7|Power Transmission

Power transmission is more than the transmission line network. Transmission is designated to mean the higher voltage levels on a given power system.

Objective:

- To recognize transmission line’s supporting structures and electrical design characteristics
- To list methods for controlling voltage and power flow for the operation of High Voltage Direct Current (HVDC) systems

Course Outline

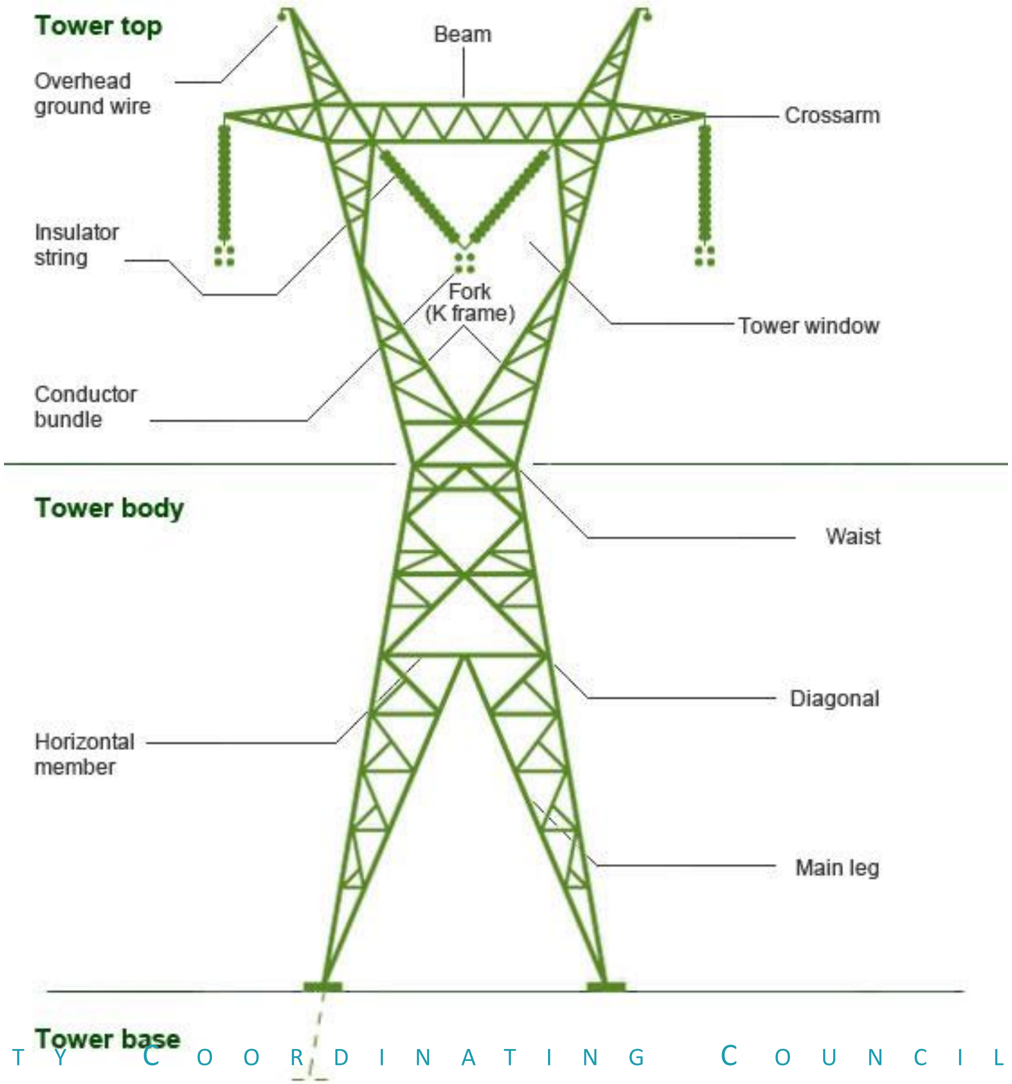
1. Introduction to WECC
2. Fundamentals of Electricity
3. Power System Overview
4. Principles of Generation
5. Substation Overview
6. Transformers
7. Power Transmission
8. System Protection
9. Principles of System Operation

Power Transmission

- Components and Interconnections
- Electrical Model
- Operating Considerations
- Circuit Restoration
- High Voltage Direct Current Transmission

Power Transmission
Components and Interconnections

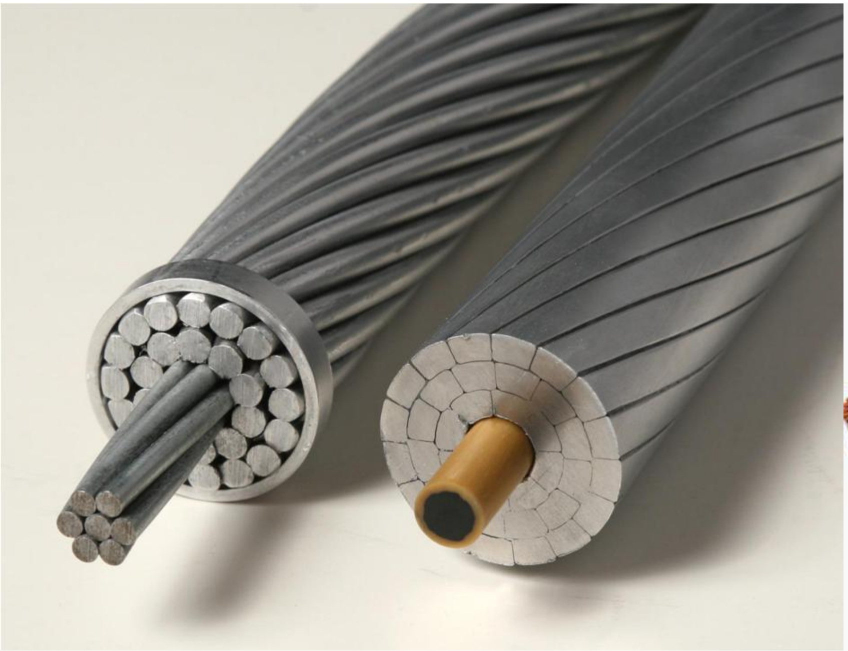
- Conductors
- Towers
- Insulators
- Shield wires
- Rights-of-way



Power Transmission
Components and Interconnections

Conductors

Conductors carry the electricity.



Overhead

Underground

Conductors

Conductors

Corona Rings

Bundle Conductors

- Bundled Conductors are used in transmission lines where the voltage exceeds 230 kV.
- At such high voltages, ordinary conductors will result in excessive corona and noise which may affect communication lines.
- The increased corona will result in significant power loss. Bundle conductors consist of three or four conductors for each phase.
- The conductors are separated from each other by means of spacers at regular intervals. Thus, they do not touch each other.

Bundled Conductor

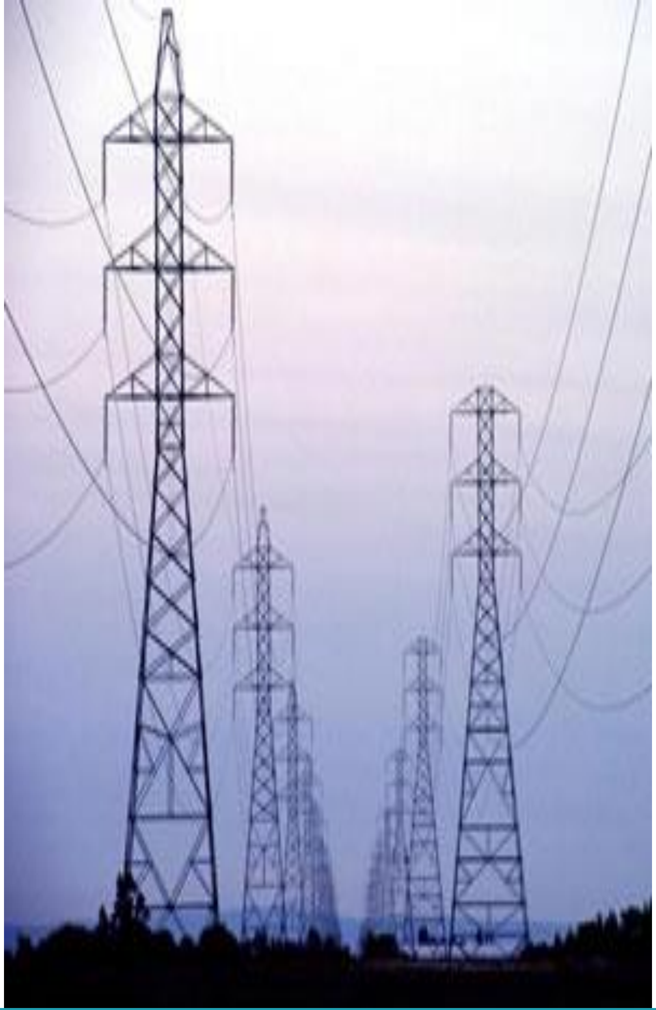
Transmission AC Line and DC Line

Power Transmission

Components and Interconnections

Towers

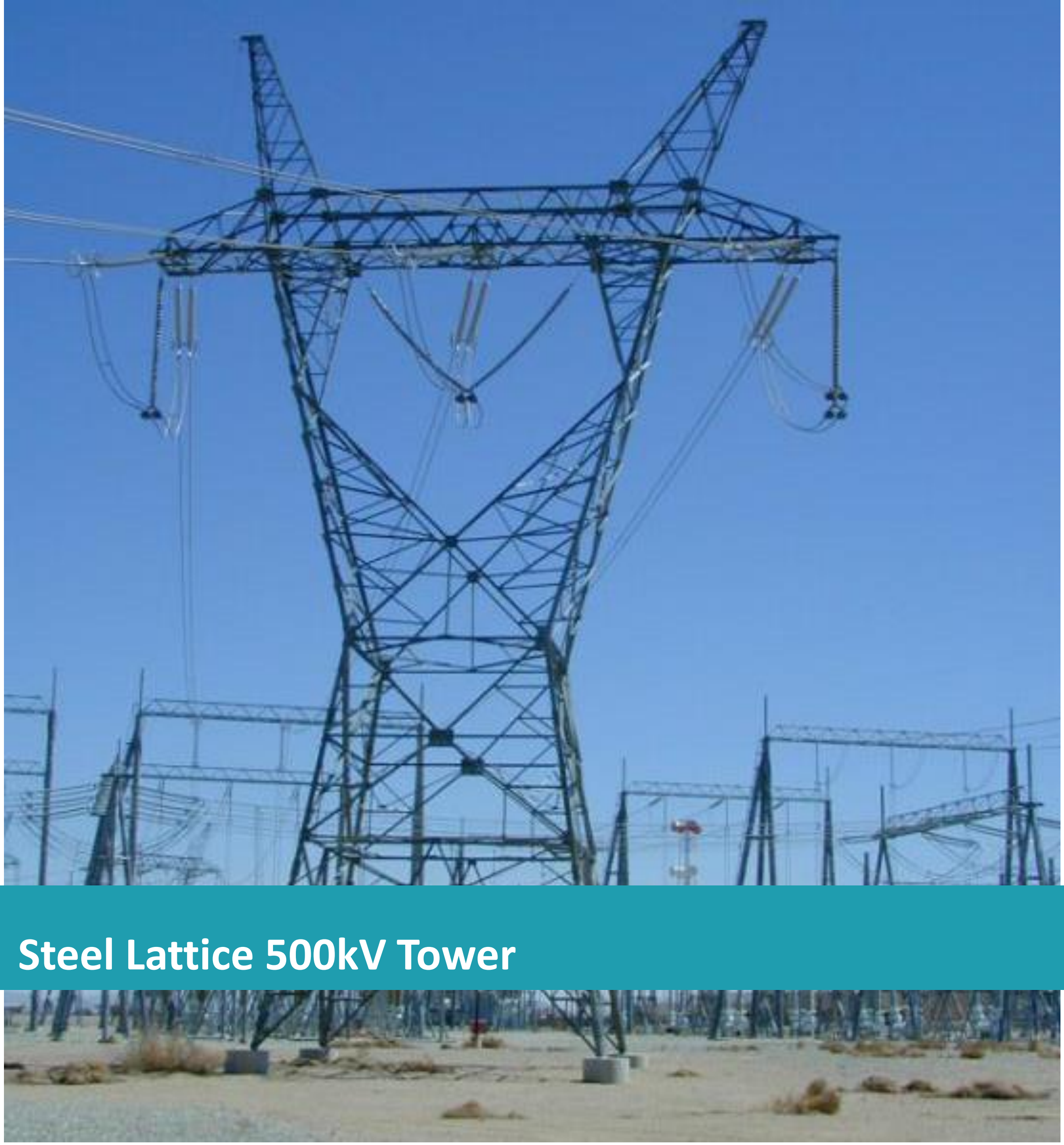
Transmission towers support high voltage transmission line conductors.



Transmission Tower

Towers showing line sag

345 kV Wooden Structures



Steel Lattice 500kV Tower

Steel Lattice 500 kV Tower

Power Transmission
Components and Interconnections

Insulators

Non-conducting devices that attach the energized lines to the support tower.

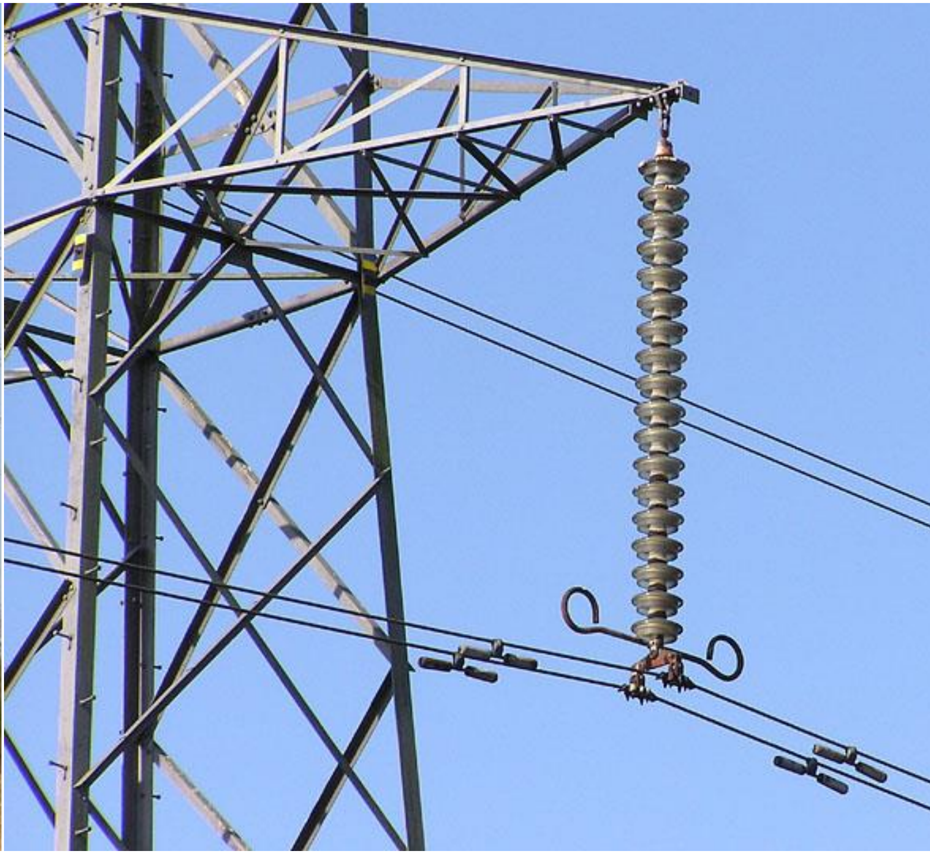
Insulators

- ***Insulators*** are non-conducting devices that attach the energized conductors to the support tower. Insulators electrically isolate conductors from each other, as well as from the ground and support towers. The insulator must have sufficient mechanical strength to support the greatest loads reasonably expected due to ice and wind.
- Insulators must withstand mechanical abuse (such as gunfire and thrown objects), lightning strikes, and power arcs without dropping the conductor.

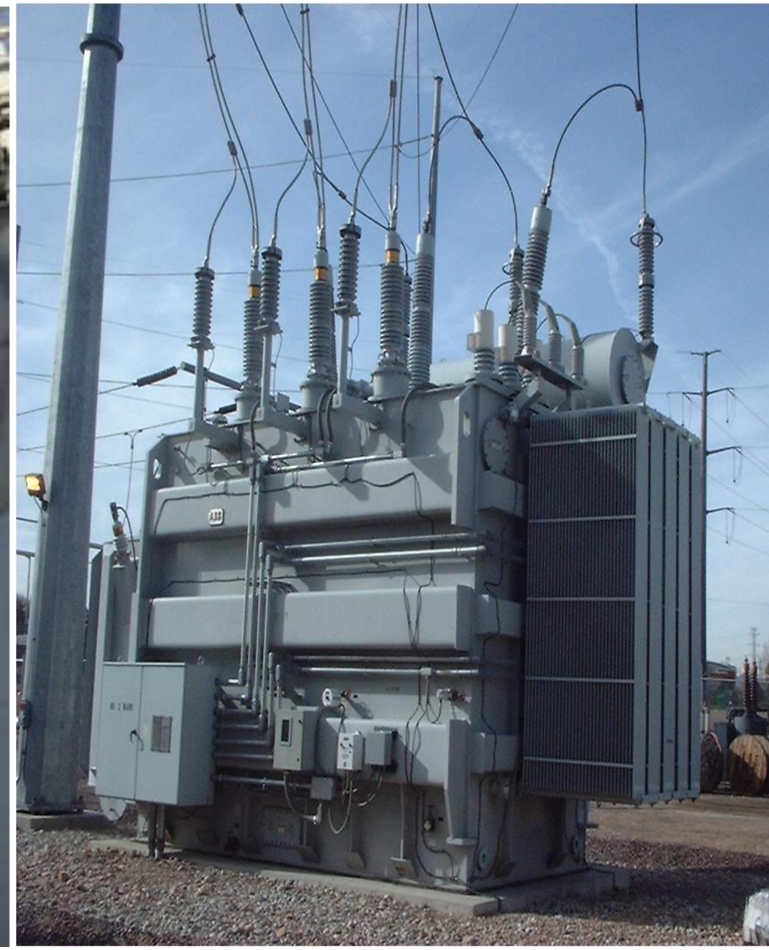
Insulators

- Insulators prevent flashover under conditions of humidity, rain, ice, or snow; and with dirt, salt, smoke, and other contaminants accumulating on the surface.
- Insulators are made of glass, polymer, or ceramic material. Most utilities use porcelain for insulators because it has excellent insulation properties and mechanical strength. Some utilities coat the porcelain with a glaze to provide a smooth surface from which contaminants can easily be washed by rainfall or wash sprays.

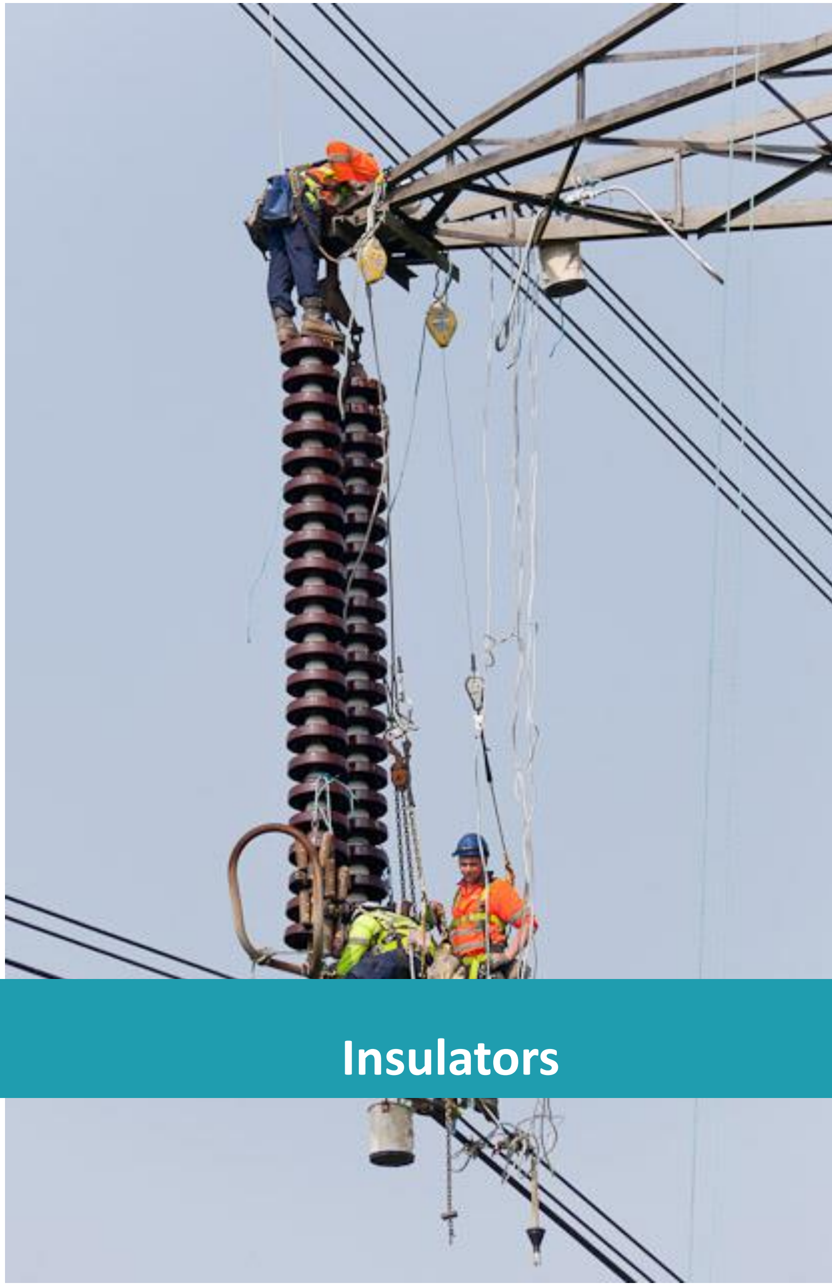
Insulators



Insulators



Insulators



Insulators

Power Transmission

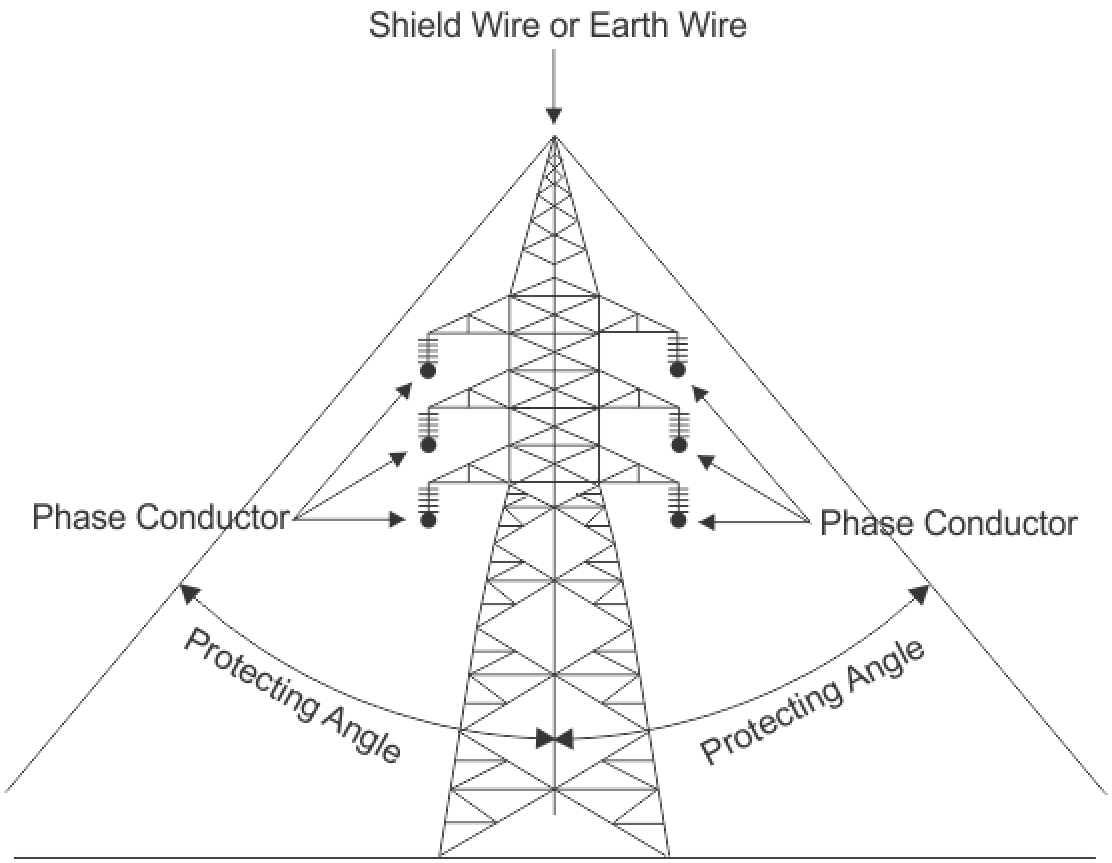
Components and Interconnections

Shield Wires

Shield wires protect energized conductors from lightning strikes.

Shield Wires (Static)

- Shield wires, mounted at the top of the support tower, protect the energized conductors from lightning strikes. With conservative tower design, almost all lightning strikes to the transmission line hit a shield wire, instead of a line conductor.
- Transmission lines require a conductive path from the shield wire to the ground to drain off electrical energy from the lighting strike to the ground.
  - With a steel tower, the tower connects directly to the shield wire.
  - With wood poles, ground wires run from the shield wire to the ground.
- Sometimes the shield wires are also used for communications.



Shield Wires (Static)

Power Transmission

Components and Interconnections

Rights-of-Ways

The land over which one or more transmission lines pass.

Rights-of-Way

- Rights-of-way are the land over which one or more transmission lines pass.
- Rights-of-way provide:
- Access to the line during construction and during subsequent line inspections, tests, and maintenance.
- Access to the vegetation (trees, brush, etc.) growing under the line to prevent it from growing up into the line and causing short circuits.
- Rights-of-way must be wide enough to have adequate clearance between the transmission line and trees and buildings that are outside the right-of-way.

Before Vegetation Management

After Vegetation Management

Rights-of-Way

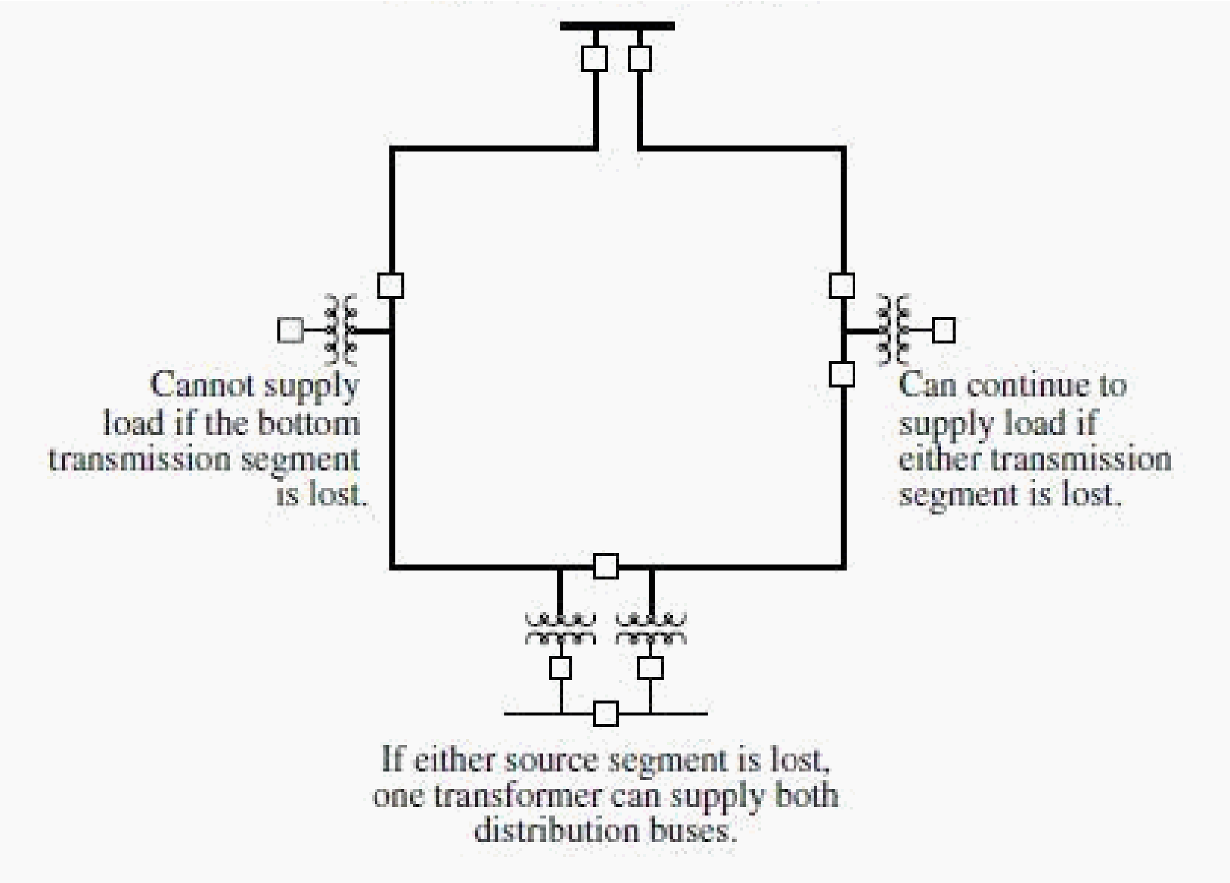
Power Transmission
Components and Interconnections

Interconnection of Transmission Lines

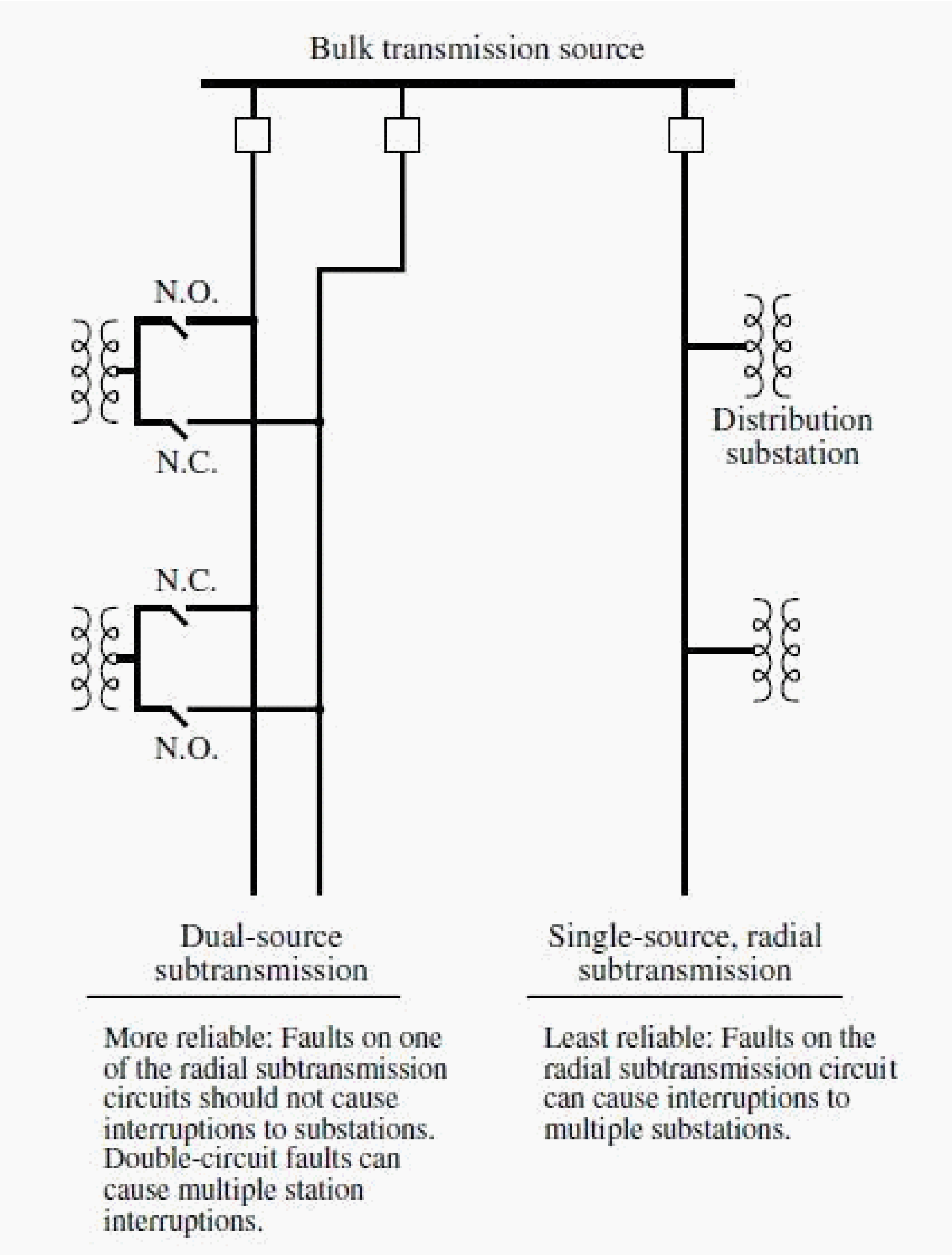
The principle objective of a transmission system is to provide multiple transmission line paths between each generator and each load, so that no generation or load is lost if a transmission line trips.

Interconnection of Transmission Lines

- The high voltage transmission system must be designed so that if one transmission line opens (that is, the line circuit breakers open):
- Major generating plants do not become separated from the rest of the power system and system instability, cascading outages, or voltage collapse do not occur.
- Customer service is not interrupted. A major transmission system outage would impact many customers.



Loop Arrangement



Grid Arrangement

Power Transmission

Components and Interconnections: RECAP

Power Transmission

- Components and Interconnections
- Electrical Model
- Operating Considerations
- Circuit Restoration
- High Voltage Direct Current Transmission

Power Transmission

Electrical Model

- Resistance
- Reactance
- Changing Current
- Voltage and Power Flow

Power Transmission

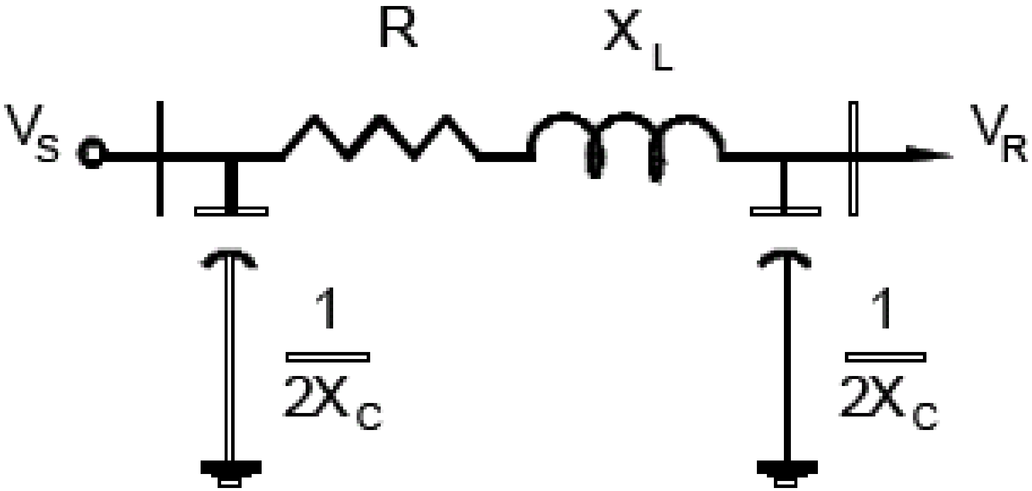
Electrical Model

Resistance, Inductance, and Capacitance relative to a transmission line.

To determine the design of a transmission line and perform other analysis functions, engineers model a transmission line in the following way:

– A resistance (R) and inductive reactance (X_L) in series

– A capacitive reactance (X_C) in shunt

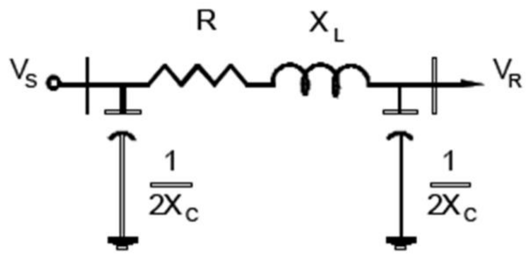


Electrical Model

Power Transmission

Electrical Model

Resistance

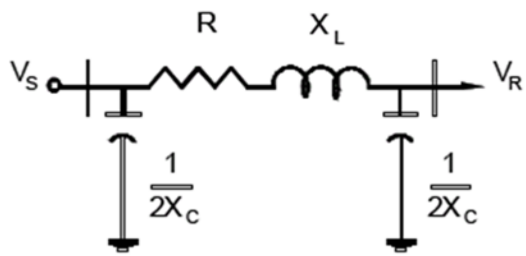


Resistance is the property of a material that opposes current by converting electric energy to heat and that real power (watt) losses occur due to I^2R heating. A transmission line's resistance is an important cause of power loss.

Power Transmission

Electrical Model

Reactance



Reactance is the name given to the opposition to current caused by capacitors and inductors and that there are also reactive power losses (I^2X) when current flows.

- Inductors produce inductive reactance. The effect of inductive reactance is that the current lags the voltage
- Capacitors produce capacitive reactance. The effect of capacitive reactance is that the current leads the voltage

Power Transmission
Reactance

Reactance

For transmission lines less than 50 miles long, the effect of capacitance is very small and is usually neglected. However, for longer lines, the capacitance becomes increasingly important.

Power Transmission

Electrical Model

Charging Current

Placing an alternating voltage on a transmission line causes the charge on the conductors to increase and decrease as the voltage increases and decreases.

Charging current is the current that flows due to the alternate charge and discharge of the line due to the alternating voltage. Even when a transmission line is open-circuited at one end, charging current flows.

- These parameters (resistance, inductance, and capacitance) combine to make up total impedance (Z) and are fairly constant for a given transmission line.

Power Transmission

Voltage & Power Flow

A transmission line's impedance, voltage, and voltage phase angle between the two ends of the transmission line determine the real power that can flow through a transmission line.

So, to change the power flow, one or more of these elements needs to be changed.

Power Transmission

Voltage & Power Flow

When fully loaded, transmission lines absorb Volt-Amperes Reactive (VARs).

At light loads, the capacitances of longer lines may become predominant and the lines become VAR generators.

Power Transmission

Voltage & Power Flow

If a line is lightly loaded, the capacitive charging current may exceed the load current. This results in the line operating with a leading power factor. Under this condition, the receiving-end voltage (V_R) rises and may exceed the voltage at the sending-end (V_S) of the line.

This voltage rise may over-stress insulation. The voltage regulating equipment at the receiving-end station may go out of range. This results in the customers receiving high voltage.

Power Transmission

Voltage & Power Flow

If a line is heavily loaded, the receiving-end voltage (V_R) drops below the sending-end voltage (V_S).

The voltage drop may result in the voltage regulating equipment at the receiving-end station going out of range. This results in reduced customer voltage.

Power Transmission

Voltage & Power Flow

When transmission lines have bundled conductors, the capacitance is greater than with single conductors. The increase in capacitance results in increased charging current. This capacitance acts as a VAR generator. As voltage increases, the capacitive charging VARs of the line increase. The power system must absorb these VARs.

For example: a 200-mile 500-kV bundled transmission line requires approximately 320 MVar of charging current.

Power Transmission

Charging Requirements

Voltage	Overhead 3Ø Charging (MVAR/mile)	Underground 3Ø Charging (MVAR/mile)
500 kV	~ 1.6-2.0	~ 30.3
345 kV	~ .85	~ 17.0
230 kV	~ .30	~ 8.8
138 kV	~ .11	~ 4.9
115 kV	~ .07	~ 3.4
69 kV	~ .03	~ 1.9

Power Transmission

Electrical Model: RECAP

Power Transmission

- Components and Interconnections
- Electrical Model
- Operating Considerations
- Circuit Restoration
- High Voltage Direct Current Transmission

Power Transmission
Operating Considerations

- Controlling Real Power Flow
- Phase Shifting Transformers
- Series Capacitors
- Controlling Voltage and Reactive Power Flow
- Shunt Reactors
- Shunt Capacitors
- Generators
- Transposing Conductors

Power Transmission
Operating Considerations

Operating considerations to minimize adverse conditions with:

- Methods of controlling real power
- Methods for controlling voltage and reactive power flow.

Power Transmission
Operating Considerations

Controlling Real Power Flow

Review:

Real power flow is determined by:

- the angle difference of the voltages at the terminals.
- the voltage level of the line.
- the impedance of the line .

Power Transmission

Operating Considerations

Real Power Flow

The real power flow between two buses is obtained from the following equation:

$$P = \frac{V_s V_r}{X} \sin\phi$$

Where:

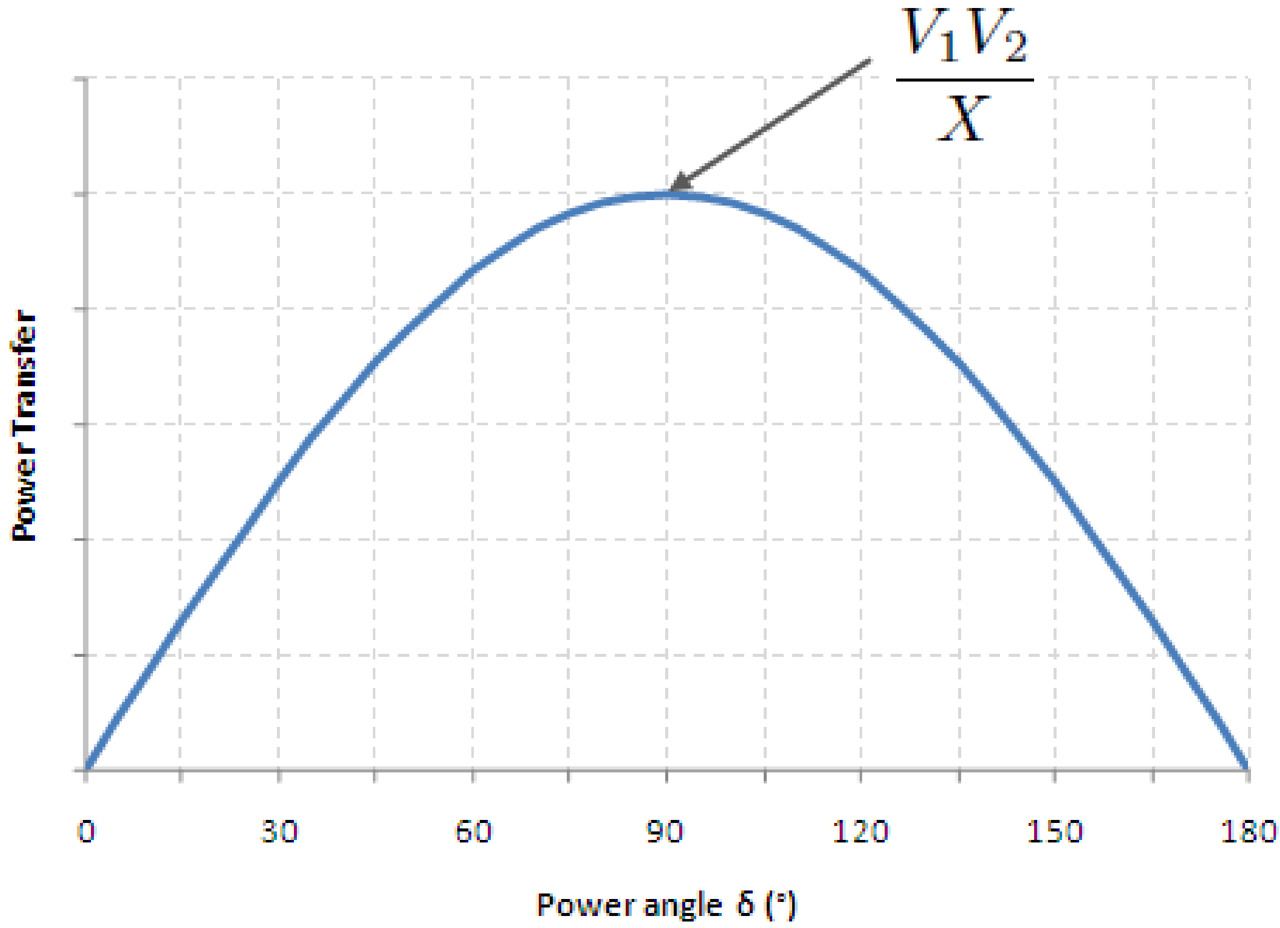
P = Real power in MW

$\mathbf{V_s}$ = Sending-end voltage

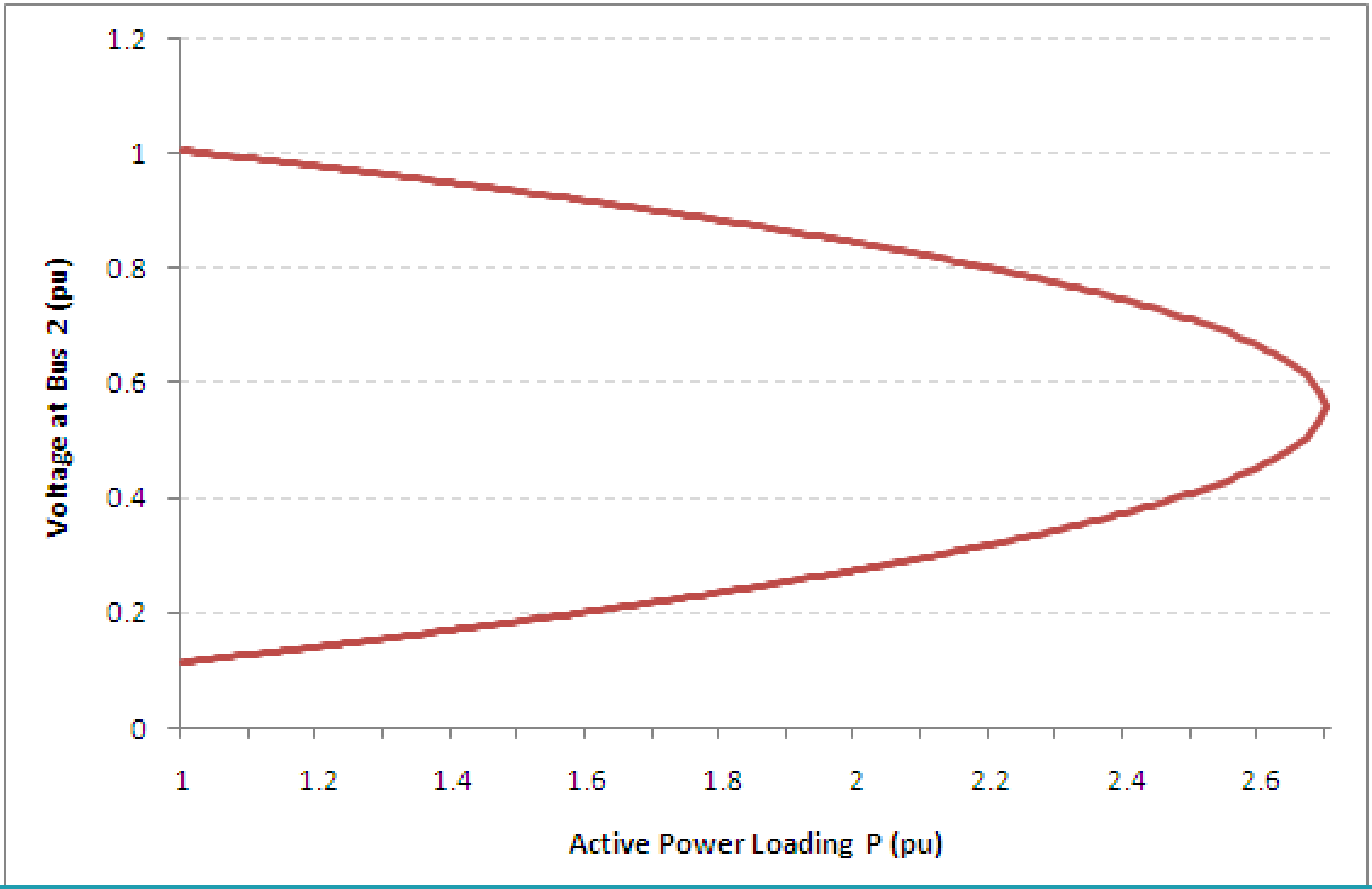
$\mathbf{V_r}$ = Receiving-end voltage

X = Reactance of the line between sending and receiving ends (the impedance is mostly made up of reactance)

ϴ = Angle between V_s and V_r (bus voltages)



Voltage Phase Angle Difference



Voltage Phase Angle Difference

Power Transmission
Operating Considerations

$$P = \frac{V_s V_r}{X} \sin\phi$$

Real Power Flow

Any method of **increasing** real power flow must address the variables in the equation. This is accomplished by using one of the following methods:

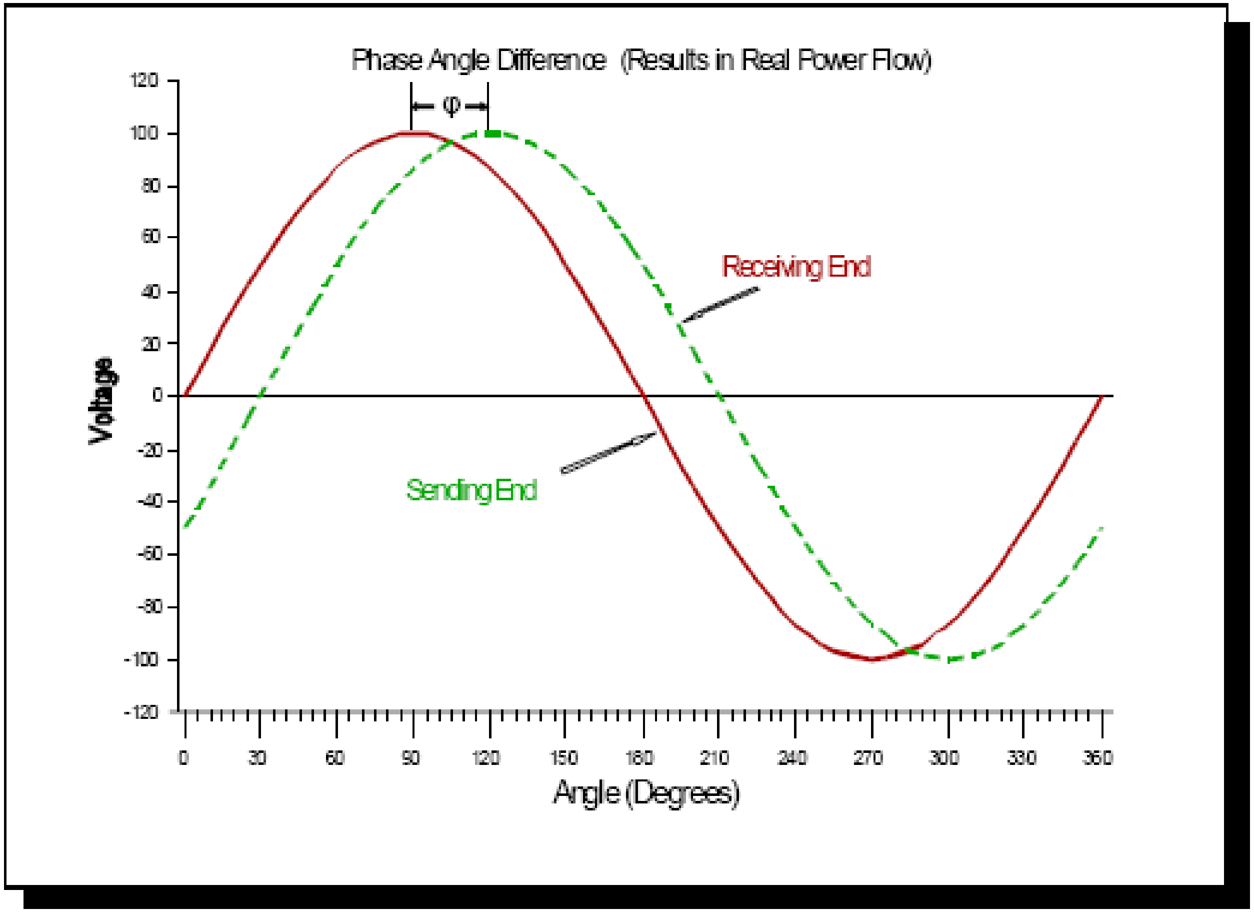
- changing the phase angle with phase shifting transformers
- changing generation patterns relative to the line terminals
- changing the impedance of the line with series capacitors

Conversely, **decreasing** real power flow can be accomplished by decreasing the phase angle with phase shifting transformers, or increasing line impedance by switching out series capacitors.

Power Transmission

Operating Considerations

Voltage Phase Angle Difference



Phase Shifting Transformer – “Phase Shifter”

Power Transmission
Operating Considerations

Series Capacitors

Series capacitors cancel some of the inductive reactance of the line, therefore decreasing impedance. This enables more real power to flow.

Utilities use series capacitors primarily to improve system stability.

Series Capacitors

Power Transmission

Operating Considerations

Controlling Voltage and Reactive Power Flow

Reactive compensation methods alleviate some of the undesirable effects of line charging.

Power Transmission

Operating Considerations

Controlling Voltage and Reactive Power Flow

In general:

The following elements are **sources** of reactive power (VARs):

- overexcited generators and synchronous condensers
- shunt capacitors
- line capacitance

The following elements **absorb or use** reactive power:

- underexcited generators and synchronous condensers
- shunt reactors
- line transformers
- motor loads

Power Transmission

Operating Considerations

Shunt Reactors

Review

During light loads, the capacitive charging current may cause excessive voltage at the receiving end of a transmission line.

- A shunt reactor is an inductor that is connected line-to-ground

- Utilities switch shunt reactors in service to absorb excess Vars supplied by transmission lines during lightly loaded periods

Shunt Reactors

Power Transmission
Operating Considerations

Shunt Capacitors

Reminder

If a line is heavily loaded, the inductive Var losses may cause insufficient voltage at the receiving end of a transmission line. Shunt capacitors compensate for this effect.

Utilities switch shunt capacitors in and out of service to meet peak load demands.

- Morning: when customer load is increasing, capacitors are switched in-service (sometimes automatically) to supply Vars to the system
- Evening when customer load is dropping off (and the Var demand is reduced), the capacitors are switched out of service

Location: Shunt capacitors are located as close to the load as practical.

Power Transmission
Operating Considerations

Static VAR Compensator (SVC)

SVCs are another device that has the ability to control voltage.

A SVC is a system of capacitors and reactors controlled with solid-state electronic devices to provide a rapidly controllable source of reactive power.

Location: SVCs are located at transmission substations.

Shunt Capacitor

Static Var Compensator (SVC)

Power Transmission
Operating Considerations

Generators

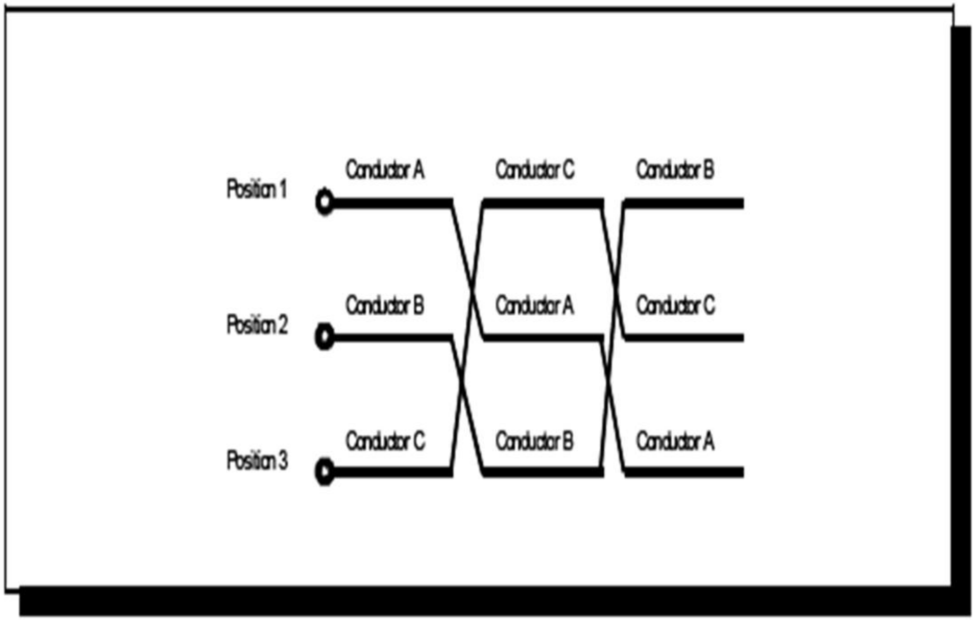
Light Load	Heavy Load
Generators may have to run under-excited; the generator absorbs VARs from the power system.	Generators may be run over-excited; supplying VARs to the system. Generators can normally supply more reactive power than they can absorb.

Power Transmission
Operating Considerations

Transposing Conductors

The amount of symmetry in the positioning of the conductors also affects line reactance.

- If phase conductors are symmetrically arranged, the series and shunt reactance of each phase are the same for each conductor
- In most cases, conductors are **not** symmetrically spaced
- The three phase conductors are frequently arranged in a horizontal line. Transposing Conductors of each phase even out reactance



Transposing Conductors

Power Transmission

Operating Considerations: RECAP

Power Transmission

- Components and Interconnections
- Electrical Model
- Operating Considerations
- Circuit Restoration
- High Voltage Direct Current Transmission

Power Transmission

Circuit Restoration

- Reclosing
- Synchronism Checks

Power Transmission

Circuit Restoration

Reclosing

Most transmission line faults are temporary. That is, whatever causes the fault usually burns off. Therefore, in most cases the line can be safely re-energized.

- ***Reclosing*** is the process of automatically re-energizing a line that opens due to a fault. Most transmission line circuit breakers automatically reclose after opening to clear a fault.

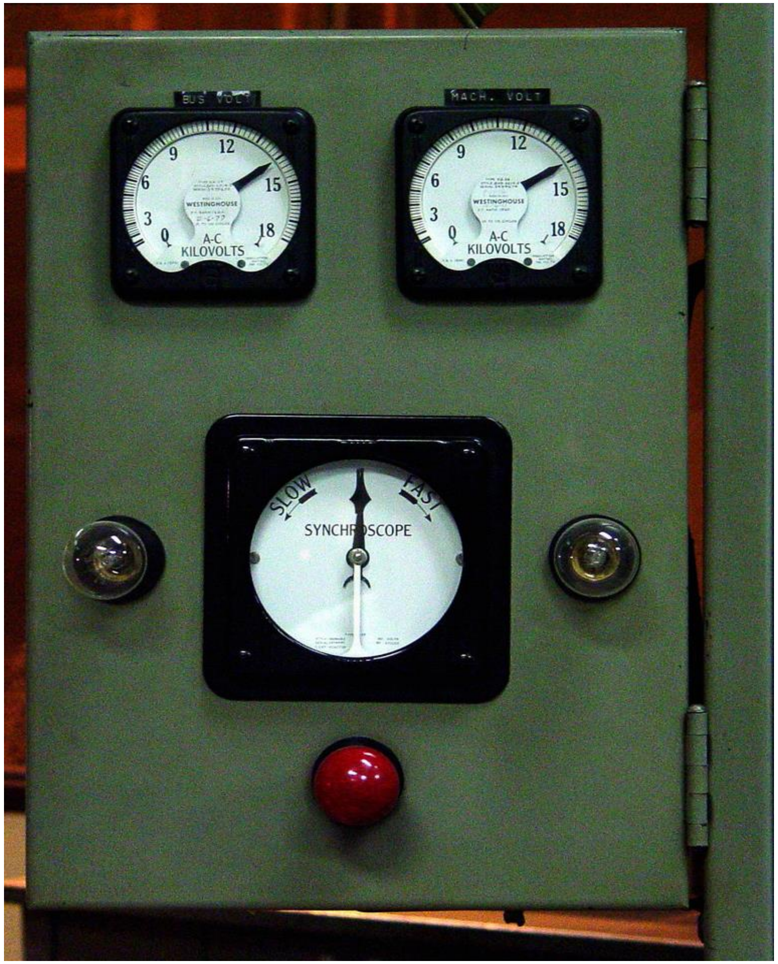
- To restore a line to service, most utilities first reclose the circuit breakers at one end of the line to energize the dead line up to the open breaker at the opposite end.

Power Transmission

Circuit Restoration

Synchronism Check (Sync Check)

- Determines whether the voltage phase angle or voltage magnitude across the breaker differs by more than a pre-specified amount.
- The two sides of the breaker may be operating at different power system frequencies.
- Voltages and generation levels on either side of the open point are adjusted so that frequencies exactly match and voltage phase angle and magnitude differences are within acceptable tolerances.



Synchronism Checks

Power Transmission

Circuit Restoration: RECAP

Power Transmission

- Components and Interconnections
- Electrical Model
- Operating Considerations
- Circuit Restoration
- High Voltage Direct Current Transmission

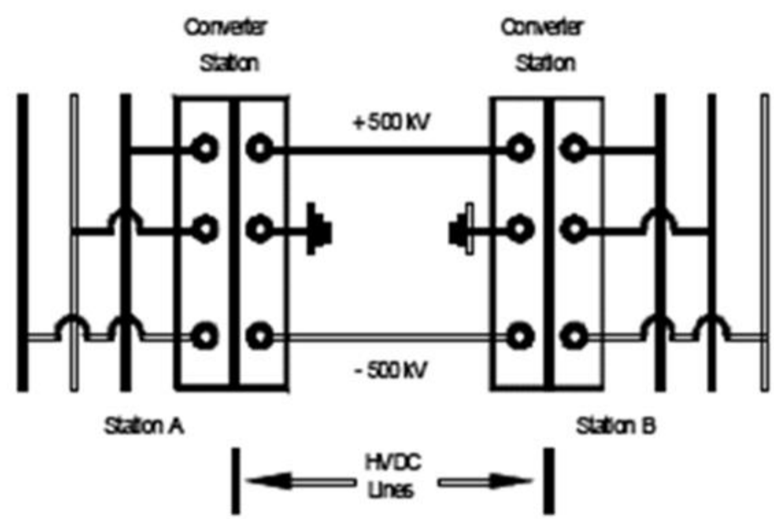
Power Transmission

High Voltage Direct Current (HVDC)

- Converter Stations
- DC Conductors

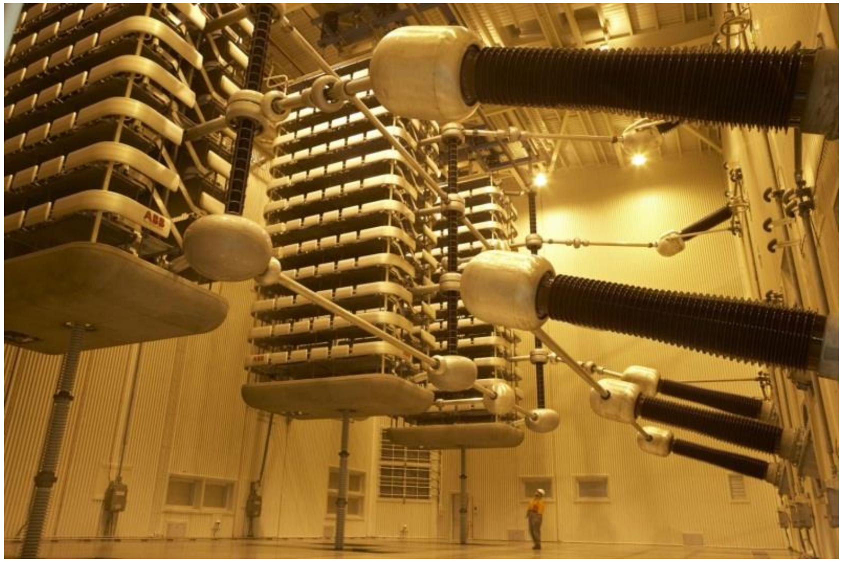
Power Transmission
High Voltage Direct Current (HVDC)

Some utilities use high-voltage direct current (HVDC) transmission lines, operating in the 500-kV to 1000-kV range. The voltages used here are line-to-line voltages and 1000 kV refers to ± 500 kV as shown in the diagram below.



Power Transmission
High Voltage Direct Current (HVDC)

HVDC Components



- Converter Stations
- DC Conductors
- DC Reactors and Filters
- Converter Transformers
- Advantages ad Disadvantages of HVDC Lines

Power Transmission
High Voltage Direct Current (HVDC)

Converter Stations

HVDC lines require a converter station, also called a ***converter bridge,*** at each end of the line.

Rectifier - The station at the line's sending end

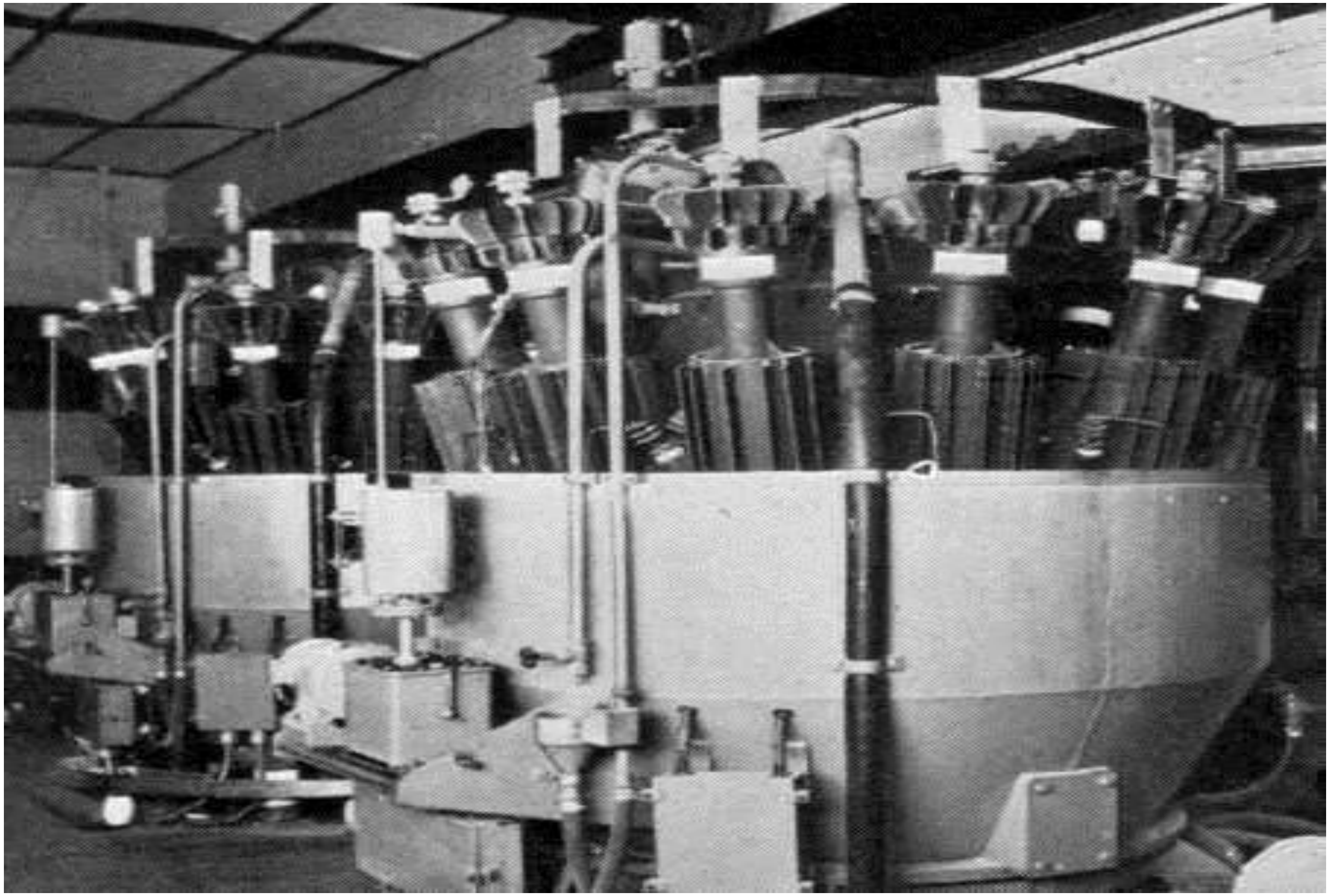
Inverter - The station at the line's receiving end

Power Transmission

High Voltage Direct Current (HVDC)

Converter Station Valves

- The valves perform the rectification or inversion
- Modern lines use electronic devices, called thyristors
- Like an electronic diode, valves conduct electricity in one direction only. However, unlike a diode, valves conduct electricity only when they receive a control signal
- By adjusting the timing of the control signals, the converter station at either end can be a rectifier or an inverter



Mercury-Arc Valves (MAV)

Thyristor Valve Stack

Power Transmission
High Voltage Direct Current (HVDC)

DC Conductors

HVDC lines have two conductors: one positive pole and one negative pole.

- One conductor operates at a positive voltage (with respect to ground) equal to one-half the line-to-line voltage
- The other conductor operates at a negative voltage (with respect to ground) equal to one-half the line-to-line voltage

Power Transmission
High Voltage Direct Current (HVDC)

DC Conductors

Under normal conditions, very little current flows through the ground. During abnormal conditions, the HVDC line can operate at reduced capacity.

- Only the positive or negative conductor is in service. The ground (either metallic or earth) serves to complete the circuit
- Operation using earth return must be limited since electrolysis in buried metallic objects, such as pipelines, can occur

Power Transmission
High Voltage Direct Current (HVDC)

DC Reactors, Filters and Transformers

- The converter station produces a DC waveform that is fairly choppy (has ripples). Reactors connected to the DC conductors at each end of the line smooth out this waveform. Installation of series reactors can limit fault current flow on the line.
- At each end of the DC line, a load-tap changing transformer connects the converter stations to the AC system.

Power Transmission

High Voltage Direct Current (HVDC)

AC Filters

- The converter station produces harmonic currents. Harmonic currents alternate at frequencies higher than 60 Hz (usually multiples of 60 Hz). Current harmonics can cause unnecessary heating on circuit elements since the equipment is not designed to operate at frequencies other than 60 Hz. Capacitors combined with reactors form filters to eliminate the harmonics.

Advantages/Disadvantages of HVDC

Electric power transmission using direct current has some advantages over AC power transmission, including:

- AC losses associated with series inductance and lines charging due to capacitance are eliminated. It is therefore possible to use overhead lines and underground cables for HVDC power transmission over long distances
- HVDC lines require only two power conductors rather than the three required for AC lines
- HVDC lines can tie together two power systems having dissimilar characteristics
- For example: HVDC lines can tie a power system operating at a frequency of 50 Hz to a system operating at 60 Hz

Advantages/Disadvantages of HVDC

- Rapid adjustments, called ***modulations,*** to power flow on DC lines can be made. During AC power system swings, the HVDC line loading can be modulated to dampen the swing and help maintain AC system stability.
- The primary disadvantage of HVDC transmission lines is the high cost of the terminal equipment at each end of the line and the high cost for associated maintenance.

Advantages/Disadvantages of HVDC

HVDC lines generally become more economical than AC lines if:

- The line length of overhead portions exceeds 400 miles
- The line length of underground cable portions exceeds 25 miles
- A special circumstance, such as a tie between two dissimilar power systems, exists. Utilities use back-to-back DC installations for this function. With this type of DC installation, the rectifier and the inverter are installed in the same location. Eight back-to-back installations currently exist between WECC and other regions.

Hot Line Work

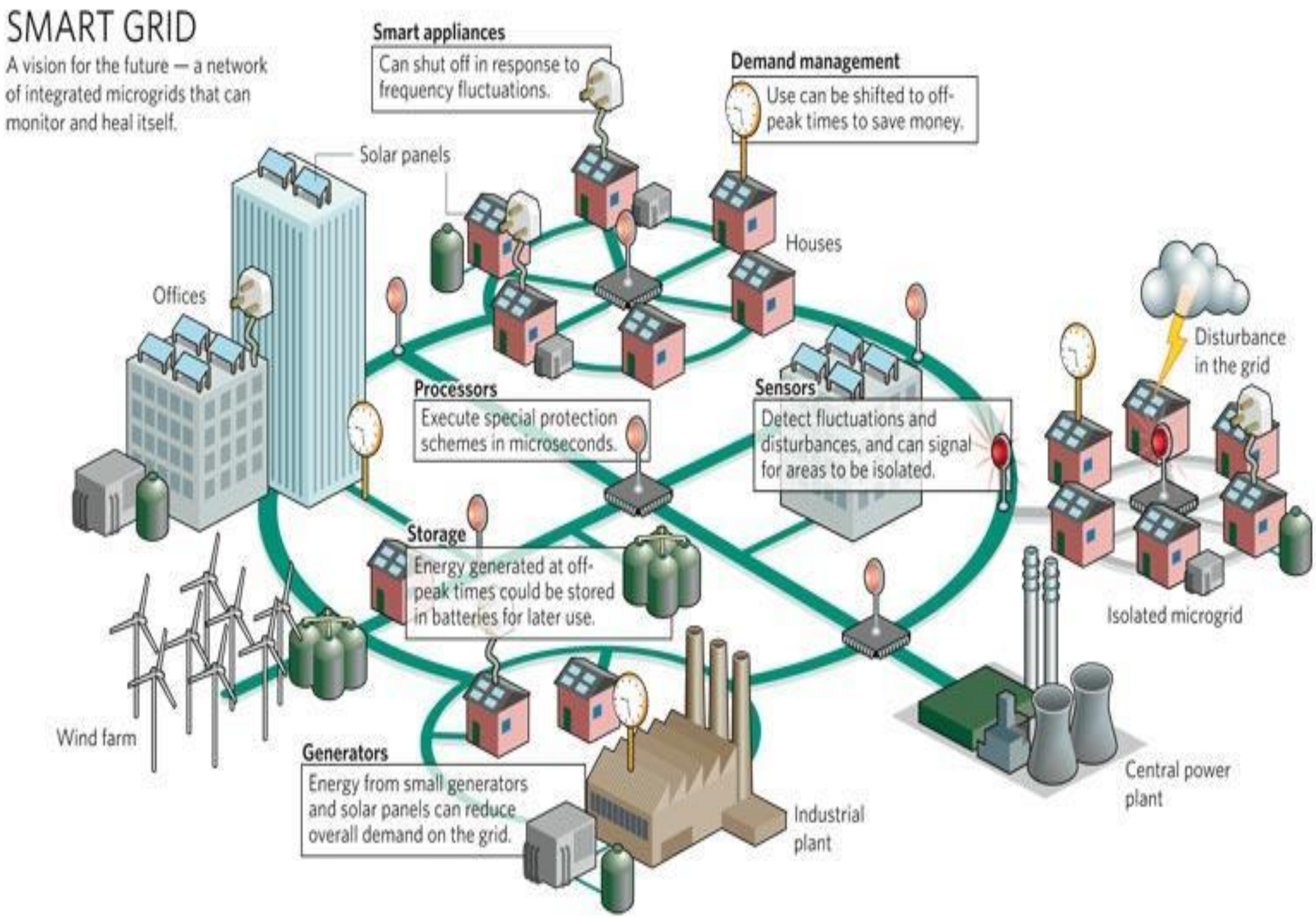
Power Transmission

High Voltage Direct Current Transmission: RECAP

Smart Grid Initiative

- The Transmission Grid: Pretty “smart” already
- The Distribution grid:
  - Not so much

Smart Grid Initiative



Smart Grid Initiative

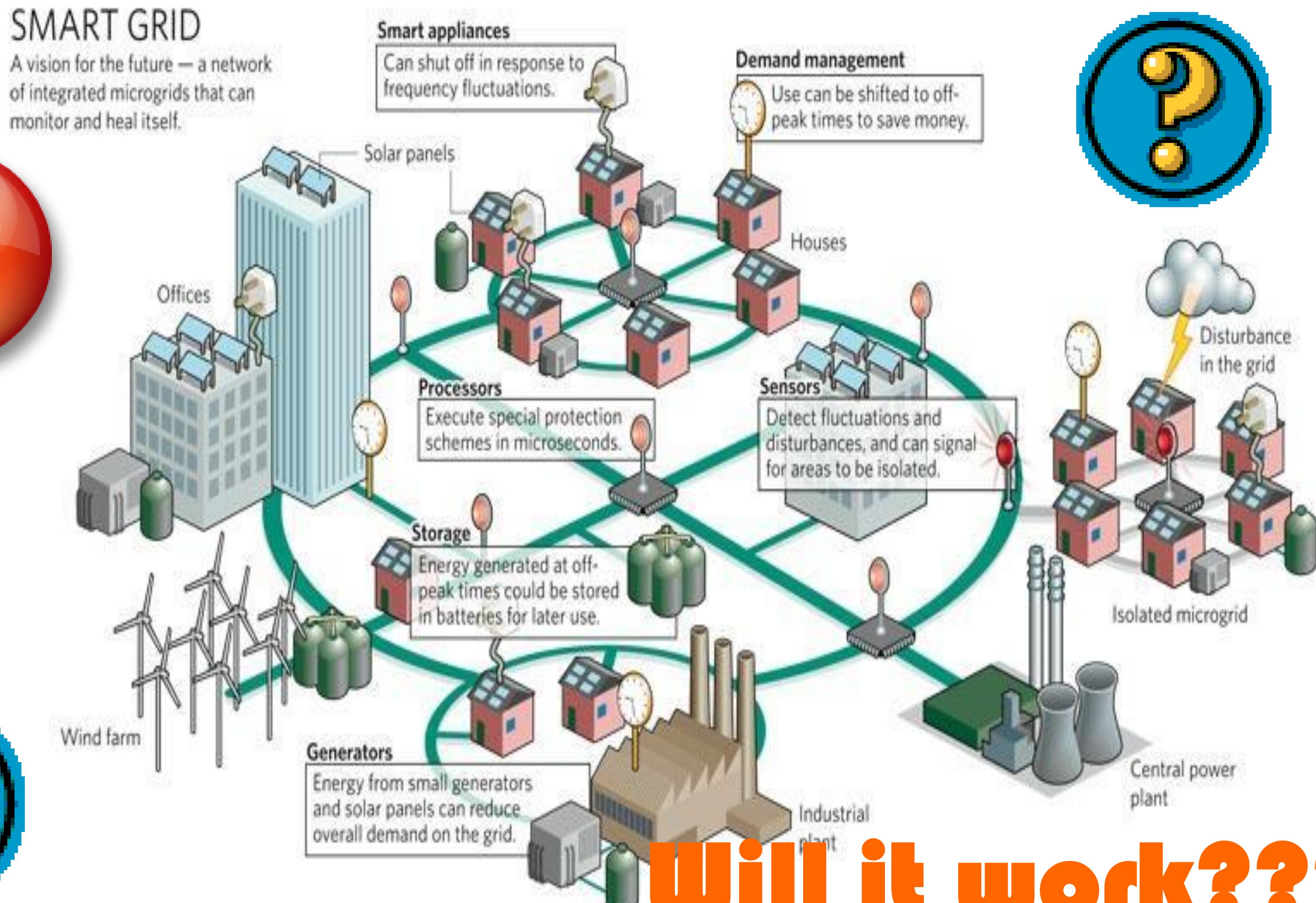
<u>Links consumers to the system</u>

- Is the power on?
  - There might be an outage in my neighborhood?
- Real-time consumption
  - What is my usage/cost profile?

Smart Grid Initiative

- Cooperative Demand Management
  - Turn off my AC when the system needs it. (Cool Keeper -- Saver Switch)
  - Back-feed the system from my solar panel or electric car.
  - ...& pay me $$ when you do it!

Smart Grid Initiative



Will it work???

What We Covered

- Components and Interconnections
- Electrical Model
- Operating Considerations
- Circuit Restoration
- High Voltage Direct Current Transmission
- Extra: Smart Grid