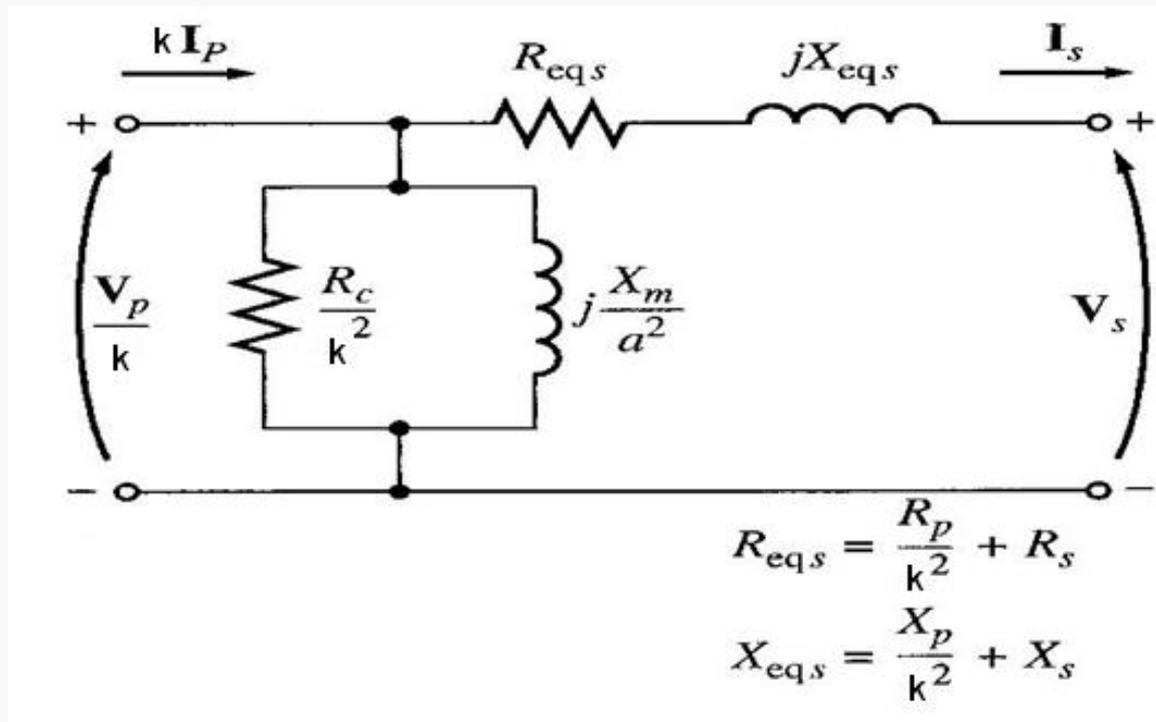


Transformer Phasor Diagram

To determine the voltage regulation of a transformer, it is necessary understand the voltage drops within it.



Transformer Phasor Diagram

Ignoring the excitation of the branch (since the current flow through the branch is considered to be small), more consideration is given to the series impedances ($R_{eq} + jX_{eq}$).

Voltage Regulation depends on magnitude of the series impedance and the phase angle of the current flowing through the transformer.

Phasor diagrams will determine the effects of these factors on the voltage regulation. A phasor diagram consist of current and voltage vectors.

Assume that the reference phasor is the secondary voltage, V_S . Therefore the reference phasor will have 0 degrees in terms of angle.

Based upon the equivalent circuit, apply Kirchhoff Voltage Law,

$$\frac{V_P}{k} = V_S + R_{eq} I_S + jX_{eq} I_S$$

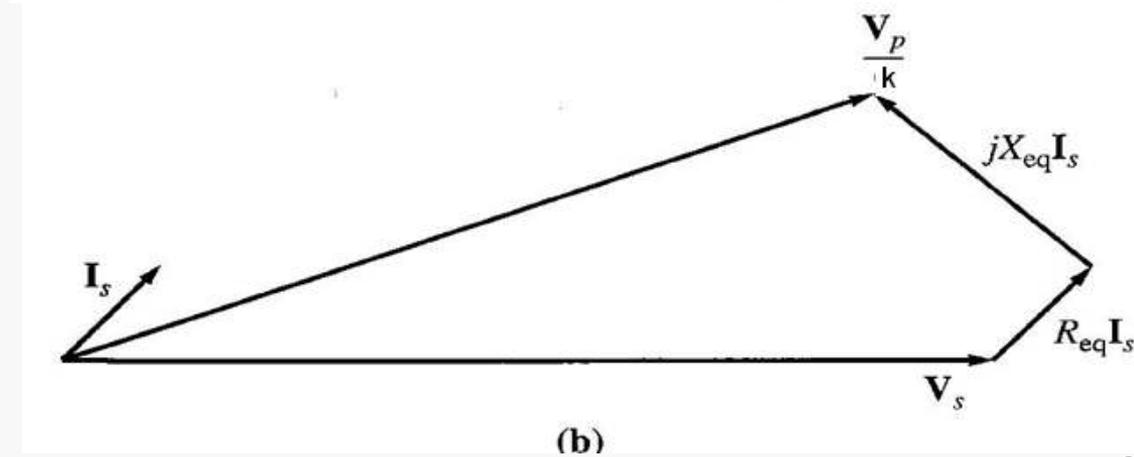
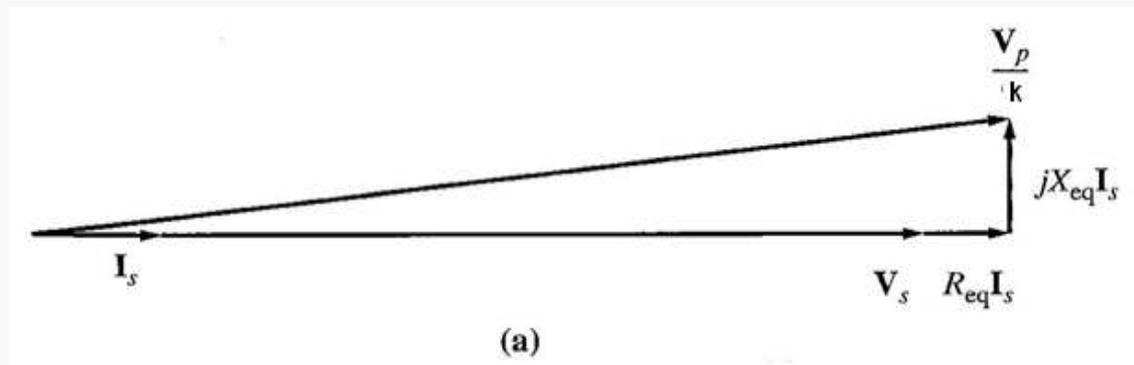
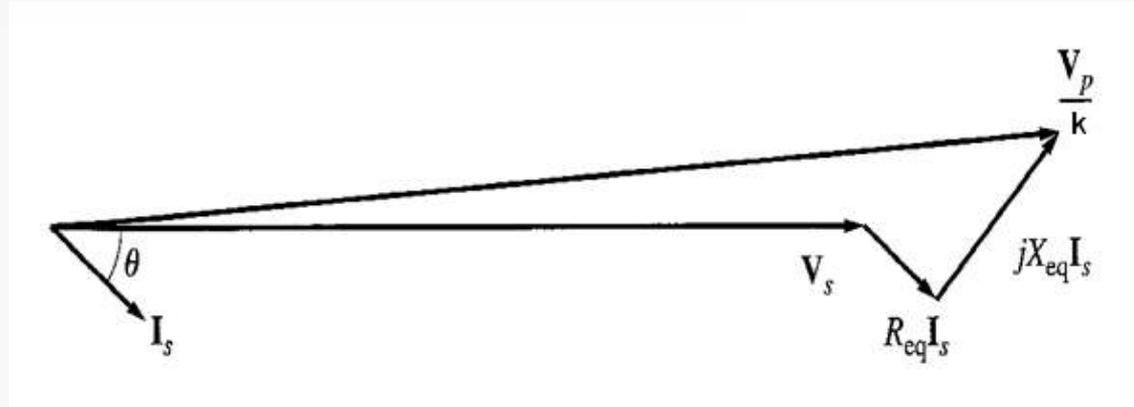
Transformer Phasor Diagram



For lagging loads,
 $V_p/a > V_s$ so the voltage regulation with lagging loads is > 0 .

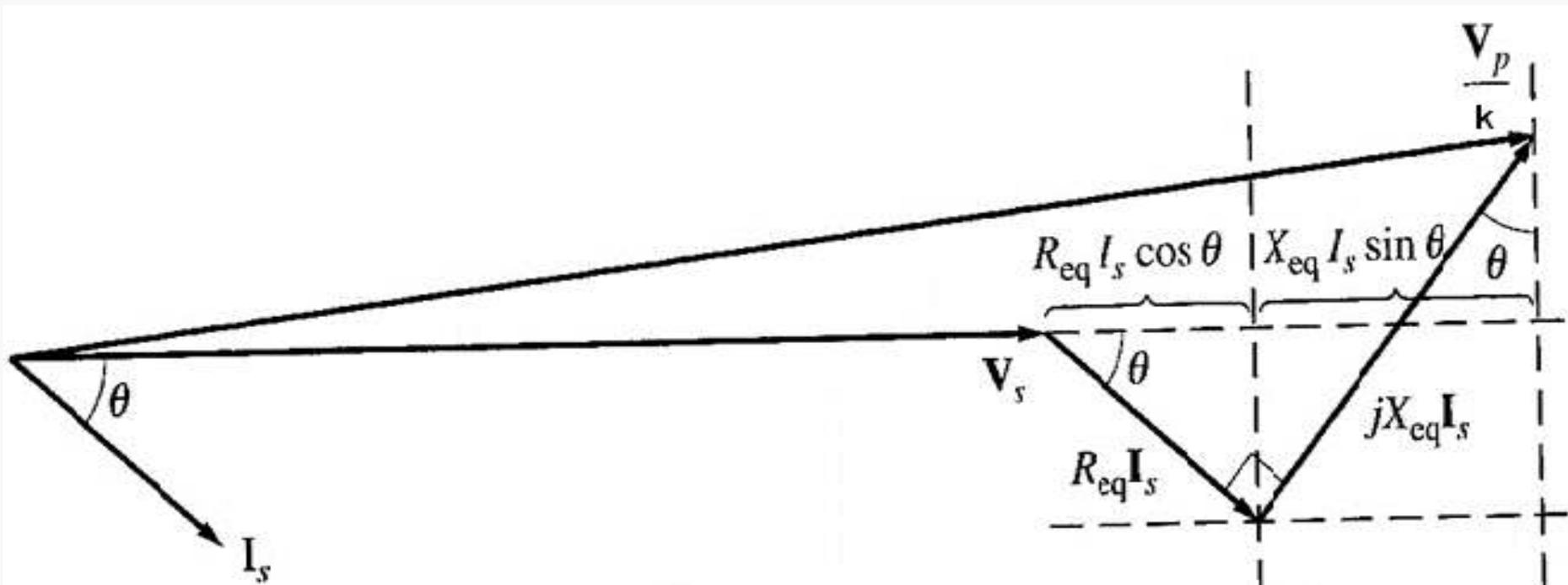
When the power factor is unity, V_s is lower than V_p so $VR > 0$.

With a leading power factor, V_s is higher than the referred V_p so $VR < 0$



Transformer Phasor Diagram

For lagging loads, the vertical components of R_{eq} and X_{eq} will partially cancel each other. Due to that, the angle of V_p/a will be very small, hence we can assume that V_p/k is horizontal. Therefore the approximation will be as follows:



Voltage Regulation of a Transformer

The *voltage regulation (VR)* of a transformer is defined as the difference between the no-load terminal voltage (V_{2NL}) to full load terminal voltage (V_{2FL}) and is expressed as a percentage of full load terminal voltage. It is therefore can be expressed as,

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

Since at no load, $V_2 = V_1/a$, the voltage regulation can also be expressed as

$$\text{Voltage Regulation} = \frac{\frac{V_1}{a} - V_{2FL}}{V_{2FL}} \times 100\%$$

Usually it is a good practice to have as small a voltage regulation as possible. For an ideal transformer, Voltage Regulation = 0 percent. It is not always a good idea to have a low-voltage regulation, sometimes high-impedance and high-voltage regulation transformers are deliberately used to reduce the fault currents in a circuit.

Approximate Expression for Voltage Regulation

The approximate expression for the no-load secondary voltage is :

$$(i) \text{ For inductive load: } E_2 = V_2 + I_2 R_{es} \cos \phi_2 + I_2 X_{es} \sin \phi_2$$

$$\text{or } E_2 - V_2 = I_2 R_{es} \cos \phi_2 + I_2 X_{es} \sin \phi_2$$

$$\text{or } \frac{E_2 - V_2}{E_2} \times 100 = \frac{I_2 R_{es}}{E_2} \times 100 \cos \phi_2 + \frac{I_2 X_{es}}{E_2} \times 100 \sin \phi_2$$

$$\text{where, } \frac{I_2 X_{es}}{E_2} \times 100 = \text{percentage reactance drop and}$$

$$\frac{I_2 R_{es}}{E_2} \times 100 = \text{percentage resistance drop}$$

$$\therefore \% \text{ Reg} = \% \text{ resistance drop} \times \cos \phi_2 + \% \text{ reactance drop} \times \sin \phi_2$$

Similarly

$$(ii) \text{ For resistive load: } \% \text{ Reg} = \% \text{ resistance drop} \quad \dots(2.64)$$

(iii) For capacitive load:

$$\therefore \% \text{ Reg} = \% \text{ resistance drop} \times \cos \phi_2 - \% \text{ reactance drop} \times \sin \phi_2$$

Example : A 75 kVA single phase transformer, 6600/230 V, requires 310 V across the primary to the primary to circulate full load current on short circuit, the power absorbed being 1.6 kW. Determine the voltage regulation and the secondary terminal voltage for half full load, 0.8 p.f. lagging.

$$\text{Transformer output} = 75 \text{ kVA} = 75 \times 10^3 \text{ VA}$$

$$\text{Primary induced voltage, } E_1 = 6600 \text{ V}$$

$$\text{Secondary induced voltage, } E_2 = 230 \text{ V}$$

$$\text{At short circuit, primary voltage, } V_{1(sc)} = 310 \text{ V}$$

$$\text{At short circuit, power absorbed, } P_{(sc)} = 1.6 \text{ kW} = 1.6 \times 10^3 \text{ W}$$

$$\text{Load p.f. } \cos \phi_2 = 0.8 \text{ lagging}$$

$$\text{Primary current at full load, } I_1 = \frac{75 \times 10^3}{6600} = 11.36 \text{ A}$$

$$\text{Primary current at short circuit } I_{1(sc)} = I_1 = 11.36 \text{ A}$$

$$\text{Equivalent resistance referred to primary, } R_{ep} = \frac{P_{sc}}{(I_{1sc})^2} = \frac{1.6 \times 10^3}{(11.36)^2} = 12.39 \Omega$$

$$\text{Equivalent impedance referred to primary, } Z_{ep} = \frac{V_{1sc}}{I_{1sc}} = \frac{310}{11.36} = 27.29 \Omega$$

$$\begin{aligned} \text{Equivalent reactance referred to primary, } X_{ep} &= \sqrt{Z_{ep}^2 - R_{ep}^2} = \sqrt{(27.29)^2 - (12.39)^2} \\ &= 24.32 \Omega \end{aligned}$$

Equivalent resistance referred to secondary.

$$R_{es} = K^2 R_{ep} = \frac{230 \times 230 \times 12.39}{6600 \times 6600} = 0.015 \Omega$$

Secondary current at full load,

$$I_2 = \frac{75 \times 10^3}{230} = 326 \text{ A}$$

Secondary current at half load,

$$I_{2hl} = \frac{I_2}{2} = \frac{326}{2} = 163 \text{ A}$$

Load p.f.,

$$\cos \phi_2 = 0.8 \text{ lag}$$

\therefore

$$\sin \phi_2 = \sin \cos^{-1} 0.8 = 0.6$$

Secondary terminal voltage at half full load,

$$\begin{aligned} V_2 &= E_2 - I_{2hl} R_{es} \cos \phi_2 - I_{2hl} X_{es} \sin \phi_2 \\ &= 230 - 163 \times 0.015 \times 0.8 - 163 \times 0.0295 \times 0.6 \\ &= \mathbf{225.16 \text{ V (Ans.)}} \end{aligned}$$

$$\begin{aligned} \text{Voltage regulation} &= \frac{E_2 - V_2}{E_2} \times 100 = \frac{230 - 225.16}{230} \times 100 \\ &= \mathbf{2.1 \% (Ans.)} \end{aligned}$$

Example : A 15 kVA. 2300/230 V, single phase transformer has 2.5 ohm resistance and 10 ohm reactance for primary and 0.02 ohm resistance and 0.09 ohm reactance for the secondary. If the secondary terminal voltage is to be maintained at 230 V and 0.8 p.f. lagging at full load current, what should be the primary voltage?

Example : A 15 kVA, 440/230 V, 50 Hz, single phase transformer gave the following test results: Open Circuit (LV side) 250 V, 1.8A, 95 W.

Short Circuit Test (HV side) 80 V, 12.0 A, 380 W.

Compute the parameters of the equivalent circuit referred to LV side?

From open circuit test performed on LV side;

$$I_w = \frac{W_0}{V_2} = \frac{95}{250} = 0.38 \text{ A}$$

$$I_{mag} = \sqrt{I_0^2 - I_w^2} = \sqrt{(1.8)^2 - (0.38)^2} = 1.75943 \text{ A}$$

$$\text{Exciting resistance, } R_0 = \frac{V_2}{I_w} = \frac{250}{0.38} = 658 \ \Omega$$

$$\text{Exciting reactance, } X_0 = \frac{V_2}{I_{mag}} = \frac{250}{1.75943} = 142 \ \Omega$$

From short circuit test performed on HV side;

$$Z_{ep} = \frac{V_{1(sc)}}{I_{1(sc)}} = \frac{80}{12} = 6.667 \ \Omega$$

$$R_{ep} = \frac{W_c}{(I_{1(sc)})^2} = \frac{380}{(12)^2} = 2.639 \ \Omega$$

$$X_{ep} = \sqrt{Z_{ep}^2 - R_{ep}^2} = \sqrt{(6.667)^2 - (2.639)^2} = 6.122 \ \Omega$$

Transformer resistance and reactance referred to LV (secondary) side;

$$R_{es} = R_{ep} \times K^2 = 2.639 \times (0.5227)^2 = 0.7211 \ \Omega$$

$$X_{es} = X_{ep} \times K^2 = 6.122 \times (0.5227)^2 = 2.673 \ \Omega$$

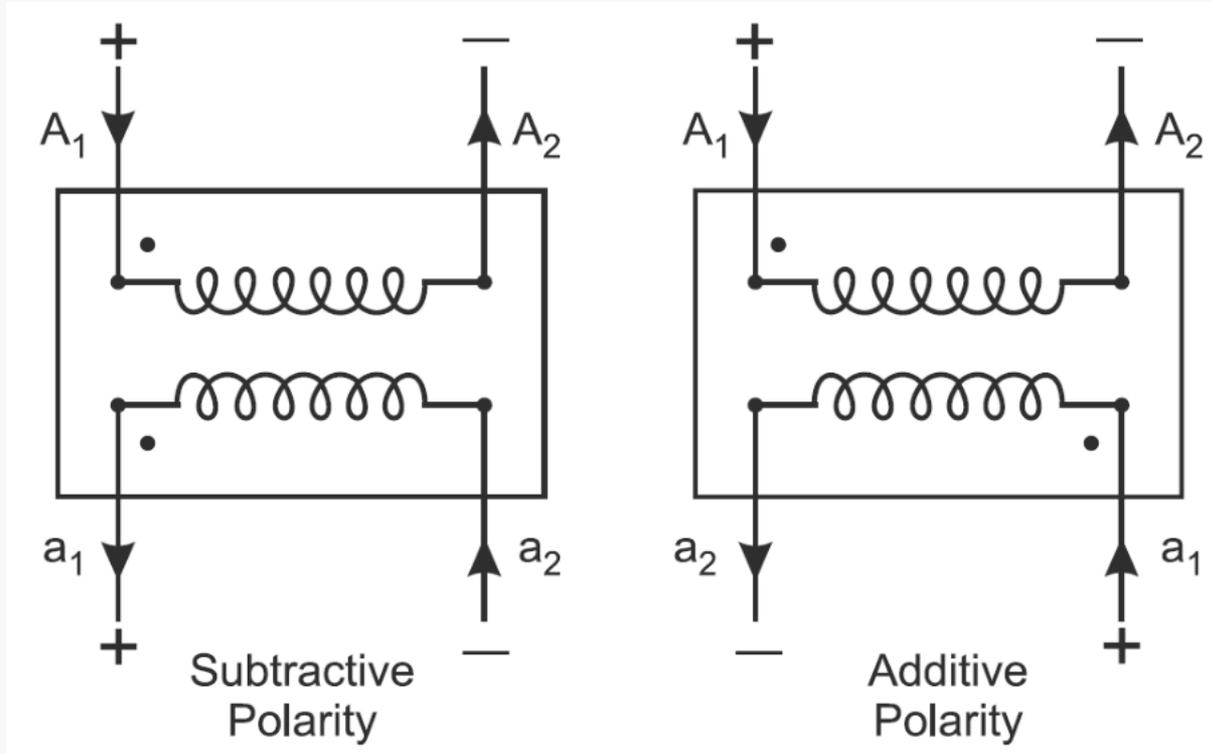
3 Phase Transformer

Basic properties of 3-phase transformer bank

- When three single-phase transformers are used to transform a 3-phase voltage, the windings can be connected in several ways. → the ratio of the 3-phase input voltage to the 3-phase output voltage depends not only upon the turns ratio of the transformers, but also upon how they are connected.
- A 3-phase transformer bank can also produce a *phase shift* between the 3-phase input voltage and the 3-phase output voltage. The amount of phase shift depends upon
 - the turns ratio of the transformers
 - how the primaries and secondaries are interconnected
- The phase shift feature enables us to change the *number of phases* → a 3-phase system can be converted into a 2-phase, a 5-phase, a 6-phase, or a 12-phase system by an appropriate choice of single-phase transformers and interconnections.

Polarity of Transformer Windings

The polarity of unmarked transformers can be found out by simple polarity tests



Transformer polarity designation

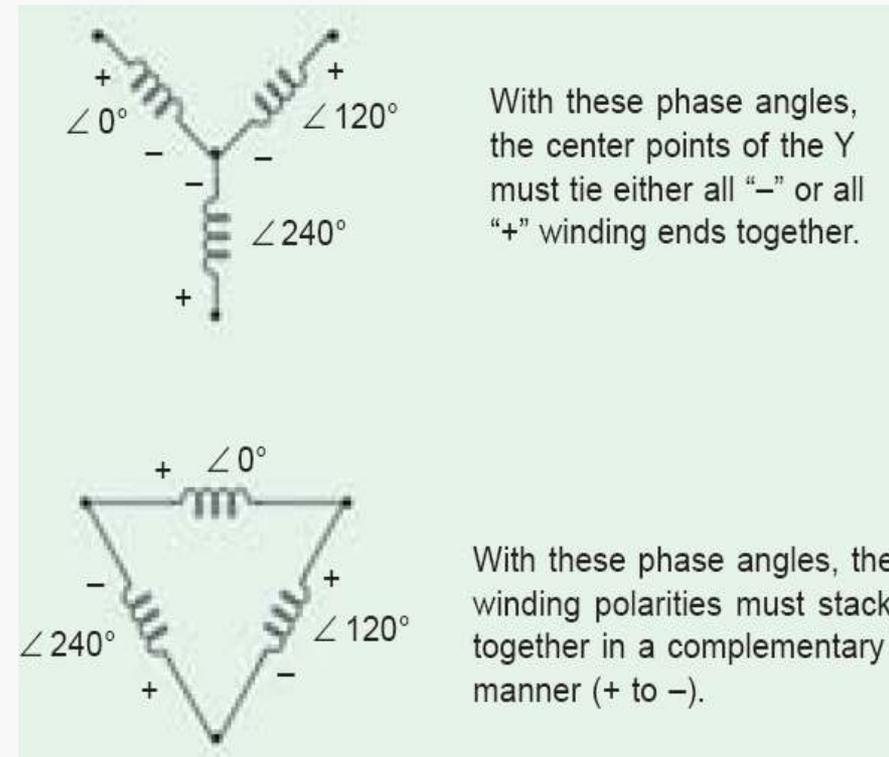
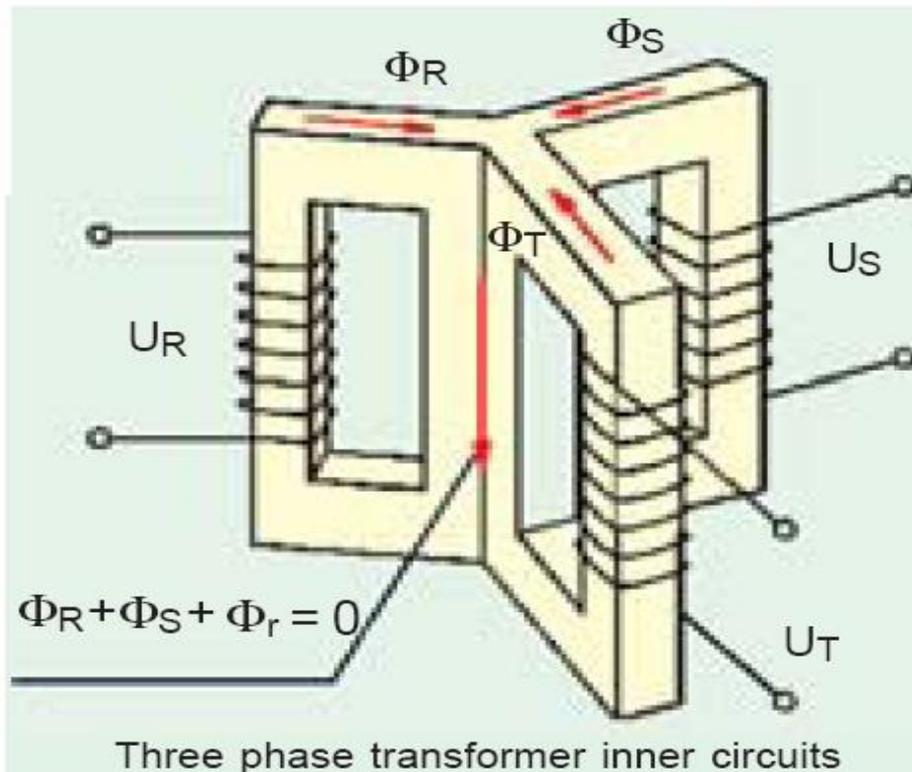
Three-phase Transformer Connections

Group 1: With 0° phase displacement : Connections with symbolic notation Yy0, Dd0, Dz0

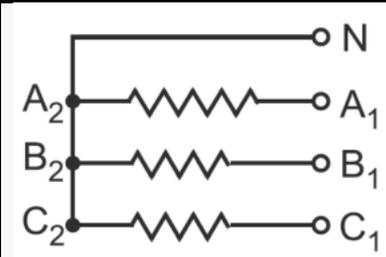
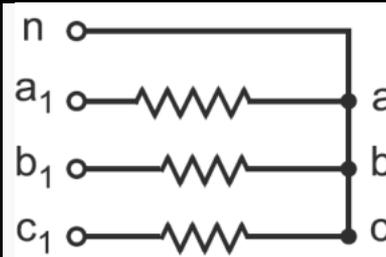
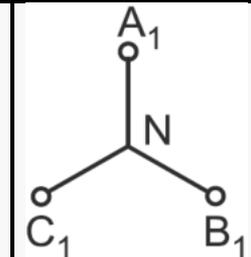
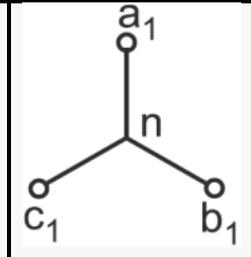
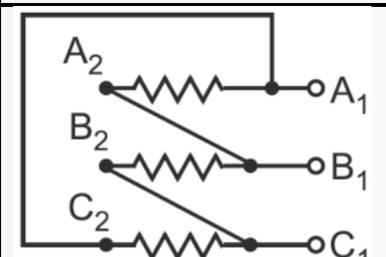
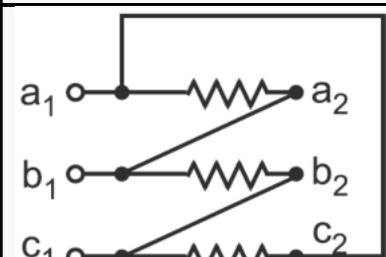
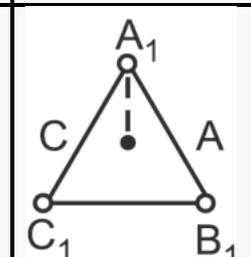
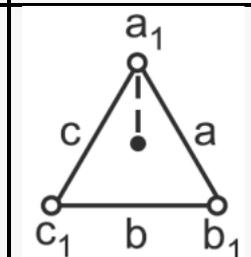
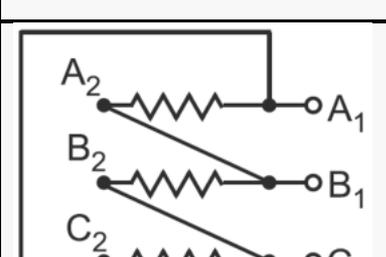
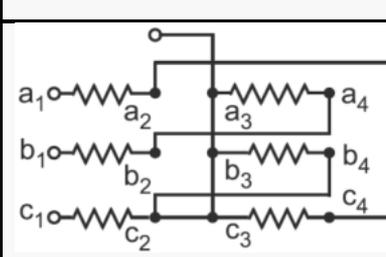
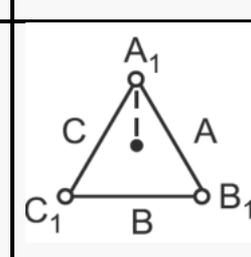
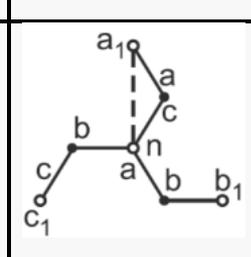
Group 2: With 180° phase displacement : Connections with symbolic notation Yy6, Dd6, Dz6

Group 3: With 30° lag phase displacement : Connections with symbolic notation Dy1, Yd1, Yz1

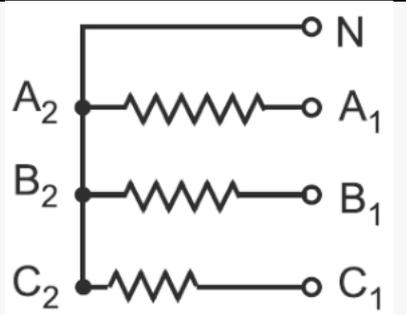
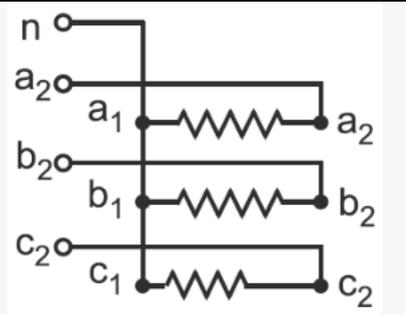
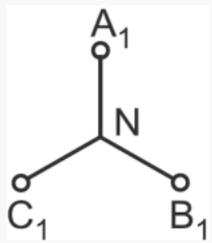
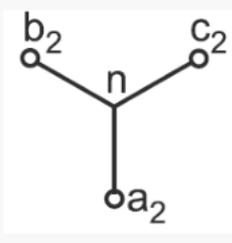
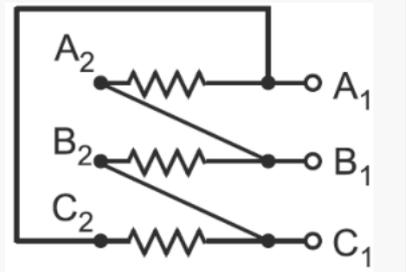
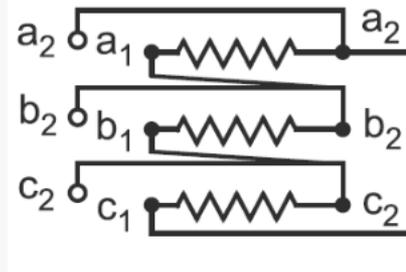
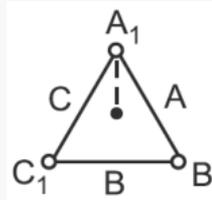
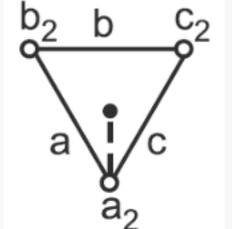
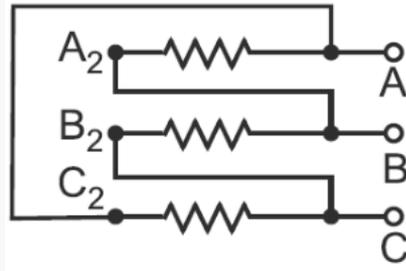
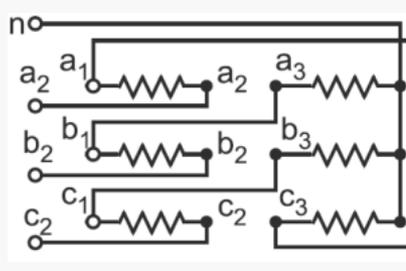
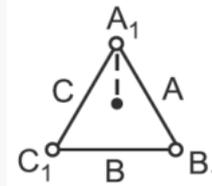
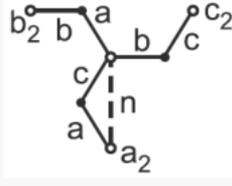
Group 4: With 30° lead phase displacement : Connections with symbolic notation Dy11, Yd11, Yz11



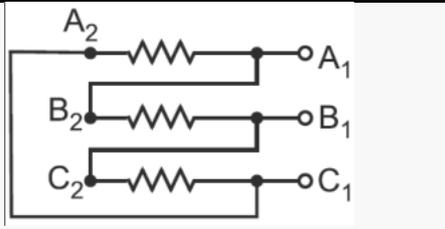
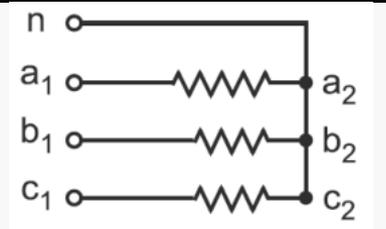
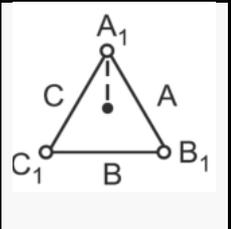
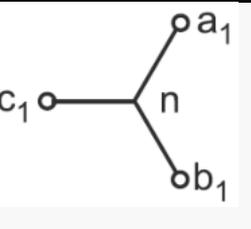
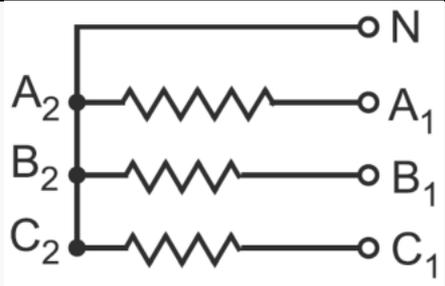
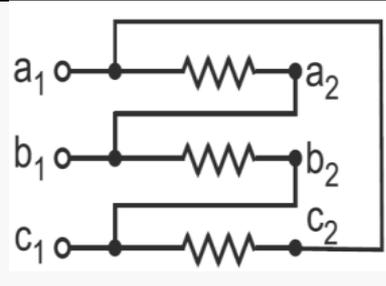
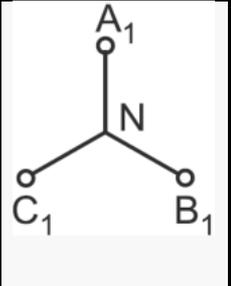
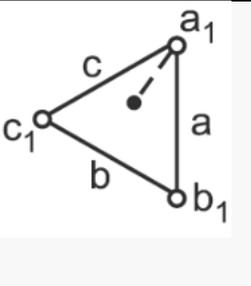
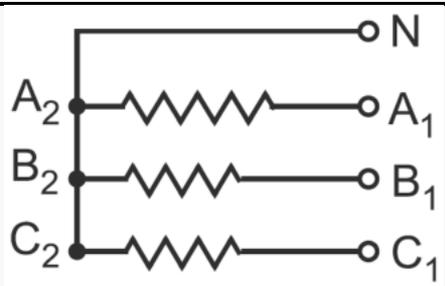
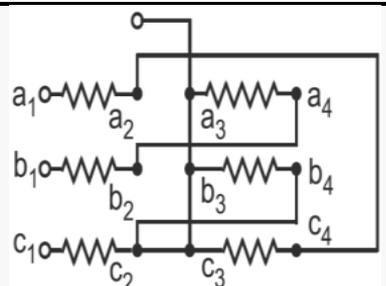
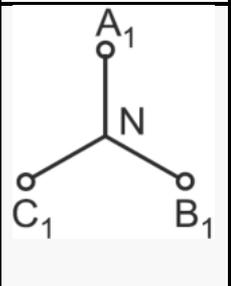
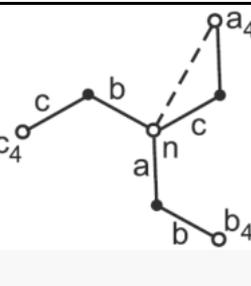
Three Phase Transformer Connections

Group N#	Phase Displacement	Symbolic notation	Winding Connection		Phasor diagram	
			HV	LV	HV	LV
1	0°	Yy0				
		Dd0				
		Dz0				

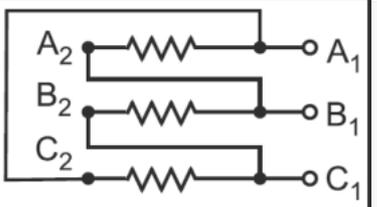
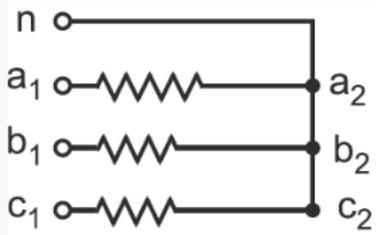
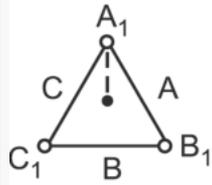
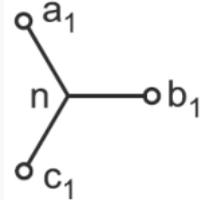
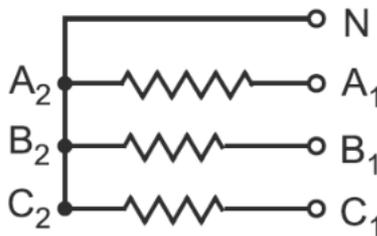
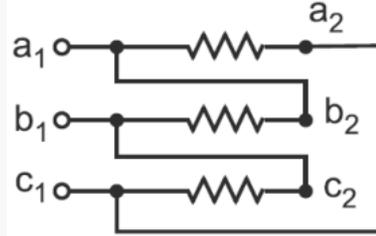
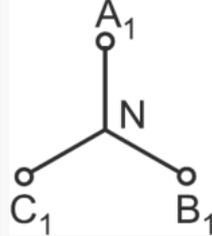
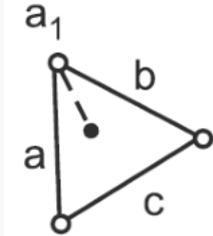
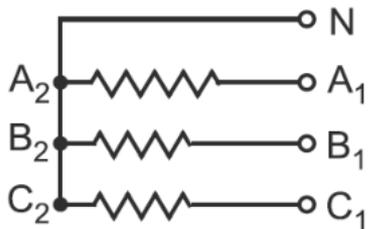
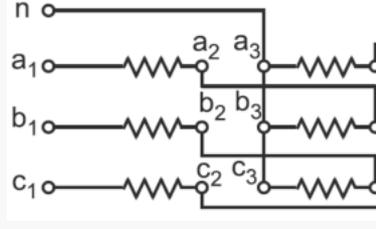
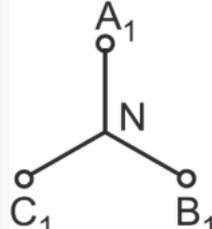
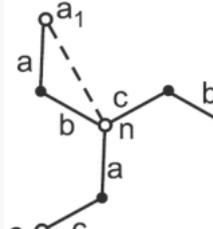
Three Phase Transformer Connections

Group N#	Phase Displacement	Symbolic notation	Winding Connection		Phasor diagram	
			HV	LV	HV	LV
2	180°	Yy6				
		Dd6				
		Dz6				

Three Phase Transformer Connections

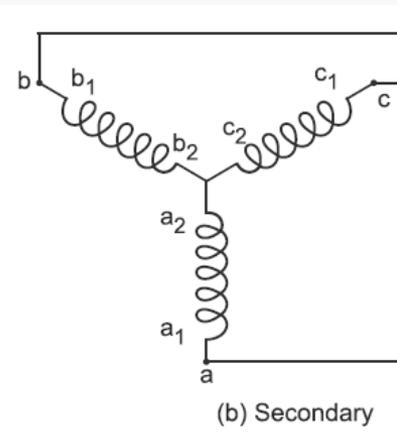
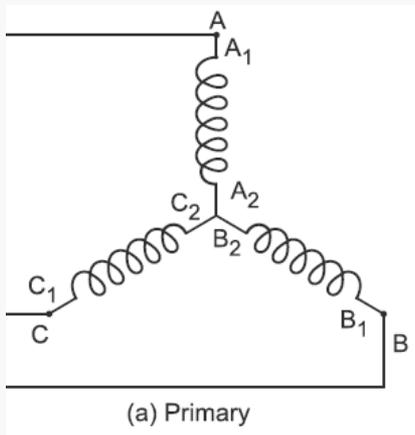
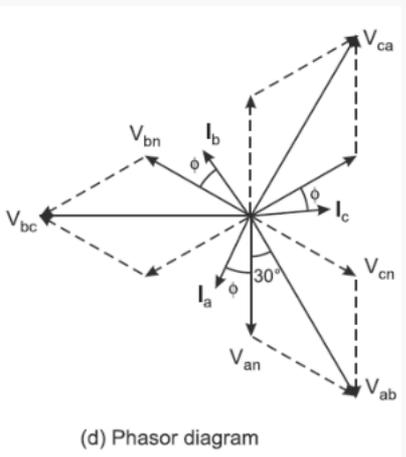
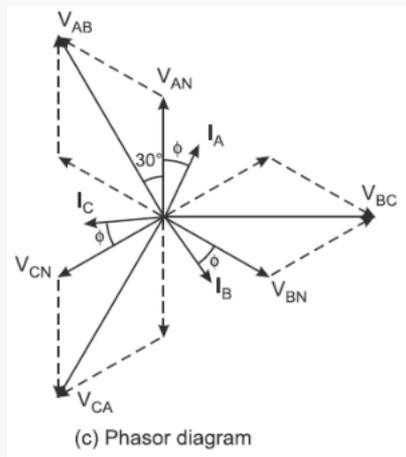
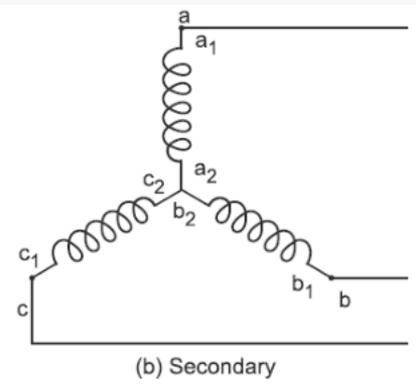
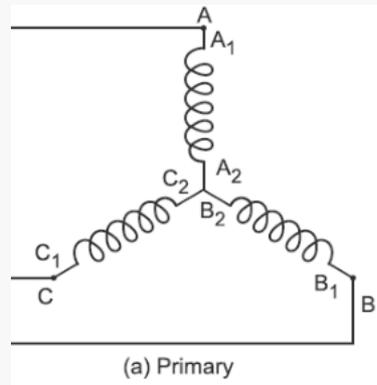
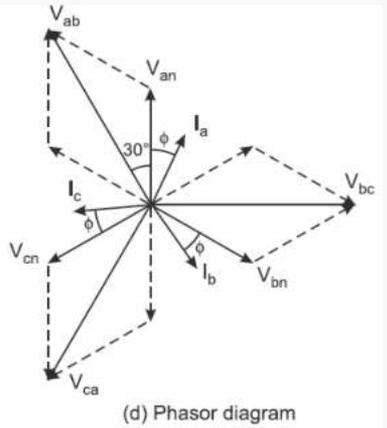
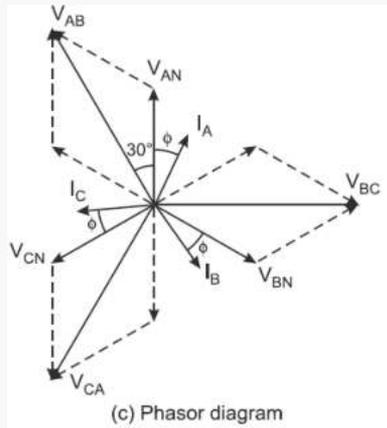
Group N#	Phase Displacement	Symbolic notation	Winding Connection		Phasor diagram	
			HV	LV	HV	LV
3	30°	Dy1				
		Yd1				
		Yz1				

Three Phase Transformer Connections

Group N#	Phase Displacement	Symbolic notation	Winding Connection		Phasor diagram	
			HV	LV	HV	LV
4	+30°	Dy11				
		Yd11				
		Yz11				

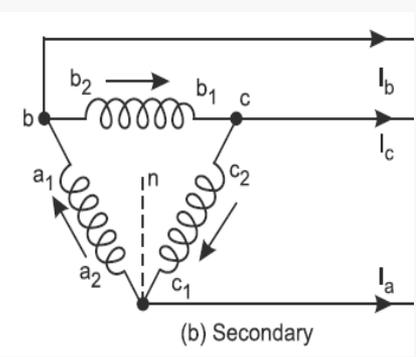
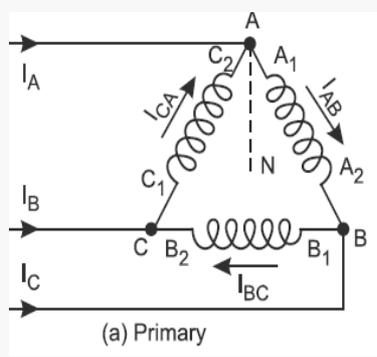
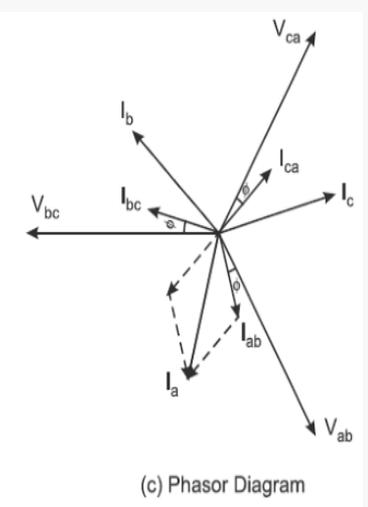
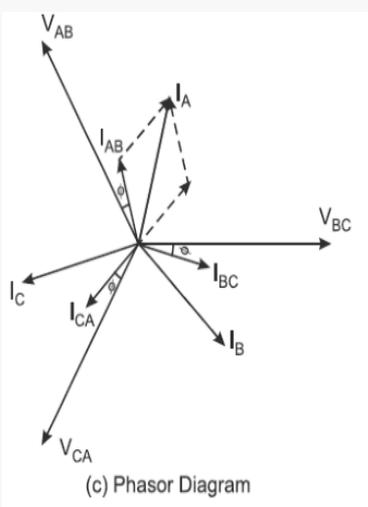
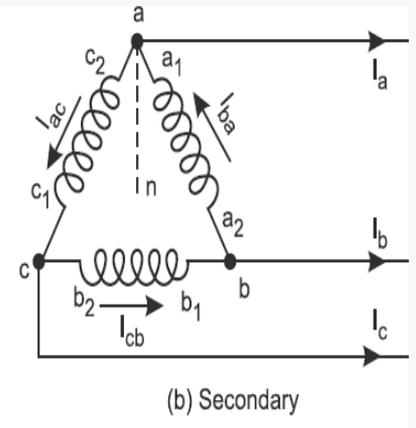
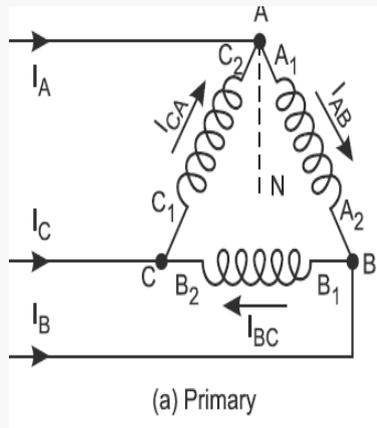
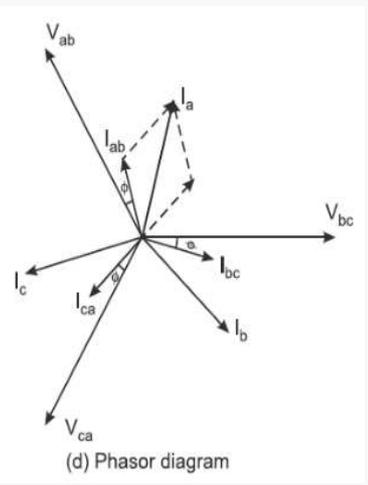
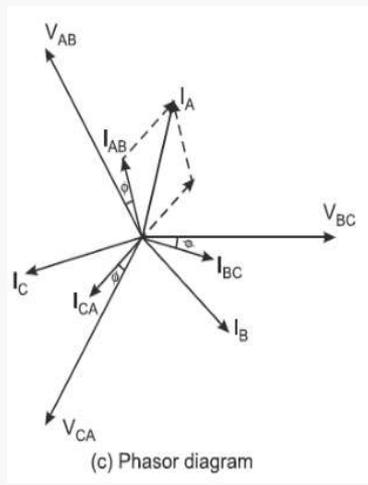
Selection of Transformer Connections

Star-Star (Yy0 or Yy6) Connections



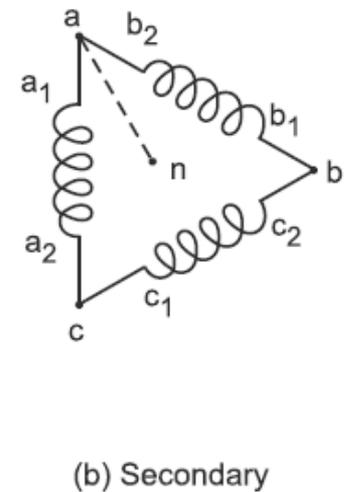
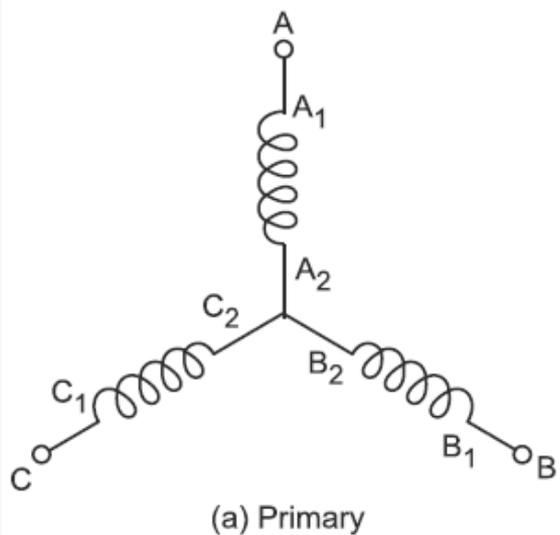
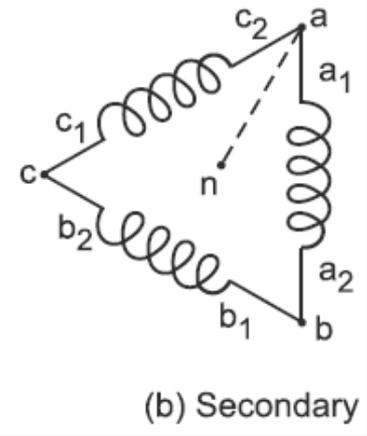
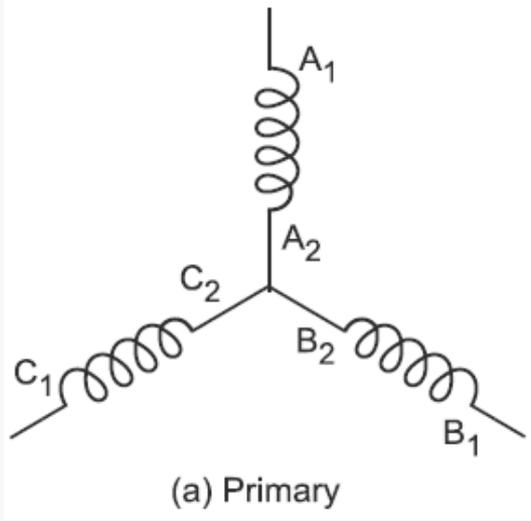
Selection of Transformer Connections

Delta-Delta (Dd0 or Dd6) Connections



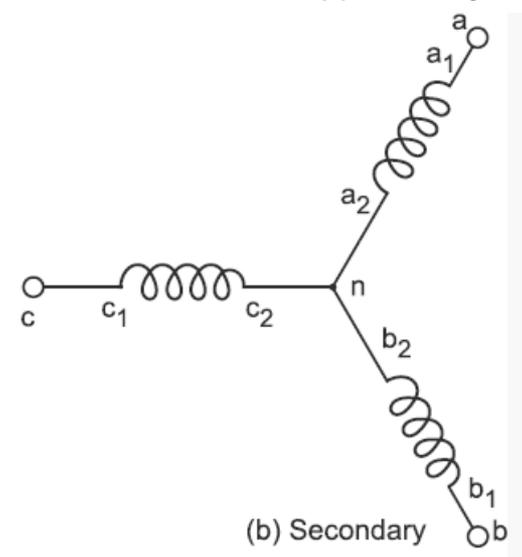
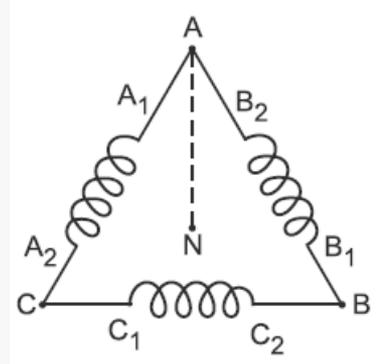
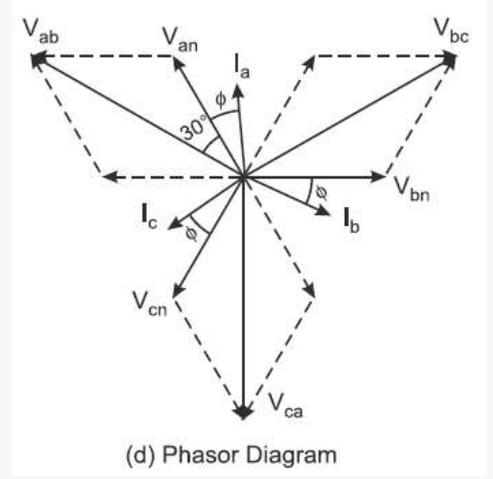
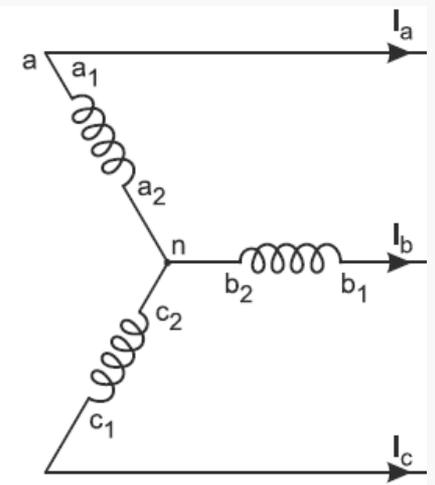
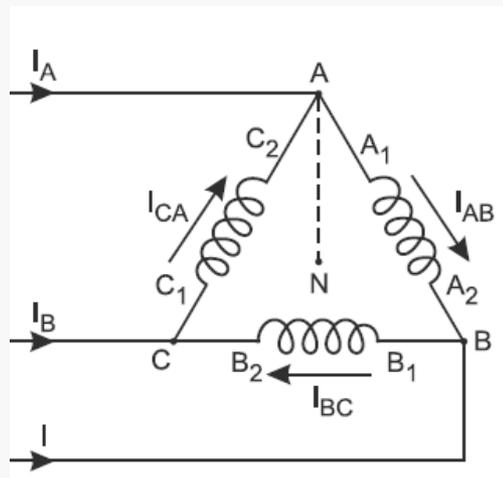
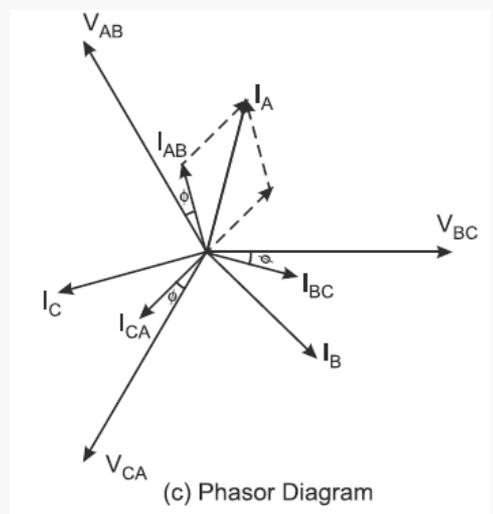
Selection of Transformer Connections

Star-Delta (Yd1 or Yd11) Connections



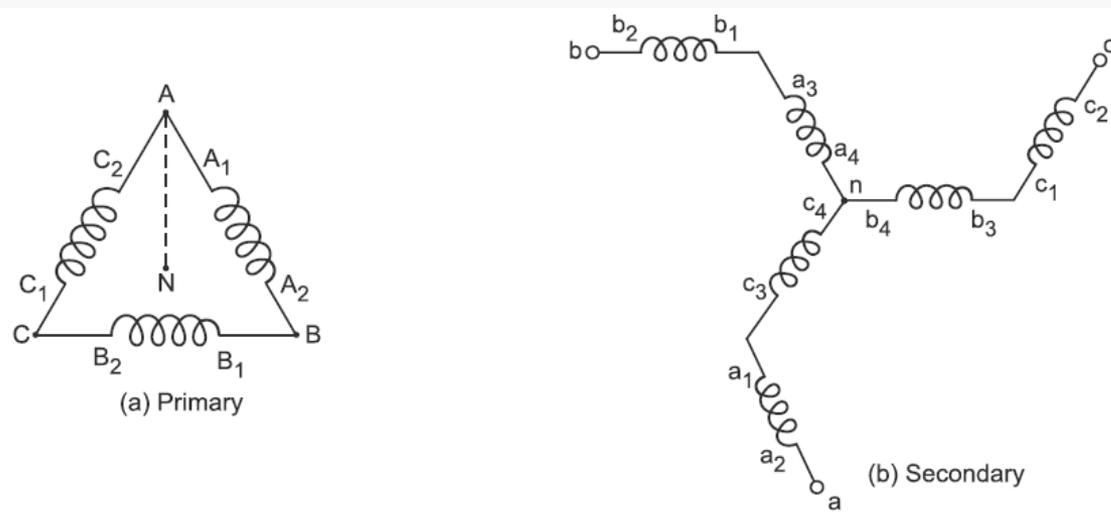
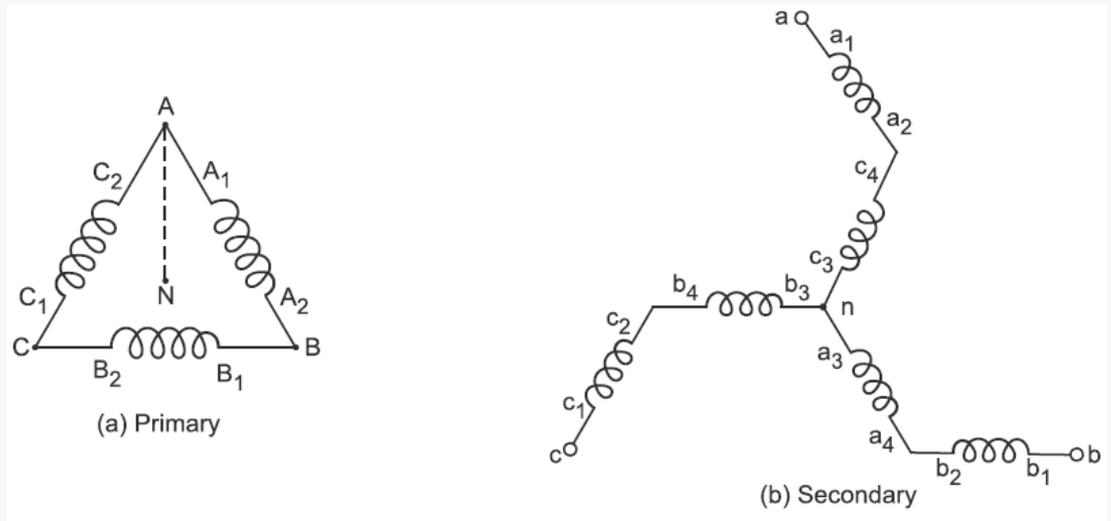
Selection of Transformer Connections

Delta-Star (Dy1 or Dy11) Connections



Selection of Transformer Connections

Delta-Zigzag Connections



Selection of Transformer Connections

Star-Zigzag Connections

