EE2029 - Introduction to Electrical Energy Systems

Transmission Lines

- Physical Components
- Line Parameters
- Line Modelling
- Line Operations

Learning Outcomes

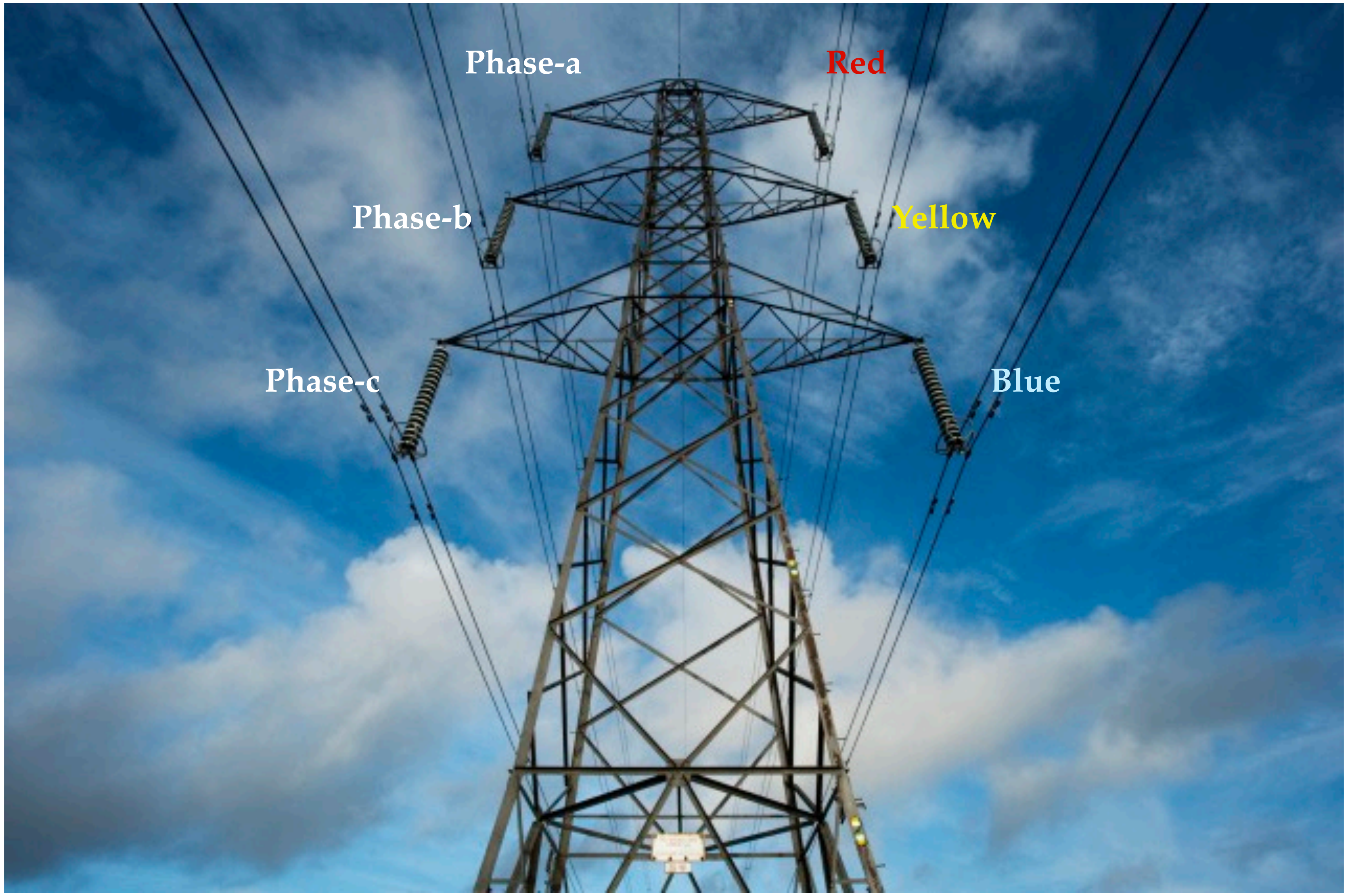
- Able to *identify* the physical components facilitating an overhead line and underground cable.
- Able to *derive* the equivalent circuits for short and medium transmission lines.
- Able to *apply* the principles of voltage regulation and systematically *solve* the transmission efficiency of power lines.

Physical Components

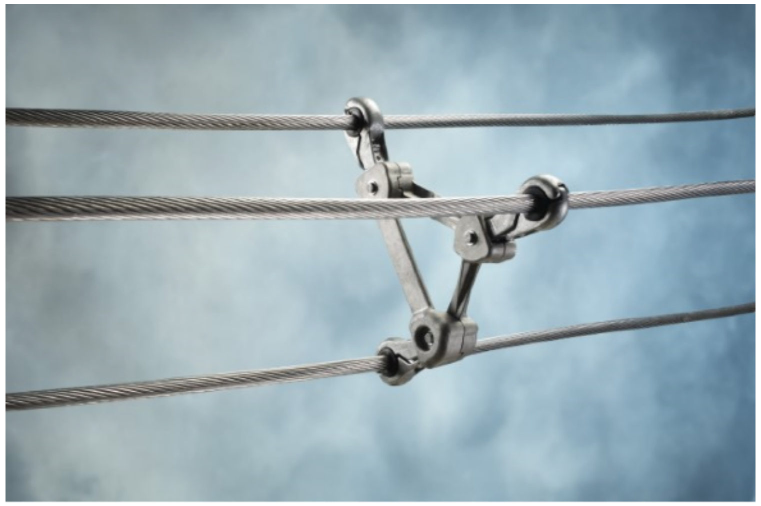
Transmission Lines

<u>Overhead</u> transmission infrastructure consists of **conductors**, **insulators**, **spacers**, and **supporting structure**.

Shield



Lattice Supporting Structure



<u>Spacer</u> - Triangular Arrangement

Glass

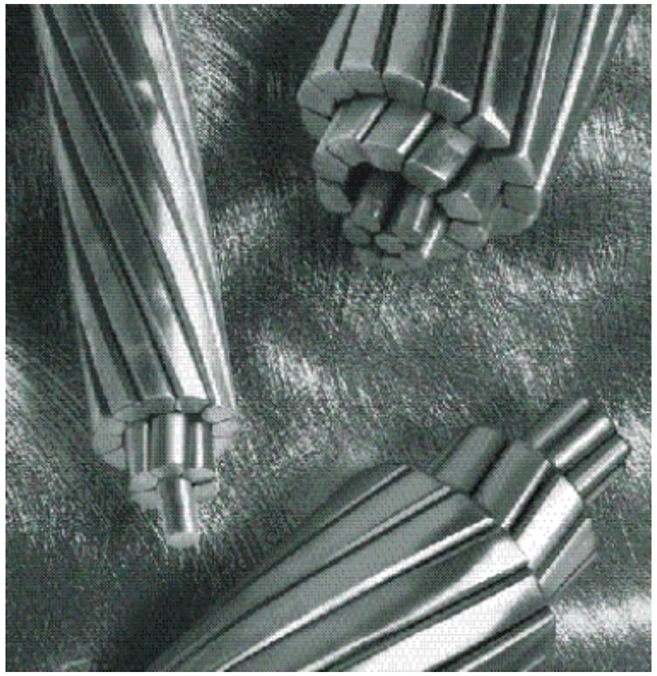
Ceramic

<u>Insulation Disc</u>

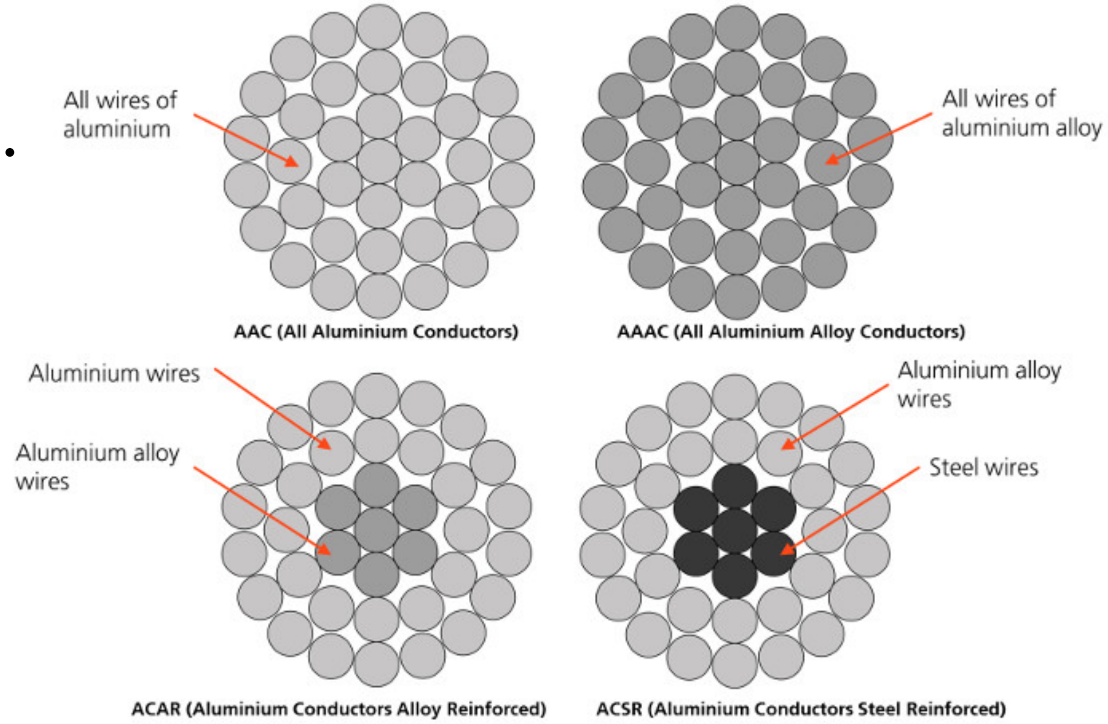
New Zealand, November 2005

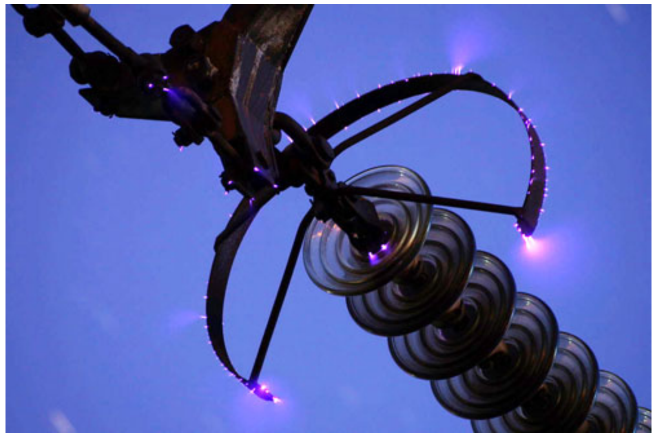
Overhead Lines

- Conductors for HV Lines are:
  - **ACSR**: Aluminium Conductor Steel Reinforced
  - **AAC**: All Aluminium Conductors
  - **AAAC**: All Aluminium-Alloy Conductors
  - **ACAR**: Aluminium Conductor Alloy Reinforced



- Each phase is usually bundled with more than one conductors using spacers.

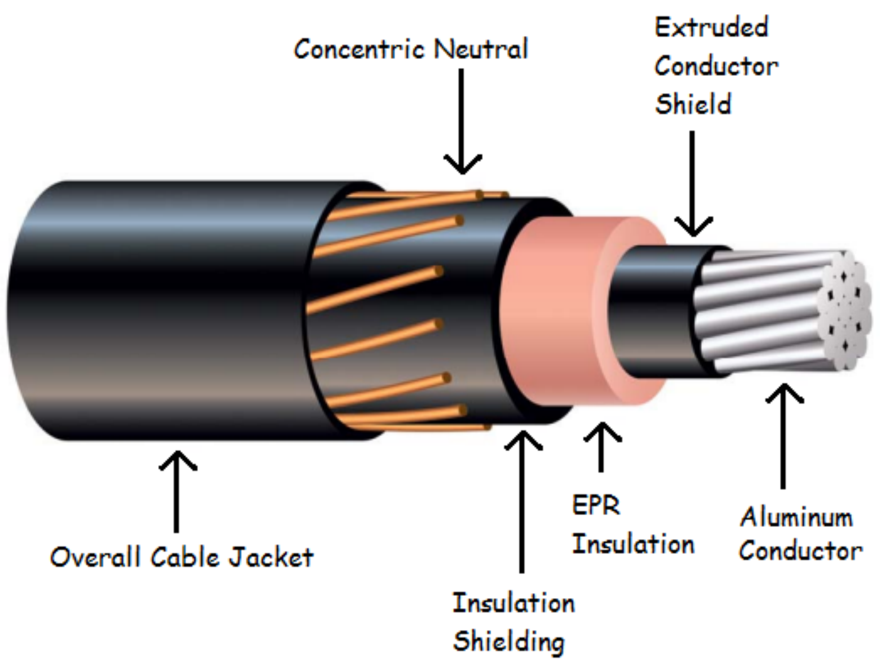




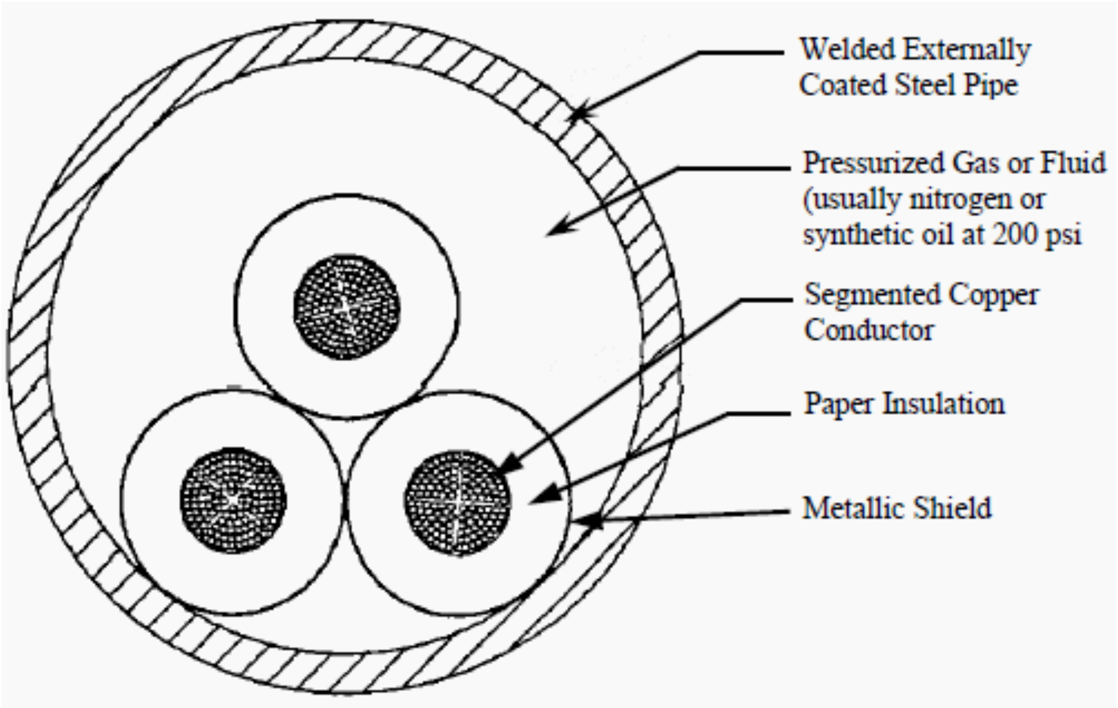
Corona effect gives a violet glow

Underground Cables

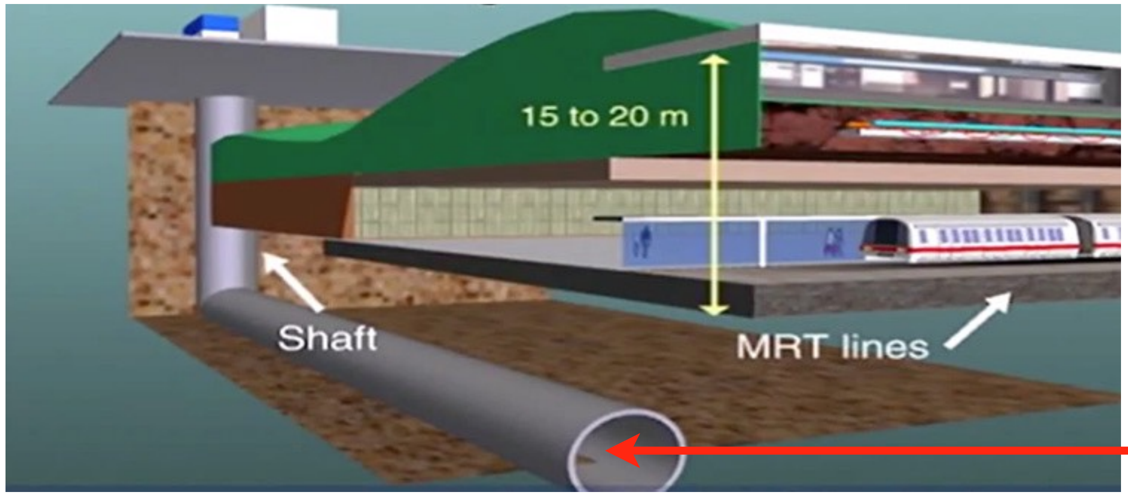
- Conductors inside a cable must be insulated from the ground.



Self-contained cable



Pipe-Type cable



Types of Cable Insulation

Three main types of insulation:

1. Plastic insulation
   - Solid cable, cross-linked polyethylene (XLPE)
2. Paper-Oil insulation
   - High-pressure, fluid-filled pipe (HPFF)
   - Self-contained fluid-filled (SCFF)
3. Paper-Gas insulation
   - High-pressure, gas-filled pipe (HPGF)

1) High insulation resistance
-> avoid leakage current

2) High di-electtic strength
-> avoid breakdown of cable

3) Should not absorb moisture from environment
-> avoid reduced lifespan

Overhead/Underground Comparison

Overhead Lines

- Lower construction cost and cable cost.
- Advantage of air for cooling and insulation of the line.
- Vulnerable to strong wind and severe weather.
- Negative visual impact.
- Easier maintenance work.
- Inductive in nature.

Underground Cables

- Expensive pipe work and cable cost.
- Expensive insulation required at high voltage.
- Immune to the severe weather because it is buried underground.
- Environment and aesthetic advantage.
- Less frequent maintenance work.
- Capacitive in nature.

Line Parameters

Resistance (R) and Conductance (G)

<u>Resistance</u>

R = work done = energy conversion & consumption (heat dissipation)

- Responsible for transmission line loss.
- Voltage drop along the line from resistive loss can be represented by a resistor along the line.

<u>Conductance</u>

G = 1/R

- Leakage current through insulators can be represented by a conductance from a line to the ground.
- Corona Discharge:
  - When the electric field strength is strong, air might become electrically ionised and conduct.
  - This is called a 'corona' effect and can be represented by a conductor from the line to the ground.
  - The power loss due to this effect is call corona loss.

https://www.youtube.com/watch?v=CB5UXvMTNVo

Inductance (L) and Capacitance (C)

<u>Ampere's Law</u>

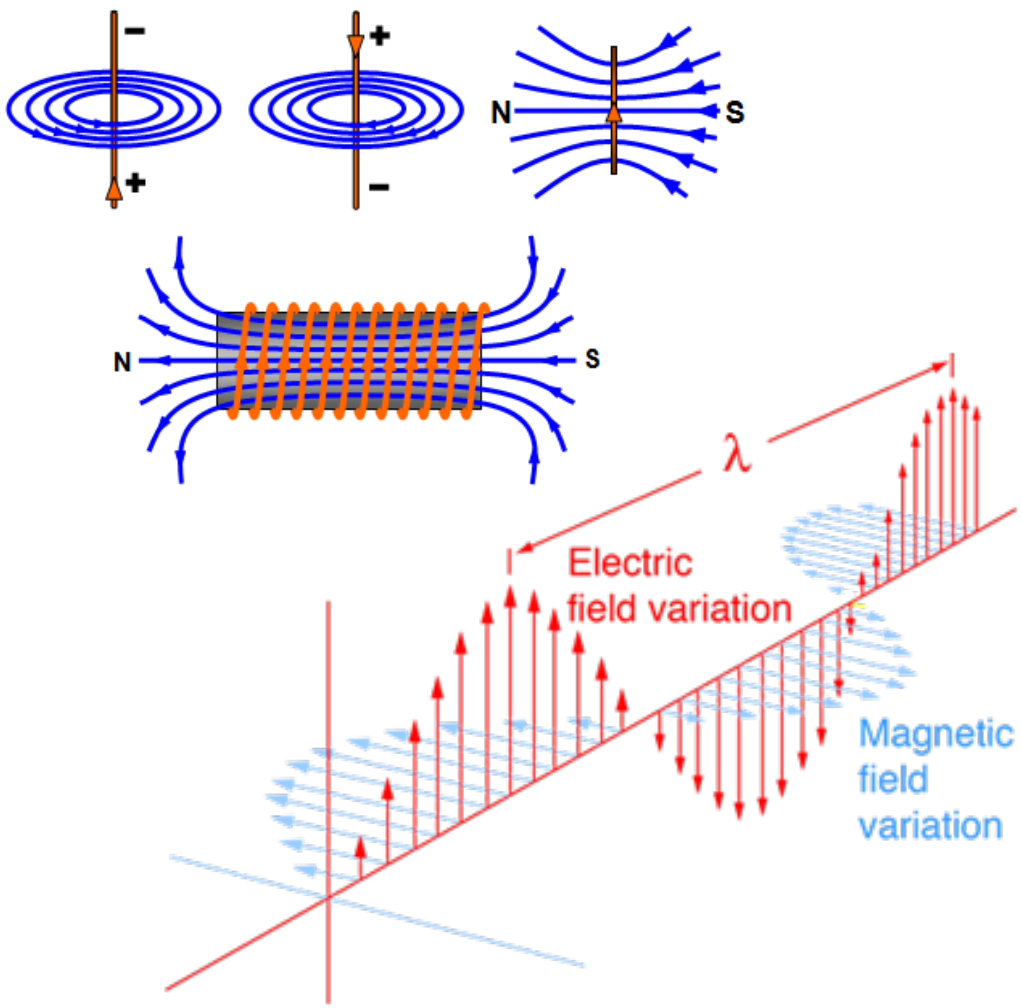
- Current passing through a conductor creates <u>magnetic field</u> around it.
- This gives *inductance* property.

inductors store energy in B fields
-> current leads voltage

<u>Gauss's Law</u>

- Electric charge is a source of <u>electric field</u>.
- This gives *capacitance* property.

capacitors store energy in E fields
-> current lags voltage



Transmission Line Parameters

- **R** from heat
  - Types, sizes of conductor determine resistance value.
- **G** from leakage current
  - Types, number of insulators determine conductance value.
- **L** from magnetic field
- **C** from electric field

All these values can be quantified!

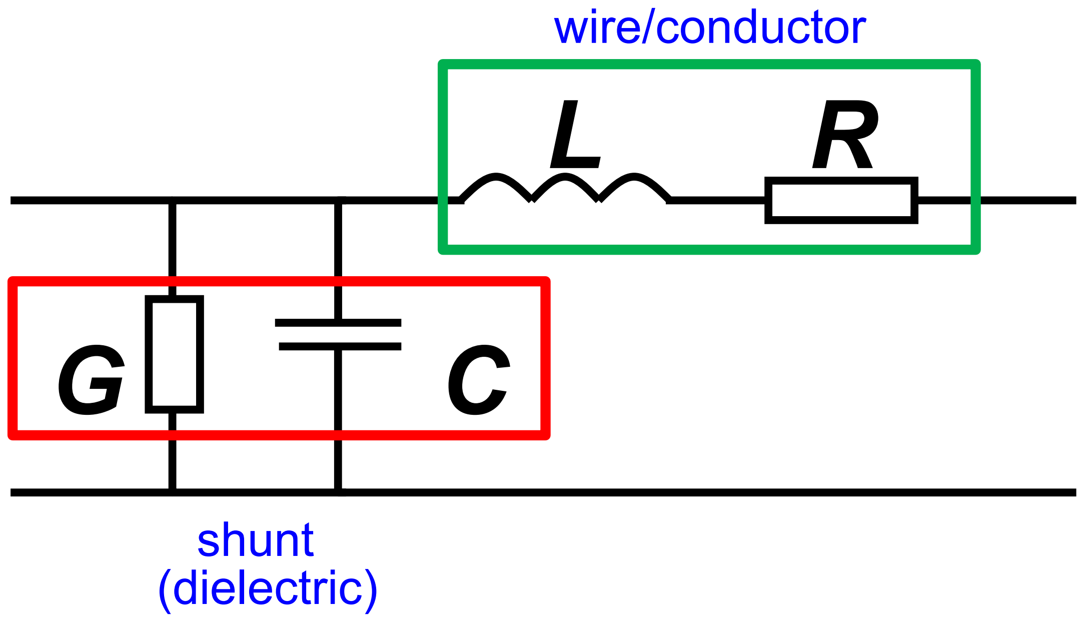
Per Phase Conductor Model

$R : \Omega / km$

$L : H / km$

$G : S / km$

$C : F / km$



$$Z_{series} = R + j\omega L$$

$$Y_{shunt} = G + j\omega C$$

- Per-phase conductor model to describe the circuit model of each phase in three-phase circuit.
- This information will be used to derive an equivalent circuit of the transmission line.

150 kV Line/Cable Parameters

Overhead Transmission Line

- R $= 0.125\ \Omega/\text{km}$
- X_L $= 0.425\ \Omega\ /\text{km}$
- X_C $= 7.7\ \text{nF}/\text{km}$ (due to Corona discharge & leakage current)
- 130 MVA rating

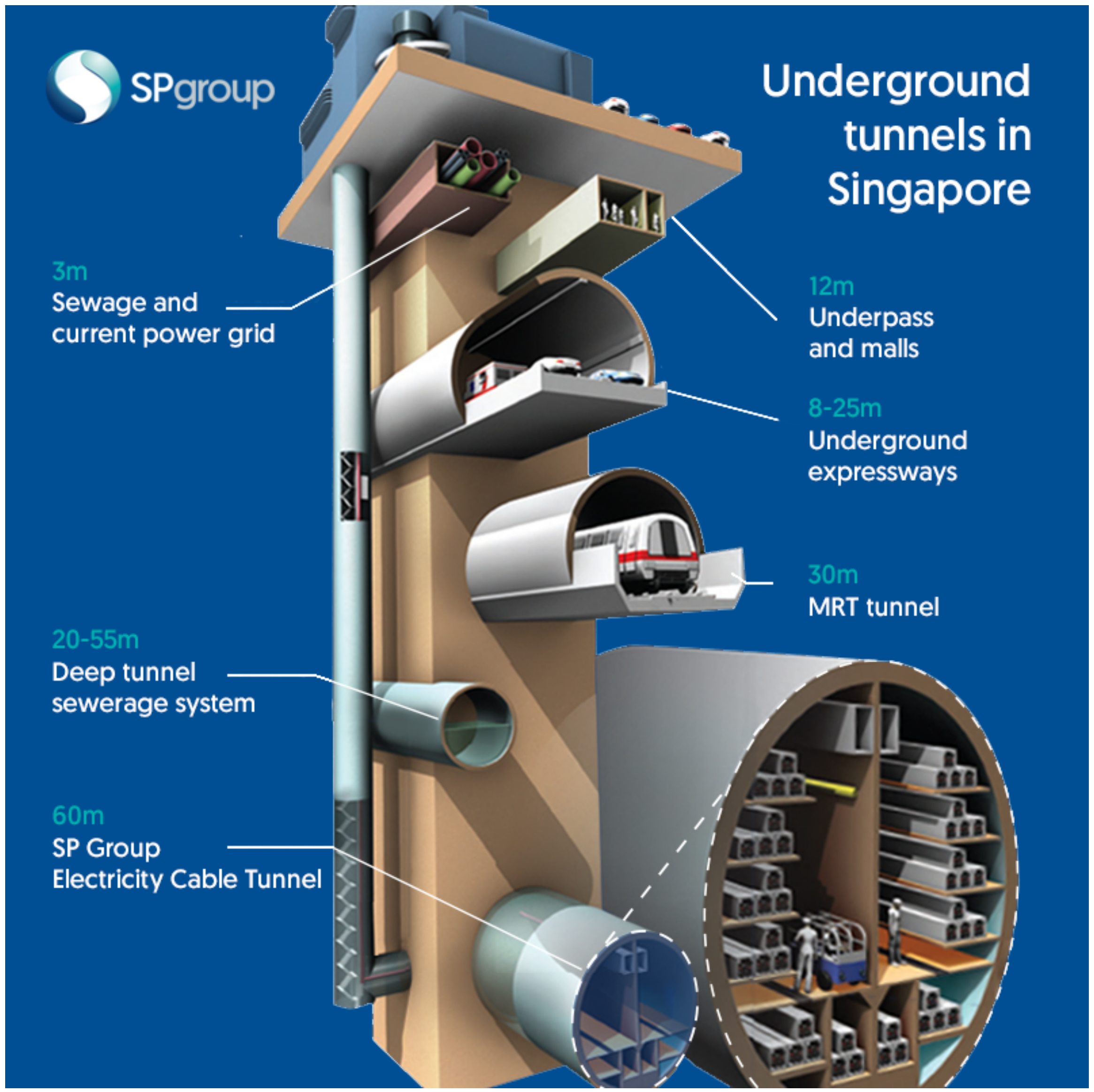
more inductive

Underground Cable

- R $= 0.12\ \Omega/\text{km}$
- X_L $= 0.166\ \Omega/\text{km}$
- X_C $= 210\ \text{nF}/\text{km}$
- 135 MVA rating

more conductive

Singapore 400kV Upgrade (2018)

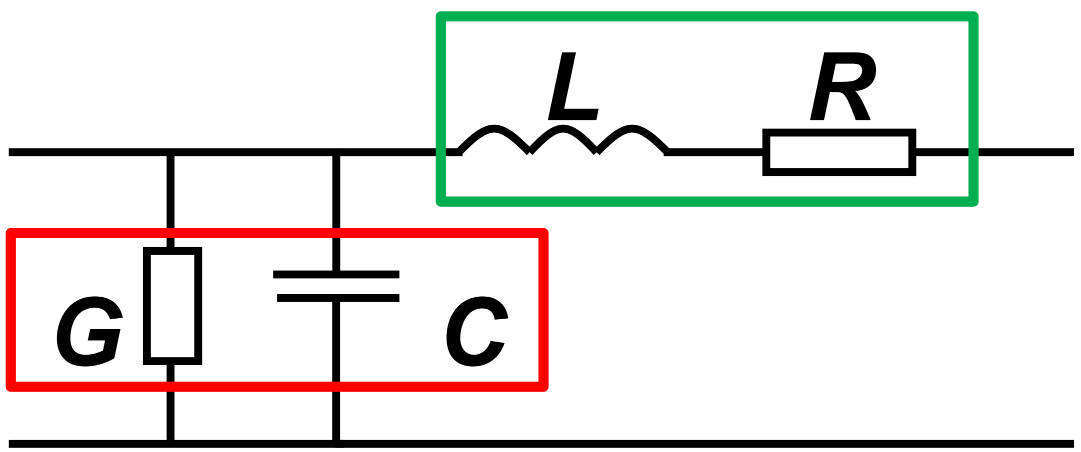


Line Modelling

Per-Phase Conductor Model

- **R** for resistive loss in the conductor
- **G** for leakage current through insulators and corona losses
- **L** to represent magnetic field
- **C** to represent electric field

stores energy
-> charge/discharge over time

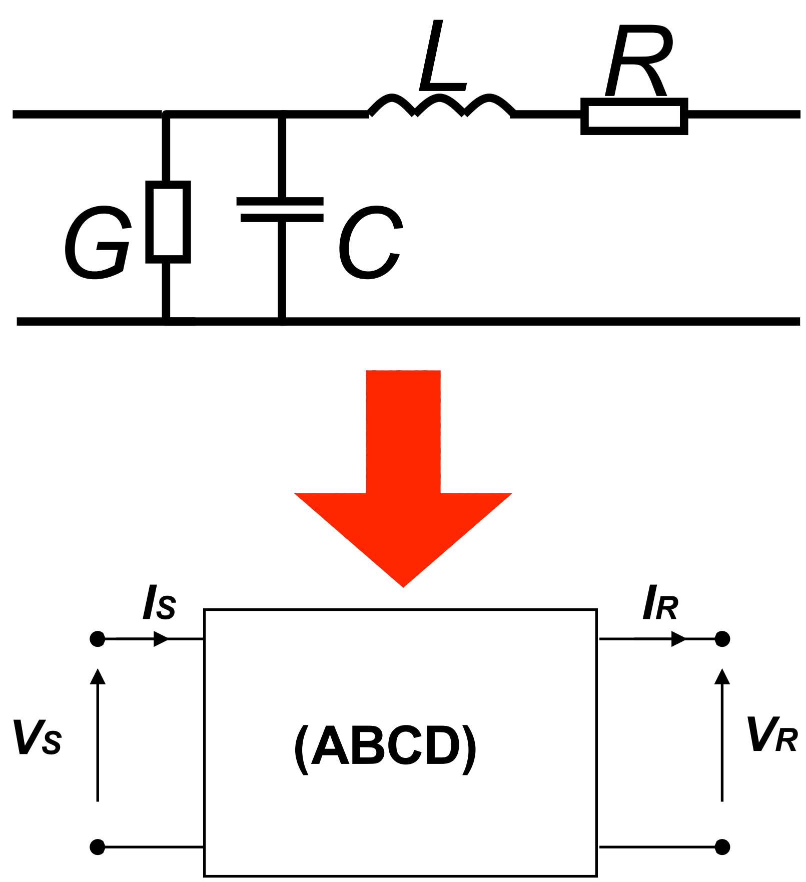


$Z_{series} = R + j\omega L \Rightarrow$ Series Impedance (Ω / m)

$Y_{shunt} = G + j\omega C \Rightarrow$ Shunt Admittance (S / m)

Equivalent Circuit (Matrix Representation)

Conductor per-phase model



Two-port network model

V sending-end = V receiving-end + V drop

$$V_S = \mathbf{A} V_R + \mathbf{B} I_R$$

$$I_S = \mathbf{C} V_R + \mathbf{D} I_R$$

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

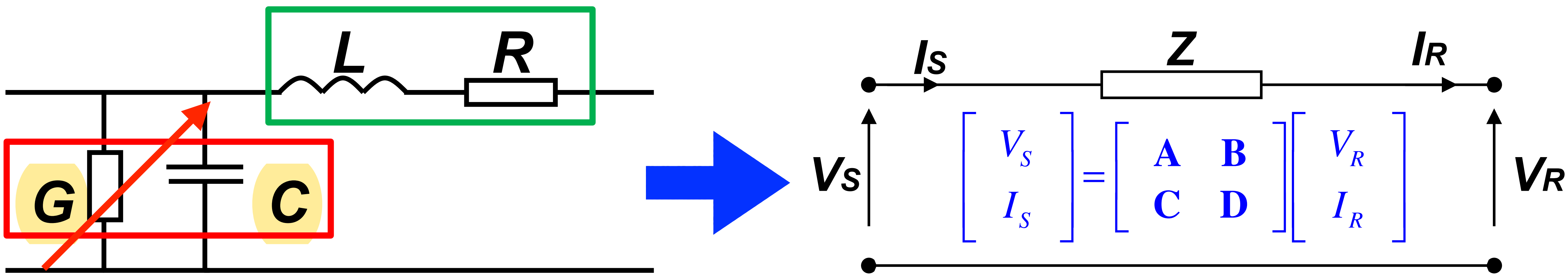
state space model of TL

Purposes of Equivalent Circuit

- To calculate the voltage at the receiving-end when the sending-end voltage is known or vice versa.
  - This is used to find the voltage difference between sending- and receiving-end.
- To find the amount of real and reactive power transfer in the line.
- To make sure the transferred power does not exceed the heating limit of the lines.
- To calculate the efficiency of the transmission line.

Short Line: A Simplified Model

- We ignore the shunt admittance and only consider series impedance.



$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

$$V_S = V_R + I_R \cdot Z = 1 \cdot V_R + Z \cdot I_R$$

$$I_S = I_R \qquad = 0 \cdot V_R + 1 \cdot I_R$$

D = 1
C = 0

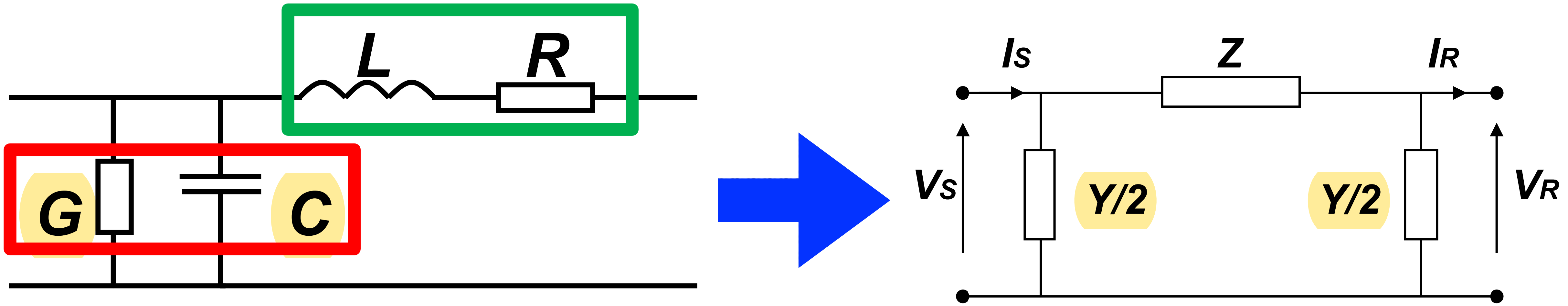
A = 1
B = Z

Example

A single-phase 50 km transmission line is supplying 8 kV to an 800 kVA, 0.9 PF lagging single-phase load. Line impedance Z is 1+j1 Ω. What is the sending end voltage and current of this transmission line?

Medium Line: A Lumped Model

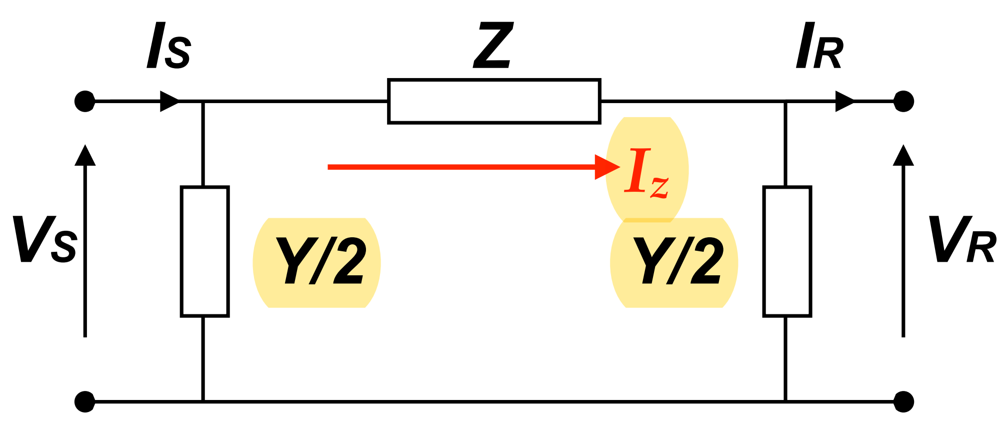
- Also known as the **nominal π-circuit**.



$$Z = R + j\omega L$$

$$Y = G + j\omega C$$

Medium Line: A Lumped Model



$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \frac{ZY}{2}+1 & Z \\ Y\left(1+\frac{ZY}{4}\right) & \frac{ZY}{2}+1 \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

KVL: $$V_S = V_R + Z \cdot I_Z$$
$$= V_R + Z \cdot \left(I_R + V_R \cdot \frac{Y}{2} \right)$$
$$= \left(1 + \frac{YZ}{2}\right) V_R + Z \cdot I_R$$

KCL: $$I_S = I_Z + V_S \cdot \frac{Y}{2}$$
$$= I_R + V_R \cdot \frac{Y}{2} + \left[\left(1 + \frac{YZ}{2}\right) V_R + Z \cdot I_R \right] \frac{Y}{2}$$
$$= \left[\frac{Y}{2} + \frac{Y}{2}\left(1 + \frac{YZ}{2}\right) \right] V_R + \left(1 + \frac{YZ}{2}\right) I_R$$
$$= \left[Y + Y\left(\frac{ZY}{4}\right) \right] V_R + \left(\frac{ZY}{2} + 1\right) I_R$$

Equivalent Models: Summary

- Short (<80 km)

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

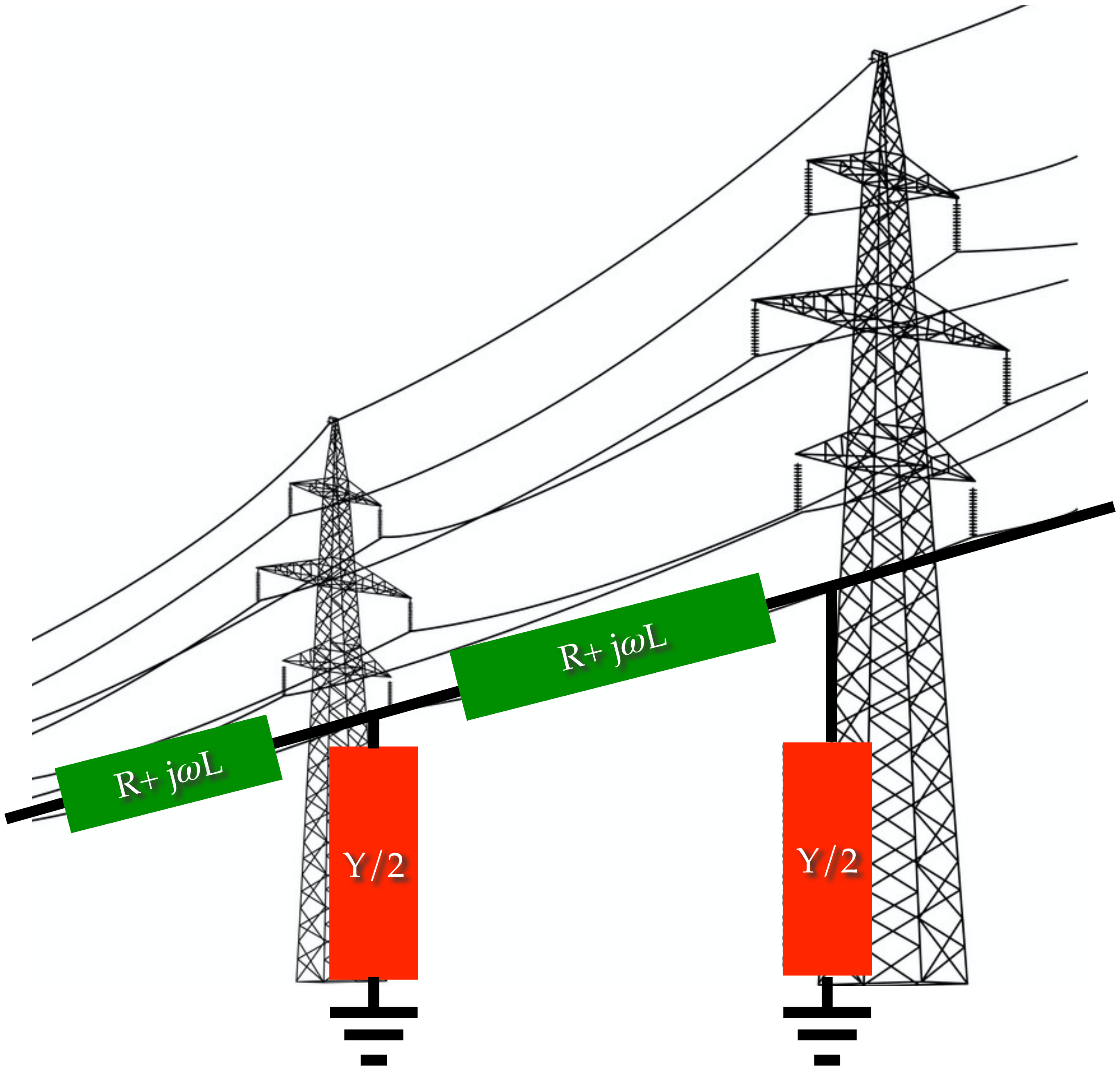
- Medium (80 km to 240 km)

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \frac{ZY}{2}+1 & Z \\ Y\left(1+\frac{ZY}{4}\right) & \frac{ZY}{2}+1 \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

- Long (>240 km) X in syllabus.

X
$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_c \sinh(\gamma l) \\ \frac{\sinh(\gamma l)}{Z_c} & \cosh(\gamma l) \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

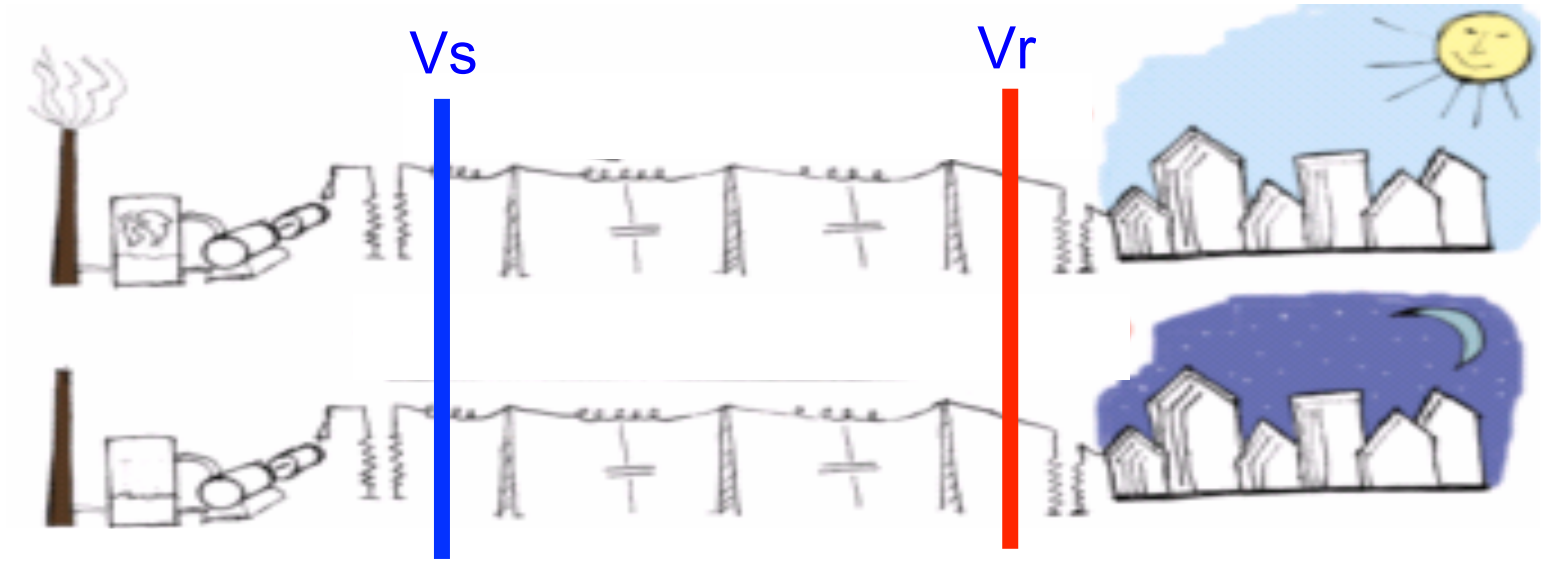
'l' is the length of the transmission line.



Line Operation

Full Load vs No Load Conditions

To ensure that Vs & Vr are within limits in all conditions!!!



Full load condition

No load condition

Sending end

generator

Receiving end

consumer/load

If the sending-end voltage is kept constant, the receiving-end voltage will vary between full load and no load conditions.

Receiving End Voltage at No Load

$$V_s = \mathbf{A}V_R + \mathbf{B}I_R$$

$$I_S = \mathbf{C}V_R + \mathbf{D}I_R$$

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

Full load condition

$$\begin{bmatrix} V_{S,FL} \\ I_{S,FL} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix} \begin{bmatrix} V_{R,FL} \\ I_{R,FL} \end{bmatrix}$$

No load condition

$$\begin{bmatrix} V_{S,FL} \\ I_{S,NL} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix} \begin{bmatrix} V_{R,NL} \\ 0 \end{bmatrix}$$

$$V_{S,FL} = A \cdot V_{R,NL}$$

$$\left|V_{R,NL}\right| = \left|\frac{V_{S,FL}}{A}\right|$$

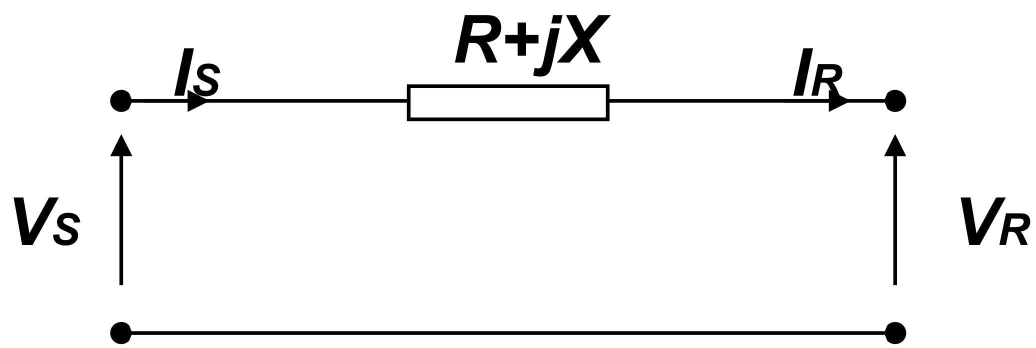
Voltage Regulation

- The variation of line voltage with different loading conditions is called 'voltage regulation'.
- About 10% voltage change between no load and full load operation is a usual practice for reliable operation.
- Voltage regulation measures the degree of change in voltage when load varies from no-load to full load **at a specific power factor**.

$$\text{Percent Regulation} = \frac{|V_{R,NL}| - |V_{R,FL}|}{|V_{R,FL}|} \times 100\%$$

Voltage Regulation of Short Line

- For simplicity, we consider a short transmission line model.



$$\text{Percent Regulation} = \frac{\cancelto{V_{S,FL}}{\left|V_{R,NL}\right|} - \left|V_{R,FL}\right|}{\left|V_{R,FL}\right|} \times 100\%$$

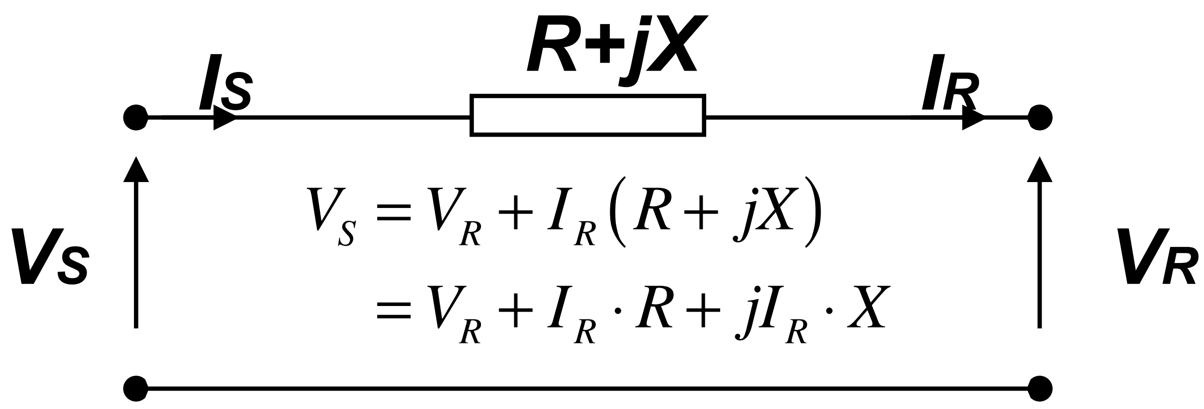
- Note that the receiving end voltage at no load condition is the same as sending end voltage at full load condition.

Vr no-load = Vs!

$$V_{R,NL} = \frac{V_{S,FL}}{A} \qquad \text{where } A = 1,\ V_{R,NL} = V_{S,FL}$$

$$\text{Percent Regualtion} = \frac{|V_s|/|A| - |V_{R,FL}|}{|V_{R,FL}|} \times 100\ \%$$

Effect of Power Factor

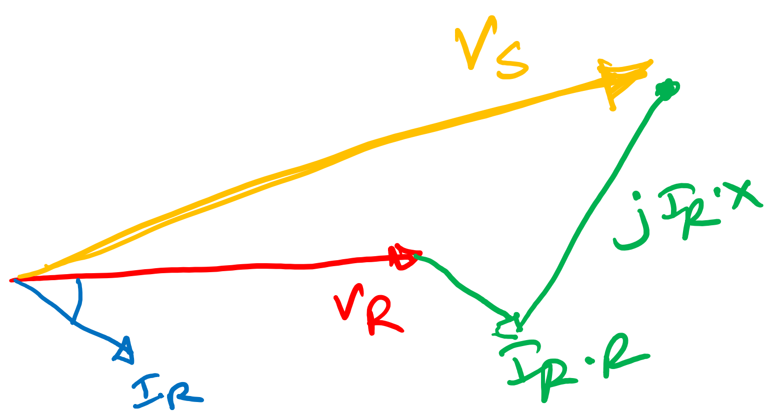


$$V_S = V_R + I_R\left(R + jX\right)$$
$$= V_R + I_R \cdot R + jI_R \cdot X$$

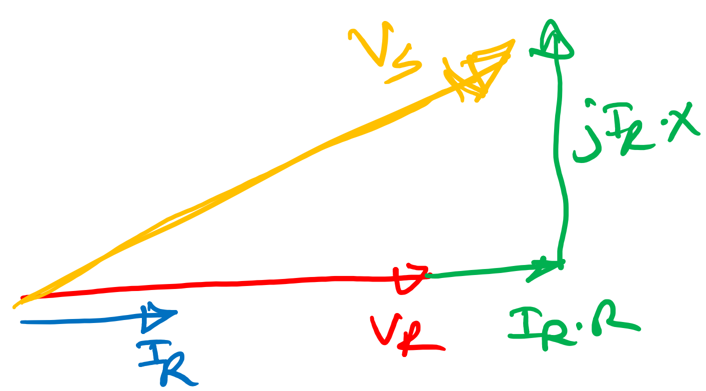
$V_{S,FL}$

$$\text{Percent Regulation} = \frac{\left|V_{R,NL}\right| - \left|V_{R,FL}\right|}{\left|V_{R,FL}\right|} \times 100\%$$

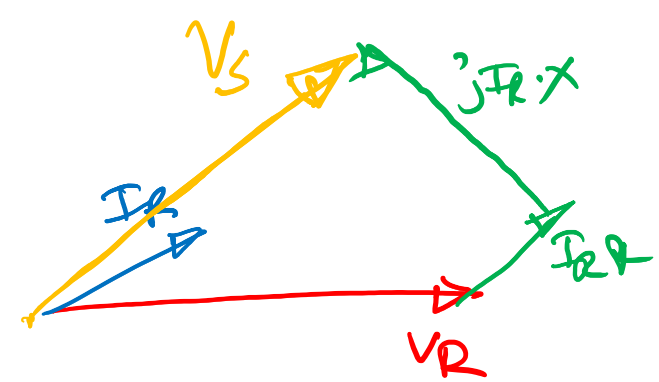
Lagging PF load



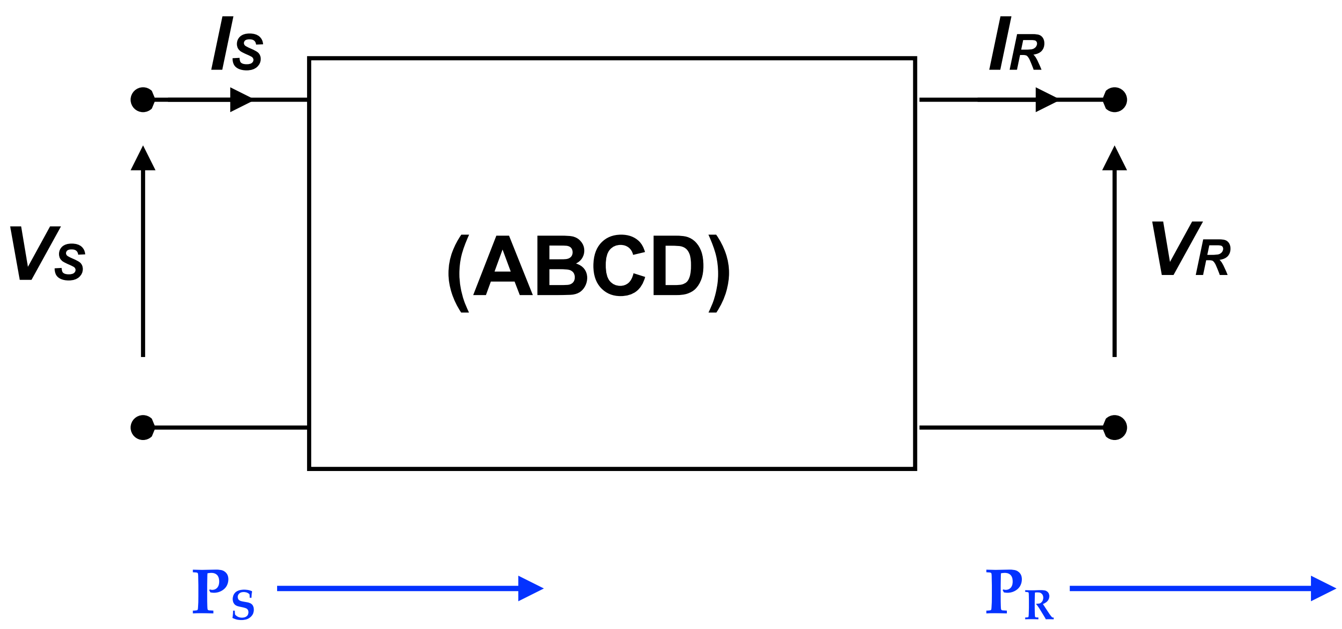
Unity PF load



Leading PF load



Transmission Efficiency



$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

Transmission Efficiency, $\eta = \dfrac{P_{R,3\phi}}{P_{S,3\phi}} \times 100\% = \dfrac{3 \times P_{R,1\phi}}{3 \times P_{S,1\phi}} \times 100\%$

Efficiency = Received / Supplied

$$\eta = \frac{\mathrm{Re}\left(V_R \cdot I_R^*\right)}{\mathrm{Re}\left(V_S \cdot I_S^*\right)} \times 100\%$$