3 UNIT

Transformers

PART-1

Magnetic Materials, B-H Characteristics, Ideal and Practical Transformer.

CONCEPT OUTLINE : PART-1

- Transformer is an AC machine that :

1. It transfers electrical energy from one electric circuit to another.
2. It does so without a change of frequency.
3. It does so by the principle of electromagnetic induction.
4. It has electric circuits that are linked by a common magnetic circuit.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.1. **Write short notes on the following :**

A. Diamagnetic
B. Paramagnetic
C. Ferromagnetic
D. Antiferromagnetic
E. Ferrimagnetic.

Answer

A. **Diamagnetic :** When a diamagnetic material is placed in a magnetic field, it becomes weakly magnetized in a direction opposite to the direction of external magnetic field. This property of material is known as diamagnetism.

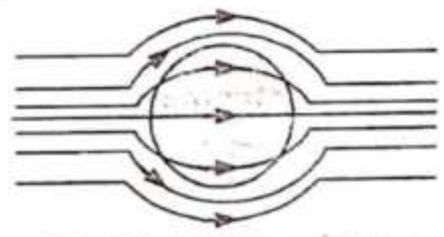

Fig. 3.1.1. Diamagnetic.

Examples : Bismuth, silver, copper and hydrogen.

B. **Paramagnetic :**

1. In paramagnetic materials the magnetic dipoles are already present. These materials are permanently magnetized but dipoles are randomly oriented and have a low net magnetism.

2. When these materials are placed in external magnetic field, the dipoles orient themselves in the direction of external magnetic field. This property is known as paramagnetism.

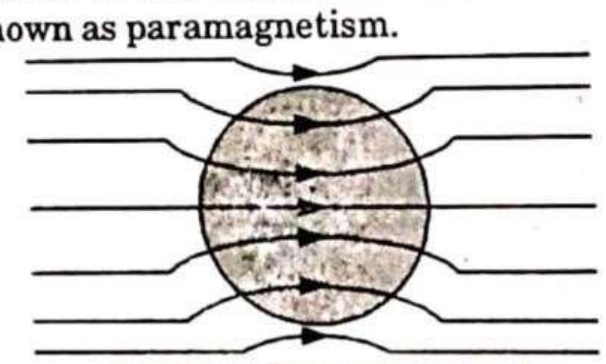

Fig. 3.1.2. Paramagnetic.

Examples : Aluminium, platinum and oxygen.

C. **Ferromagnetic :** When a ferromagnetic material is placed in external magnetic field, it strongly attracts the magnetic lines of force and the domains orient themselves in the direction of the field to increase the flux produced by the external field. This property is known as ferromagnetism.
Examples : Iron, cobalt, nickel.

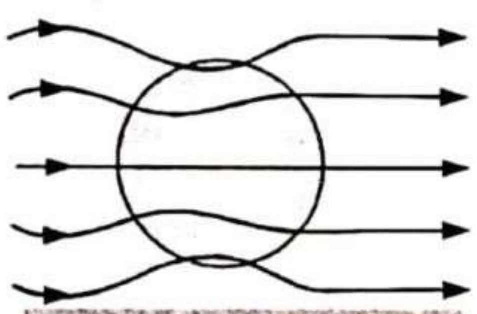

Fig. 3.1.3. Ferromagnetic.

D. **Antiferromagnetic :**
1. In antiferromagnetic material the atomic magnetic dipoles line up antiparallel to each other and cancel out exactly.
2. Therefore, these have no external magnetic field effects. This property is called antiferromagnetism.
Examples : Chromium, manganese, MnO, MnS and FeO.

E. **Ferrimagnetic :** In ferrimagnetic materials the atomic magnetic dipoles line up antiparallel to each other, but do not cancel out, because they have different magnetic dipole moments. The resultant magnetic moment may be quite large. This property is called ferrimagnetism.
Examples : MeO, Fe_2O_3.

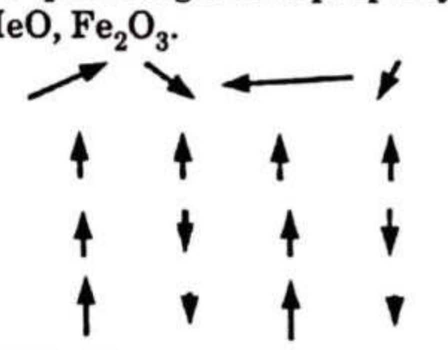

Fig. 3.1.4. Schematic illustration of a paramgnetic, ferromagnetic, antiferromagnetic and ferrimagnetic arrangement of spins.

Que 3.2. Discuss the *B-H* curve for a magnetic material and identify the retentivity and the coercive field on the curve.

Answer

1. The graph between flux density *B* and magnetizing force *H*, drawn for increasing and decreasing values of magnetizing force *H* is known as *B-H* curve.
2. When a ferromagnetic material is placed in a magnetization field, magnetic induction lags behind the magnetization field. This phenomenon is known as hysteresis.
3. The *B-H* curve drawn for one complete cycle of magnetization and demagnetization is known as hysteresis loop.
4. **Hysteresis curve :**
i. Plotting a graph between *B* and *H* for a ferromagnetic material is known as hysteresis curve or *B–H* curve as shown in Fig. 3.2.1.
ii. **Retentivity :** According to curve at point *c*, $H = 0$ but *B* is not zero and $B \to B_r$ is known as remanence or residual magnetism.

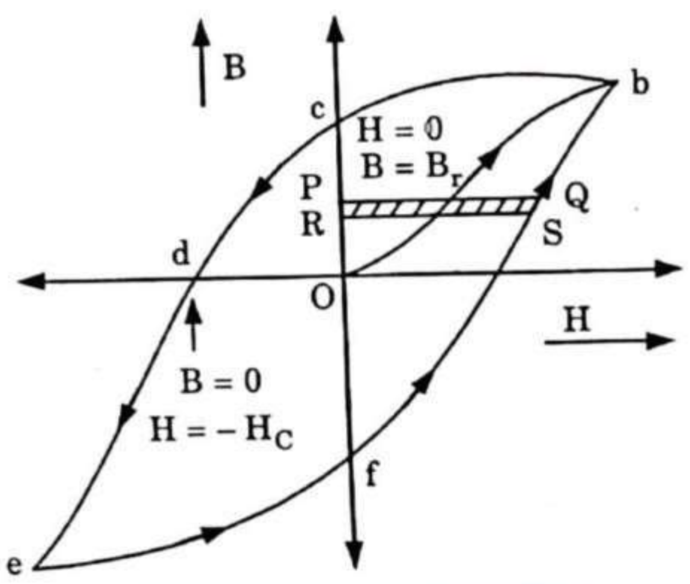

Fig. 3.2.1. Hysteresis loop.

iii. **Coercivity :** According to graph at the point *d*, $B = 0$ and $H \to H_C$ is known as coercivity.
iv. **Residual magnetism :** It is defined as the magnetic flux density which still persists in magnetic material even when the magnetising force is completely removed. In Fig. 3.2.1 on reducing the value of *H* from the saturation region to zero there remains a flux density B_r which is residual magnetism.
v. **Coercive force (field) :** It is defined as demagnetizing force which is necessary to neutralize completely the magnetism in an electromagnet when the value of magnetizing force becomes zero. In Fig. 3.2.1, H_C is required to reduce flux density to zero and is called coercive force.

Que 3.3. **What are soft magnetic materials ? Also, give its characteristics.**

Answer

A. Soft magnetic materials :

1. Soft magnetic materials are those which have thin and narrow *B-H* curves, *i.e.*, the area within the hysteresis loop is small.
2. Hence, soft magnetic materials are used in devices that are subjected to alternating magnetic fields and in which energy losses must be low.
3. A material possessing these properties may reach its saturation magnetization with a relatively low applied field and still has low hysteresis energy losses.

The *B-H* curve for soft magnetic materials is shown in Fig. 3.3.1.

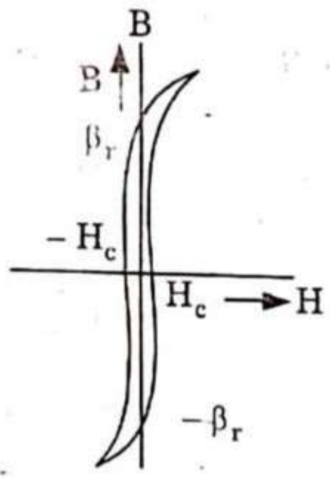

Fig. 3.3.1. Hysteresis curve for soft magnetic materials.

B. Soft magnetic materials have following characteristics :

1. Magnetically soft materials have high permeability, negligible coercive force and have low remanence.
2. Their *B-H* curve is steep and area under *B-H* curve is small.
3. They have high permeability.
4. They have low remanence.

C. Examples : Pure iron, cast iron, carbon steels, silicon steels, manganese and nickel steels, and ferrites.

Que 3.4. **Discuss about magnetically hard materials. Also, enumerate characteristics of hard materials.**

Answer

A. Hard magnetic materials :

1. Hard magnetic materials are those which retain a considerable amount of their magnetic energy after the magnetizing force has been removed *i.e.*, the materials, which are difficult to demagnetize.
2. These materials are also called permanent magnetic materials.

3. Magnetically hard materials are used for making permanent magnets.

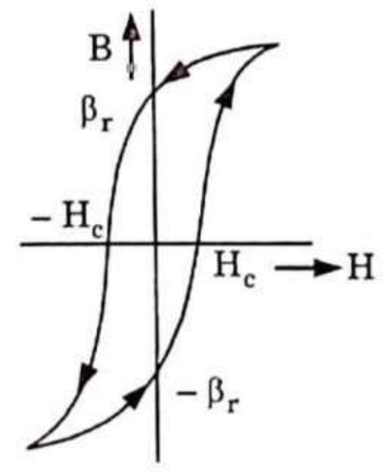

Fig. 3.4.1. Hysteresis curve for hard magnetic materials.

4. Steel containing carbon, tungsten, chromium or cobalt is used for making permanent magnets.

B. Magnetically hard materials have following characteristics :

1. They have large area under hysteresis loop.
2. High retentivity.
3. High coercivity.

C. Examples : Alnico, tungsten steel, cobalt steel and chromium steel.

PART-2

Equivalent Circuit, Lossess in Transformer, Regulation and Efficiency.

CONCEPT OUTLINE : PART-2

- **Step-up transformer :** A transformer in which output (secondary) voltage is greater than its input (primary) voltage.
- **Step-down transformer :** A transformer in which output (secondary) voltage is less than its input (primary) voltage.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.5. **What is transformer ? Explain the constructional features of different types of transformer.**

AKTU 2014-15(Sem-1), Marks 05

Answer

A. **Transformer :** A transformer is a static electrical device transfer electrical energy between two or more circuits through electromagnetic induction.

B. **Types :**

a. **Core-type transformer :**

1. In the core-type transformer, the magnetic circuit consists of two vertical legs or limbs with two horizontal sections, called yokes.
2. To keep the leakage flux to a minimum, half of each winding is placed on each leg of the core as shown in Fig. 3.5.1.
3. The low-voltage winding is placed next to the core and the high-voltage winding is placed around the low-voltage winding to reduce the insulating material required.
4. Thus, the two windings are arranged as concentric coils. Such a winding is, therefore, called concentric winding or cylindrical winding.

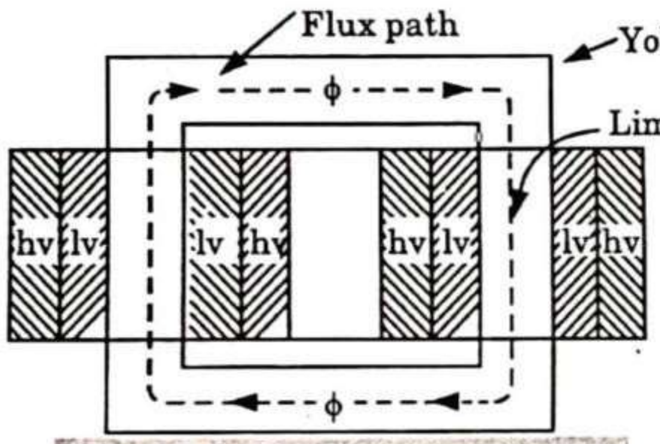

Fig. 3.5.1. Core-type transformer.

b. **Shell-type transformer :**

1. In the shell-type transformer (Fig. 3.5.2), both primary and secondary windings are wound on the central limb, and the two outer limbs complete the low-reluctance flux paths.

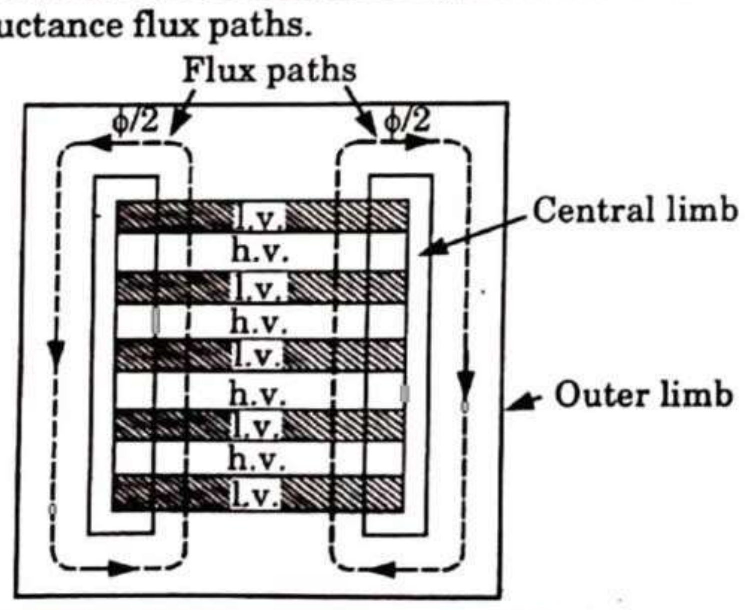

Fig. 3.5.2. Shell-type transformer.

2. Each winding is subdivided into sections. Low-voltage (lv) and high-voltage (hv) subsections are alternately put in the form of a sandwich. Such a winding is, therefore, called sandwich or disc winding.

Que 3.6. **Define ideal transformer and practical transformer. Compare ideal transformer and practical transformer.**

Answer

1. **Transformer :** A transformer is a static electrical device that transfers electrical energy between two or more circuits through electromagnetic induction.
2. **Ideal transformer :** The transformer which is free from all types of losses is known as ideal transformer. It has no core loss, no ohmic resistance, no leakage flux etc.
3. **Practical transformer :** In this types of transformer all types of losses are present.

S. No.	Ideal transformer	Practical transformer
1.	It has 100 % efficiency.	It has below 100 % efficiency.
2.	It has no losses.	It has losses.
3.	There is no ohmic resistance drop.	There is ohmic resistance drop.
4.	It has no leakage drop.	It has leakage drop.

Que 3.7. **Explain working of single phase transformer.**

Answer

1. Consider two coils 1 and 2 wound ~~on a simple magnetic~~ in circuit as shown in Fig. 3.7.1. These two coils are insulated from each other and there is no electrical connection between them.

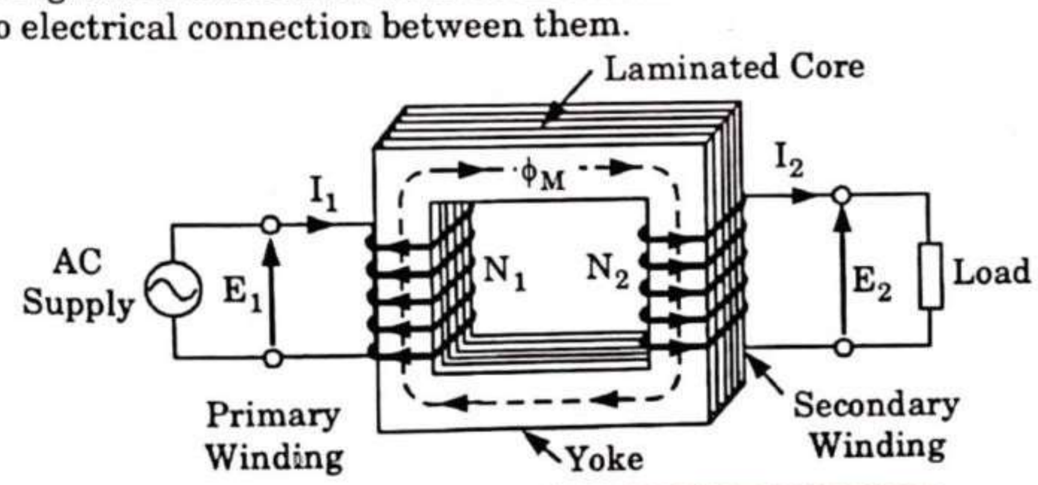

Fig. 3.7.1. Arrangements of a transformer.

2. Let N_1 and N_2 be the number of turns in coils 1 and 2 respectively.

3. When a source of alternating voltage V_1 is applied to coil 1, an alternating current I_0 flows in it. This alternating current produces an alternating flux ϕ_M in the magnetic circuit.
4. The mean path of this flux is shown in Fig. 3.7.1 by the dotted line.
5. This alternating flux links the turns N_1 of coil 1 and induces in them an alternating voltage E_1 by self-induction.
6. Thus, all the flux produced by coil 1 also links N_2 turns of coil 2 and induces in them a voltage E_2 by mutual induction.
7. If coil 2 is connected to a load then an alternating current will flow through it and energy will be delivered to the load.
8. Thus, electrical energy is transferred from coil 1 to coil 2 by a common magnetic circuit.
9. Coil 1, which receives energy from the source of AC supply, is called the primary coil or primary winding or simply the primary.
10. Coil 2, which is connected to load and delivers energy to the load, is called the secondary coil or secondary winding or simply the secondary.

Que 3.8. Explain the principle of operation of transformer. Derive emf equation of single-phase transformer.

AKTU 2015-16(Sem-1), Marks 10

OR

Derive the induced emf-flux relationship of the transformer.

AKTU 2014-15(Sem-1), Marks 05

OR

Discuss the principle of operation of a single phase transformer. Derive emf-equation for a single phase transformer.

AKTU 2017-18(Sem-2), Marks 07

Answer

A. **Principle of operation of 1-ϕ transformer :** Refer Q. 3.7, Page 3–8D, Unit-2.

B. **Derivation :**

1. Let the flux at any instant be given by

$$\phi = \phi_m \sin \omega t \quad ...(3.8.1)$$

2. The instantaneous emf induced in a coil of N turns linked by this flux is given by Faraday's law as

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

$$e = E_m \sin (\omega t - \pi/2) \quad ...(3.8.2)$$

where $E_m = N\omega\phi_m$ = Maximum value of e.

3. For a sine wave, the rms value of emf is given by

$$E_{rms} = E = E_m / \sqrt{2}$$

$$\therefore \quad E = \frac{N\omega\phi_m}{\sqrt{2}} = \frac{N(2\pi f)\phi_m}{\sqrt{2}}$$

$$E = 4.44\, \phi_m f N \quad ...(3.8.3)$$

eq. (3.8.3) is called the emf equation of a transformer.

4. The emf induced in each winding of the transformer can be calculated from its emf equation. Let subscripts 1 and 2 be used for primary and secondary quantities. The primary rms voltage is

$$E_1 = 4.44\, \phi_m f N_1 \quad ...(3.8.4)$$

5. The secondary rms voltage is

$$E_2 = 4.44\, \phi_m f N_2 \quad ...(3.8.5)$$

where ϕ_m is the maximum of flux in webers (Wb), f is the frequency in hertz (Hz) and E_1 and E_2 are in volts.

Que 3.9. A single phase, 50 Hz core type transformer has square cores of 20 cm side, permissible maximum flux density is 1 Wb/m². Calculate the number of turns per limb on high and low voltage sides for a 300/220 V ratio.

AKTU 2017-18(Sem-2), Marks 07

Answer

Given : Core length = 20 cm, f = 50 Hz, B_{max} = 1 Wb/m² per limb, N = 300/220

To Find : Number of turns per limb.

1. Core area = 20 × 20 = 400 cm² = 0.04 m²

Maximum value of permissible flux

$$\phi_{max} = B_{max} \times a = 1 \times 0.04 = 0.04 \text{ Wb}$$

2. Number of turns of low voltage winding

$$N_2 = \frac{E_2}{4.44 f \phi_{max}} = \frac{220}{4.44 \times 50 \times 0.04} = 24.77 \approx 26$$

(Number of turns is rounded off to the next higher even number in order that maximum flux density does not exceed the permissible maximum flux density).

3. Number of turns of high voltage winding,

$$N_1 = \frac{E_1}{E_2} \times N_2 = \frac{300}{220} \times 26 = 36$$

4. Number of HV turns on each limb = $\frac{36}{2} = 18$

5. Number of LV turns on each limb = $\frac{26}{2} = 13$

Que 3.10. **Explain why the hysteresis loss and eddy current loss occur in a transformer ? Explain how these losses can be reduced in a transformer ?**

AKTU 2016-17(Sem-1), Marks 3.5

OR

Explain various types of losses occur in transformers.

Answer

A. **Iron or core losses :** Iron loss is caused by the alternating flux in the core and consists of hysteresis and eddy current losses :

a. **Hysteresis loss :**

1. The core of a transformer is subjected to an alternating magnetizing force and for each cycle of emf a hysteresis loop is traced out.
2. The hysteresis loss per second,

$$P_h = \eta'(B_{max})^x fv \text{ joules per second or watts} \quad ...(3.10.1)$$

where, f = Supply frequency in Hz

v = Volume of core in cubic metres

η' = Hysteresis coefficient

B_{max} = Peak value of flux density in the core

x = Between 1.5 and 2.5 depending upon the material and is often taken as 1.6.

b. **Eddy current loss :**

1. If the magnetic circuit is made up of iron and if the flux in the circuit is variable, currents will be induced by induction in the iron circuit itself. All such currents are known as eddy currents.
2. Eddy currents result in a loss of power, with consequent heating of the material.
3. The eddy current loss,

$$P_e = K_e(B_{max})^2 f^2 t^2\, v \text{ watts or joules per second} \quad ...(3.10.2)$$

4. The hysteresis and eddy current losses depend upon the maximum flux density in the core and supply frequency.
5. These losses are determined from the open-circuit test.

Minimization : These losses are minimized by using steel of high silicon content for the core and by using very thin laminations (0.3 mm to 0.5 mm) insulated from each other either by insulating varnish or by layer of papers.

B. **Copper or Ohmic losses :**

1. These losses occur due to ohmic resistance of the transformer windings.
2. If I_1 and I_2 are the primary and secondary currents respectively and R_1 and R_2 are the respective resistances of primary and secondary windings then copper losses occurring in primary and secondary windings will be $I_1^2R_1$ and $I_2^2R_2$ respectively.
3. So total copper losses will be $(I_1^2R_1 + I_2^2R_2)$.
4. These losses vary as the square of the load current or kVA.
5. Copper losses are determined on the basis of constant equivalent resistance R_{eq} determined from the short-circuit test.

Minimization :

1. The windings of the transformer are made thick so that the resistances are minimized.
2. **Vacuum Pressure Impregnation (VPI) :** In this technique the transformer is kept in vacuum then high pressure varnish is passed so that the smallest of the air gaps are also filled, hence reducing the copper losses.

Que 3.11. **Derive and explain the equivalent circuit of a transformer.**

AKTU 2014-15(Sem-2), Marks 05

Answer

1. Transformer has 3 main parts :
   i. Primary winding
   ii. Core
   iii. Secondary winding.
2. Primary winding is shown by series combination of resistance R_1 and reactance X_{L1}, whereas secondary winding is shown by series combination of resistance R_2 and reactance X_{L2}.
3. The core of transformer is assumed to be parallel combination of resistance R_0 and reactance X_0. R_0 represents the core loss and hence known as core loss resistance, whereas X_0 represents magnetising reactance of the core.

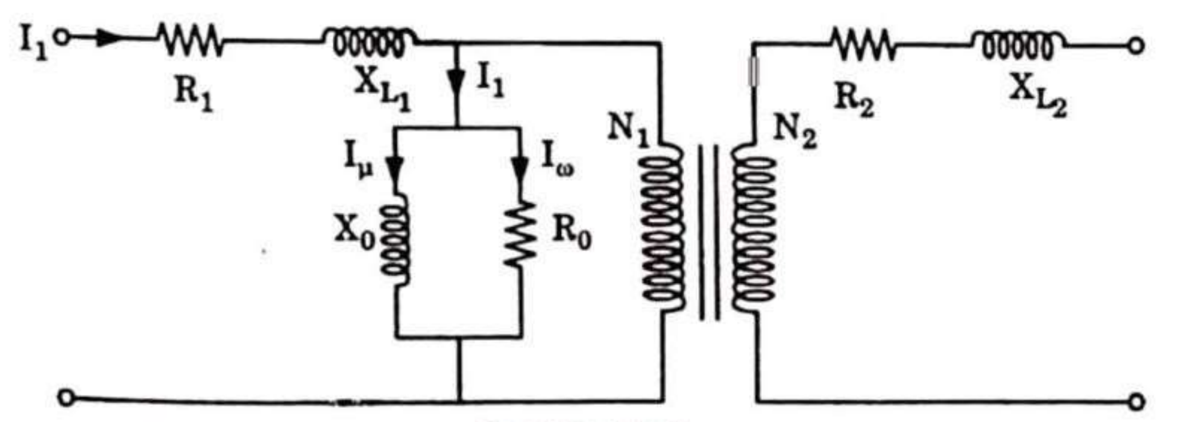

Fig. 3.11.1.

4. N_1 and N_2 show number of turns. The voltage levels of primary and secondary are different.
5. To bring all the components of equivalent circuit to one voltage level, either primary side components are to be shifted on secondary or secondary side components to be shifted on primary.

i. **Equivalent circuit as referred to primary or secondary components shifted to primary :**

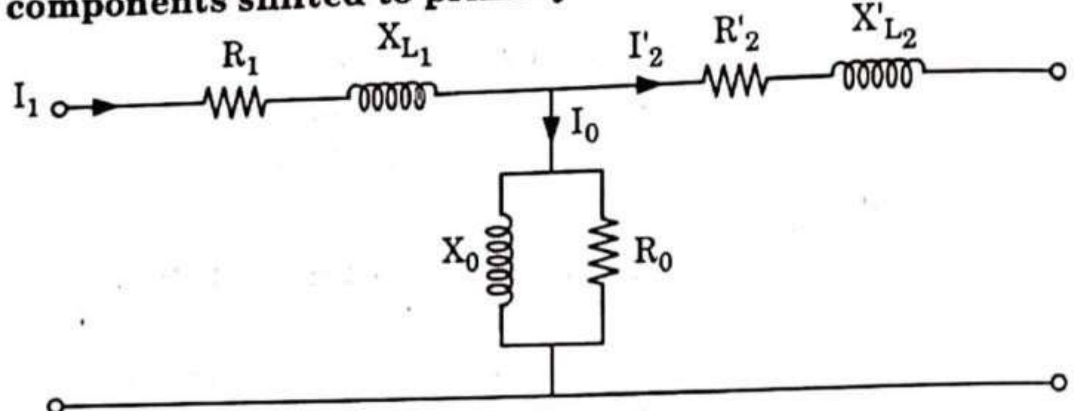

Fig. 3.11.2.

1. R_2' = Secondary resistance transferred to primary.

$$R_2' = \frac{R_2}{K^2}$$

X'_{L_2} = Secondary leakage reactance as transferred to primary.

$$X'_{L_2} = \frac{X_{L_2}}{K^2}$$

where $$K = \frac{N_2}{N_1} = \frac{V_2}{V_1}$$

2. As compared to primary component of secondary current I_2', I_0 is much less, $I_0 << I_2'$.
3. So, Neglecting I_0, approximate equivalent circuit as referred to primary is given by

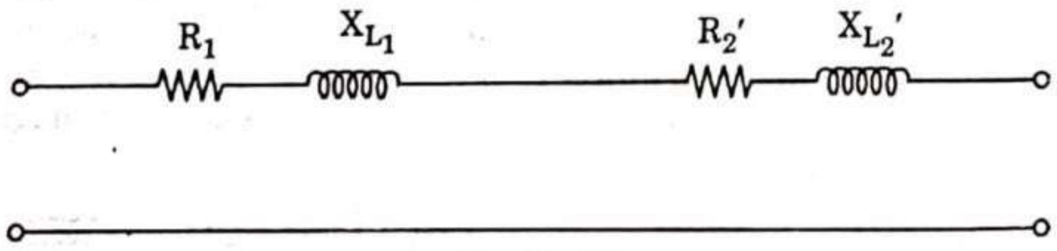

Fig. 3.11.3.

4. It can be simplified further as,

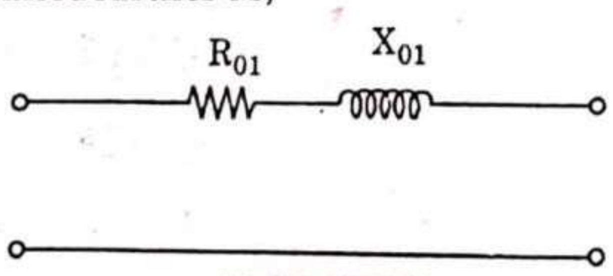

Fig. 3.11.4.

$\therefore$ where $R_{01} = R_1 + R_2'$

i.e., $R_{01} = R_1 + \dfrac{R_2}{K^2}$ known as equivalent resistance of transformer as referred to primary.

and $X_{01} = X_{L1} + X_{L2}' = X_{L1} + \dfrac{X_{L_2}}{K^2}$, known as equivalent reactance as referred to primary.

ii. **Equivalent circuit as referred to secondary :**

1. It can be obtained by transferring R_1, X_1, R_0 and X_0 to secondary side.

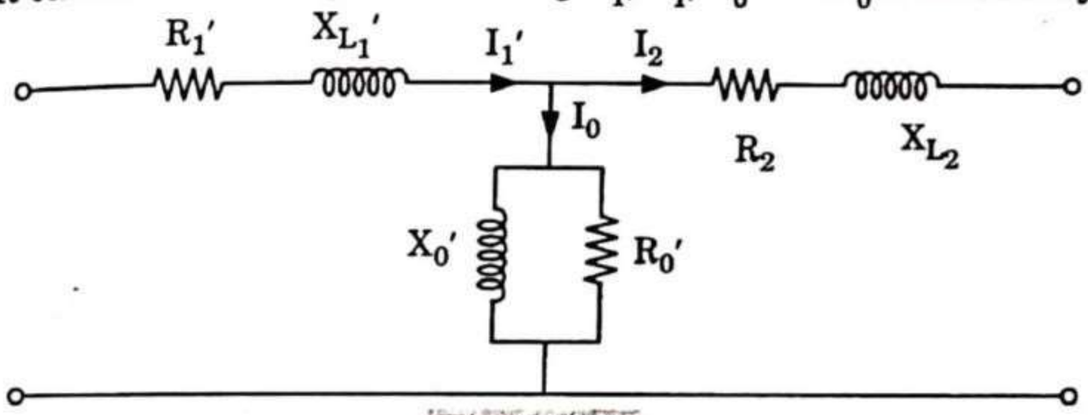

Fig. 3.11.5.

2. Since $I_0' << I_2$, I_0' *i.e.* shunt branch parameters R_0 and X_0 can be skipped.

$\therefore$ Approximate equivalent circuit as referred to secondary is

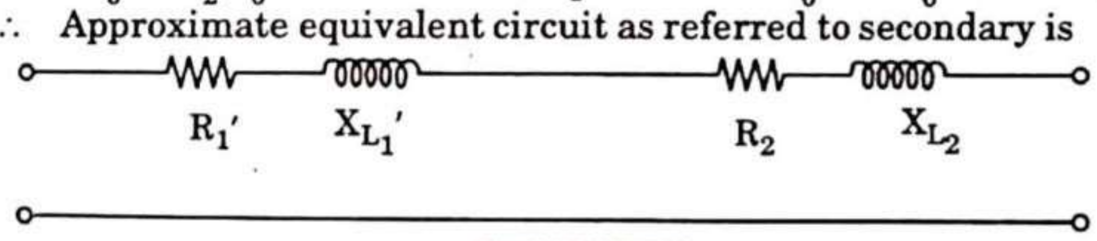

Fig. 3.11.6.

where $R_1' = K^2R_1$ – Primary resistance as referred to secondary.
and $X'_{L1} = K^2X_{L1}$ – Primary reactance as referred to secondary.

3. It can be further simplified as,

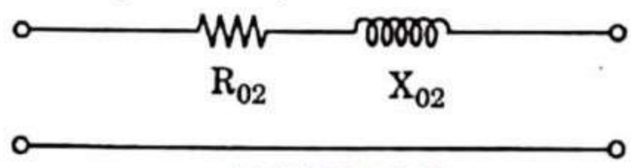

Fig. 3.11.7.

$$R_{02} = R_1' + R_2 = R_2 + K^2R_1$$
$$X_{02} = X_{L1}' + X_{L2} = X_{L2} + K^2X_{L1}$$

where R_{02} = Equivalent resistance of transformer as referred to secondary.

and X_{02} = Equivalent reactance of transformer as referred to secondary.

Que 3.12. ~~Define~~ efficiency of transformer. Find condition for maximum efficiency of transformer.

AKTU 2014-15(Sem-2), Marks 05

OR

What do you understand by the efficiency of a transformer ? Deduce the condition for maximum efficiency.

AKTU 2016-17(Sem-1), Marks 3.5

OR

Explain working of a single phase transformer and also derive the condition for maximum efficiency in the transformer.

AKTU 2017-18(Sem-1), Marks 3.5

Answer

A. **Working of transformer :** Refer Q. 3.7, Page 3–8D, Unit-3.

B. **Transformer efficiency :**

1. The ratio of the output power to input power in a transformer is known as transformer efficiency (η).

$$\eta = \frac{\text{Output power}}{\text{Input power}}$$

$$= \frac{\text{Output power}}{\text{Output power + Copper loss + Iron loss}} \text{ pu}$$

2. Thus, the per unit efficiency at load current I_2 and power factor $\cos\phi_2$ is

$$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + I_2^2 R_{e_2} + P_i} \text{ pu}$$

where, η = Efficiency
V_2 = Load voltage
I_2 = Load current
R_{e2} = Equivalent resistance
$\cos\phi_2$ = Power factor
P_i = Iron loss.

C. **Condition for maximum efficiency :**

1. $$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + I_2^2 R_{e_2} + P_i}$$

$$= \frac{V_2 \cos\phi_2}{V_2 \cos\phi_2 + I_2 R_{e_2} + (P_i / I_2)}$$

2. At maximum efficiency

$$\frac{d\eta}{dI_2} = 0 \text{ and } \frac{d^2\eta}{dI_2^2} < 0$$

3. Since V_2 and $\cos\phi_2$ are constants for a given load, the efficiency will be maximum when the denominator $D_r\left(= V_2\cos\phi_2 + I_2 R_{e_2} + \frac{P_i}{I_2}\right)$ is minimum.

4. For a minimum value of the denominator D_r

$$\frac{dD_r}{dI_2} = 0 \text{ and } \frac{d^2D_r}{dI_2^2} > 0$$

$$\frac{dD_r}{dI_2} = \frac{d}{dI_2}\left(V_2\cos\phi_2 + I_2 R_{e_2} + \frac{P_i}{I_2}\right) = 0 + R_{e_2} - \frac{P_i}{I_2^2}$$

5. For a minimum D_r,

$$R_{e_2} - \frac{P_i}{I_2^2} = 0$$

$$I_2^2 R_{e_2} = P_i \qquad \text{...(4.12.1)}$$

6. Also, $$\frac{d^2D_r}{dI_2^2} = \frac{d}{dI_2}\left(R_{e_2} - \frac{P_i}{I_2^2}\right) = 0 + \frac{2P_i}{I_2^3} > 0$$

7. Since $\frac{d^2D_r}{dI_2^2}$ is positive, the expression given by eq. (4.12.1) is a condition for the minimum value of D_r, and therefore the condition for maximum value of efficiency.

8. The efficiency of a transformer for a given power factor is a maximum when the variable copper loss is equal to the constant iron (core) loss.

Que 3.13. **List the various losses occurring in transformer and the condition for maximum efficiency. In a 25 kVA, 2000/200 V transformer the iron and copper losses are 200 W and 400 W respectively. Calculate the efficiency at half load and 0.8 power factor lagging. Determine also the maximum efficiency and the corresponding load.**

AKTU 2015-16(Sem-1), Marks 10

OR

In a 25 kVA, 2000 V/200 V transformer the iron and copper losses are 200 W and 400 W respectively. Calculate the efficiency of half load and 0.8 pf lagging. Also determine the maximum efficiency and corresponding load.

AKTU 2016-17(Sem-2), Marks 07

Answer

A. **Losses in transformer :** Refer Q. 3.10, Page 3–11D, Unit-3.

B. **Condition for maximum efficiency :** Refer Q. 3.12, Page 3–14D, Unit-3.

C. **Numerical :**

Given : Volt-ampere rating = 25 kVA, P_i = 200 W, P_{Cu} = 400 W, pf = $\cos\phi$ = 0.8

To Find : η_{max}, Load for maximum efficiency and Efficiency at half load.

1. **Efficiency at half load :**

i.e., $x = 0.5$

$$\eta_{hl} = \frac{x \times \text{kVA} \times 10^3 \times \cos\phi}{x \times \text{kVA} \times 10^3 \times \cos\phi + P_i + x^2 P_{Cu}}$$

$$= \frac{0.5 \times 25 \times 10^3 \times 0.8}{0.5 \times 25 \times 10^3 \times 0.8 + 200 + 0.5^2 \times 400}$$

$= 0.9708$ or $97.08\ \%$

2. **Load for maximum efficiency :**
Let x = Percentage of load at which maximum efficiency occurs

$$x = \sqrt{\frac{P_i}{P_{Cu}}} = \sqrt{\frac{200}{400}} = 0.707$$

$\therefore$ Load for maximum η = Full load $\times x = 25 \times 0.707 = 17.68$ kVA

3. **Maximum efficiency**

$$\eta_{max} = \frac{x \times \text{kVA} \times 10^3 \times \cos\phi}{x \times \text{kVA} \times 10^3 \times \cos\phi + P_i + x^2 P_{Cu}}$$

$$= \frac{0.707 \times 25 \times 10^3 \times 0.8}{0.707 \times 25 \times 10^3 \times 0.8 + 200 + 0.707^2 \times 400}$$

$= 0.9725$

$\%\ \eta_{max} = 97.25\ \%$

Que 3.14. **The efficiency of a 400 kVA, single-phase transformer is 98.77 % at full load 0.8 pf and 99.13 % at half load unity pf. Find Iron and Cu losses at half load.** **AKTU 2013-14(Sem-1), Marks 05**

Answer

Given : Volt-ampere rating = 400 kVA, η_{fl} = 98.77 %, pf = 0.8 and η_{hl} = 99.13 %, pf = 1
To Find : Copper loss, P_{Cu}; Iron loss, P_i.

A. At full-load and 0.8 power factor :
1. Output power, $P = 400 \times 0.8 = 320$ kW
2. Transformer efficiency, η = 98.77 % or 0.9877
3. Transformer input power $= \frac{P}{\eta} = \frac{320}{0.9877} = 323.985$ kW
4. Transformer losses,
$(P_i + P_{Cu})$ = Input – Output
$= 323.985 - 320 = 3.985$ kW ...(3.14.1)

B. At half-load and unity power factor :
1. Output power, $P' = \frac{1}{2} \times 400 \times 1 = 200$ kW
2. Transformer efficiency, η' = 99.13 % or 0.9913
3. Transformer input power $= \frac{P}{\eta} = \frac{200}{0.9913} = 201.755$ kW

4. Total losses $= P_i + \left(\frac{1}{2}\right)^2 P_{Cu}$ = Input – Output = 201.755 – 200 = 1.755 kW
or $P_i + 1/4\ P_{Cu} = 1.755$ kW ...(3.14.2)

C. Solving eq. (3.14.1) and (3.14.2), we have
i. Iron loss at full load = Iron loss at half load = P_i = 1.0117 kW
ii. Copper loss at full-load, P_c = 2.9733 kW

Then, Copper loss at half-load $= \left(\frac{1}{2}\right)^2 \times 2.9733 = 0.743325$ kW

Que 3.15. **A single phase 250 kVA transformer has an efficiency of 96 % on full load at 0.8 power factor and 97 % efficiency at half full load unit power factor. Calculate on half load :**
i. Iron losses
ii. Full load copper losses. **AKTU 2013-14(Sem-2), Marks 10**

Answer

The procedure is same as Q. 3.14, Page 3–17D, Unit-3.
(**Ans.** $P_{i\,hl}$ = 2.33 kW; $P_{Cu\,hl}$ = 1.49 kW; $P_{Cu\,fl}$ = 5.36 kW)

Que 3.16. **Derive the emf equation of a single-phase transformer. A single phase 100 kVA, 6.6 kV/230 V, 50 Hz transformer has 90 % efficiency at 0.8 lagging power factor both at full load and also at half load. Determine iron and copper loss at full load for transformer.** **AKTU 2014-15(Sem-2), Marks 10**

Answer

A. EMF equation : Refer Q. 3.8, Page 3–9D, Unit-3.
B. Numerical :
The procedure is same as Q. 3.14, Page 3–17D, Unit-3.
(**Ans.** $P_{c\,fl}$ = 5925.98 W; P_i = 2962.91 W)

Que 3.17. **A 25 kVA, 2000/200 V transformer has full-load copper and iron losses are 1.8 kW and 1.5 kW respectively.**
Find :
i. The efficiency at half the rated kVA and at unity power factor.
ii. The efficiency at full-load and at 0.8 power factor lagging.
iii. kVA load for maximum efficiency and value of maximum efficiency. **AKTU 2017-18(Sem-1), Marks 07**

Answer

Given : Volt-ampere rating = 25 kVA, N = 2000/200 V, P_i = 1.5 kW, P_{Cu} = 1.8 kW

To Find :
i. η at $x = 1/2$ and $\cos\phi = 1$
ii. η at $x = 1$ and $\cos\phi = 0.8$
iii. kVA_{max} and η_{max}.

i. **At half-load,**

i.e., $x = 1/2$ and $\cos\phi = 1$

Efficiency,
$$\eta = \frac{x \times kVA \times \cos\phi}{x \times kVA \times \cos\phi + P_i + x^2 P_{Cu}}$$
$$= \frac{\frac{1}{2} \times 25 \times 1}{\frac{1}{2} \times 25 \times 1 + 1.5 + \left(\frac{1}{2}\right)^2 \times 1.8}$$
$$= \frac{12.5}{12.5 + 1.5 + 0.45} = 0.865 \text{ (or } 86.5\text{ \%)}$$

ii. **At full-load,**

i.e, $x = 1$ and $\cos\phi = 0.8$

Efficiency,
$$\eta_{fl} = \frac{x \times kVA \times \cos\phi}{x \times kVA \times \cos\phi + P_i + x^2 P_{Cu}}$$
$$= \frac{1 \times 25 \times 0.8}{(1 \times 25 \times 0.8) + 1.5 + (1^2 \times 1.8)}$$
$$= \frac{20}{20 + 1.5 + 1.8} = 0.8584 \text{ (or } 85.84\text{ \%)}$$

iii. **kVA load for maximum efficiency**

$$kVA_{max} = \text{Rated kVA} \times \sqrt{\frac{P_i}{P_c}} = 25 \times \sqrt{\frac{1.5}{1.8}} = 22.82 \text{ kVA}$$

Losses at maximum efficiency,
$$P_i = x^2 P_{Cu} = 1.5 \text{ kW}$$

Maximum efficiency,
$$\eta_{max} = \frac{kVA_{max} \cos\phi}{kVA_{max} \cos\phi + P_i + P_i} = \frac{22.82 \times 1}{22.82 + 1.5 + 1.5}$$
$$= 0.8838 \text{ (or } 88.38\text{ \%)}$$

Que 3.18. **A 50 kVA transformer has a core loss of 400 W and a full load copper loss of 800 W. The power factor of the load is 0.9 lagging, calculate**

i. **Full load efficiency**
ii. **The maximum efficiency and the load at which maximum efficiency occurs.** **AKTU 2015-16(Sem-2), Marks 10**

Answer

The procedure is same as Q. 3.17, Page 3–18D, Unit-3.

(Ans. i. η = 97 %, **ii.** η_{max} = 97.55 % and kVA = 35.35 kVA)

PART-3

Auto-Transformer and Three-Phase Transformer Connections.

CONCEPT OUTLINE : PART-3

- **Single-phase auto-transformer :** It is a single-winding transformer in which a part of the winding is common to both high-voltage and low-voltage sides.
- A 3ϕ system is used to generate and transmit large amount of power.
- 3ϕ transformers are required to step up or step down voltages in various stages of a power system network.

Questions-Answers

M.M **Long Answer Type and Medium Answer Type Questions**

Que 3.19. **Explain single-phase auto-transformer and give its two applications.** **AKTU 2015-16(Sem-2), Marks 7.5**

Answer

A. **1ϕ auto-transformer :**

1. A 1ϕ auto-transformer is a one winding transformer in which a part of the winding is common to both high-voltage and low-voltage sides.
2. A two-winding transformer when electrically connected is known as auto transformer.
3. Let the two-winding transformer connected as an auto-transformer be regarded as ideal. With this assumption all voltages will be in phase and so will be all currents.
4. The two winding voltage ratio is

$$a = \frac{V_1 - V_2}{V_2} = \frac{N_1}{N_2} \quad \text{...(3.19.1)}$$

5. The auto transformer voltage ratio is

$$a' = \frac{V_1}{V_2} = \frac{(V_1 - V_2) + V_2}{V_2}$$

$$a' = 1 + a \qquad ...(3.19.2)$$

6. Now $(VA)_{TW} = (V_1 - V_2) I_1 = (I_2 - I_1) V_2$ ...(3.19.3)

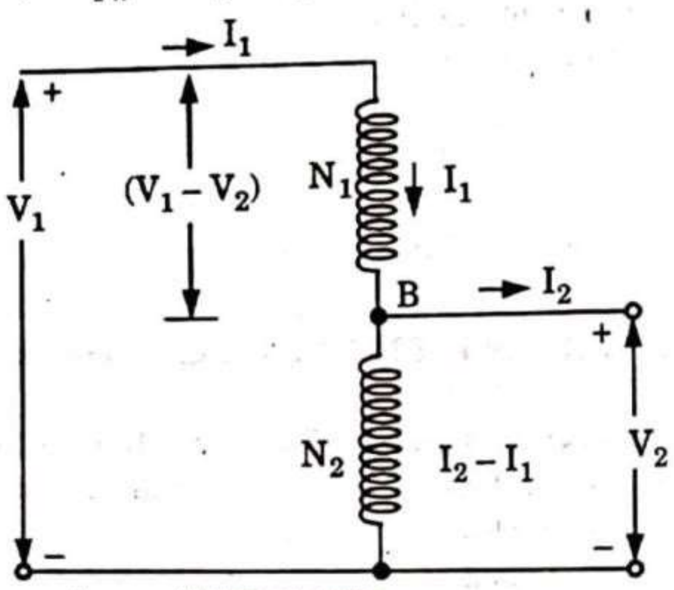

Fig. 3.19.1.

$$(VA)_{Auto} = V_1 I_1 = V_2 I_2$$

7. But $\dfrac{I_2 - I_1}{I_1} = \dfrac{N_1}{N_2} = a$

$$\frac{I_1}{I_2} = \frac{1}{1+a} \qquad ...(3.19.4)$$

8. Substituting eq. (3.19.4) in eq. (3.19.3)

$$(VA)_{TW} = \left(1 - \frac{1}{1+a}\right) V_2 I_2 = \left(1 - \frac{1}{a'}\right) (VA)_{Auto}$$

$$(VA)_{Auto} = \left(\frac{1}{1 - 1/a'}\right) (VA)_{TW} \qquad ...(3.19.5)$$

$$(VA)_{Auto} > (VA)_{TW} \qquad ...(3.19.6)$$

9. It is easily seen from eq. (3.19.5) that the nearer a' is to unity, the larger is $(VA)_{Auto}$ compared to $(VA)_{TW}$.
10. An auto transformer is applied for voltage ratios close to unity.

B. Applications :

1. It is used as balance coil to give neutral in a 3-wire AC distribution system.
2. It is used as boosters to raise the voltage in AC feeders.

Que 3.20. Draw delta-delta connection for 0° and 180° phase shift.

Answer

A. Delta-Delta (Δ-Δ) connection for 0° phase shift :

1. Fig. 3.20.1(*a*) shows the Δ – Δ connection of three identical single-phase transformers or three identical windings on each of the primary and secondary sides of the 3ϕ transformer.
2. Fig. 3.20.1(*b*) shows the phasor diagrams for lagging power factor cos ϕ.
3. The secondary line-to-line voltage V_{ab}, V_{bc} and V_{ca} are in phase with primary line-to-line voltage V_{AB}, V_{BC} and V_{CA} with voltage ratios equal to the turns ratio :

$$\frac{V_{AB}}{V_{ab}} = \frac{V_{BC}}{V_{bc}} = \frac{V_{CA}}{V_{ca}} = a$$

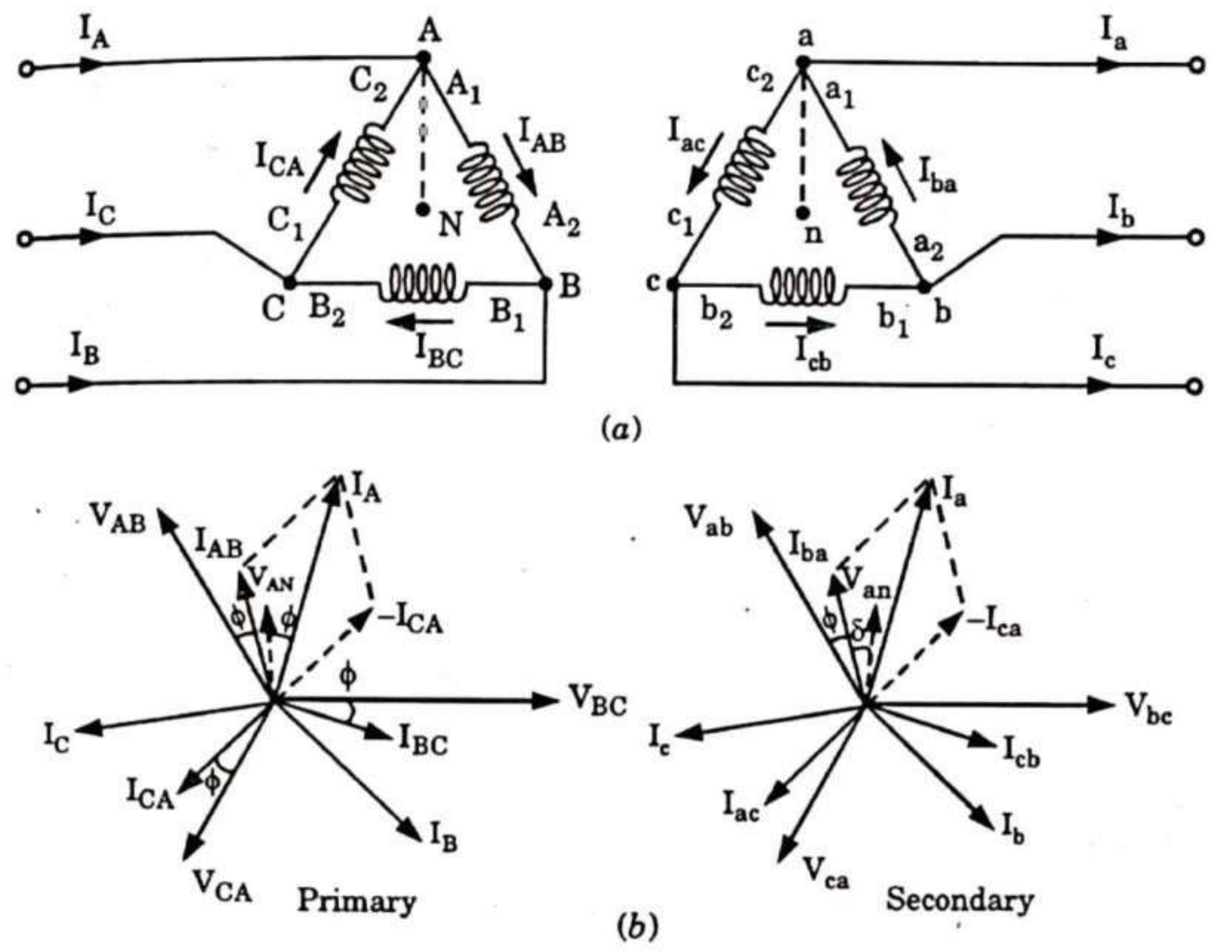

Fig. 3.20.1. Delta-Delta connection of transformer (0° phase shift).

4. The current ratios when the magnetizing current is neglected are

$$\frac{I_{AB}}{I_{ab}} = \frac{I_{BC}}{I_{bc}} = \frac{I_{CA}}{I_{ca}} = \frac{I_A}{I_a} = \frac{I_B}{I_b} = \frac{I_C}{I_c} = \frac{1}{a}$$

5. It is to be noted that in Fig. 3.20.1 each winding is drawn along the line of the phasor of its induced voltage.
6. The primary and secondary line voltages are in phase. This connection is called 0° – connection.

B. Delta-Delta connection (Δ – Δ) for 180° phase shift :

1. The connections of the phase windings are reversed on either side to obtain the phase difference of 180° between the primary and secondary systems. Such a connection is known as 180° – connection.
2. In Fig. 3.20.2 delta-delta connection with 180° phase shift is shown.

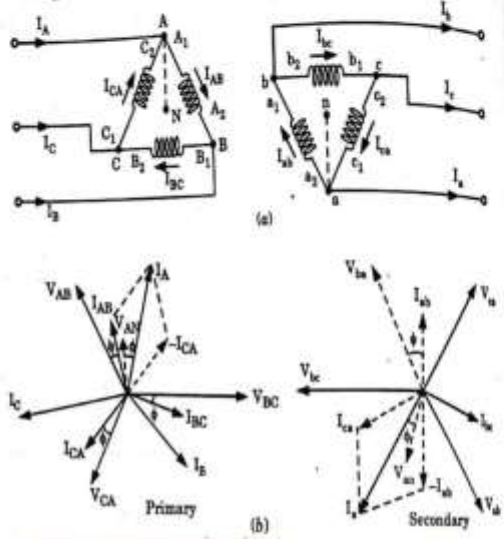

Fig. 3.20.2. Delta-Delta connection of transformer (180° phase shift).

Que 3.21. Draw and explain the connection diagram of Y-Y transformer.

Answer

1. Fig. 3.21.1 shows the $Y - Y$ connection of three identical single-phase transformers or the three identical windings on each of the primary and secondary sides of the 3ϕ transformer.
2. The phase current is equal to the line current and they are in phase.
3. The line voltage is $\sqrt{3}$ times the phase voltage. There is a phase separation of 30° between line and phase voltages.
4. For ideal transformer the voltage ratios are

$$\frac{V_{AN}}{V_{an}} = \frac{V_{BN}}{V_{bn}} = \frac{V_{CN}}{V_{cn}} = a$$

and current ratios are

$$\frac{I_A}{I_a} = \frac{I_B}{I_b} = \frac{I_C}{I_c} = \frac{1}{a}$$

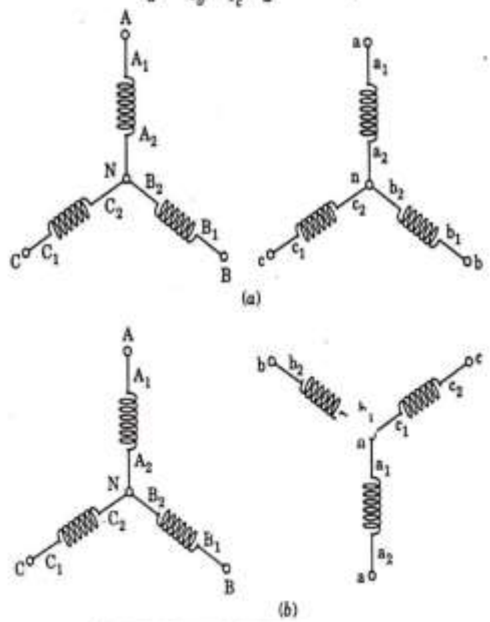

Fig. 3.21.1. Star-star connection of transformer
(*a*) 0° phase shift (*b*) 180° phase shift.

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