8.1 Transmission Lines

Tuesday, March 08, 2022 11:07 AM

EE2029: Introduction to Electrical Energy System

Transmission Lines

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Learning Outcomes

- Able to identify the various physical components facilitating an overhead line and underground cable.
- Able to derive the equivalent circuit for short and medium transmission lines.
- Able to apply the concept of voltage regulation to assess transmission efficiency of power lines.

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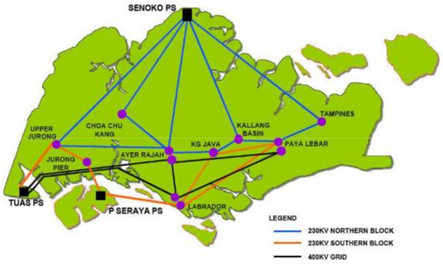
Singapore Electric Power Grid



- Fully underground cable.
- 400 kV grid
- 230 kV Northern/Southern block
  - To alleviate power quality issue.
- 66 kV/22 kV distribution

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https://www.straitstimes.com/singapore/what-will-happen-to-singapores-ageing-cables-and-how-the-cable-tunnel-serves-the-future

Types of Transmission Lines

Overhead Transmission Line

Underground Cables

Fig. 5. Typical colony of termites found around the cables.

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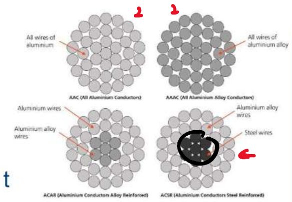
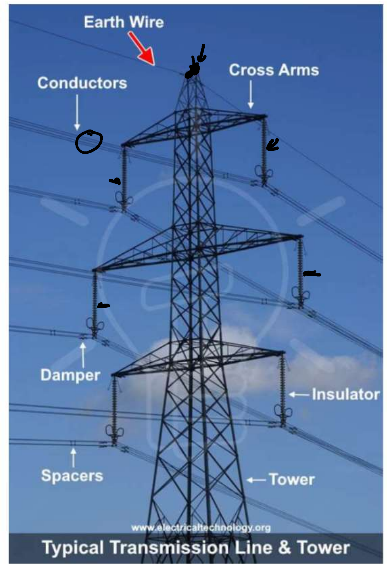
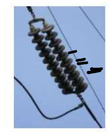
Overhead Transmission Line



- Support structure
- Conductors
- Insulators
  - Insulators are used to isolate the transmission lines from the tower t connected to ground
- Shield wires (earth wire)
  - Shield wires are wires installed on all overhead transmission lines to protect them from lightning
- Damper
  - The damper is designed to dissipate the energy of oscillations in the main cable to an acceptable level
- Spacers
  - A line spacer is used to separate the multiple conductors





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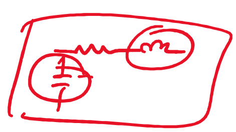
Source: https://www.electricaltechnology.org/2012/04/what-is-purpose-of-ground-wires-in-over.html



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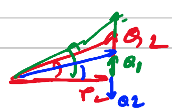
$L \rightarrow +Q_1$ | Q_L P_2

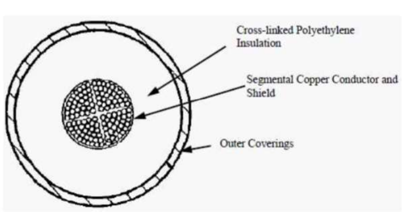
$C \rightarrow -Q_C$ | Q_L P_L

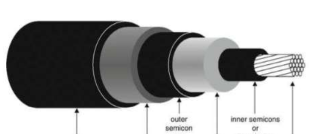
$S = (P_2 + P_{trans}) + j(Q_L + Q_{tran})$

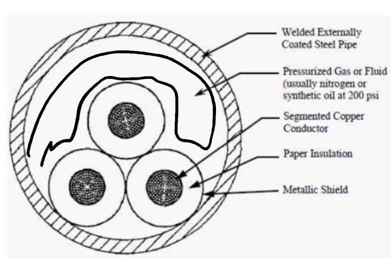


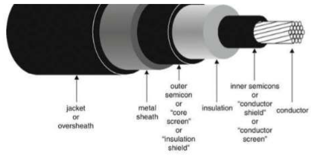
Underground Cables

- Self –Contained Cable
- Pipe-Type Cable









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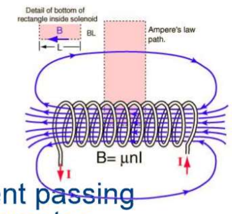
Source:
- http://coppercanada.ca/publications/pub21e/21e-Section6.html
- http://electrical-engineering-portal.com/understanding-underground-electric-transmission-cables
- https://link.springer.com/referenceworkentry/10.1007%2F978-1-4419-0851-3_758

Overhead Line Vs Underground Cables

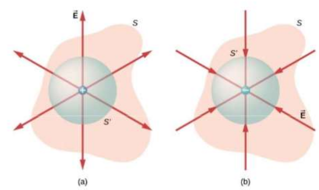
Overhead Line	Underground Cable
Lower construction cost and cable cost	Expensive pipe work and cable cost
Advantage of air for cooling and insulation of the line	Expensive insulation required at high voltage
Vulnerable to strong wind and severe weather	Less vulnerable to the severe weather because it is buried underground
Negative visual impact	Environment and aesthetic advantage
Easier maintenance/repair work	Tedious and costly maintenance/repair work
Inductive in nature	Capacitive in nature

Line Parameters



- Resistance (R)
  - Voltage drop along the line from resistive loss
  - This effect can be represented by a resistor along the line
- Conductance (G)
  - Leakage current through insulators which allows the current to pass the tower to the ground.
  - This effect can be represented by a conductance from a line to the ground
  - When the electric field strength is strong, air might become electrically ionized and conduct

- Inductance (L)
  - Ampere's Law: Current passing through a conductor creates magnetic field around it.
  - This gives inductance property
- Capacitance (C)
  - Gauss's Law: Electric charge is a source of electric fields
  - This gives capacitance property



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Line Parameters

- R from Ohmic losses
  - Types, sizes of conductor determine resistance value
- G from insulator leakage current and corona losses
  - Types, number of insulators determine conductance value
- L from magnetic field and C from electric field
  - Conductor spacing, bundling, determines magnetic and electric field strength
- All these values can be measured

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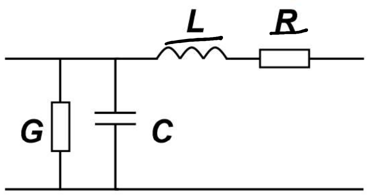
Per Phase Conductor Model

- We can now use the per phase conductor model to describe the circuit model of each phase in three-phase circuit.



Z

Series Impedance (Ω/m) $z = r + j\omega l$

Shunt Admittance (S/m) $y = g + j\omega c$

Siemens
Mho(℧)

- These parameters are given as per, unit length of the transmission line.
- We will use this information to derive an equivalent circuit of the transmission line.

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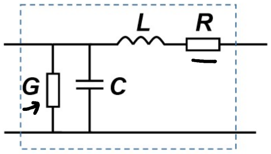
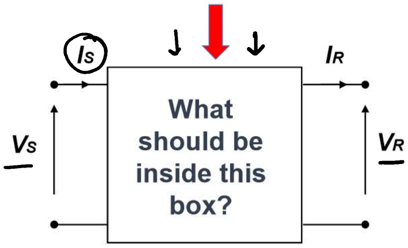
Equivalent Circuit of A Transmission Line

- An equivalent circuit of a transmission line is given in *per-phase* representation.
  - I_S = Sending end current (A)
  - I_R = Receiving end current (A)
  - V_S = Sending end voltage, line to neutral value (V)
  - V_R = receiving end voltage, line to neutral value (V)
- We can write a matrix representation to describe the sending end voltage and current by receiving end voltage and current

$$V_S = AV_R + BI_R$$
$$I_S = CV_R + DI_R$$

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





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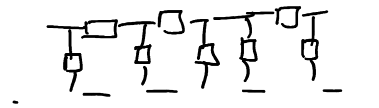
Purposes of Equivalent Circuit

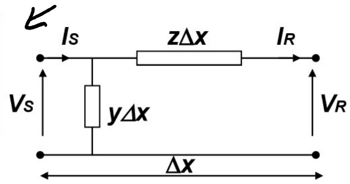
- To calculate the voltage at the receiving end when the sending end voltage is known or vice versa
  - This is used to find the voltage difference between sending and receiving end
- To find the amount of real and reactive power transfer in the line
- To make sure that the power does not exceed the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



Transmission Line Models

$l > 250Km$

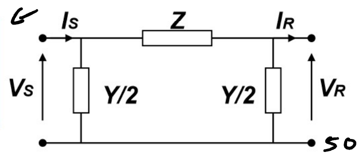
Long-Line Model: Distributed Model



z: Series Impedance (Ω/m)
y: Shunt Admittance (S/m)
Δx: distance (m)

Simplification

Medium-Line Model: Lumped Model

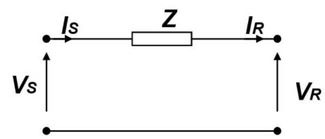


Z: Series Impedance (Ω) = zΔx
Y: Shunt Admittance (S) = yΔx

$50 < l < 250$ km.

Simplification

Short-Line Model



Z: Series Impedance (Ω) = zΔx
Y ≈ 0

$l < 50km$
80Km

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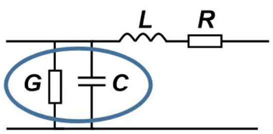
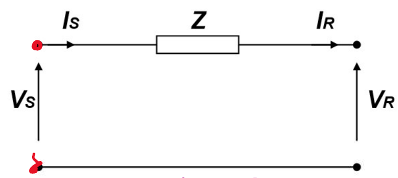
Short Line: A Simplified Model

- In this model, we ignore the shunt admittance and only consider series impedance.





$z = r + j\omega l$ Series Impedance (Ω/m)

$y = g + j\omega c = 0$ Shunt Admittance (S/m)

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{array}{c} \begin{matrix} A & B \end{matrix} \\ \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \\ \begin{matrix} C & D \end{matrix} \end{array} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

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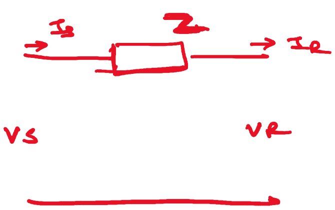
a) Short transmission line.



$I_S = I_R$

$V_S = I_R Z + V_R$

$V_S = A V_R + B I_R$

$I_S = C V_R + D I_R$

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

$V_S = \overset{A}{1} \cdot V_R + \overset{B}{Z} \cdot I_R$

$I_S = \underset{C}{0} \cdot V_R + \underset{D}{1} \cdot I_R$

$$\begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$$

A = D.

Example 1 : The 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 . What is the sending end voltage and current of this transmission line

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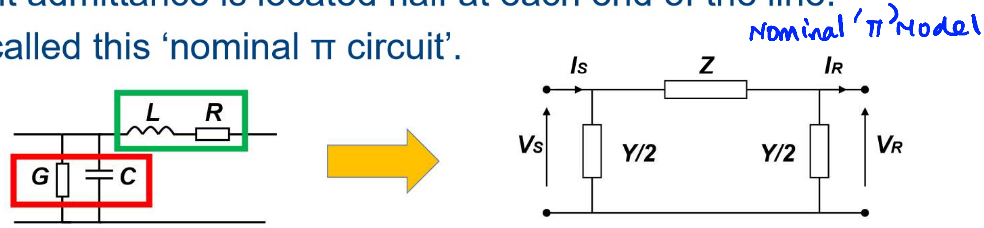
Medium Line: A Lumped Model

- In this model, series impedance and shunt admittance values are ***lumped*** together to form **Z** (series impedance in ohm) and **Y** (shunt admittance in siemens).
- Shunt admittance is located half at each end of the line.
- We called this 'nominal π circuit'.



$z = r + j\omega l$ **Series Impedance (Ω/m)**

$y = g + j\omega c$ **Shunt Admittance (S/m)**

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

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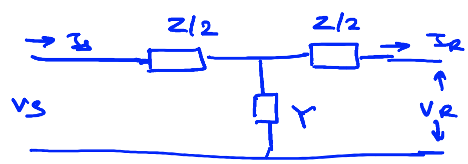
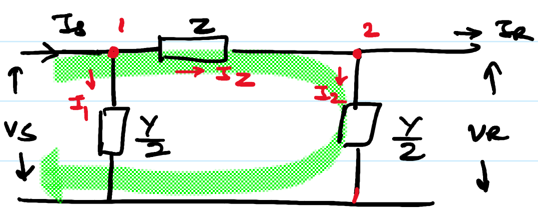
Nominal 'T' Model.





Ohms law → $I = V/Z$

$I = V \cdot$ (Admittan

$I_1 = V_s \cdot \frac{Y}{2}$

$I_2 = V_R \cdot \frac{Y}{2}$

KCL @ junction ①.

$I_s = I_Z + I_1$

KCL @ junction ②

$I_Z = I_R + I_2$,

$I_s = I_R + I_2 + I_1$

$= I_R + V_R \cdot \frac{Y}{2} + V_s \frac{Y}{2}$

KVL along

$V_s = I_Z Z + V_R$

$V_s = (I_R + I_2) Z + V_R$

$= I_R Z + V_R \cdot \frac{YZ}{2} + V_R$

$V_s = V_R\left(1 + \frac{YZ}{2}\right) + Z \cdot I_R$

$$= I_R + V_R \cdot \frac{Y}{2} + V_S \frac{Y}{2}$$

$$I_S = I_R + V_R \frac{Y}{2} + \left(V_R\left(1 + \frac{YZ}{2}\right) + Z I_R \right) \frac{Y}{2}$$

$$= I_R + V_R \frac{Y}{2} + V_R \cdot \frac{Y}{2}\left(1 + \frac{YZ}{2}\right) + \frac{YZ}{2} \cdot I_R$$

$$= V_R\left(\frac{Y}{2} + \frac{Y}{2} + \frac{Y^2 Z}{4} \right) + I_R\left(1 + \frac{YZ}{2} \right)$$

$$= V_R\left(Y + \frac{Y^2 Z}{4} \right) + I_R\left(1 + \frac{YZ}{2} \right)$$

$$= Y\left(1 + \frac{YZ}{4} \right) \cdot V_R + \left(1 + \frac{YZ}{2} \right) \cdot I_R$$

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

Example 2: A three-phase transmission line is 40 km long. It has a total series impedance of Z = 5+j20 ohm and a total shunt admittance of $Y = j133\times10^{-6}$ S. 'Full Load' at the receiving end of the line is a Y-connected load of 40 MW at a voltage of 220 kV with a power factor 0.9 lagging. Find the voltage at the sending end using the medium line model.

$I\cos\theta$

$$A = 1+\frac{YZ}{2} = 1+\frac{(5+j20)\cdot(j133\times10^{-6})}{2} = D \;;\; B = Z = 5+j20$$

$$C = Y\left(1+\frac{YZ}{4}\right) = j133\times10^{-6}\left(1+\frac{(5+j20)(j133\times10^{-6})}{4}\right)$$

$$V_R = \frac{220\times10^3}{\sqrt{3}}\angle 0^\circ$$

Load $\rightarrow$ $40\text{MW} = P = 3 V_{ph} I_{ph} \cos\theta$

$$|I_R| = I_{ph} = \frac{40\times10^6}{3\times\frac{220\times10^3}{\sqrt{3}}\times0.9} = 116.6\text{A}$$

$$I_R = 116.6\angle -25.8\text{A}$$

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

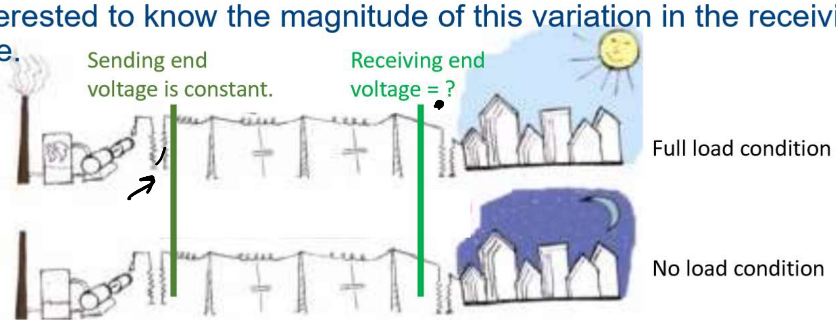
$$V_S = 128.38\angle 0.84^\circ \text{kV}$$

$$I_S = CV_R + DI_R$$

$=$

Full Load VS No Load Conditions

- In daily operation, the load at the end of a transmission line varies from day to night.
- Consider two extreme cases: full load and no load.
- If the *sending end voltage is kept constant*, receiving end voltage will vary between full load and no load conditions.
- We are interested to know the magnitude of this variation in the receiving end voltage.



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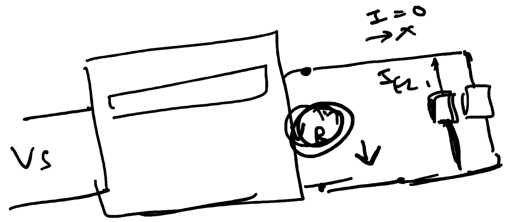


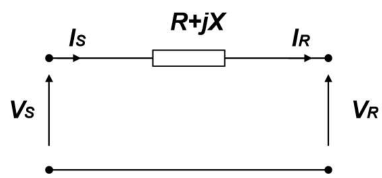
Voltage Regulation

- 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.

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

Voltage Regulation of a Short Line

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



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

$= \overline{V}_{S,FL}$

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

$$\boxed{V_{R,NL} = \frac{\underline{V_{S,FL}}}{A}}$$

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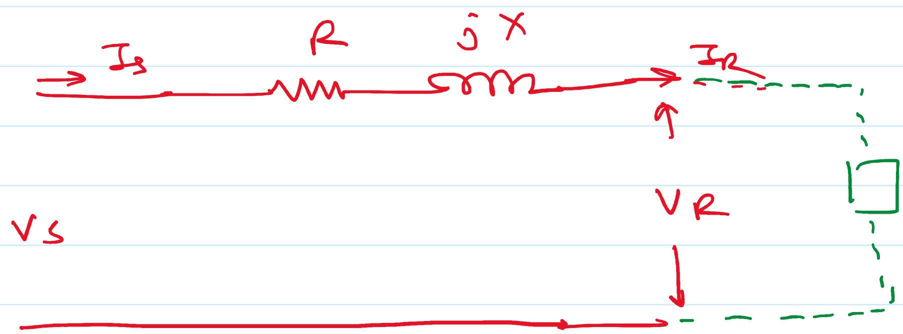
* Voltage Regulation a Short Line Transmission :



If no load $\Rightarrow$ $I_R = 0$

$\Rightarrow$ $I_S = 0$

Drop across $(R + jX) = 0$

$\Rightarrow \boxed{V_R = V_S}$

If $I_R \neq 0$ $I_R = I_{R_{F-L}}$.

$V_R = V_S - I_R(R + jX)$

$$\% VR = \frac{|V_{R_{N-L}}| - |V_{R_{F-L}}|}{|V_{R_{F-L}}|} \times 100\%$$

a) Given some load conditions $\Rightarrow V_{R_{F-L}}$

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{R_{FL}} \\ I_{R_{FL}} \end{bmatrix}$$

$\rightarrow V_S$ & I_S

b) V_S will not change

$\rightarrow$ No-Load at the Receiving End.

$I_{R_{N-L}} = 0$

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{R_{N-L}} \\ I_{R_{N-L}} \end{bmatrix}$$

$$V_S = A\,V_{RN-L} + B\,I_{RN-L} \Rightarrow (1)$$

$$V_{RN-L} = \frac{V_S}{A}$$

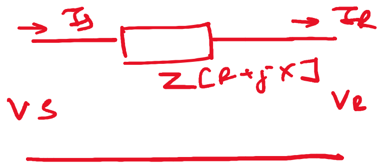
→ Short Transmission line $A = 1$

$\Rightarrow V_{RN-L} = V_S$

→ Medium → $A = 1 + \frac{YZ}{2}$

Effect of Different Power Factor

★ Effect of Power Factor on V.R [Short]



$$V_S = V_R + I_R(R+jX)$$

$$\%\,VR = \frac{|V_{R\,N-L}| - |V_{R\,F-L}|}{|V_{R\,F-L}|} \times 100\%$$

$$= \frac{|V_{S-FL}| - |V_{R\,F-L}|}{|V_{R\,F-L}|} \times 100\%$$

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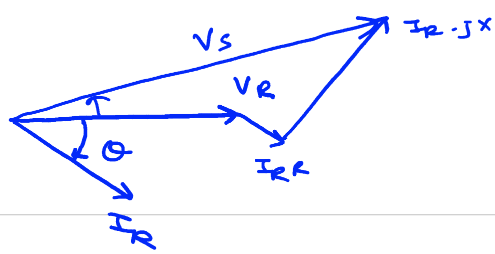
a) I_R is lagging.

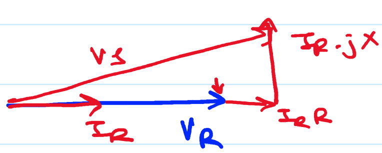


$|V_S| > |V_R|$

→ % VR is always +ve

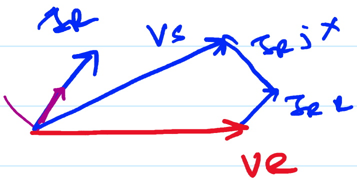
b) Load is unity p.f.

$|V_S| > |V_R|$



→ % VR is always +ve.

c) Load is leading.

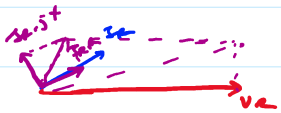


$|V_S| > |V_R|$

$=$

$<$

% VR may be +ve/-ve



Transmission Line Efficiency

- We can compute the transmission line efficiency (%) from the ratio of the real power at the receiving end to real power at the sending end.

$$\eta = \frac{P_{R,3\Phi}}{P_{S,3\Phi}} \times 100$$

$$S_{R,3\Phi} = 3V_{R,\text{line-to-neutral}} I_R^* = P_{R,3\Phi} + jQ_{R,3\Phi}$$

$$S_{S,3\Phi} = 3V_{S,\text{line-to-neutral}} I_S^* = P_{S,3\Phi} + jQ_{S,3\Phi}$$

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Extra: 150 kV Line/Cable Parameters

Overhead Transmission Line

- R = 0.125 Ω/km
- XL = 0.425 Ω /km
- C = 7.7 nF/km
- 130 MVA rating.

Underground Cable

- R = 0.12 Ω/km
- XL = 0.166 Ω/km
- C = 210 nF/km
- 135 MVA rating.

The main difference in electrical properties between overhead transmission lines and underground cables.

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