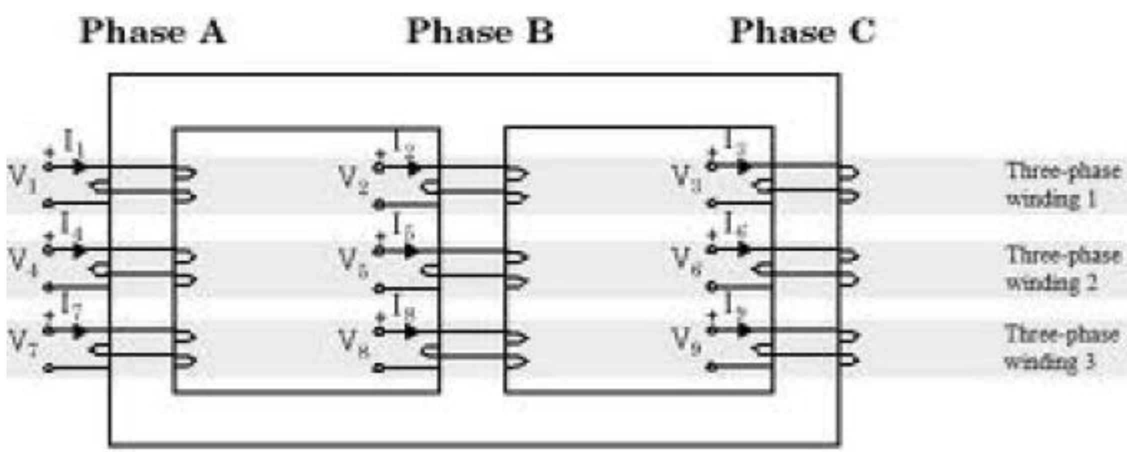
CHAPTER 6

Three-Phase Transformers

Learning Outcomes:

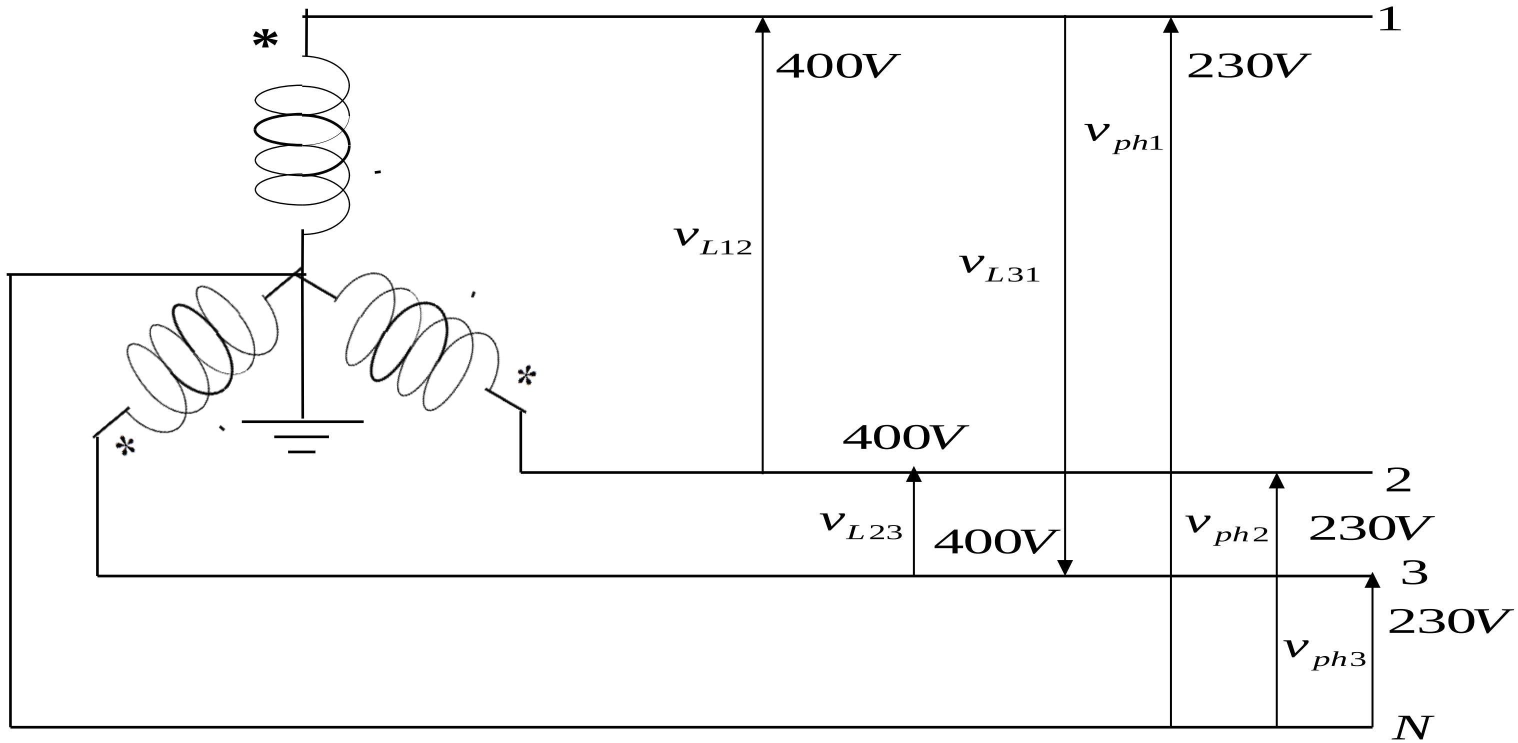
- Star and delta winding connection
- Transformers – star-star, delta-delta, star-delta, delta-star; values – primary and secondary turns, voltage, current, VA.
- The relationship between line and phase values of voltage, current, and volt-amps (VA) are stated for star and delta winding configurations.
- Transformer efficiencies are calculated from given data for different values of secondary load
- Measurements are made according to industry practice

Three-Phase Transformers

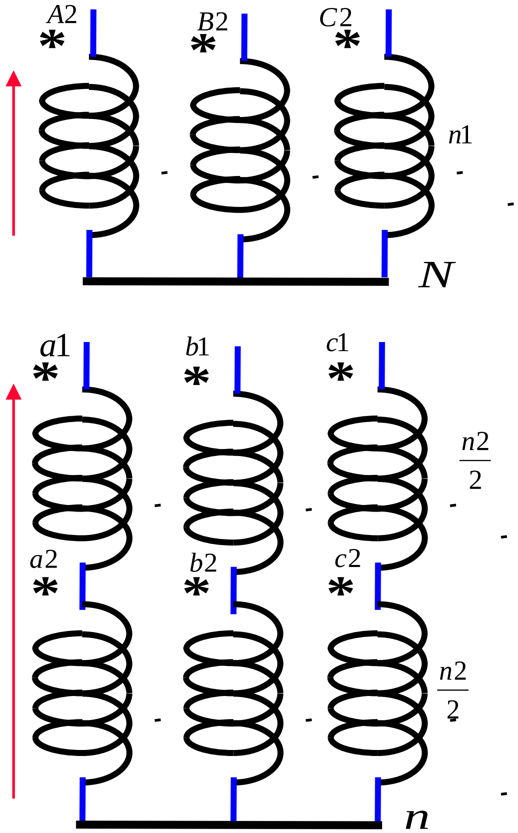


Y/Y, Y/Δ, Δ/Y and Δ/Δ

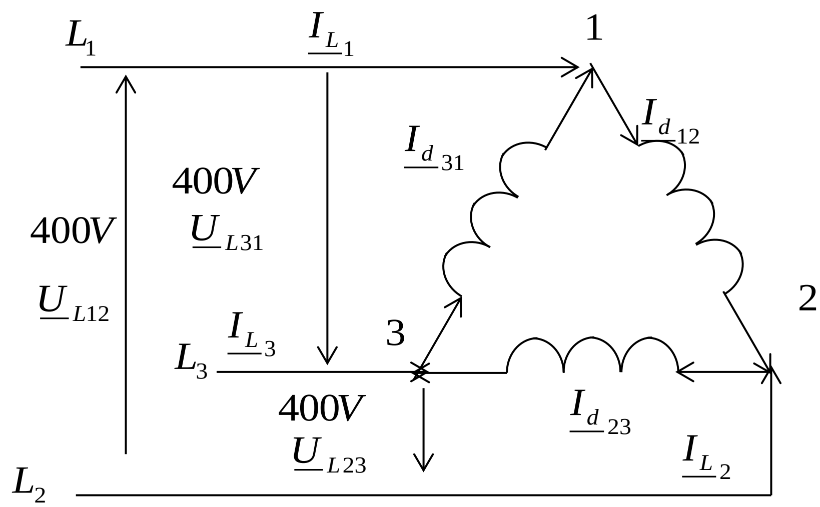
Wye Connections



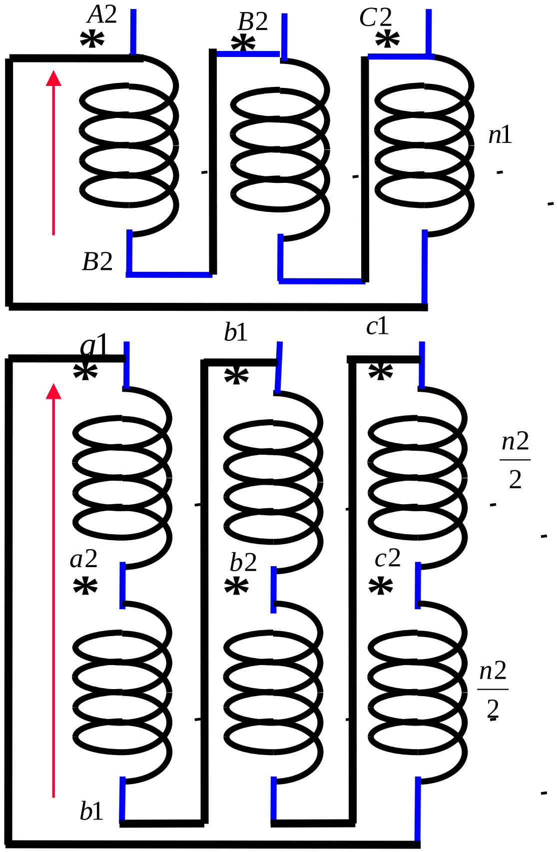
Wye-wye (Yy_0)



Delta Connections



Delta-delta (Dd_0)



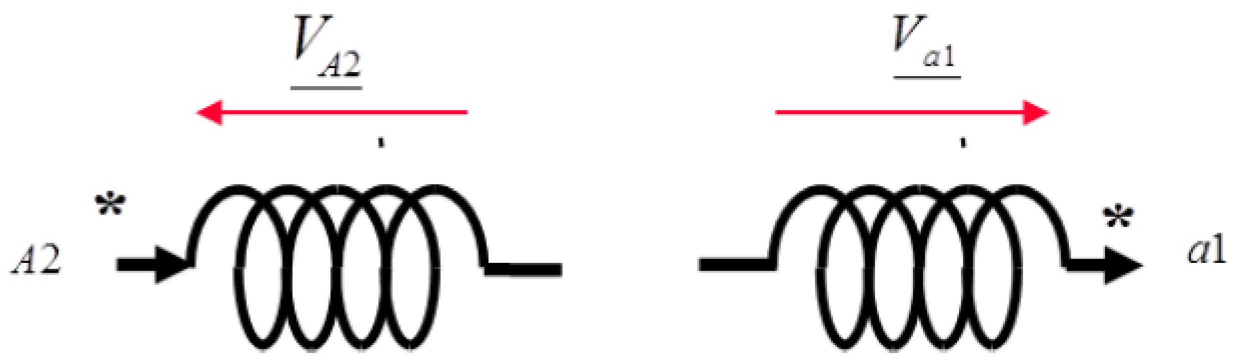
Symbol designation

- D or d: Delta winding,
- Y or y: Wye winding, (also called a star).

A, B, C: capital letters indicates primary.
a, b, c: small letters indicates secondary

Transformer Polarity:

The black dots, as shown in the figure, indicate that for a given instant in time: ***when A_2 is positive, then a_1 is positive in the same instant of time.***

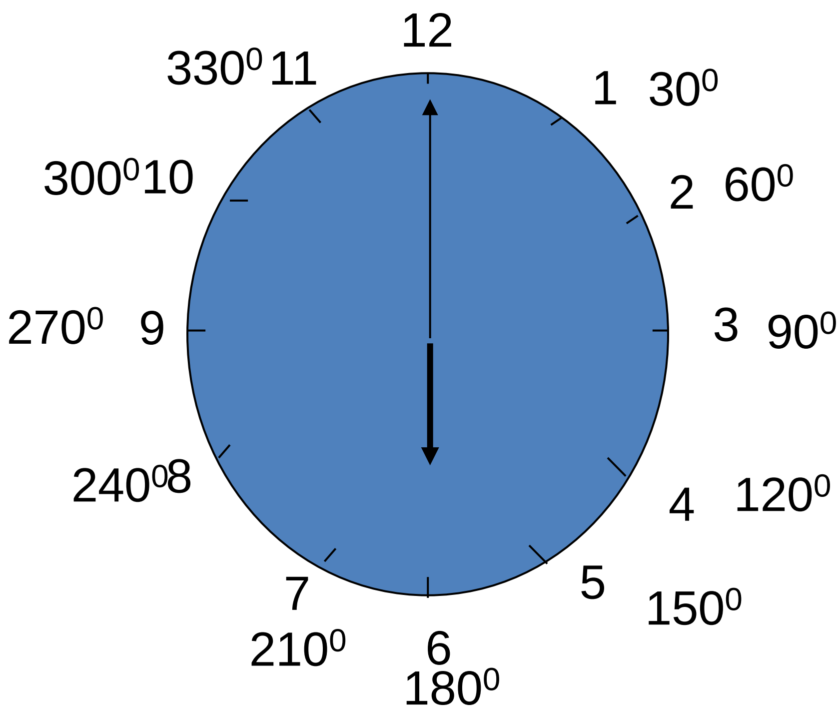


Phase displacement

Phase rotation is always counterclockwise (internationally adopted convention) and indicates multiples of 30 degree lag for secondary winding using the primary winding as the reference.

Thus 1 = 30°, 2 = 60°, 3 = 90°, 4 = 120°, 5 = 150°, 6 = 180°, 7 = 210°, 8 = 240°, 9 = 270°, 10 = 300°, 11 = 330° and 12 = 0° or 360°.

$$H = \frac{\theta}{30^\circ}$$



$$H = \frac{180^\circ}{30^\circ} = 6$$

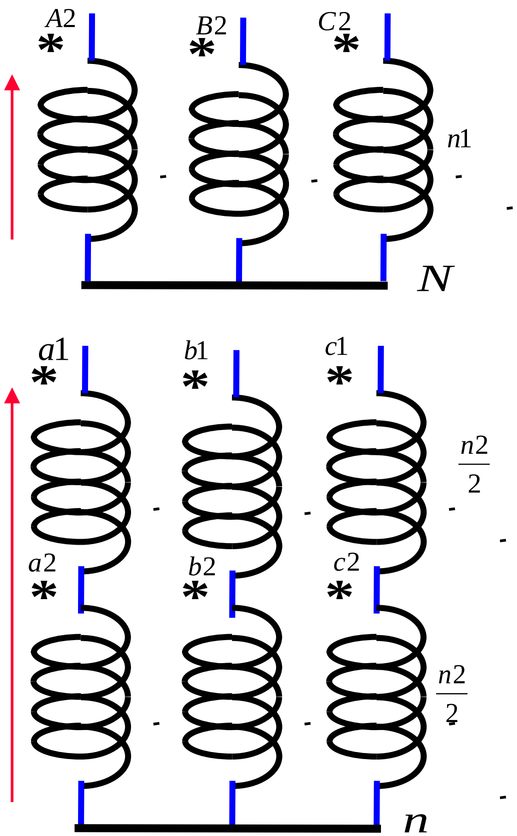
$$\overline{V_a} = me^{-j\pi}\overline{V_A}$$

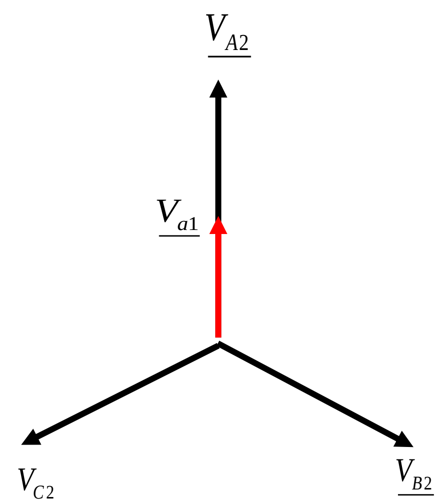
Application of Transformer according to Uses: Yy_0, Yd_{11}, Dy_{11}, Dd_0

Wye-wye (Yy_0)

Mainly used for large system tie-up transformer. In these transformers insulation cost is highly reduced. Neutral wire can permit mixed loading.

The angular displacement of secondary with respect to the primary are shown as clock position, 0°





$$H = \frac{\theta}{30^\circ}$$

$$\frac{V_{a1}}{n_2} = \frac{1}{n_1}(V_{A2}) * e^{-j0^\circ}$$

$$V_{a1} = \frac{n_2}{n_1} * V_{A2} * e^{-j0^\circ}$$

$$\frac{V_{a1}}{V_{A2}} = \frac{n_2}{n_1} e^{-j0^\circ} = m e^{-j\theta}$$

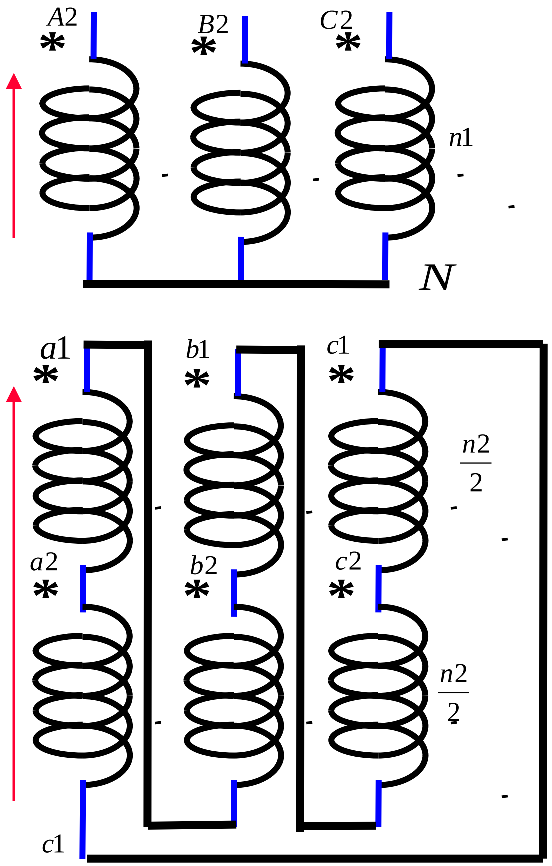
$$m = \frac{n_2}{n_1}$$

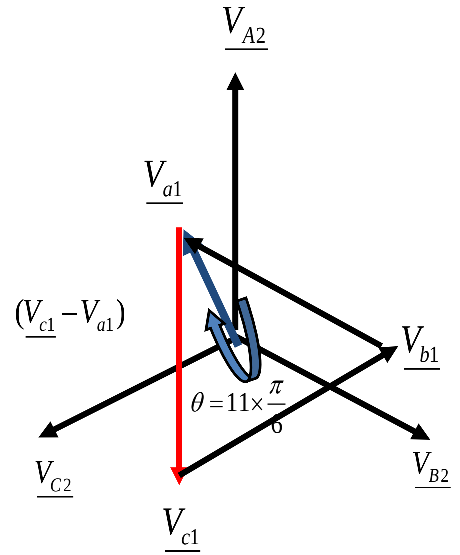
$$\theta = 0^\circ$$

Wye-delta (Yd_{11})

Mainly used for machine and main transformer in large power station and transmission substation.

The angular displacement of secondary with respect to the primary are shown as clock position, 330°





$$\frac{(\underline{V}_{c1} - \underline{V}_{a1})}{n_2} = \frac{1}{n_1} (\underline{V}_{A2}) * e^{-j\pi}$$

$$\sqrt{3}\underline{V}_{a1} = \frac{n_2}{n_1} * \underline{V}_{A2} * e^{-j11\frac{\pi}{6}}$$

$$\frac{\underline{V}_{a1}}{\underline{V}_{A2}} = \frac{1}{\sqrt{3}} \frac{n_2}{n_1} e^{-j11\frac{\pi}{6}} = me^{-j\theta}$$

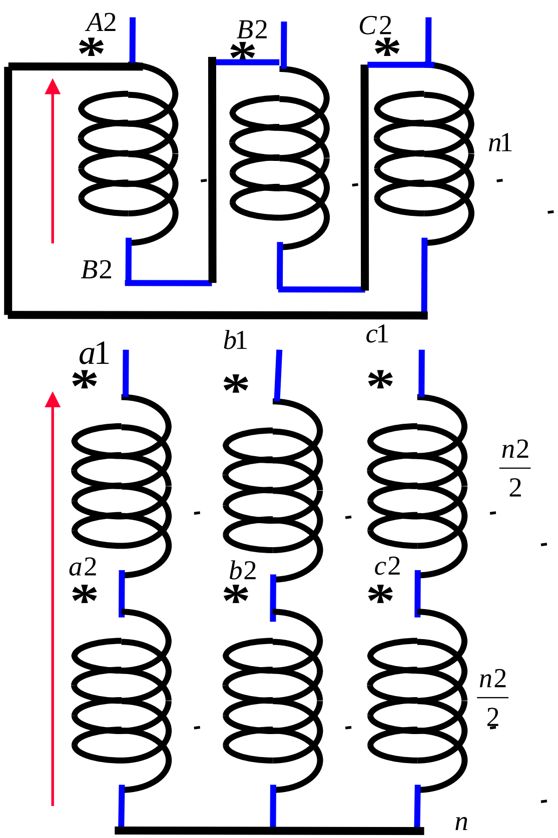
$$m = \frac{1}{\sqrt{3}} \frac{n_2}{n_1}$$

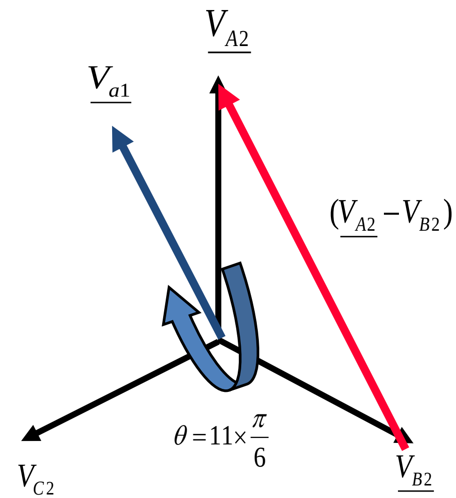
$$\theta = 11 \times \frac{\pi}{6}$$

Delta-wye (Dy_{11})

Normally Dy_{11} vector group using at distribution system

The angular displacement of secondary with respect to the primary are shown as clock position, 330°





$$\frac{\underline{V}_{a1}}{n_2} = \frac{1}{n_1}(\underline{V}_{A2} - \underline{V}_{B2}) \times e^{j0}$$

$$\underline{V}_{a1} = \frac{n_2}{n_1}\sqrt{3} \times \underline{V}_{A2} \times e^{-j11\frac{\pi}{6}}$$

$$\frac{\underline{V}_{a1}}{\underline{V}_{A2}} = \frac{n_2}{n_1}\sqrt{3}e^{-j11\frac{\pi}{6}} = me^{-j\theta}$$

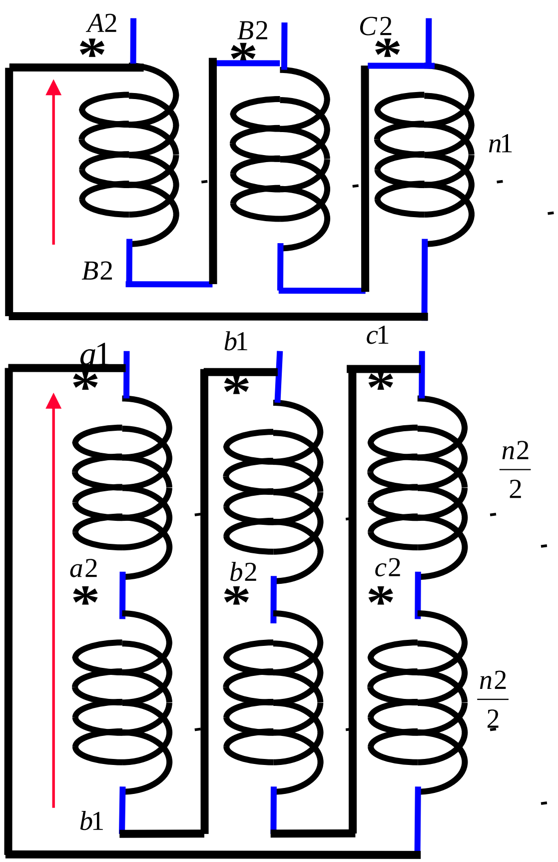
$$m = \sqrt{3}\,\frac{n_2}{n_1}$$

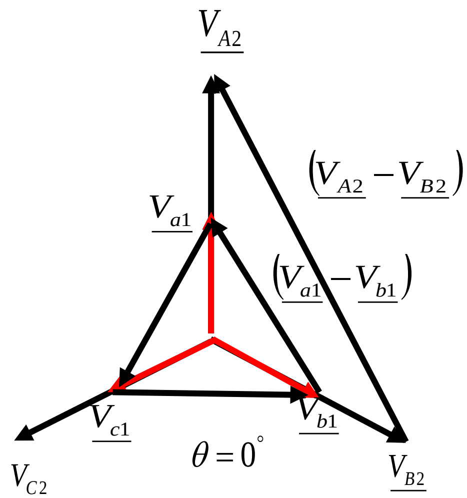
$$\theta = 11 \times \frac{\pi}{6}$$

Delta-delta (Dd_0)

. Delta permits a circulating path for triple harmonics thus attenuates the same.

The angular displacement of secondary with respect to the primary are shown as clock position, 0°





$$\frac{(\underline{V}_{a1} - \underline{V}_{b1})}{n_2} = \frac{1}{n_1}(\underline{V}_{A2} - \underline{V}_{B2}) * e^{-j0^\circ}$$

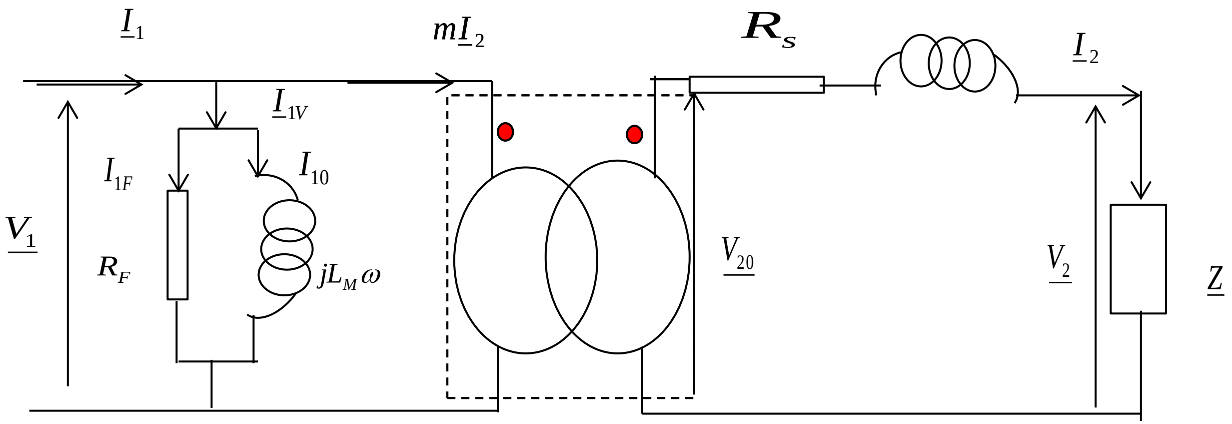
$$\sqrt{3}\underline{V}_{a1} = \frac{n_2}{n_1} * \sqrt{3}\underline{V}_{A2} * e^{-j0^\circ}$$

$$\frac{\underline{V}_{a1}}{\underline{V}_{A2}} = \frac{n_2}{n_1} e^{-j0^\circ} = m e^{-j\theta}$$

$$m = \frac{n_2}{n_1}$$

$$\theta = 0^\circ$$

Single-phase equivalent circuit of 3 phase transformers



$$m = \frac{U_{20}}{U_1} \qquad R_F = \frac{U_1^2}{P_{1V}} \qquad L_M\omega = \frac{U_1^2}{Q_{1V}} \qquad Q_{1V} = \sqrt{S_{1V}^2 - P_{1V}^2} \qquad S_{1V} = \sqrt{3}U_1 I_{1V}$$

$$R_s = \frac{P_{cc}}{3\times I_{2cc}^2} \qquad l_s\omega = \frac{Q_{cc}}{3\times I_{2cc}^2} \qquad Q_{cc} = \sqrt{S_{1cc}^2 - P_{cc}^2} \qquad S_{1cc} = \sqrt{3}U_{1cc} I_{1cc}$$

Voltage Drop Calculations

$$\Delta U_2 = \sqrt{3}\left(R_s I_2 \cos\varphi_2 + l_s\omega I_2 \sin\varphi_2\right)$$

The efficiency

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\sqrt{3}U_2 I_2 \cos\varphi_2}{\sqrt{3}U_2 I_2 \cos\varphi_2 + P_{1oc} + 3\times R_s \times I_{2sc}^2}$$

Review 6

1. If the primary of a transformer has more turns than the secondary, it is a _________ transformer.
2. If the primary of a transformer has fewer turns than the secondary, it is a _________ transformer.
3. The secondary voltage of an iron-core transformer with 240 V on the primary, 40 A on the primary, and 20 A on the secondary is _________ V.
4. A single-phase transformer with a 480 V and a maximum load current of 20 A must have an apparent power rating of at least _________ kVA.
5. A wye-connected, three-phase transformer secondary, with 208 V line-to-line will have _________ V line-to neutral.

Answers

1) Step-down;

2) step-up;

3) 480;

4) 9.6;

5) 120.

Exercise 2.6. *A 150000 VA, 20000V/400 V, 50 Hz* transformer has been tested to determine its equivalent circuit. The results of the tests are shown below.

Open-circuit test
$U_{1oc}=20000V$, $U_{2oc} = 420\ V$
$I_{1OC} = 0.43$ A
$P_{OC} = 2000$ W

Short-circuit test
$U_{1SC} = 1000$ V
$I_{2SC} = 206$ A
$P_{SC} = 1500$ W

(A) Find the single phase equivalent circuit of this transformer referred to the secondary side and gives the transformer parameters

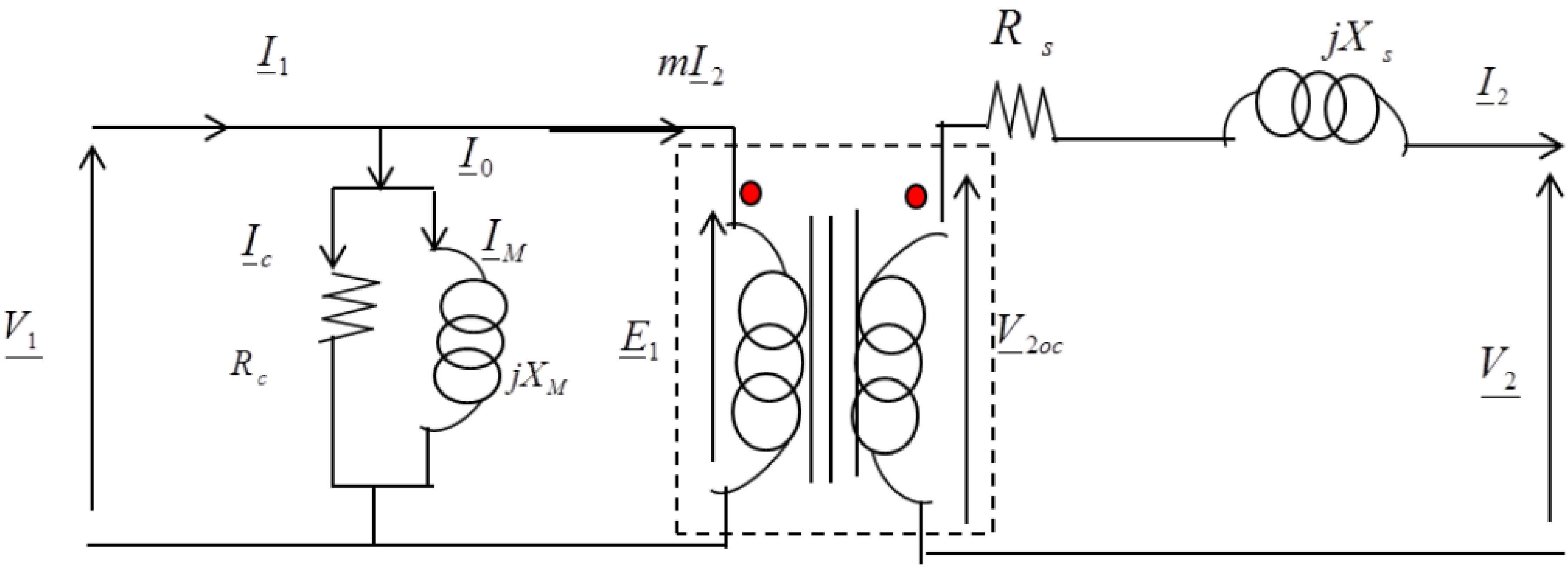
(B) Assume that the load on the transformer is 126 kW at $I_2 = 196A$. Determine the transformer's efficiency at rated conditions.

Solution:

A). Single-phase equivalent circuit of 3 phase transformers

Solution

(A) Find the single phase equivalent circuit of this transformer referred to the secondary side and gives the transformer parameters



OPEN CIRCUIT TEST:

$$m = \frac{U_{2oc}}{U_1} = 0{,}021$$

$$R_c = \frac{U_1^2}{P_{oc}} = 200k\Omega$$

$$X_M = \frac{U_1^2}{Q_{oc}} \cong 27k\Omega$$

SHORT CIRCUIT TEST:

$$R_s = \frac{P_{sc}}{3 \times I_{2sc}^2} = 11{,}7m\Omega$$

$$X_s = \frac{Q_{sc}}{3 \times I_{2sc}^2} = 57{,}6m\Omega$$

(B) Assume that the load on the transformer is 126 kW at $I_2 = 196A$. Determine the transformer's efficiency at rated conditions.

At these conditions, the input power of this transformer is

$$P_1 = P_2 + P_{oc} + 3 \times R_s \times I_2^2 = 129{,}948 kW$$

Therefore the efficiency of this transformer at these conditions is

$$\eta = \frac{P_2}{P_2 + P_{oc} + 3 \times R_s \times I_2^2} = 0{,}974$$


The End