Course: EEL 2043 Principles of Electric Machines
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كلّيـــات الـتـقـنـيـة العلـيـا
HIGHER COLLEGES OF TECHNOLOGY

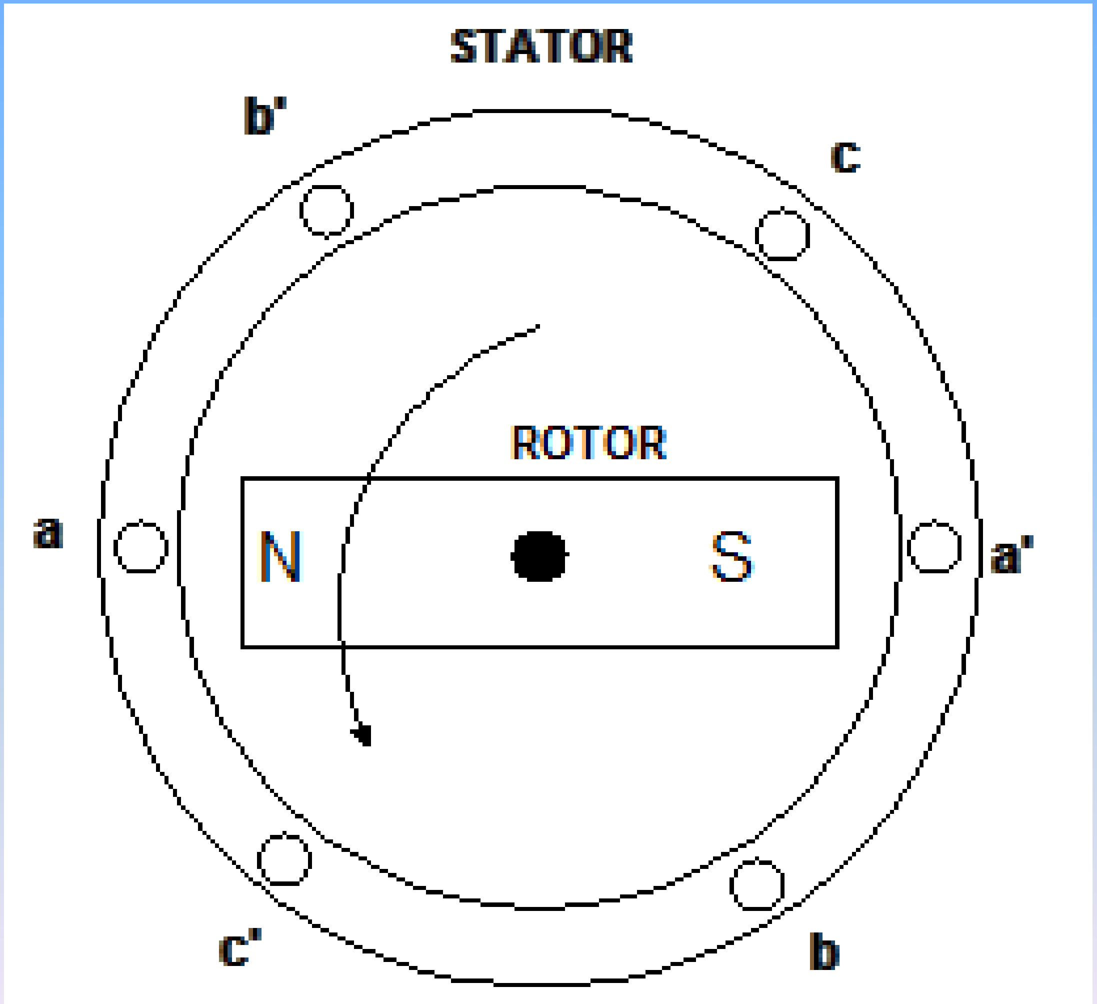
LO 1: Three Phase Circuits

Three Phase AC System

- Three phase is generated by a generator with three sets of independent windings which are physically spaced 120 degrees around the stator.

- Voltages are labeled phase a, phase b, and phase c and have the same magnitude but differ in phase angle by 120 degrees.

Three Phase AC System



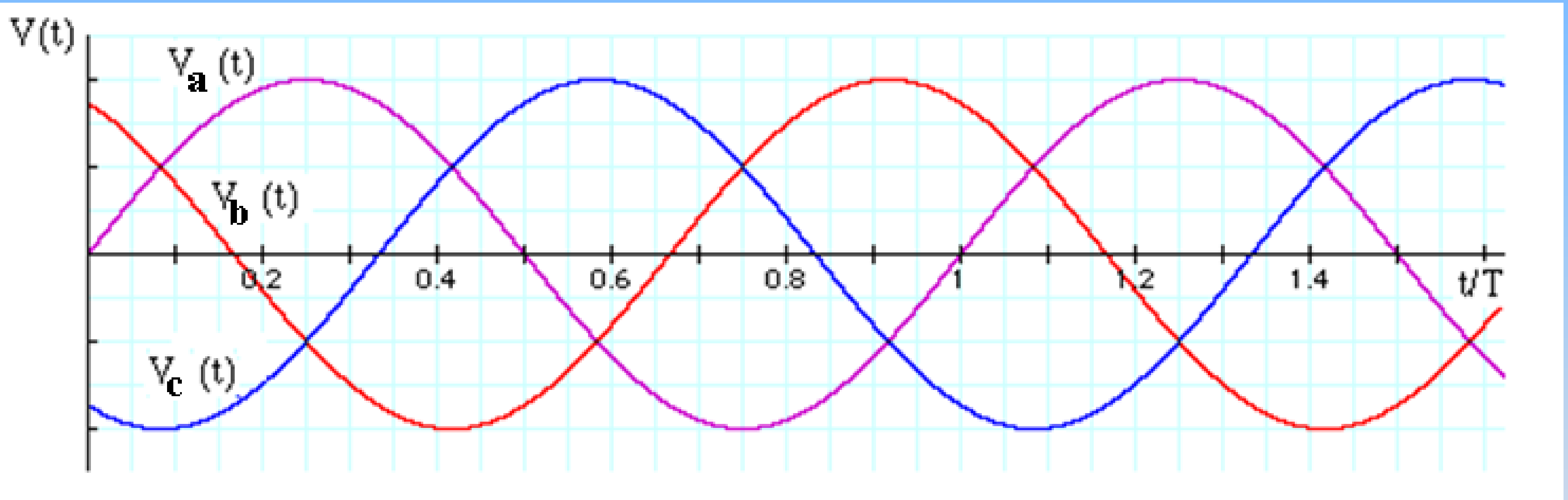
Three Phase AC System

http://www.youtube.com/watch?v=Cq3Yzyv88pU

http://www.youtube.com/watch?v=HLNugJwBRow

Three Phase AC System

The waveform of a three-phase ac generator

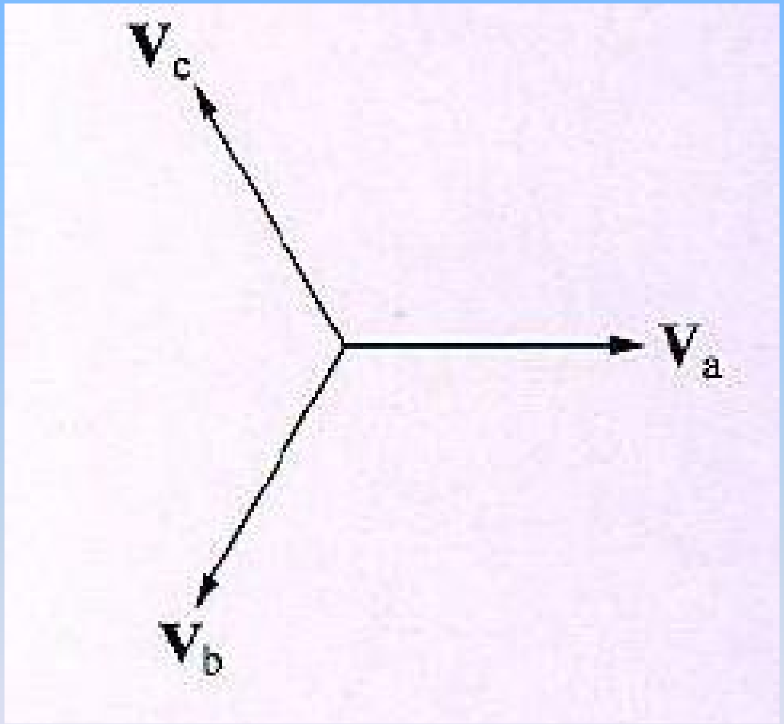


Three Phase AC System

- Three-phase systems have either three or four conductors.
- There are three-phase conductors identified as A, B, and C.
- The three phases are 120 degrees out of phase with each other (360 divided by 3).
- There is sometimes a fourth conductor, which is the neutral.

Three Phase AC System

The *abc* (or *positive*) phase sequence



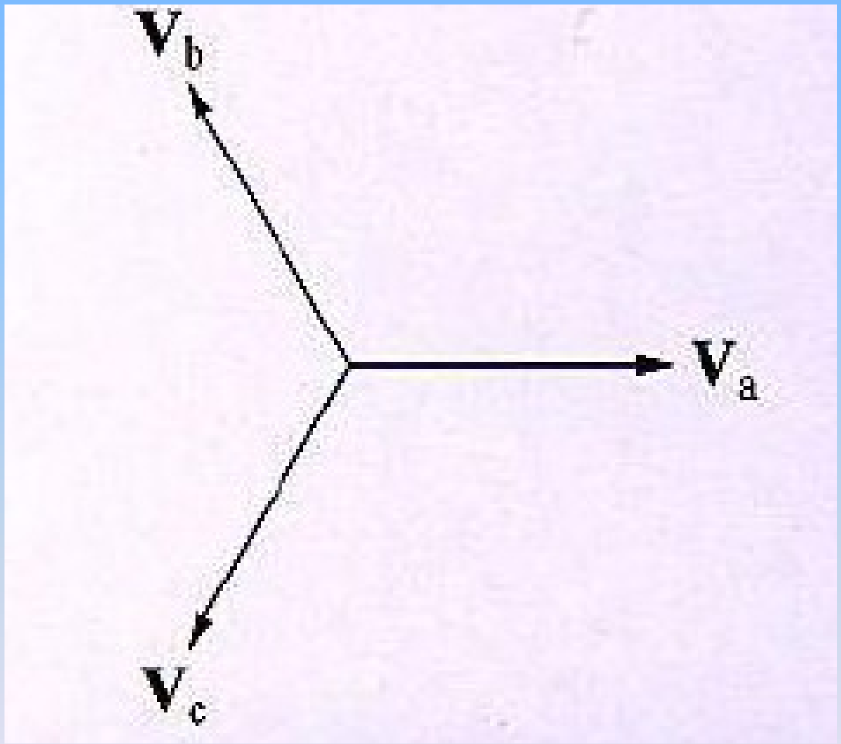
$$\mathbf{V}_a = V_m \angle 0^\circ,$$

$$\mathbf{V}_b = V_m \angle -120^\circ,$$

$$\mathbf{V}_c = V_m \angle +120^\circ,$$

Three Phase AC System

The *acb* (or *negative*) phase sequence



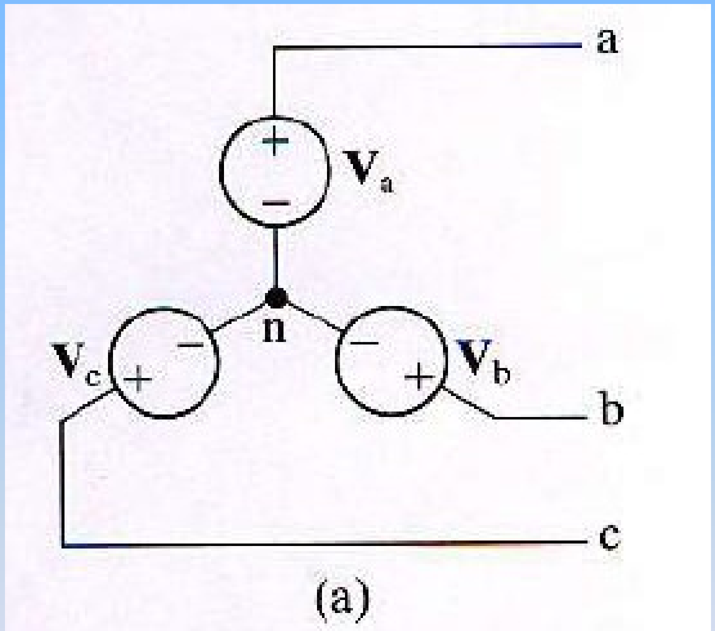
$$\mathbf{V}_a = V_m \angle 0^\circ,$$

$$\mathbf{V}_b = V_m \angle +120^\circ,$$

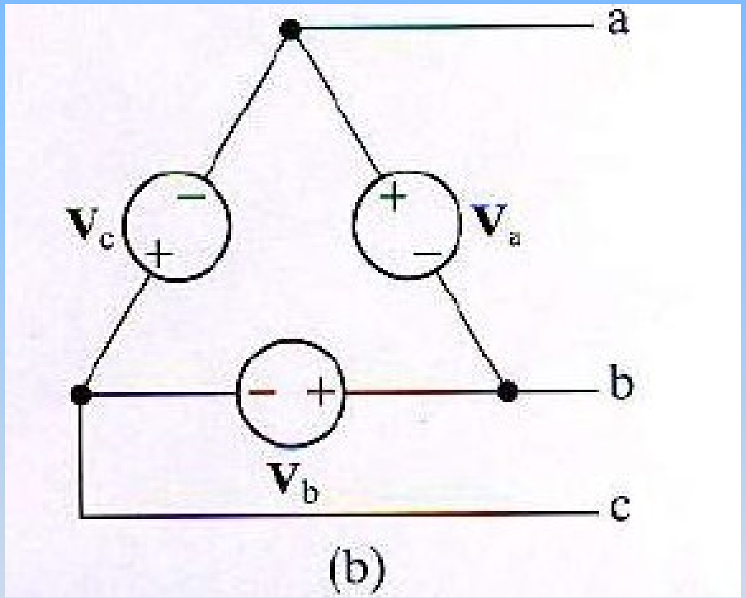
$$\mathbf{V}_c = V_m \angle -120^\circ.$$

Three Phase AC System

- The two basic connections of ac three-phase source

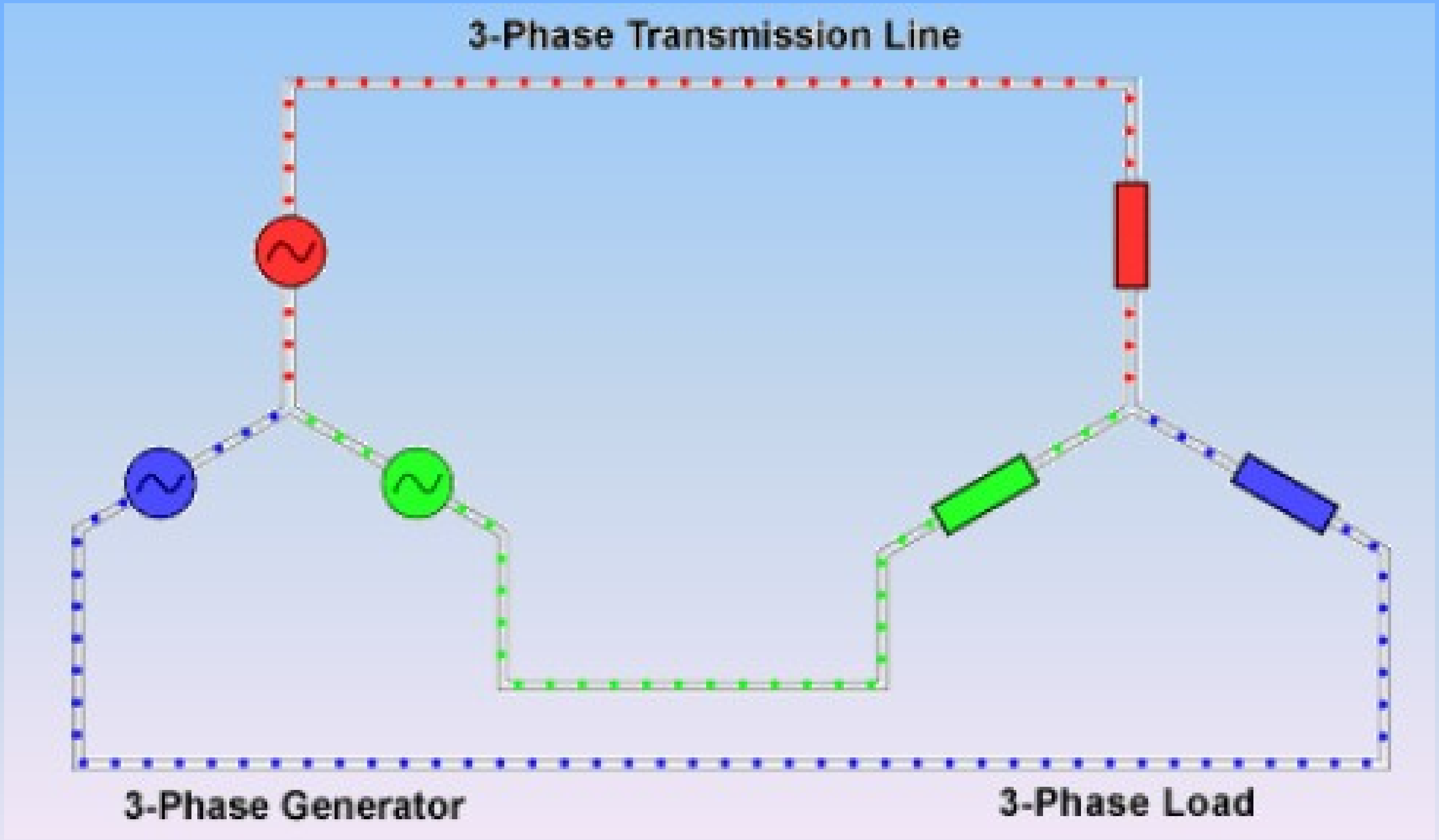


Y-connected source



Δ-connected source

Three Phase AC System



Three Phase AC System

- **Why use 3-phase?**
  - 3-phase motors, generators, and transformers are more efficient
  - Smooth torque on generator shaft
  - Delivery of constant power to a 3-phase load
  - 3 or 4 Wires and not 6
  - Can deliver more power for a given weight and cost
  - Voltage regulation is better

Three Phase AC System

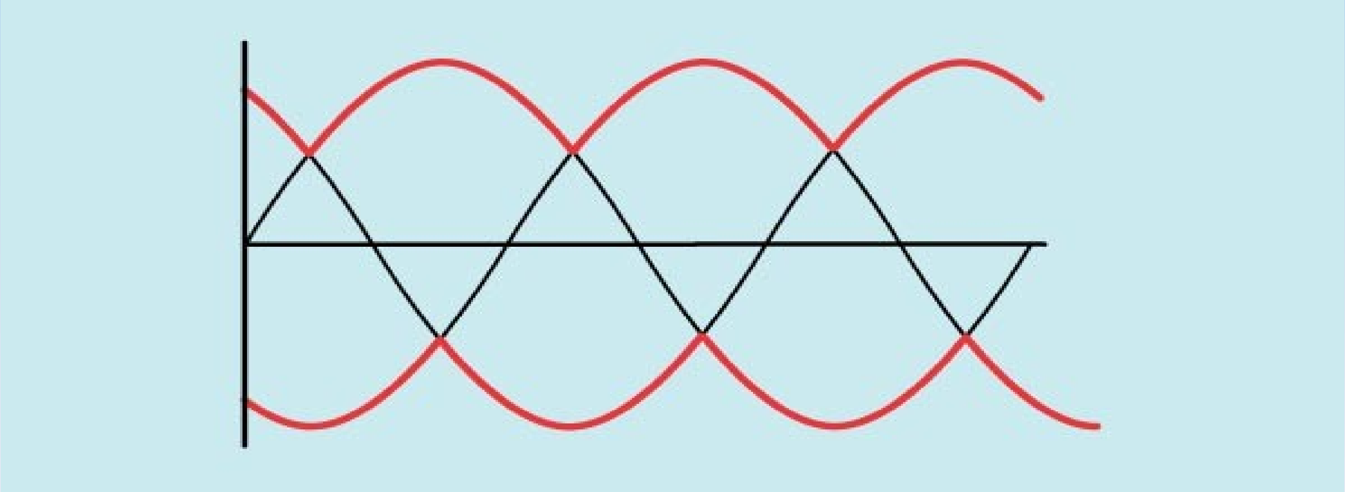
- **Why use 3-phase?**

The horsepower rating of three-phase motors and the kVA rating of three-phase transformers are 150% greater than single-phase motors or transformers of similar frame size.

Three Phase AC System

- **Why use 3-phase?**

The power delivered by a single-phase system pulsates and falls to zero. The three-phase power never falls to zero. The power delivered to the load in a three-phase system is the same at any instant. This produces superior operating characteristics for three-phase motors.



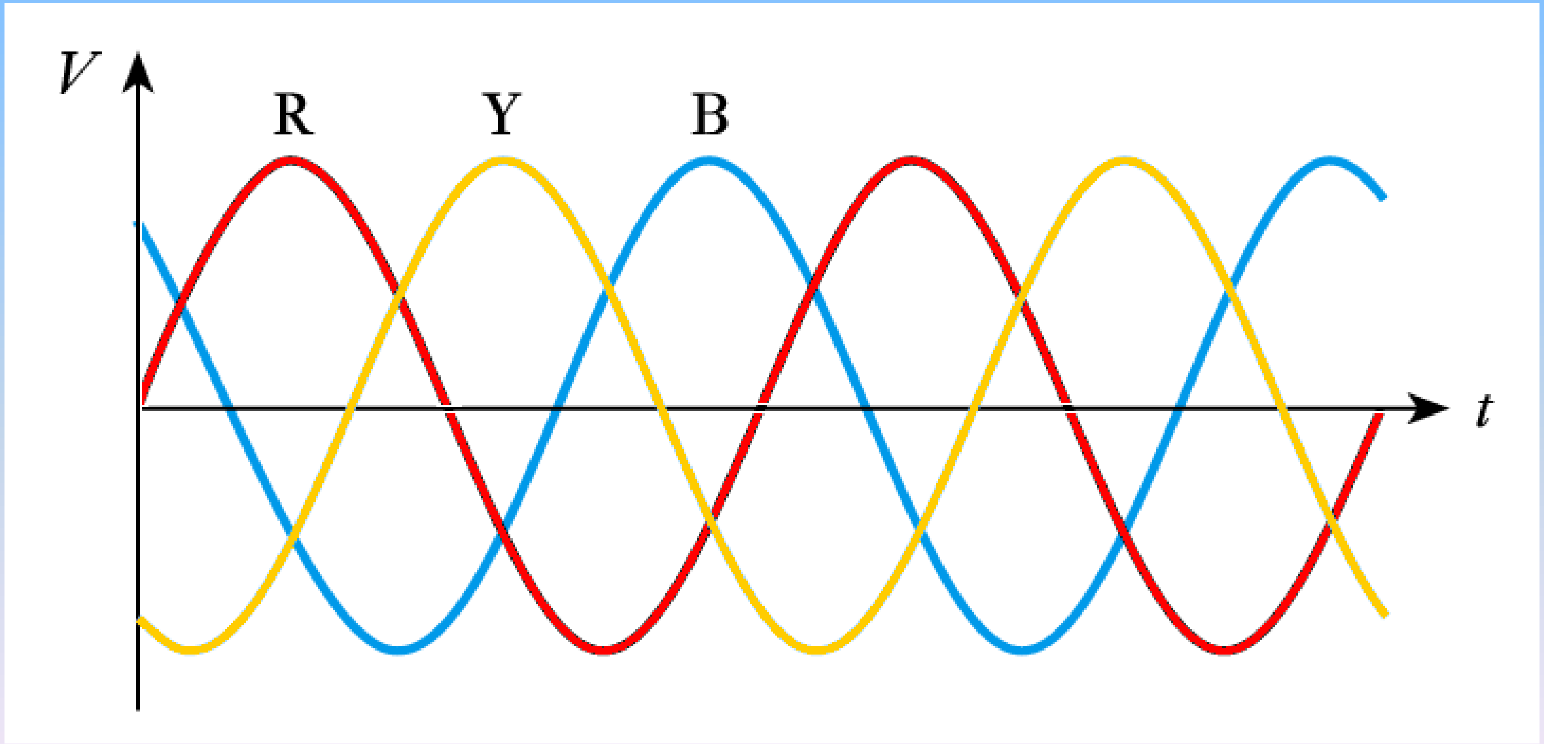
Three Phase AC System

- **Why use 3-phase?**

A three-phase system needs three conductors; however, each conductor is only 75% the size of the equivalent kVA rated single-phase conductors.

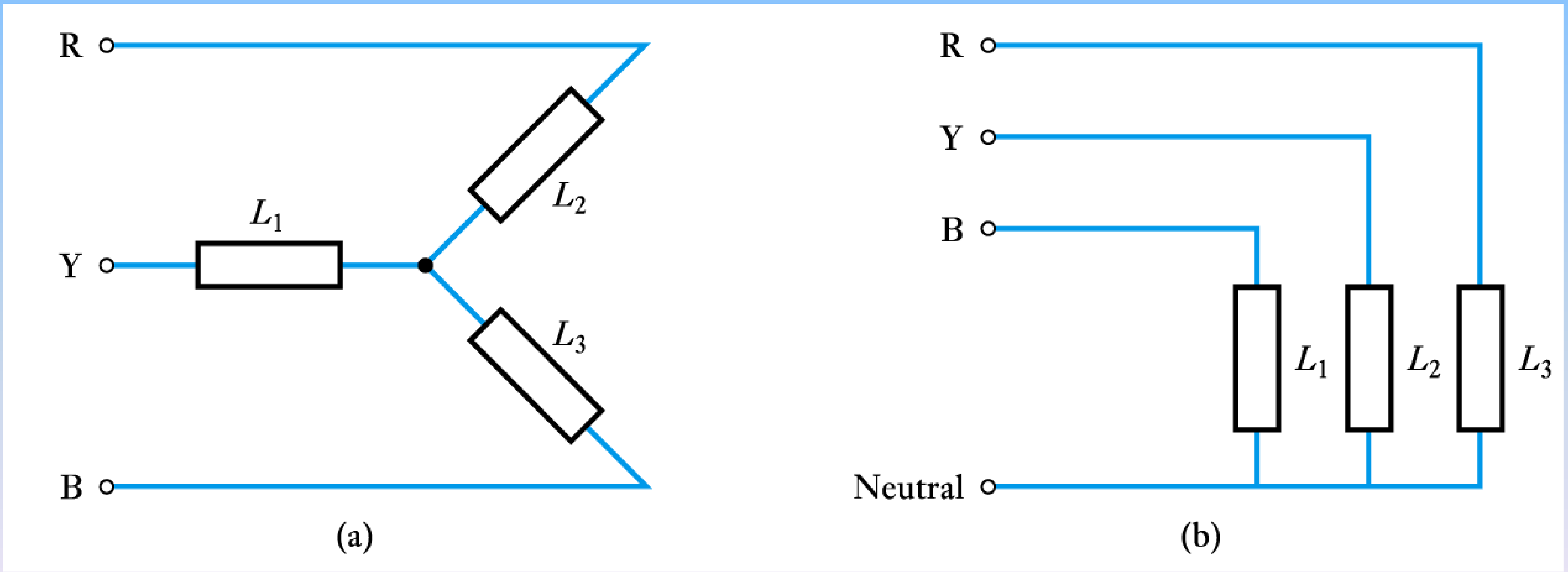
Three-Phase Systems

- Relationship between the phases in a three-phase arrangement

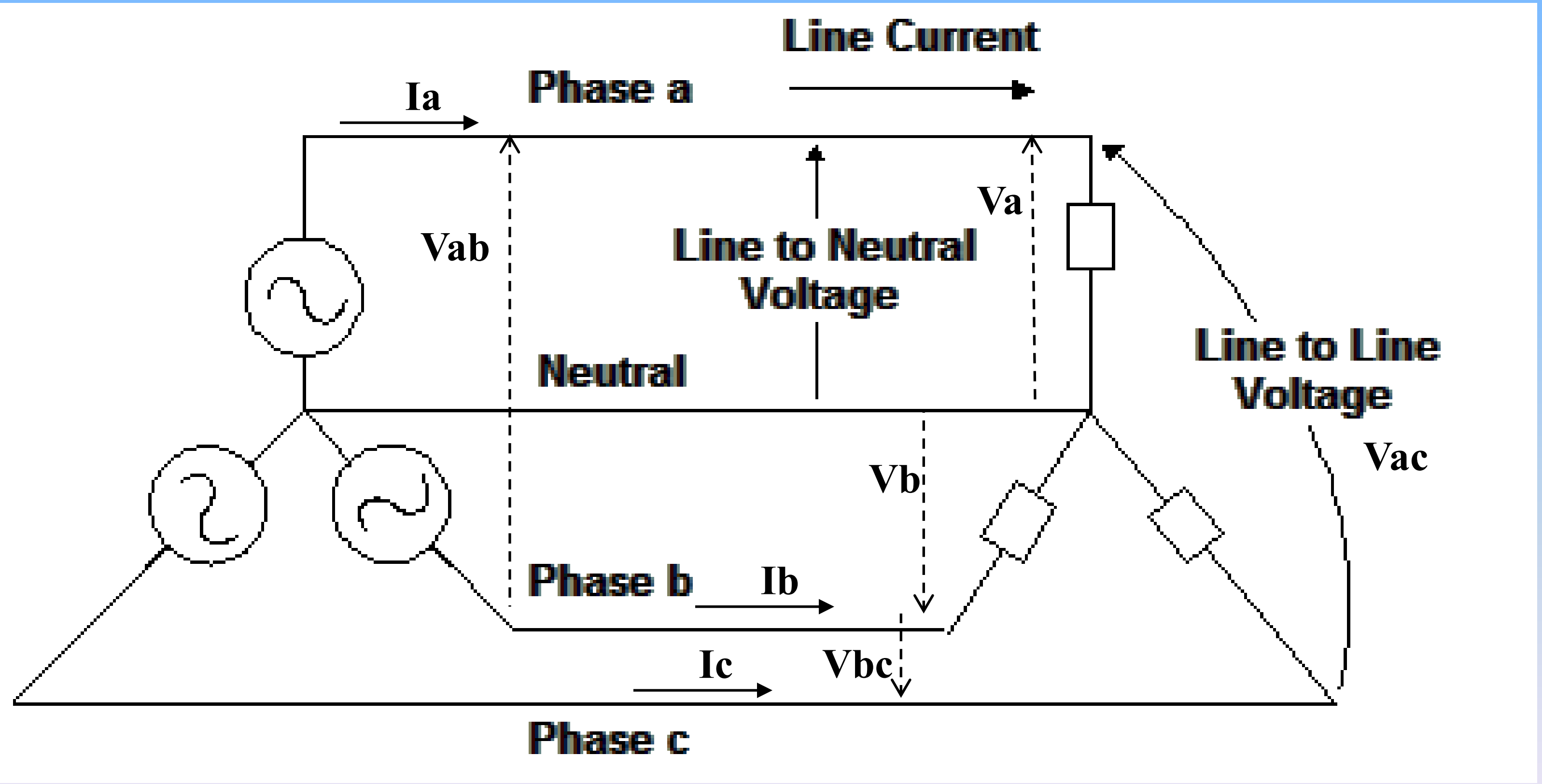


Three-Phase Systems

- Three-phase arrangements may use either 3 or 4 conductors

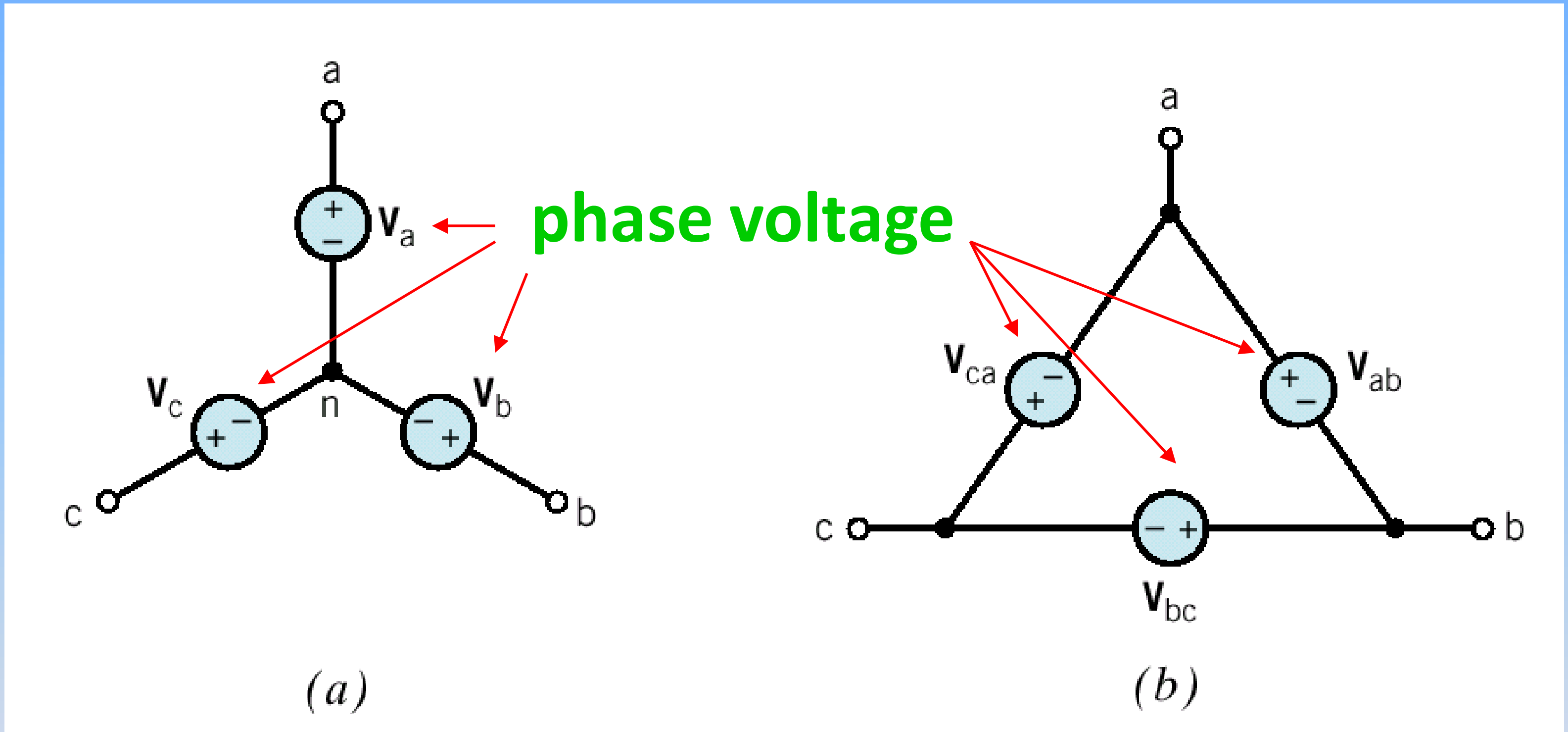


Three Phase AC System



Star/Delta Connections

Two Common Methods Three-phase Connection



(*a*) Y-connected sources

(b) Δ-connected sources

Star Connection

- The wye, or star, connection is made by connecting one end of each of the phase windings together in a common node.
- Each phase winding has a voltage drop known as the phase voltage.
- The line voltage is measured from phase conductor to a different phase conductor.

Star Connection

- The line voltage is higher than the phase voltage by a factor of the square root of 3 (1.732)

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

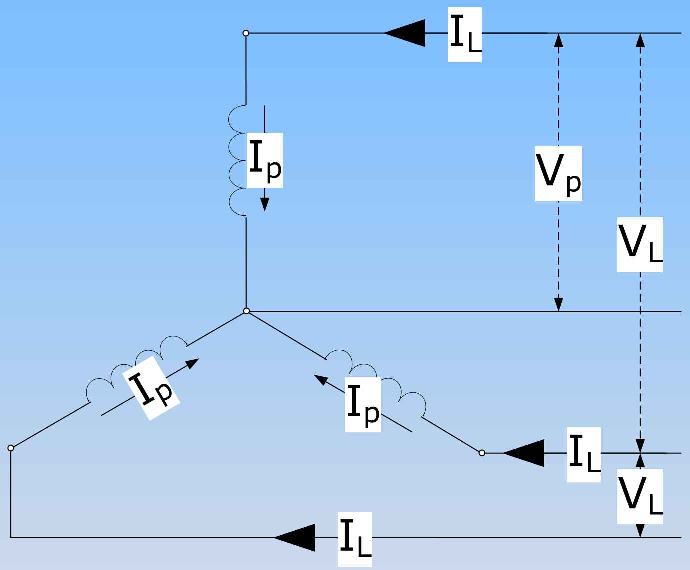
- The line current is equal to the phase current

$$I_L = I_p$$

Star Connection

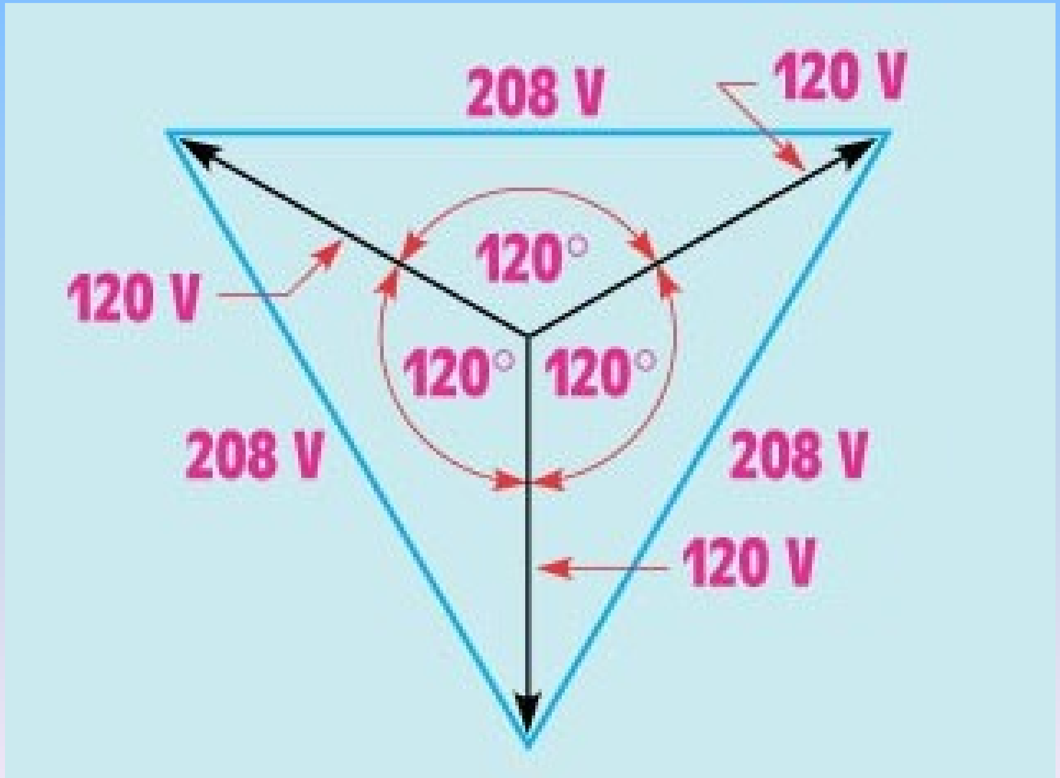
$$I_L = I_p$$

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

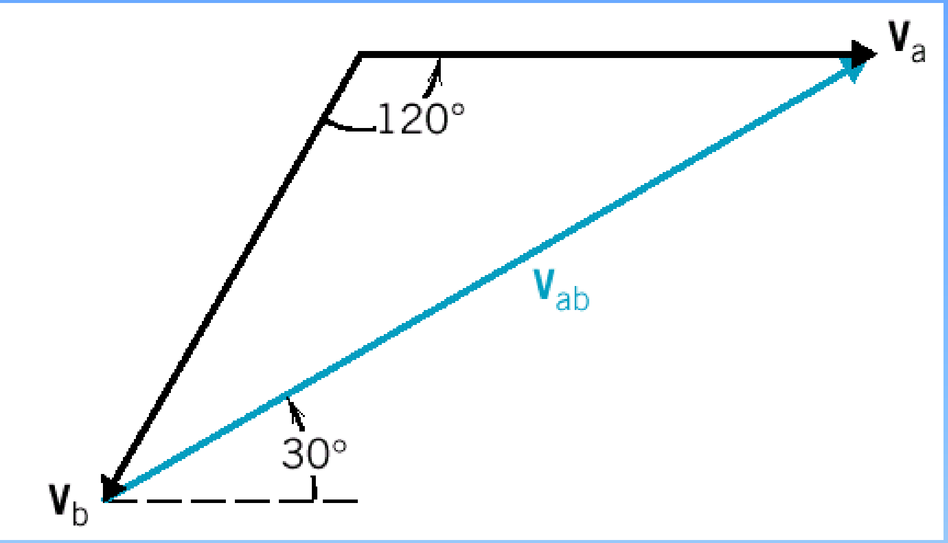


Star Connection

- Vector sum of typical wye system voltages



Phase and Line Voltages



The line-to-line voltage $\mathbf{V}_{ab}$ of the Y-connected source

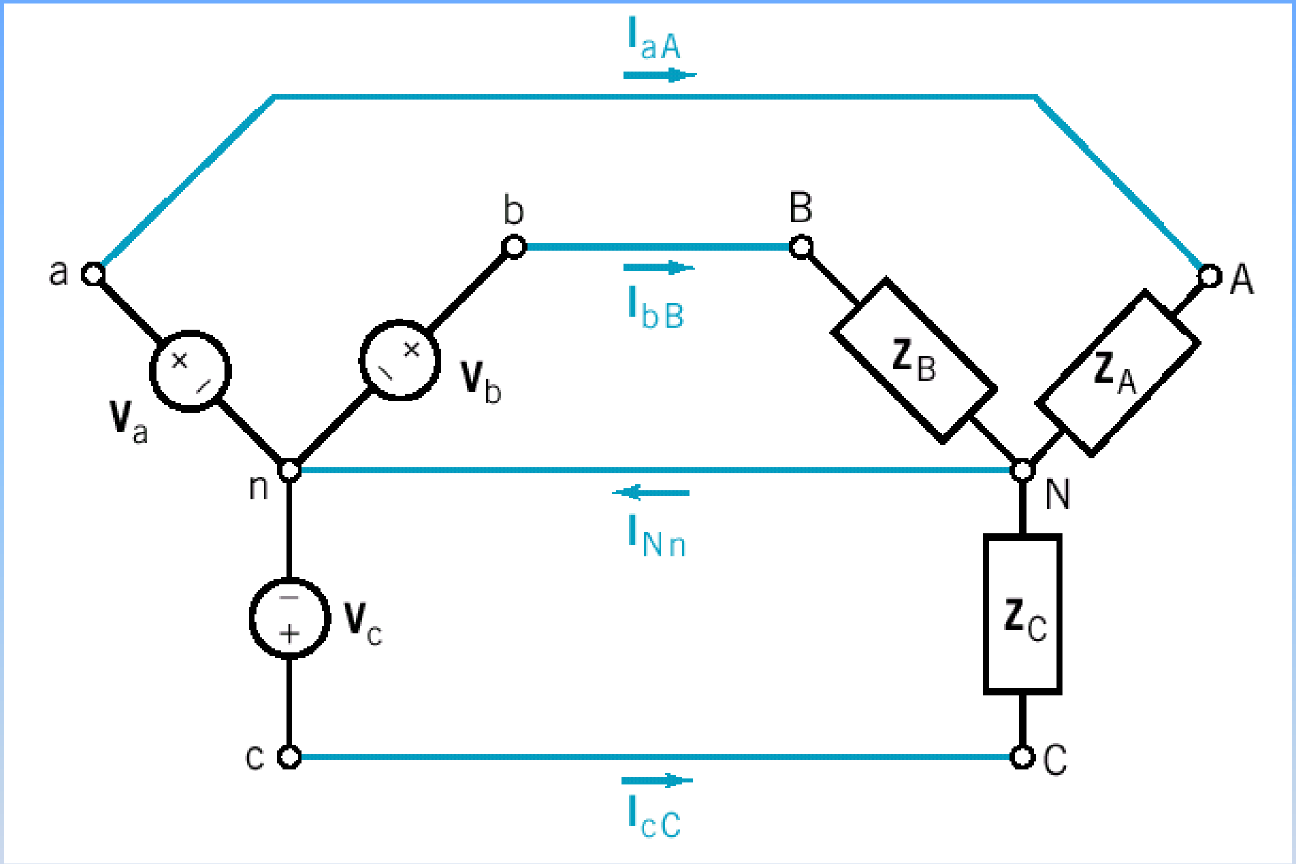
$$
\begin{aligned}
\mathbf{V}_{ab} &= \mathbf{V}_a - \mathbf{V}_b \\
&= V_p\angle 0° - V_p\angle -120° \\
&= V_p - V_p(-0.5 - j0.866) \\
&= \sqrt{3}V_p\angle 30°
\end{aligned}
$$

Similarly

$$\mathbf{V}_{bc} = \sqrt{3}V_p\angle -90°$$

$$\mathbf{V}_{ca} = \sqrt{3}V_p\angle -210°$$

The Y-to-Y Circuit



A four-wire Y-to-Y circuit

Four - wire

- $\mathbf{I}_{aA} = \dfrac{\mathbf{V}_a}{\mathbf{Z}_A},$
- $\mathbf{I}_{bB} = \dfrac{\mathbf{V}_b}{\mathbf{Z}_B},$ and
- $\mathbf{I}_{cC} = \dfrac{\mathbf{V}_c}{\mathbf{Z}_C}$

$$\mathbf{I}_{nN} = \mathbf{I}_{aA} + \mathbf{I}_{bB} + \mathbf{I}_{cC}$$

The average power delivered by the three-phase source to the three-phase load

$$P = P_A + P_B + P_C$$

- When $Z_A = Z_B = Z_C$ the load is said to be ***balanced***

- $$\mathbf{I}_{aA} = \frac{\mathbf{V}_a}{\mathbf{Z}_A} = \frac{V\angle 0°}{Z\angle\theta} \longrightarrow \mathbf{I}_{aA} = \frac{V}{Z}\angle -\theta°$$

- $$\mathbf{I}_{bB} = \frac{\mathbf{V}_b}{\mathbf{Z}_B} = \frac{V\angle -120°}{Z\angle\theta} \longrightarrow \mathbf{I}_{bB} = \frac{V}{Z}\angle(-\theta - 120°)$$

- $$\mathbf{I}_{cC} = \frac{\mathbf{V}_c}{\mathbf{Z}_C} = \frac{V\angle 120°}{Z\angle\theta} \longrightarrow \mathbf{I}_{cC} = \frac{V}{Z}\angle(-\theta + 120°)$$

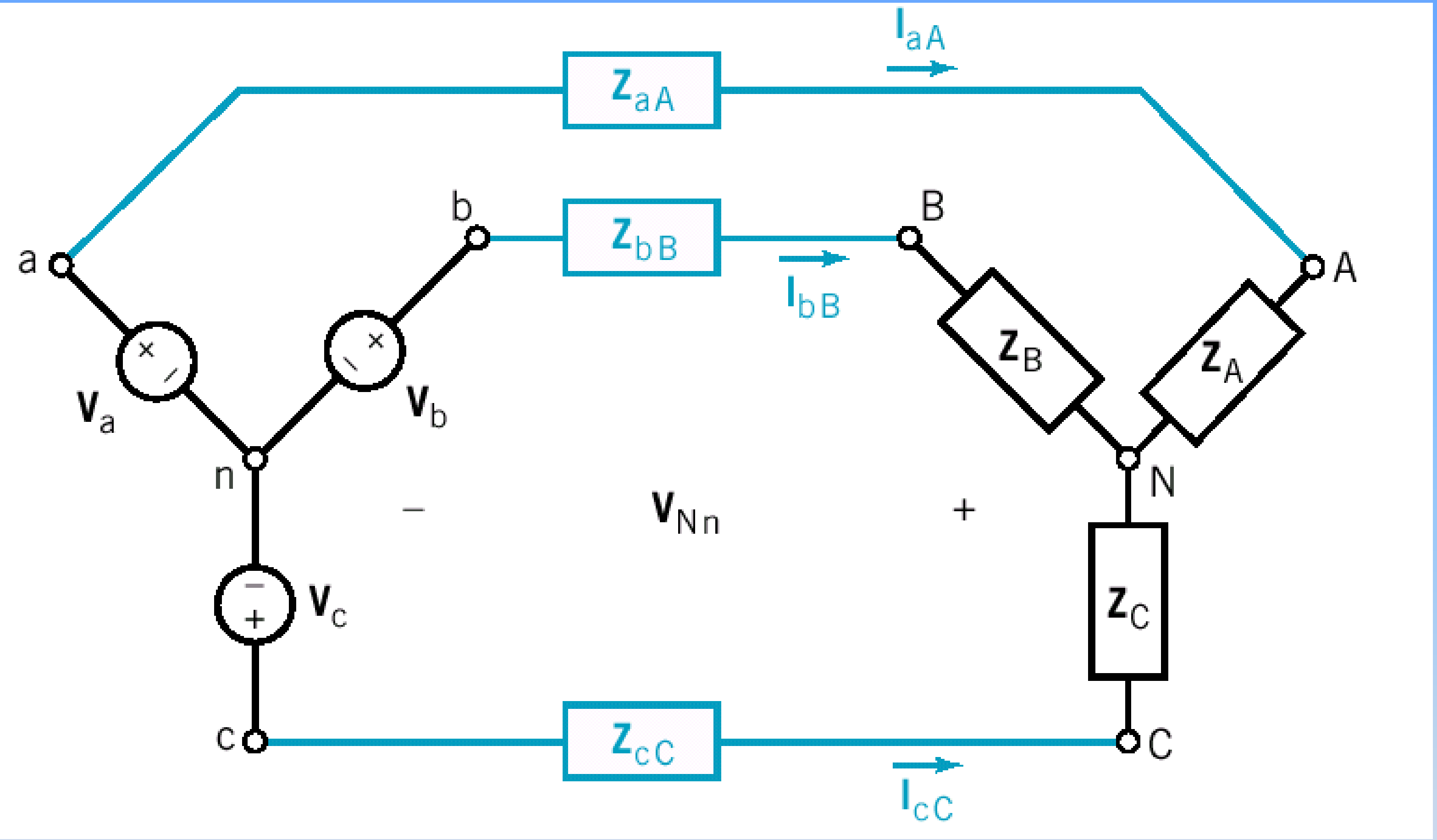
- There is no current in the wire connecting the neutral node of the source to the neutral node of the load.

$$\mathbf{I}_{nN} = \mathbf{I}_{aA} + \mathbf{I}_{bB} + \mathbf{I}_{cC} = 0$$

- The average power delivered to the load is:

$$\begin{aligned} P &= P_A + P_B + P_C \\ &= V\frac{V}{Z}\cos(-\theta) + V\frac{V}{Z}\cos(-\theta) + V\frac{V}{Z}\cos(-\theta) \\ &= 3\frac{V^2}{Z}\cos(\theta) \end{aligned}$$

The Y-to-Y Circuit (3-wire)



A three-wire Y-to-Y circuit

Y-Y Three - wire

We need to solve for $\boldsymbol{V_{Nn}}$

$$0 = I_{aA} + I_{bB} + I_{cC}$$

$$\mathbf{I}_{aA} = \frac{\mathbf{V}_a - \mathbf{V}_{Nn}}{\mathbf{Z}_A}, \mathbf{I}_{bB} = \frac{\mathbf{V}_b - \mathbf{V}_{Nn}}{\mathbf{Z}_B}, \text{ and } \mathbf{I}_{cC} = \frac{\mathbf{V}_c - \mathbf{V}_{Nn}}{\mathbf{Z}_C}$$

$$0 = \frac{\mathbf{V}_a - \mathbf{V}_{Nn}}{\mathbf{Z}_A} + \frac{\mathbf{V}_b - \mathbf{V}_{Nn}}{\mathbf{Z}_B} + \frac{\mathbf{V}_c - \mathbf{V}_{Nn}}{\mathbf{Z}_C}$$

$$= \frac{V\angle 0^\circ - \mathbf{V}_{Nn}}{\mathbf{Z}_A} + \frac{V\angle -120^\circ - \mathbf{V}_{Nn}}{\mathbf{Z}_B} + \frac{V\angle 120^\circ - \mathbf{V}_{Nn}}{\mathbf{Z}_C}$$

- Solve for $\boldsymbol{V_{Nn}}$

$$\mathbf{V}_{Nn} = \frac{(V\angle -120^\circ)\mathbf{Z}_A\mathbf{Z}_C + V\angle 120^\circ \mathbf{Z}_A\mathbf{Z}_B + V\angle 0^\circ \mathbf{Z}_B\mathbf{Z}_C}{\mathbf{Z}_A\mathbf{Z}_C + \mathbf{Z}_A\mathbf{Z}_B + \mathbf{Z}_B\mathbf{Z}_C}$$

- When the circuit is ***balanced*** ***i.e.*** $Z_A = Z_B = Z_C$

$$\mathbf{V}_{Nn} = \frac{(V\angle -120^\circ)\mathbf{ZZ} + V\angle 120^\circ\mathbf{ZZ} + V\angle 0^\circ\mathbf{ZZ}}{\mathbf{ZZ}+\mathbf{ZZ}+\mathbf{ZZ}}$$

$$= 0$$

- The average power delivered to the load is:

$$P = P_A + P_B + P_C$$

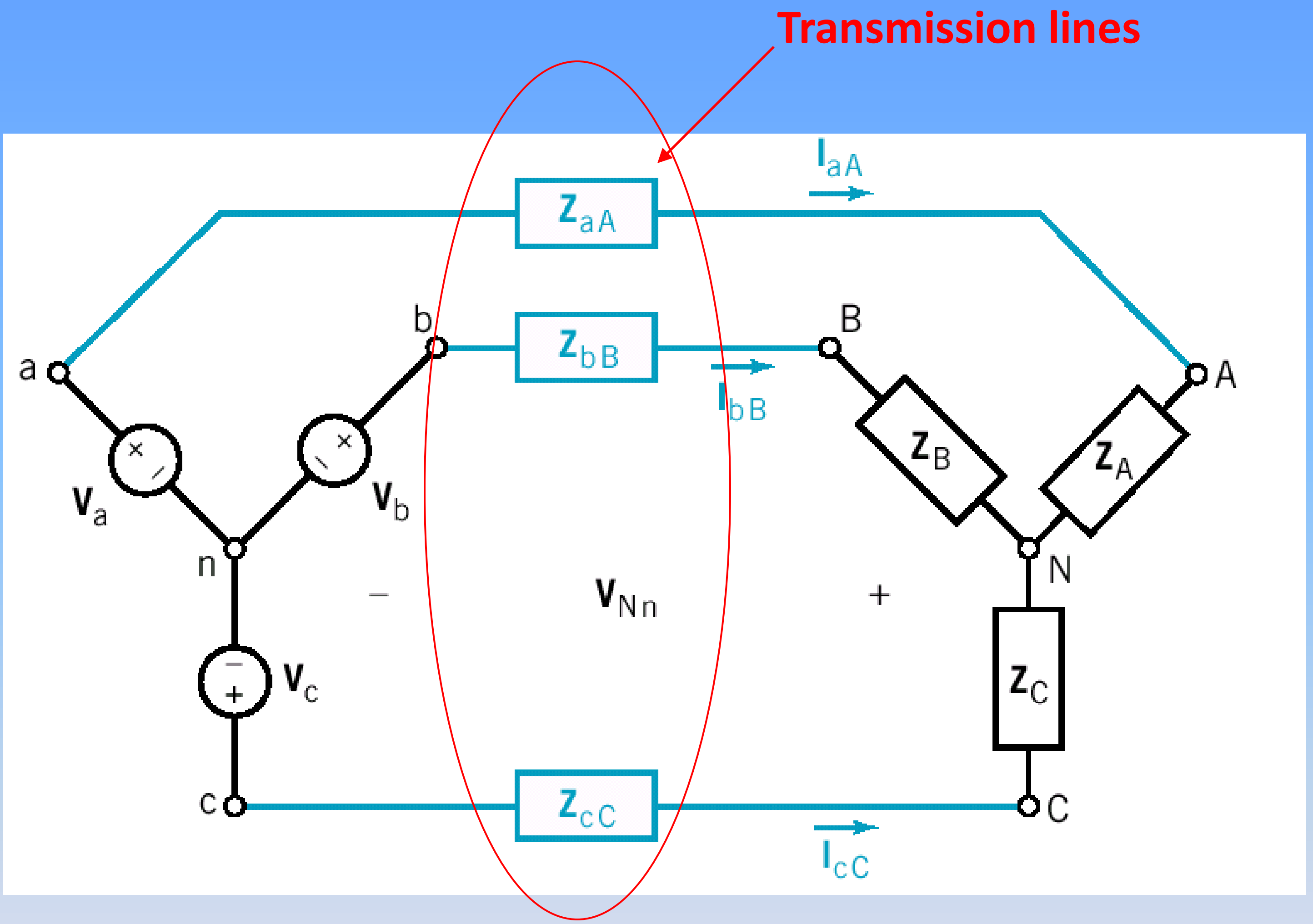
$$= 3\frac{V^2}{Z}\cos(\theta)$$

- or

$$P = 3\,V\;I\;\cos\theta,$$

$$Q = 3\,V\;I\;\sin\theta,$$

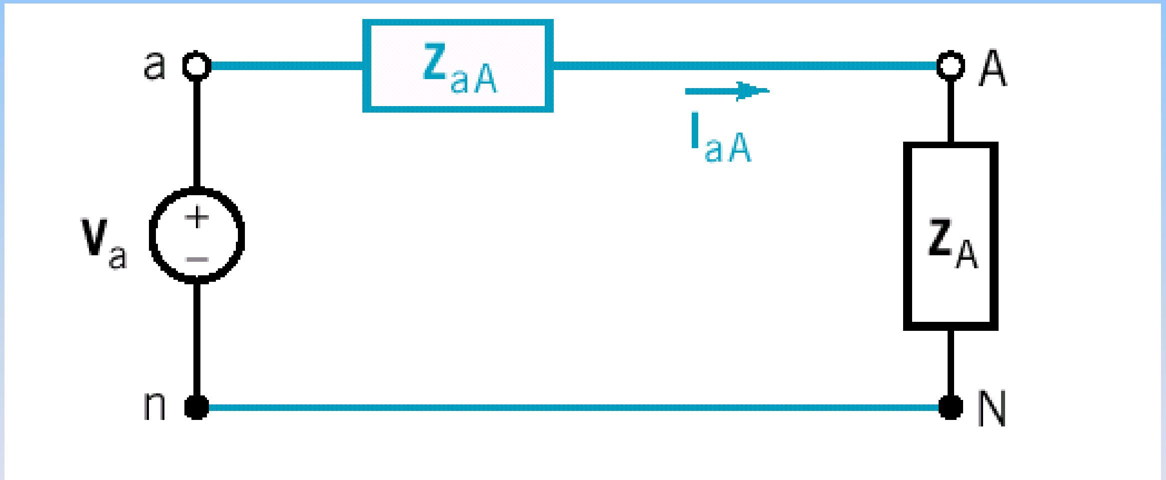
$$S = 3\,V\;I^*$$



A three-wire Y-to-Y circuit with line impedances

➢ The analysis of ***balanced Y-Y circuits*** is ***simpler*** than the analysis of ***unbalanced Y-Y circuits***.

- $\boldsymbol{V_{Nn}}$ = 0. It is not necessary to solve for $\boldsymbol{V_{Nn}}$.
- The line currents have equal magnitudes and differ in phase by 120 degree.
- Equal power is absorbed by each impedance.



Per-phase equivalent circuit

Delta Connection

- The line current is higher than the phase current by a factor of the square root of 3 (1.732)

$$I_L = \sqrt{3} \times I_P$$

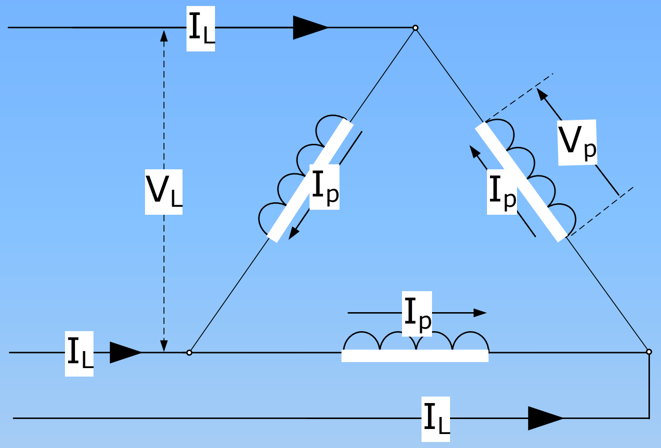
- The line current is equal to the phase current

$$V_L = V_P$$

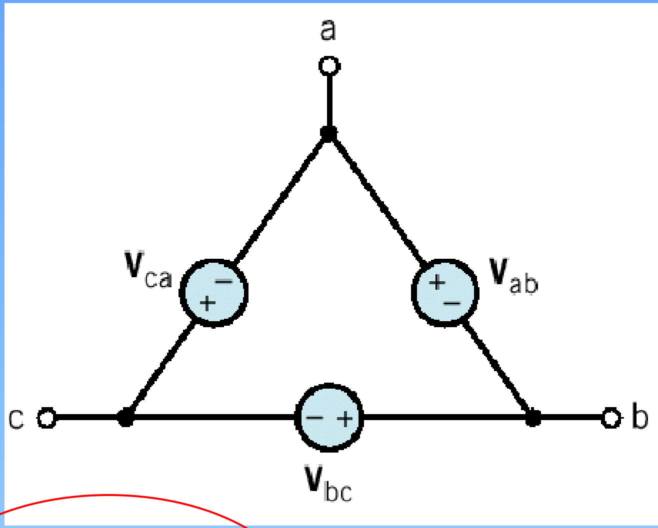
Delta Connection

$$V_L = V_P$$

$$I_L = \sqrt{3} \times I_P$$



The Δ-Connected Source and Load



$$\mathbf{V}_{ab} = 120\angle 0° \quad \mathrm{V_{rms}}$$
$$\mathbf{V}_{bc} = 120.1\angle -121° \quad \mathrm{V_{rms}}$$
$$\mathbf{V}_{ca} = 120.2\angle 121° \quad \mathrm{V_{rms}}$$

Circulating current

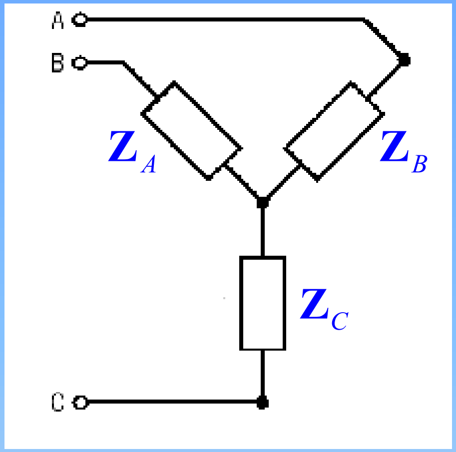
$$\mathbf{I} = \frac{(\mathbf{V}_{ab} + \mathbf{V}_{bc} + \mathbf{V}_{ca})}{1} \approx -3.75 \quad \mathrm{A}$$

Unacceptable

Total resistance around the loop

Therefore the Δ sources connection is seldom used in practice.

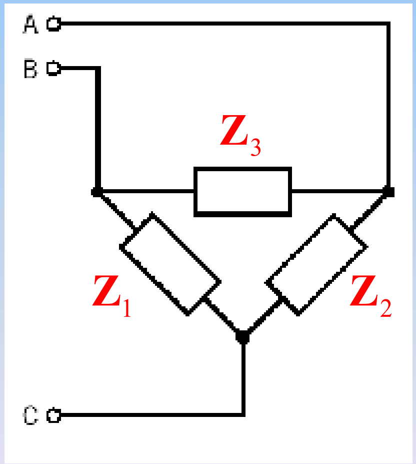
The Δ-Y and Y- Δ Transformation



$$Z_A = \frac{Z_1 Z_3}{Z_1 + Z_2 + Z_3}$$

$$Z_B = \frac{Z_2 Z_3}{Z_1 + Z_2 + Z_3}$$

$$Z_C = \frac{Z_1 Z_2}{Z_1 + Z_2 + Z_3}$$

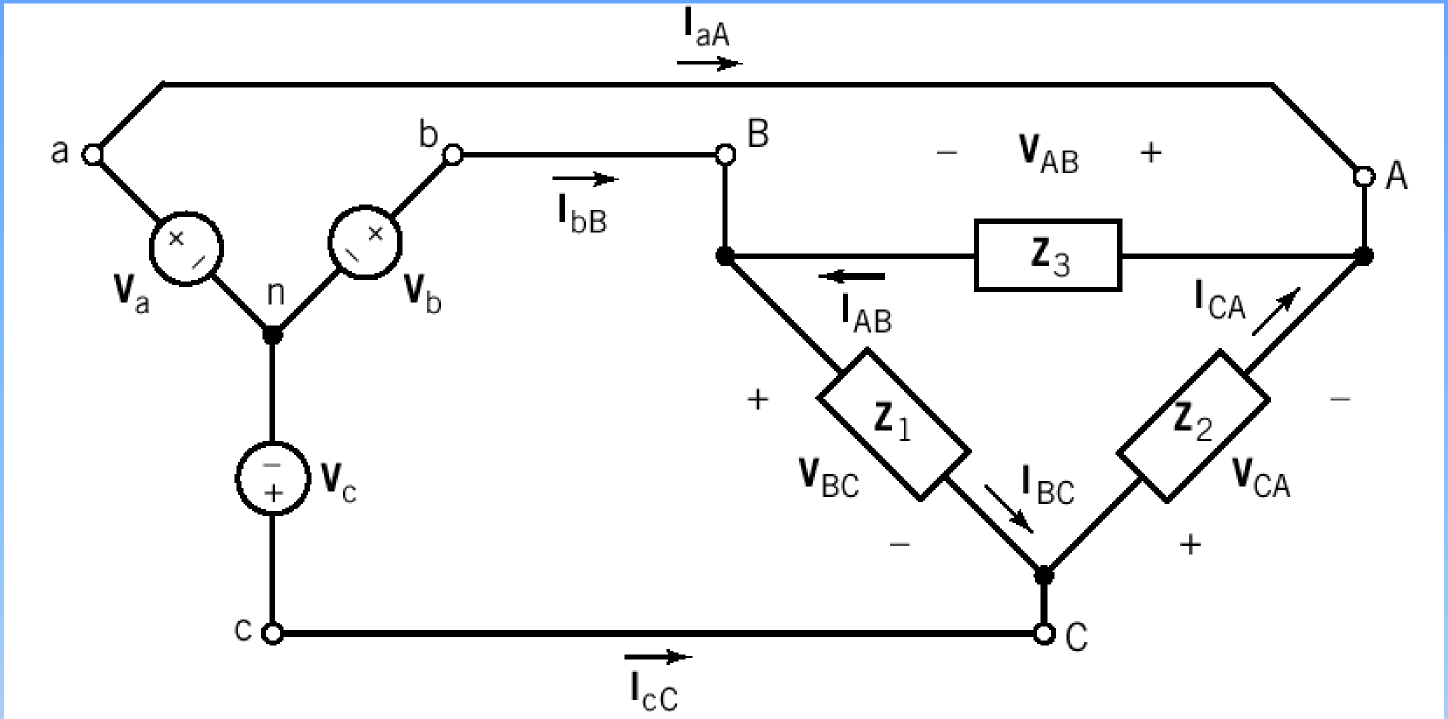


$$Z_1 = \frac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_B}$$

$$Z_2 = \frac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_A}$$

$$Z_3 = \frac{Z_A Z_B + Z_B Z_C + Z_A Z_C}{Z_C}$$

The Y- Δ Circuits



$$\mathbf{I}_{aA} = \mathbf{I}_{AB} - \mathbf{I}_{CA}$$

$$\mathbf{I}_{bB} = \mathbf{I}_{BC} - \mathbf{I}_{AB}$$

$$\mathbf{I}_{cC} = \mathbf{I}_{CA} - \mathbf{I}_{BC}$$

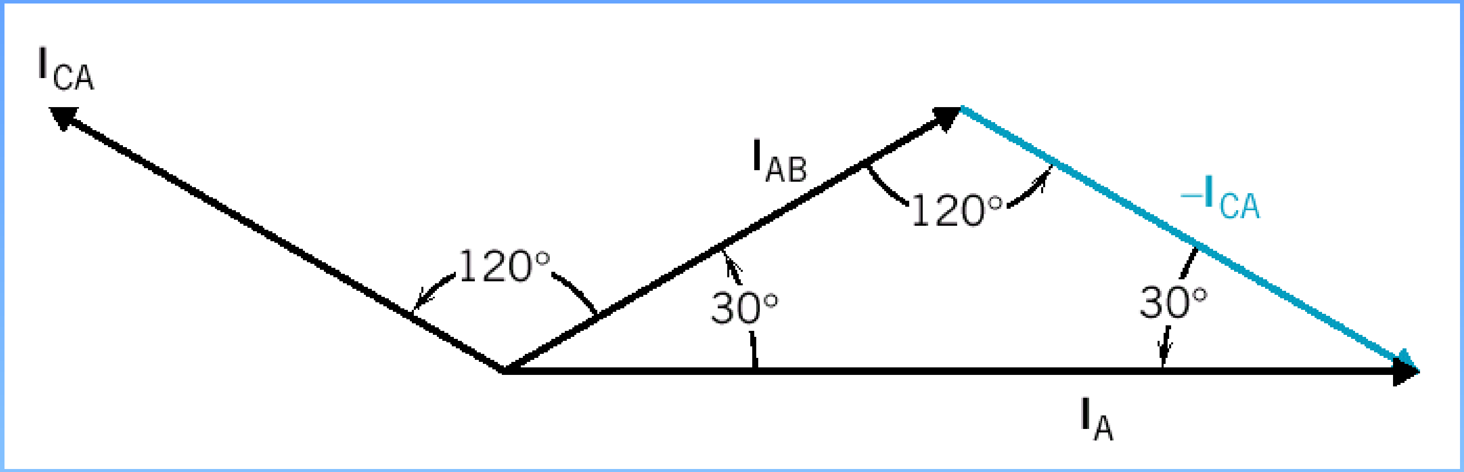
where

$$\mathbf{I}_{AB} = \frac{\mathbf{V}_{AB}}{\mathbf{Z}_3}$$

$$\mathbf{I}_{BC} = \frac{\mathbf{V}_{BC}}{\mathbf{Z}_1}$$

$$\mathbf{I}_{CA} = \frac{\mathbf{V}_{CA}}{\mathbf{Z}_2}$$

The Y- Δ Circuits (cont.)

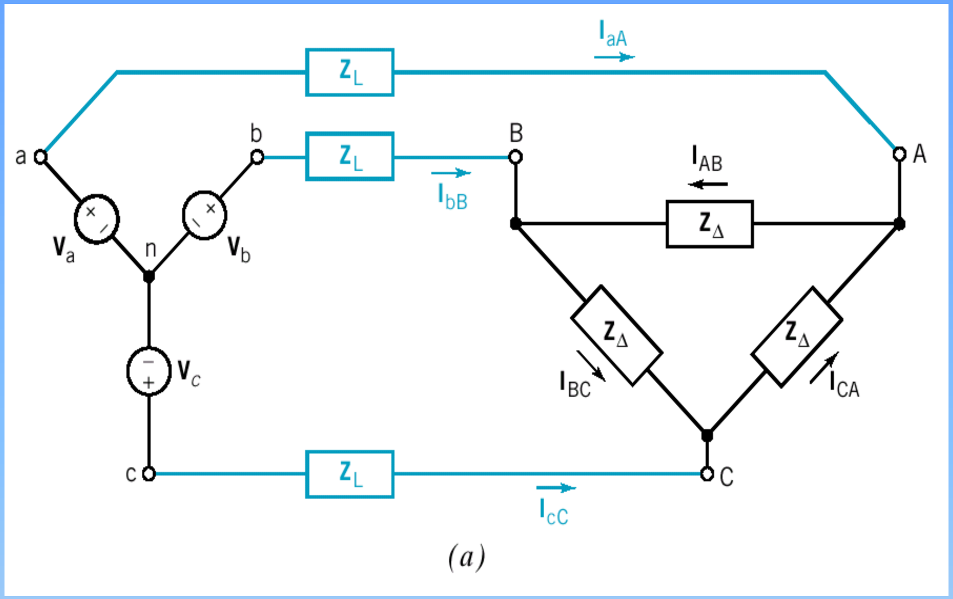


$$\mathbf{I}_{aA} = \mathbf{I}_{AB} - \mathbf{I}_{CA}$$
$$= I\cos\phi + j\sin\phi - I\cos(\phi + 120°) - j\sin(\phi + 120°)$$
$$= \sqrt{3} I \angle(\phi - 30°)$$

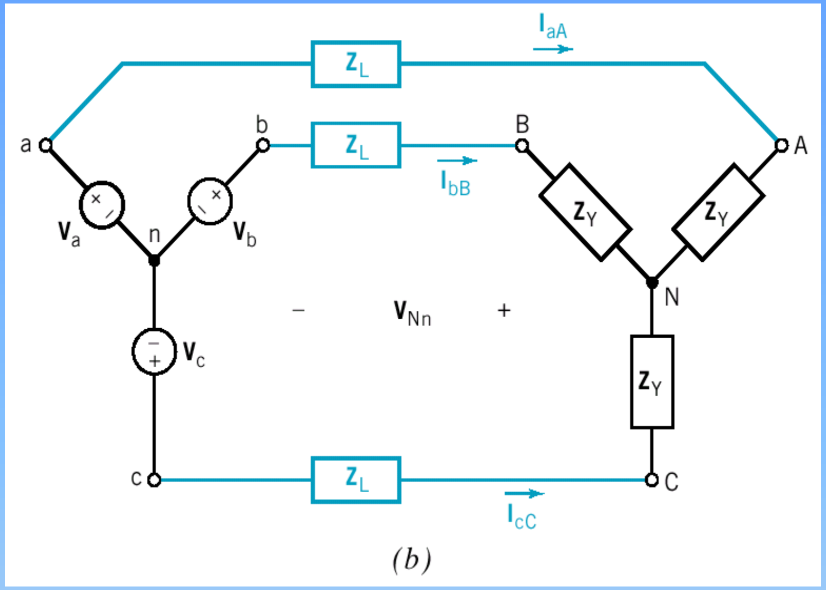
or

$$|\mathbf{I}_{aA}| = \sqrt{3}\,|I| \quad \Rightarrow \quad I_L = \sqrt{3} I_p$$

The Balanced Three-Phase Circuits

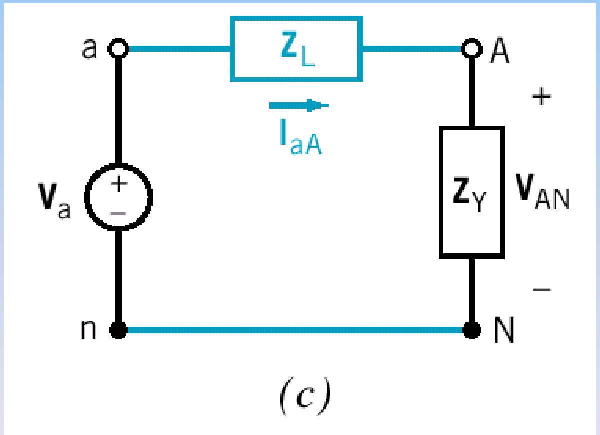


Y-to-Δ circuit



equivalent Y-to-Y circuit

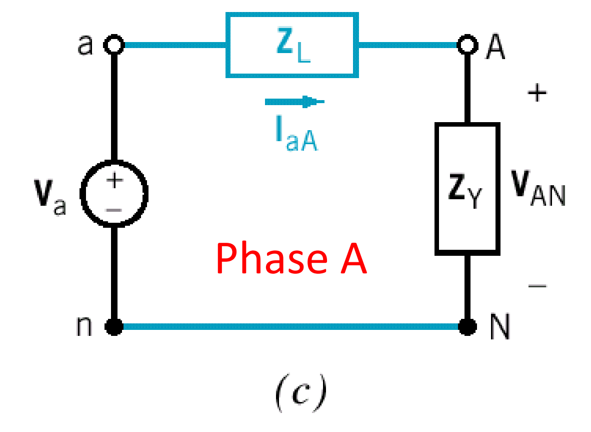
$$\mathbf{Z}_Y = \frac{\mathbf{Z}_\Delta}{3}$$



per-phase equivalent circuit

Instantaneous and Average Power

The total average power delivered to the balanced Y-connected load is

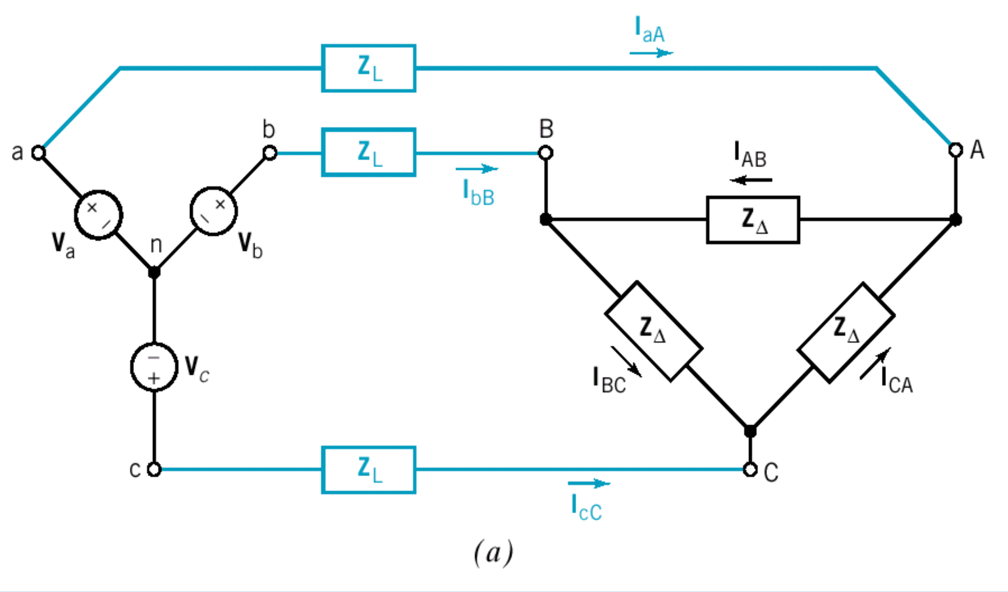


$$\mathbf{I}_{aA} = I_L \angle \theta_{AI}, \mathbf{V}_{AN} = V_P \angle \theta_{AV}$$

$$\begin{aligned} P_Y &= 3P_A = 3V_P I_L \cos(\theta_{AV} - \theta_{AI}) \\ &= 3V_P I_L \cos(\theta) \\ &= 3\frac{V_L}{\sqrt{3}} I_L \cos(\theta) \\ &= \sqrt{3} V_L I_L \cos(\theta) \end{aligned}$$

Instantaneous and Average Power in Balanced Three Phase Circuits

The total average power delivered to the balanced Δ-connected load is



$$P = 3P_{AB} = 3V_{AB} \times I_{AB} \times \cos\theta$$

$$P = 3 \times V_P \times I_P \times \cos\theta$$

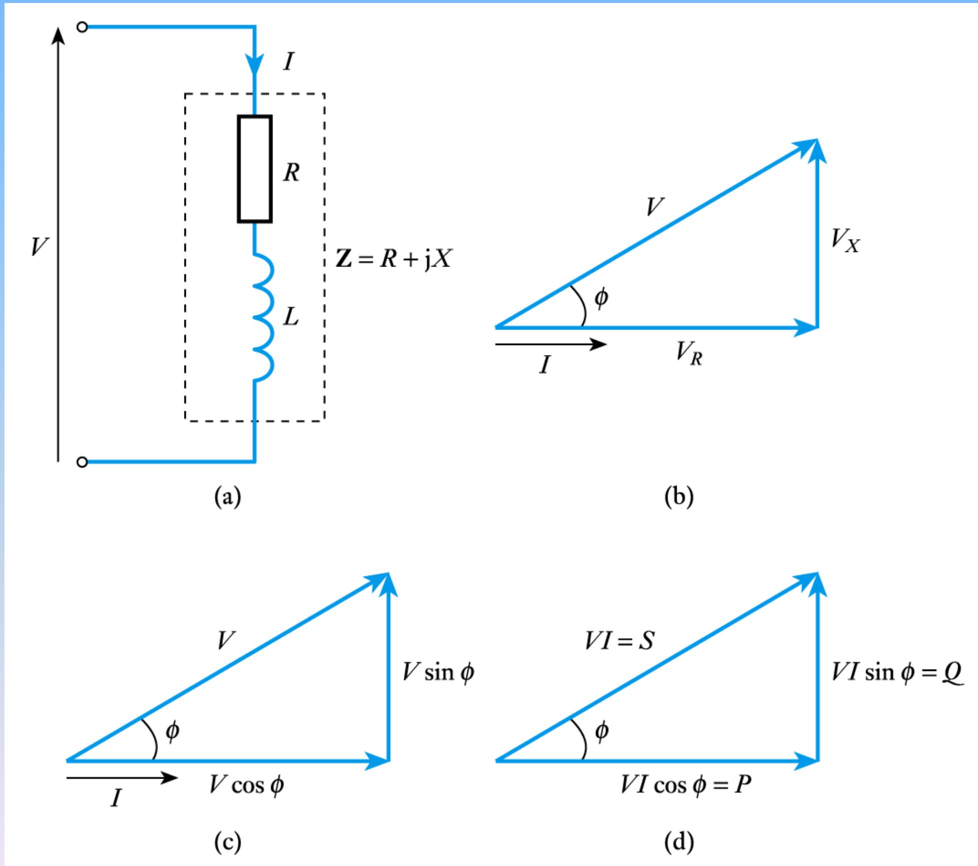
$$P = \sqrt{3} \times V_L \times I_L \times \cos\theta$$

Active and Reactive Power

- When a circuit has resistive and reactive parts, the resultant power has 2 parts:
  - The first is *dissipated* in the resistive element. This is the **active power, *P***
  - The second is *stored* and *returned* by the reactive element. This is the **reactive power**, ***Q*** , which has units of **volt amperes reactive** or **var**
- While reactive power is not dissipated it does have an effect on the system
  - for example, it increases the current that must be supplied and increases losses with cables

Active and Reactive Power

- Consider an RL circuit
  - the relationship between the various forms of power can be illustrated using a power triangle



Three Phase Power

- Single phase power

$$P = V \times I \times \cos\theta$$

- In a balanced 3 phase system the total power is equal to three times the power in any one phase

$$P = 3 \times V_P \times I_P \times \cos\theta$$

- In star and delta, 3 phase power can also be calculated using this formula

$$P = \sqrt{3} \times V_L \times I_L \times \cos\theta$$

- Note that this is the same on wye or delta systems

Active and Reactive Power

- For Single Phase:

Active Power	$P = V \times I \times \cos\theta$	watts
Reactive Power	$Q = V \times I \times \sin\theta$	var
Apparent Power	$S = V\, I^*$	VA

$$S^2 = P^2 + Q^2$$

Active and Reactive Power

- For 3-Phase:

Active Power	$P = 3 \times V_P \times I_P \times \cos\theta$	watts
Reactive Power	$Q = 3 \times V_P \times I_P \times \sin\theta$	var
Apparent Power	$S = 3 \times V_P \times I_P^{*}$	VA

$$S^2 = P^2 + Q^2$$

Active and Reactive Power

- For 3-Phase:

Active Power	$P = \sqrt{3} \times V_L \times I_L \times \cos\theta$	watts
Reactive Power	$Q = \sqrt{3} \times V_L \times I_L \times \sin\theta$	var
Apparent Power	$S = \sqrt{3} \times V_L \times I_L^{*}$	VA

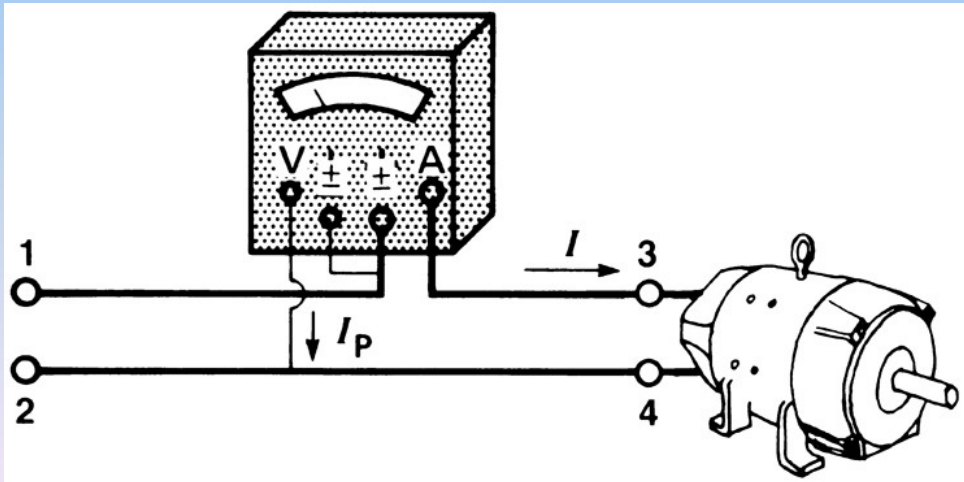
$$S^2 = P^2 + Q^2$$

Power Measurement

- When using AC, *power* is determined not only by the r.m.s. values of the **voltage** and **current**, but also by the **phase angle** (which determines the **power factor**)
  - consequently, you cannot determine the power from independent measurements of current and voltage

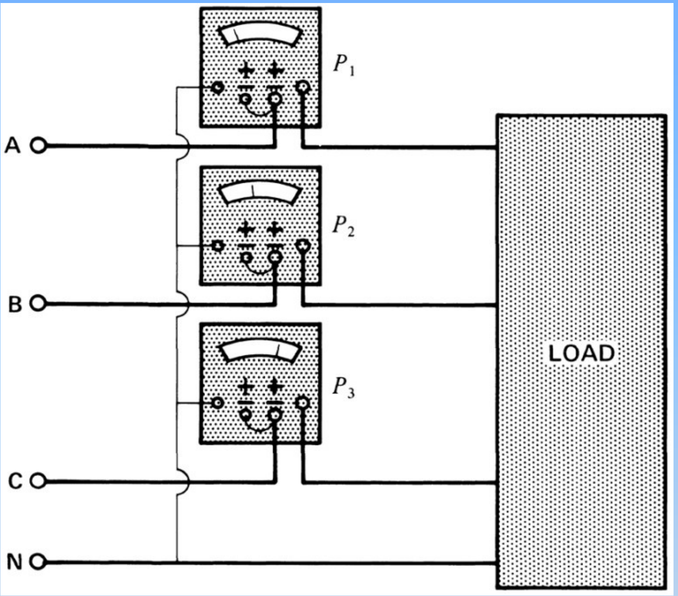
Power Measurement

- In **single-phase systems** power is normally measured using a **watt-meter**
  - measures power directly using a single meter which effectively multiplies instantaneous current and voltage



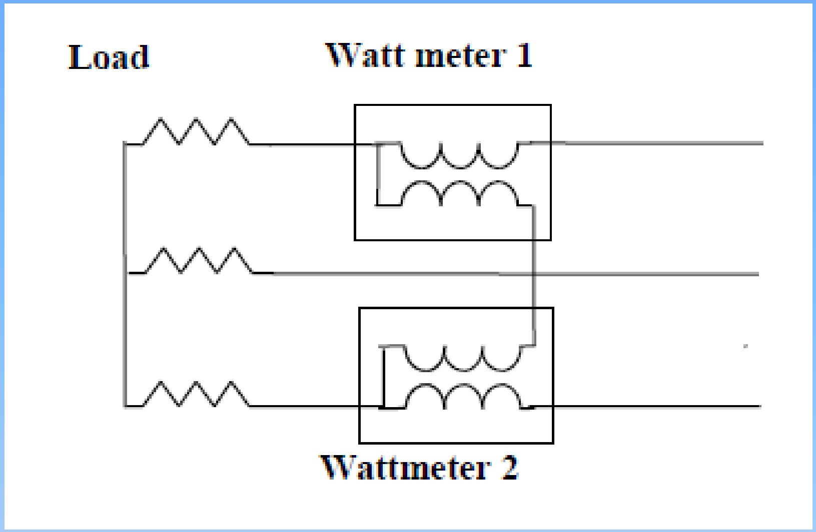
Power Measurement

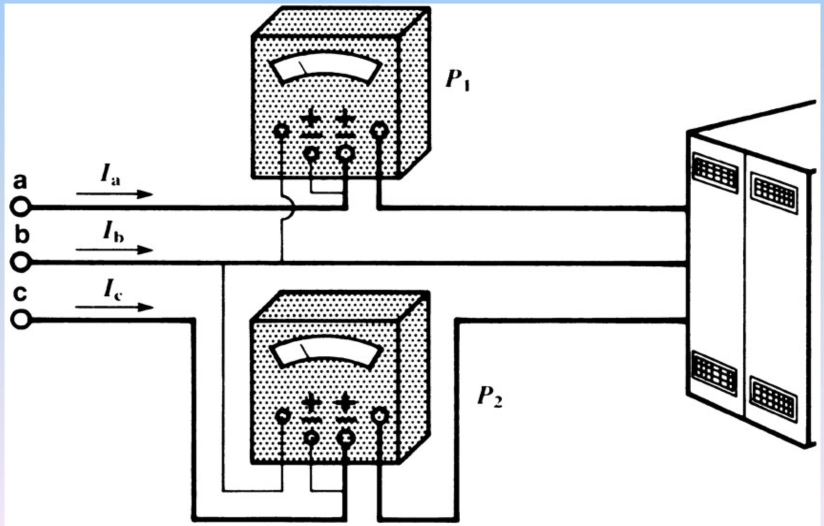
- In **three-phase systems** we need to sum the power taken from the various phases
  - in a four-wire system it may be necessary to use 3 single-phase watt-meters
  - in balanced systems (systems that take equal power from each phase) a single wattmeter can be used, its reading being multiplied by 3 to get the total power



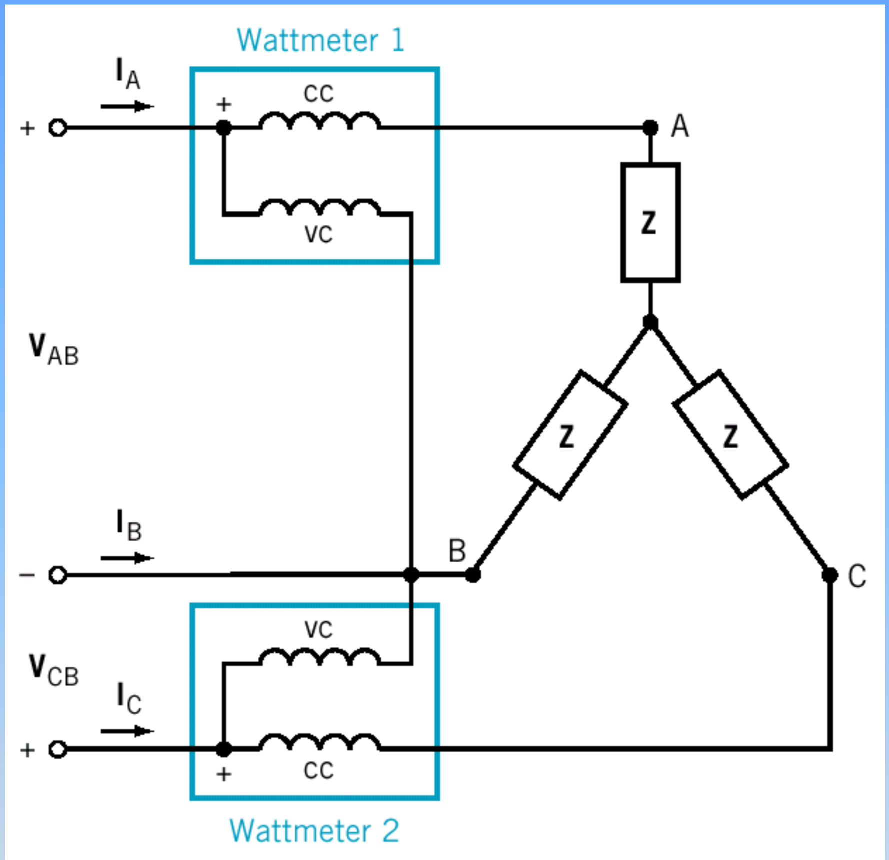
Power Measurement

- In three-wire arrangements we can deduce the total power from measurements using 2 single-phase watt-meters
- The watt-meters are supplied by the line current and the line-to-line voltage.
- The total power is the algebraic sum of the two watt-meters reading.





Two-Wattmeter Power Measurement



cc = current coil
vc = voltage coil

W1 read

$$P_1 = V_{AB} I_A \cos\theta_1$$

W2 read

$$P_2 = V_{CB} I_C \cos\theta_2$$

For balanced load with *abc* phase sequence

$$\theta_1 = \theta_a + 30^\circ \quad \text{and} \quad \theta_2 = \theta_a - 30^\circ$$

θ_a is the angle between phase current and phase voltage of phase a

Two-Wattmeter Power Measurement (cont.)

$$P = P_1 + P_2$$
$$= 2V_L I_L \cos\theta \cos 30°$$
$$= \sqrt{3} V_L I_L \cos\theta$$

To determine the power factor angle

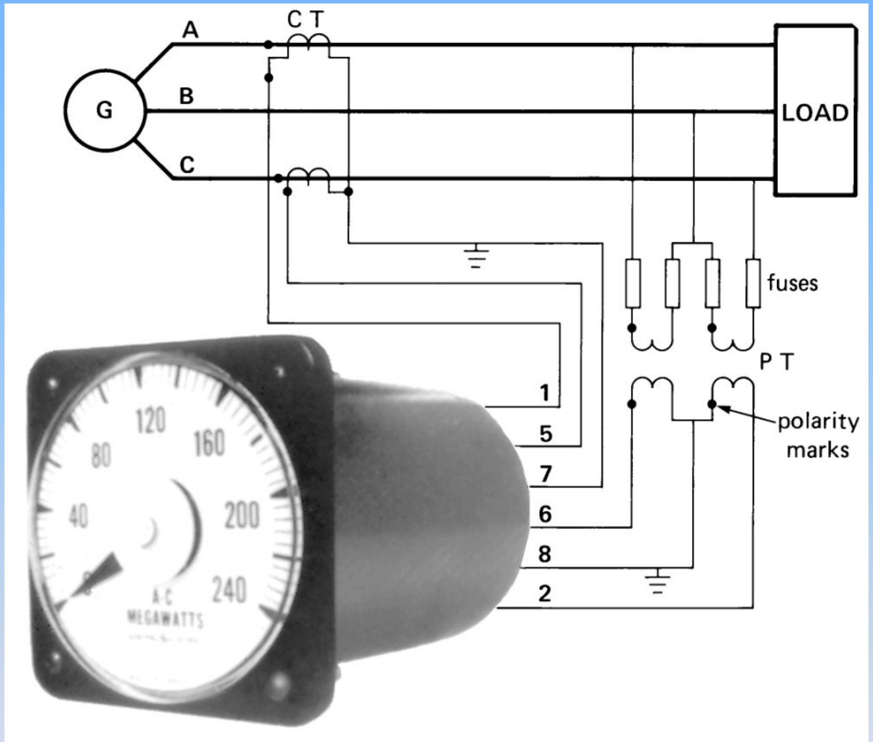
$$P_1 + P_2 = V_L I_L 2\cos\theta \cos 30°$$
$$P_1 - P_2 = V_L I_L (-2\sin\theta \sin 30°)$$

$$\frac{P_1 + P_2}{P_1 - P_2} = \frac{V_L I_L 2\cos\theta \cos 30°}{V_L I_L (-2\sin\theta \sin 30°)} = \frac{-\sqrt{3}}{\tan\theta}$$

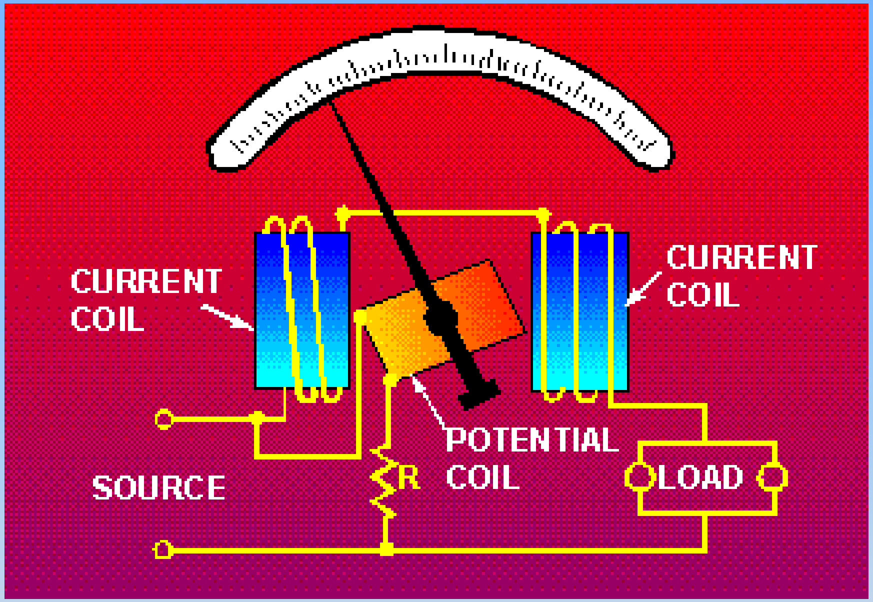
$$\therefore \tan\theta = \sqrt{3}\,\frac{P_1 - P_2}{P_1 + P_2} \quad \text{or} \quad \theta = \tan^{-1}\left(\sqrt{3}\,\frac{P_1 - P_2}{P_1 + P_2}\right)$$

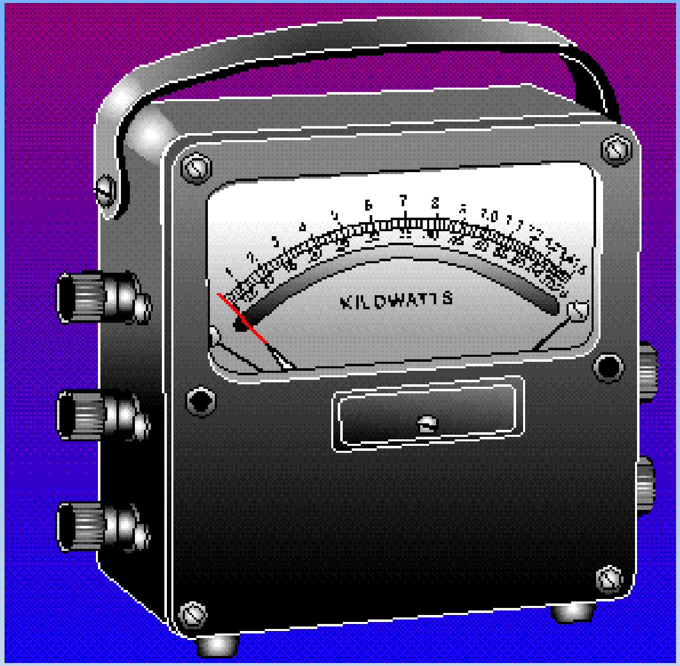
Power Measurement

– Some wattmeters, such as those used on switchboards, are specially designed to give a direct read out of the 3-phase power . The Figure shows a megawatt-range wattmeter circuit that measures the power in a generating station. The current transformers (CT) and potential transformers (PT) step down the line currents and voltages to values compatible with the instrument rating.



Electrodynamic Wattmeter





Digital Power Meter

VAR Meter

pf Meter

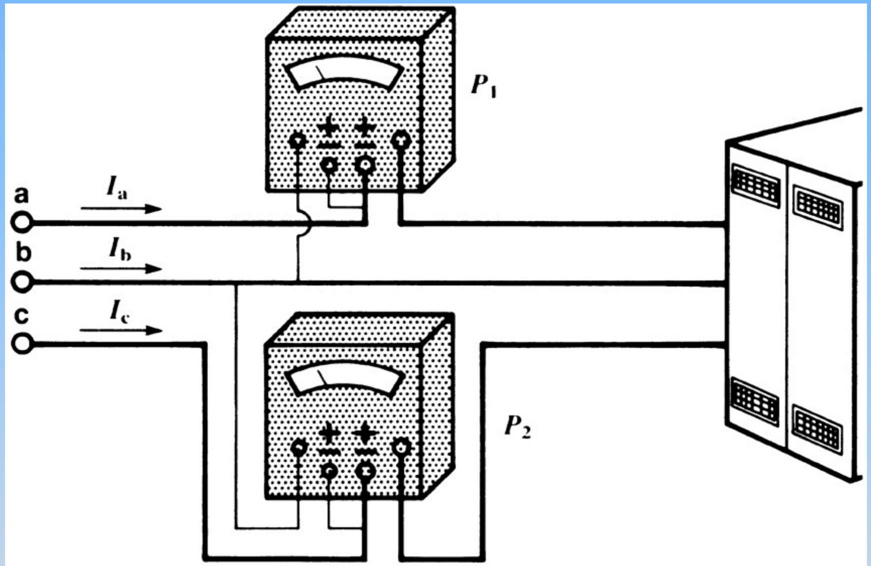
VARmeter

- A VARmeter indicates the reactive power in a circuit. It is built the same way as a wattmeter is, but an internal circuit shifts the line voltage by 90°before it is applied to the potential coil.

- VARmeters are mainly employed in the control rooms of generating stations and the substations of electrical utilities and large industrial consumers.

VARmeter

– In 3-phase, 3-wire balanced circuits, we can calculate the reactive power from the two wattmeter readings by simply multiplying the difference of the two readings by √3.
– For example, if the two wattmeters indicate +5950 W and +2380 W respectively, the reactive power is (5950 -2380) × √3 = 6176 VAR.
– Note that this method of VAR measurement is only valid for balanced 3-phase circuits.



Example 1

- A balanced star connected 3 phase load of 10Ω per phase is supplied from a 400V 50 Hz mains supply at unity power factor
- Calculate the phase voltage, the line current and the total power consumed

Example 1

- A balanced star connected 3 phase load of 10Ω per phase is supplied from a 400V 50 Hz mains supply at unity power factor
- Calculate the phase voltage, the line current and the total power consumed

$$I_L = I_p$$

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

$$V_P = \frac{V_L}{\sqrt{3}}$$

$$V_P = \frac{400}{\sqrt{3}} = 230.9V$$

Example 1

- A balanced star connected 3 phase load of 10Ω per phase is supplied from a 400V 50 Hz mains supply at unity power factor
- Calculate the phase voltage, the line current and the total power consumed

$$I_L = I_p$$

$$I = \frac{V}{R}$$

$$I_L = I_P = \frac{V_P}{R_P}$$

$$I_L = I_P = \frac{230}{10} = 23A$$

Example 1

- A balanced star connected 3 phase load of 10Ω per phase is supplied from a 400V 50Hz mains supply at unity power factor
- Calculate the phase voltage, the line current and the total power consumed

$$P = \sqrt{3} \times V_L \times I_L \times \cos\theta$$

$$P = \sqrt{3} \times 400 \times 23 \times 1 = 16kW$$

Example 2

- A 20 kW 400V balanced delta connected load has a power factor of 0.8
- Calculate the line current and the phase current

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- Calculate the line current and the phase current

$$P = \sqrt{3} \times V_L \times I_L \times \cos\theta$$

$$I_L = \frac{P}{\sqrt{3} \times V_L \times \cos\theta}$$

$$I_L = \frac{20000(w)}{\sqrt{3} \times 400 \times 0.8}$$

$$I_L = 36A$$

Example 2

- A 20 kW 400V balanced delta connected load has a power factor of 0.8
- Calculate the line current and the phase current

$$I_L = 36A$$

Delta connection therefore

$$I_L = \sqrt{3} \times I_P$$

$$I_P = \frac{I_L}{\sqrt{3}}$$

$$I_P = \frac{36}{\sqrt{3}}$$

$$I_P = 20.78A$$

Example 3

- A 3Ph, 60 Hz wye connected generator generates a line to-line voltage of 23,900 V. Calculate

a. The line-to-neutral voltage

b. The voltage induced in the individual windings

c. The time interval between the positive peak voltage of phase A and the positive peak of phase B

d. The peak value of the line voltage

Example 3

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a. The line-to-neutral voltage

b. The voltage induced in the individual windings

c. The time interval between the positive peak voltage of phase A and the positive peak of phase B

d. The peak value of the line voltage

(a) The line-to-neutral voltage is:

$$E_p = E_L / \sqrt{3} = 23{,}900 / \sqrt{3} = 13{,}800 \text{ V}$$

(b) The windings are connected in wye, consequently, the voltage induced in each winding is 13,800 V.

(c) One complete cycle (360°) corresponds to 1/60 s. Consequently, a phase angle of 120° corresponds to an interval of

$$T = 120 / 360 \times 1/60 = 5.55 \text{ ms}$$

(d) The peak line voltage is:

$$E_{l(peak)} = \sqrt{2}\, E_L = 23{,}900 \sqrt{2} = 33{,}800 \text{ V}$$

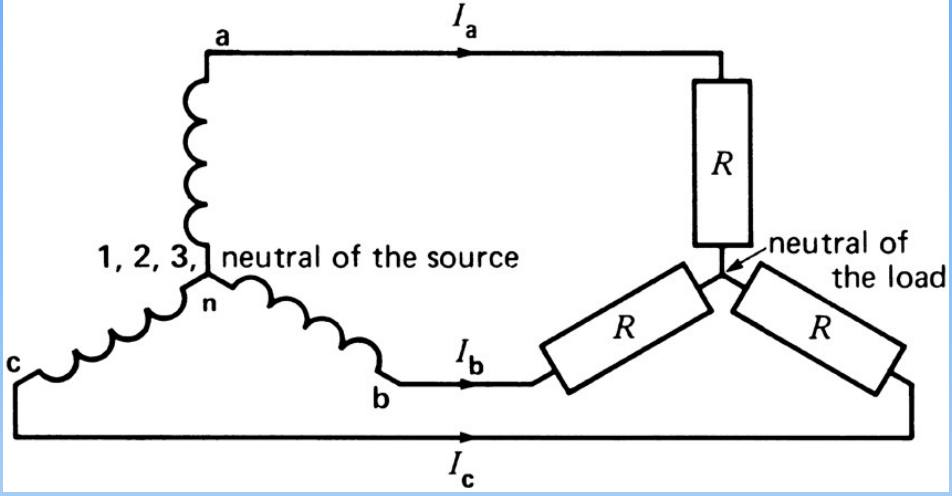
Example 4

- The generator in the Figure generates a line voltage of 865 V, and each load resistor has an impedance of 50 Ω. Calculate

a. The voltage across each resistor

b. The current in each resistor

c. The total power output of the generator



Example 4

- The generator in the Figure generates a line voltage of 865 V, and each load resistor has an impedance of 50 Ω. Calculate

a. The voltage across each resistor

b. The current in each resistor

c. The total power output of the generator

(a) The voltage across each resistor is:

$E_p = E_L / \sqrt{3} = 865 / \sqrt{3} = 500\ V$

(b) The current in each resistor is:

$I_p = E_p / R = 500 / 50 = 10\ A$

All the line currents are equal to10 A.

(c) Power absorbed by each resistor is:

$P = E_p\ I_p = 500 \times 10 = 5000\ W$

The power delivered by the generator to all three resistors is:

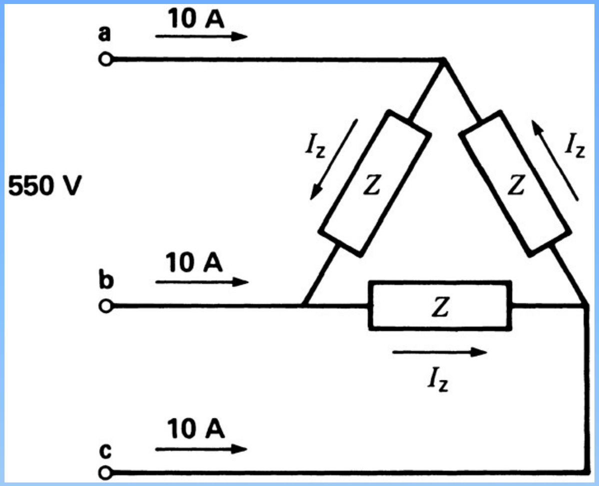
$P = 3 \times 5000 = 15\ kW$

Example 5

- Three identical impedances are connected in delta across a 3-phase, 550 V line. If the line current is 10 A, calculate the following:

a. The current in each impedance

b. The value of each impedance



Example 5

- Three identical impedances are connected in delta across a 3-phase, 550 V line. If the line current is 10 A, calculate the following:

a. The current in each impedance

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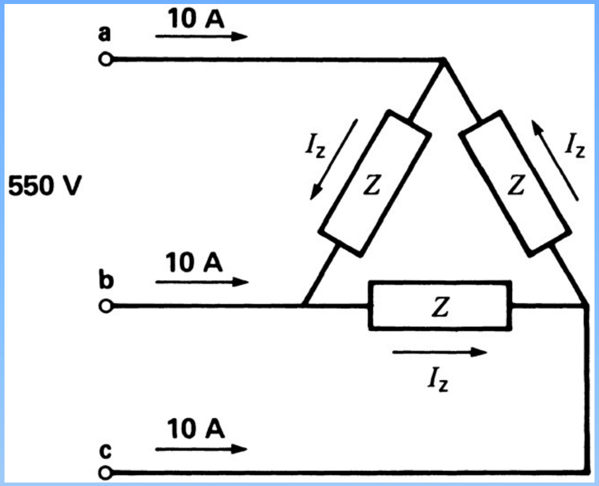


(a) The current in each impedance is:

$I_z = 10 / \sqrt{3} = 5.77\ A$

(b) The voltage across each impedance is 550 V. Consequently:

$Z = E / I_z = 550 / 5.77 = 95\ \Omega$

Example 6

- A 3-phase motor, connected to a 440 V line, draws a line current of 5 A. If the power factor of the motor is 80 percent, calculate the following:

a. The total apparent power

b. The total active power

c. The total reactive power absorbed by the machine

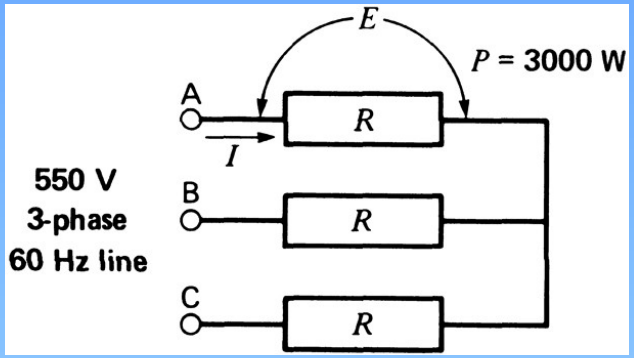
Example 7

- Three identical resistors dissipating a total power of 3000 W are connected in wye across a 3-phase, 550 V line. Calculate:

a. The current in each line

b. The value of each resistor

c. In Figure shown, the phase sequence of the source is known to be A-C-B. Draw the phasor diagram of the line voltages.



Example 7

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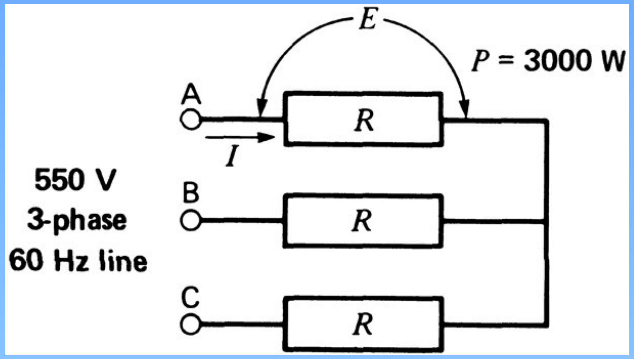
a. The current in each line

b. The value of each resistor



(a) The power dissipated by each resistor is:

P = 3000 W/3 =1000 W

The voltage across the terminals of each resistor is:

E =550V / √3 =318V

The current in each resistor is: I = P/E =1000 W / 318 V = 3.15 A

The current in each line is also 3.15 A.

(b) The resistance of each element is: R = E / I = 318 / 3.15 =101 Ω

Example 7

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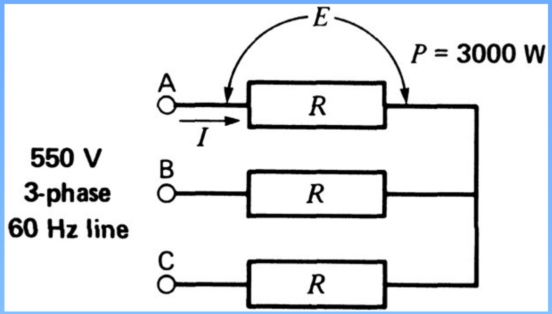
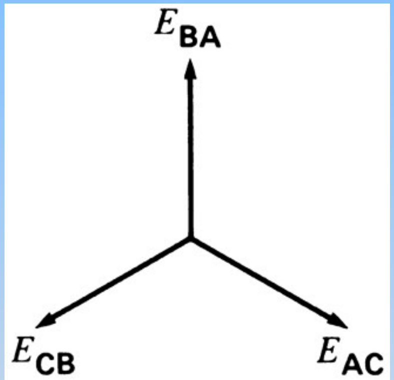
c. In Figure shown, the phase sequence of the source is known to be A-C-B. Draw the phasor diagram of the line voltages.





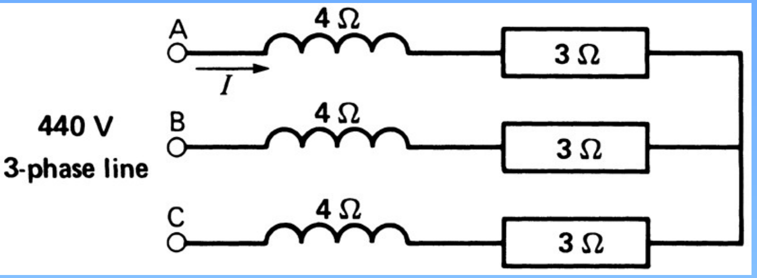
(c) The voltages follow the sequence A-C-B, which is the same as the sequence AC-CB-BA-AC.... Consequently, the line voltage sequence is E_{AC}-E_{CB}- E_{BA} and the corresponding phasor diagram is shown. We can reverse the phase sequence of a 3-phase line by interchanging any two conductors.

Example 8

- In the circuit shown, calculate the following:

a. The current in each line

b. The voltage across the inductor terminals

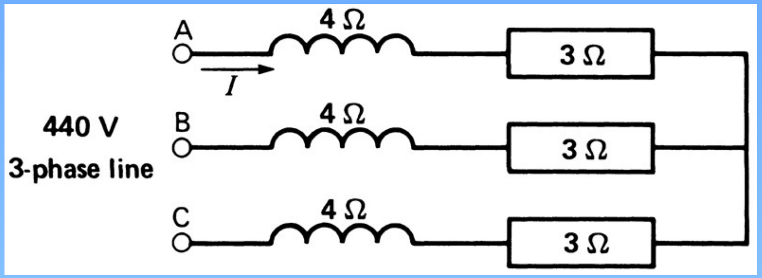


Example 8

- In the circuit shown, calculate the following:

a. The current in each line

b. The voltage across the inductor terminals



(a) Each branch is composed of an inductive reactance X_L=4 Ω in series with a resistance R=3 Ω. Therefore, the impedance of each branch is Z_p = 5 Ω.

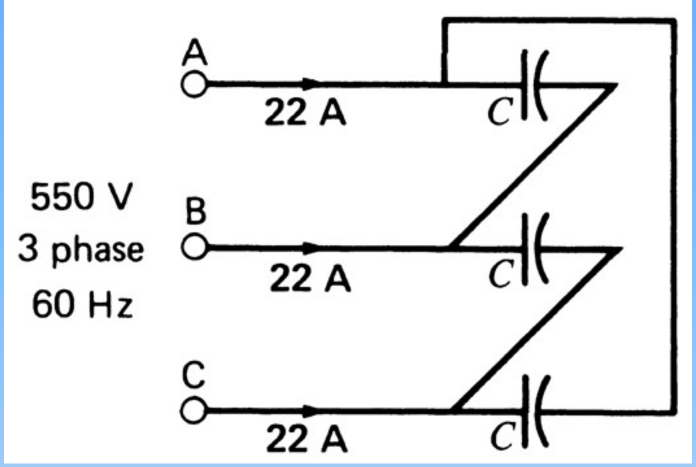
The voltage across each branch is: $E_p = E_L/\sqrt{3} = 440\ V/\sqrt{3} = 254\ V$

The current in each circuit element is: $I_p = E_p / Z_p = 254 / 5 = 50.8\ A$

(b) The voltage across each inductor is: $E = I X_L = 50.8 \times 4 = 203.2\ V$

Example 9

- A 3-phase, 550 V, 60 Hz line is connected to three identical capacitors connected in delta. If the line current is 22 A, calculate the capacitance of each capacitor.



Example 9

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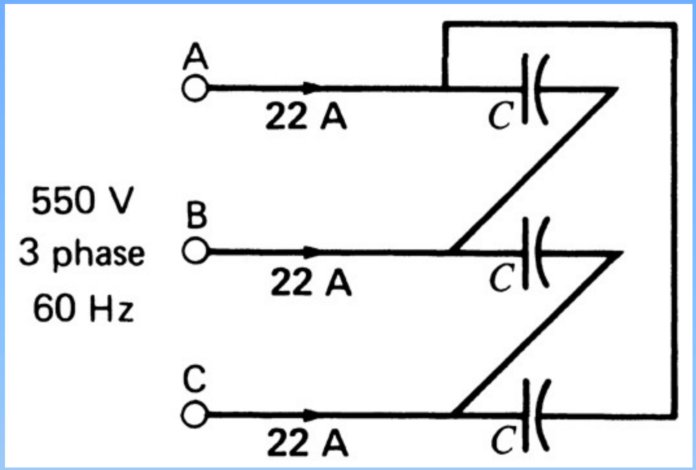


(a) The current in each capacitor is: $I_p = I_L / \sqrt{3} = 22\ A / \sqrt{3} = 12.7\ A$

Voltage across each capacitor is: $E_p = 550\ V$

Capacitive reactance X_c of each capacitor is: $X_c = E_p / I_p = 550/12.7 = 43.3\Omega$.

(a) The capacitance of each capacitor is: $C = 1 / (2 \pi f X_c) = 61.3\ \mu F$

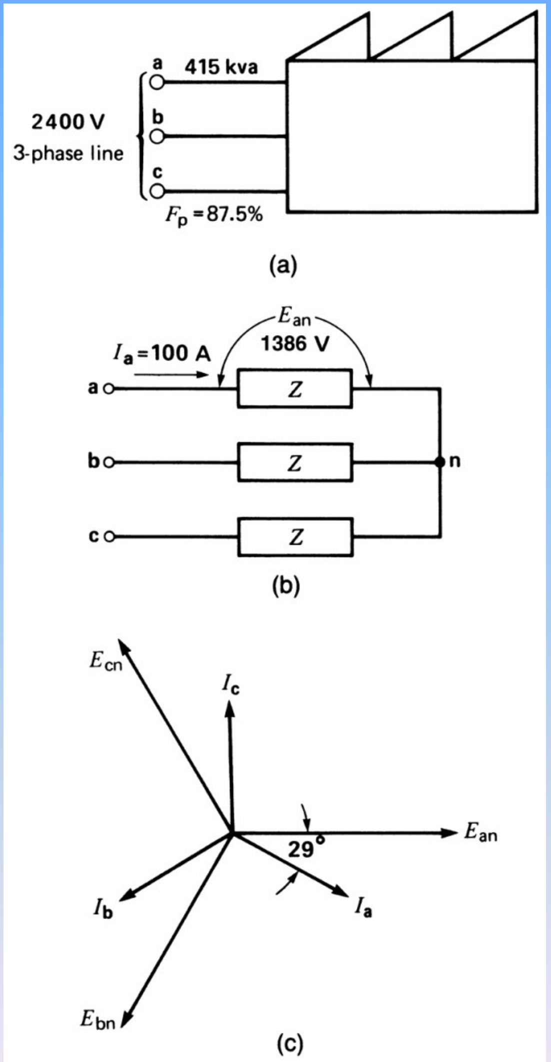
Example 10

- A manufacturing plant draws a total of 415 kVA from a 2400 V (line-to-line), 3-phase line. If the plant power factor is 87.5 percent lagging, calculate:

a. The impedance of the plant, per phase

b. The phase angle between the line-to-neutral voltage and the line current

c. The complete phasor diagram for the plant



Example 10

- A manufacturing plant draws a total of 415 kVA from a 2,400 V (line-to-line), 3-phase line. If the plant power factor is 87.5 percent lagging, calculate:

a. The impedance of the plant, per phase

b. The phase angle between the line-to-neutral voltage and the line current

c. The complete phasor diagram for the plant

(a) We assume a wye connection composed of three identical impedances Z.

The voltage per branch is:

$E_p = 2,400 / \sqrt{3} = 1,386 V$

The current per branch is: $I_p = S / (3 E_p)$

$I_p = 415,000 / (3 \times 1,386) = 100 A$

The impedance per branch is:

$Z = E_p / I_p = 1,386 / 100 = 13.9 \Omega$

(b) The phase angle between the line-to-neutral voltage (1386 V) and the corresponding line current (100 A) is given by:

$\cos \theta = 0.875 \rightarrow \theta = 29^\circ$

The current in each phase lags 29° behind the line-to-neutral voltage.

Example 11

- A 5000 hp, wye-connected motor is connected to a 4000 V, 3-phase, 60 Hz line. A delta-connected capacitor bank rated at 1800 kvar is also connected to the line. If the motor produces an output of 3594 hp at an efficiency of 93% and a power factor of 90% (lagging), calculate the following:

a. The active power absorbed by the motor

b. The reactive power absorbed by the motor

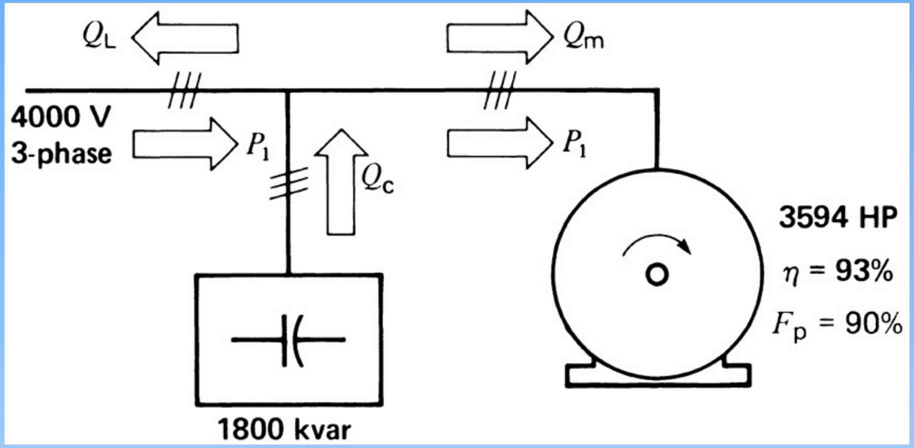
c. The reactive power supplied by the transmission line

d. The apparent power supplied by the transmission line

e. The transmission line current

f. The motor line current

g. Draw the complete phasor diagram for one phase



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c. The reactive power supplied by the transmission line

d. The apparent power supplied by the transmission line

e. The transmission line current

f. The motor line current

g. Draw the complete phasor diagram for one phase

(a) Active power output is:

$P_2 = 3594\ hp \times 0.746 = 2681\ kW$

Active power input to motor:

$P_m = P_2 / \eta = 2681 / 0.93 = 2883\ kW$

(b) Apparent power absorbed by the motor:

$S_m = P_m / \cos\theta = 2883 / 0.90 = 3203\ kVA$

Reactive power absorbed by the motor:

$Q_m = \sqrt{(S_m{}^2 - P_m{}^2)} = 1395\ kvar$

Example 11

- A 5000 hp, wye-connected motor is connected to a 4000 V, 3-phase, 60 Hz line. A delta-connected capacitor bank rated at 1800 kvar is also connected to the line. If the motor produces an output of 3594 hp at an efficiency of 93% and a power factor of 90% (lagging), calculate the following:

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c. The reactive power supplied by the transmission line

d. The apparent power supplied by the transmission line

e. The transmission line current

f. The motor line current

g. Draw the complete phasor diagram for one phase

(c) Reactive power supplied by the capacitor bank: $Q_c = -1800$ *kvar*

Total reactive power absorbed by the load:

$Q_L = Q_c + Q_m = -1800 + 1395 = -405$ *kvar*

This is an unusual situation because reactive power is being returned to the line. In most cases the capacitor bank furnishes no more than Q_m *kilovars of reactive power.*

(d) Active power supplied by the line is

$P_L = P_m = 2883$ *kW*

Apparent power supplied by the line is:

$S_L = \sqrt{(P_L^{\,2} + Q_L^{\,2})} = 2911$ *kVA*

Example 11

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a. The active power absorbed by the motor

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c. The reactive power supplied by the transmission line

d. The apparent power supplied by the transmission line

e. The transmission line current

f. The motor line current

g. Draw the complete phasor diagram for one phase

(e) Transmission line current is:

$I_L = S_L / (E_L \times \sqrt{3}) = 420\ A$

(f) Motor line current is:

$I_m = S_m / (E_L \times \sqrt{3}) = 462\ A$

(g) The line-to-neutral voltage is

$E_p = 4000/\sqrt{3} = 2309V$

Phase angle θ between the motor current and the line-to-neutral voltage is:

$\cos\theta = 0.9 \rightarrow \theta = 25.8°$

(The motor current lags 25.8° behind the voltage, as shown in the phasor diagram.)

Line current drawn by the capacitor bank is:

$I_c = Q_c / (E_L \times \sqrt{3}) = 1800000 / (4000 \times \sqrt{3}) = 260\ A$

Example 11

- A 5000 hp, wye-connected motor is connected to a 4000 V, 3-phase, 60 Hz line. A delta-connected capacitor bank rated at 1800 kvar is also connected to the line. If the motor produces an output of 3594 hp at an efficiency of 93% and a power factor of 90% (lagging), calculate the following:

a. The active power absorbed by the motor

b. The reactive power absorbed by the motor

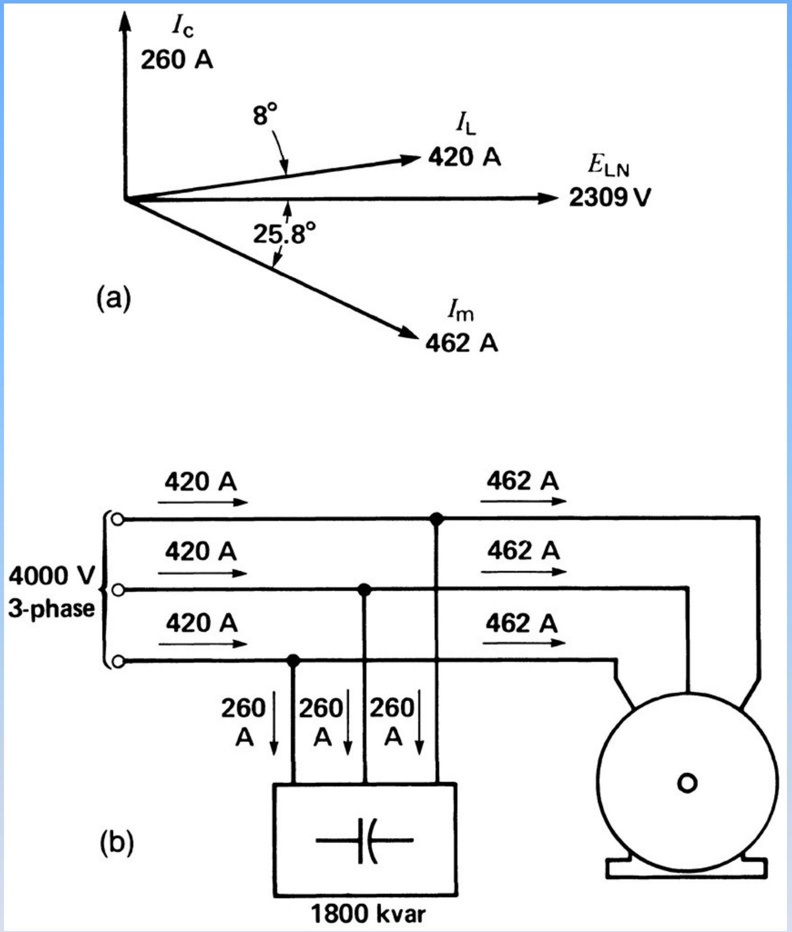
c. The reactive power supplied by the transmission line

d. The apparent power supplied by the transmission line

e. The transmission line current

f. The motor line current

g. Draw the complete phasor diagram for one phase



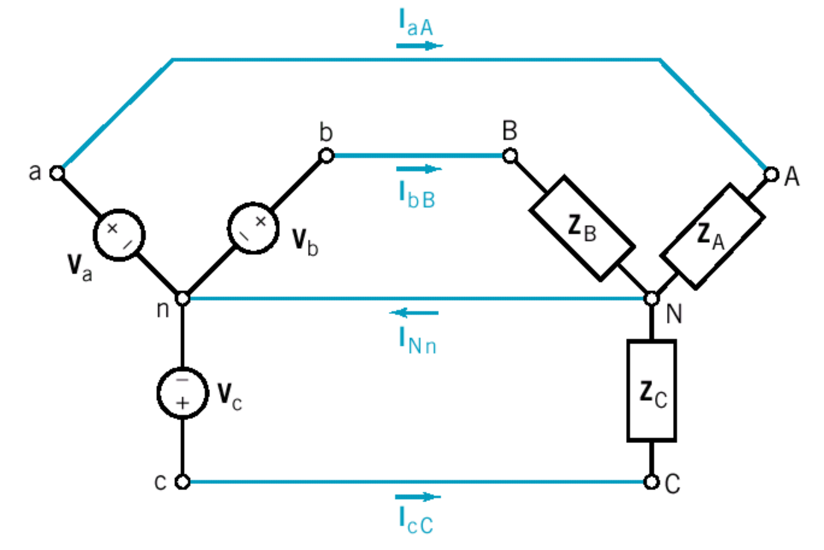
Example #12

Calculate the total apparent power for three-phase Y-Y connected balanced system shown if the phase voltage is 110 V, and load impedance per phase is 50 ∠60⁰ Ω.

$$\mathbf{V}_a = 110\angle 0^\circ \quad \mathrm{V_{rms}}$$

$$\mathbf{V}_b = 110\angle -120^\circ \quad \mathrm{V_{rms}}$$

$$\mathbf{V}_c = 110\angle 120^\circ \quad \mathrm{V_{rms}}$$



$$\mathbf{Z}_A = 50\angle 60^\circ \ \Omega = \mathbf{Z}_B = \mathbf{Z}_C$$

$$\mathbf{I}_{aA} = \frac{\mathbf{V}_a}{\mathbf{Z}_A} = \frac{110\angle 0^\circ}{50\angle 60^\circ} = 2.2\angle -60^\circ \ \mathrm{A_{rms}}$$

$$\mathbf{I}_{bB} = \frac{\mathbf{V}_b}{\mathbf{Z}_B} = \frac{110\angle -120^\circ}{50\angle 60^\circ} = 2.2\angle -180^\circ \ \mathrm{A_{rms}}$$

$$\mathbf{I}_{cC} = \frac{\mathbf{V}_c}{\mathbf{Z}_C} = \frac{110\angle 120^\circ}{50\angle 60^\circ} = 2.2\angle 60^\circ \ \mathrm{A_{rms}}$$

$$S = 3\ V\ I^* = 3\times 110\angle 0^0 \times 2.2\angle 60^0$$

$$= 726\angle 60^0\ VA$$

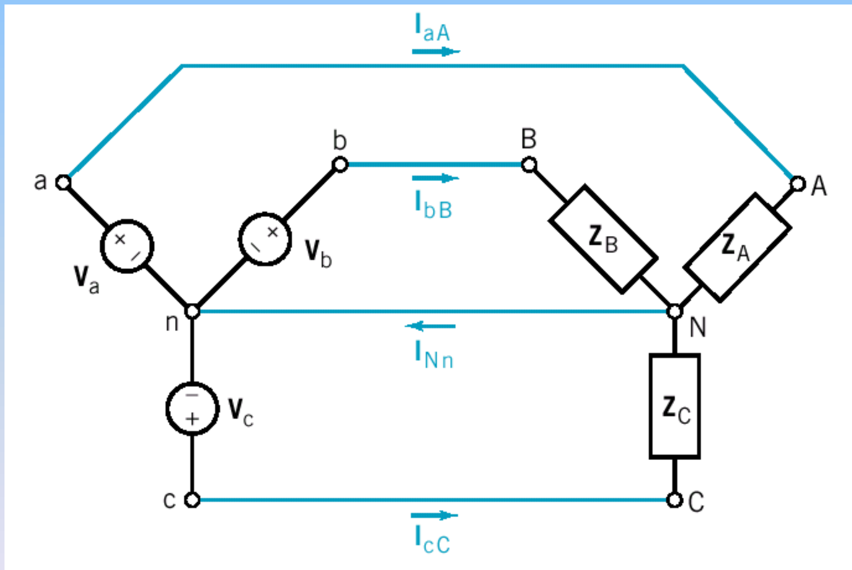
- *Repeat the last example, if the source voltage is 230 V (rms) and the load impedance is 100 $\angle 40^0\Omega$?*

Example #13

Calculate the total apparent power for three-phase 4-wire Y-Y connected shown in if the phase voltage is 110 V, and load impedances are:

$$\mathbf{Z}_A = 50 + j80 \quad \Omega$$
$$\mathbf{Z}_B = j50 \quad \Omega$$
$$\mathbf{Z}_C = 100 + j25 \quad \Omega$$

$$\mathbf{V}_a = 110\angle 0° \quad \mathrm{V_{rms}}$$
$$\mathbf{V}_b = 110\angle -120° \quad \mathrm{V_{rms}}$$
$$\mathbf{V}_c = 110\angle 120° \quad \mathrm{V_{rms}}$$



Unbalanced 4-wire

$$\mathbf{I}_{aA} = \frac{\mathbf{V}_a}{\mathbf{Z}_A} = \frac{110\angle 0°}{50 + j80} = 1.16\angle -58° \quad \mathrm{A_{rms}}$$

$$\mathbf{I}_{bB} = \frac{\mathbf{V}_b}{\mathbf{Z}_B} = \frac{110\angle -120°}{j50} = 2.2\angle 150° \quad \mathrm{A_{rms}}$$

$$\mathbf{I}_{cC} = \frac{\mathbf{V}_c}{\mathbf{Z}_C} = \frac{110\angle 120°}{100 + j25} = 1.07\angle \quad 106° \quad \mathrm{A_{rms}}$$

$$\mathbf{S}_A = \mathbf{I}_{aA}^{*}\mathbf{V}_a = 68 + j109 \quad \mathrm{VA}$$

$$\mathbf{S}_B = \mathbf{I}_{bB}^{*}\mathbf{V}_b = j242 \quad \mathrm{VA}$$

$$\mathbf{S}_C = \mathbf{I}_{cC}^{*}\mathbf{V}_c = 114 + j28 \quad \mathrm{VA}$$

$$\mathbf{S} = \mathbf{S}_A + \mathbf{S}_B + \mathbf{S}_C = 182 + j379 \quad \mathrm{VA}$$

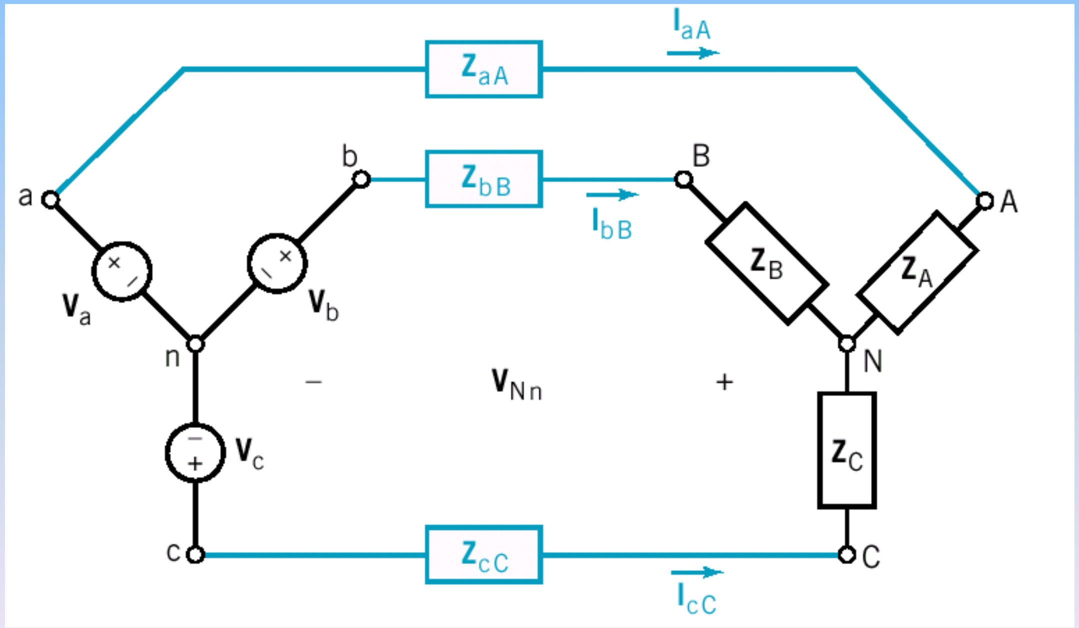
Example #14

Calculate the total apparent power for three-phase 3-wire Y-Y connected shown if the phase voltage is 110 V, and load impedances are:

$$\mathbf{Z}_A = 50 + j80 \quad \Omega$$

$$\mathbf{Z}_B = j50 \quad \Omega$$

$$\mathbf{Z}_C = 100 + j25 \quad \Omega$$



$$\mathbf{V}_{Nn} = \frac{(110\angle -120°)\mathbf{Z}_A\mathbf{Z}_C + 110\angle 120°\mathbf{Z}_A\mathbf{Z}_B + 110\angle 0°\mathbf{Z}_B\mathbf{Z}_C}{\mathbf{Z}_A\mathbf{Z}_C + \mathbf{Z}_A\mathbf{Z}_B + \mathbf{Z}_B\mathbf{Z}_C}$$

$$= 56\angle -151° \quad \mathrm{V_{rms}}$$

$$\mathbf{I}_{aA} = \frac{\mathbf{V}_a - \mathbf{V}_{Nn}}{\mathbf{Z}_A}, \mathbf{I}_{bB} = \frac{\mathbf{V}_b - \mathbf{V}_{Nn}}{\mathbf{Z}_B}, \text{ and } \mathbf{I}_{cC} = \frac{\mathbf{V}_c - \mathbf{V}_{Nn}}{\mathbf{Z}_C}$$

$$\mathbf{I}_{aA} = 1.71\angle -48°, \mathbf{I}_{bB} = 1.37\angle 74°, \text{ and } \mathbf{I}_{cC} = 1.19\angle 79°$$

$$\mathbf{S}_A = \mathbf{I}_{aA}^*\mathbf{V}_a = \mathbf{I}_{aA}^*(\mathbf{I}_{aA}\mathbf{Z}_A) = 146 + j234 \quad \mathrm{VA}$$

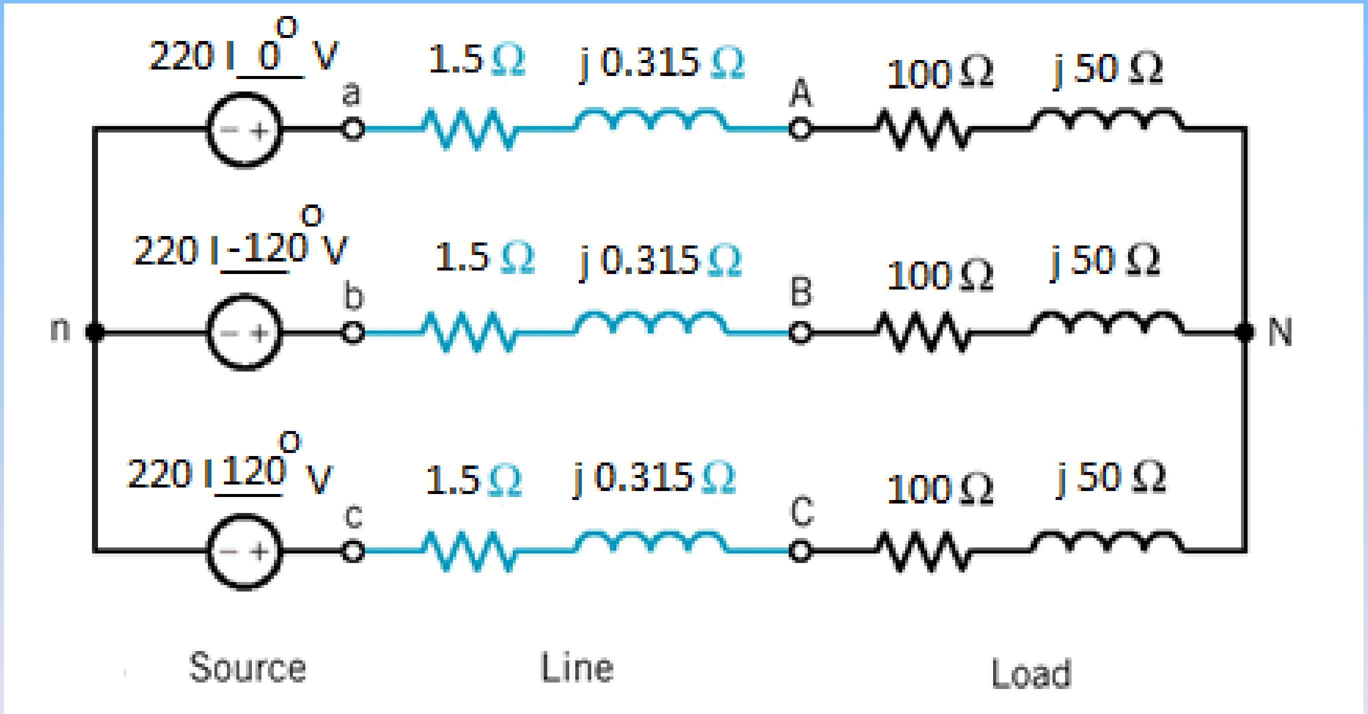
$$\mathbf{S}_B = \mathbf{I}_{bB}^*\mathbf{V}_b = \mathbf{I}_{bB}^*(\mathbf{I}_{bB}\mathbf{Z}_B) = j94 \quad \mathrm{VA}$$

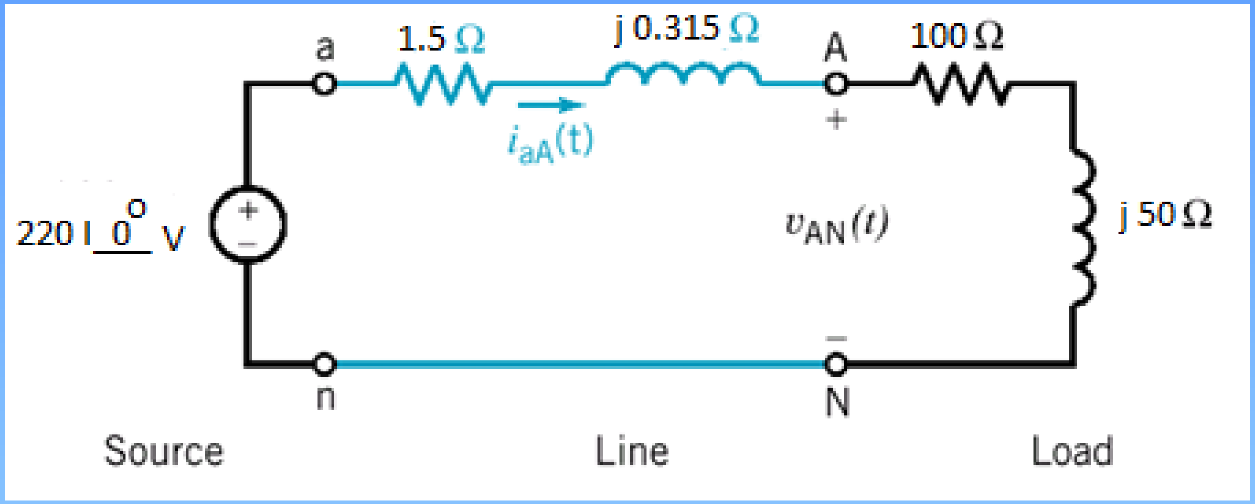
$$\mathbf{S}_C = \mathbf{I}_{cC}^*\mathbf{V}_c = \mathbf{I}_{cC}^*(\mathbf{I}_{cC}\mathbf{Z}_C) = 141 + j35 \quad \mathrm{VA}$$

$$\mathbf{S} = \mathbf{S}_A + \mathbf{S}_B + \mathbf{S}_C = 287 + j364 \quad \mathrm{VA}$$

Example #15

Calculate the total source real power, the total power delivered to the load, and the total power loss in the transmission line for three-phase 3-wire Y-Y connected shown in the Figure.





$$I_{aA} = \frac{V_a}{Z_{Line} + Z_{load-A}} = \frac{220\angle 0^0}{(1.5 + j0.315) + (100 + j50)} = \_\_\_\_\_\_ \angle$$

$$P_a = V_a \times I_{aA} \times \cos(\theta_v - \theta_I) = \_\_\_\_\_\_\_\_\_\_\_\_\_\_ watt$$

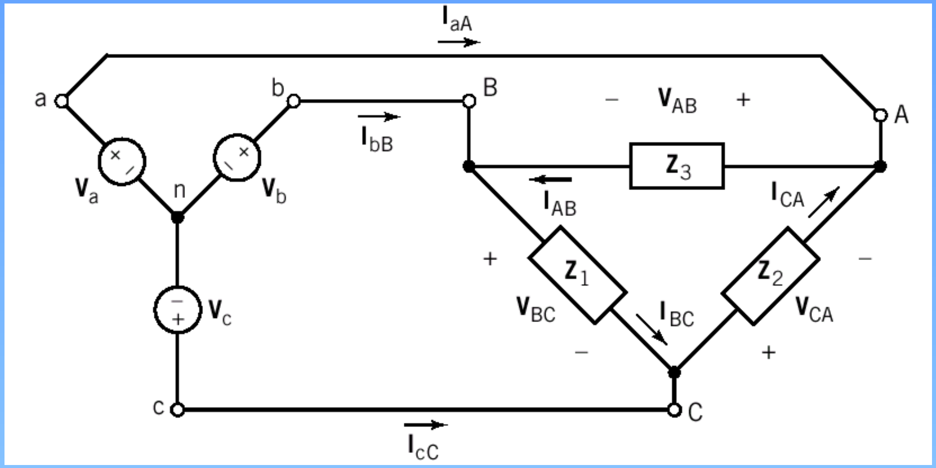
$$P_T = 3 \times P_a = \_\_\_\_\_\_\_\_ watt$$

$$P_{Load-A} = \left|I_{aa}\right|^2 \times \text{Real}\left(Z_{L-A}\right) = \_\_\_\_\_\_\_\_\_\_ \; watt$$

$$P_{Total\,Load} = 3 \times P_{Load-A} = \_\_\_\_\_\_\_\_\_\_\_\_\_ \; watt$$

$$P_{Total\,Line\,loss} = 3 \times P_{Lineloss-A} = \_\_\_\_\_\_\_\_\_\_\_ \; watt$$

Example -16 $I_P = ?$ $I_L = ?$



$$\mathbf{V}_a = \frac{220}{\sqrt{3}}\angle -30^\circ \quad \text{V}_{\text{rms}}$$

$$\mathbf{V}_b = \frac{220}{\sqrt{3}}\angle -150^\circ \quad \text{V}_{\text{rms}}$$

$$\mathbf{V}_c = \frac{220}{\sqrt{3}}\angle 90^\circ \quad \text{V}_{\text{rms}}$$

The Δ-connected load is balanced with

$$\mathbf{Z}_\Delta = 10\angle 50^\circ$$

$$\mathbf{V}_{AB} = \mathbf{V}_a - \mathbf{V}_b = 220\angle 0^\circ \quad \text{V}_{\text{rms}}$$

$$\mathbf{V}_{BC} = \mathbf{V}_b - \mathbf{V}_c = 220\angle -120^\circ \quad \text{V}_{\text{rms}}$$

$$\mathbf{V}_{CA} = \mathbf{V}_c - \mathbf{V}_a = 220\angle -240^\circ \quad \text{V}_{\text{rms}}$$

$$\Rightarrow$$

$$\mathbf{I}_{AB} = \frac{\mathbf{V}_{AB}}{\mathbf{Z}_\Delta} = 22\angle 50^\circ \quad \text{A}_{\text{rms}}$$

$$\mathbf{I}_{BC} = \frac{\mathbf{V}_{BC}}{\mathbf{Z}_\Delta} = 22\angle -70^\circ \quad \text{A}_{\text{rms}}$$

$$\mathbf{I}_{CA} = \frac{\mathbf{V}_{CA}}{\mathbf{Z}_\Delta} = 22\angle -190^\circ \quad \text{A}_{\text{rms}}$$

The line currents are

$$\mathbf{I}_{aA} = \mathbf{I}_{AB} - \mathbf{I}_{CA} = 22\sqrt{3}\angle 20^\circ, \mathbf{I}_{bB} = 22\sqrt{3}\angle -100^\circ, \mathbf{I}_{cC} = 22\sqrt{3}\angle -220^\circ$$

Example - 17 $I_P = ?$

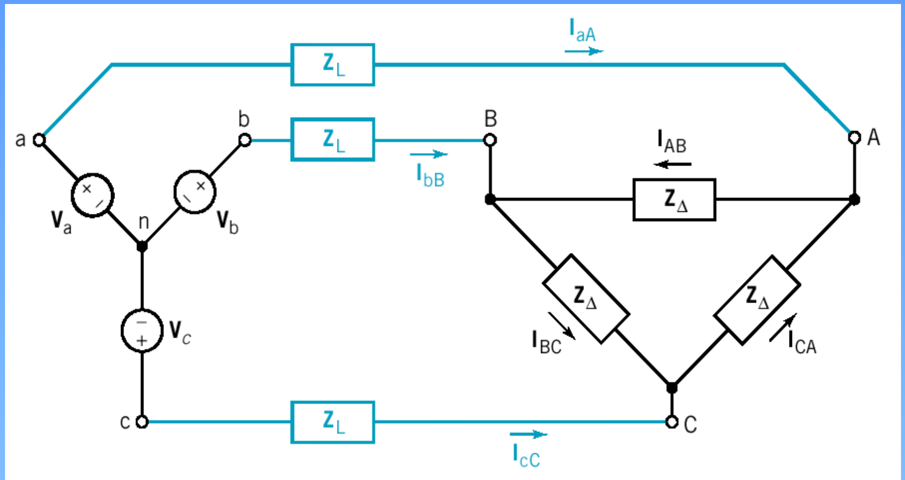
$$\mathbf{V}_a = 110\angle 0° \quad \mathrm{V_{rms}}$$

$$\mathbf{V}_b = 110\angle -120° \quad \mathrm{V_{rms}}$$

$$\mathbf{V}_c = 110\angle 120° \quad \mathrm{V_{rms}}$$

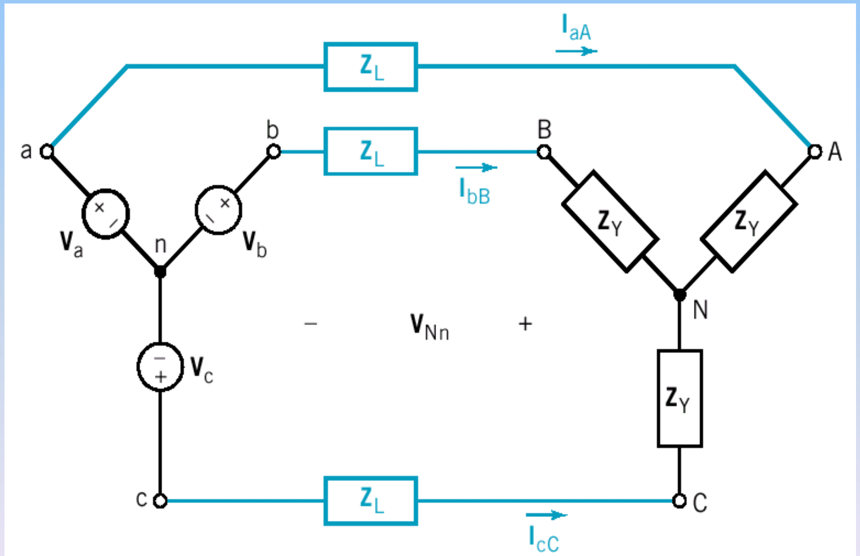
$$\mathbf{Z}_L = 10 + j5 \quad \Omega$$

$$\mathbf{Z}_\Delta = 75 + j225 \quad \Omega$$

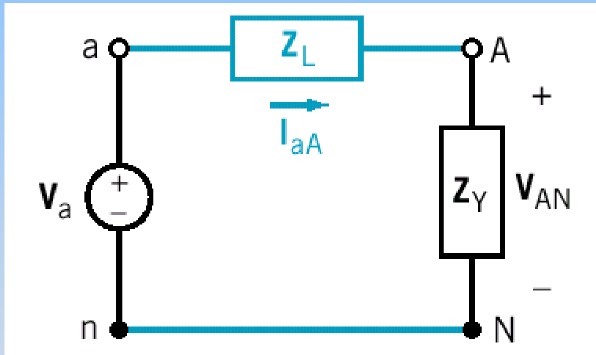


(a)

$$\mathbf{Z}_Y = \frac{\mathbf{Z}_\Delta}{3} = 25 + j75 \quad \Omega$$



(b)



(c)

$$\mathbf{I}_{aA} = \frac{\mathbf{V}_a}{\mathbf{Z}_L + \mathbf{Z}_Y} = 1.26\angle -66° \ \mathrm{A_{rms}}$$

$$\mathbf{I}_{bB} = 1.26\angle -186° \text{ A}_{\text{rms}} \quad \text{and} \quad \mathbf{I}_{cC} = 1.26\angle -54° \text{ A}_{\text{rms}}$$

The voltages in the per-phase equivalent circuit are

$$\mathbf{V}_{AN} = \mathbf{I}_{aA}\mathbf{Z}_{Y} = 99.6\angle 5° \quad \text{V}_{\text{rms}}$$

$$\mathbf{V}_{BN} = 99.6\angle -115° \quad \text{V}_{\text{rms}}$$

$$\mathbf{V}_{CN} = 99.6\angle 125° \quad \text{V}_{\text{rms}}$$

The line-to-line voltages are

$$\mathbf{V}_{AB} = \mathbf{V}_{AN} - \mathbf{V}_{BN} = 172\angle 35° \quad \text{V}_{\text{rms}}$$

$$\mathbf{V}_{BC} = \mathbf{V}_{BN} - \mathbf{V}_{CN} = 172\angle -85° \quad \text{V}_{\text{rms}}$$

$$\mathbf{V}_{CA} = \mathbf{V}_{CN} - \mathbf{V}_{AN} = 172\angle 155° \quad \text{V}_{\text{rms}}$$

$$\Rightarrow$$

$$\mathbf{I}_{AB} = \frac{\mathbf{V}_{AB}}{\mathbf{Z}_{\Delta}} = 0.727\angle -36° \quad \text{A}_{\text{rms}}$$

$$\mathbf{I}_{BC} = \frac{\mathbf{V}_{BC}}{\mathbf{Z}_{\Delta}} = 0.727\angle -156° \quad \text{A}_{\text{rms}}$$

$$\mathbf{I}_{CA} = \frac{\mathbf{V}_{CA}}{\mathbf{Z}_{\Delta}} = 0.727\angle 84° \quad \text{A}_{\text{rms}}$$

Example 18 $P = ?$

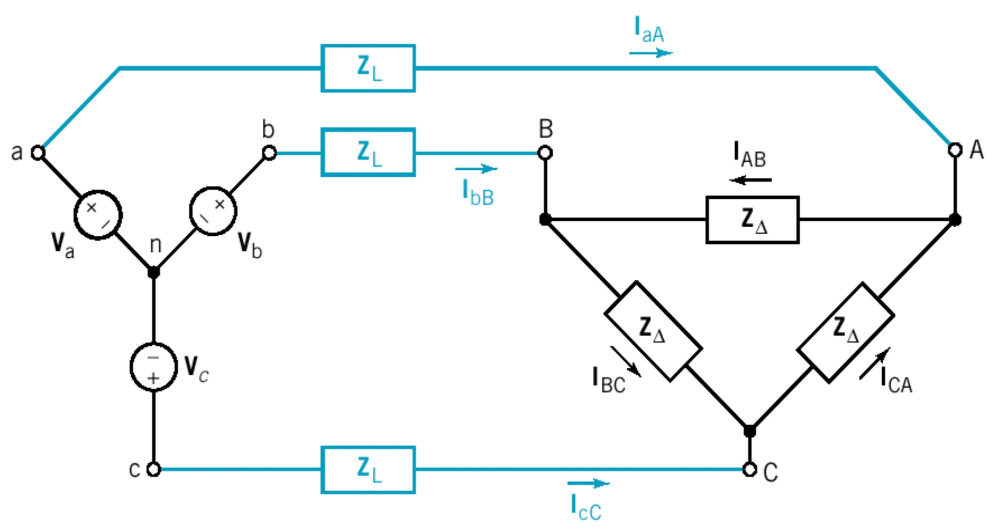
$$\mathbf{V}_a = 110\angle 0^\circ \quad \mathrm{V_{rms}}$$

$$\mathbf{V}_b = 110\angle -120^\circ \quad \mathrm{V_{rms}}$$

$$\mathbf{V}_c = 110\angle 120^\circ \quad \mathrm{V_{rms}}$$

$$\mathbf{Z}_L = 10 + j5 \quad \Omega$$

$$\mathbf{Z}_\Delta = 75 + j225 \quad \Omega$$



(a)

$$\mathbf{I}_{aA} = \frac{\mathbf{V}_a}{\mathbf{Z}_L + \mathbf{Z}_Y} = 1.26\angle -66^\circ \ \mathrm{A_{rms}}$$

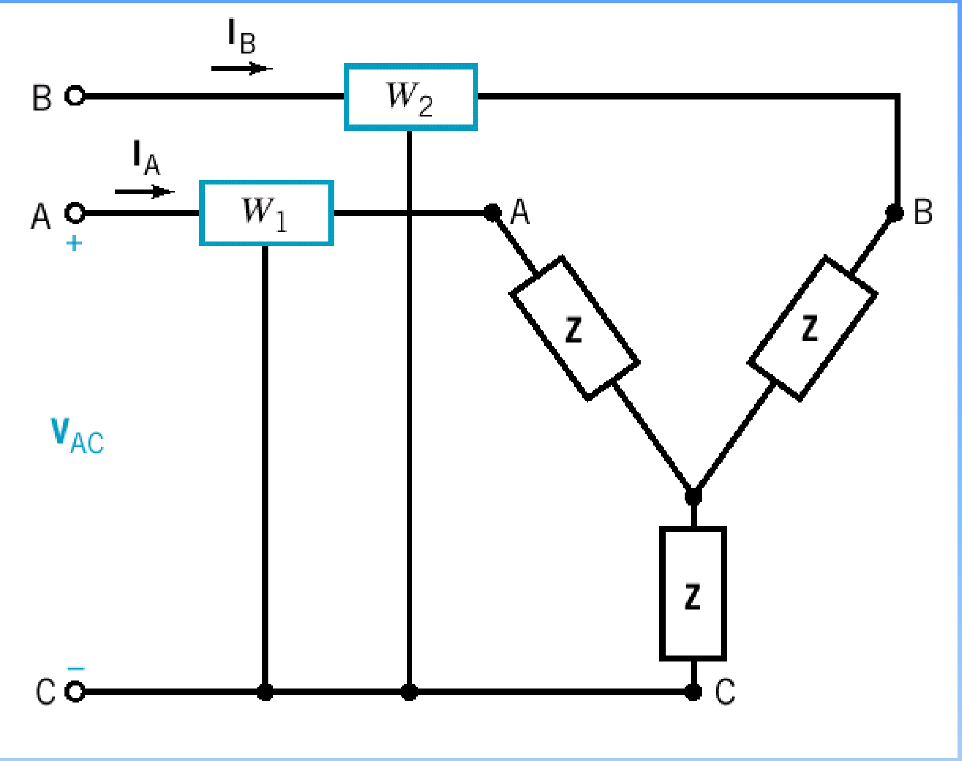
$$\mathbf{V}_{AN} = \mathbf{I}_{aA}\mathbf{Z}_Y = 99.6\angle 5^\circ \quad \mathrm{V_{rms}}$$

$$P = 3(99.6)(1.26)\cos(5^\circ - (-66^\circ)) = 122.6 \quad \mathrm{W}$$

Example 19 $P = ?$

$$\mathbf{Z} = 10\angle 45^\circ$$

line-to-line voltage = 220Vrms



The phase voltage

$$\mathbf{V}_A = \frac{220}{\sqrt{3}}\angle -30^\circ$$

The line current

$$\mathbf{I}_A = \frac{\mathbf{V}_A}{\mathbf{Z}} = \frac{220\angle -30^\circ}{10\sqrt{3}\angle 45^\circ} = 12.7\angle -75^\circ \quad \text{and} \quad \mathbf{I}_B = 12.7\angle -195^\circ$$

$$P_1 = V_{AC} I_A \cos\theta_1 = 2698 \quad \text{W}$$

$$P_2 = V_{BC} I_B \cos\theta_2 = 723 \quad \text{W}$$

$$\Rightarrow P = P_1 + P_2 = 3421 \quad \text{W}$$

Example 20

- A full-load test on a 10 hp, 3-phase motor yields the following results: P_1 = + 5,950 W; P_2 = + 2,380 W; the current in each of the three lines is 10 A; and the line voltage is 600 V. Calculate the power factor of the motor.

Example 20

- A full-load test on a 10 hp, 3-phase motor yields the following results: P_1 = + 5,950 W; P_2 = + 2,380 W; the current in each of the three lines is 10 A; and the line voltage is 600 V. Calculate the power factor of the motor.

Apparent power supplied to the motor is:

$S_L = \sqrt{3} \times E_L \times I_L = = \sqrt{3} \times 600 \times 10 = 10{,}390\ VA$

Active power supplied to the motor is:

$P = 5{,}950 + 2{,}380 = 8{,}330\ W$

$P.F. = \cos \theta = P / S = 8{,}330 / 10{,}390 = 0.80$, or 80%

Example 21

- When the motor in the previous example runs at no-load, the line current drops to 3.6 A and the wattmeter readings are P_1 = +1295 W; P_2 = -845 W.

  Calculate the no-load losses and power factor.

Example 21

- When the motor in the previous example runs at no-load, the line current drops to 3.6 A and the wattmeter readings are $P_1 = +1295$ W; $P_2 = -845$ W.

  Calculate the no-load losses and power factor.

Apparent power supplied to the motor is:

$S_L = \sqrt{3} \times E_L \times I_L = = \sqrt{3} \times 600 \times 3.6 = 3{,}741\ VA$

No-load losses are:

$P = P_1 + P_2 = 1{,}295 - 845 = 450\ W$

$P.F. = \cos\theta = P / S = 450 / 3741 = 0.12 = 12\%$