Electrical Theory

Power Flow on AC Transmission Lines

PJM State & Member Training Dept.

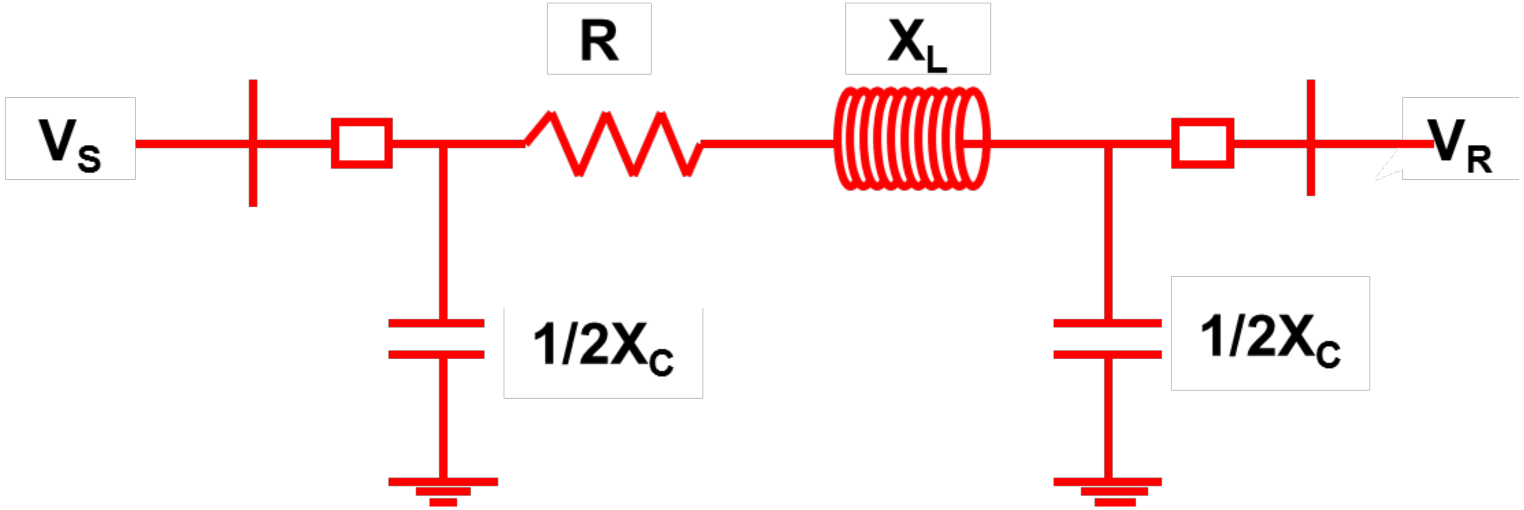
Objectives

At the completion of this training, the learner will be able to:

- Describe the basic make-up and theory of an AC transmission line
- Given the formula for real power, calculate reactive power flow on an AC transmission facility
- Given the formula for reactive power, calculate reactive power flow on an AC transmission facility
- Given voltage magnitudes and phase angle information between 2 busses, determine how real and reactive power will flow

AC Power Flow

AC Power Flow Overview



- Different lines have different values for R, X_L, and X_C, depending on:
  - Length
  - Conductor spacing
  - Conductor cross-sectional area
- X_C is equally distributed along the line

Power in Out-of-Phase AC Circuits

- Inductance and capacitance depend on:
  - Conductor cross-sectional area
  - Conductor length
  - Distance between phase conductors
- Inductive reactance:
  - Decreases as the cross-sectional area of the conductor increases
  - Increases as the conductor spacing increases
- Capacitive reactance:
  - Increases as the cross-sectional area of the conductor increases
  - Decreases as the conductor spacing increases

Power in Out-of-Phase AC Circuits

- Capacitance is always greater for underground cables where conductors and ground are very close
- AC voltage causes the charge on the conductors to increase and decrease as the voltage increases and decreases
- Charging Current is current that flows due to the alternate charge and discharge of the line due to alternating voltage regardless of whether the circuit is closed or open-ended

Review

- Total impedance (Z) is made up of resistance, inductance, and capacitance
- The reactive component (X) of impedance is made up of inductance and capacitance and is greater than the resistive (R) component of a line
- The Reactive components magnitude correlate with the voltage level

Real Power Flow

Power Flow

- MW flow on a transmission facility is the result of the resistive component (R)
  - Real power is measured in watts (W) and is in-phase with the load
- VAR flow on a transmission facility is the result of the reactive component (X)
  - Reactive power is measured in volt amperes reactive (VAR) and is out of phase with the load
- VARs supply magnetizing current for inductive loads and charging current for capacitive loads

Real Power Flow

Real Power (P_R) flow between two buses is obtained by:

$$P_R = \frac{V_S \times V_R}{X} \times \sin\delta$$

Where,

P = Real power in MW

V_S = Sending-end voltage

V_R = Receiving-end voltage

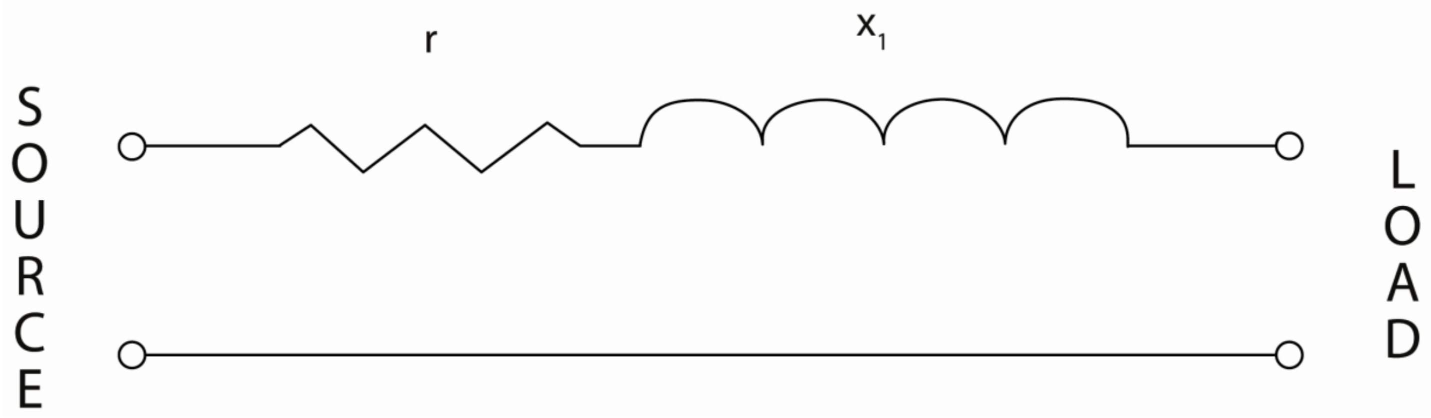
X = Line reactance between buses

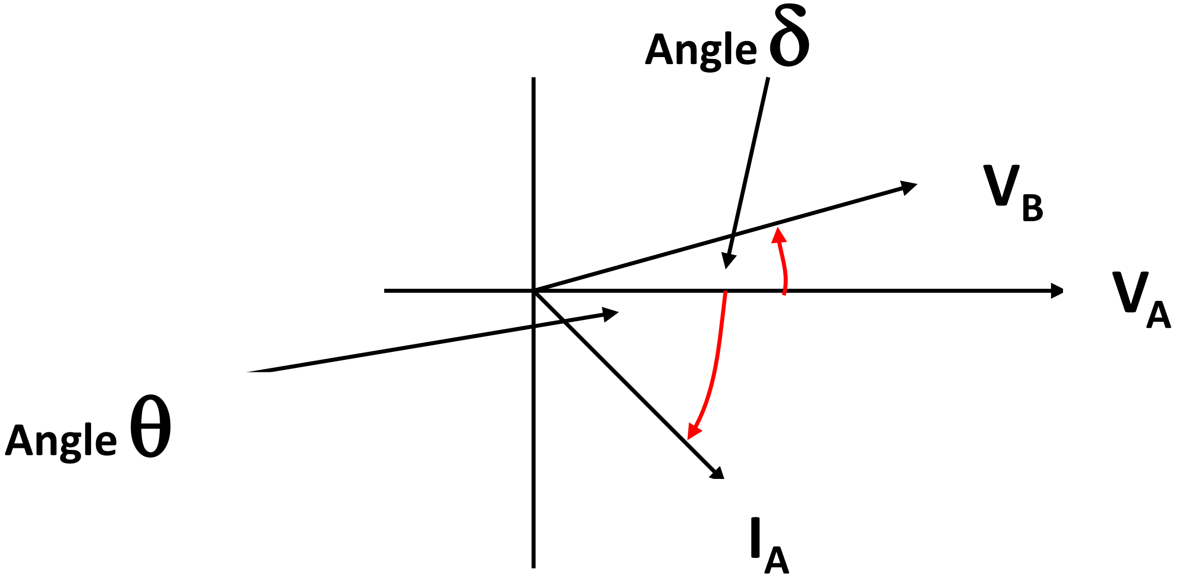
δ = Angle delta between bus voltages

Real Power Flow

- Angle theta, θ is the symbol for the angle difference between current and voltage
  - Used in determining power factor indicating the portion of total current and voltage that is producing real power
- Angle delta, δ is the symbol for phase angle difference between the sending and receiving voltages
  - Negative MW's indicate flow into the sending bus Positive MW's indicate flow out of the sending bus

Real Power Flow





Angular difference between buses

Real Power Flow

- In order to transfer real power across a transmission line, there must be an angle (delta) between the voltages at each end of the line
- Greater phase angle difference; more real power transferred
- Maximum power transfer theoretically occurs at 90^o
- Real Power flows "downhill" to a more lagging angle

Flow of Real Power Summary

- Increasing reactance results in a decrease in real power transfer
- Increasing the phase angle difference increases real power transfer
- Neither increasing or decreasing voltage magnitudes has a significant effect on the flow of real power
- If impedances of parallel lines are equal, power flow is equally distributed
- If impedances of parallel lines are different, real power flow is inversely proportional to line impedance

Reactive Power Flow

Flow of Reactive Power

- Reactive Power (P_Q) flow on a transmission line is a result of the inductive reactance of the load requirement and is obtained by:

$$P_Q = \left\{\frac{(V_S)(V_S - V_R)}{X}\right\} \cos\delta$$

Where,

Q = Reactive Power in MVAR

V_S = Sending-end voltage

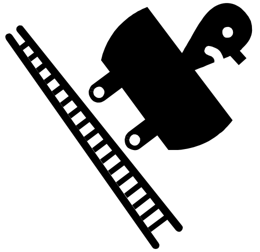
ΔV = Difference between bus voltages V_S and V_R

X = Line reactance between buses

δ = Phase angle between VS and VR

Flow of Reactive Power

- VARS flow only if there is a difference in bus voltage potential
- VAR's flow downhill from a higher per unit value to a lower per unit value of voltage
- Reactive power flow is similar to real power flow:
  - Negative VAR value indicates flow into the reference bus
  - Positive VAR value indicates flow out of the reference bus



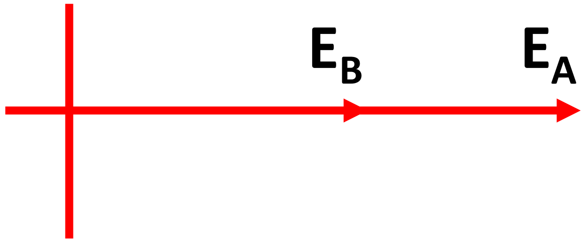
Flow of Reactive Power Summary

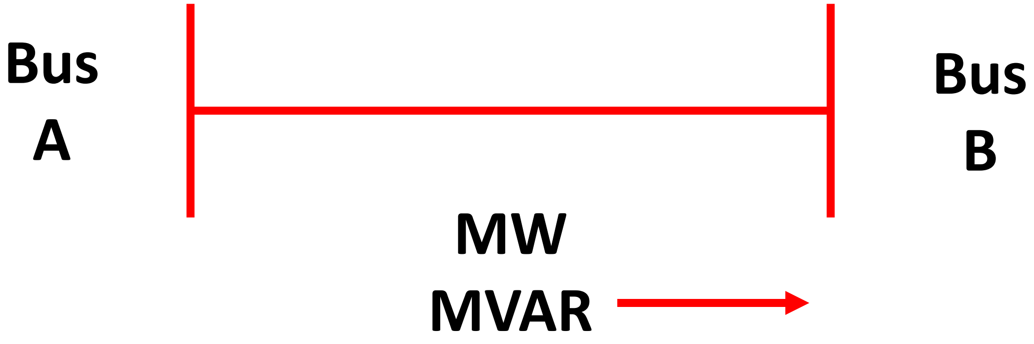
- Increasing the voltage magnitude at the sending end increases the reactive power flow toward the receiving end
- Increasing the voltage magnitude at the receiving end decreases the reactive power flow toward the receiving end
- Increasing the path reactance between the two buses decreases the reactive power flow towards the receiving end

Integrating Real & Reactive Power Flows

Scenario 1

- Voltages are in-phase; Bus A voltage > Bus B voltage

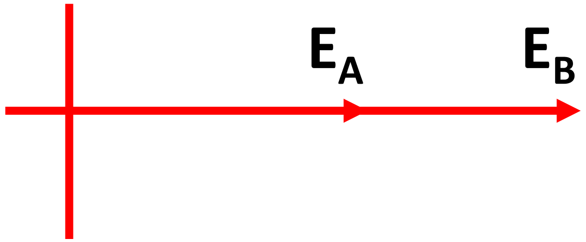


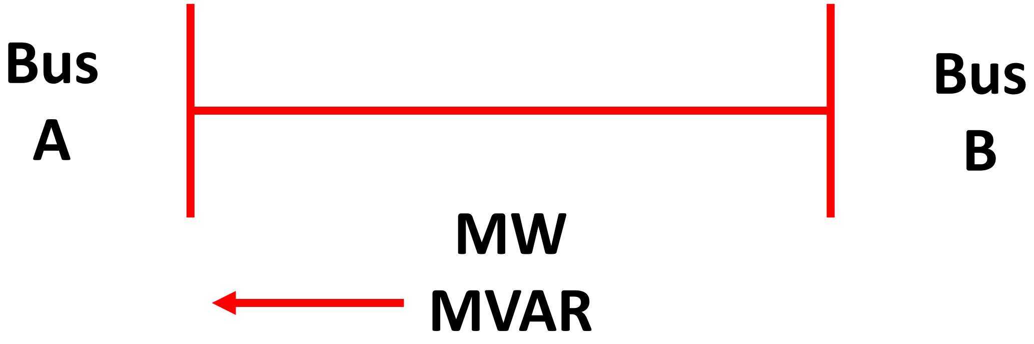


- No MW flow; no phase angle difference
- VAR's flow from Bus A to Bus B

Scenario 2

- Voltages are in-phase; Bus A voltage < Bus B voltage

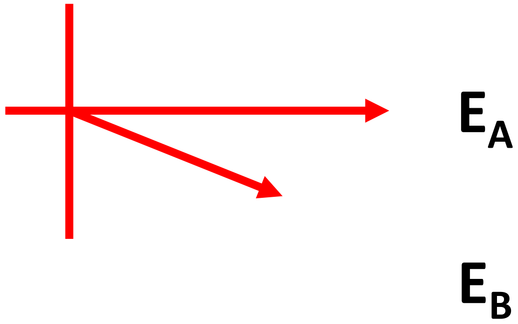


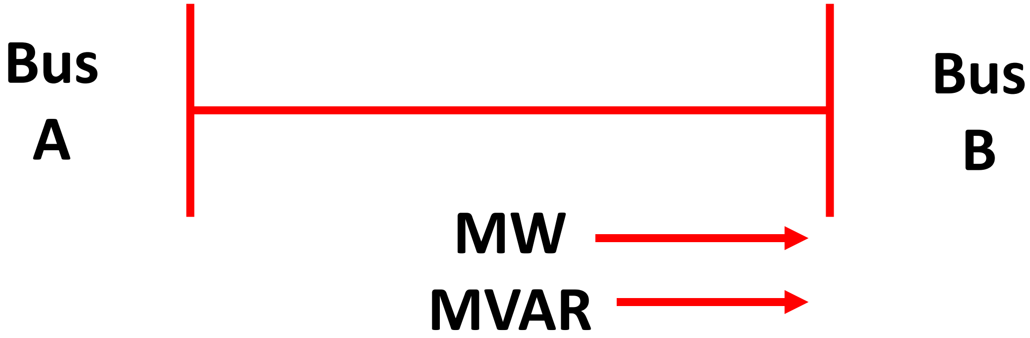


- No MW flow; no phase angle difference
- VAR's flow from Bus B to Bus A

Scenario 3

- Voltages are not in-phase; Bus A voltage > Bus B voltage

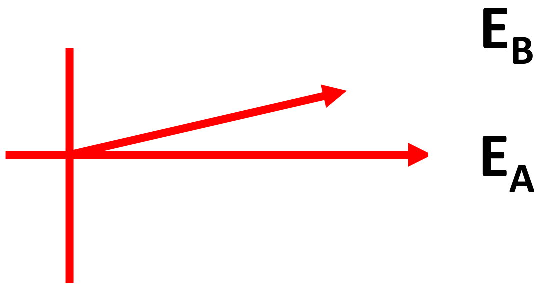


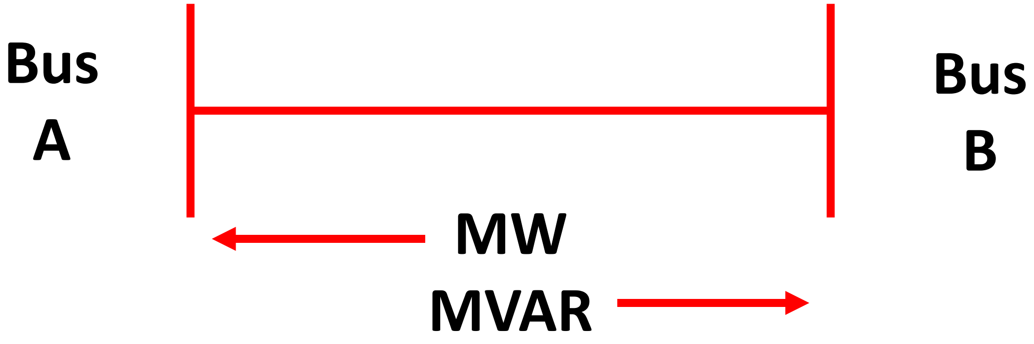


- MW flow; Bus B voltage is lagging Bus A voltage
- VAR’s flow from Bus A to Bus B

Scenario 4

- Voltages are not in-phase; Bus A voltage > Bus B voltage

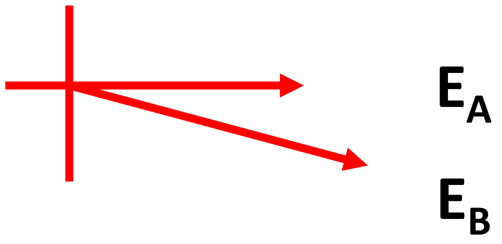


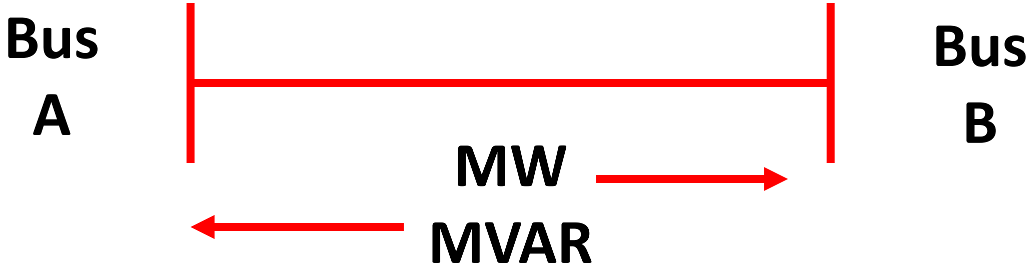


- MW flow; Bus A voltage is lagging Bus B voltage
- VAR's flow from Bus A to Bus B

Scenario 5

- Voltages are not in-phase; Bus A voltage < Bus B voltage

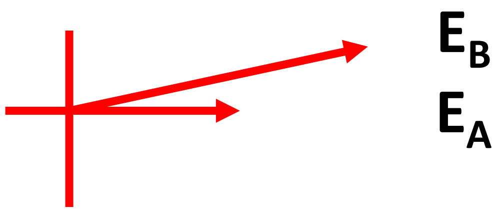


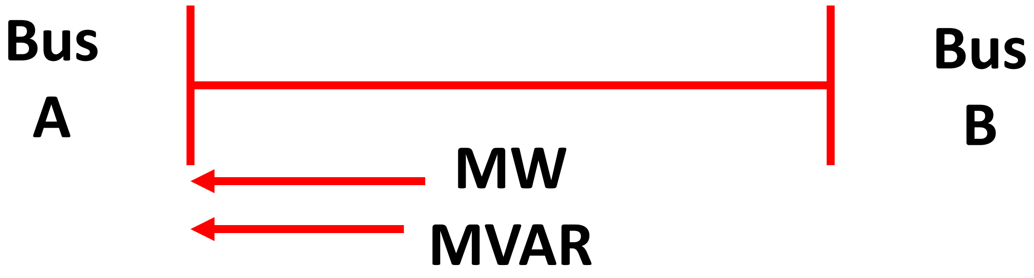


- MW flow; Bus B voltage is lagging Bus A voltage
- VAR's flow from Bus B to Bus A

Scenario 6

- Voltages are not in-phase; Bus A voltage < Bus B voltage

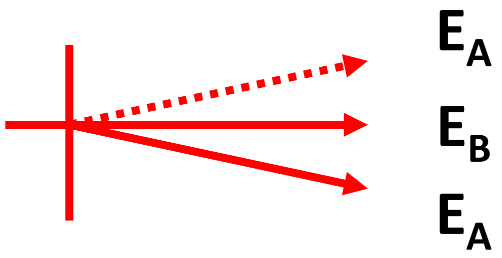


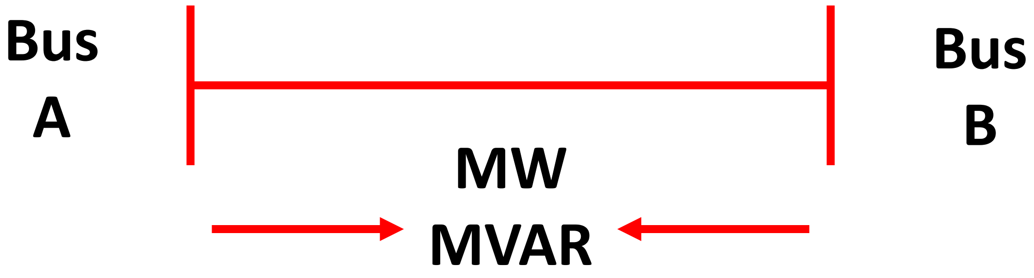


- MW flow; Bus A voltage is lagging Bus B voltage
- VAR's flow from Bus B to Bus A

Scenario 7

- Voltages are not in-phase; Bus A voltage = Bus B voltage





- MW flow
  - Bus A voltage lags Bus B voltage, MW flow into Bus A
  - Bus B voltage lags Bus A voltage, MW flow out of Bus A
- VAR’s flow from Bus B and from Bus A into the line

Questions?

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The Member Community is PJM's self-service portal for members to search for answers to their questions or to track and/or open cases with Client Management & Services

Resources & References

Miller, R. & Malinowski, J. (1994). *Power System Operation*. Boston, MA. McGraw-Hill

Rustebakke, H.M. (Ed) (1983). *Electric Utility Systems & Practices.* 4th edition, Wiley Interscience