PSA_1

Power System Basics

- All power systems have three major components: Generation, Load and Transmission.
- Generation: Creates electric power.
- Load: Consumes electric power.
- Transmission: Transmits electric power from generation to load.

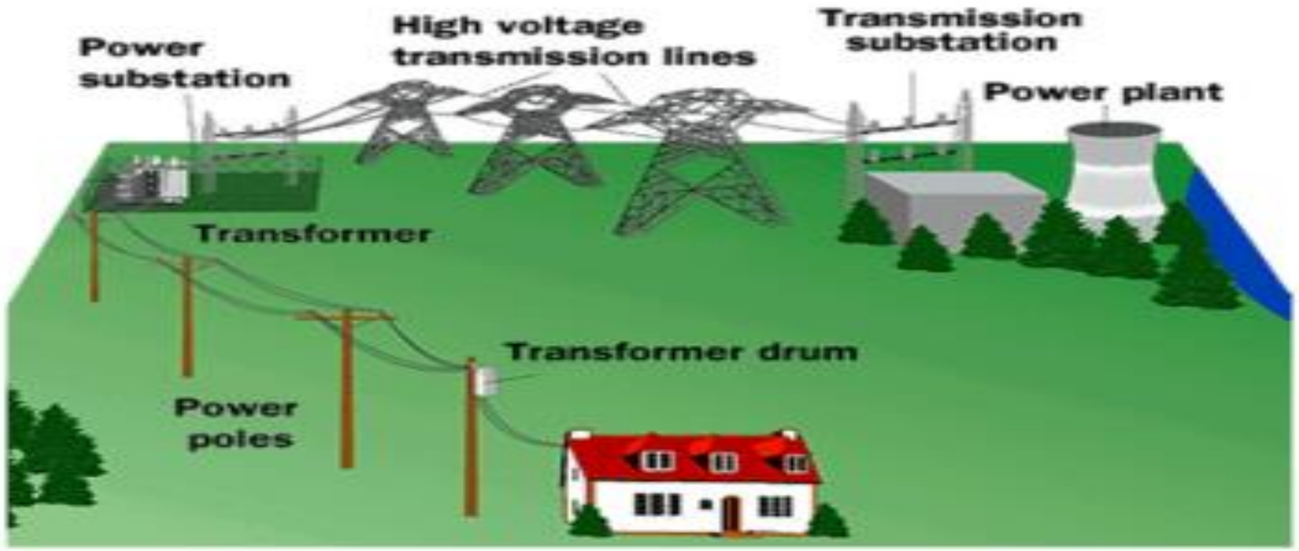
Power system

Generation

Transmission

Loads

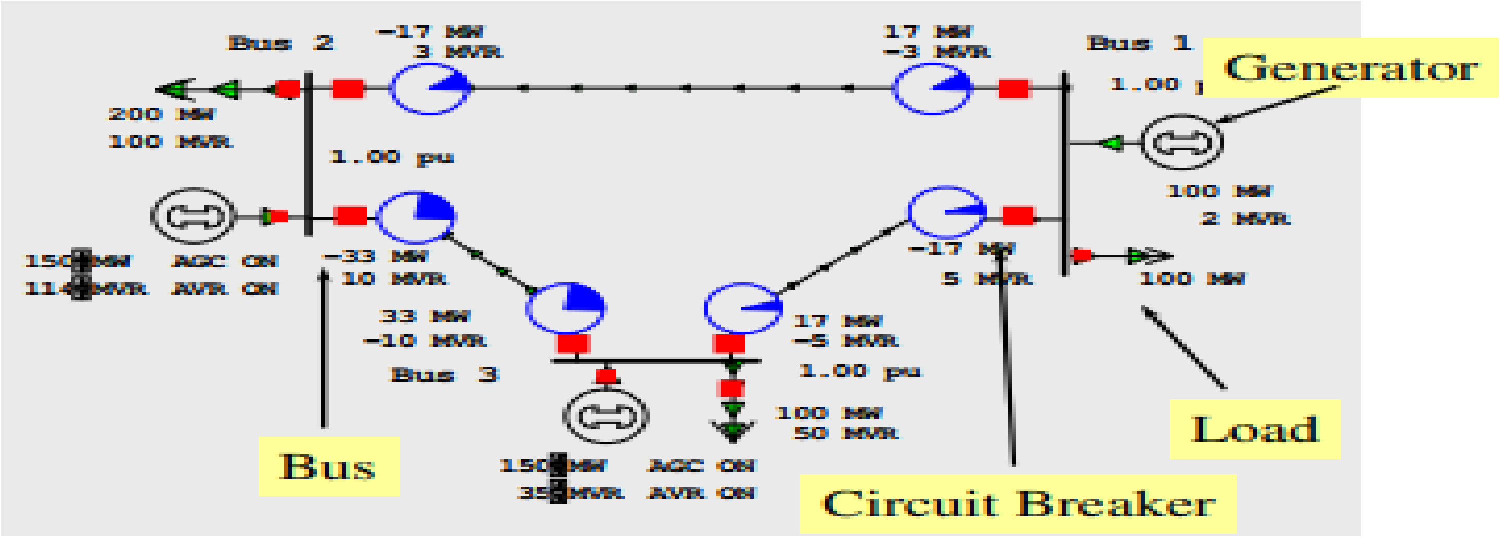
Power system



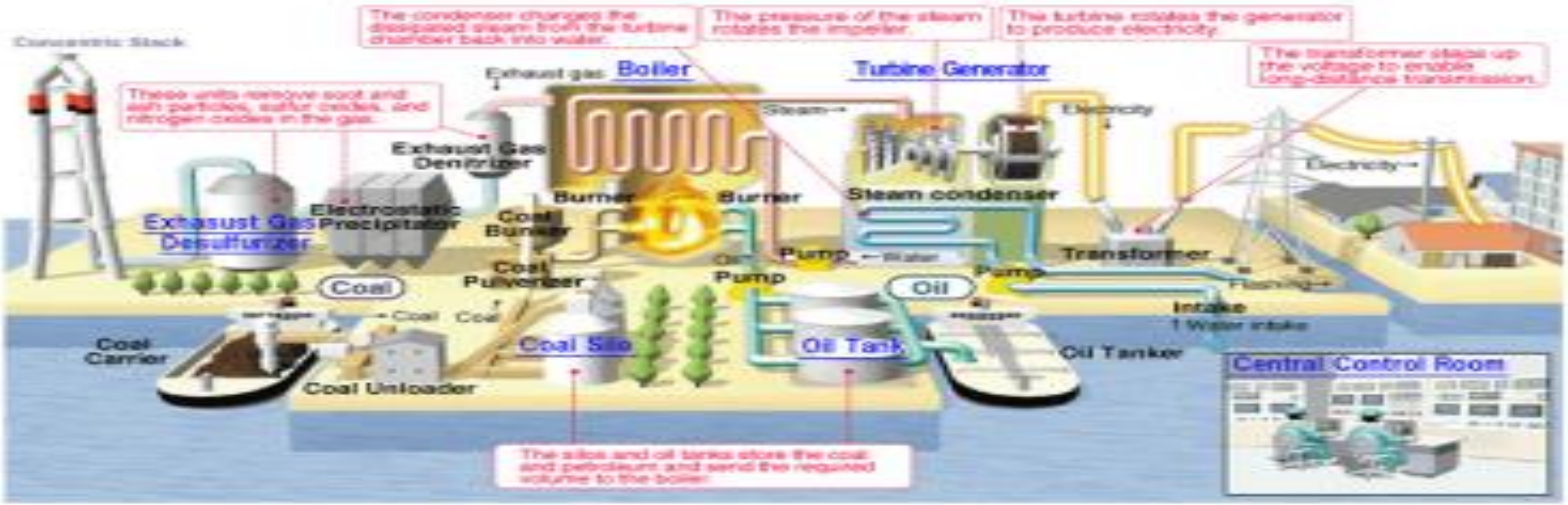
One-line Diagram

- Most power systems are balanced three phase systems.
- A balanced three phase system can be modeled as a single (or one) line.
- One-lines show the major power system components, such as generators, loads, transmission lines.
- Components join together at a bus.

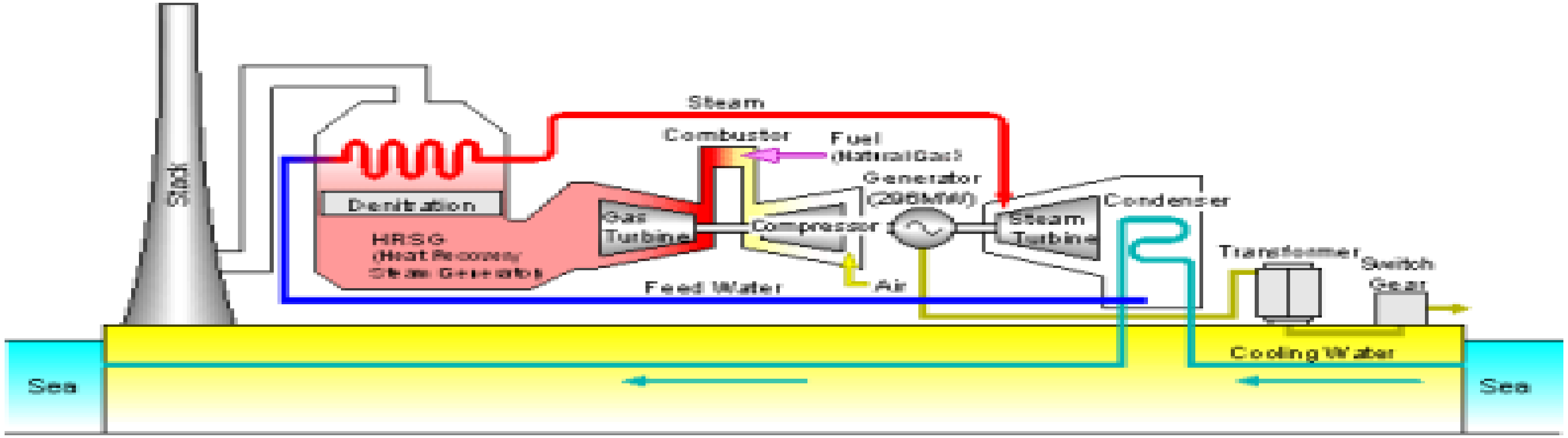
Example One-Line Diagram



CHARACTERISTICS OF STEAM UNITS



CHARACTERISTICS OF COMBINED CYCLE UNITS



Loads

- Can range in size from less than a single watt to 10's of MW.
- Loads are usually aggregated.
- The aggregate load changes with time, with strong daily, weekly and seasonal cycles.

Transmission

- Goal is to move electric power from generation to load with as low of losses and cost as possible.
- $P \propto V I$ or $P/V \propto I$
- Losses are $3 * I^2 R$ (for three phase)
- Less losses at higher voltages, but more costly to construct and insulate.

Transmission

500 kV transmission line

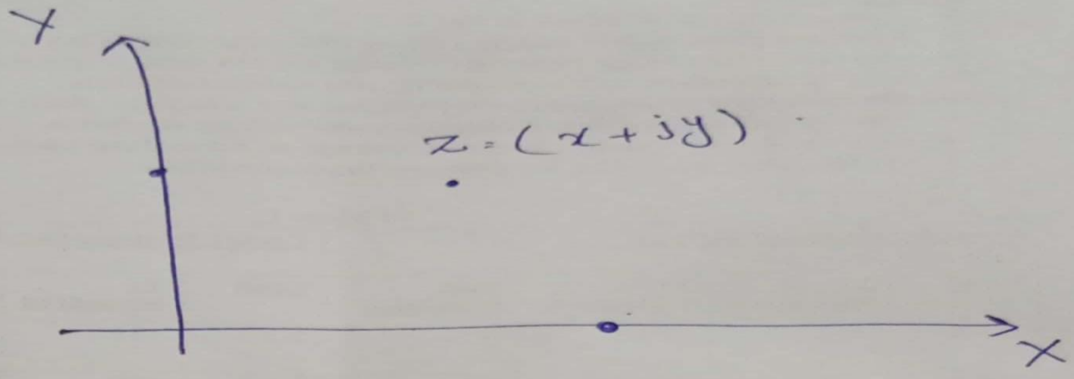
132 kV transmission line

69 kV transmission line

Transmission and Distribution

- Typical high voltage transmission voltages are 500, 345, 230, 161, 138 and 69 kV.
- Transmission tends to be a grid system, so each bus is supplied from two or more directions.
- Lower voltage lines are used for distribution, with a typical voltages of 13.8, 11 and 6.6 kV.

Complex Number :



$$Z = x + jy$$

$$|Z| = \sqrt{x^2 + y^2}$$

$$Q = \tan^{-1}\left(\frac{y}{x}\right)$$

$$Z = |Z| \angle Q$$

$$V = |V| \angle Q$$

$$I = |I| \angle Q$$

S = Apparant Power

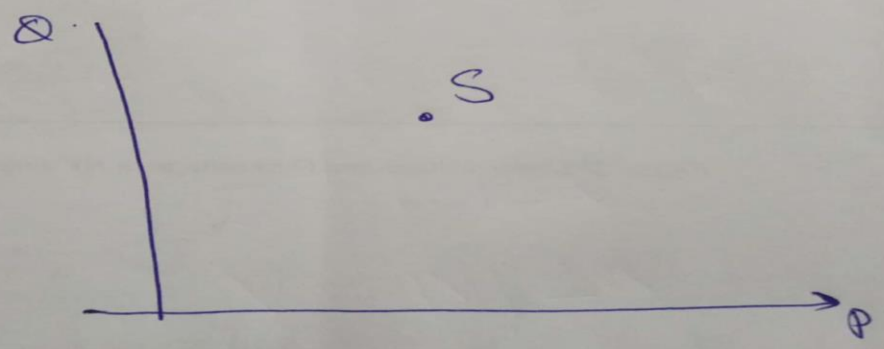
P = ~~Comp~~ Real Power

Q = Reactive Power.

$$S = P + jQ.$$

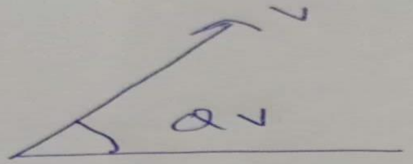
$$P = VI \cos\theta.$$

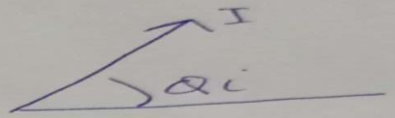
$$Q = VI \sin\theta.$$

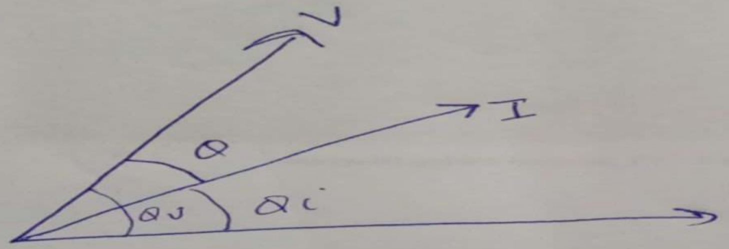


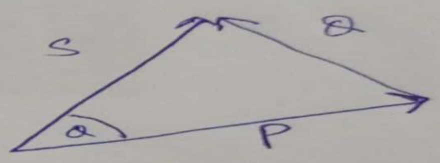
$V = |V| \angle \theta_v$

$I = I \angle \theta_i$









$S = V I^*$

$= |V||I| \angle \theta_v - \theta_i$

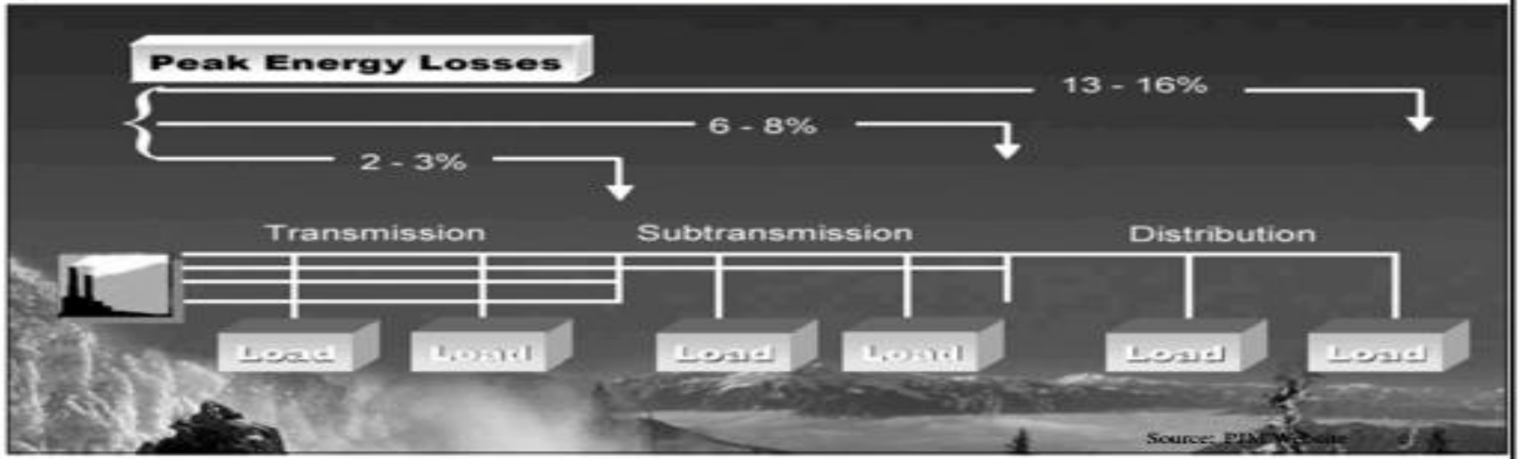
$S = |V||I| \angle \theta$

$$S = |V||I| \cos\theta + j|V||I| \sin\theta .$$

$$S = VI^{*} = P + jQ$$

$$|S| = \sqrt{P^2 + Q^2}$$

Electric Power Delivery Efficiency



Power Balance Constraints

- Power flow refers to how the power is moving through the system.
- At all times the total power flowing into any bus MUST be zero!
- This is know as Kirchhoff's law. And it can not be repealed or modified.
- Power is lost in the transmission system.

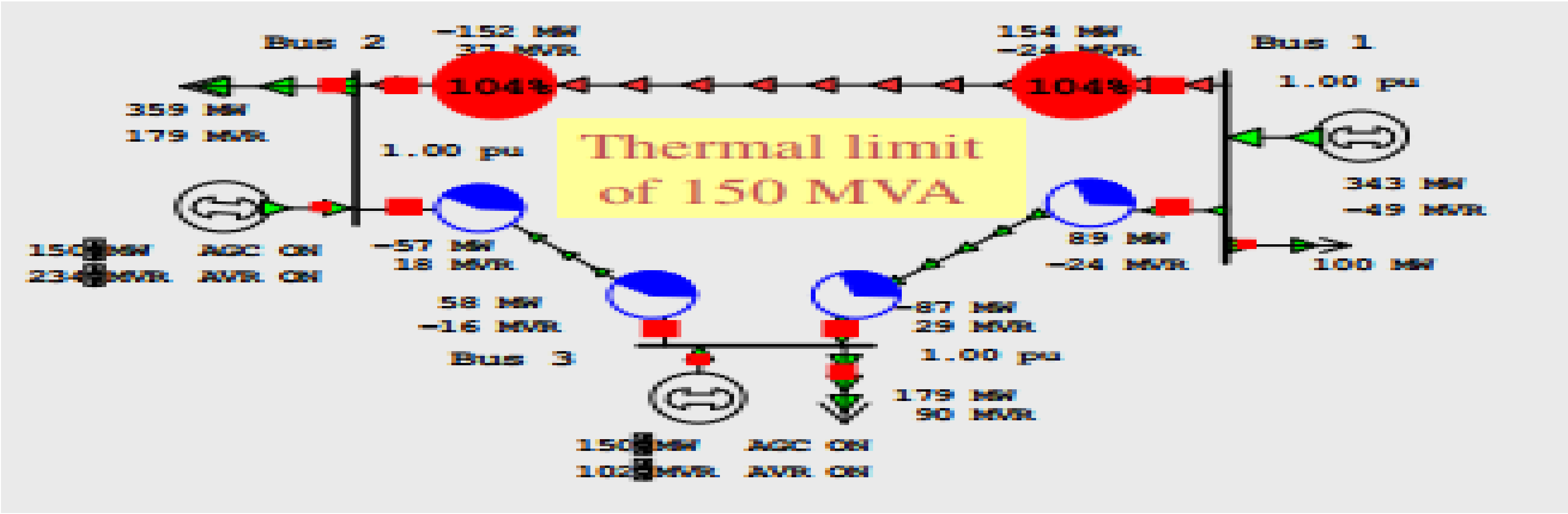
Basic Power Control

- Opening a circuit breaker causes the power flow to instantaneously(nearly) change.
- No other way to directly control power flow in a transmission line.
- By changing generation we can indirectly change this flow.

Transmission Line Limits

- Power flow in transmission line is limited by a number of considerations.
- Losses ($I^2 R$) can heat up the line, causing it to sag. This gives line an upper thermal limit.
- Thermal limits depend upon ambient conditions. Many utilities use winter/summer limits.

Overloaded Transmission Line



Reactive Power

- Reactive power is supplied by:
  - generators
  - capacitors
  - transmission lines
  - loads
- Reactive power is consumed by
  - loads
  - transmission lines and transformers

Voltage Magnitude

- Power systems must supply electric power within a narrow voltage range, typically with 5% of a nominal value.
- For example, wall outlet should supply 220 volts, with an acceptable range from 209 to 231 volts.
- Voltage regulation is a vital part of system operations.

Balanced Three-phase Circuits

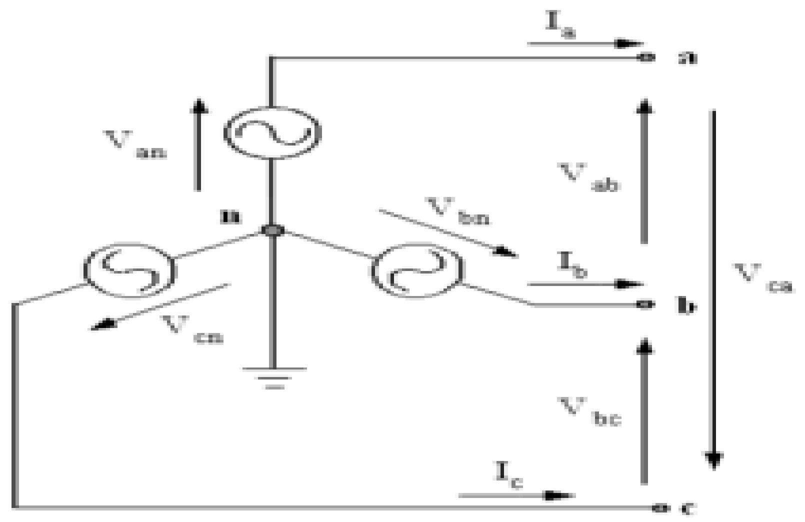
Wye-Connected System

- The neutral point is grounded
- The three-phase voltages have equal magnitude.
- The phase-shift between the voltages is 120 degrees.

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

$$\mathbf{V}_{bn} = |V|\angle -120^{\circ}$$

$$\mathbf{V}_{cn} = |V|\angle -240^{\circ}$$



Balanced Y-Connections

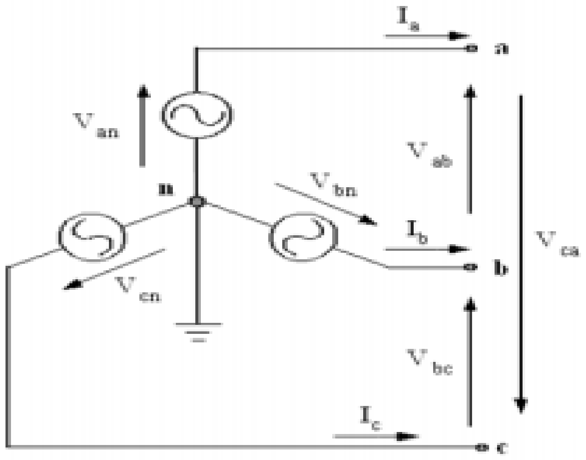
Wye-Connected System

- Line-to-line voltages are the difference of the phase voltages

$$V_{ab} = V_{an} - V_{bn} = \sqrt{3}\ V\ \angle 30$$

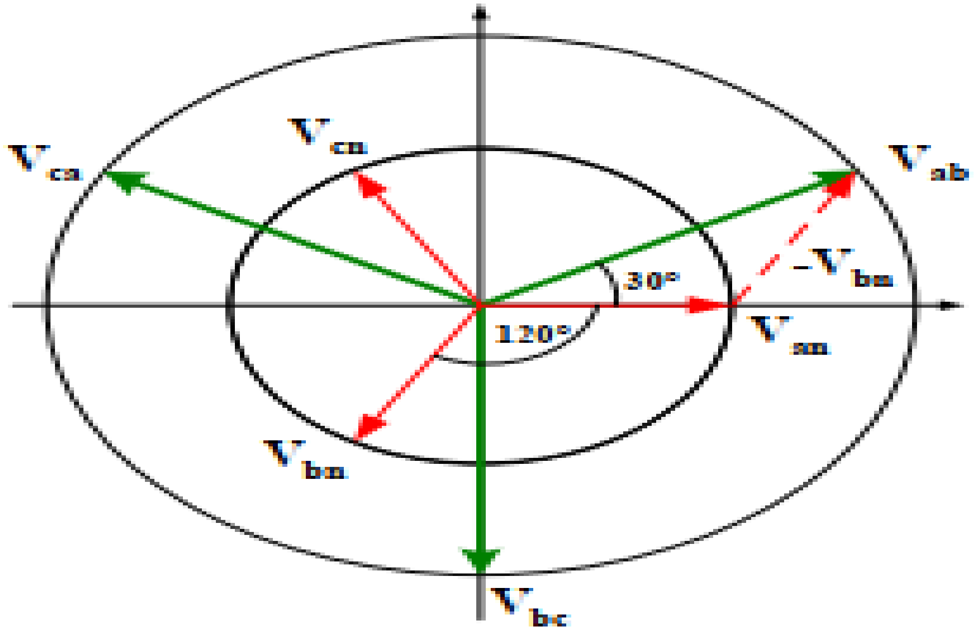
$$V_{bc} = V_{bn} - V_{cn} = \sqrt{3}\ V\ \angle -90$$

$$V_{ca} = V_{cn} - V_{an} = \sqrt{3}\ V \angle 150$$

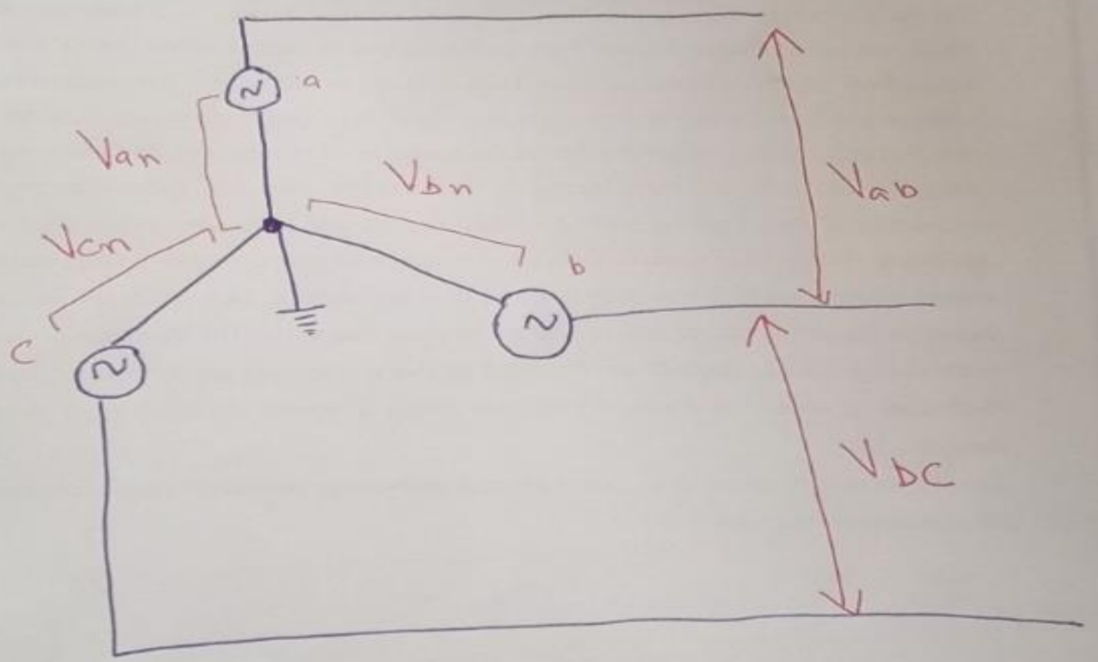


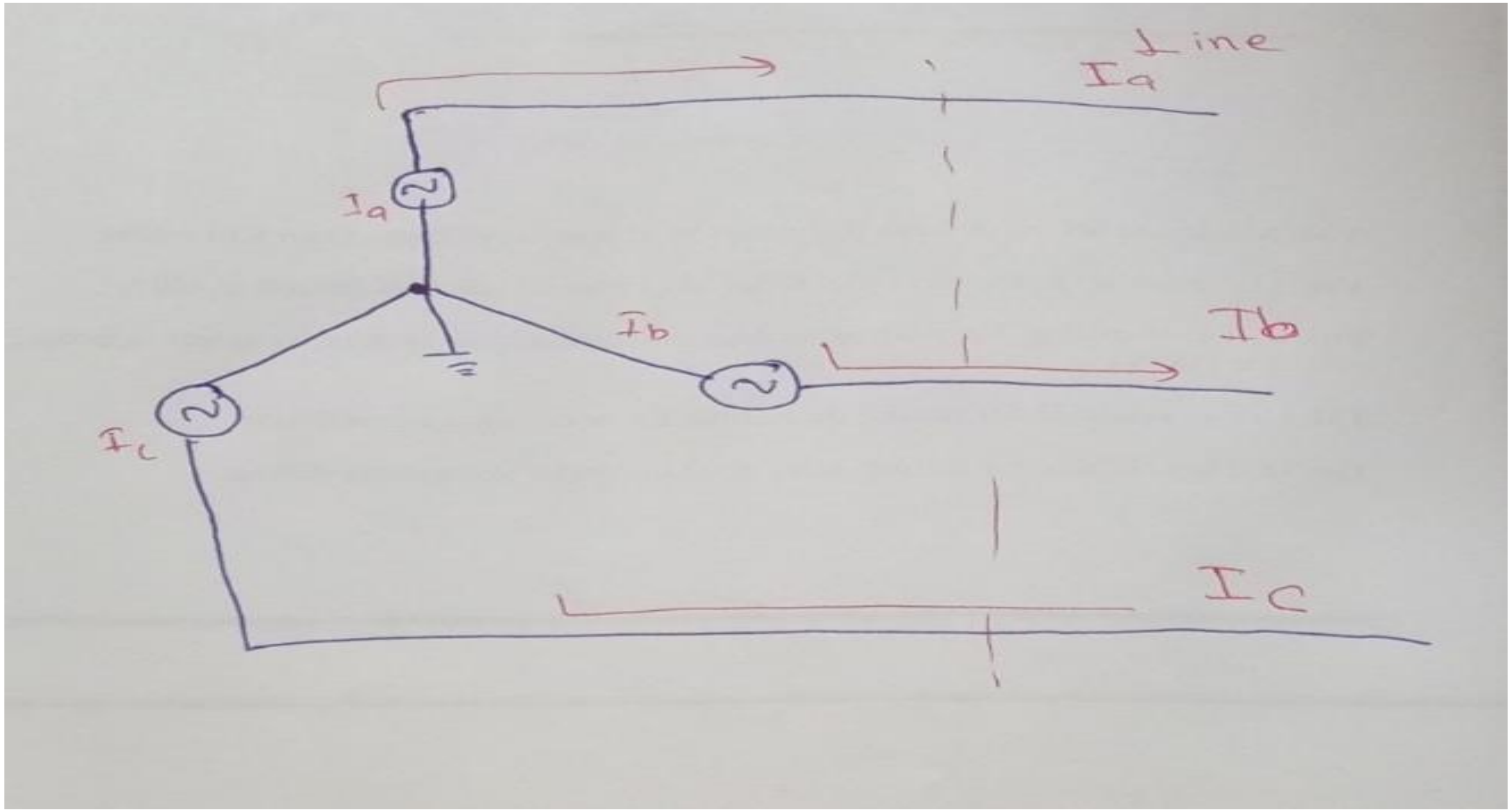
Balanced Y-Connections

- Phasor diagram is used to visualize the system voltages
- Wye system has two type of voltages: Line-to-neutral, and line-to-line.
- The line-to-neutral voltages are shifted with 120°
- The line-to-line voltage leads the line to neutral voltage with 30°
- The line-to-line voltage is $\sqrt{3}$ times the line-to-neutral voltage.



$V_{ab} = V_{an} - bn = \sqrt{3}\, V_p \angle 30$



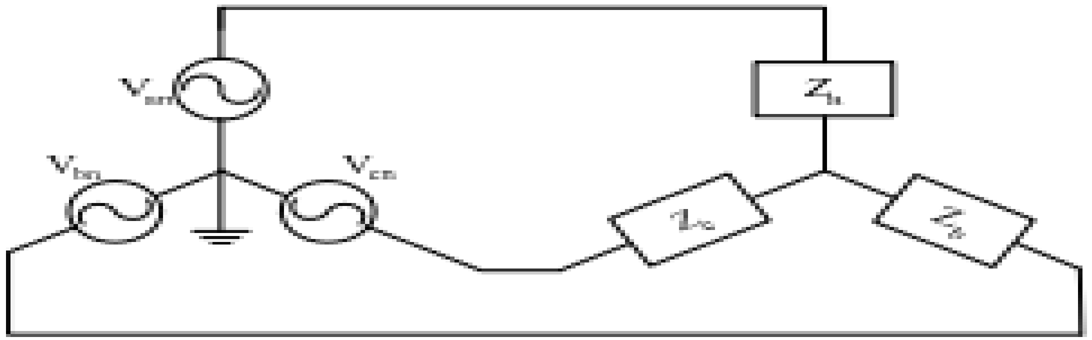


Line
Ia
Ib
Ic

Balanced Y-Connections

Y-Connected Loaded System

- The load is a balanced and each one = Z
- Each phase voltage drives current through the load.
- The phase current expressions are:

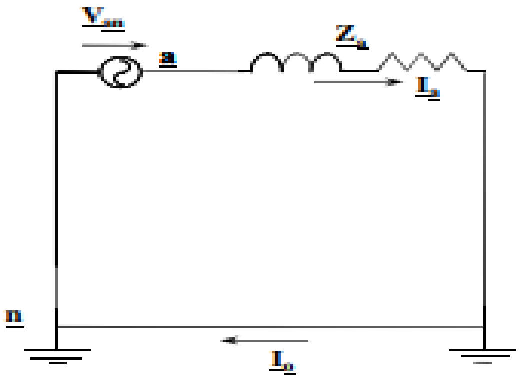


$$I_a = \frac{V_{an}}{Z}, \quad I_b = \frac{V_{bn}}{Z}, \quad I_c = \frac{V_{cn}}{Z}$$

Balanced Y-Connections

Wye-Connected Loaded System

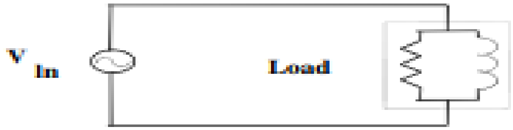
- Since the load is balanced ($Z_a = Z_b = Z_c$) then: Neutral current = 0
- This case single phase equivalent circuit can be used (phase a, for instance, only).
- Phase b and c are eliminated.



Balanced Y-Connections

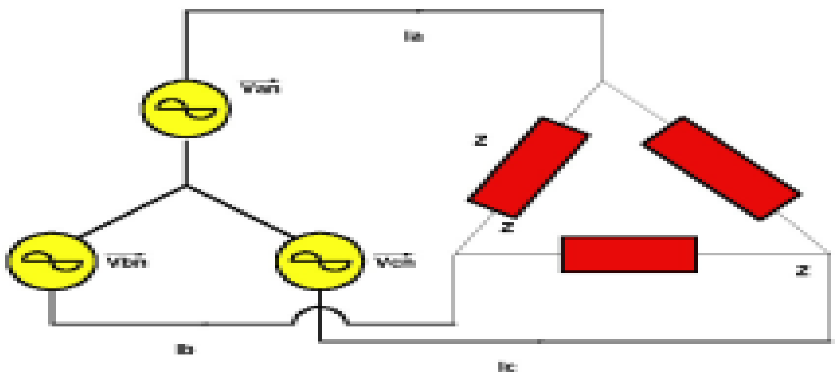
Wye-Connected System with balanced load

- **A single-phase equivalent circuit is used**
- **Only phase a is drawn, because the magnitude of currents and voltages are the same in each phase. Only the phase angles are different (-120° phase shift)**
- **The supply voltage is the line to neutral voltage.**
- **The single phase loads are connected to neutral or ground.**



Balanced Δ Loads

- The system has only one voltage : the line-to-line voltage (   )
- The system has two currents : V_{LL}
  - line current
  - phase current
- The phase currents are:



$$I = \frac{V_{ab}}{Z}$$

Balanced Δ Loads

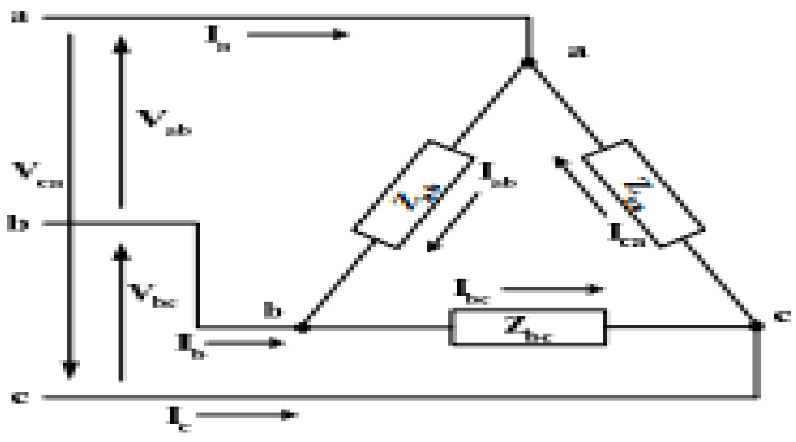
<u>Delta-Connected System</u>

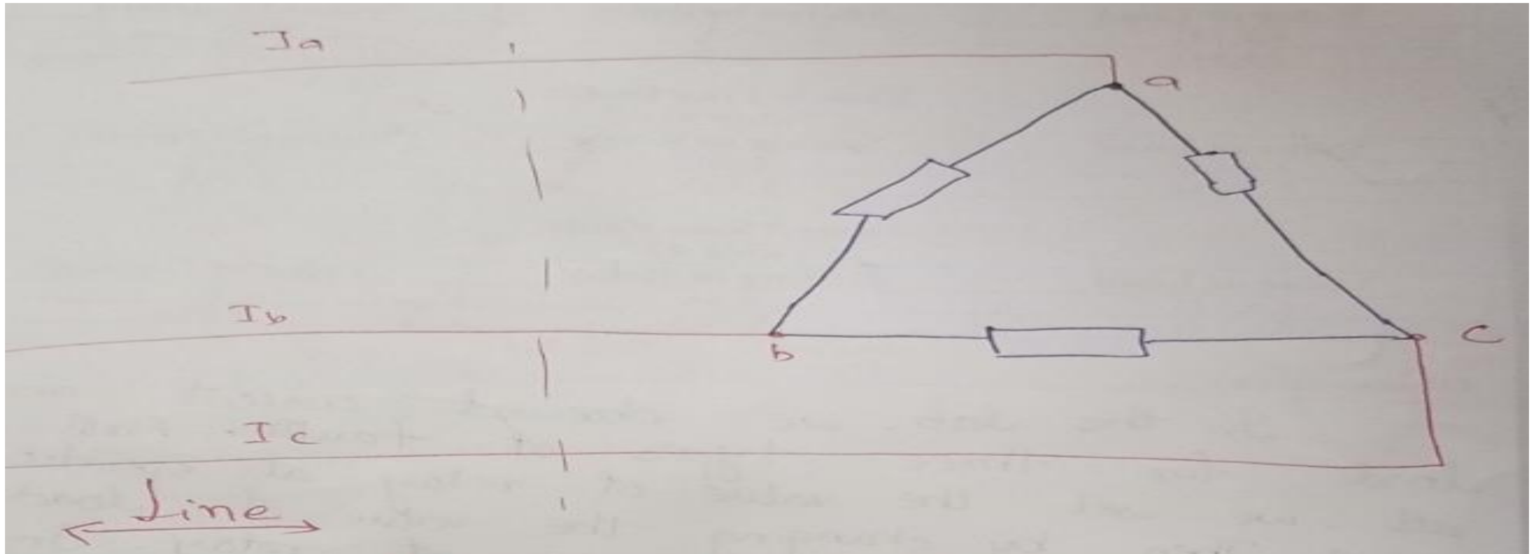
The line currents are:

$$\mathbf{I}_a = \mathbf{I}_{ab} - \mathbf{I}_{ca}$$
$$\mathbf{I}_b = \mathbf{I}_{bc} - \mathbf{I}_{ab}$$
$$\mathbf{I}_c = \mathbf{I}_{ca} - \mathbf{I}_{bc}$$

- In a balanced case the line currents are:

$$I_{line} = \sqrt{3} I_{phase} \angle -30$$





$$I_a = I_{ab} - I_{ca}$$

$$I_b = I_{bc} - I_{ab}$$

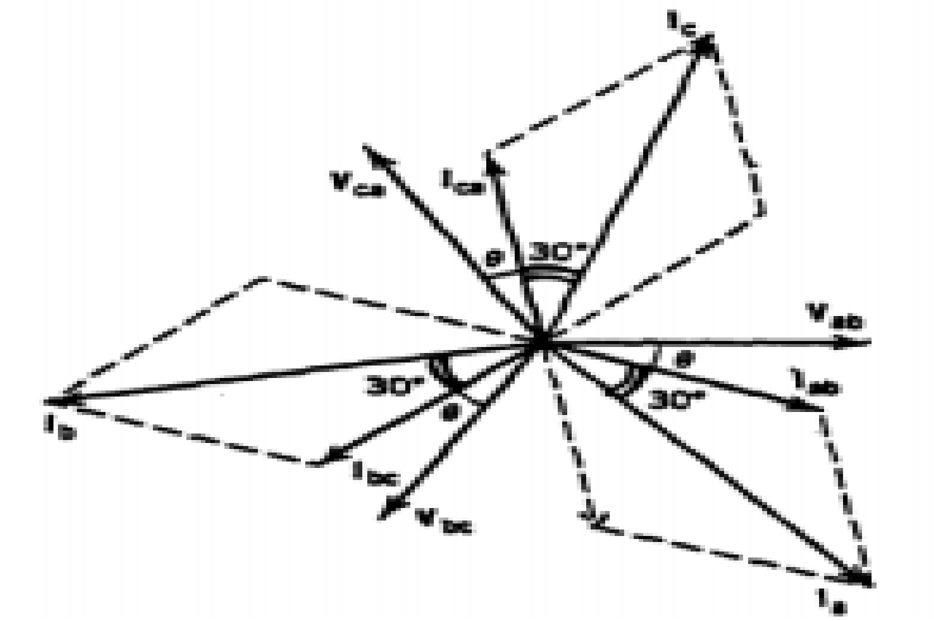
$$I_c = I_{ca} - I_{bc}$$

$$I_{Line} = \sqrt{3}\, I_p \angle -30^\circ$$

Balanced Δ Loads

<u>Delta-Connected System</u>

- The phasor diagram is used to visualize the system currents
- The system has two type of currents: <u>line and phase currents</u>.
- The delta system has only <u>line-to-line voltages,</u> that are shifted by 30
- The phase currents lead the line currents by 30
- The line current is $\sqrt{3}$ times the phase current and shifted by 30 degree.



Three-phase Circuit

Power Calculation

- The three phase power is equal the sum of the phase powers

$$P = P_a + P_b + P_c$$

- If the load is balanced:

$$P = 3\, P_{phase} = 3\, V_{phase} I_{phase} \cos(\phi)$$

- Wye system: $V_{phase} = V_{LN}$ $\quad I_{phase} = I_L$ $\quad V_{LL} = \sqrt{3}\, V_{LN}$

$$P = 3\, V_{phase} I_{phase} \cos(\phi) = \sqrt{3}\, V_{LL} I_L \cos(\phi)$$

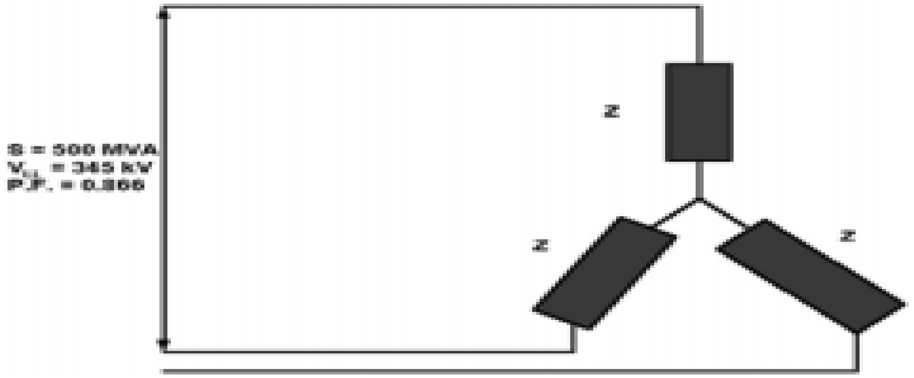
- Delta system: $I_{Line} = \sqrt{3}\, I_{phase}$ $\quad V_{LL} = V_{phase}$

$$P = 3\, V_{phase} I_{phase} \cos(\phi) = \sqrt{3}\, V_{LL} I_L \cos(\phi)$$

Balanced Δ –Y Loads

Example 1: A 345 kV, three phase transmission line delivers 500 MVA, 0.866 power factor lagging, to a three phase load connected to its receiving end terminals. Assume the load is Y connected and the voltage at the receiving end is 345 kV, find:

- The load impedance per phase.
- The line and phase currents.
- The total real and reactive power.



$$(a)\ Z_\phi = \frac{V_\phi}{I_\phi}$$

$$V_\phi = \frac{345\ kV}{\sqrt{3}}\angle 0V, \left|\mathrm{I}_\phi\right| = \frac{S}{\sqrt{3}V_L} = \frac{500\ MVA}{\sqrt{3}\,345\ kV} = 836.7\,A$$

$$I_\phi = 836.7\angle -\cos^{-1}(0.866) = 836.7\angle -30$$

$$Z_\phi = 238\angle 30 = 206 + j119$$

$$(b)\ I_L = I_\phi = 836.7\angle -30$$

$$(c)\ P = \sqrt{3}V_L I_L \cos(\theta) = 433\ \text{MW}$$

$$Q = \sqrt{3}V_L I_L \sin(\theta) = 249.9\ \text{MVAR}$$

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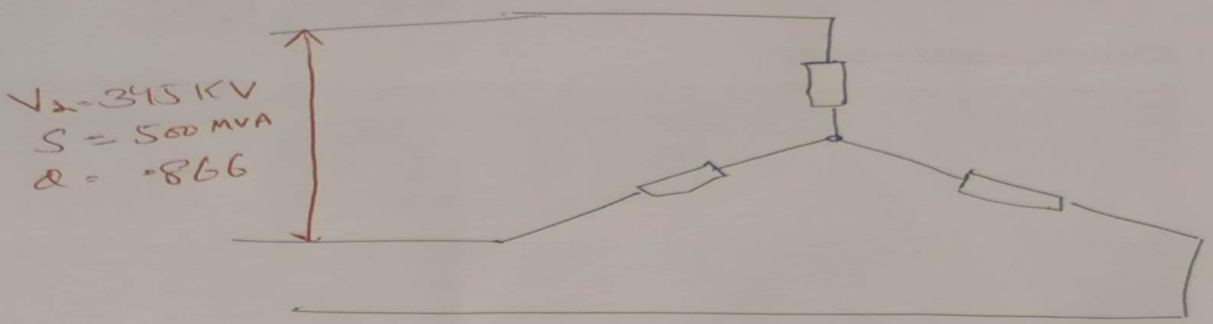


(a) $Z_\phi = \dfrac{V_\phi}{I_\phi}$

$I_\phi = ?$

$V_\phi = \dfrac{345\,KV}{\sqrt{3}}$

$S = 3\, I_\phi V_\phi$

$S = \sqrt{3}\, V_L I_L$

$I_L = \dfrac{S}{\sqrt{3}\, V_L}$

$I_L = I_\phi$

$I_\phi = \dfrac{S}{\sqrt{3}\, V_L}$

$I_\phi = 836.7 \angle -30$

$$Z_\phi = \frac{V_\phi}{I_\phi} = 238\angle 30^\circ$$

(b)

$$I_L = I_\phi = 8367\angle -30$$

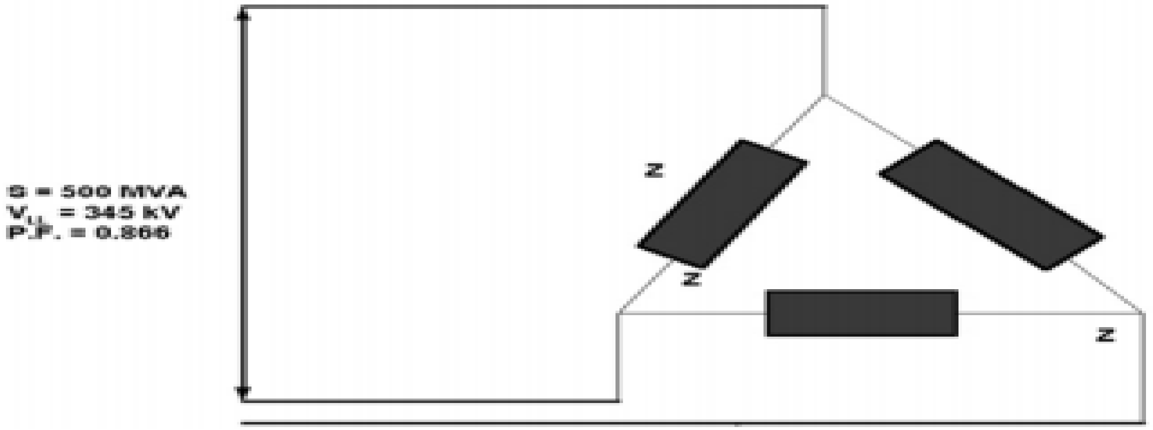
(c)

$$P = \sqrt{3}\, V_L I_L \cos\theta = 433\ \text{MW}$$

$$Q = \sqrt{3}\, V_L I_L \sin\theta = 249.9\ \text{MVAR}$$

Balanced Δ –Y Loads

Example 2: Repeat example 1 assuming the load is Delta connected.



$$(a)\ V_\phi = V_L = 345\ kV\angle 0V,$$

$$\left|\mathrm{I}_\phi\right| = \frac{S}{3V_L} = \frac{500\ MVA}{3*345\ kV} = 483.1A$$

$$I_\phi = 483.1\angle -\cos^{-1}(0.866) = 483.1\angle -30$$

$$Z_\phi = \frac{V_\phi}{I_\phi} = 714\angle 30 = 618.3 + j357$$

$$(b)\ I_L = \sqrt{3}I_\phi\angle -30 = 836.7\angle -60$$

$$(c)\ P = \sqrt{3}V_L I_L\cos(\theta) = 433\ \mathrm{MW}$$

$$Q = \sqrt{3}V_L I_L\sin(\theta) = 249.9\ \mathrm{MVAR}$$

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Advantages of Balanced Three Phase Versus Single Phase System

- Smooth flow of power (instantaneous power is constant).
- Constant torque (reduced vibrations).
- The power delivery capacity tripled (increased by 200%) by increasing the number of conductors from 2 to 3 (increased by 50%).