ELL100: INTRODUCTION TO ELECTRICAL ENGG.

3 Phase AC Power Circuits

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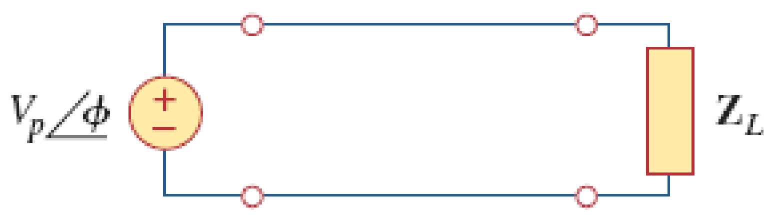
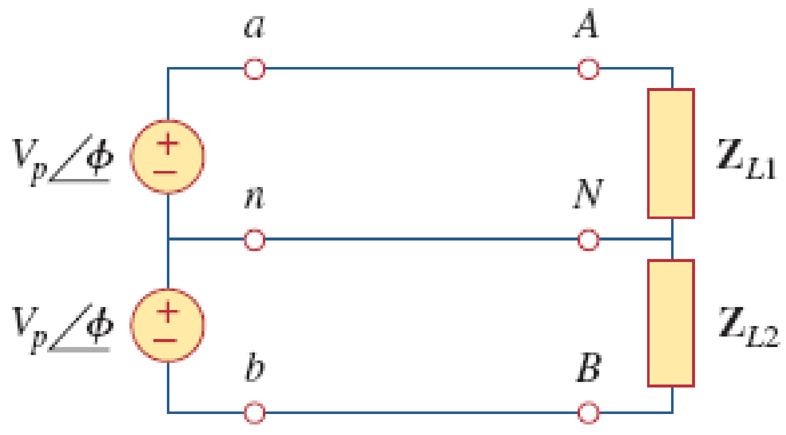
Single Phase Circuits

- Single Phase AC Power: Power source (generator) and load connected via *a pair* of wires.
- Or Combination of sources which are ***in phase***.



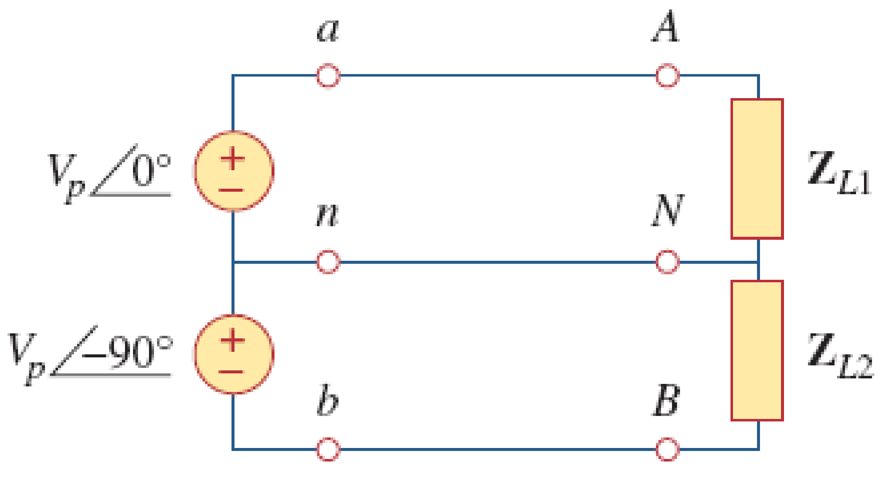
Single phase two wire type



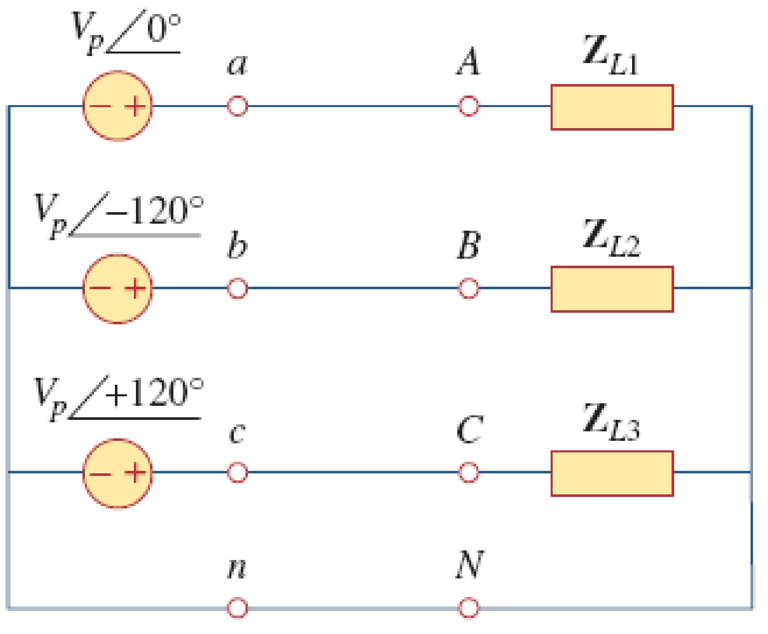
Single phase three wire type

Polyphase Circuits

- Polyphase AC Power: Sources operate at **same frequency** but are **not in phase**
- Two phase system has a phase difference 90 degrees
- Three phase system has a phase difference of 120 degrees



Two phase three-wire system



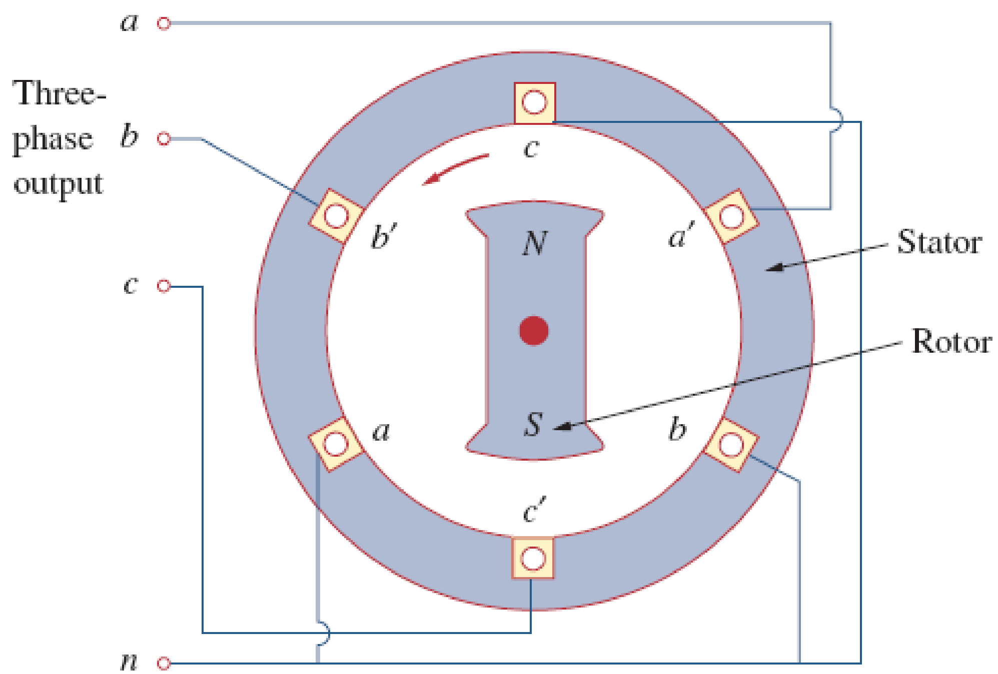
Three phase four-wire system

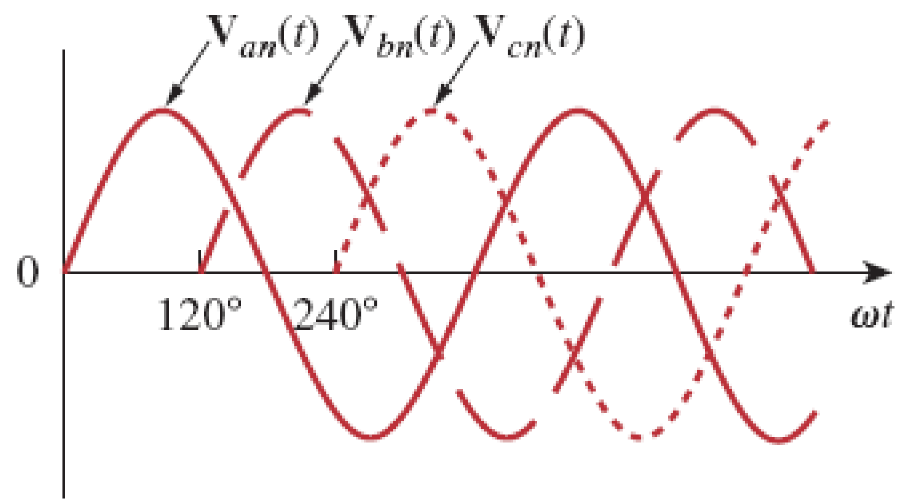
Polyphase Circuits: Advantages

- One/Two phase inputs can be taken out from a three phase supply.
- Capable of delivering constant instantaneous power.
- More economical than single phase in power delivery. Less amount of wire required.
  - Increasing the number of phases, increases efficiency but also increases complexity of transmission.
  - A ‘balance’ is found when the number of phases is **three**.

Balanced Three Phase Voltage

- A three phase supply is typically produced from a three phase generator whose stator coils are placed 120 deg apart.

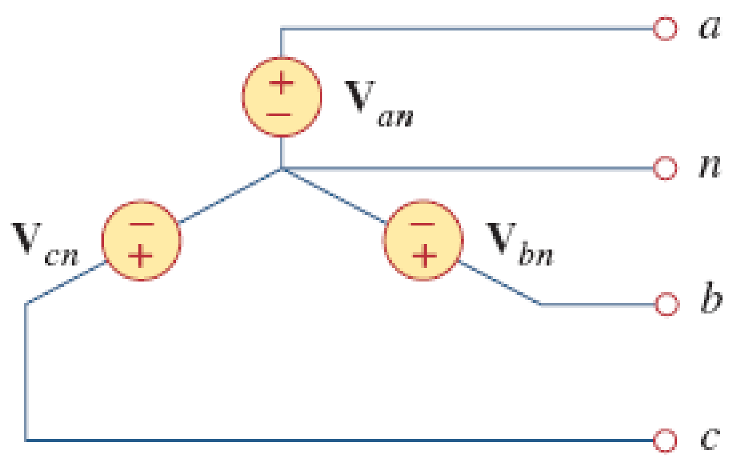




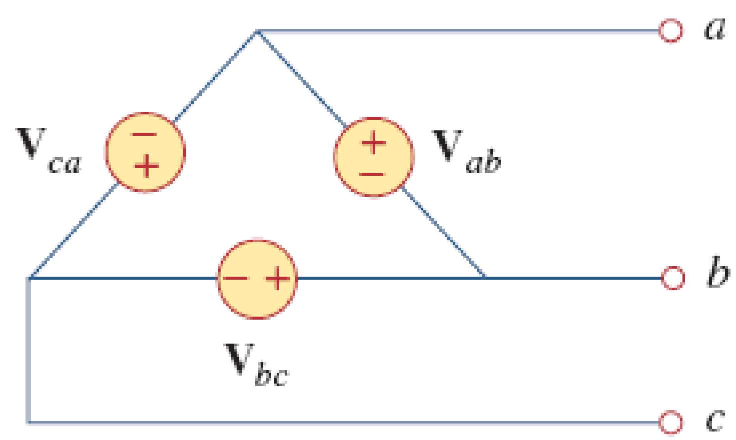
- The three voltages are equal in magnitude but out of phase by 120 deg.

Three Phase System

- Typical 3-phase system has 3 voltage sources connected to loads via 3 or 4 wires
- The sources (and the loads) can be either Delta-connected or Y-connected



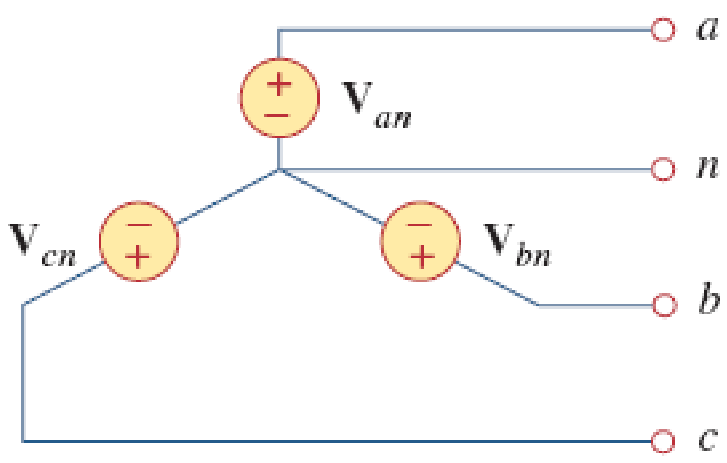
Y-connected



Δ-connected

Balanced Three Phase Source

- Consider the Wye connected source

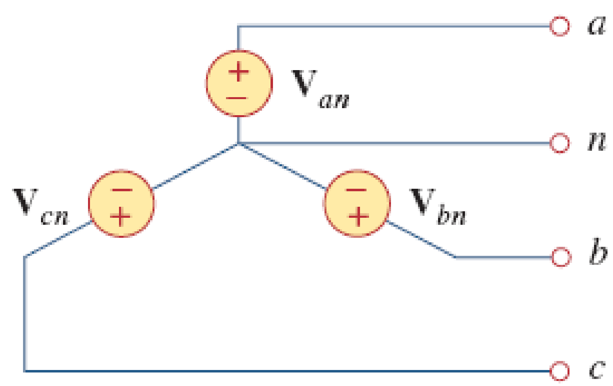


- Voltages V_{an}, V_{bn}, V_{cn} are voltages between the **lines** a, b, c and the **neutral line** n. They are called **phase voltages**.
- The voltages between the lines, i.e., V_{ab}, V_{bc}, V_{ca} are called as **line voltages**.
- The source is said to be **balanced** if
  - Sources are of same amplitude and frequency and are out of phase with each other by 120 degrees.

$$\mathbf{V}_{an} + \mathbf{V}_{bn} + \mathbf{V}_{cn} = 0$$

$$|\mathbf{V}_{an}| = |\mathbf{V}_{bn}| = |\mathbf{V}_{cn}|$$

Phase Sequence



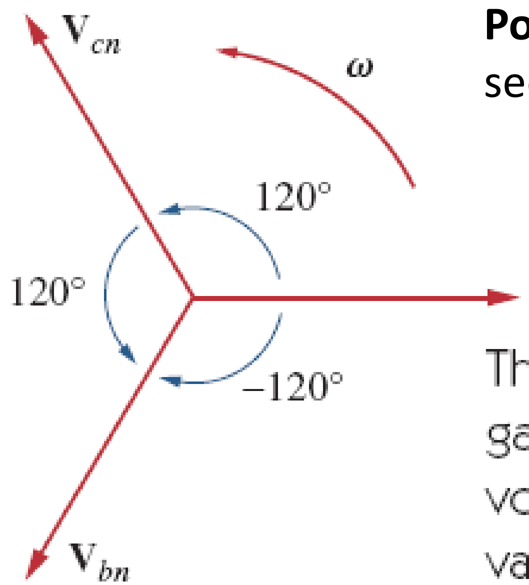
- There are two possible ways in which a source can be balanced

$$\mathbf{V}_{an} + \mathbf{V}_{bn} + \mathbf{V}_{cn} = 0$$

$$|\mathbf{V}_{an}| = |\mathbf{V}_{bn}| = |\mathbf{V}_{cn}|$$

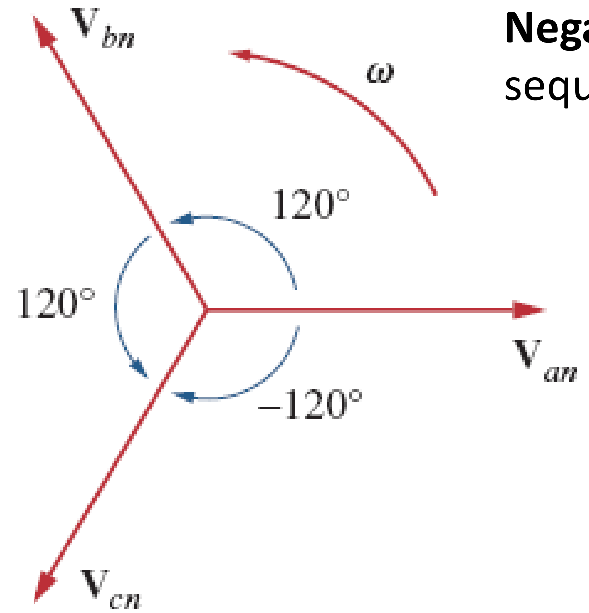
$$\begin{aligned} \mathbf{V}_{an} &= V_p\angle 0^\circ \\ \mathbf{V}_{bn} &= V_p\angle -120^\circ \\ \mathbf{V}_{cn} &= V_p\angle -240^\circ = V_p\angle +120^\circ \end{aligned}$$

$$\begin{aligned} \mathbf{V}_{an} &= V_p\angle 0^\circ \\ \mathbf{V}_{cn} &= V_p\angle -120^\circ \\ \mathbf{V}_{bn} &= V_p\angle -240^\circ = V_p\angle +120^\circ \end{aligned}$$



Positive or abc sequence

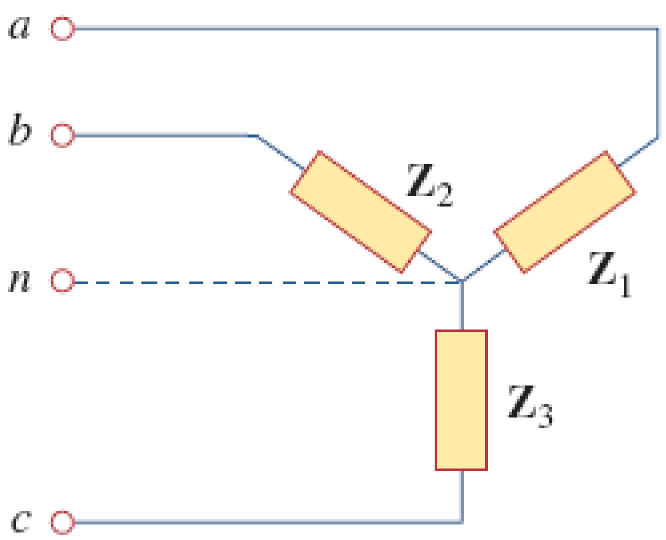
The phase sequence may also be regarded as the order in which the phase voltages reach their peak (or maximum) values with respect to time.



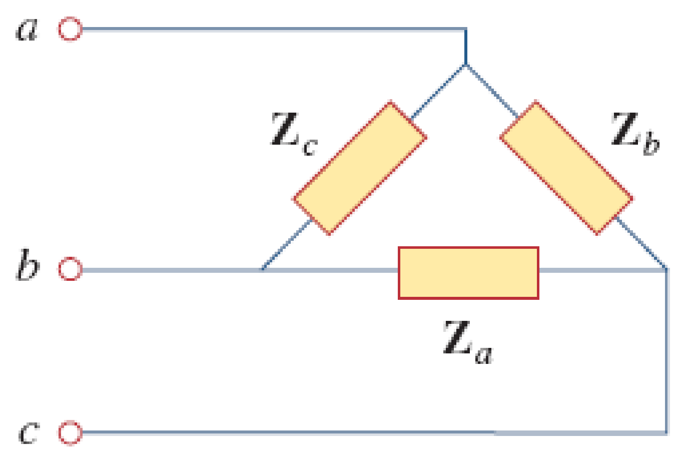
Negative or acb sequence

Balanced Three Phase Load

- Similar to the source, the load can also be Delta or Wye connected.
- A balanced load is one in which the phase impedances are equal in magnitude and in phase.



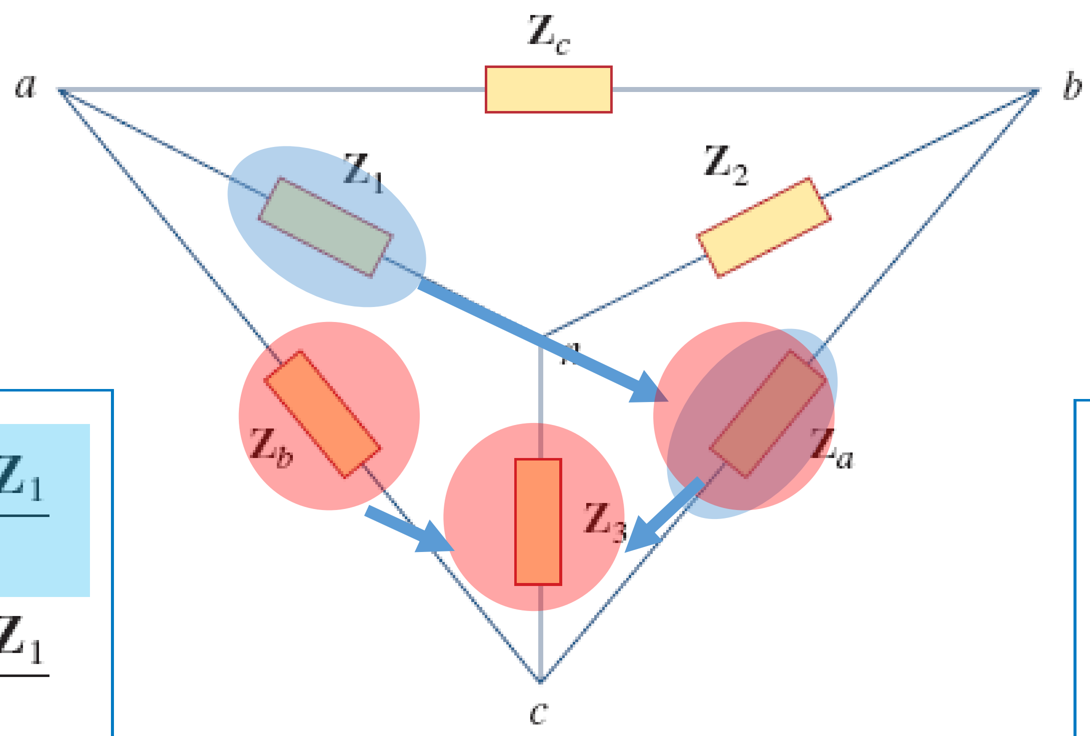
$$\mathbf{Z}_1 = \mathbf{Z}_2 = \mathbf{Z}_3 = \mathbf{Z}_Y$$



$$\mathbf{Z}_a = \mathbf{Z}_b = \mathbf{Z}_c = \mathbf{Z}_\Delta$$

Y←→ Delta Conversion for the loads

- Recalling the Y-Delta conversions (in two port networks)



Y-Δ Conversion:

$$Z_a = \frac{Z_1Z_2 + Z_2Z_3 + Z_3Z_1}{Z_1}$$

$$Z_b = \frac{Z_1Z_2 + Z_2Z_3 + Z_3Z_1}{Z_2}$$

$$Z_c = \frac{Z_1Z_2 + Z_2Z_3 + Z_3Z_1}{Z_3}$$

Δ-Y Conversion:

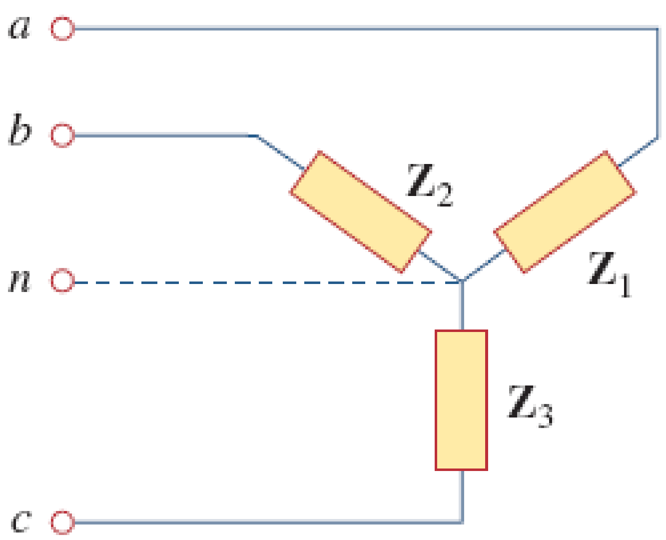
$$Z_1 = \frac{Z_bZ_c}{Z_a + Z_b + Z_c}$$

$$Z_2 = \frac{Z_cZ_a}{Z_a + Z_b + Z_c}$$

$$Z_3 = \frac{Z_aZ_b}{Z_a + Z_b + Z_c}$$

Balanced Three Phase Load

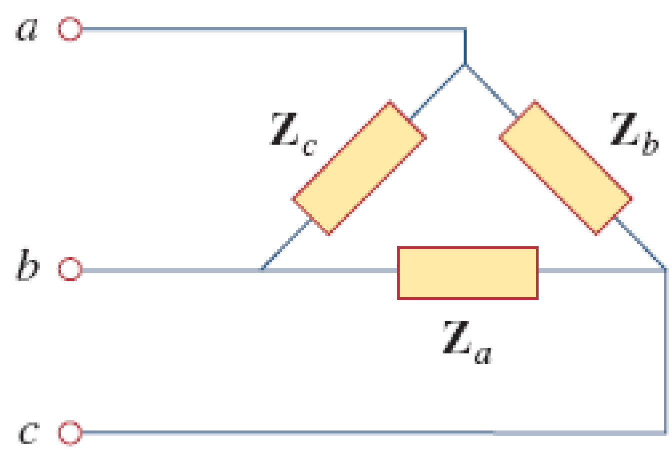
- Similar to the source, the load can also be Delta or Wye connected.
- A balanced load is one in which the phase impedances are equal in magnitude and in phase.



$$\mathbf{Z}_1 = \mathbf{Z}_2 = \mathbf{Z}_3 = \mathbf{Z}_Y$$

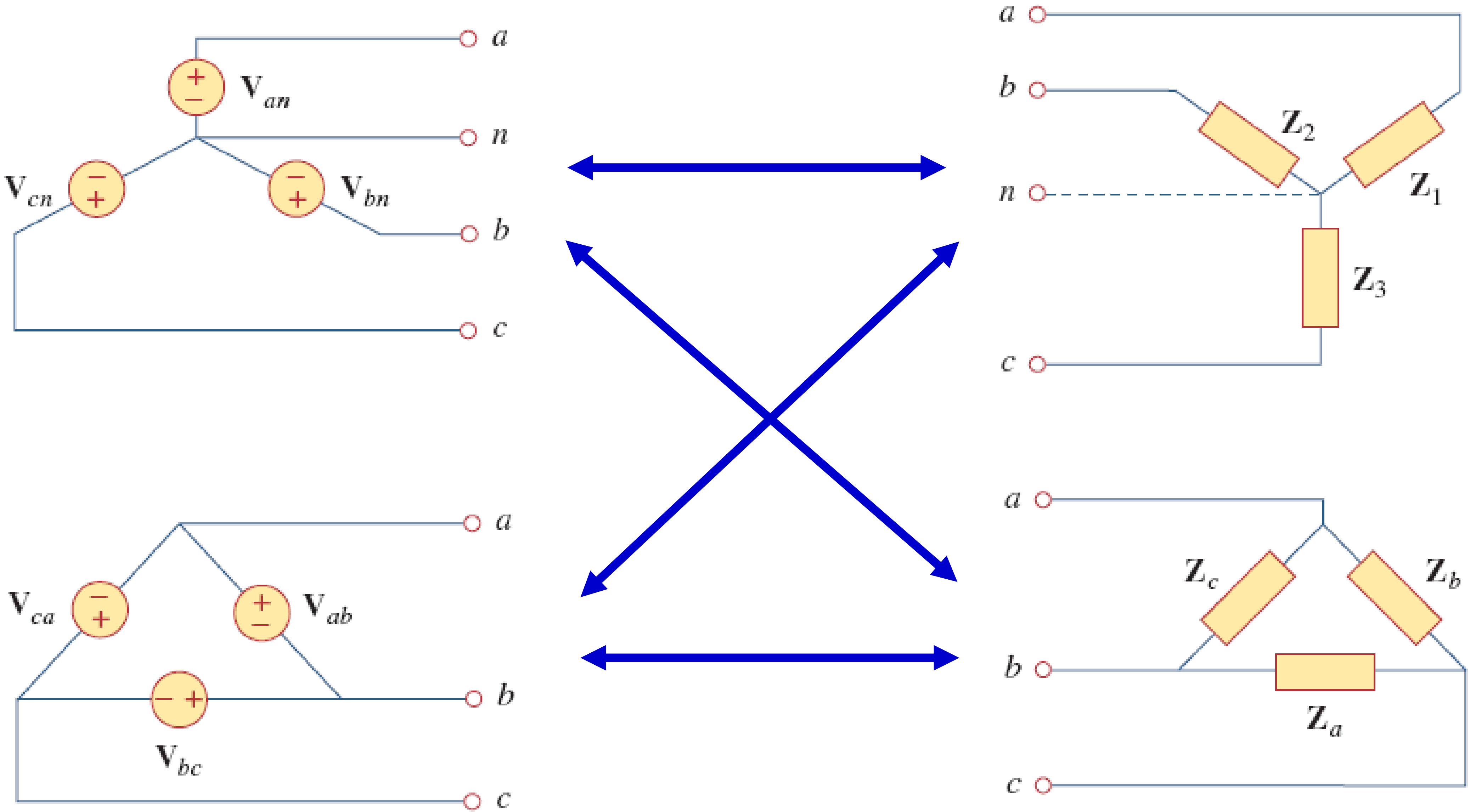
When load is balanced equivalent load is

$$\mathbf{Z}_\Delta = 3\mathbf{Z}_Y \quad \text{or} \quad \mathbf{Z}_Y = \frac{1}{3}\mathbf{Z}_\Delta$$



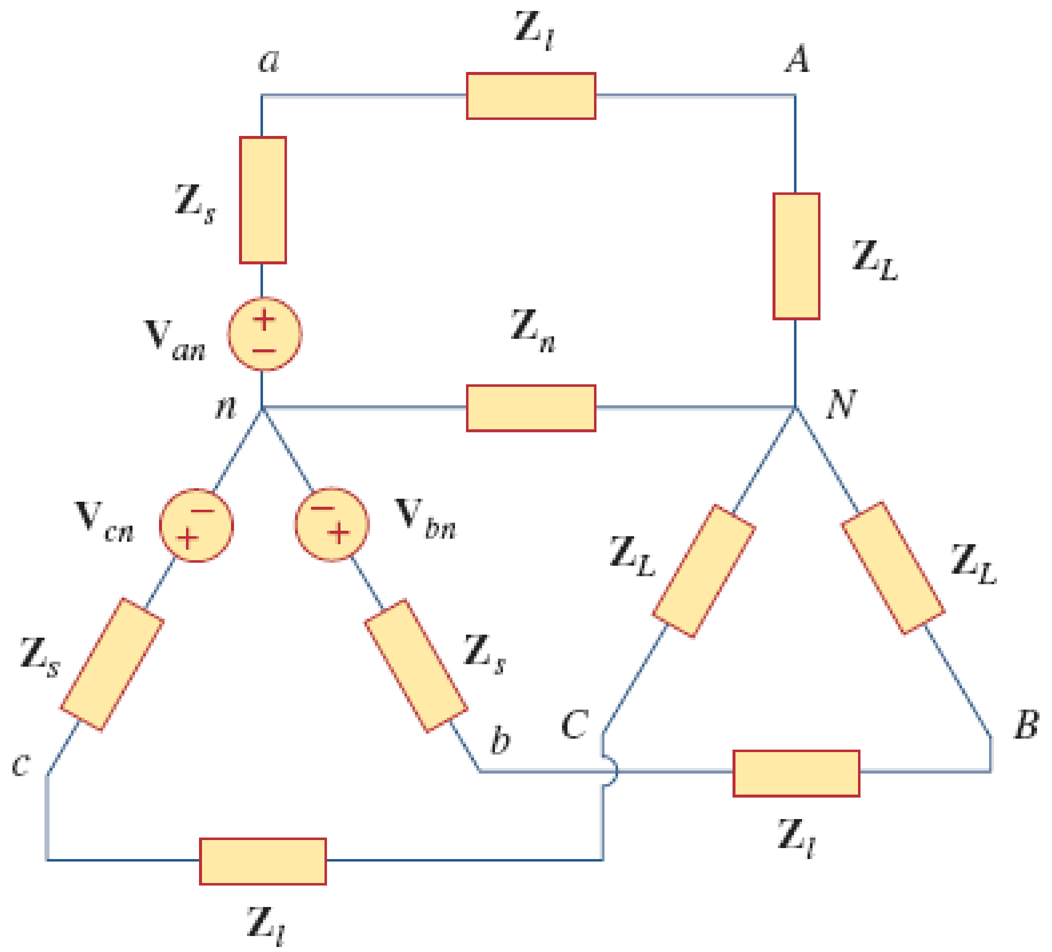
$$\mathbf{Z}_a = \mathbf{Z}_b = \mathbf{Z}_c = \mathbf{Z}_\Delta$$

Configurations in 3 Phase Circuits



Balanced Y-Y Connection

- A balanced Y-Y system is easy to analyze.
- Other configurations can be reduced to Y-Y configuration.
- Consider the 3 phase 4 wire Y-Y connection as shown.



Balanced Y-Y Connection

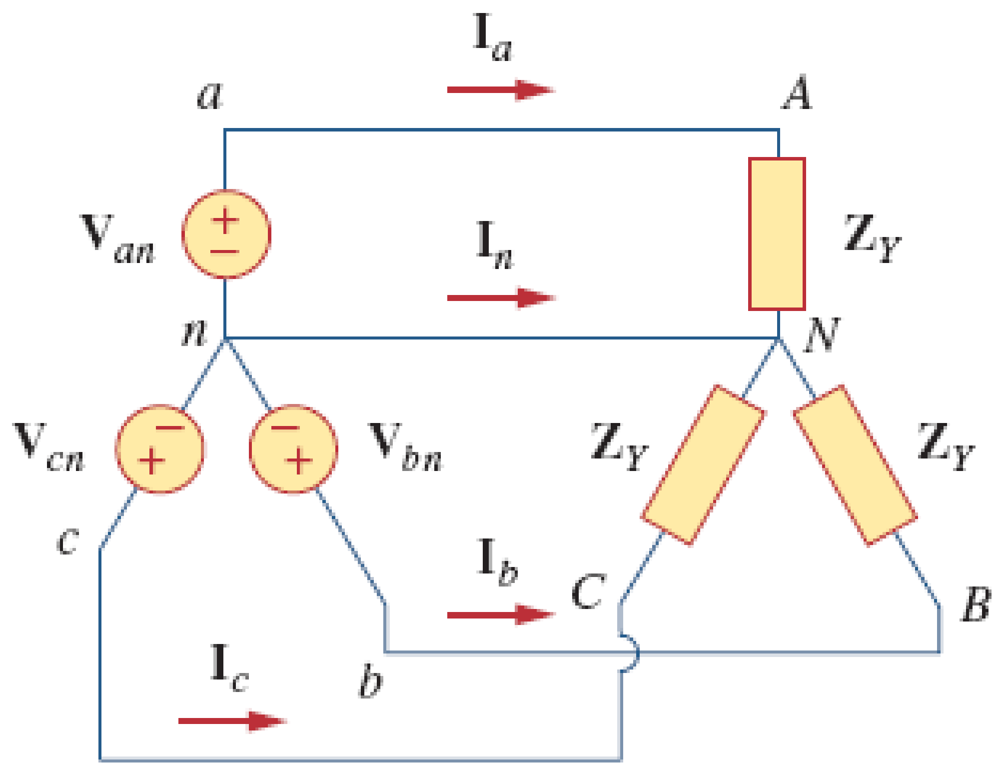
- Consider the 3 phase 4 wire Y-Y connection as shown.

$$\mathbf{Z}_Y = \mathbf{Z}_s + \mathbf{Z}_\ell + \mathbf{Z}_L$$

- The source *phase* voltages are

$$\mathbf{V}_{an} = V_p\angle 0^\circ$$

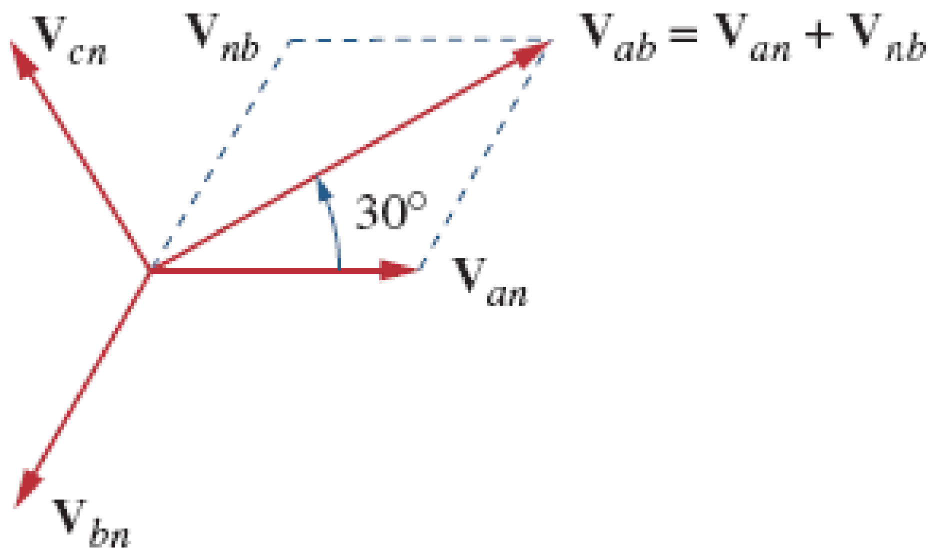
$$\mathbf{V}_{bn} = V_p\angle -120^\circ, \qquad \mathbf{V}_{cn} = V_p\angle +120^\circ$$



Balanced Y-Y Connection

- Consider the 3 phase 4 wire Y-Y connection as shown.

$$\mathbf{Z}_Y = \mathbf{Z}_s + \mathbf{Z}_\ell + \mathbf{Z}_L$$



- The source *phase* voltages are

$$\mathbf{V}_{an} = V_p\angle 0^\circ$$

$$\mathbf{V}_{bn} = V_p\angle -120^\circ, \qquad \mathbf{V}_{cn} = V_p\angle +120^\circ$$

- The line voltages can be found as

$$\mathbf{V}_{ab} = \mathbf{V}_{an} + \mathbf{V}_{nb} = \mathbf{V}_{an} - \mathbf{V}_{bn} = V_p\angle 0^\circ - V_p\angle -120^\circ$$

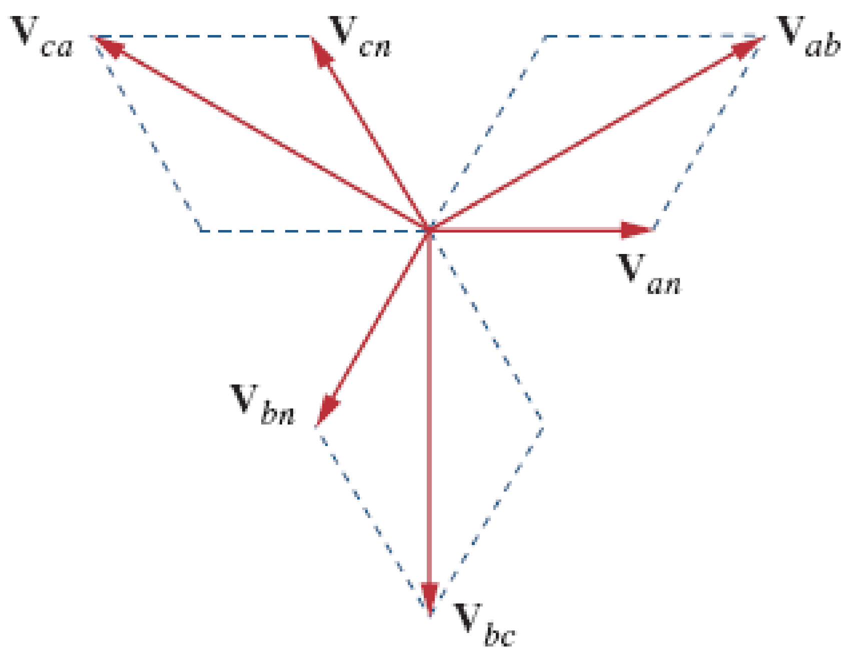
$$= V_p\left(1 + \frac{1}{2} + j\frac{\sqrt{3}}{2}\right) = \sqrt{3}V_p\angle 30^\circ$$

$$\mathbf{V}_{bc} = \mathbf{V}_{bn} - \mathbf{V}_{cn} = \sqrt{3}V_p\angle -90^\circ$$

$$\mathbf{V}_{ca} = \mathbf{V}_{cn} - \mathbf{V}_{an} = \sqrt{3}V_p\angle -210^\circ$$

Balanced Y-Y Connection

- Thus the *line **voltages*** are $\sqrt{3}$ **times** the source phase voltages and **lead** them by **30** deg. and are 120 deg. out of phase with one another in a **Y connected** source



$$V_p = |\mathbf{V}_{an}| = |\mathbf{V}_{bn}| = |\mathbf{V}_{cn}|$$

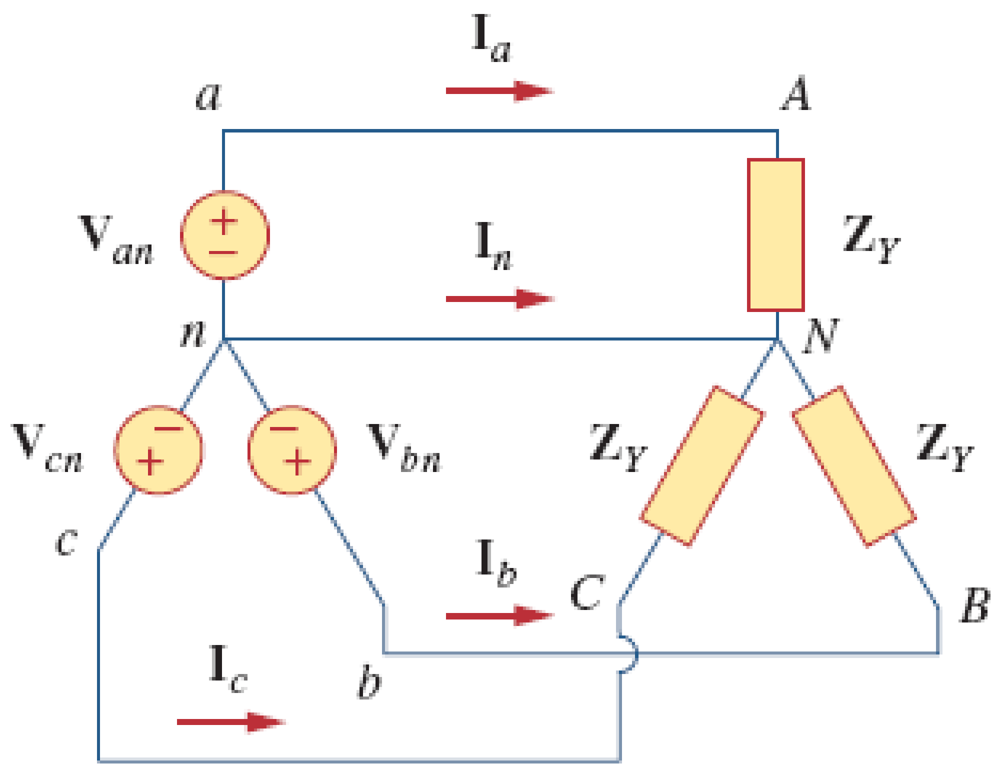
$$V_L = |\mathbf{V}_{ab}| = |\mathbf{V}_{bc}| = |\mathbf{V}_{ca}|$$

$$V_L = \sqrt{3}V_p$$

Balanced Y-Y Connection

- In addition, because of balanced load

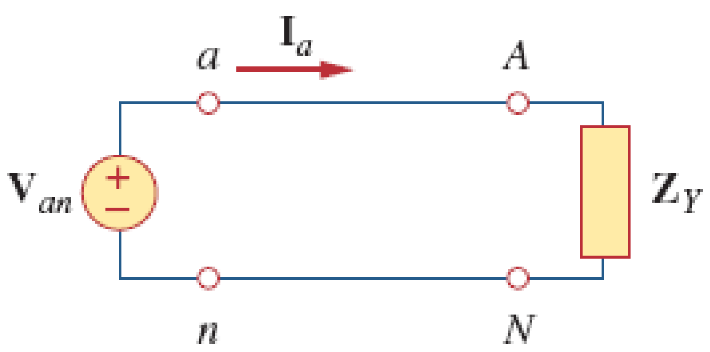
$$
\begin{aligned}
I_n &= -(I_a + I_b + I_c) \\
&= -\frac{1}{Z_Y}(V_{an} + V_{bn} + V_{cn}) \\
&= 0 \\
V_{nN} &= I_n Z_n = 0
\end{aligned}
$$



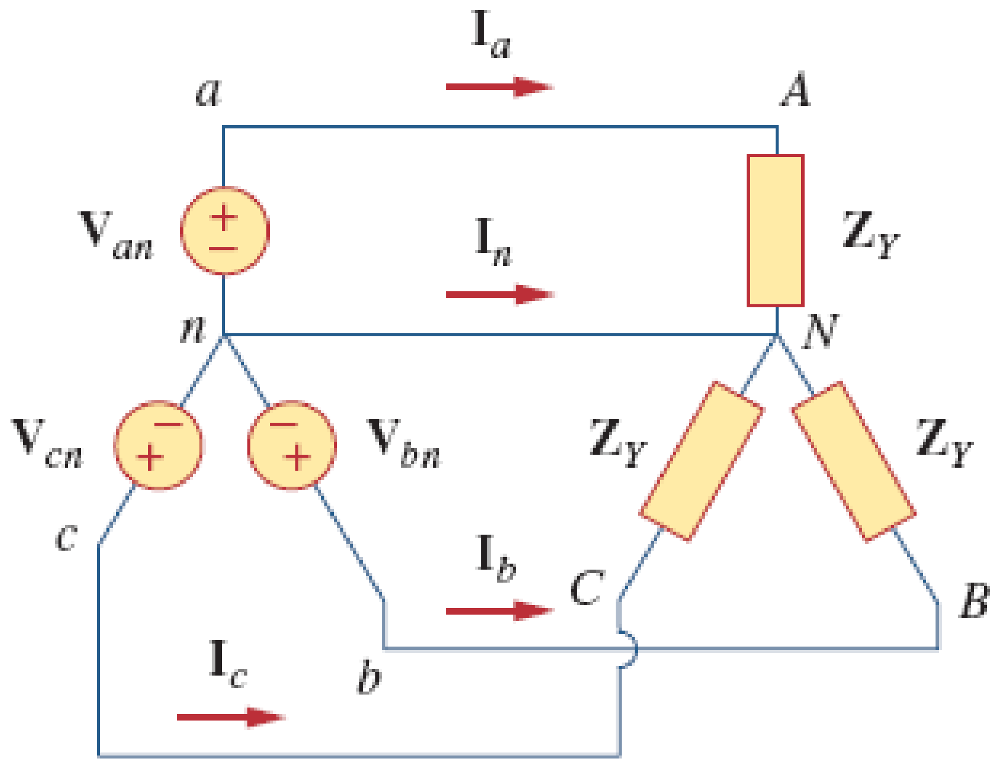
- Voltage across neutral wire is zero.
- Earth is usually the neutral line.

Balanced Y-Y Connection

- The **line current** is the current in each line (A-a,B-b,C-c), the **phase current** is the current in each phase of load.
- **For Y-Y, both are equal**.
- In case of Y-Y, we can also do per phase analysis.



$$I_a = \frac{V_{an}}{Z_Y}$$



Example 1: Balanced Y-Y Connection

- Find the line currents.

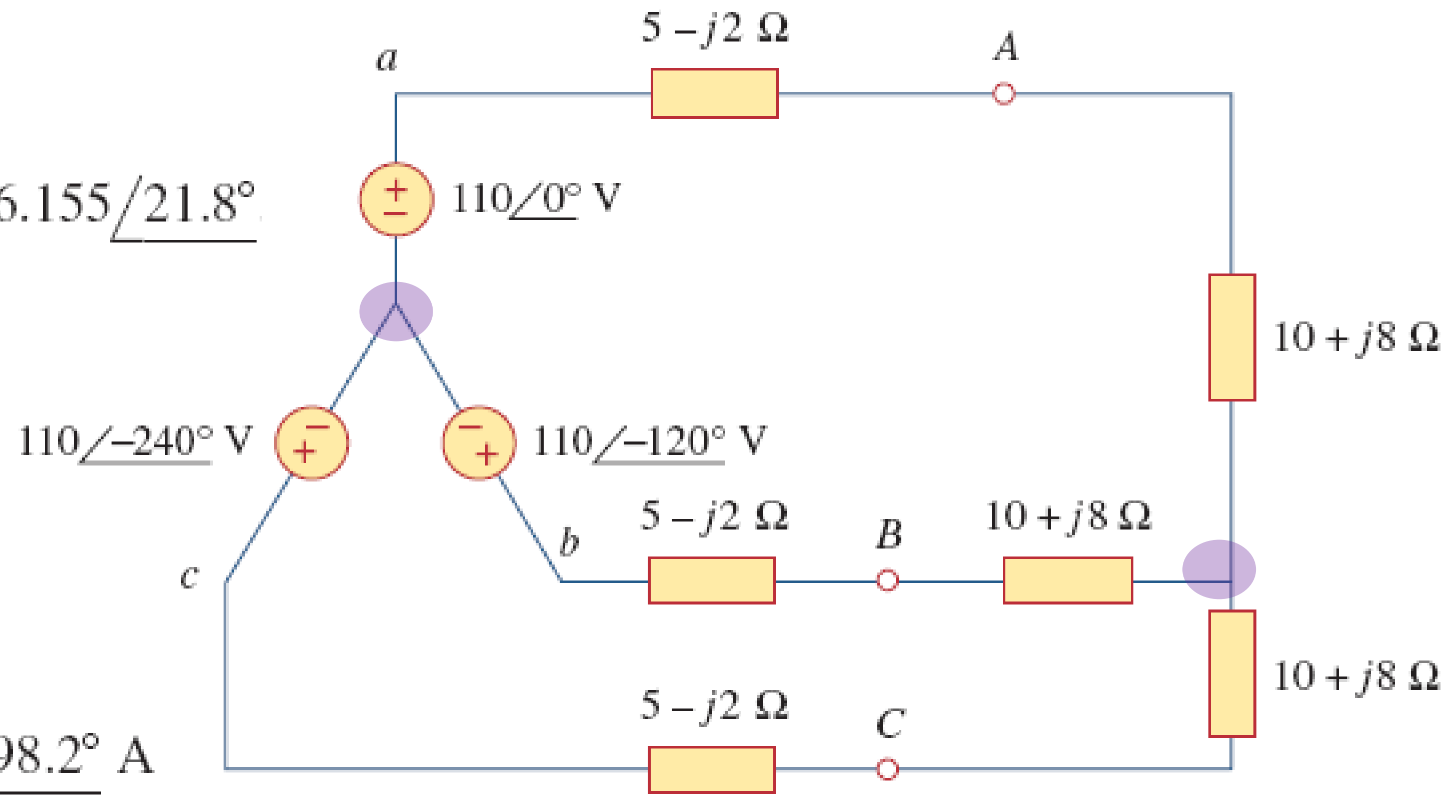
$$\mathbf{I}_a = \frac{\mathbf{V}_{an}}{\mathbf{Z}_Y}$$

$$\mathbf{Z}_Y = (5 - j2) + (10 + j8) = 15 + j6 = 16.155\angle 21.8^\circ$$

$$\mathbf{I}_a = \frac{110\angle 0^\circ}{16.155\angle 21.8^\circ} = 6.81\angle -21.8^\circ \text{ A}$$

$$\mathbf{I}_b = \mathbf{I}_a\angle -120^\circ = 6.81\angle -141.8^\circ \text{ A}$$

$$\mathbf{I}_c = \mathbf{I}_a\angle -240^\circ = 6.81\angle -261.8^\circ \text{ A} = 6.81\angle 98.2^\circ \text{ A}$$



Power in Balanced 3-Phase Connections

- In a balanced three phase connection, with balanced source and balanced load ($Z\angle\theta$) in each phase
- Consider a Y-connected load
- Let V_{ph} be rms value of the load phase voltage

$$
\begin{aligned}
v_{A,ph} &= \sqrt{2}V_{ph}\cos(\omega t) \\
v_{B,ph} &= \sqrt{2}V_{ph}\cos(\omega t - 120^\circ) \\
v_{C,ph} &= \sqrt{2}V_{ph}\cos(\omega t + 120^\circ)
\end{aligned}
$$

- Due to the load, phase currents would lag phase voltage by θ

$$
\begin{aligned}
i_{A,ph} &= \sqrt{2}I_{ph}\cos(\omega t - \theta) \\
i_{B,ph} &= \sqrt{2}I_{ph}\cos(\omega t - 120^\circ - \theta) \\
i_{C,ph} &= \sqrt{2}I_{ph}\cos(\omega t + 120^\circ - \theta) \\
I_{ph} &= \frac{V_{ph}}{Z}
\end{aligned}
$$

Power in 3 Balanced Phase Connections

- Now, the instantaneous power is :

$$\begin{aligned} p &= p_A + p_B + p_C \\ &= v_{A,ph} i_{A,ph} + v_{B,ph} i_{B,ph} + v_{C,ph} i_{C,ph} \\ &= 2V_{ph} I_{ph} \left[\cos(\omega t)\cos(\omega t - \theta) \right. \\ &\quad + \cos(\omega t - 120^\circ)\cos(\omega t - 120^\circ - \theta) \\ &\quad \left. + \cos(\omega t + 120^\circ)\cos(\omega t + 120^\circ - \theta)\right] \end{aligned}$$

- Using $\boxed{\cos A \cos B = \frac{1}{2}[\cos(A - B) + \cos(A + B)]}$

$$p = V_{ph} I_{ph} \left[3\cos(\theta) + \cos(\alpha) + \cos(\alpha - 240^\circ) + \cos(\alpha + 240^\circ)\right]$$
$$\text{where } \alpha = 2\omega t - \theta$$

Power in 3 Balanced Phase Connections

- Instantaneous power is :

$$p = V_{ph} I_{ph} \left[3\cos(\theta) + \cos(\alpha) + \cos(\alpha - 240°) + \cos(\alpha + 240°)\right]$$
$$\text{where } \alpha = 2\omega t - \theta$$

$$\begin{aligned} p &= V_{ph} I_{ph} [3\cos(\theta) + \cos(\alpha) + \cos(\alpha)\cos(240°) \\ &\quad + \cancel{\sin(\alpha)\sin(240°)} + \cos(\alpha)\cos(240°) - \cancel{\sin(\alpha)\sin(240°)}] \end{aligned}$$

$$p = V_{ph} I_{ph} \left[3\cos(\theta) + \cos(\alpha) + 2\cos(\alpha)(-0.5)\right] = \boxed{3 V_{ph} I_{ph} \cos(\theta)}$$

- **Total instantaneous power in a balanced 3-phase system is constant (Advantage 1)**

Power in 3 Balanced Phase Connections

- Since, instantaneous power is constant and circuit is balanced, total power and average per phase power are

$$P = 3V_{ph}I_{ph}\cos(\theta) \qquad\qquad P_p = V_{ph}I_{ph}\cos(\theta)$$

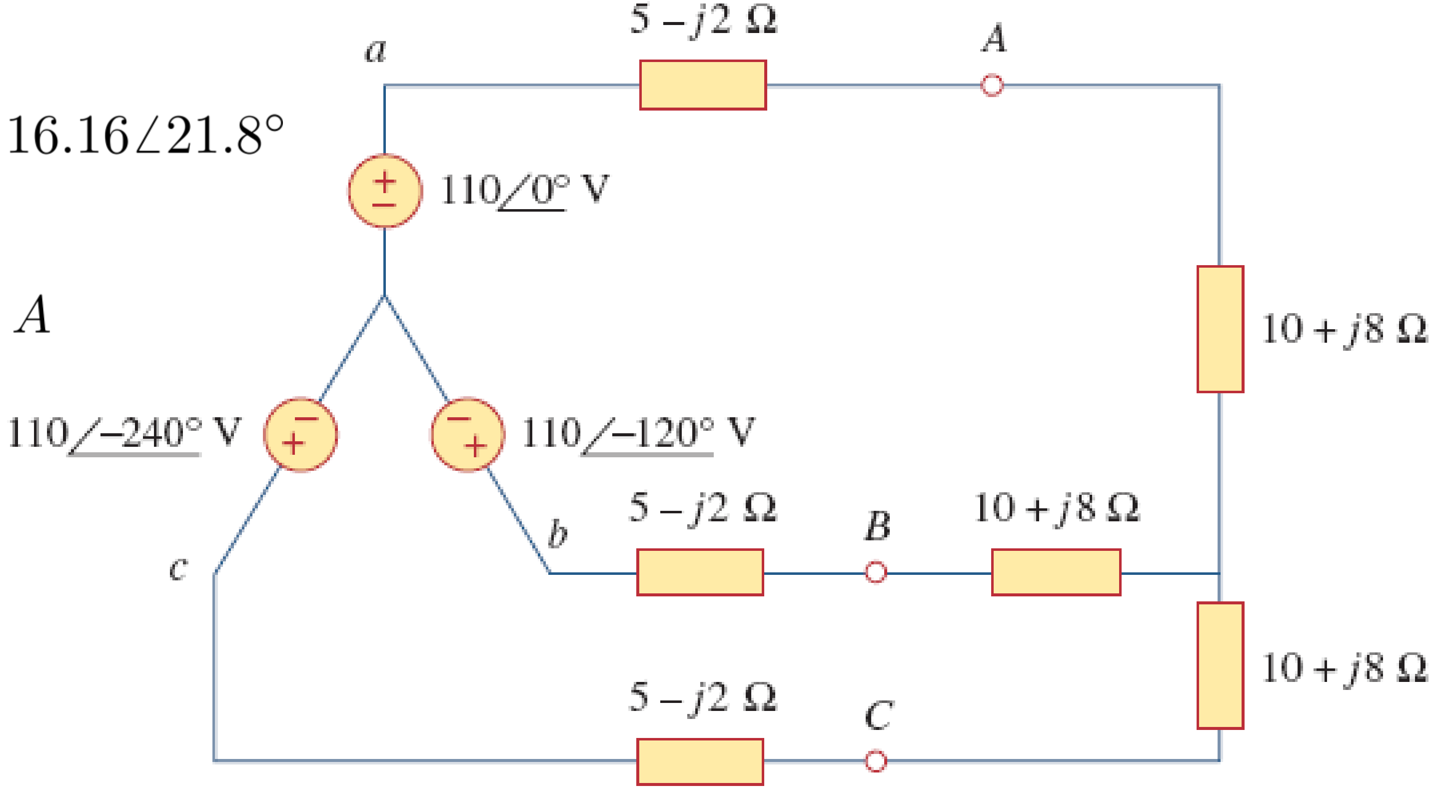
- The corresponding reactive power, apparent power, and complex power would be

$$\begin{aligned} Q &= 3V_{ph}I_{ph}\sin(\theta) & Q_p &= V_{ph}I_{ph}\sin(\theta) \\ S &= 3V_{ph}I_{ph} & S_p &= V_{ph}I_{ph} \\ \mathbf{S} &= P + jQ = 3\mathbf{V}_{ph}\mathbf{I}^*_{ph} & \mathbf{S}_p &= P_p + jQ_p = \mathbf{V}_{ph}\mathbf{I}^*_{ph} \end{aligned}$$

Example 2

- Find the total average power consumed by the load.

$$\mathbf{I}_a = \frac{\mathbf{V}_{an}}{Z_Y}$$



$$Z_Y = (5 - j2) + (10 + j8) = 15 + j6 = 16.16\angle 21.8°$$

$$\mathbf{I}_{ph} = \mathbf{I}_a = \frac{110\angle 0°}{16.15\angle 21.8°} = 6.81\angle(-21.8°)\ A$$

$$\mathbf{V}_{ph} = \mathbf{I}_{ph} Z_L$$
$$P = 3|\mathbf{V}_{ph}||\mathbf{I}_{ph}|\cos(\angle Z_L) = 3|\mathbf{I}_{ph}|^2 R_{ph}$$

$$P = 3 \times (6.81)^2 \times 15 = 2087\ W$$

Polyphase Circuits: Advantages

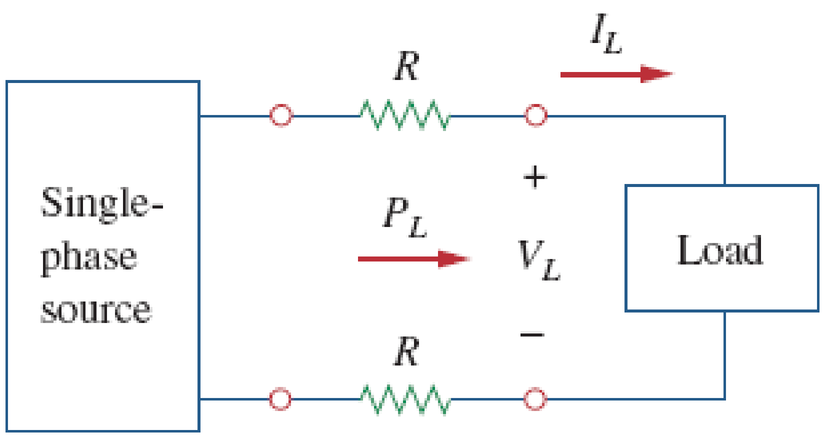
- Capable of delivering constant instantaneous power
- One/Two phase inputs can be taken out from a three phase supply.
- More economical than single phase in power delivery. Less amount of wire required.
  - Increasing the number of phases, increases efficiency but also increases complexity of transmission.
  - A ‘balance’ is found when the number of phases is **three**.

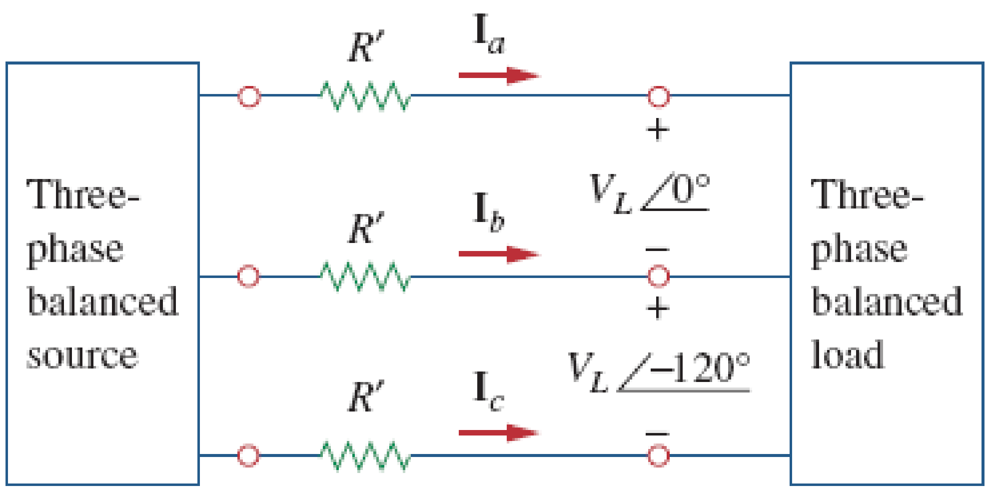
Advantage 2: Economical Transmission

- Consider an amount of power P_L being transmitted at the same line voltage V_L using
  - Single phase supply
  - 3-phase balanced supply
- Power dissipation in transmission

$$I_L = \frac{P_L}{V_L}$$
$$P_{loss} = 2I_L^2 R = 2R\frac{P_L^2}{V_L^2}$$

$$I_L' = |\mathbf{I}_a| = |\mathbf{I}_b| = |\mathbf{I}_c| = P_L/(\sqrt{3}V_L)$$
$$P_{loss}' = 3(I_L')^2 R' = 3R'\frac{P_L^2}{3V_L^2} = R'\frac{P_L^2}{V_L^2}$$





Advantage 2: Economical Transmission

- Power dissipation in transmission

$$P_{loss} = 2I_L^2 R = 2R\frac{P_L^2}{V_L^2} \qquad P'_{loss} = 3(I'_L)^2 R' = 3R'\frac{P_L^2}{3V_L^2} = R'\frac{P_L^2}{V_L^2}$$

$$R = \frac{\rho l}{\pi r^2} \qquad R' = \frac{\rho l}{\pi (r')^2}$$

$$\frac{P_{loss}}{P'_{loss}} = \frac{2(r')^2}{r^2}$$

- If same amount of power loss is to be allowed $r^2 = 2(r')^2$
- Ratio of material required for transmission wires

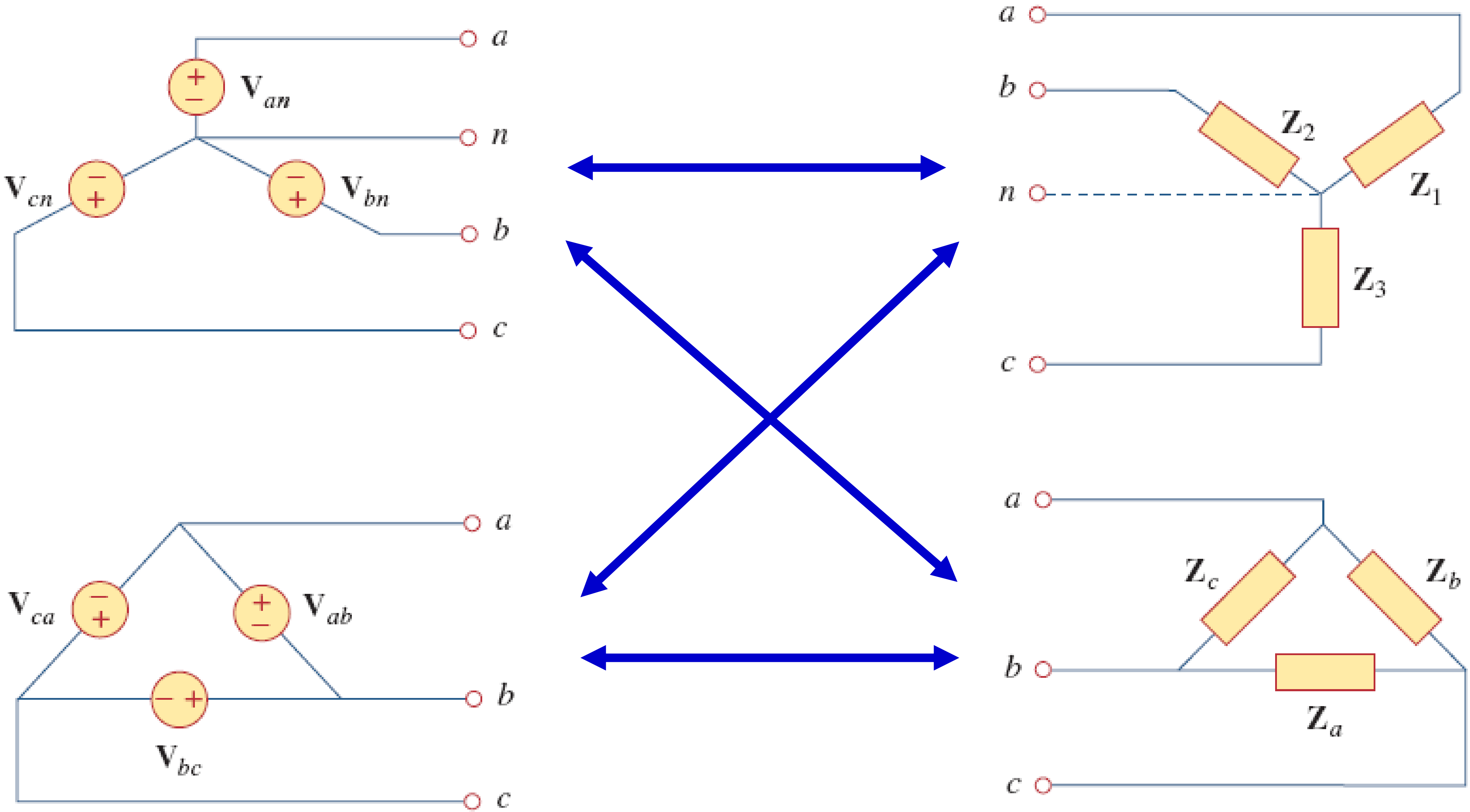
$$\begin{aligned} \frac{\text{material in single ph}}{\text{material in 3-ph}} &= \frac{2(\pi r^2 l)}{3(\pi r'^2 l)} \\ &= \frac{2}{3}\left(\frac{r}{r'}\right)^2 = \frac{2}{3}(2) = \frac{4}{3} \end{aligned}$$

In other words, a 3-phase supply can deliver power, and follow power loss constraints using only 75% of the material as an equivalent single phase supply.

Polyphase Circuits: Advantages

- Capable of delivering constant instantaneous power.
- One/Two phase inputs can be taken out from a three phase supply.
- More economical than single phase in power delivery. Less amount of wire required.
  - Increasing the number of phases, increases efficiency but also increases complexity of transmission.
  - A ‘balance’ is found when the number of phases is **three**.

Other Configurations



Balanced Y-Δ Connection

- Source is Y Connected and load is Delta connected.
- Source Side:
  - Phase Voltages

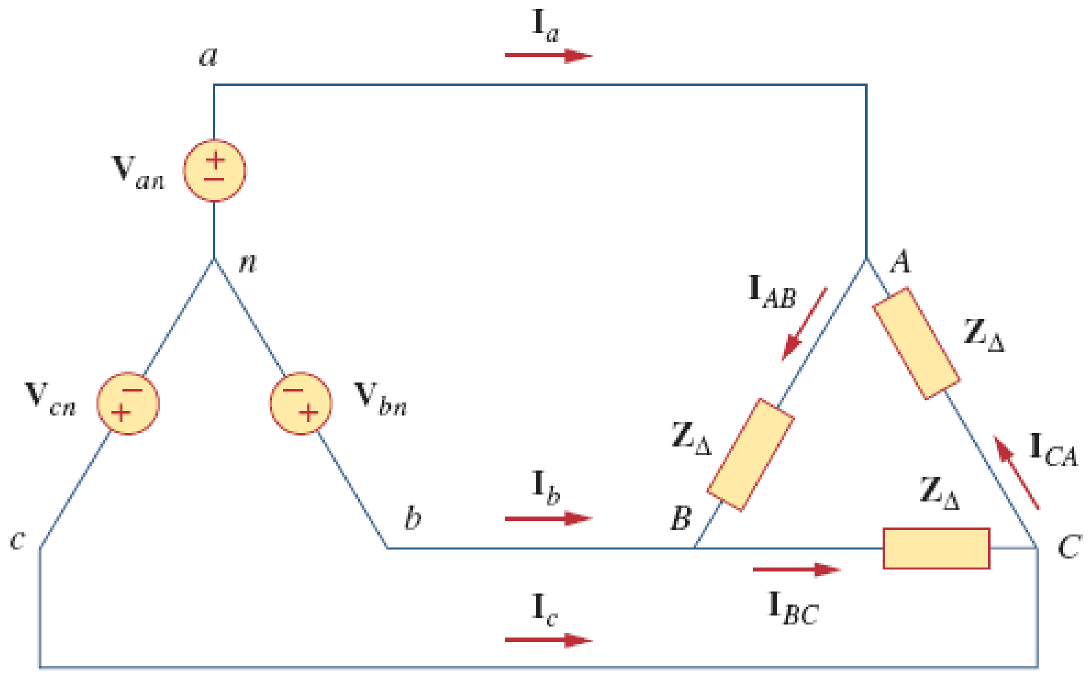
$$\mathbf{V}_{an} = V_p\angle 0^\circ$$

$$\mathbf{V}_{bn} = V_p\angle -120^\circ, \qquad \mathbf{V}_{cn} = V_p\angle +120^\circ$$

  - Line Voltages

$$\mathbf{V}_{ab} = \sqrt{3}V_p\angle 30^\circ = \mathbf{V}_{AB}, \qquad \mathbf{V}_{bc} = \sqrt{3}V_p\angle -90^\circ = \mathbf{V}_{BC}$$

$$\mathbf{V}_{ca} = \sqrt{3}V_p\angle -150^\circ = \mathbf{V}_{CA}$$



Note that the line voltage is equal to the phase voltage of the Delta load

Balanced Y-Δ Connection

- Source is Y Connected and load is Delta connected.
- Load Side:
  - Phase currents

$$\mathbf{I}_{AB} = \frac{\mathbf{V}_{AB}}{\mathbf{Z}_\Delta}, \qquad \mathbf{I}_{BC} = \frac{\mathbf{V}_{BC}}{\mathbf{Z}_\Delta}, \qquad \mathbf{I}_{CA} = \frac{\mathbf{V}_{CA}}{\mathbf{Z}_\Delta}$$

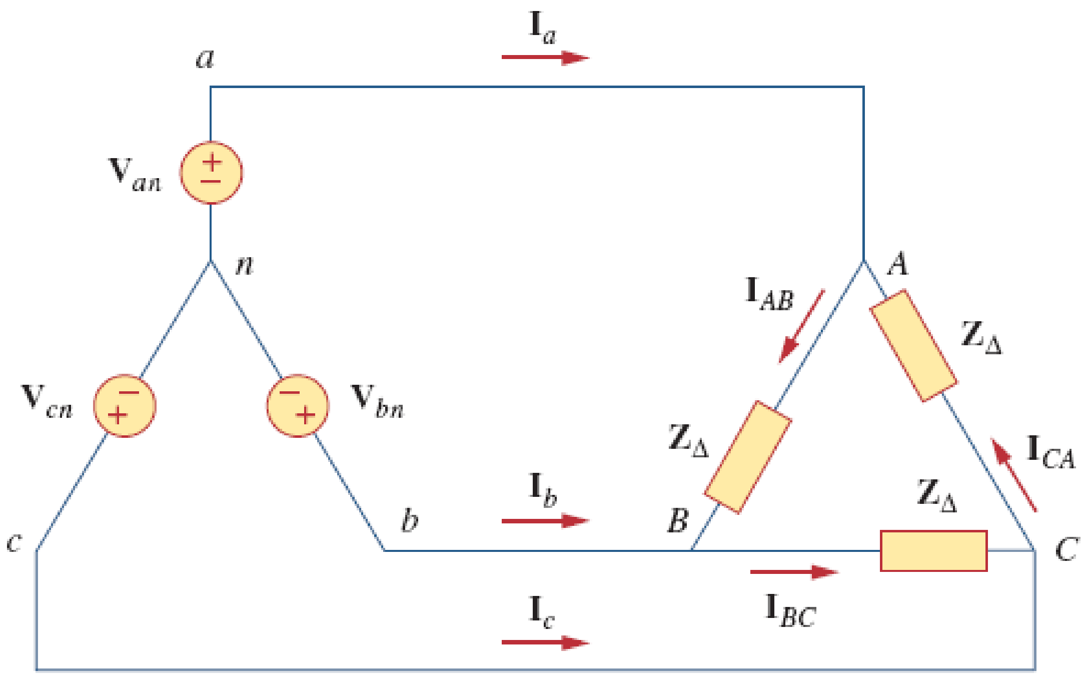
  - Line Currents

$$\mathbf{I}_a = \mathbf{I}_{AB} - \mathbf{I}_{CA}, \qquad \mathbf{I}_{CA} = \mathbf{I}_{AB}\underline{/-240^\circ},$$

$$\mathbf{I}_a = \mathbf{I}_{AB} - \mathbf{I}_{CA} = \mathbf{I}_{AB}(1 - 1\underline{/-240^\circ})$$

$$= \mathbf{I}_{AB}(1 + 0.5 - j0.866) = \mathbf{I}_{AB}\sqrt{3}\underline{/-30^\circ}$$

$$I_L = \sqrt{3} I_p$$



Line Current is $\sqrt{3}$ times the phase current and lags it by 30 deg. in a Delta connected load.

Note : *The load can be replaced by an equivalent Y load* $Z_Y = Z_\Delta/3$*, and can be analyzed as a Y-Y config*

Example 3: Balanced Y-Δ Connection

- A balanced abc-sequence Y-connected source with $V_{an} = 100\angle 10^{\circ} V$ is connected to a Δ connected balanced load (8+j4)Ω per phase. Calculate the phase and line currents.

- Converting the balanced Δ load into equivalent Y load,

$$Z_Y = Z_\Delta/3 = \frac{8+j4}{3} = 2.981\angle 26.6^\circ$$

- Thus, the line currents can be computed using single phase analysis of Y-Y connection

$$\mathbf{I}_a = \frac{\mathbf{V}_{an}}{Z_Y} = \frac{100\angle 10^\circ}{2.98\angle 26.6^\circ} = 33.54\angle -16.6^\circ \ A$$

$$\mathbf{I}_b = \mathbf{I}_a\angle -120^\circ = 33.54\angle -136.6^\circ$$
$$\mathbf{I}_c = 33.54\angle 103.4^\circ$$

- The phase currents in balanced Δ load are related to line currents as

$$\mathbf{I}_{AB} = \frac{\mathbf{I}_a}{\sqrt{3}}\angle 30^\circ = 19.36\angle 13.4^\circ$$

$$\mathbf{I}_{BC} = \mathbf{I}_{AB}\angle -120^\circ = 19.36\angle -106.6^\circ$$
$$\mathbf{I}_{CA} = 19.36\angle 133.4^\circ$$

Balanced Δ-Δ Connection

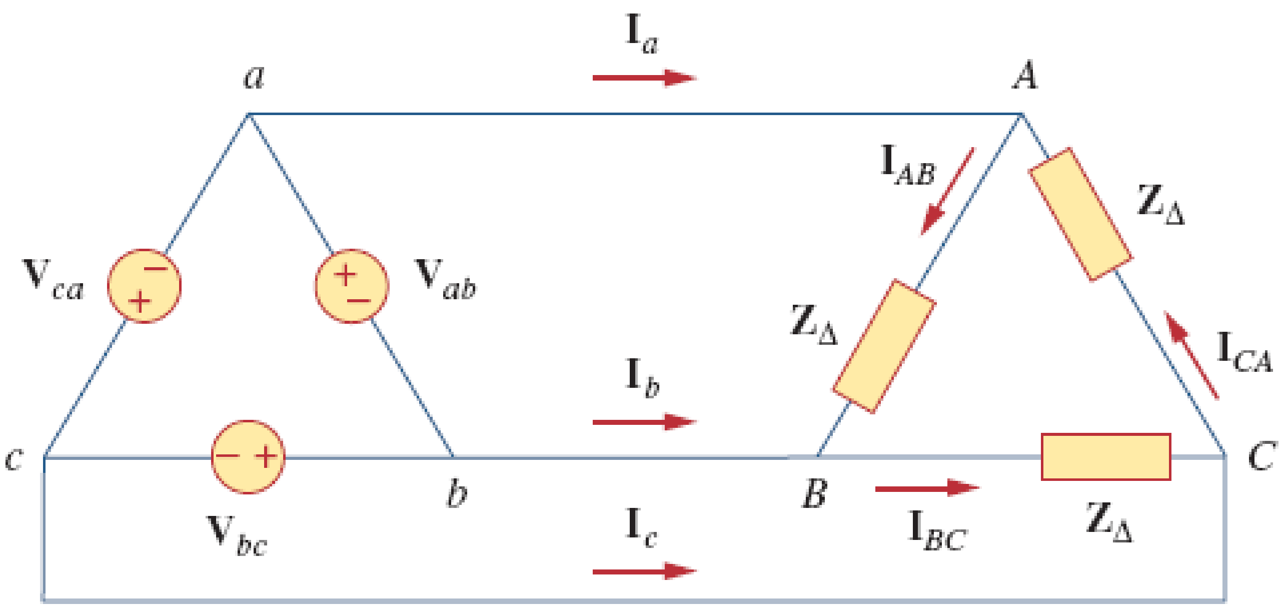
- Both source and load are Delta connected.
- Since both sides are Delta connected, Phase Voltages=Line Voltages

$$\mathbf{V}_{ab} = \mathbf{V}_{AB}, \qquad \mathbf{V}_{bc} = \mathbf{V}_{BC}, \qquad \mathbf{V}_{ca} = \mathbf{V}_{CA}$$

- Phase currents are

$$\mathbf{I}_{AB} = \frac{\mathbf{V}_{AB}}{Z_\Delta} = \frac{\mathbf{V}_{ab}}{Z_\Delta}, \qquad \mathbf{I}_{BC} = \frac{\mathbf{V}_{BC}}{Z_\Delta} = \frac{\mathbf{V}_{bc}}{Z_\Delta}$$

$$\mathbf{I}_{CA} = \frac{\mathbf{V}_{CA}}{Z_\Delta} = \frac{\mathbf{V}_{ca}}{Z_\Delta}$$

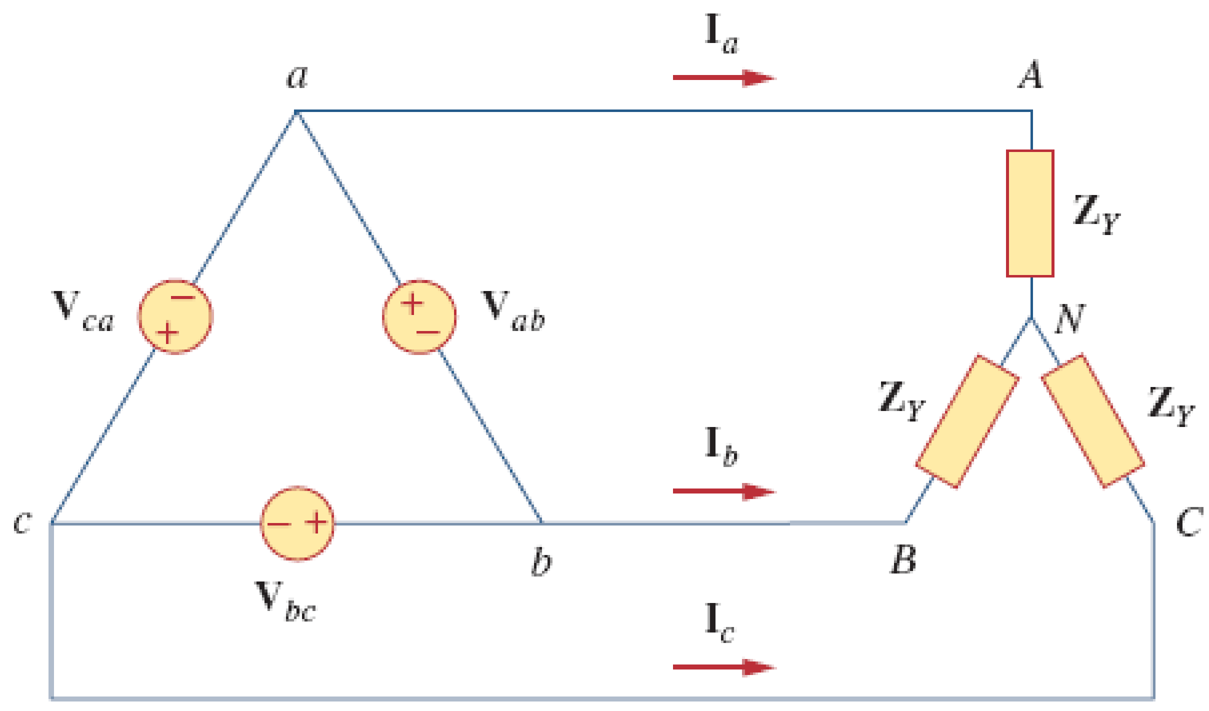


Line Current is related to phase current as (but lags it by 30 deg)

$$I_L = \sqrt{3} I_p$$

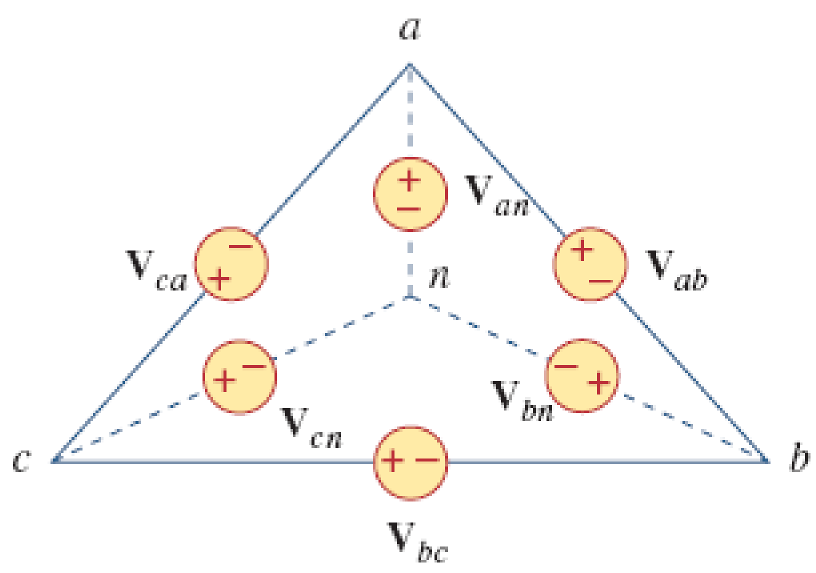
Balanced Δ-Y Connection

- Source is Delta connected, Load is Y connected
- The line currents are equal to the phase currents (because of Y connected load).
- The line voltages
  - Are same as phase voltages of the source side.
  - But are $\sqrt{3}$ times the load phase voltages and lead them by 30 degrees.



Δ-Y Source Transformation

- Another possible way to analyze the Delta-Y connection
  - Transform Delta connected source to Y connected source
  - Analyze the Y-Y connection.
- Observing the phase voltage to line voltage relation in the Y-Y connection



$$\mathbf{V}_{ab} = V_p\angle 0^\circ, \qquad \mathbf{V}_{bc} = V_p\angle -120^\circ$$
$$\mathbf{V}_{ca} = V_p\angle +120^\circ$$

$$\rightarrow$$

$$\mathbf{V}_{an} = \frac{V_p}{\sqrt{3}}\angle -30^\circ$$
$$\mathbf{V}_{bn} = \frac{V_p}{\sqrt{3}}\angle -150^\circ, \qquad \mathbf{V}_{cn} = \frac{V_p}{\sqrt{3}}\angle +90^\circ$$

Example 4 - Balanced Δ-Y Connection

- A balanced abc-sequence Y-connected load with a phase impedance (40+j25) Ω is supplied by a balanced, positive sequence, Δ-connected source with line voltage of 210 V. Calculate the phase currents.
- The load impedance is

$$Z_Y = 40 + j25 = 47.17\angle 32^\circ$$

- The source voltage is $\mathbf{V}_{ab} = 210\angle 0^\circ$
- Transforming the Delta source, to Y source $\mathbf{V}_{an} = \frac{\mathbf{V}_{ab}}{\sqrt{3}}\angle(-30^\circ) = 121.2\angle(-30^\circ)$
- The phase currents are same as line currents in Y-connected load

$$\mathbf{I}_a = \frac{\mathbf{V}_{an}}{Z_Y} = 2.57\angle(-62^\circ)$$

$$\mathbf{I}_b = \mathbf{I}_a\angle -120^\circ = 2.57\angle 178^\circ)$$
$$\mathbf{I}_c = 2.57\angle 58^\circ$$

Observations on Balanced Connections

- Line currents and line voltage interpretations are independent of the configuration of the source or load (Delta or Y)
- Phase current is current through each phase
  - It is **same** as line current in **Y** connected Source/Load, $I_{AN} = I_a$
  - Phase current **leads** line current by **30 degrees** and **has** $\mathbf{1}/\sqrt{\mathbf{3}}$ times the magnitude in **Delta** connected source/load, $I_{AB,\Delta} = \frac{1}{\sqrt{3}} I_a \angle 30^{\circ}$
- Phase voltage is voltage across each phase
  - It is **same** as line voltage in **Delta** connected Source/Load, $V_{AB,\Delta} = V_{ab}$
  - Phase voltage lags line voltage by 30 degrees and has $\mathbf{1}/\sqrt{\mathbf{3}}$ times the magnitude in Y connected source/load, $V_{AN} = \frac{1}{\sqrt{3}} V_{ab} \angle(-30^{\circ})$

Observations on Balanced Connections

- Notice that:
  - For Delta load: $V_{ph} = V_L,\, I_{ph} = I_L/\sqrt{3}$
  - For Star or Y load: $V_{ph} = V_L/\sqrt{3},\, I_{ph} = I_L$
- Thus, total average power: $P = \sqrt{3} V_L I_L \cos(\theta)$

irrespective of the configuration of the balanced load/source