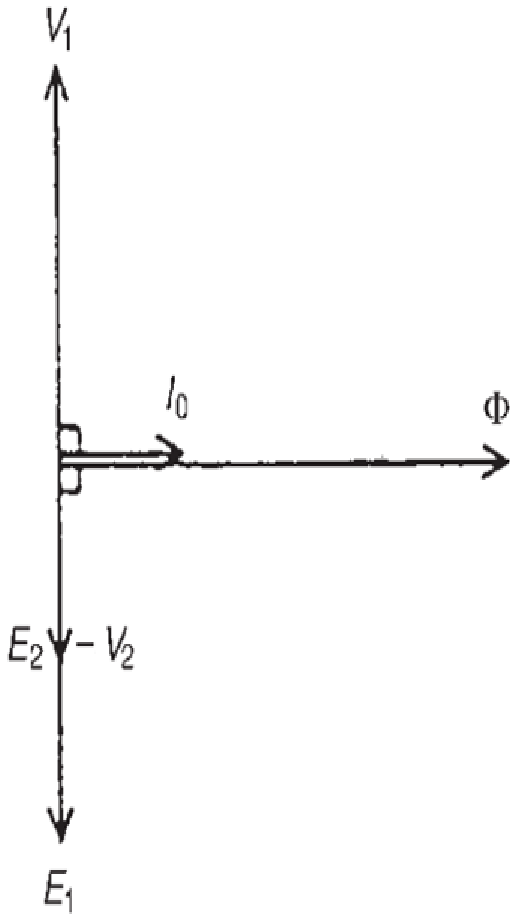
# Non-Ideal Transformer or Practical Transformer



# Transformer on No Load

For Ideal Transformer

- The core flux is common to both primary and secondary windings in a transformer and is thus taken as the reference phasor in a phasor diagram.
- On no-load the primary winding takes a small no-load current $I_0$ and since, with losses neglected, the primary winding is a pure inductor, this current lags the applied voltage $V_1$ by $90^0$.
- The primary induced e.m.f. $E_1$ is in phase opposition to $V_1$ (by Lenz's law) and is shown $180^0$ out of phase with $V_1$ and equal in magnitude.
- The secondary induced e.m.f. is shown for a 2:1 turns ratio transformer.



# Transformer on No Load

For Non-Ideal Transformer

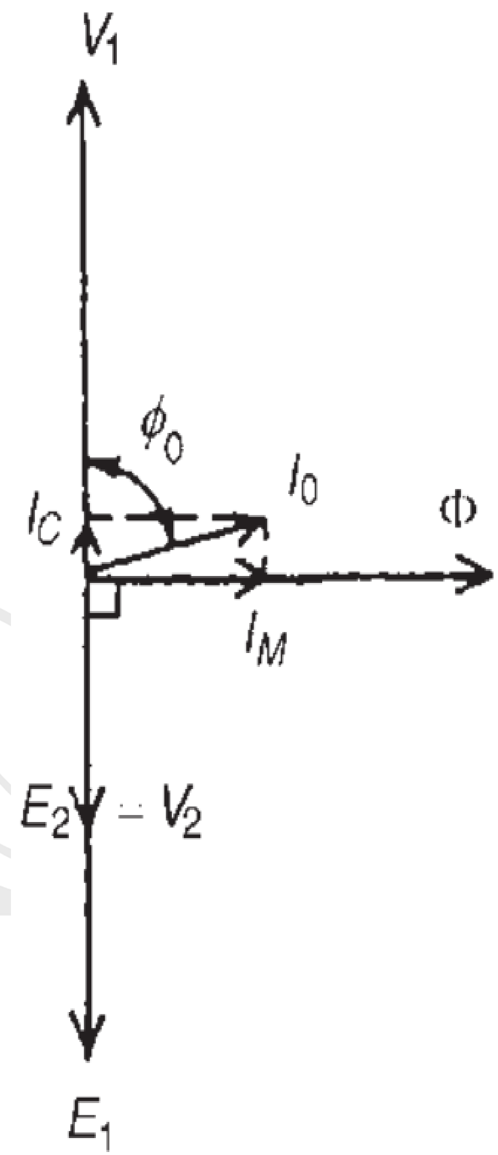
- A no-load phasor diagram for a practical transformer is shown in Figure.
- If current flows then losses will occur. When losses are considered then the no-load current $I_0$ is the phasor sum of two components

  (a) $I_M$, the magnetizing component

  (b) $I_C$, the core loss component

- No-load current, $I_0 = \sqrt{I_M^2 + I_C^2}$

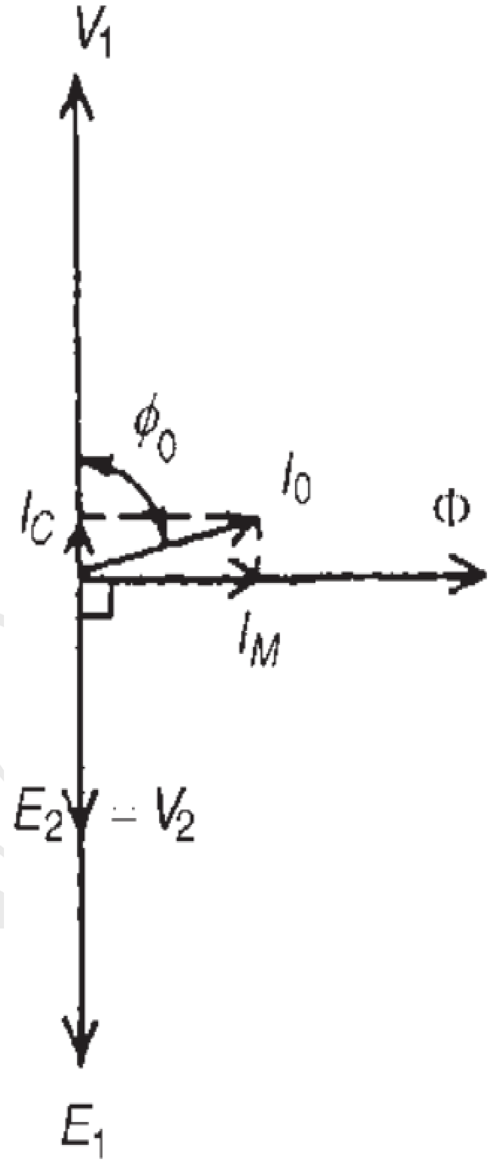
  where $I_M = I_0 \sin\emptyset_0$ ; $I_C = I_0 \cos\emptyset_0$
- The secondary induced e.m.f. is shown for a 2:1 turns ratio transformer.



# Transformer on No Load

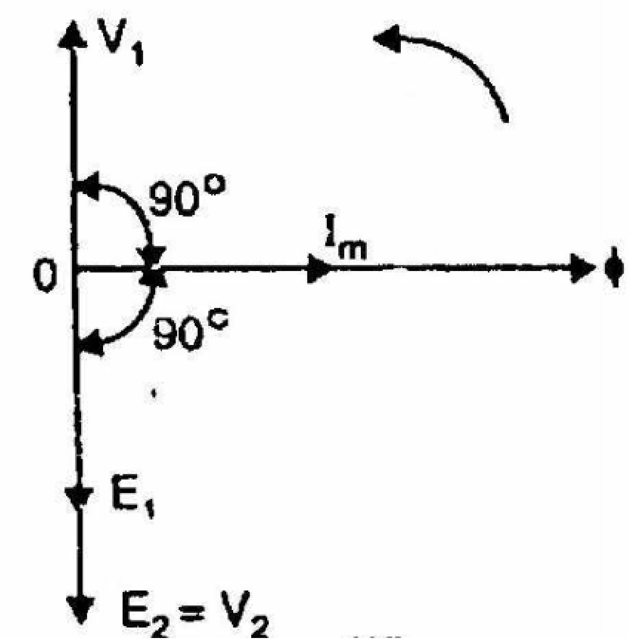
$$\text{Power factor on no-load} = \cos\phi_0 = \frac{I_C}{I_0}$$

$$\text{The total core losses (i.e. iron losses)} = V_1 I_0 \cos\phi_0$$



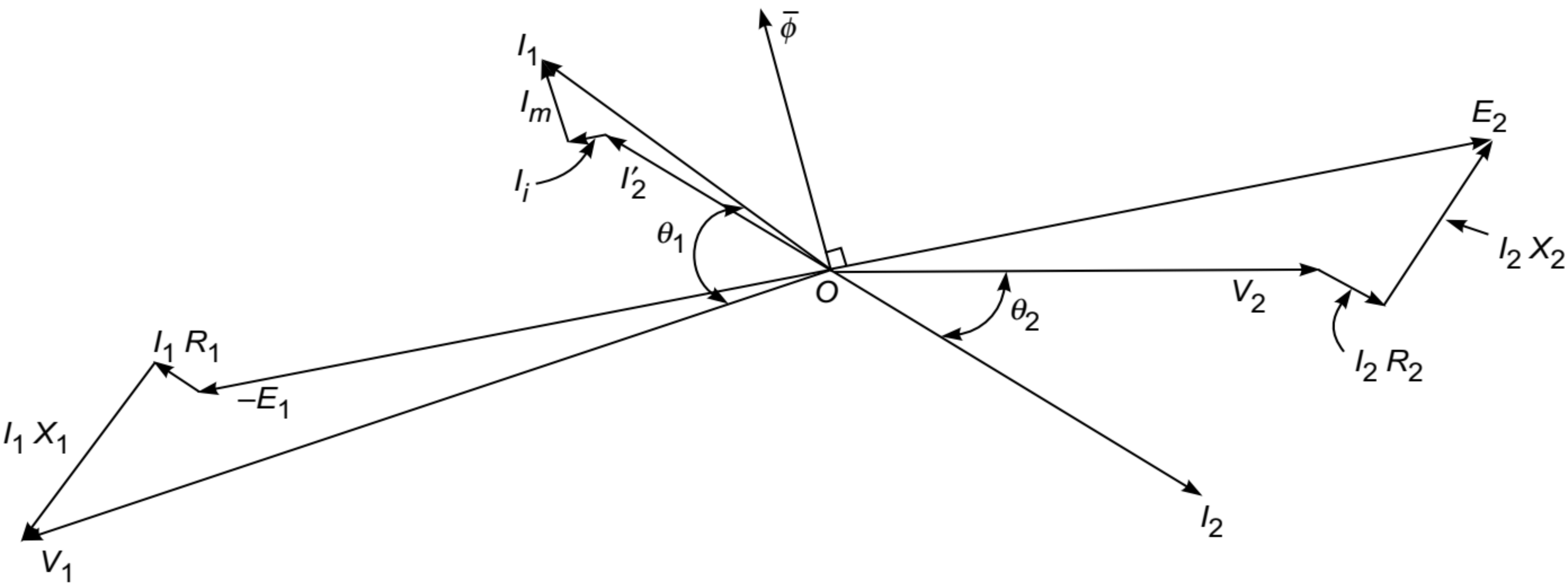
# Phasor Diagram of Transformer

- Following figure shows the phasor diagram of an ideal transformer at no load.
- Since flux is common to both the windings, it has been taken as the reference phasor. The primary e.m.f. E1 and secondary e.m.f. E2 lag behind the flux by 90°.
- Note that E1 and E2 are in phase. But E1 is equal to V1 and 180° out of phase with it.



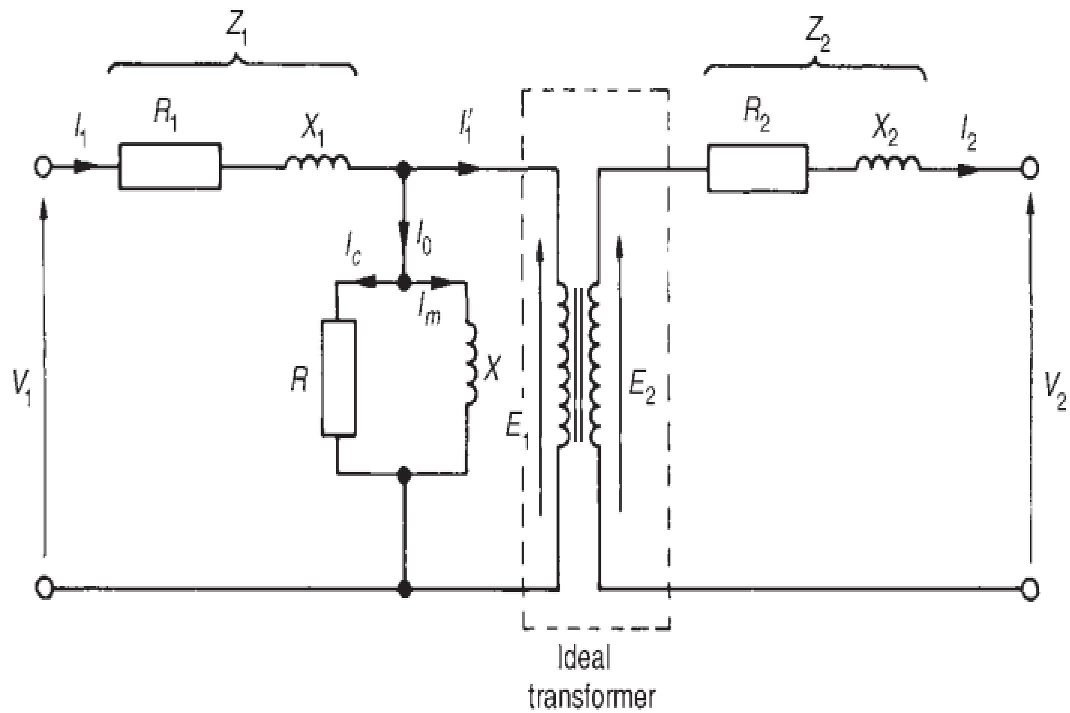
# Phasor Diagram of Transformer

- Following figure shows the phasor diagram of a transformer on full load of lagging power factor.
- Since flux is common to both the windings, it has been taken as the reference phasor. The primary e.m.f. E1 and secondary e.m.f. E2 lag behind the flux by 90°.
- Note that E1 and E2 are in phase. But E1 is equal to V1 and 180° out of phase with it.



# Equivalent Circuit of A Transformer

- Figure shows an equivalent circuit of a transformer. Here $R_1$, $R_2$ represent the resistances and $X_1$, $X_2$ represent the reactance's of the primary and secondary windings.
- The core losses are allowed by resistance R which takes a current $I_C$, Reactance X takes the magnetizing component $I_M$.



# Evaluation of Equivalent Circuit of a Transformer

Let $R_2'$ is the resistance of secondary winding referred/reflected to the primary winding. Therefore the power consumed by $R_2'$ when carrying the primary current is equal to the power consumed by $R_2$ due to secondary current. That is

$$I_1^2 R_2' = I_2^2 R_2 \rightarrow R_2' = \left(\frac{I_2^2}{I_1^2}\right)^2 R_2$$
$$R_2' = a^2 R_2$$

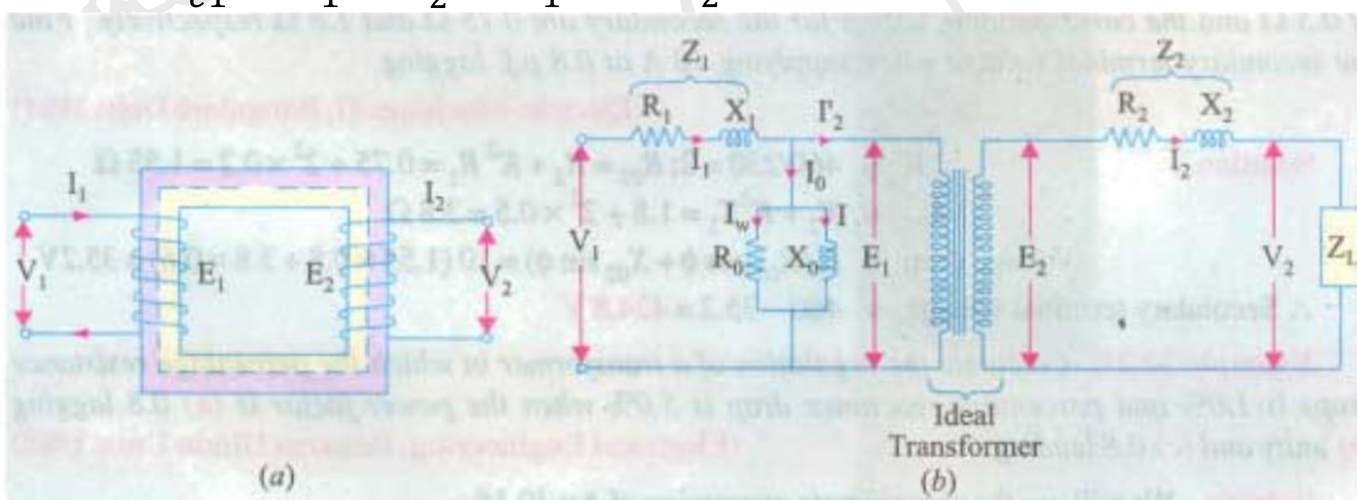
Similarly,

$$X_2' = a^2 X_2$$

Let $R_{e1}, X_{e1}$ and $Z_{e1}$ represent the effective resistance, effective reactance and effective impedance of whole transformer in primary side and given as

$$R_{e1} = R_1 + R_2' = R_1 + a^2 R_2$$
$$X_{e1} = X_1 + X_2' = X_1 + a^2 X_2$$

**Figure:** Exact Equivalent circuit diagram of Transformer



# Evaluation of Equivalent Circuit of a Transformer

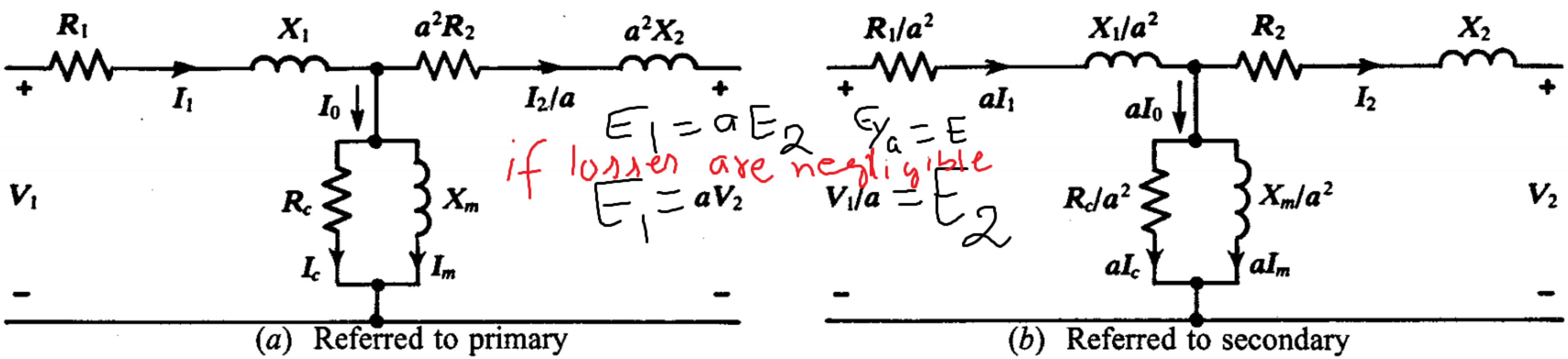
$$Z_{e1} = Z_1 + Z_2' = Z_1 + a^2 Z_2$$

Similarly, effective constant parameters of whole transformer in secondary side.

$$R_{e2} = R_2 + R_1' = R_2 + \frac{R_1}{a^2}$$

$$X_{e2} = X_2 + X_1' = X_2 + \frac{X_1}{a^2}$$

$$Z_{e2} = Z_2 + Z_1' = Z_2 + \frac{Z_1}{a^2}$$




**Equivalent circuits of a nonideal transformer.**

**Figure:** Exact **e**quivalent circuit diagram of the transformer referred to primary and secondary side.

# Voltage Regulation of A Transformer

- The voltage regulation is the percentage of voltage difference between no load and full load voltages of a transformer with respect to its no load voltage.

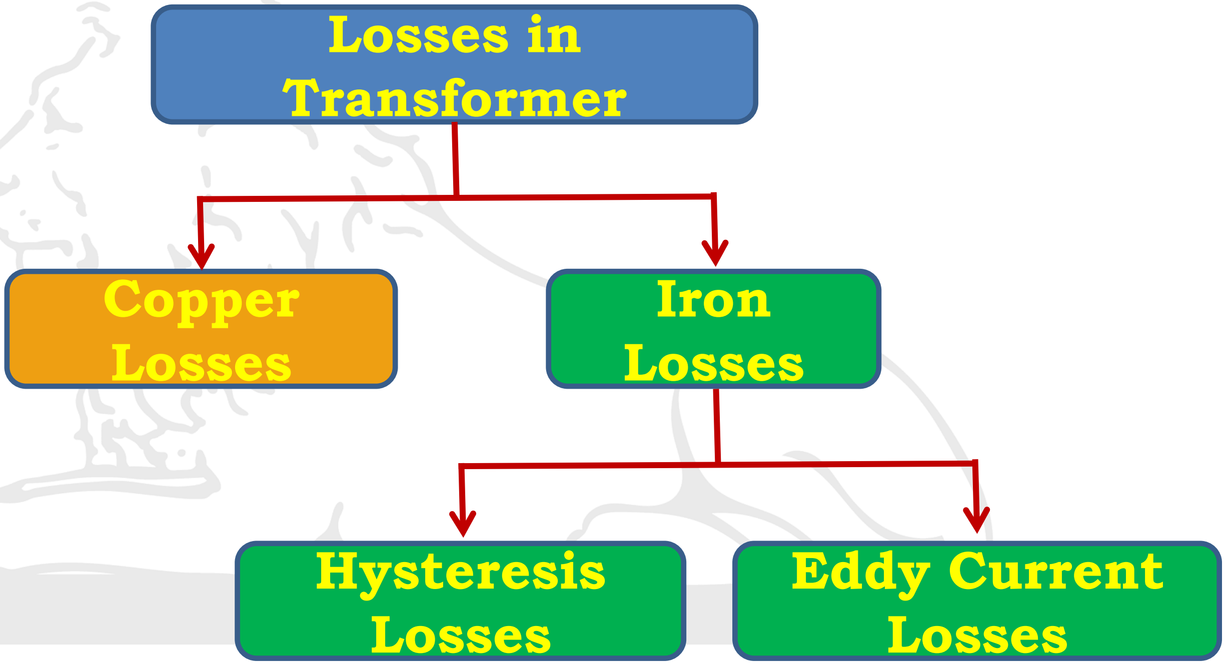
$$\text{Regulation} = \frac{V_{2NL} - V_{2FL}}{V_{2NL}} \times 100\%$$

## Problems

1. A 5 kVA, 200 V/400 V, single-phase transformer has a secondary terminal voltage of 387.6 volts when loaded. Determine the regulation of the transformer.
2. The open-circuit voltage of a transformer is 240 V. A tap-changing device is set to operate when the percentage regulation drops below 2.5%. Determine the load voltage at which the mechanism operates.

# Transformer Losses and Efficiency

- There are broadly two types of losses in transformers on load, these being copper losses and iron losses.



# Losses in Transformer

The transformer has no moving parts so that its efficiency is much higher than that of rotating machines. However, there various losses in a transformer that can be briefly explained as follows:

(a) core losses—eddy current and hysteresis losses

(b) copper losses—in the resistance of the windings

***(a) Core loss (iron loss)*:**

- When a magnetic material undergoes cyclic magnetization, two kinds of power losses occur in it—hysteresis and eddy-current losses—which together are known as core-loss.
- The core-loss is important in determining heating, temperature rise, rating and efficiency of transformers.
- The hysteresis and eddy-current losses resulting from alternations of magnetic flux in the core.
- The core-loss is constant for a transformer operated at constant voltage and frequency.

# Losses in Transformer

***Reasons for hysteresis loss:*** The core of the transformer is subjected to an alternating magnetizing force, and for each cycle of emf, a hysteresis loop is traced out. Power is dissipated in the form of heat known as hysteresis loss and given by

$$p_h = k_h f B_m^{1.6}$$

***Reasons for eddy current-loss:***

- When a magnetic core carries a time-varying flux, voltages are induced in all possible paths enclosing the flux. The result is the production of circulating currents in the core of the transformer.
- These currents are known as eddy-currents and have power loss ($\boldsymbol{i^2R}$) associated with them called eddy-current loss.
- This loss depends upon the resistivity of the material and lengths of the paths of circulating currents for a given cross-section

$$p_e = k_e f^2 B_m^2$$

And

core loss ($\boldsymbol{p_i}$) = hysteresis loss ($\boldsymbol{p_h}$) + eddy current loss ($\boldsymbol{p_e}$).

These losses are called ***constant losses.***

# Losses in Transformer

**(ii) *Copper loss:***

- This loss occurs in winding resistances when the transformer carries the load current.
- This loss varies as the square of the loading expressed as a ratio of the full-load. If $I_1$ and $I_2$ are the currents in the primary and secondary of the transformer, and $R_1$ and $R_2$ are the resistances of the primary and secondary windings, then copper loss is given as,

$$P_C = I_1^2 R_1 + I_2^2 R_2$$

Copper losses are known as ***variable losses***.

# Losses in Transformer

***Why iron (core) losses are known as constant losses***

- Both hysteresis and eddy current losses depend upon (i) maximum flux density Bm in the core and (ii) supply frequency f.
- Since transformers are connected to constant-frequency, constant voltage supply, both f and Bm are constant.
- Hence, core or iron losses are practically the same at all loads.
- The hysteresis loss can be minimized by using steel of high silicon content whereas eddy current loss can be reduced by using core of thin laminations.

# Transformer Losses and Efficiency

- Transformer efficiency

$$\eta = \frac{Output\ Power}{Input\ Power}$$

$$= \frac{Input\ Power - Losses}{Input\ Power}$$

$$= \frac{Output\ Power}{Output\ Power + Losses}$$

- Output power = $V_2 I_2 \cos\varphi_2$
- Total losses = Copper loss + Iron losses
- Input power = Output power + Losses

# Problems

1. A 200 kVA rated transformer has a full-load copper loss of 1.5 kW and an iron loss of 1 kW. Determine the transformer efficiency at full load and 0.85 power factor (Efficiency=98.55%)
2. Determine the efficiency of the transformer in Problem 1 at half full load and 0.85 power factor (Efficiency=98.41%)
3. A 400 kVA transformer has a primary winding resistance of 0.5Ω and a secondary winding resistance of 0.001Ω. The iron loss is 2.5 kW and the primary and secondary voltages are 5 kV and 320 V respectively. If the power factor of the load is 0.85, determine the efficiency of the transformer (a) on full load, and (b) on half load. (Efficiency=97.91%, 97.87%)

# Maximum efficiency

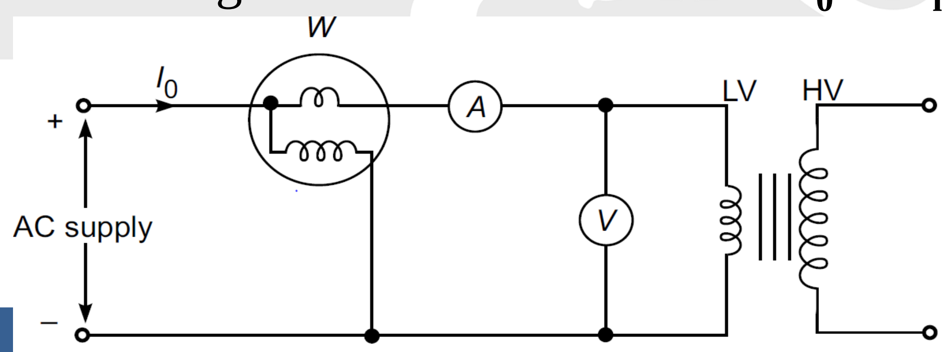
- The efficiency of a transformer is a maximum when the variable copper loss is equal to the constant iron losses.

## Problems

1. A 500 kVA transformer has a full load copper loss of 4 kW and an iron loss of 2.5 kW. Determine (a) the output kVA at which the efficiency of the transformer is a maximum, and (b) the maximum efficiency, assuming the power factor of the load is 0.75

# Open Circuit Test of Transformer

- This is also called as ***no-load test and performed at rated voltage of low voltage winding.***
- Open circuit and short circuit tests are useful for the determination of the circuit constants, efficiency and regulation.
- In both these tests voltage, current and power are measured and using them, the resistance and reactance of the input impedance can be found.
- This test is usually performed from the low voltage (LV) side, while the high voltage (HV) side is kept open circuited as shown in following figure.
- In this case, the no-load current $I_0$ is so small (it is usually 2-6% of the rated current) and $R_1$ and $X_1$ are also small. Therefore, $V_1$ can be regarded as = $E_1$ by neglecting the series impedance.
- This means that for all practical purposes the power input on no-load equals the core (iron) loss as we have neglected the resistances i.e. $\mathbf{P_0 = P_i}$ **(iron losses)**



# Open Circuit Test of Transformer

- This test is conducted to determine the iron losses (or core losses) and parameters $R_0$ and $X_0$ of the transformer.
- The wattmeter measure the power which is equal to the core (iron) loss as we have neglected the resistances means copper losses are zero.

$$P_i = V_1 I_0 cos\phi_0$$

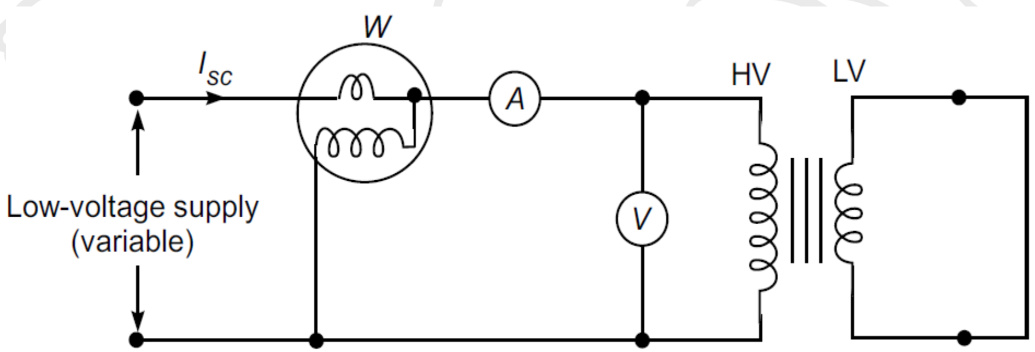
$$cos\phi_0 = \frac{P_i}{V_1 I_0}$$

$$I_w = I_0 cos\phi_0,\ I_\mu = I_0 sin\phi_0$$

$$R_0 = \frac{V_1}{I_w},\ X_0 = \frac{V_1}{I_\mu}$$

# Short Circuit Test of Transformer

- Generally, this test is conducted from the HV side of the transformer by keeping the LV side short circuited as shown in the following figure.
- Applied voltage $V_{SC}$ needed to circulate the full-load current in low winding (secondary winding) and this applied voltage is as low as 5-8% of the rated voltage.
- Since the applied voltage is low as 5-8% of the rated voltage, and current is flowing full rated current due to this core losses are negligible as compared to copper losses and wattmeter measure copper loss.
- This test is conducted to determine $R_{e_{hv}}$ (or $R_{e_{lv}}$), $X_{e_{hv}}$ (or $X_{e_{lv}}$ ) and full-load copper losses of the transformer.



# Short Circuit Test of Transformer

- While conducting the SC test, the supply voltage is gradually raised from zero till the transformer draws full-load current. The meter readings under these conditions are: voltage = $\mathbf{V_{SC}}$; current = $\mathbf{I_{SC}}$; power input = $\mathbf{P_{SC}}$

Since the transformer is excited at very low voltage, the iron-loss is negligible (shunt branch is left out), the power input corresponds only to the copper-loss, i.e.

$$\mathbf{P_0 = P_c} \textbf{ (copper losses)}$$

The equivalent resistance is given as,

$$R_{e_{hv}} = \frac{P_{sc}}{(I_{sc})^2}$$

From the equivalent circuit

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

The equivalent reactance is determined as,

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

# Rating of Transformers

- **Transformer is rated in KVA.**

**Why Transformer Rating in kVA**

- Losses are the determining factor in the rating of a machine.
- Copper loss in a transformer depends on current and iron loss depends on voltage.
- Therefore, the total loss in a transformer depends on the volt-ampere product only
- It does not depend on the phase angle between voltage and current i.e., it is independent of load power factor.
- For this reason, the rating of a transformer is in kVA and not kW.

# Summary of Transformer

- Transformer is used for ac signals only.
- A transformer can work step up or step down, depending upon the connection with supply.
- Transformer can not change frequency, i.e. frequency of primary winding and secondary winding is same.
- Induced voltage in transformer $E = 4.44\,\phi_m\, f N$
- Mmf of primary winding is same as the mmf secondary winding, i.e.

$$N_1 I_1 = N_2 I_2$$

- Apparent power (or in kVA) of primary winding is same as the secondary winding provided that losses are approximately negligible, i.e.

$$V_1 I_1 = V_2 I_2$$

- Turn ratio of transformer is defined as

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

- In OC test, we will get

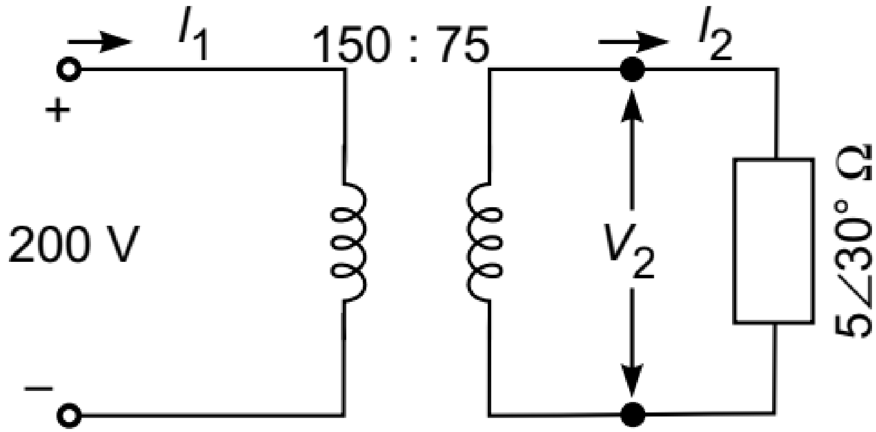
$$cos\phi_0 = \frac{P_i}{V_1 I_0},\ I_w = I_0 cos\phi_0,\ I_\mu = I_0 sin\phi_0, R_0 = \frac{V_1}{I_w},\ X_0 = \frac{V_1}{I_\mu}$$

- In SC test, we will get

$$R_{e_{hv}} = \frac{P_{sc}}{(I_{sc})^2},\ Z_{e_{hv}} = \frac{V_{sc}}{I_{sc}} = \sqrt{{R_{e_{hv}}}^2 + {X_{e_{hv}}}^2},\ X_{e_{hv}} = \sqrt{{Z_{e_{hv}}}^2 - {R_{e_{hv}}}^2}$$

# Numerical Examples

1. *The maximum flux density in the core of a 250/3000 V, 50Hz single phase transformer is $1.2\, Wb/m^2$. If the e.m.f. per turn is 8 volts, determine (a) primary and secondary turns (b) area of the core.*
2. *A 25-kVA transformer has 500 turns in primary and 50 turns in secondary winding. The primary winding is connected to 3000V, 50Hz supply. Find the full load primary and secondary currents, secondary emf and maximum flux in core.*
3. *Assume the transformer of following figure to be the ideal transformer. The secondary is connected to a load of 5<30° ohm. Calculate the primary and secondary side impedances, current and their pf, and the real powers. What is the secondary terminal voltage?*



# Numerical Examples

**Q.4.**

~~Example 32.36.~~ *Obtain the equivalent circuit of a 200/400-V, 50-Hz, 1-phase transformer from the following test data :*

*O.C test : 200 V, 0.7 A, 70 W – on L.V. side*

*S.C. test : 15 V, 10 A, 85 W – on H.V. side*

**Q.5.**

The results of open-circuit and short-circuit tests on a 25-kVA, 440-V/220-V, 60-Hz transformer are as follows:

**Open-circuit test.** Primary open-circuited, with instrumentation on the low-voltage side. Input voltage, 220 V; input current, 9.6 A; input power, 710 W.

**Short-circuit test.** Secondary short-circuited, with instrumentation on the high-voltage side. Input voltage, 42 V; input current, 57 A; input power, 1030 W.

Obtain the parameters of the exact equivalent circuit referred to the high-voltage side.

# Numerical Examples

Ans. 1

(a) N1=31.25(No. of turn never fraction)=32, N2=375.

(b) A=0.03$m^2$

(i) *primary and secondary turns* (ii) *area of the core.*

(Electrical Engg.-I, Nagpur Univ. 1991)

**Solution.** (i) $E_1 = N_1 \times$ e.m.f. induced/turn

$N_1 = 250/8 = 32$; $N_2 = 3000/8 = 375$

(ii) We may use $E_2 = -4.44 f N_2 B_m A$

$\therefore$ $3000 = 4.44 \times 50 \times 375 \times 1.2 \times A$; **A = 0.03m².**

Ans. 2

**Solution.** $K = N_2/N_1 = 50/500 = 1/10$

Now, full-load $I_1 = 25{,}000/3000 = 8.33$ **A.** F.L. $I_2 = I_1/K = 10 \times 8.33 = 83.3$ **A**

e.m.f. per turn on primary side $= 3000/500 = 6$ V

$\therefore$ secondary e.m.f. $= 6 \times 50 = 300$ **V** (or $E_2 = KE_1 = 3000 \times 1/10 = 300\ V$)

Also, $E_1 = 4.44 f N_1 \Phi_m$; $3000 = 4.44 \times 50 \times 500 \times \Phi_m$ $\therefore$ $\Phi_m = 27$ **mWb**

# Numerical Examples

**Ans. 3**

$$\bar{Z}_2 = 5 \angle 30° \ \Omega$$

$$a = N_1/N_2 = 150/75 = 2$$

$$\bar{Z}_1 = \bar{Z}_2' = (2)^2\, 5 \angle 30° = 20 \angle 30° \ \Omega$$

$$V_2 = 200/2 = 100 \text{ V};$$

(secondary terminal voltage)

$$\bar{I}_2 = 100 \angle 0°/5 \angle 30° = 20 \angle -30° \text{ A}$$

$$I_2 = 20 \text{ A}; \text{ pf} = \cos 30° = 0.866 \text{ lagging}$$

$$\bar{I}_1 = \bar{I}_2' = 20 \angle 30°/2 = 10 \angle -30° \text{ A}$$

$$P_2 \text{ (secondary power output)} = (20)^2 \times \text{Re } 5 \angle 30°$$

$$= 400 \times 4.33 = 1.732 \text{ kW}$$

$$P_1 \text{ (primary power input)} = P_2 \text{ (as the transformer is lossless)}$$

$$= 1.732 \text{ kW}$$

$$P_1 = V_1 I_1 \cos \theta_1 = 200 \times 10 \times 0.866$$

$$= 1.732 \text{ kW}$$

# Numerical Examples

**Ans. 4**

**Solution. From O.C. Test**

$$V_1 I_0 \cos\phi_0 = W_0$$

$$\therefore \quad 200 \times 0.7 \times \cos\phi_0 = 70$$

$$\cos\phi_0 = 0.5 \text{ and } \sin\phi_0 = 0.866$$

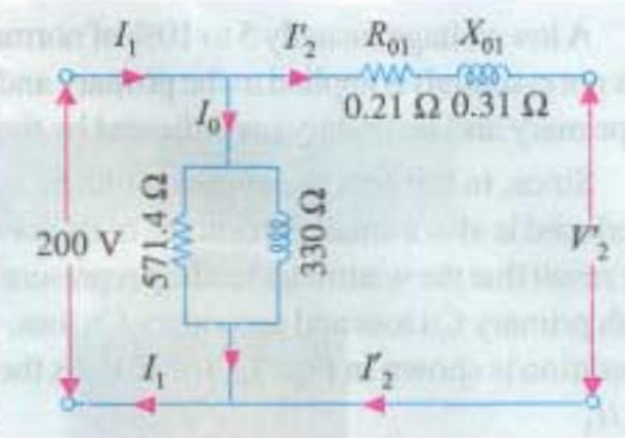
$$I_w = I_0 \cos\phi_0 = 0.7 \times 0.5 = 0.35 \text{ A}$$

$$I_\mu = I_0 \sin\phi_0 = 0.7 \times 0.866 = 0.606 \text{ A}$$

$$R_0 = V_1/I_w = 200/0.35 = 571.4\ \Omega$$

$$X_0 = V_1/I_\mu = 200/0.606 = 330\ \Omega$$

As shown in Fig. 32.48, these values refer to primary *i.e.* low-voltage side.




**From S.C. Test**

It may be noted that in this test, instruments have been placed in the secondary *i.e.* high-voltage winding whereas the low-voltage winding *i.e.* primary has been short-circuited.

Now, as shown in Art. 32.32

$$Z_{02} = V_{sc}/I_2 = 15/10 = 1.5\ \Omega\ ;\ K = 400/200 = 2$$

$$Z_{01} = Z_{02}/K^2 = 1.5/4 = 0.375\ \Omega$$

Also $$I_2^2 R_{02} = W;\ R_{02} = 85/100 = 0.85\ \Omega$$

$$R_{01} = R_{02}/K^2 = 0.85/4 = 0.21\ \Omega$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{0.375^2 - 0.21^2} = 0.31\ \Omega$$

$$\text{Output kVA} = 5/0.8\ ;\ \text{Output current } I_2 = 5000/0.8 \times 400 = 15.6 \text{ A}$$

This value of $I_2$ is approximate because $V_2$ (which is to be calculated as yet) has been taken equal to 400 V (which, in fact, is equal to $E_2$ or ${}_0V_2$).

Now, $$Z_{02} = 1.5\ \Omega,\ R_{02} = 0.85\ \Omega \quad \therefore \quad X_{02} = \sqrt{1.5^2 - 0.85^2} = 1.24\ \Omega$$

# Numerical Examples

**Ans. 5**

From the short-circuit test:

$$Z_{s1} = \frac{42}{57} = 0.737\ \Omega$$

$$R_{s1} = \frac{1030}{(57)^2} = 0.317\ \Omega$$

$$X_{s1} = \sqrt{(0.737)^2 - (0.317)^2} = 0.665\ \Omega$$

From the open-circuit test:

$$\theta_0 = \cos^{-1}\frac{710}{(9.6)(220)} = \cos^{-1} 0.336 = 70^\circ$$

$$I_w = I_0 \cos\theta_0 = 9.6 \times 0.336$$
$$= 3.2256$$

$$R_{0\,LV} = \frac{220}{3.2256} = 68.2044$$

$$I_\mu = I_0 \sin\theta_0 = 9.6 \times \sin 70^\circ$$
$$= 9.021$$

$$X_{0\,LV} = \frac{220}{9.021} = 24.3874$$

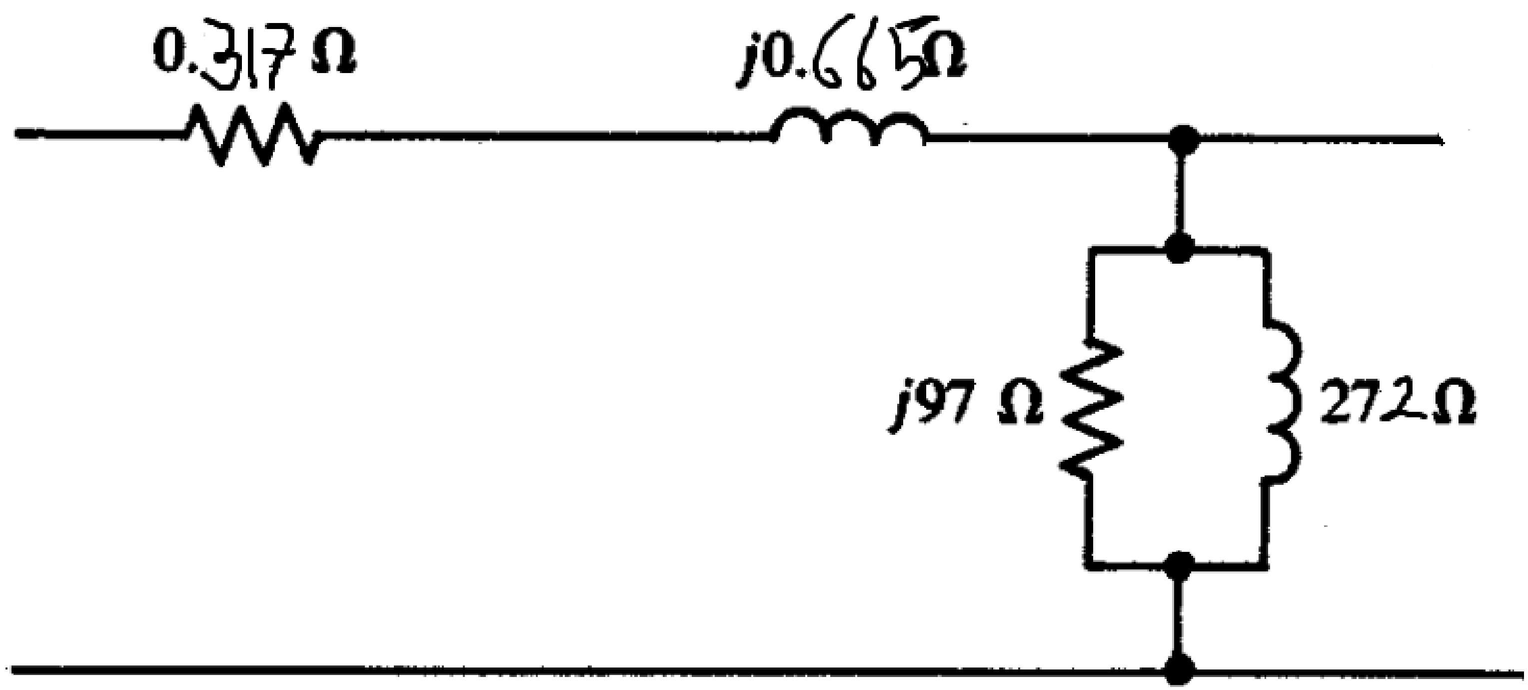
$R_0$ & $X_0$ in high voltage side

$$a = \frac{440}{220} = 2$$

# Numerical Examples

$$R_{o_{hv}} = a^2 R_{o_{lv}} = 2^2 \times 68.204 = 272$$

$$X_{o_{hv}} = a^2 X_{o_{lv}} = 2^2 \times 24.3874 = 97.5496$$




Exact equivalent circuit referred to the high-voltage side.

# Thanks…