Power System Elements

Transmission Facilities

PJM State & Member Training Dept.

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Objectives

- Given a typical Transmission line and/or cable, describe the equipment design and components that determine its operational limits
- Describe the operation of line sectionalizing devices and their use
- Given two types of substation configurations, determine which is the most reliable in supporting the BES
- Describe the operation of circuit breakers and their use at substations
- Describe the operation of Circuit Switchers and their use at substations
- Describe the operation of disconnects and their use at substations

Objectives

- Given a BES transformer, describe its operational and design criteria as part of the BES
- Given a Phase Angle Regulator (PAR), describe its basic principle of operation
- Given a BES Shunt Capacitor, discuss its components and its use on the BES
- Given a BES Shunt Reactor, discuss its components and its use on the BES
- Given a BES Static Var Compensator (SVC), discuss its components and its use on the BES
- Given a one-line diagram, identify the equipment located at a Substation or Switchyard

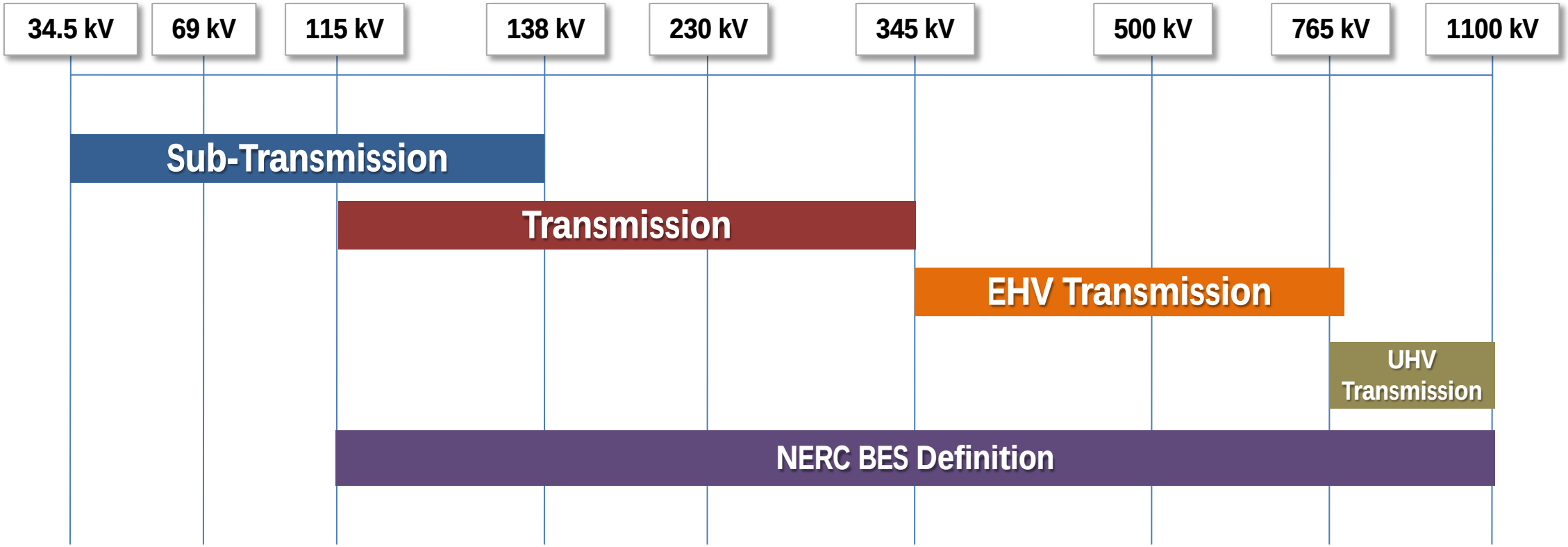
BES Transmission Line Equipment

- **What is considered Transmission?**
  - NERC/FERC definition:
    - Bulk Electric System (BES) – Interconnected Electrical facilities operated at 100 kV and above
      - § Radial Transmission is generally not included
  - PJM Transmission voltage levels

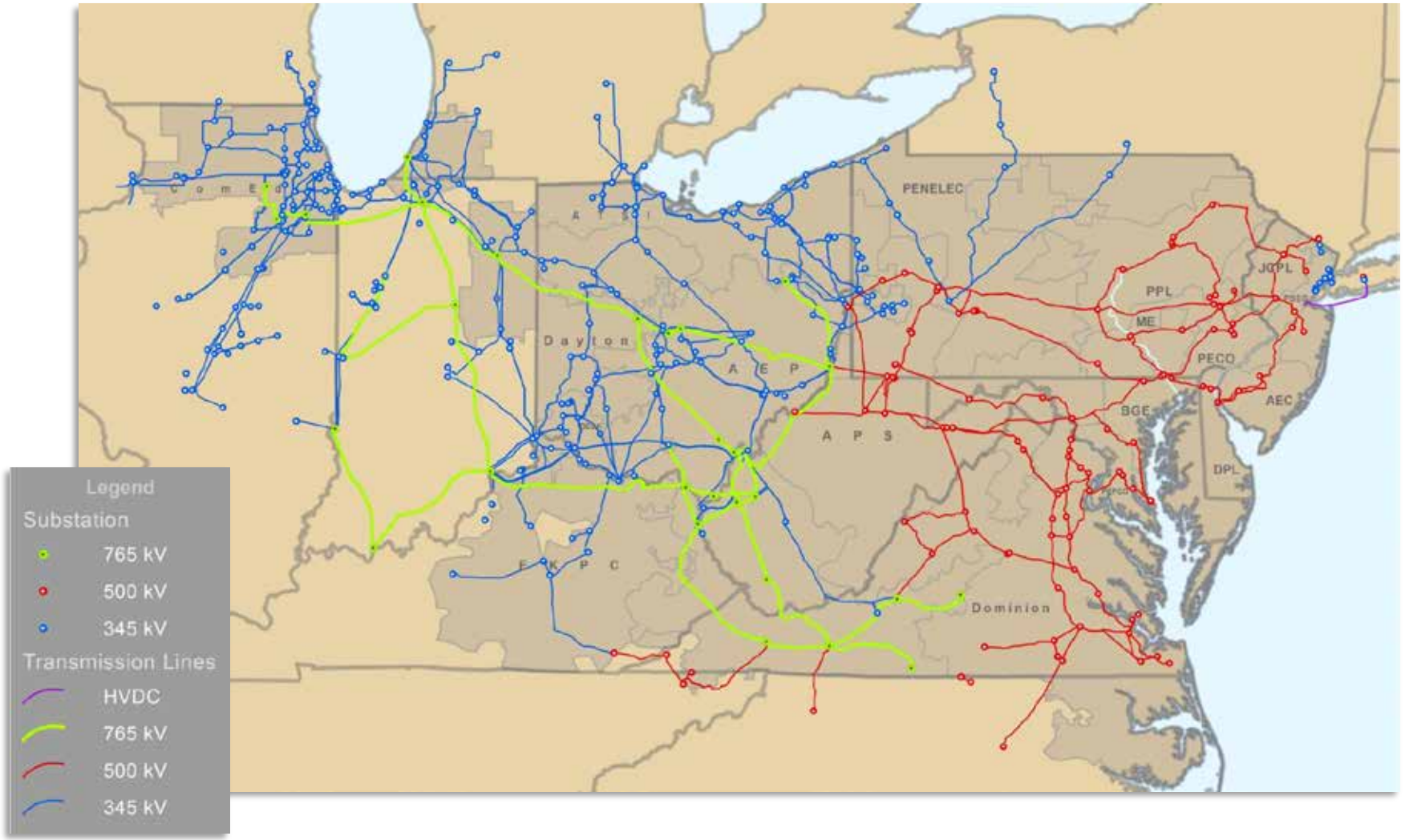
765 kV	500 kV	345 kV
230 kV	138 kV	115 kV

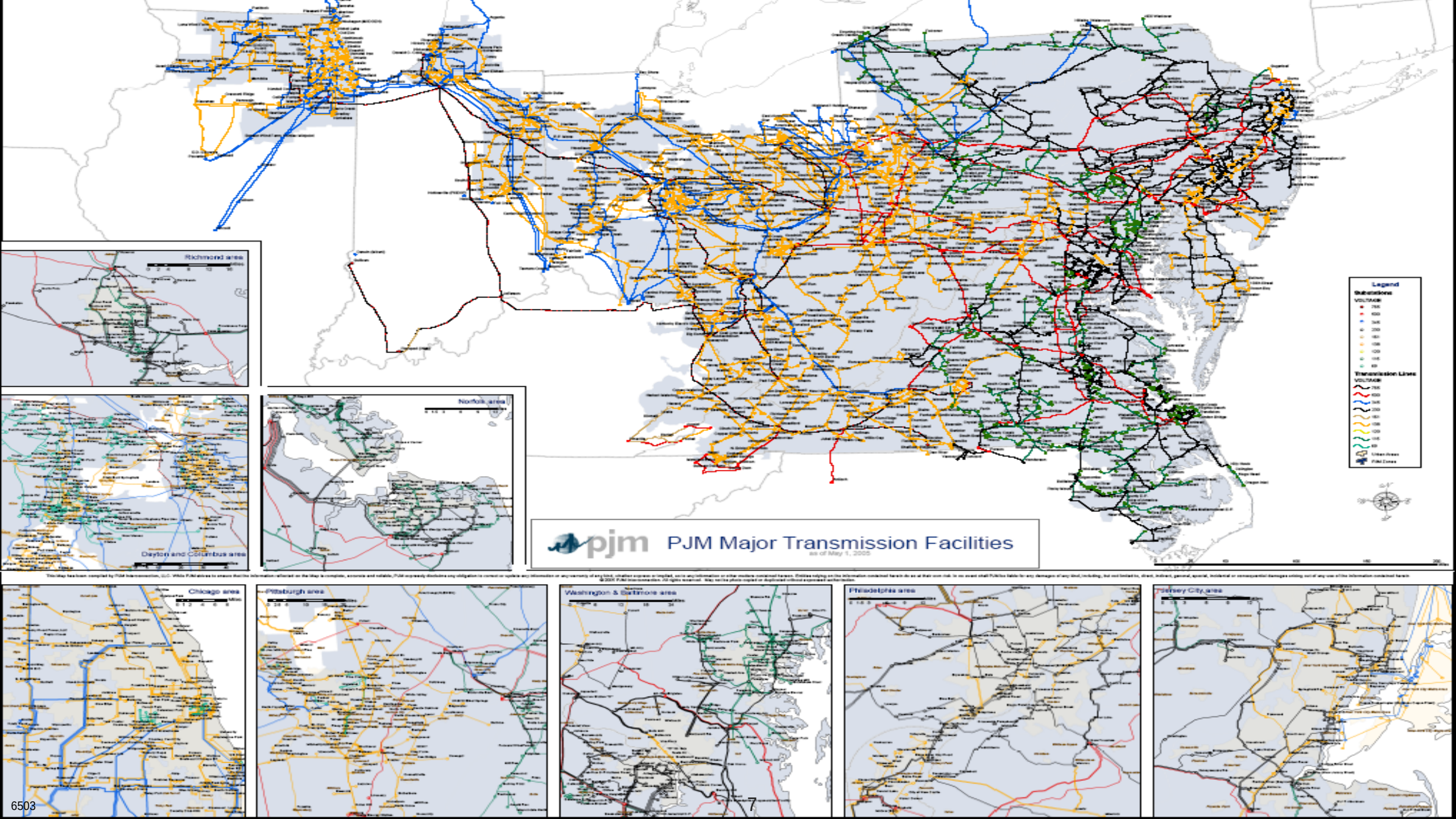
BES Transmission Line Equipment

Company Designations May Vary



PJM Transmission Backbone




Richmond area
Dayton and Columbus area
Norfolk area
Chicago area
Pittsburgh area
Washington & Baltimore area
Philadelphia area
Jersey City area
Legend
Substations
Transmission Lines
pjm PJM Major Transmission Facilities

Bulk Electric System (BES)

The Bulk Electric System (BES) within the Reliability First footprint is defined as all…

- Individual generation resources larger than 20 MVA or a generation plant with aggregate capacity greater than 75 MVA that is connected via a step-up transformer(s) to facilities operated at voltages 100 kV or higher
- Lines operated at voltages 100 kV or higher
- Transformers (other than generator step-up) with both primary and secondary windings of 100 kV or higher
- Associated auxiliary and protection and control system equipment that could automatically trip a BES facility, independent of the protection and control equipment's voltage level

BES Transmission Lines

Transmission Components

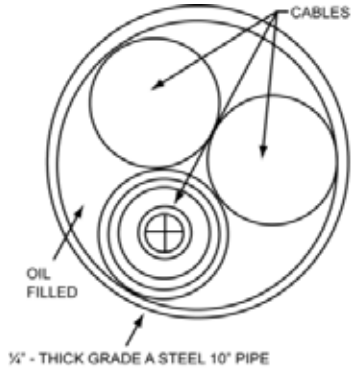
- Conductors – or the “wires” up in the air
  - **Copper**
    - Older vintage lines
    - Great conductor material, but is now very costly
    - Not particularly rigid
  - **All-Aluminum (AAC) and All-Aluminum Alloy (AAAC)**
    - Second-best conductor types
    - Not the most rigid or strong, but light weight
    - OK for use in areas with little or no snow/ice/sleet accumulations

BES Transmission Cables

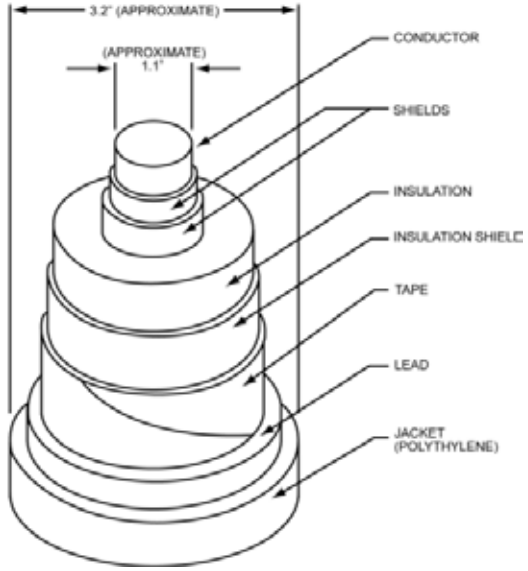
- **Underground/Underwater Cable**
  - Virtually immune to environmental impacts (weather, trees)
  - Significantly more costly to install (2.5 to 15 X or more)
    - Cable itself is more expensive
    - Requires special equipment to install/maintain
  - Oil-filled cable systems can present operating challenges, especially during a system restoration
  - Special transition “Terminators” required between overhead and underground sections
  - If a fault does occur on the Cable, repair times are significantly longer than for overhead lines
  - Capacitive charging for cables is much higher than for an overhead line (Greater source of VARS)

BES Transmission Cables

Representative Transmission Cable Schematics



Cross-Sectional View of 345kV Pipe-Type Cable



138 kV Solid Dielectric Cable



BES Transmission Cables

Examples of 138 kV Cable Terminations





BES Transmission Cables

DC Cables

- AC and DC systems can be “linked” by the use of Converter stations. Converter stations convert AC power to DC power (and vice versa) via the use of high power, high voltage semiconductor valves
  - Semiconductor valves are devices which (simply put) allow current to flow in only one direction, and prevent current from flowing in the opposite direction
  - Computer control over the valves allows the amount of power flowing on a DC circuit to be precisely controlled
- The Eastern Interconnection, Western Interconnection, and ERCOT are linked together via DC ties
- There are also several DC ties between New York/New England and Canada

BES Transmission Cables

DC Cables *(con't.)*

- Currently this technology is in use at the Neptune Regional Transmission System, and the Hudson Transmission Project. (Although other projects are in the planning stages)
- The Neptune RTS is a merchant transmission system interconnecting two regional control areas, PJM and NYISO
- Power transfer levels and changes to that level are "set" in terms of magnitude and time by the Neptune RTS operator, as directed by the PJM dispatcher
- The Neptune RTS is a monopolar, 500 kV HVDC interconnection consisting of 2 converter stations

BES Transmission Cables

DC Cables *(con't.)*

- The western terminus, the Sayreville Converter Station, interconnects PJM at the Raritan River Substation, at 230 kV AC, in Sayreville, NJ
- FE owns, maintains and operates the Raritan River Substation
- The eastern terminus, the Duffy Ave. Converter Station, interconnects NYISO at the Newbridge Road Substation, at 345 kV AC, in Levittown, NY
- LIPA owns, maintains and operates the Newbridge Road substation
- Neptune RTS owns, maintains, and operates the NRTS equipment
- The Neptune RTS master control is at Duffy Ave Converter Station. The backup master control location is at the Sayreville Converter Station

BES Transmission Cables

Neptune RTS



BES Transmission Cables

- The Neptune RTS has a nameplate Power Transfer Capability of 600 MW
- Its continuous Power Transfer Capability is 660 MW, and its minimum Power flow is 60 MW
- There is a 4-hour, 750 MW Emergency Power Transfer Rating (as measured at Newbridge Road) for those instances when the NYISO directs LIPA to provide Emergency Power to PJM

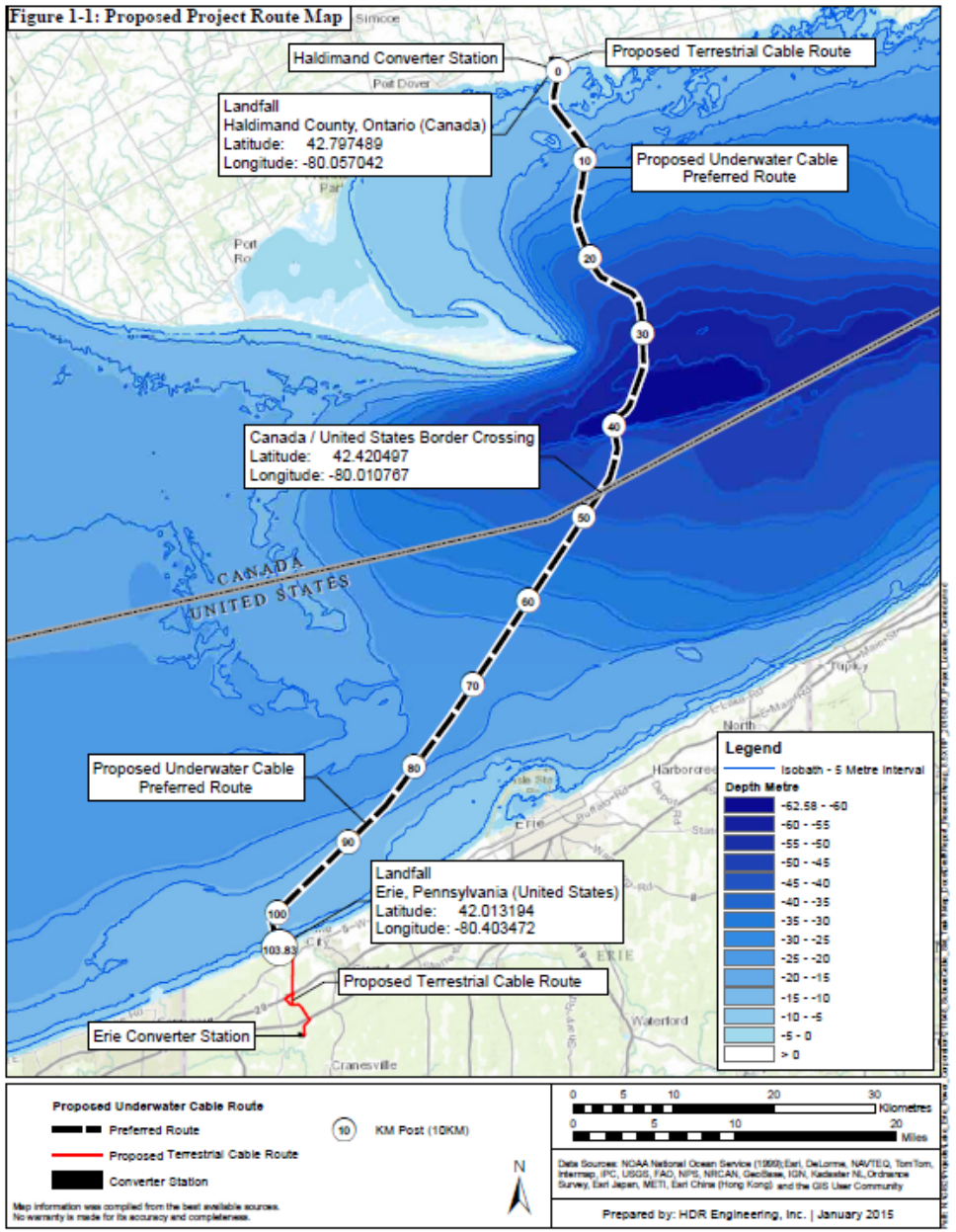
BES Transmission Cables

- **Hudson Transmission Project**
  - Hudson Transmission Project, from PSEG's Bergen Substation in New Jersey to ComEd's West 49th Street Station in Manhattan
  - Up to 660 MWs of transfer capability
  - In service June 2013

BES Transmission Cables

- **Lake Erie Connector**

  - Future use of HVDC in PJM:
    - Lake Erie Connector
      - 1000 MW, 320kV HVDC tie between PJM and IESO (Independent Electric System Operator in Ontario)



BES Transmission Line Structures

- **Transmission Components**
  - **Insulators** – keep the conductors electrically removed from the towers/poles to prevent the line from becoming grounded
    - Porcelain Bells –
      - § Oldest type
      - § Ceramic Composites



BES Transmission Line Structures

- **Epoxy Insulators**
  - Less weight, lower cost
  - Less likely to become “Contaminated”
  - Care must be taken to ensure that insulators remain free of contaminants, to prevent the conductor from “tracking” or flashing over to ground
    - Salt
    - Cement dust
    - Ash



BES Transmission Line Structures

- It may be possible to identify the voltage level of the line by counting the number of insulators on the string:

Voltage of Conductor	Number of “Bells” on Insulator
69 kV	4-5
138 kV	7
230 kV	12-16
500 kV	24-28

- Some lines may be built and insulated for a higher voltage level than that at which they are currently operated

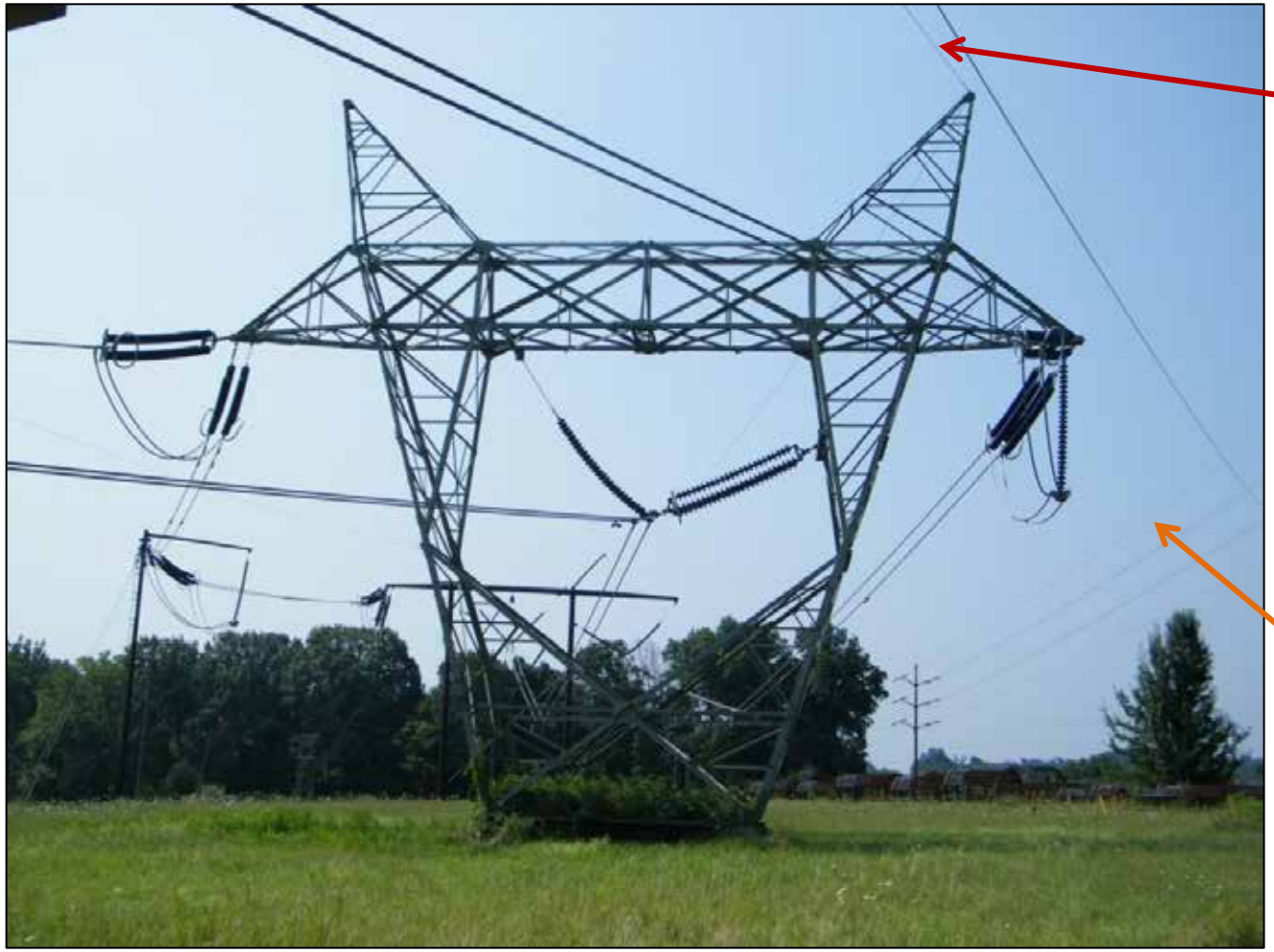
BES Transmission Line Structures

Transmission Components

- **Shield (Static) Wires**
  - Designed to “shield” the energized conductors from lighting strikes
    - These are the highest wires run on the towers
  - If lightning strikes the shield wire, it creates 2 “waves” of current which travel down the line in both directions
    (at a speed of ~ 1000 feet / microsecond)
  - This current is passed to the towers, and down through the ground path for the tower, away from the conductors

BES Transmission Line Structures

Examples of Static Wires on Towers and Poles



500 kV Static Wire

138 kV Static Wire

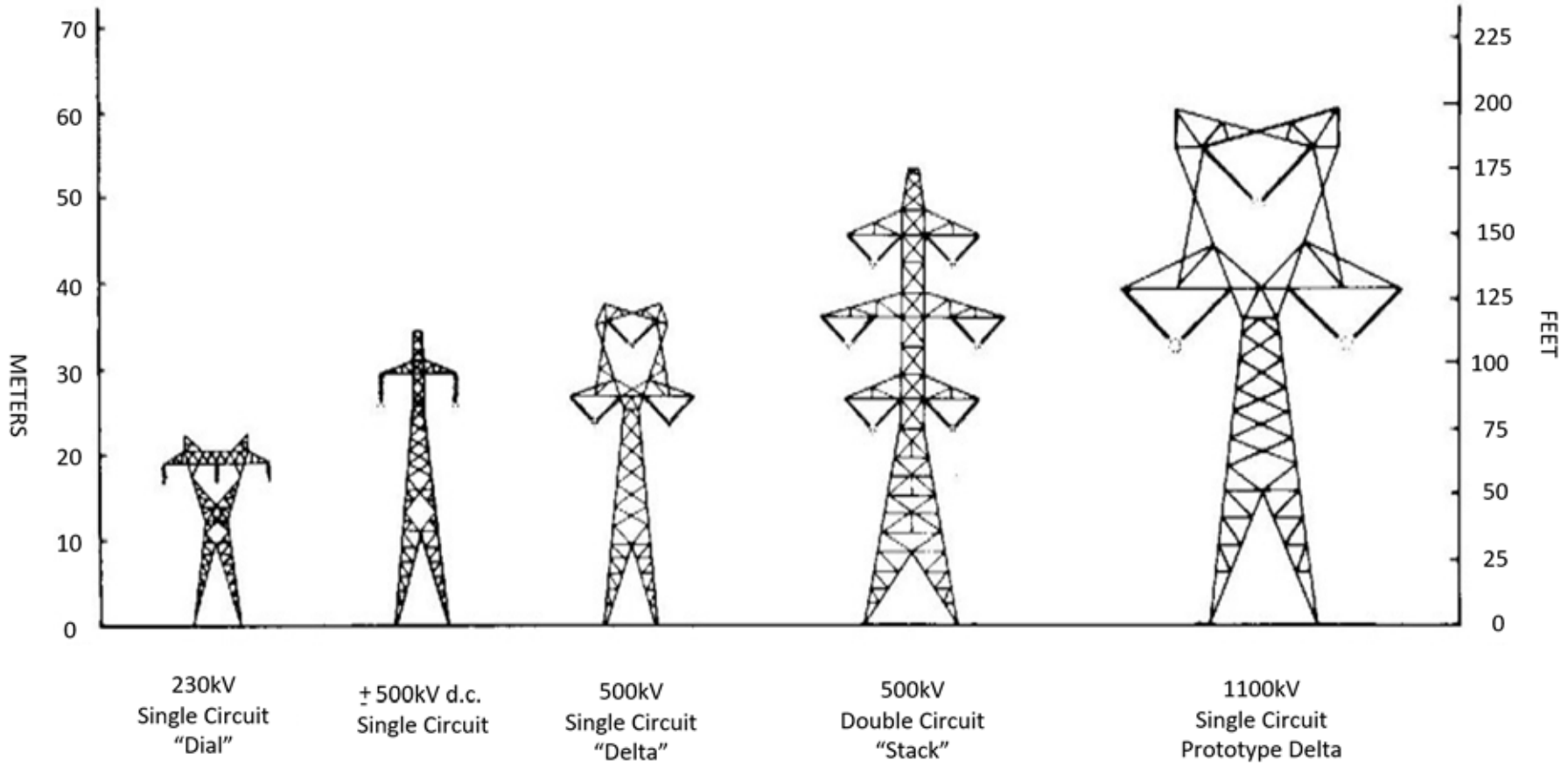
BES Transmission Line Structures

Transmission Components

- **Support Structures**
  - Keep the wires/cables in the air
  - Must be designed to be able to support the weight of the conductors, insulators, shield wires, and other accessories
    - Also must include the weight of the maximum ice loading expected for each component
  - Can be towers, poles, H-structures, etc.

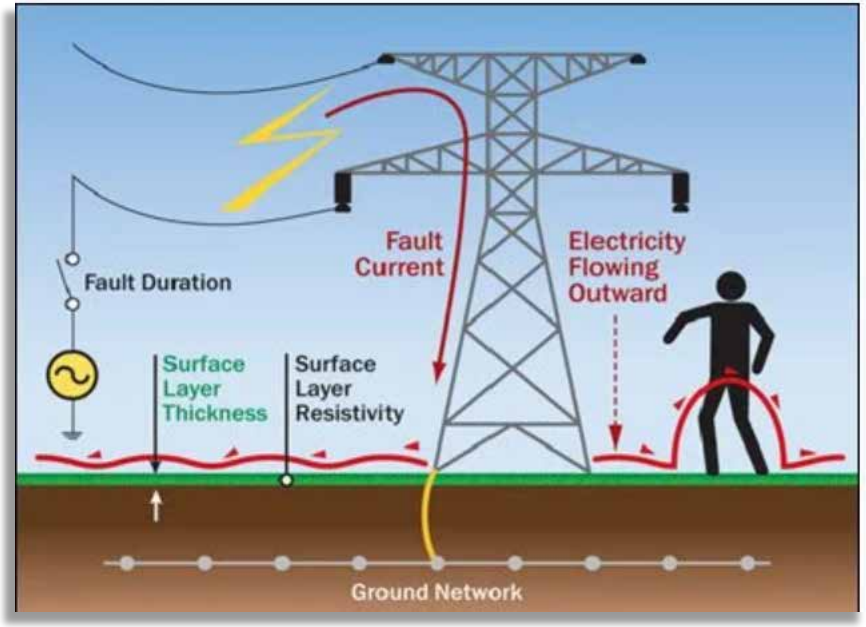
BES Transmission Line Structures

Generic Transmission Tower Designs



BES Transmission Line Structures

- Support structures must be securely grounded
  - To ensure the conductors are properly isolated from a ground path through the tower/pole
  - To ensure that any lightning strikes to the tower or the static wire can be safely dissipated to ground
    - An increase in line trippings caused by lightning strikes has been seen as a result of deteriorated (or stolen) tower grounds



- Support structures must be sized to ensure that the conductors have adequate space between them to prevent a flash-over between phases as the conductors move in the wind

BES Transmission Line Structures

Spacing Required Between Phases at Various Voltage Levels

Voltage (kV)	Conductors per Phase	Spacing Between Phases (feet)
230	1	18
345	1 or2	28
500	1, 2, or 3	38
765	3 or 4	48

BES Transmission Line Right Of Way (ROW)

- Generally, the right-of way is determined by the path of least cost to construct the line, considering;
  - Cost of real estate
  - Population density
  - Bodies of water
  - Environmental concerns
  - Maintenance accessibility
- This is a timely issue with the construction of new transmission lines
  - Delay in the Susquehanna-Roseland Project
  - Several state/federal/local authorities with overlapping jurisdiction can each deny a project the ability to move forward

BES Transmission Line Right Of Way (ROW)

- Events like the 2003 Northeast Blackout have provoked FERC/NERC to rigorously enforce the Reliability Standards around Vegetation Management in transmission Rights-of-Way

  NERC Standard FAC-003 states Utilities must maintain Minimum Vegetation Clearance Distances (MVCDs)

  - Transmission Owner shall manage vegetation to prevent encroachments into the MVCD of its applicable line(s)
  - Each Transmission Owner shall perform a Vegetation Inspection of 100% of its applicable transmission lines (measured in units of choice - circuit, pole line, line miles or kilometers, etc.) at least once per calendar year

BES Transmission Line Right Of Way (ROW)

FAC-003 — TABLE 2 — Minimum Vegetation Clearance Distances (MVCD)[7]
For **Alternating Current** Voltages (feet)

(AC) Nominal System Voltage (KV)	(AC) Maximum System Voltage (kV)[8]	MVCD (feet) Over sea level up to 500 ft	MVCD (feet) Over 500 ft up to 1000 ft	MVCD feet Over 1000 ft up to 2000 ft	MVCD feet Over 2000 ft up to 3000 ft	MVCD feet Over 3000 ft up to 4000 ft	MVCD feet Over 4000 ft up to 5000 ft	MVCD feet Over 5000 ft up to 6000 ft	MVCD feet Over 6000 ft up to 7000 ft	MVCD feet Over 7000 ft up to 8000 ft	MVCD feet Over 8000 ft up to 9000 ft	MVCD feet Over 9000 ft up to 10000 ft	MVCD feet Over 10000 ft up to 11000 ft
765	800	8.2ft	8.33ft	8.61ft	8.89ft	9.17ft	9.45ft	9.73ft	10.01ft	10.29ft	10.57ft	10.85ft	11.13ft
500	550	5.15ft	5.25ft	5.45ft	5.66ft	5.86ft	6.07ft	6.28ft	6.49ft	6.7ft	6.92ft	7.13ft	7.35ft
345	362	3.19ft	3.26ft	3.39ft	3.53ft	3.67ft	3.82ft	3.97ft	4.12ft	4.27ft	4.43ft	4.58ft	4.74ft
287	302	3.88ft	3.96ft	4.12ft	4.29ft	4.45ft	4.62ft	4.79ft	4.97ft	5.14ft	5.32ft	5.50ft	5.68ft
230	242	3.03ft	3.09ft	3.22ft	3.36ft	3.49ft	3.63ft	3.78ft	3.92ft	4.07ft	4.22ft	4.37ft	4.53ft
161*	169	2.05ft	2.09ft	2.19ft	2.28ft	2.38ft	2.48ft	2.58ft	2.69ft	2.8ft	2.91ft	3.03ft	3.14ft
138*	145	1.74ft	1.78ft	1.86ft	1.94ft	2.03ft	2.12ft	2.21ft	2.3ft	2.4ft	2.49ft	2.59ft	2.7ft
115*	121	1.44ft	1.47ft	1.54ft	1.61ft	1.68ft	1.75ft	1.83ft	1.91ft	1.99ft	2.07ft	2.16ft	2.25ft
88*	100	1.18ft	1.21ft	1.26ft	1.32ft	1.38ft	1.44ft	1.5ft	1.57ft	1.64ft	1.71ft	1.78ft	1.86ft
69*	72	0.84ft	0.86ft	0.90ft	0.94ft	0.99ft	1.03ft	1.08ft	1.13ft	1.18ft	1.23ft	1.28ft	1.34ft

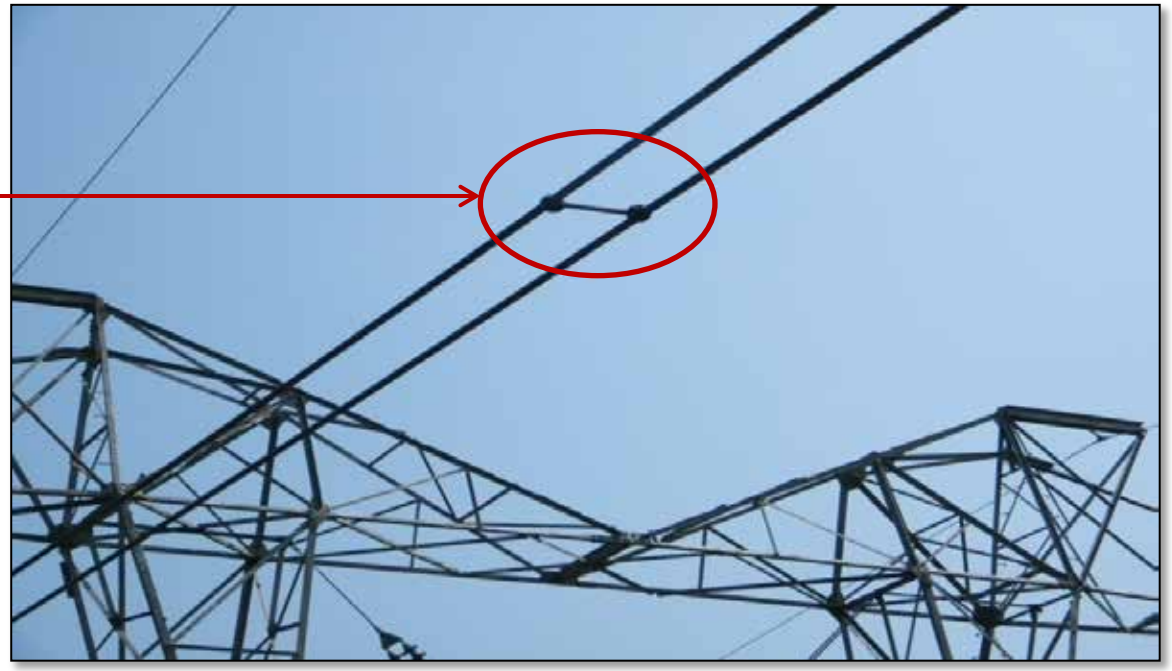
* Such lines are applicable to this standard only if PC has determined such per FAC-014 (refer to the Applicability Section above)

BES Transmission Line Equipment

Transmission Components

- **Line Spacers**
  - Used to prevent the conductors in a 2 or 3-conductor per phase line from slapping together in the wind

500 kV Line Spacer

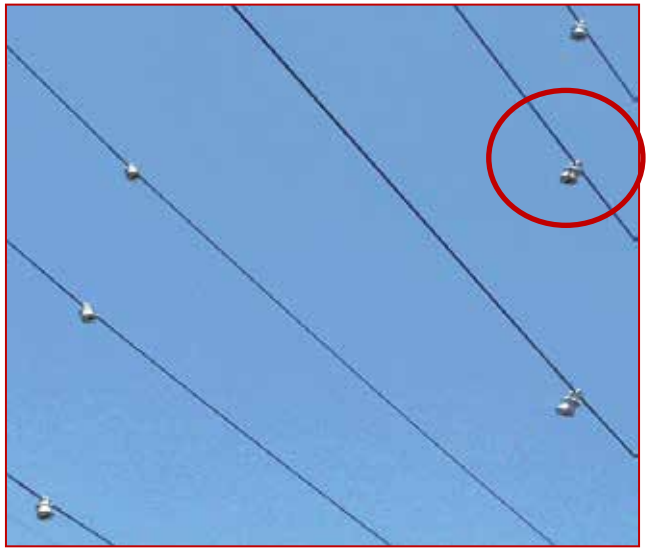


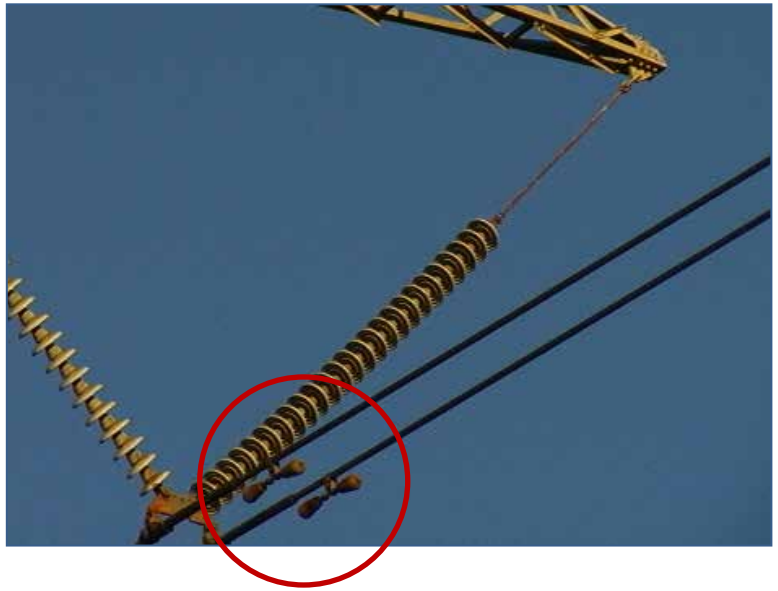
BES Transmission Line Equipment

Transmission Components

Vibration Dampeners (Bottles)

– Weights placed on the conductors to protect against vibration effects that could cause phase-to-phase (or Phase-to-ground) faults if allowed to go unchecked





BES Transmission Line Equipment

Types of Conductor Vibration

1. Aeolian Vibration

- Caused by the low pressure area formed on the leeward (downwind) side of a cylindrical object in the wind. (Von Karman vortex shedding)
- Same phenomenon that makes the rigging in ships whistle, and flag poles and street light poles vibrate
- Can be reduced by installing vibration dampeners, or reducing the tension on the conductor
- Has resulted in failures of conductors, especially near suspension points where the movement would be greatest

BES Transmission Line Equipment

Types of Conductor Vibration *(con't)*

2. Sub Conductor Vibration

- Only seen on bundled conductor installations, and generally in wide-open areas with strong, sustained winds
- The conductor that is most windward creates a "wake" effect for the conductors alee, causing shear flow in addition to the wind effects
- This can potentially cause the leeward conductor to begin oscillating back and forth. This oscillation is transmitted to the other conductors because of the spacers
- This can lead to failure of the spacers as well as the conductor
- Vibration dampeners are only partially successful in eliminating this phenomenon. New dampers are being developed

BES Transmission Line Equipment

Types of Conductor Vibration *(con't)*

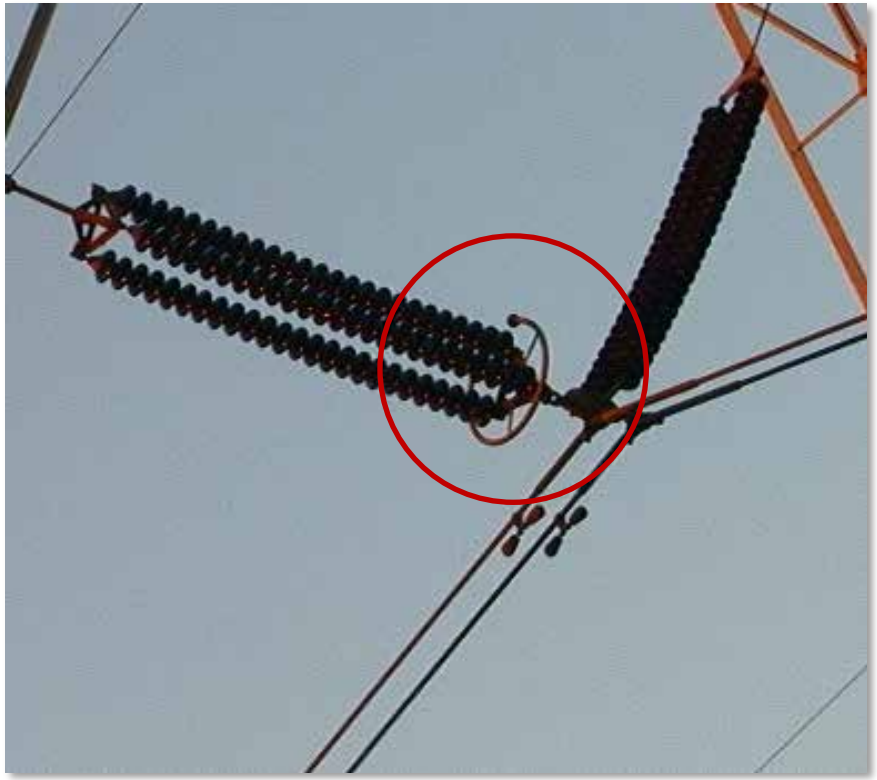
3. Corona Vibration

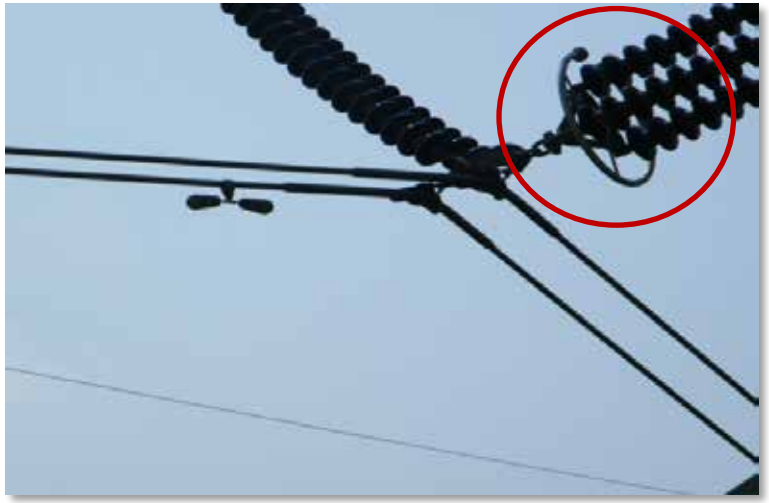
- During wet weather, rain drops cling to the underside of conductors, and the electrostatic field builds up and eventually forces the drops off
- This small motive force imparts a small, low-frequency vibration to the conductor that can build up to a noticeable effect mid-span (Between the towers)
- This is not generally a problem for current transmission systems, but has the potential to become an issue as UHV systems are developed and placed in service
- Vibration dampeners are ineffective in preventing or mitigating this phenomenon

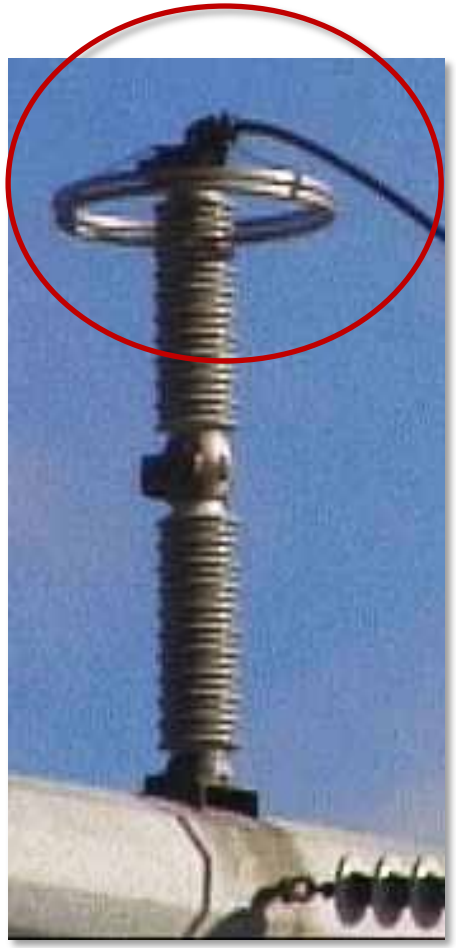
BES Transmission Line Equipment

Transmission Components

Corona Rings







BES Transmission Line Equipment

Transmission Components - Corona Rings *(con't)*

- At times, the surface potential of a conductor is so high that it actually exceeds the dielectric strength of the air around it, and it causes the air to ionize
- When this happens, it creates an audible hissing sound, radio-frequency interference, and localized glow points and ionized "streamers" that can be seen in the dark
- These effects are most notable around rough or sharp spots on the conductors or the structures
- Using corona rings at locations where rough or sharp spots occur helps to eliminate this problem

BES Transmission Line Equipment

Transmission Components

Transmission Line Switches

- Most higher-voltage (230 kV and above) transmission lines are one continuous circuit from switchyard to switchyard
- But sub-transmission systems with several substations tapped off the line are often equipped with switches.
  - This allows the line to be sectionalized, facilitating routine maintenance and/or the ability to find and isolate faults

BES Transmission Line Equipment

Transmission Line Switches *(con't)*

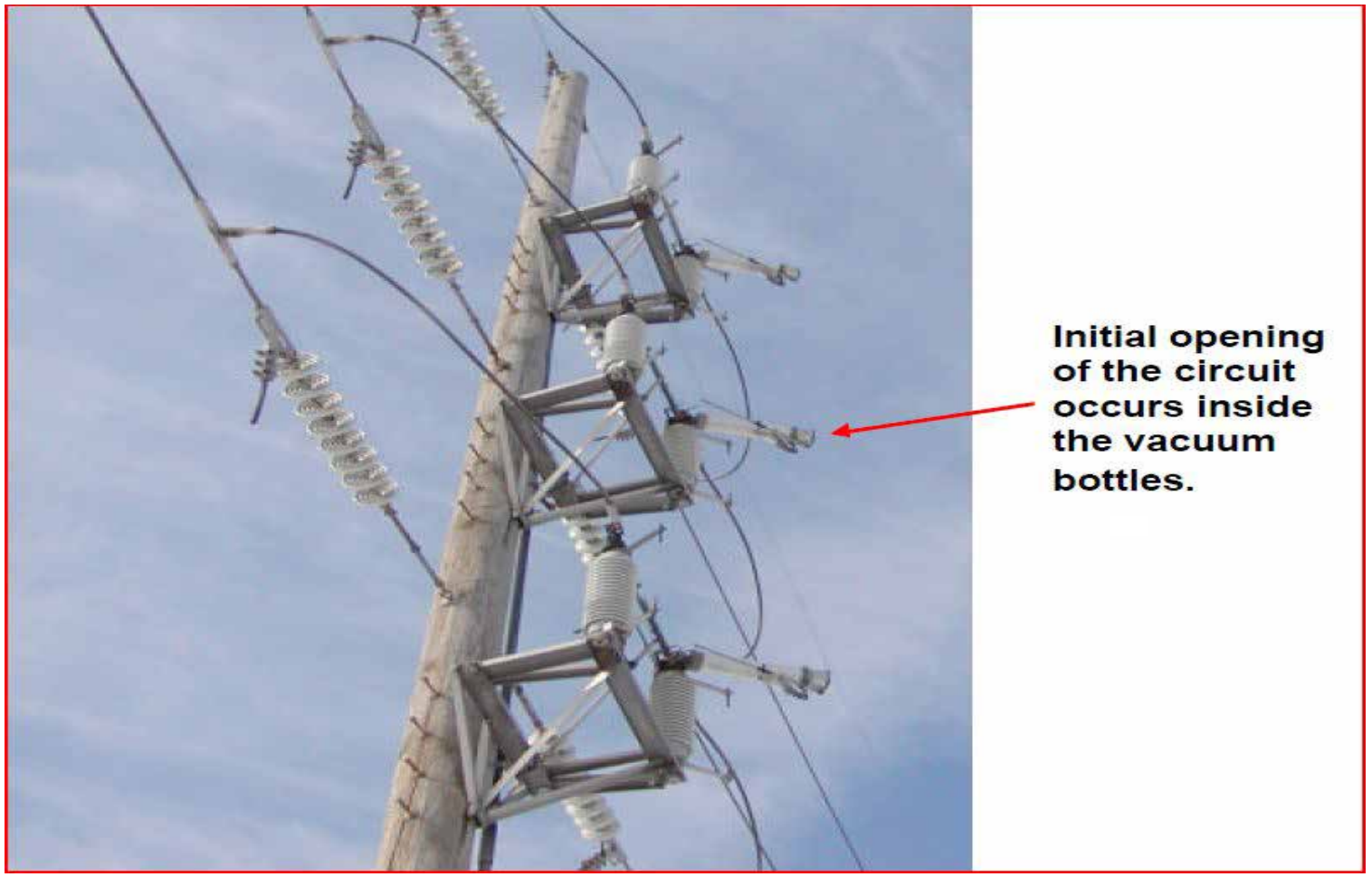
- These switches are of different types, and different abilities. Operators should know the capabilities of the switches that they direct field crew to operate
- The exact naming of the switch types also varies from company to company, but the general switch types are;
  - **Air Brake Switches (ABS or AB)**
    - These switches use a thin metal "whip" to break the arc created when their blades are opened. The whip breaks the electrical connection and the arc is extinguished in the air
    - These switches are commonly used to energize and de-energize power transformers and de-energize relatively short spans of conductor

BES Transmission Line Equipment

- **Parallel Break Air Brake (PBAB)**
  - These switches use Vacuum bottles to extinguish the arc when making/breaking parallel circuits between energized sources
  - These switches should NOT be used to energize or de-energize line sections or transformers
- **Line Sectionalizing Air Brake (LSAB)**
  - These switches use a combination of vacuum or gas-filled bottles and whips to perform the functions of both and ABS and a PBAB

BES Transmission Line Equipment

LSAB Switch



BES Transmission Line Equipment

- All these switches are gang-operated, meaning that all 3 phases are linked together on one operating mechanism
- The mechanism can be either hand-operated or motor operated;



-VS -



BES Transmission Line Equipment

Circuit Switchers

- These switches are used both as line sectionalizing devices, and within substations to de-energize equipment
- They use a combination of gas bottles (generally SF-6) and switches to perform the same functions as a LSAB, but on higher voltage level Equipment, where the arcs would be greater



Environmental Effects on Transmission

- **Wildlife**
  - Animals can build nests on Transmission and sub-station components
  - The nests themselves can create an inadvertent ground path, or interfere with the operation of devices



Environmental Effects on Transmission

Mount Storm Ice Storm of 2003

(courtesy of Virginia Power)





Environmental Effects on Transmission

Transmission devices may become (literally) frozen in place and may not operate when called upon





Environmental Effects on Transmission

Heat *(con't)*

- This causes the wire to heat up
  - Like any metal that is heated, the wire begins to expand, and lengthen This is referred to as ***line sag***
    - Sagging lines have reduced clearance between themselves and objects below (like trees or structures)
    - This can lead to flash-over, or direct contact, resulting in line trippings *(and NERC fines)*
  - Once the loading on the line decreases, or the temperature decreases, and the heat in the conductor is dissipated, it contracts again, raising the conductor
    - But it will never return fully to it's pre-sag state

Environmental Effects on Transmission

Heat *(con't)*

- This slow heating and cooling process is know as ***annealing***
- Annealing is a great concern for transmission lines, because it causes a reduction in the strength of the conductor
- Annealing is a cumulative effect - it only gets worse with time
- The severity of the annealing effects are based on several factors
  - The type of metal
  - The amount and type of alloys used
  - The amount of "cooling" times between periods of heating and sag

Environmental Effects on Transmission

Heat *(con't)*

- As temperatures increase in the summer, lines are less able to cool themselves efficiently, and can carry less current (MW) (Summer vs. Winter ratings)
- PJM has several "rating sets" that limit the amount of MW's conductors can carry according to the ambient temperature
- Wind and rain can increase the ability of a line to dissipate heat, and reduce the likelihood of line sag occurring
  - PJM has explored the use of "dynamic" ratings to take these and other factors into account

BES Transmission Substation Equipment

BES Transmission Substations

- A ***substation*** is a part of the power system where one or more Transmission lines are connected
- Substations allow one or more of the following functions;
  - Switching, or isolating and reconnecting parts of the system from each other
  - Voltage Transformation (either up or down)
  - Voltage Control

BES Transmission Substations

Substations can look radically different, depending on their location







BES Transmission Substations

They consist of one or more “Buses” to which the transformers, circuit breakers, and supporting equipment are connected

We’ll start by examining Buses

- The PJM system has two basic Bus types:
  - **Open Bus Type** – in which the energized bus is exposed
  - **Bus Duct Type** – in which the energized bus is enclosed in some sort of structure

BES Transmission Substations

Duct Bus Example

3-Phase Duct Bus (SF-6 in this case)

500 KV Line
(3 Phases)



BES Transmission Substations

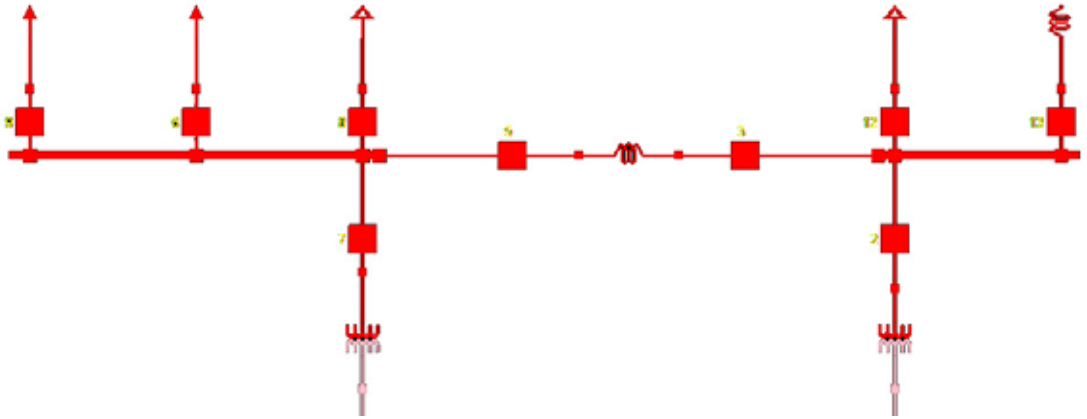
- **Why use a Duct Bus?**
  - Space limitations
    - Remember the distance to be maintained between 500 kV conductors?
    - The ducted conductors are less than a foot apart!
    - SF-6 is such a good insulator that the physical separation distance can be greatly reduced
  - Reduce the risk of transient faults on equipment
    - You can touch/walk on this 500 kV bus

More about SF-6 later in the presentation……

BES Transmission Substations

Substations Configurations

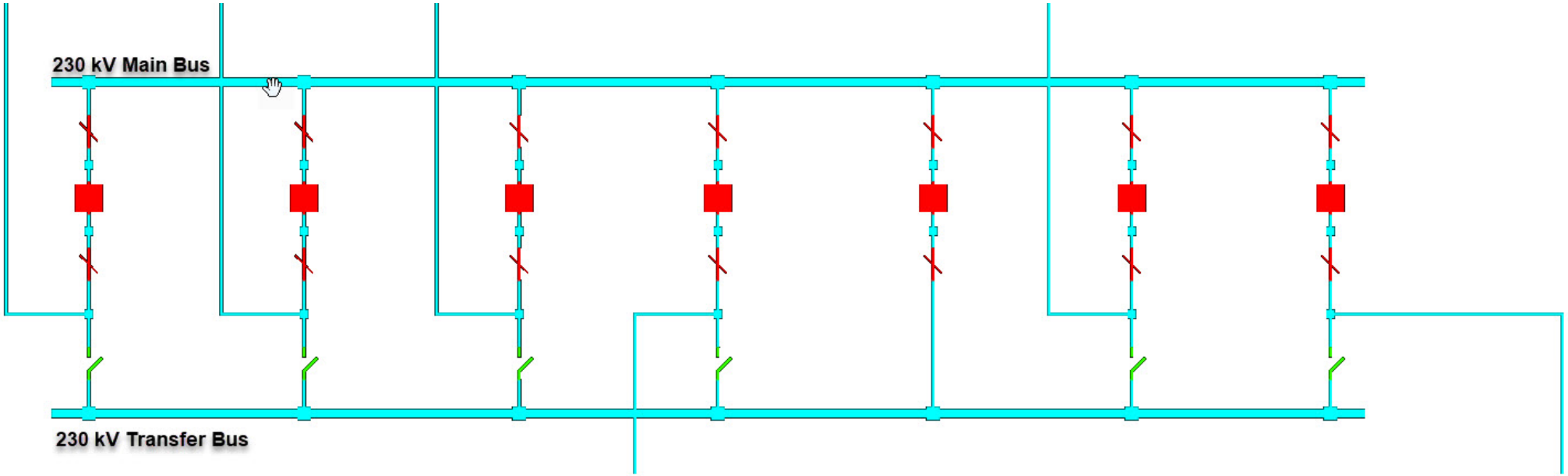
- There are a variety of configurations, which vary greatly in cost and reliability;
  - Single Bus



  - All equipment terminates on the same bus. A fault on this bus will trip all equipment
  - Taking equipment out of service for maintenance generally requires a line or transformer outage

BES Transmission Substations

- A variation of the Single Bus Design is the **Transfer** or **Feeder Bus**:

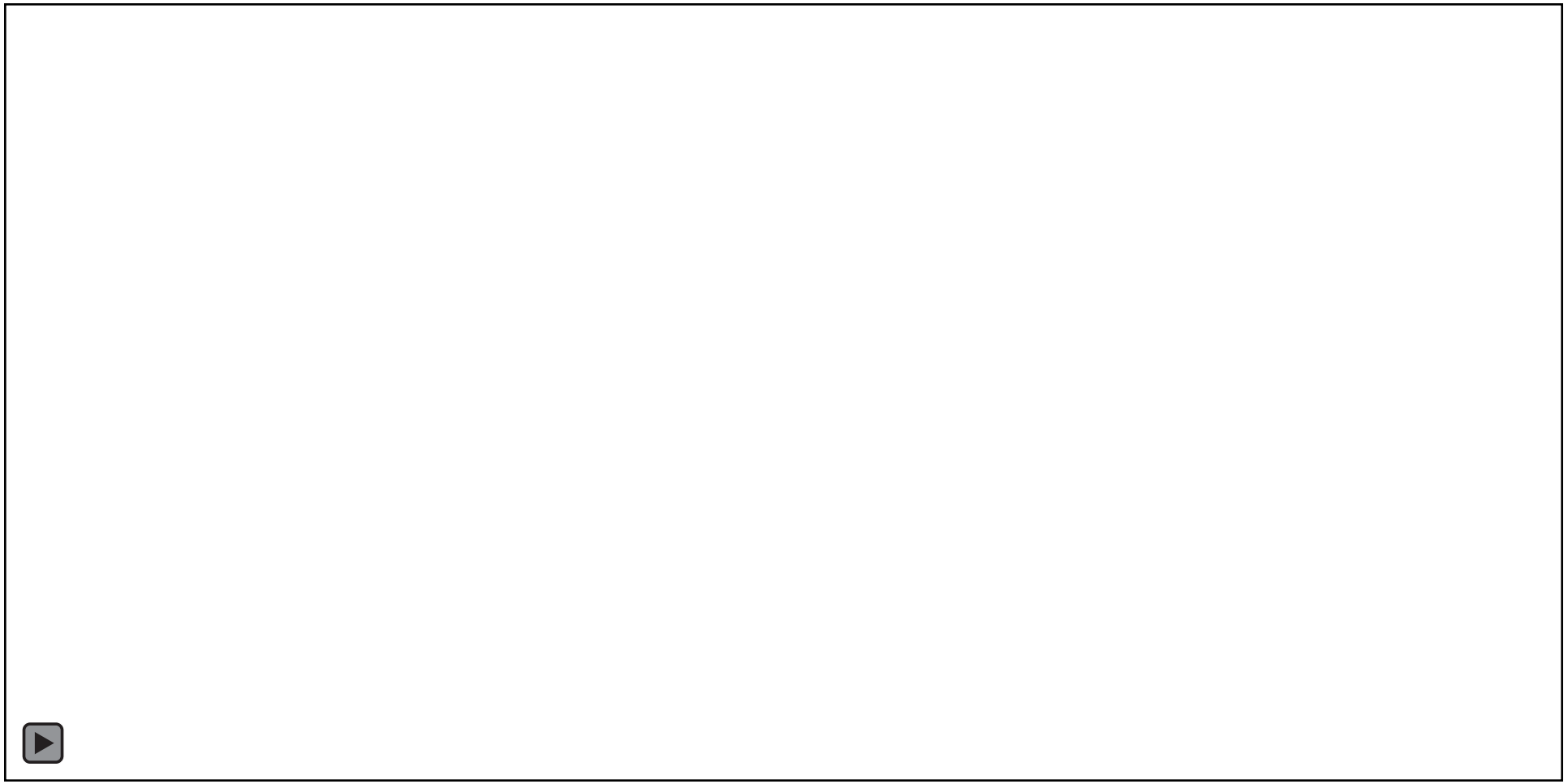


  - Allows maintenance to be performed on equipment while keeping all lines in service

- Single Bus designs are quite cheap to construct, but not very reliable

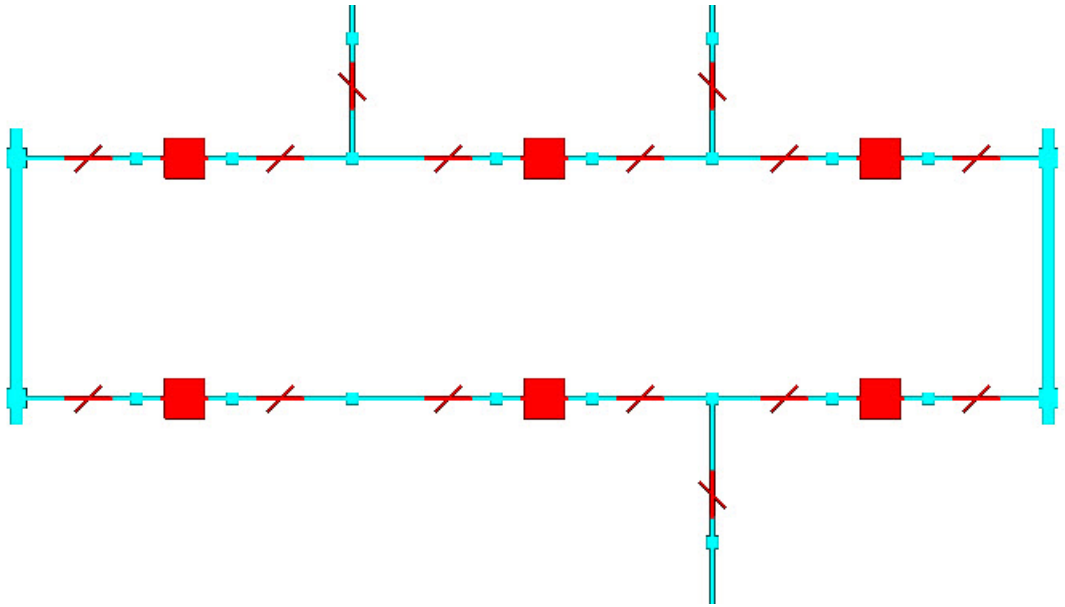
BES Transmission Substations

- Using the Transfer Bus for a Line CB outage



BES Transmission Substations

Ring Bus

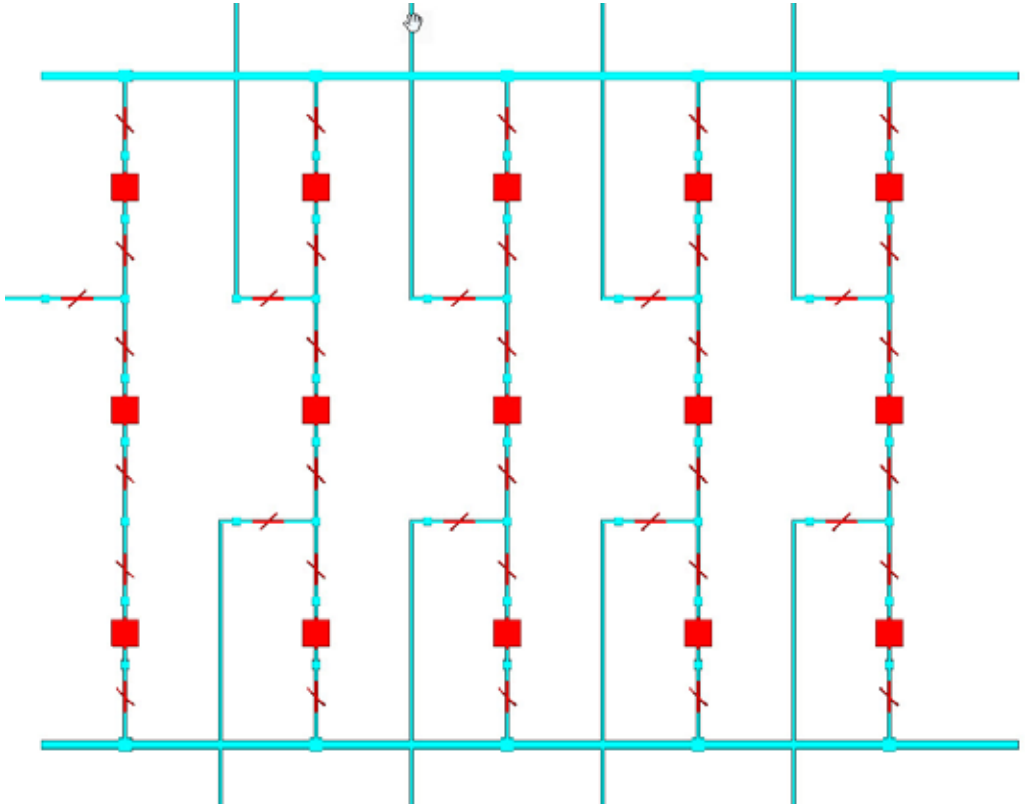


- A fault on any individual bus section will trip 2 of the circuit breakers, and the connected equipment, but the remaining equipment will remain in service
- Slightly more expensive to design and construct
- Definite increase in reliability

BES Transmission Substations

Breaker-and-a-Half Scheme

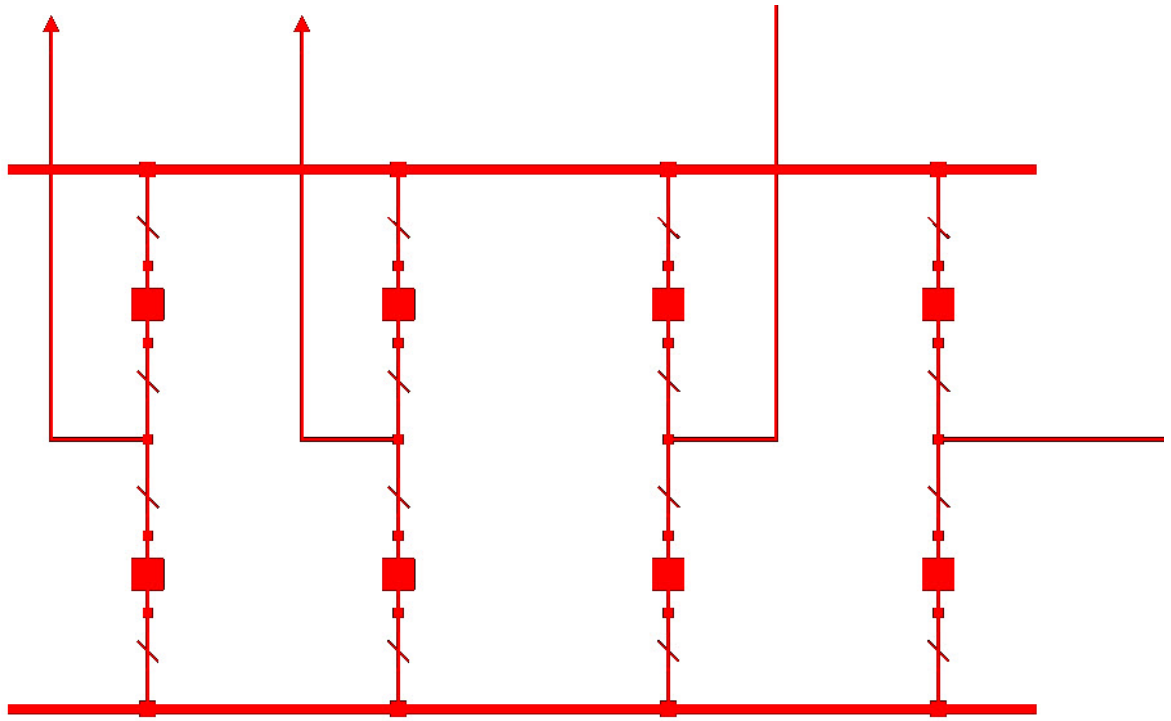
- A fault on either bus will interrupt NO equipment
- Each line is served by 2 breakers, one of which is “shared”
- Another increase in reliability, but cost continues to increase
  (More equipment, more complex relaying)



BES Transmission Substations

Double Bus – Double Breaker Scheme

- Loss of either bus still has all equipment in service
- The “BMW” of Substation design. Maximum reliability
- Also maximum cost. Lots of redundant equipment, very complex relaying



BES Transmission Substation Equipment

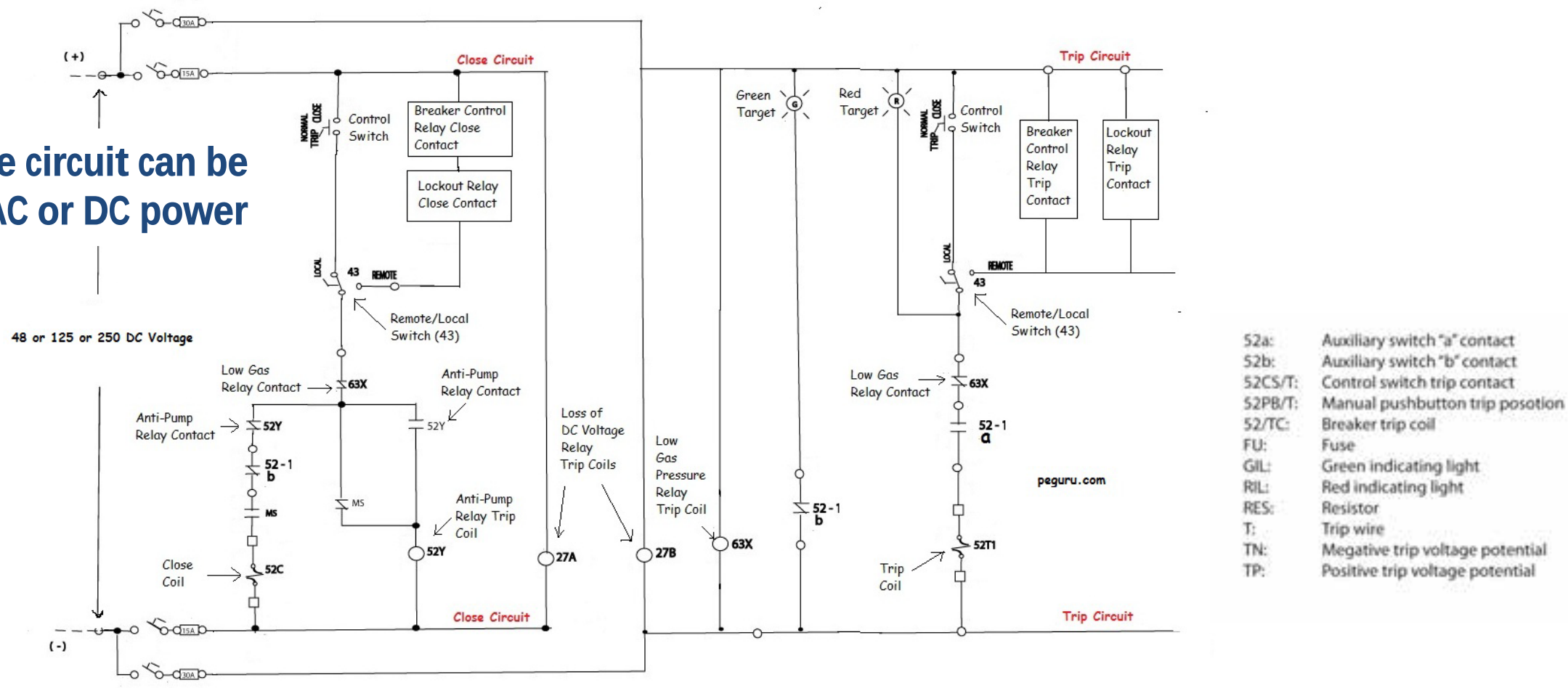
Circuit Breakers

- Circuit Breakers (CB's) maintain and interrupt the flow of current in a electrical circuit under both normal and fault conditions
- CB's operate on DC power, which is supplied from the station batteries
  - Why is DC power chosen for CB controls?
  - If breakers relied on AC power, and all power to a station was lost, we would be unable to operate them!

BES Transmission Substation Equipment

- A basic circuit diagram for circuit breaker relay and control

Close circuit can be AC or DC power



52a:	Auxiliary switch "a" contact
52b:	Auxiliary switch "b" contact
52CS/T:	Control switch trip contact
52PB/T:	Manual pushbutton trip posotion
52/TC:	Breaker trip coil
FU:	Fuse
GIL:	Green indicating light
RIL:	Red indicating light
RES:	Resistor
T:	Trip wire
TN:	Megative trip voltage potential
TP:	Positive trip voltage potential

BES Transmission Substation Equipment

- CBs have mechanisms that move the breaker contacts to open or close the circuit when the CB operates
- The operating mechanism for the CB can be hydraulic, mechanical, or pneumatic
- When the contacts open, an arc is created. The various types of circuit breaker use various means to extinguish the arc, and interrupt the current flow

BES Transmission Substation Equipment

Air Circuit Breakers (Con't)

- To operate properly, the circuit breaker must have sufficient stored air pressure to be able to extinguish the arc
- These breakers are equipped with pressurizing systems to keep the air pressure above the required levels
- Should air pressure decrease, an interlock will operate, preventing the breaker from being opened while energized

BES Transmission Substation Equipment

Oil Circuit Breakers

are used at a wide range of voltage levels



Oil Circuit Breaker

BES Transmission Substation Equipment

Gas Circuit Breakers

- This type of circuit breaker uses an insulating gas (Sulfur Hexaflouride, or SF-6) as a dielectric medium. These breakers use bursts of SF-6 gas to extinguish the arcs, and the gas itself provides an insulating medium between the phases
- In this type of circuit breaker, a spring mechanism is used to open and close the contacts
- The high dielectric qualities of the SF-6 gas allow a much smaller design to be used for this type of circuit breaker, even when they are operating at higher voltage levels

BES Transmission Substation Equipment



69 kV SF-6 Circuit Breaker

230 kV SF-6 Circuit Breaker



BES Transmission Substation Equipment



500 kV SF-6 Circuit Breakers

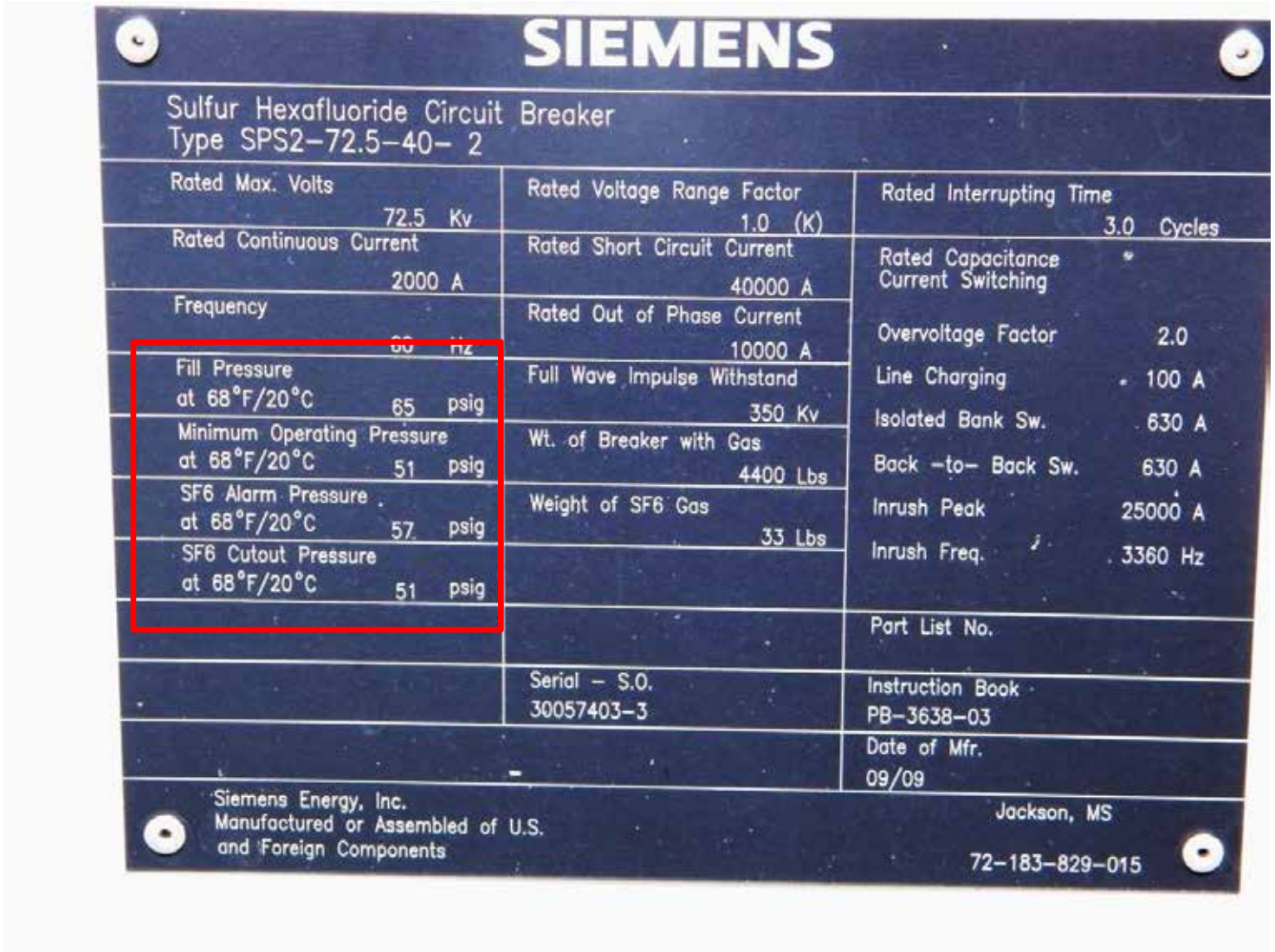
BES Transmission Substation Equipment

- Like the air in air blast breakers, the SF-6 gas needs to remain above a certain pressure to allow the breaker to open, to ensure that the arc can be extinguished
- An interlock will prevent the breaker from opening if pressure gets below the determined set point
- While SF-6 breakers and buses have definite advantages, they do provide some operating challenges;
  - The SF-6 Buses were designed to be installed inside enclosed substations (indoors)
  - Those companies who have chosen to ignore this recommendation and install them outdoors have noted that they do not weather well, and are prone to leakage

BES Transmission Substation Equipment

- The SF-6 gas is can be corrosive, and tends to leak out of even properly installed systems, so periodic checking of pressure on these devices is required
- If the pressure drops below a certain point, it is not safe to add gas back to these breakers with the breaker still energized. Any debris in the bottom of the tank might be stirred up when the gas is added, and cause an internal flash-over inside the breaker (due to the small distance between the contacts in the breaker design)
- The breaker must be completely isolated from the system before gas is added under these conditions

BES Transmission Substation Equipment



SF-6 Breaker rating nameplate, showing critical pressure limits

BES Transmission Substation Equipment

Circuit Switchers

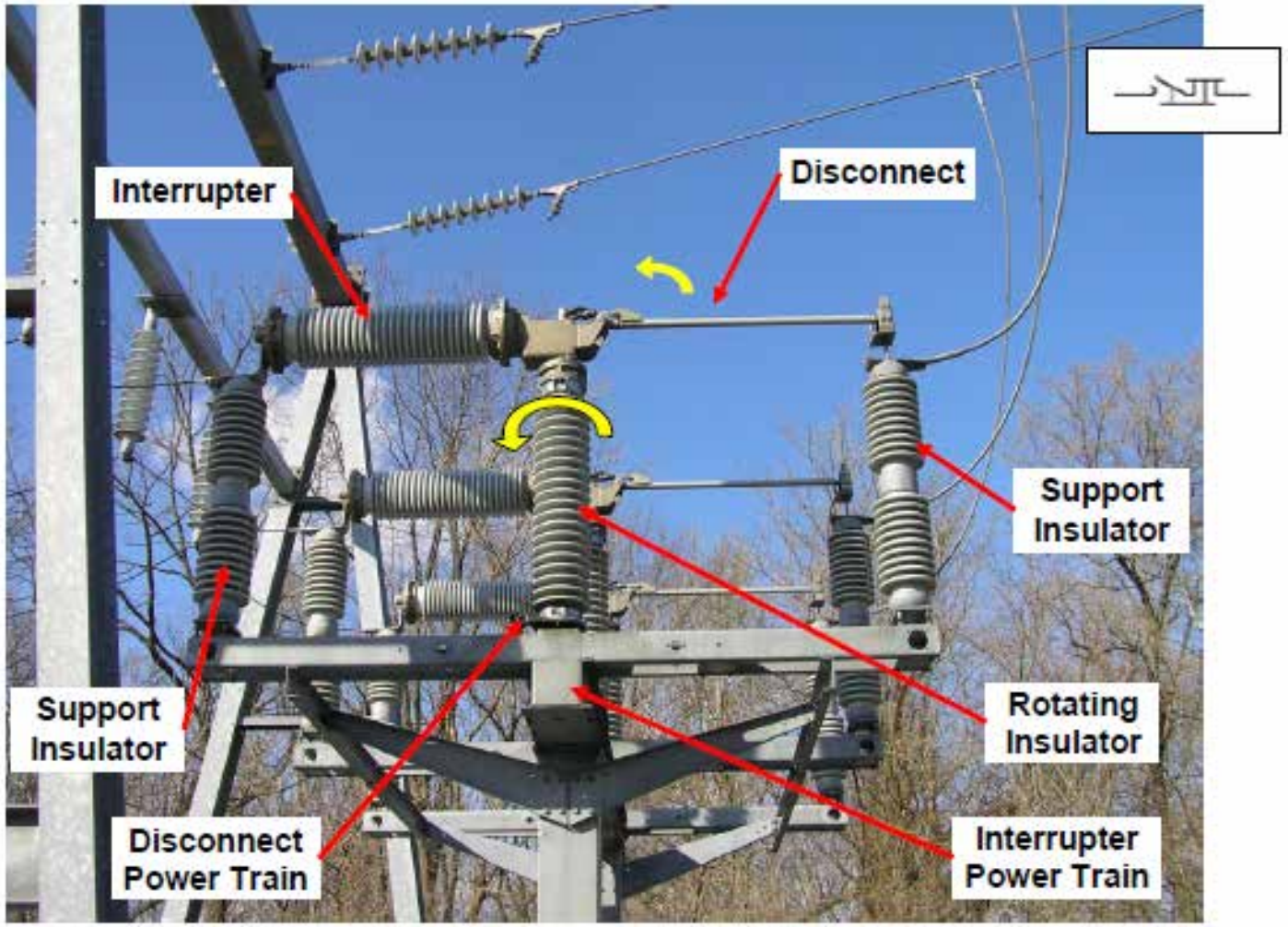
- Circuit Switchers are used to energize or de-energize higher voltage level (≥ 138 kV) equipment such as transformers that have a high magnetizing current
- They are more useful to an operator because they also have the ability to interrupt fault current
- This would allow a faulted transformer to isolate itself from a transmission line, without a permanent outage occurring on that line

BES Transmission Line Equipment

- These switches are used both as line sectionalizing devices, and within substations to de-energize equipment
- They use a combination of gas bottles (generally SF-6) and whips to perform the same functions as a LSAB, but on higher voltage level Equipment, where the arcs would be greater



BES Transmission Line Equipment



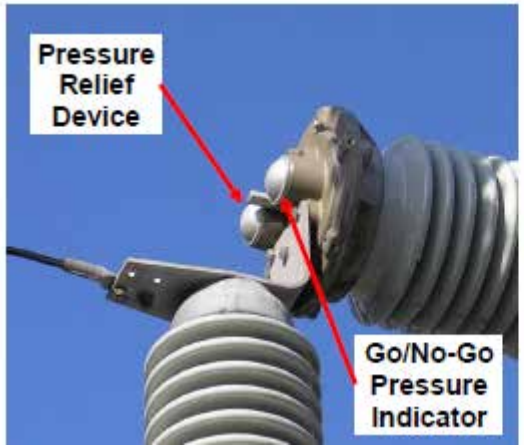
- The interrupter is an SF6 gas filled unit that is permanently sealed. On the operating end of the horizontal style interrupter, there is a mechanical linkage inside the unit that translates the vertical motion of the operator into a horizontal break for the contacts inside the interrupter.

BES Transmission Substation Equipment

Circuit Switchers - generally motor-operated, ganged devices

BES Transmission Substation Equipment

- All these devices have a pressure indicator to measure the pressure of the SF-6 gas which is used to extinguish the arc created when the device opens





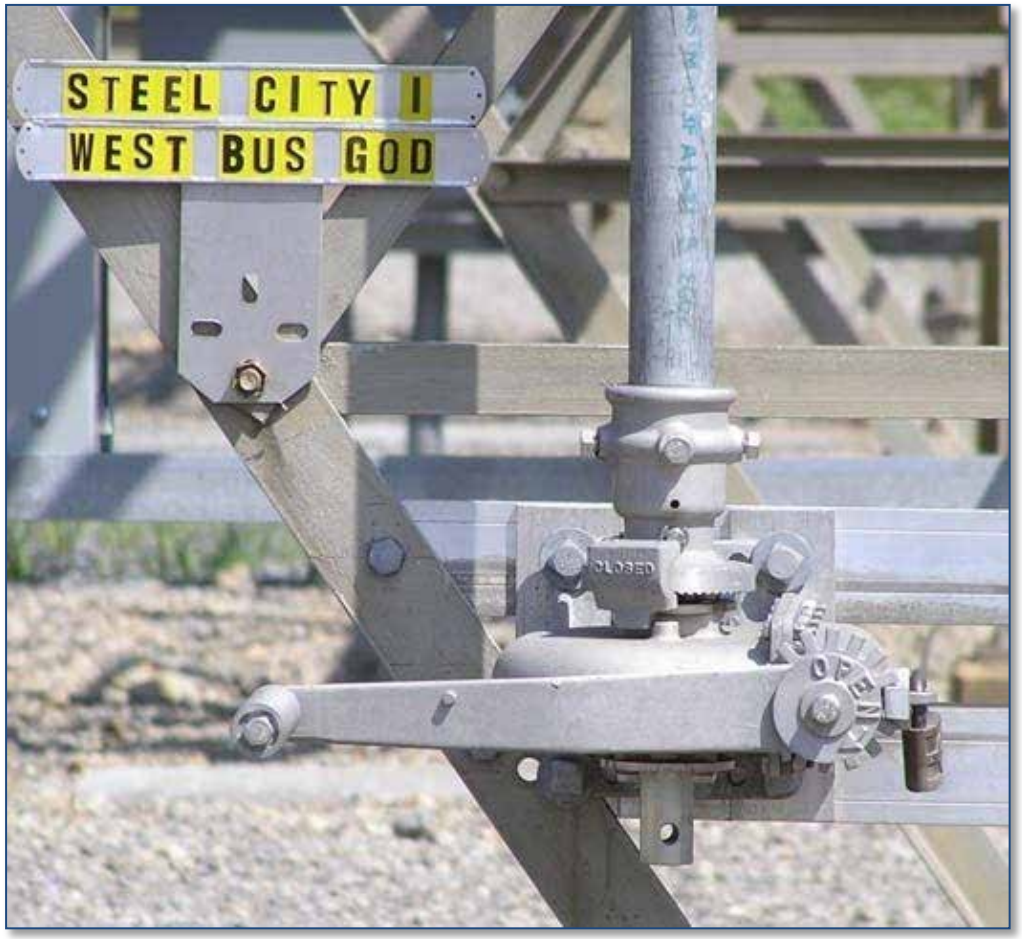
- A second visual indicator is usually included that will show a yellow “flag”, that indicates the pressure in the SF-6 gas assembly is too low to safely open the device
    - On motor-operated devices, automatic tripping may be disabled
    - A substation crew must then add gas to the device before it can be relied upon to function properly

BES Transmission Substation Equipment

- **Disconnects**
  - Disconnects are devices installed primarily to provide a visible break between pieces of equipment and the remainder of the power system, to allow personnel to work safely to maintain or repair BES components
  - Disconnects generally have no ability to interrupt fault current or drop load. They can only energize or de-energize equipment

BES Transmission Substation Equipment

- They can be hand operated, or motor operated





BES Transmission Substation Equipment

- Some common device **names** are:
  - **Disconnects**
  - **Gang Operated Disconnects (GOD's)**
  - **Motor Operated Disconnects (MOD's)**

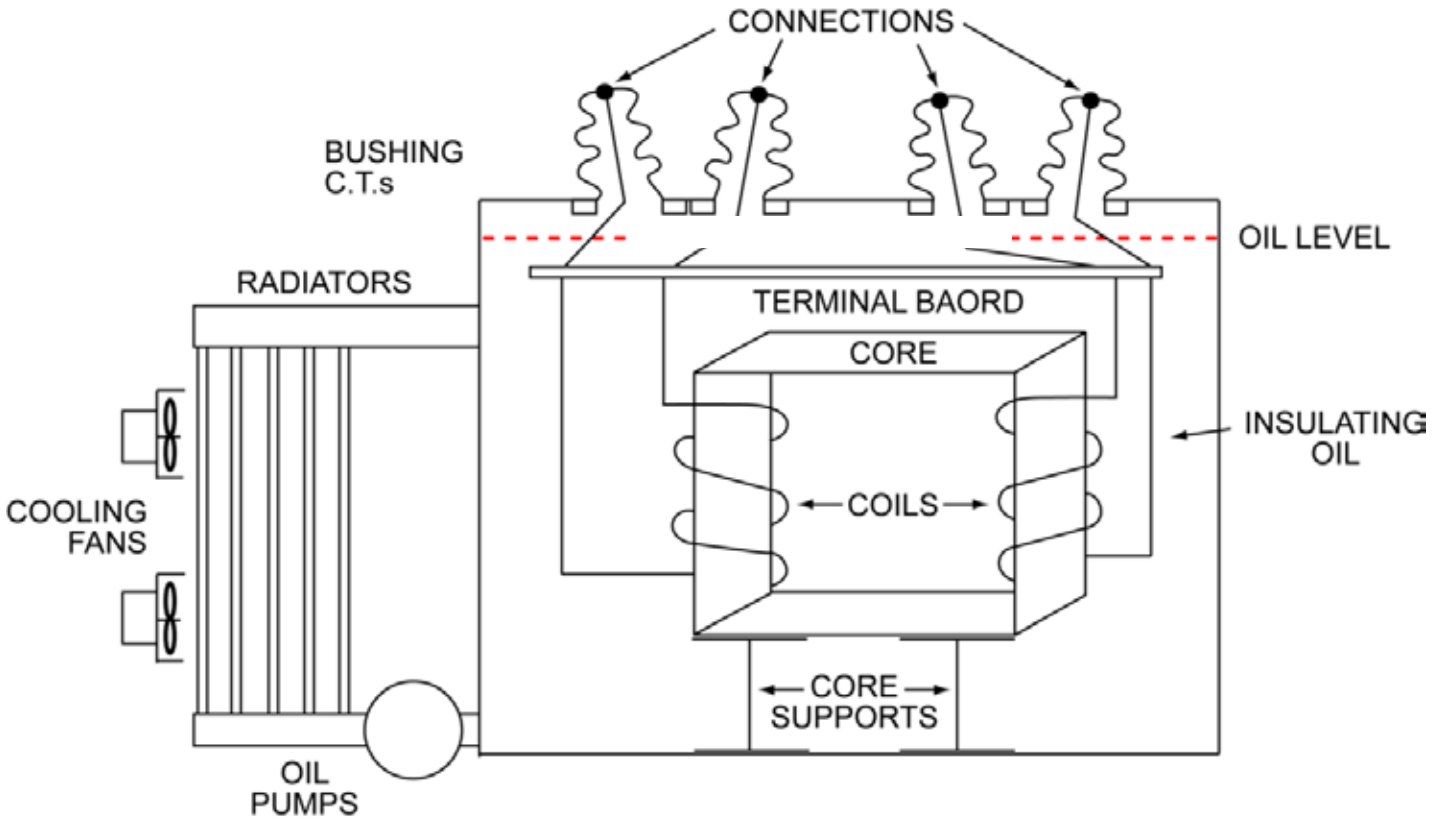
BES Transformers

- **Transformers**



BES Transformers

Basic Schematic of a Power Transformer



BES Transformers

- The level to which the voltage changes within the transformer is dependent upon the turns ratio;

$$Vs = Vp \frac{Ns}{Np}$$

- Virtually all Power Transformers have Taps in one or more windings to slightly vary the turns ratio, and allow slight adjustment of the system voltage
  - Some sub-Transmission, and most distribution transformers, have Taps which are “fixed”. These taps can be changed, but only by hand, and only when the transformer is de-energized

BES Transformers

- On the BES, the use of LTC's allows the Transformers to act as MVAR "shovels"
  - Reactive Power (MVAR's) can be transferred from one voltage level to another
- The transformers themselves do not create MVAR's, they merely have the ability to move them from the high voltage side to the low voltage side (or vice versa)
- MVAR losses within a transformer increase as the loading on the transformer increases

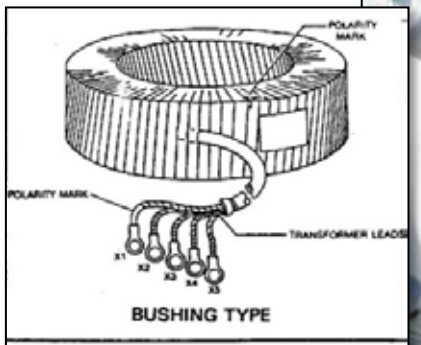
BES Transmission Substation Equipment

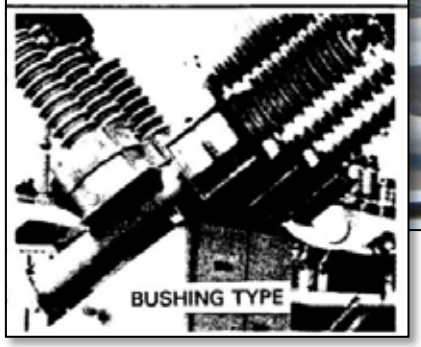
- In addition to the main Power Transformer, most substations also use transformers in additional applications:
  - Station Service Transformers:
    - Used to supply switchyard lighting, control house lighting and HVAC, and to supply the battery charger for station batteries
    - Most BES Substations have at least 2 station service transformers, supplied from independent sources. In most cases the sources will automatically transfer from one source to another if the feed to that source is lost



BES Transmission Substation Equipment

- Current Transformers**
  - Used to change BES current measurements into levels of current that can be used by relay/monitoring equipment





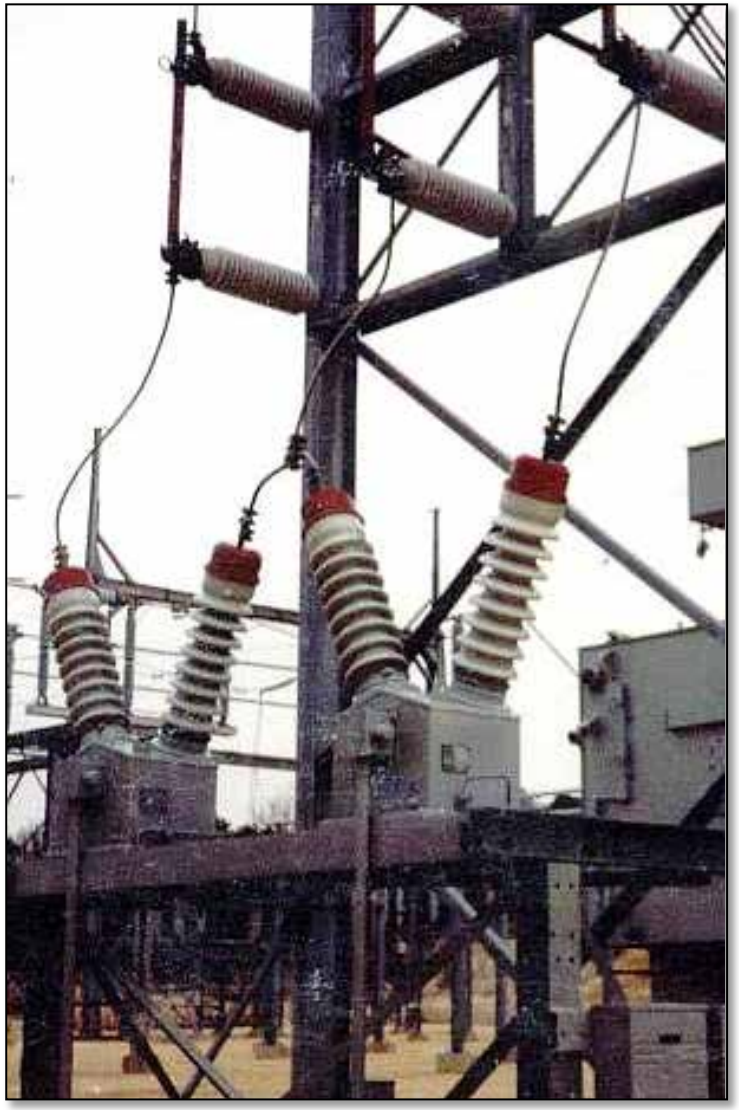


** More about these in the relay module

BES Transmission Substation Equipment

- Potential Transformers
  - Used to change BES Voltage measurements into measurements that can be used by relay/monitoring equipment





BES Transmission Substation Equipment

- Power Transformers can be either:
  - **Step-up** – Which increase the voltage level of the power. These are most commonly employed at Generating stations to raise the voltage from Generator output levels (~ 24 kV) to Transmission level voltages
  - **Step-down** – Which decrease the voltage level from Transmission to sub-transmission, or distribution levels
- Power Transformers can be either sets of single-phase units, or a single 3-phase unit. Generally, the higher the primary voltage level, the more likely it is to be single-phase units

BES Transmission Substation Equipment

- Transformer ratings are determined primarily by the manufacturer, and are generally dictated by how well the transformer can disperse the heat generated by its operation
- To cool the oil, transformers are equipped with a set of pumps, which circulate the oil through a set of radiators external to the transformer oil tank. These radiators help to cool the oil
- Most BES transformers also have one or more banks of fans, which blow air onto the radiators to assist in the cooling process

BES Transmission Substation Equipment

- Transformer ratings are given in levels, depending on how many of these cooling mechanisms are in service



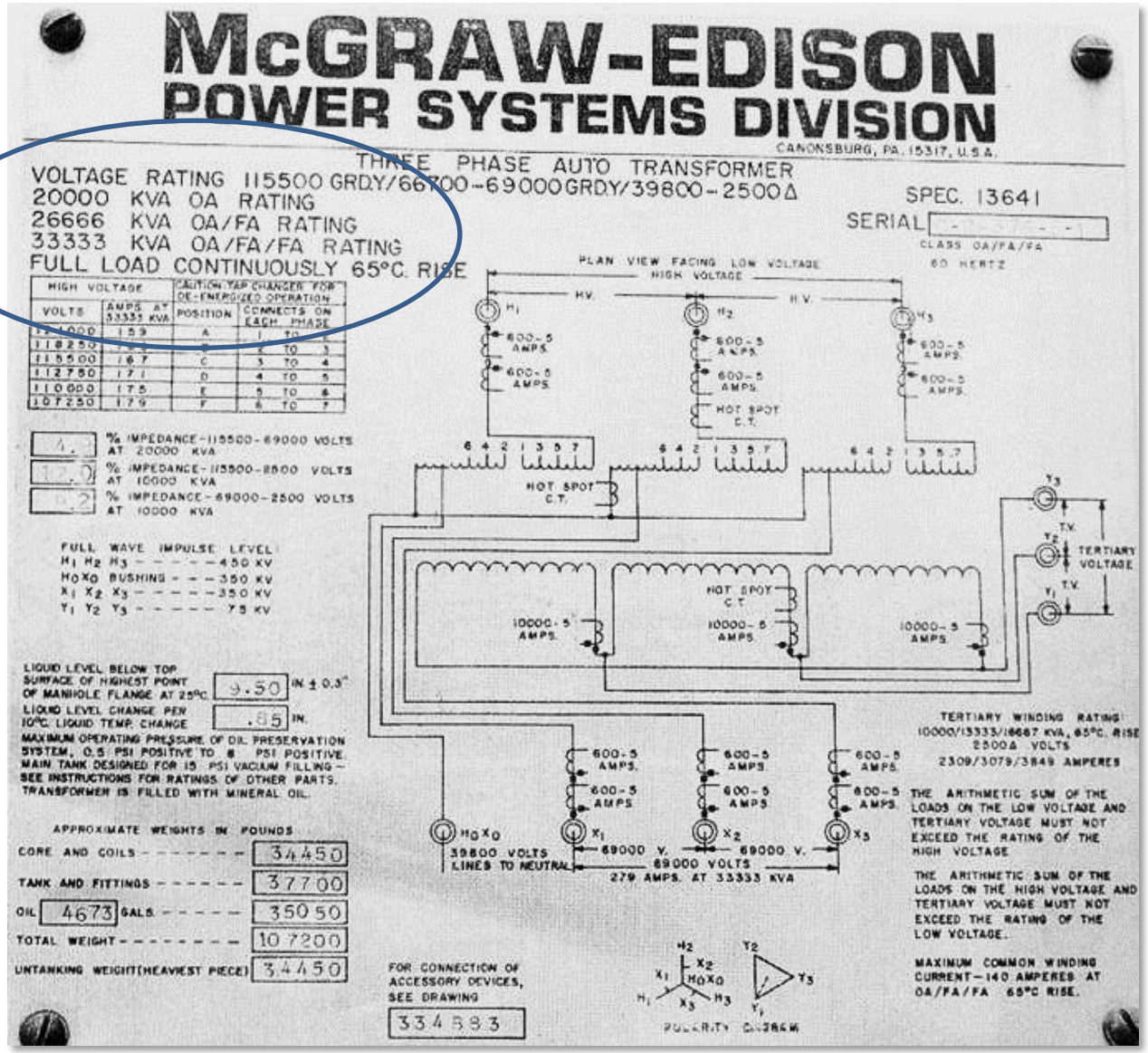
Designations and descriptions of the cooling classes used in power transformers

Previous designation	IEC designation	Description
OA	ONAN	Oil-air cooled (self-cooled)
FA	ONAF	Forced-air cooled
OA/FA/FA	ONAN/ONAF/ONAF	Oil-air cooled (self-cooled), followed by two stages of forced-air cooling (fans)
OA/FA/FOA	ONAN/ONAF/OFAF	Oil-air cooled (self-cooled), followed by one stage of forced-air cooling (fans), followed by 1 stage of forced oil (oil pumps)
OA/FOA	ONAF/ODAF	Oil-air cooled (self-cooled), followed by one stage of directed oil flow pumps (with fans)
OA/FOA/FOA	ONAF/ODAF/ODAF	Oil-air cooled (self-cooled), followed by two stages of directed oil flow pumps (with fans)
FOA	OFAF	Forced oil/air cooled (with fans) rating only—no self-cooled rating
FOW	OFWF	Forced oil / water cooled rating only (oil / water heat exchanger with oil and wa- ter pumps)—no self-cooled rating
FOA	ODAF	Forced oil / air cooled rating only with di- rected oil flow pumps and fans—no self-cooled rating
FOW	ODWF	Forced oil / water cooled rating only (oil / water heat exchanger with directed oil flow pumps and water pumps)—no self-cooled rating

These banks of fans come on in stages, depending on the temperature of the oil

BES Transmission Substation Equipment

Transformer Name Plate, showing the ratings with various cooling systems in service



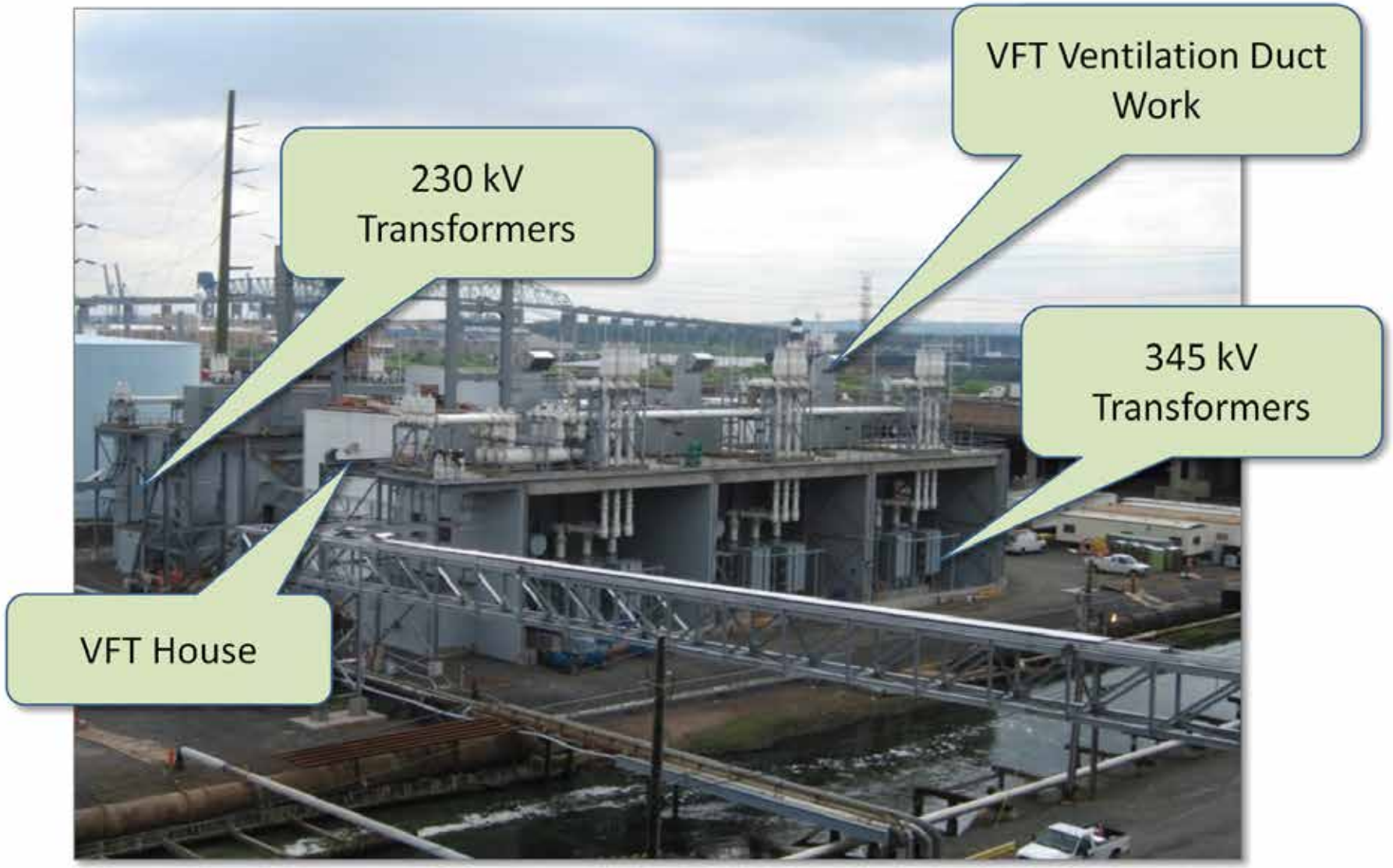
BES Transmission Substation Equipment

- If a set of fans (or the pumps) becomes inoperative, the rating of the transformer may need to be decreased, to prevent damage
- Transformer fans and pumps are generally supplied via Station Service Transformers
- Excessive heating of a transformer can lead to breakdown of the insulation, which can decrease the life of the transformer
- In excessive heat conditions, some companies have also been known to spray down their heavily loaded transformers with water to help in cooling

BES Transmission Substation Equipment

- Another installation on the PJM system is a Variable Frequency Transformer (VFT)
- Installed between the Linden Co-Gen facilities and the PSE&G 230 kV system
- Its purpose is to balance the power output of the Linden Co-Gen plant between the PSE&G 230 kV system and the NYISO 345 kV system
- This tie is also regulated via the PARs between Linden and Goethels

BES Transmission Substation Equipment



BES Transmission Substation Equipment

- The Linden VFT creates 300 MW of transfer capability between the associated 230 kV and 345 kV systems
- Scheduling power flows is similar to scheduling flows on the Neptune Cable
- Can be operated in “Local Control Mode” or “PJM automatic” mode
  - On the “PJM Automatic” mode, the VFT’s will follow PJM dispatch signals to control power flow
  - Each VFT can respond at 100 MW/min (Max)
  - Normal ramp rate is 10 MW/min

BES Transmission Substation Equipment

- **Phase Angle Regulators (PARs)**

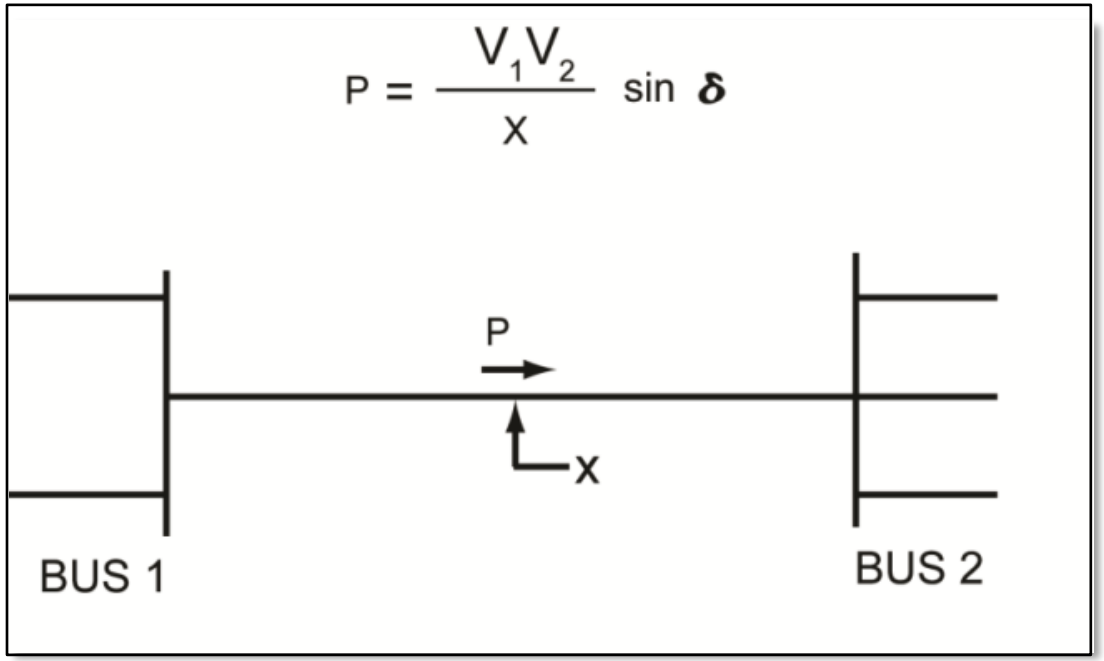


BES Transmission Substation Equipment

- Phase Angle Regulators are used to control power flow across electric paths on the BES
- Rather than re-directing MVAR flow, they change the rate of MW flowing on the lines to which they are connected
- Their construction is similar to that of a transformer:
  - In a PAR, the phase angle of the secondary winding is adjusted by connecting an excited winding to the phases
  - Adjusting the voltage in the secondary windings changes the power angle through the PAR, affecting power flow on the connected line

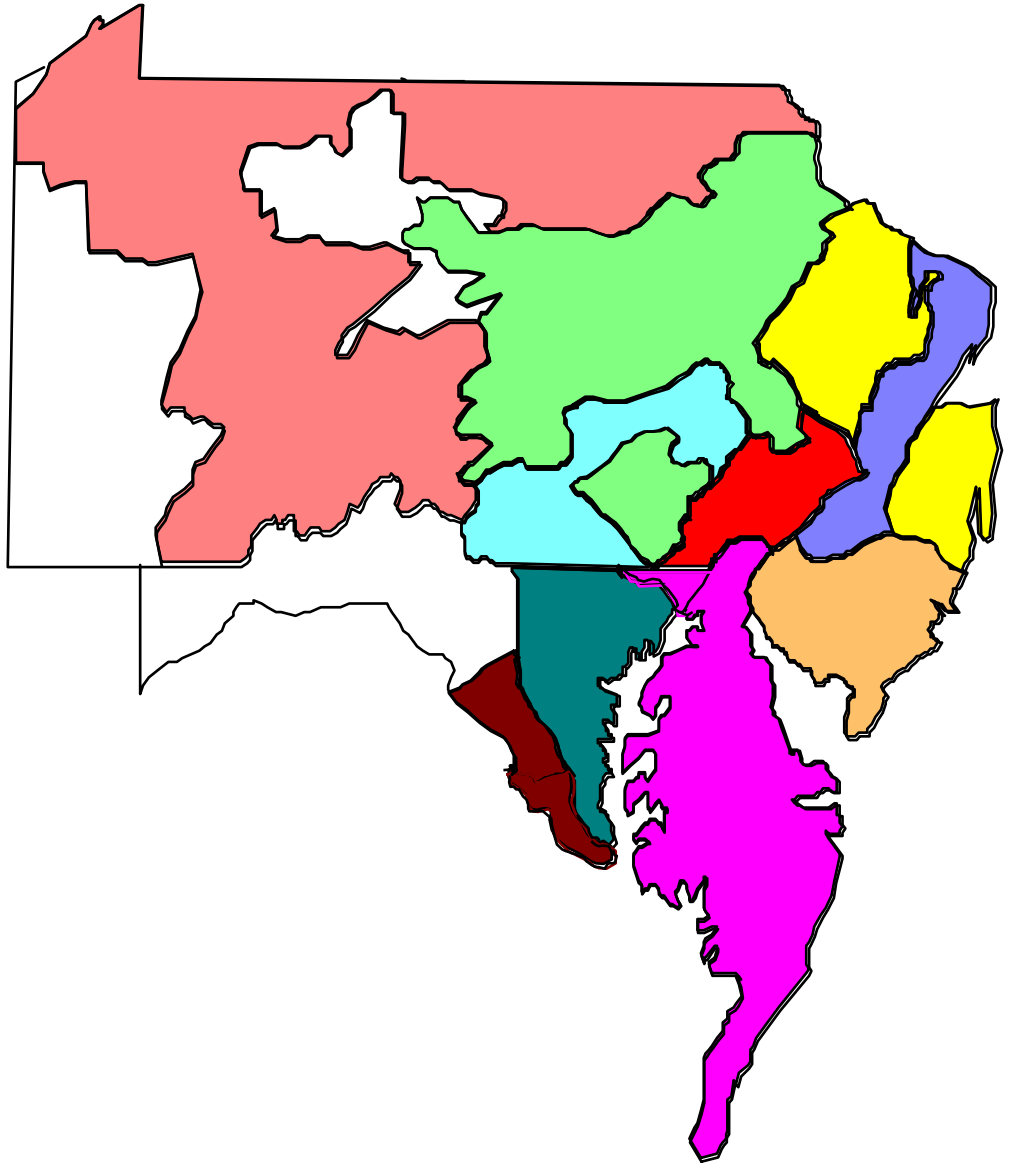
BES Transmission Substation Equipment

- PARs provide an artificial increase or decrease in the phase angle difference between 2 buses
  - ***Remember:*** MWs flow "downhill" on Phase Angle



P = Power Flow from 1 to 2 (MW)
V_1 = Voltage at 1 (kv)
V_2 = Voltage at 2 (kv)
X = Impedance from 1 to 2 (Ω)
δ = Phase Angle Difference Between V_1 and V_2

BES Transmission Substation Equipment



PAR Locations within PJM

NY

- Farrugut 345kv (2) -- Hudson (PS) interface
- Goethals 345kv -- Linden (PS) interface
- Ramapo 345kv (2) – Branchburg (PS) interface

PS

- Linden 230kv
- Waldwick 230 (3)
- New Freedom 230kv (2)
- Trenton 138kv

PEP

- O Street 138kv (2)
- Ft Slocum 69kv

ComEd

- Pars surround city of Chicago to control flow on lines thru and around the city

BES Transmission Substation Equipment

- To adjust the position of a PAR (and by extension, change the power flows across an interface), all parties involved must be in agreement
- ***Increasing*** the voltage in the secondary windings will ***Increase*** flows on the line to which the PAR is connected
- The NY and PS PARs move after discussions between PJM and NYISO
- The PEP PARs can be moved as needed by PEPCO

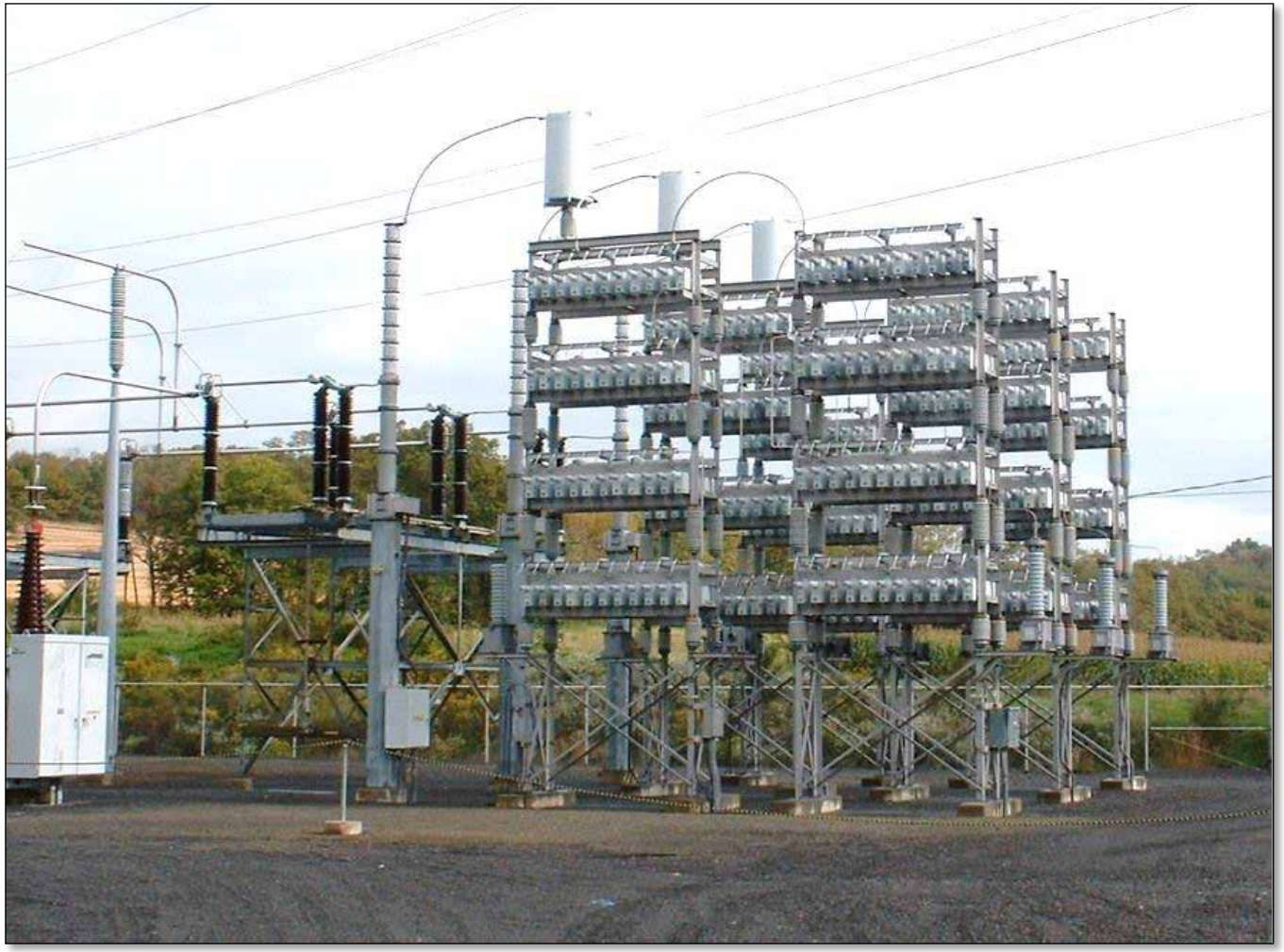
BES Transmission Substation Equipment

- **Shunt Capacitors**
  - Because Reactive Power (MVAR) does not travel well, we need a source of MVAR's close to our loads to ensure that our customers are served with the proper power factor
  - Capacitors are installed on the BES to provide this Power Factor Correction, and to support the increased MVAR requirements that result from operating transmission lines above their SIL values

BES Transmission Substation Equipment



69 kV Capacitor Bank



230 kV Capacitor Bank

BES Transmission Substation Equipment

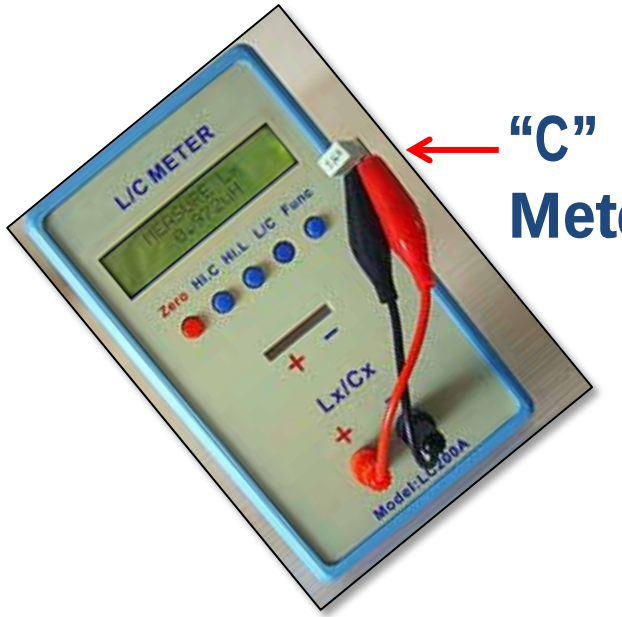
- Capacitor banks consist of individual capacitor cans paralleled together into groups
  - These groups are then connected in series between the primary voltage source and ground to form single-phase banks
  - Three single-phase banks connected in a grounded-wye configuration form a three-phase bank

BES Transmission Substation Equipment

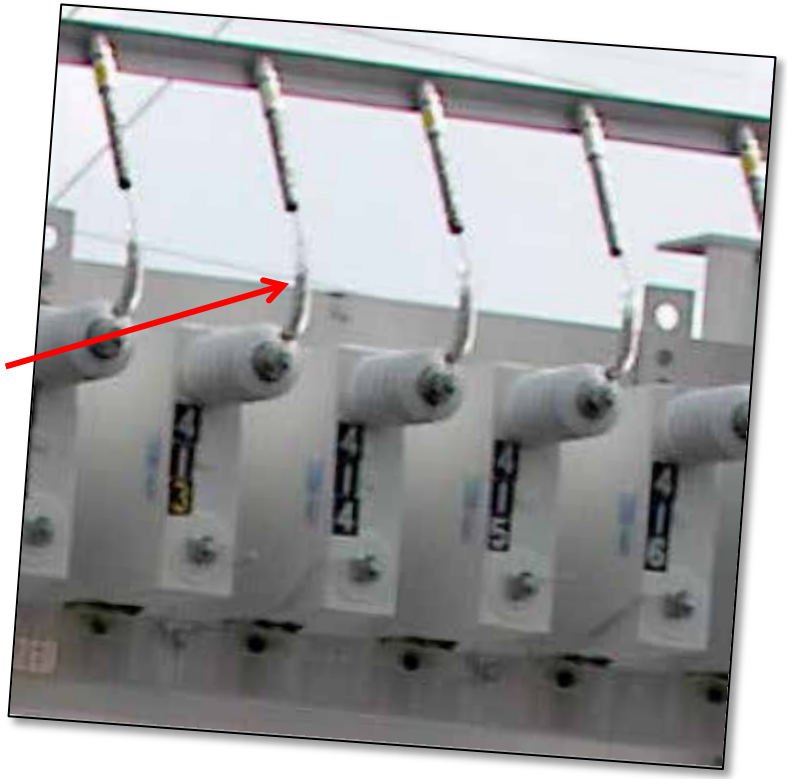
- Capacitor “Banks” are rated to provide a set amount of MVAR’s when connected to the system *at nominal voltage levels*
  - Remember that capacitor output is dependent upon the ***square*** of the source voltage
  - At 90% of nominal voltage, a capacitor would put out only 81% of its stated MVARs
    - § $(0.9)^2 = 0.81$ or 81%

BES Transmission Substation Equipment

- Each individual capacitor “Can”, or unit, has it own fuse to protect the Bank as a whole if the can should develop a fault
  - A failed can will cause it’s fuse to operate, isolating it from the system, but allowing the rest of the bank to remain in service



“C” Meter



Fuse

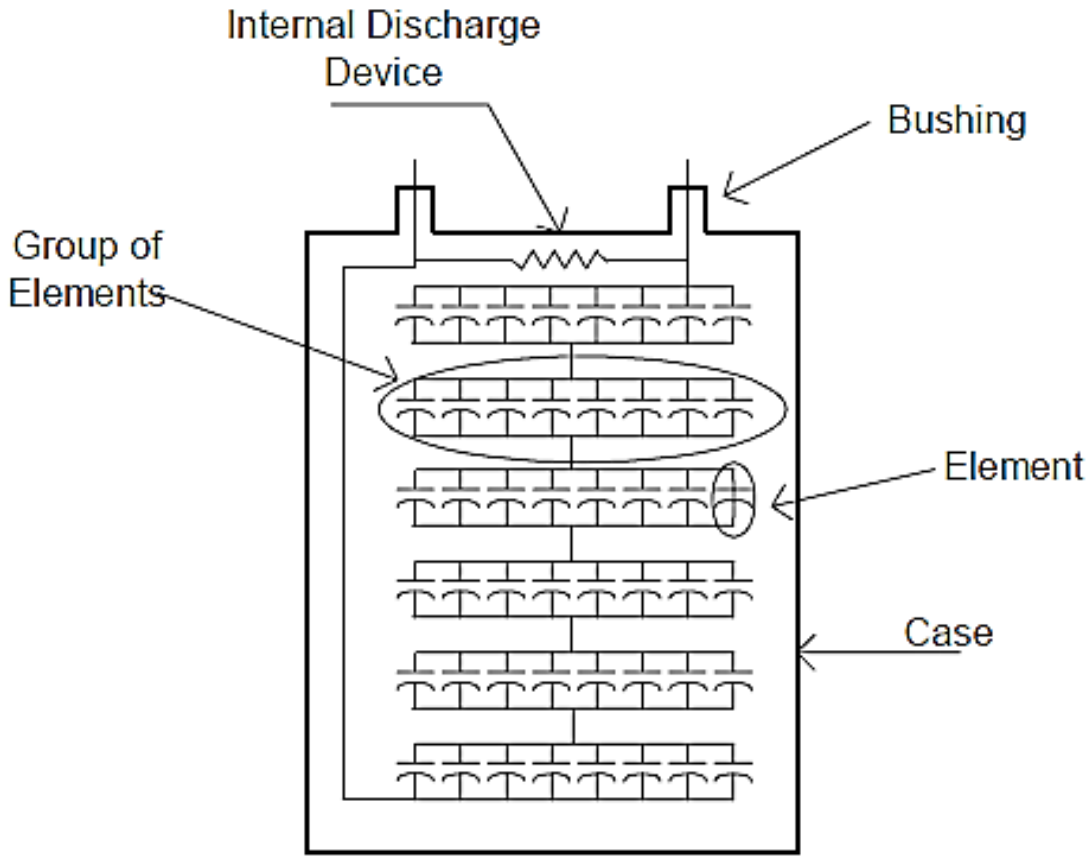
BES Transmission Substation Equipment

- Capacitors act as a source of MVARs for the BES. Placing a capacitor in service at a substation bus will raise the voltage at that location
- Removing a capacitor from service will lower the voltage at that location
- In addition to the fuses for each individual can, capacitor banks are connected to the system via circuit switchers, or by a combination of circuit breakers and disconnect switches



BES Transmission Substation Equipment

- It is important to remember that capacitors are not immediately de-energized once they are disconnected from the BES
  - The nature of a capacitor is to store electric charge.
    - This can be as high as 500 kV
- A discharge resistor is connected across the capacitor terminals which gradually discharges the capacitor, reducing the voltage across the terminals
  - 5-15 minutes for discharge to safe voltage levels



BES Transmission Substation Equipment

- **Series Capacitors**
  - Series capacitors are used primarily to reduce the inductance of long transmission lines, which makes the lines appear “shorter” to power flows
  - This has the effect of reducing the power angle across the line, allowing power transfers across that line to be increased, without a corresponding decrease in system stability

BES Transmission Substation Equipment

- Series capacitors can be either “fixed” (the whole bank in or out of service as a unit) or thyristor controlled
- A Thyristor Controlled Series Capacitor (TCSC) has the added advantage of allowing control of the current (power) flow on parallel transmission lines, which further improves system stability
- Advanced TCSC’s are even capable of helping to dampen Power system Oscillations



BES Transmission Substation Equipment

- Series capacitors are widely used in the Western Interconnection, because so many of their transmission lines are very long
- A few Series capacitors are installed in the AEP area of PJM, on the 345 kV system, at the Kanawa River substation

BES Transmission Substation Equipment

- **Shunt Reactors**
  - On the BES, long transmission lines are subject to the *ferranti effect*, which causes an open-ended (or very lightly loaded) transmission line to look like a large capacitor, supplying MVARs from the line, and raising system voltages
  - To remove these MVARs from the system when they could cause problems, (as in during light load periods or during system restoration efforts) we employ Shunt Reactors, which act as VAR **sinks**

BES Transmission Substation Equipment

- Shunt reactors are basically an iron core surrounded by coils of wire
  - Large reactors may be cooled by surrounding the core with an oil-filled tank
  - Smaller reactors can have their cores cooled sufficiently by being open to the air
- When energized, a shunt reactor will absorb MVARs from the BES
  - Each reactor is rated to absorb a set amount of MVARs

BES Transmission Substation Equipment

Air-Cooled Reactor



BES Transmission Substation Equipment

Oil-Cooled Shunt Reactor



BES Transmission Substation Equipment

- Reactors act as a sink for MVARs for the BES. Placing a reactor in service at a substation bus will ***lower*** the voltage at that location
- Removing a reactor from service will ***raise*** the voltage at that location
- Like capacitors, Reactors are connected to the system via circuit switchers, or by a combination of circuit breakers and disconnect switches

BES Transmission Substation Equipment



- **Series Reactors**
  - Series reactors are installed to either;
    - Reduce the amount of available fault current or
    - To match the impedance of parallel feeders
  - When Generation capacity is expanded, or additional feeders are added to an existing substation, the impedance of the connected circuits changes, changing the amount of available fault current at that station

BES Transmission Substation Equipment

- As a result, the new level of fault current may exceed the rating of some of the installed equipment
- Installing Fault Limiting Series Reactors adds impedance to the system, reducing the amount of available fault current at their location, and preventing the need to replace equipment along with system upgrades
- Fault Limiting reactors are installed throughout the PJM system

BES Transmission Substation Equipment

- **Static Var Compensators (SVC's)**
  - SVC's are a combination of Reactors and Capacitors at the same substation, which are under a common computer control scheme.
  - The computer will monitor the voltage at the substation, and switch the individual reactors and capacitors in and out of service as necessary to maintain the desired voltage schedule at that location.
    - Accomplished by using high-speed thyristors

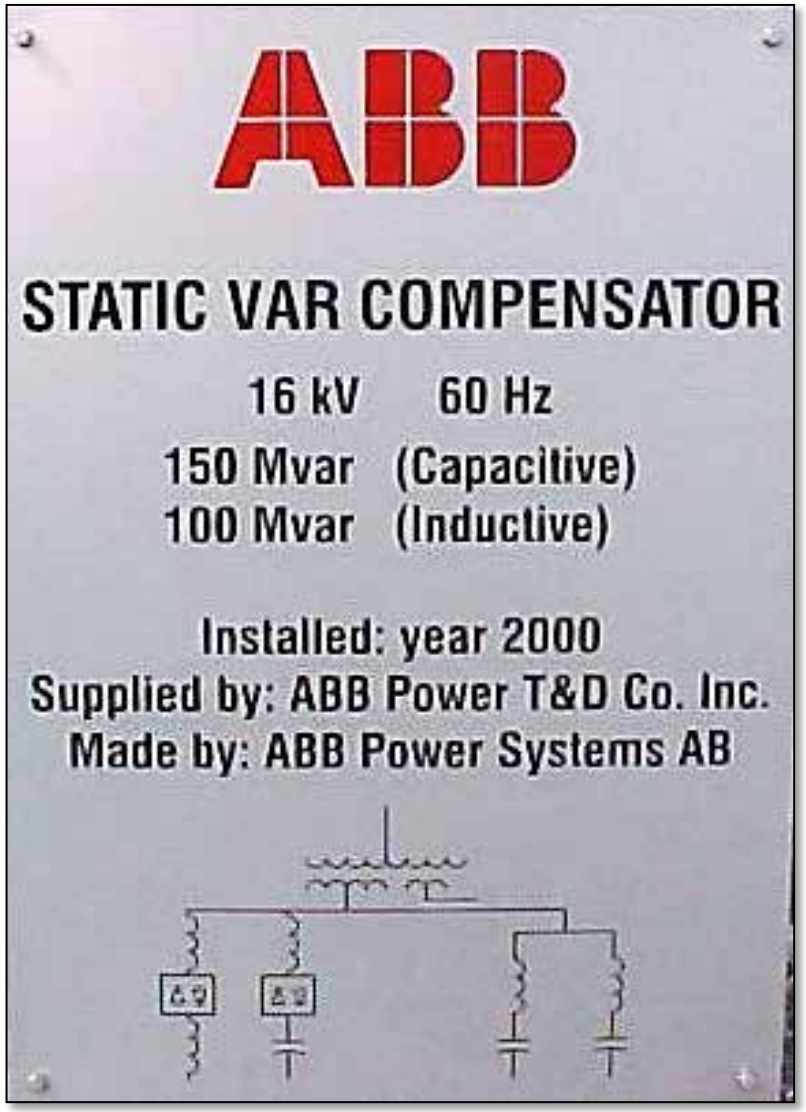
BES Transmission Substation Equipment

SVC Installation



BES Transmission Substation Equipment

- SVCs are rated according to their maximum MVAR intake and output abilities;
  - Max inductive means all reactors are in service, all capacitors are out of service
  - Max Capacitive means all Capacitors are in service, all Reactors are out of service
  - In this case, SVC has a total range of 250 MVAR

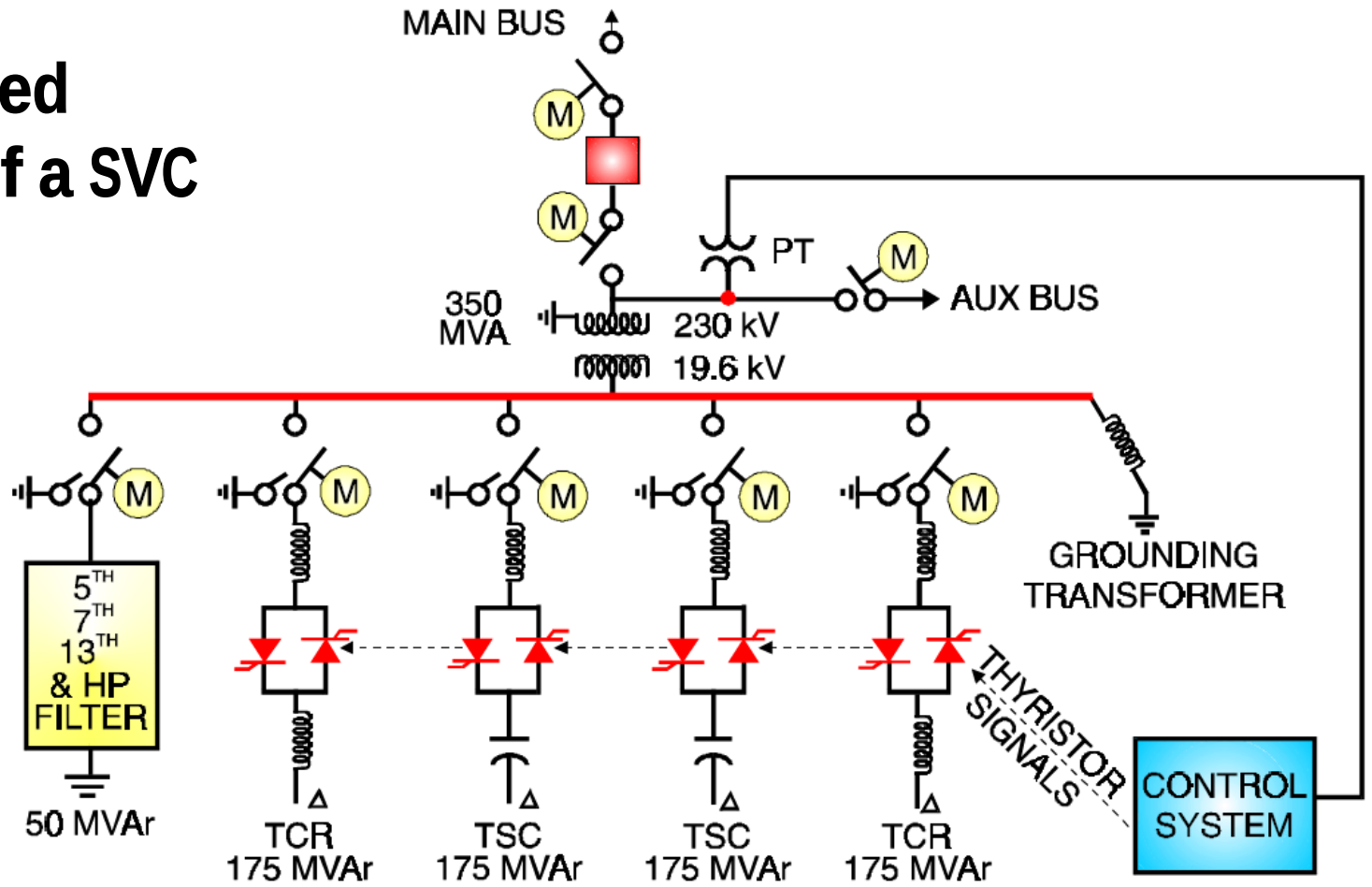


BES Transmission Substation Equipment

- Because SVC's use capacitors, their ability to supply MVARs is also directly linked to the voltage at the time the units are energized
  - Remember – Capacitor output is proportional to the *square* of the voltage
- SVC's are coming into more common use throughout PJM
  - Black Oak – Has the largest SVC currently on the system, connected to their 500 kV yard
    - Can range from 145 MVAR inductive to 575 MVAR Capacitive

BES Transmission Substation Equipment

Simplified Schematic of a SVC



BES Transmission Substation Equipment

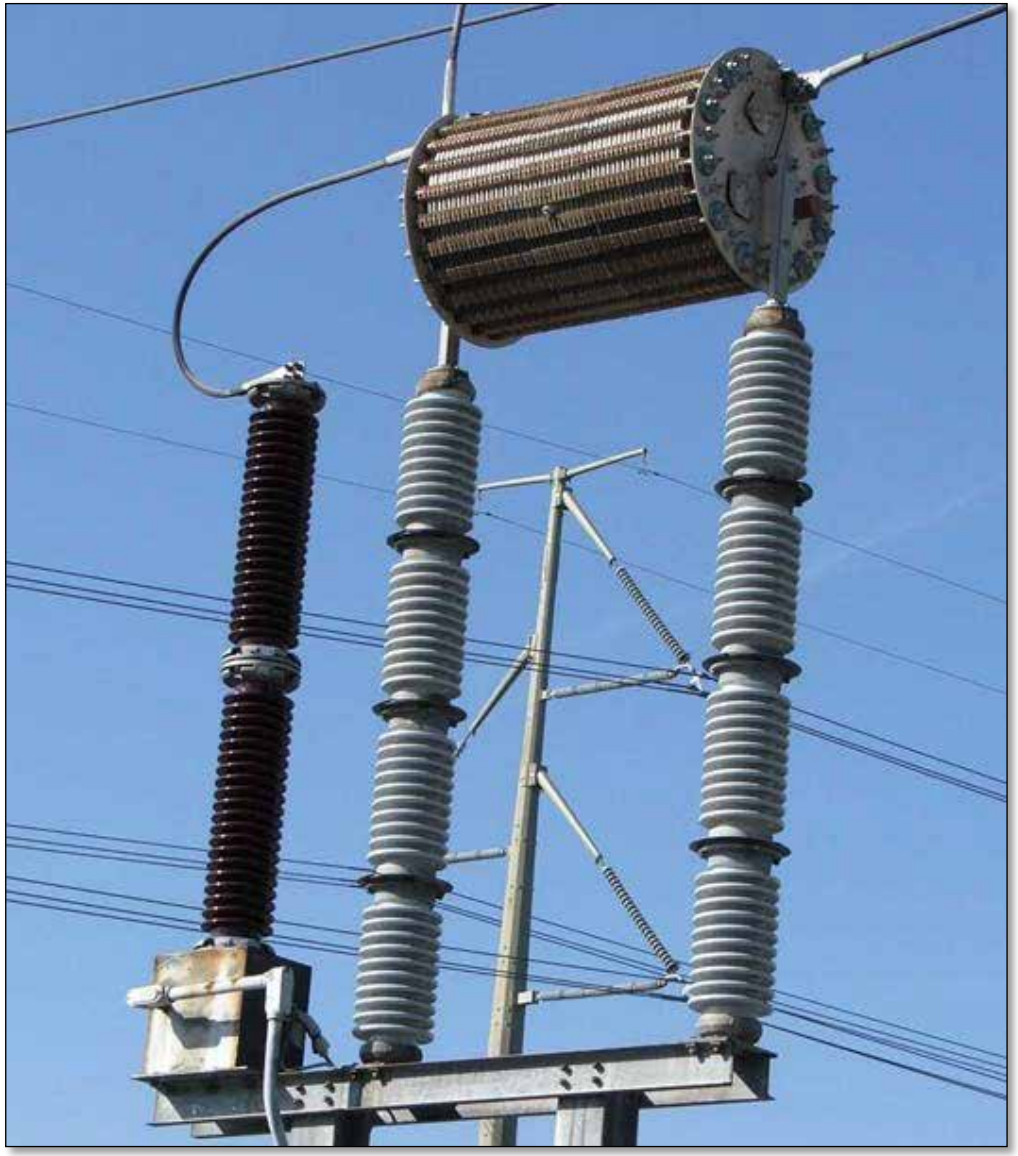
Other Substation Equipment

- **Wave Traps**
  - Wave Traps are inductors and capacitors installed in parallel in a single device
  - They act as high impedance “trap” to prevent Carrier wave signals from impacting the transformers and other Substation equipment
  - Carrier Waves are used on the BES in high-speed relaying applications and will be discussed more in the ITP Relay module

BES Transmission Substation Equipment

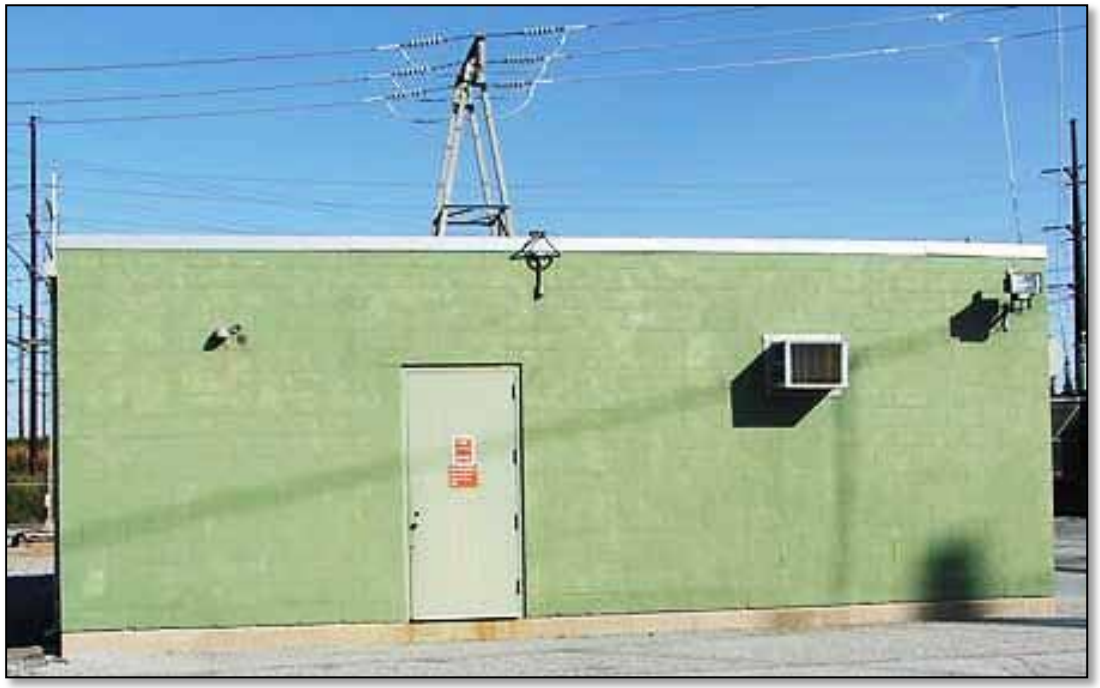
500 kV Wave Trap





BES Transmission Substation Equipment

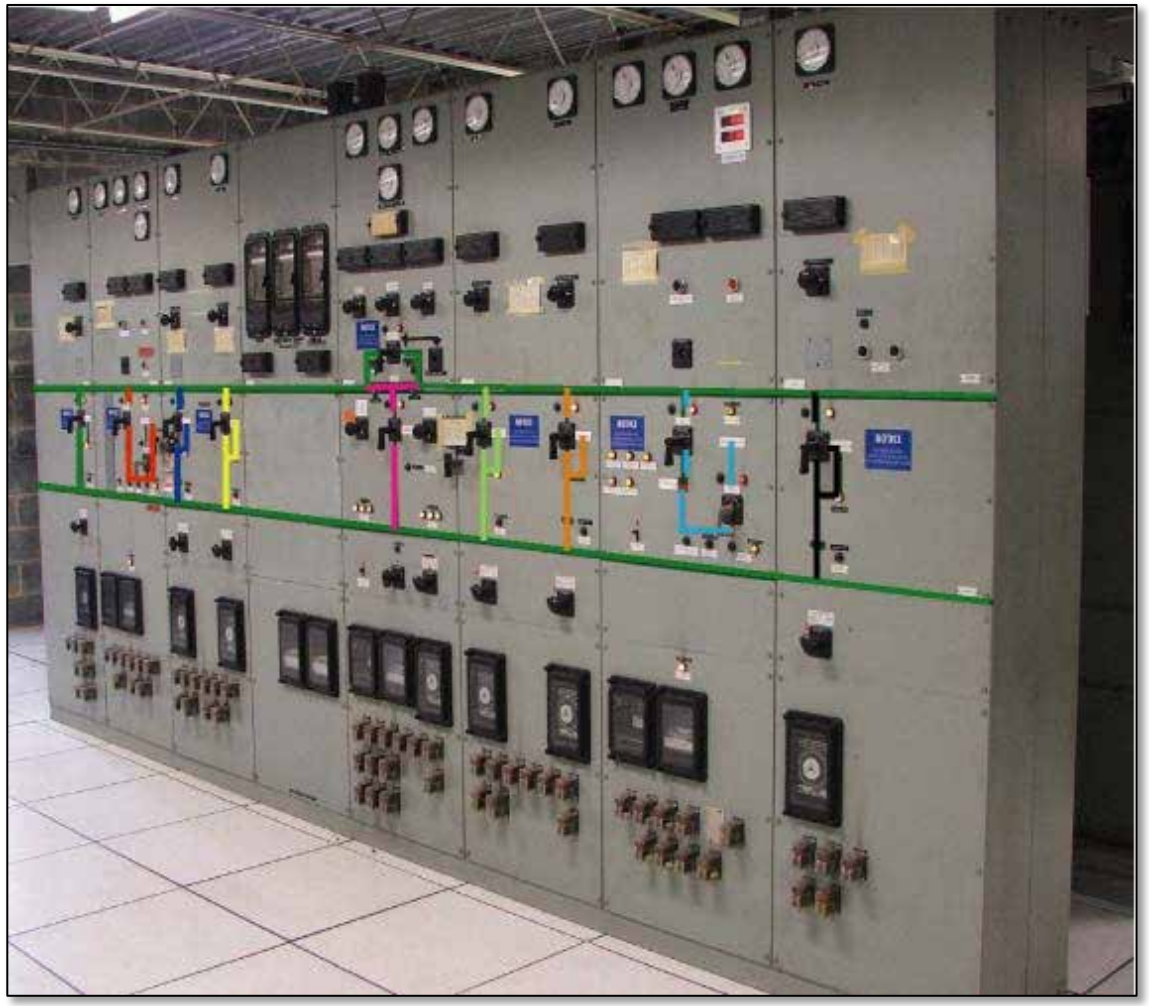
- **Control House**
- The control house contains switchboard panels, batteries, battery chargers, supervisory control, power-line carrier, meters, and relays and provides all weather protection and security for the control equipment



BES Transmission Substation Equipment

- A control panel is used in many substations to allow “remote” control to the circuit breakers, MOD’s, circuit switchers and other devices
  - The panel is set up to represent (or mimic) the electrical layout of the substation
- Indicating lights built into the panel near the control switches show the current status of the equipment in the yard
- If the substation has a synchroscope, it will be attached to the panel
  - We’ll discuss the importance of a synchroscope during the System Restoration Module

BES Transmission Substation Equipment



Control Panel



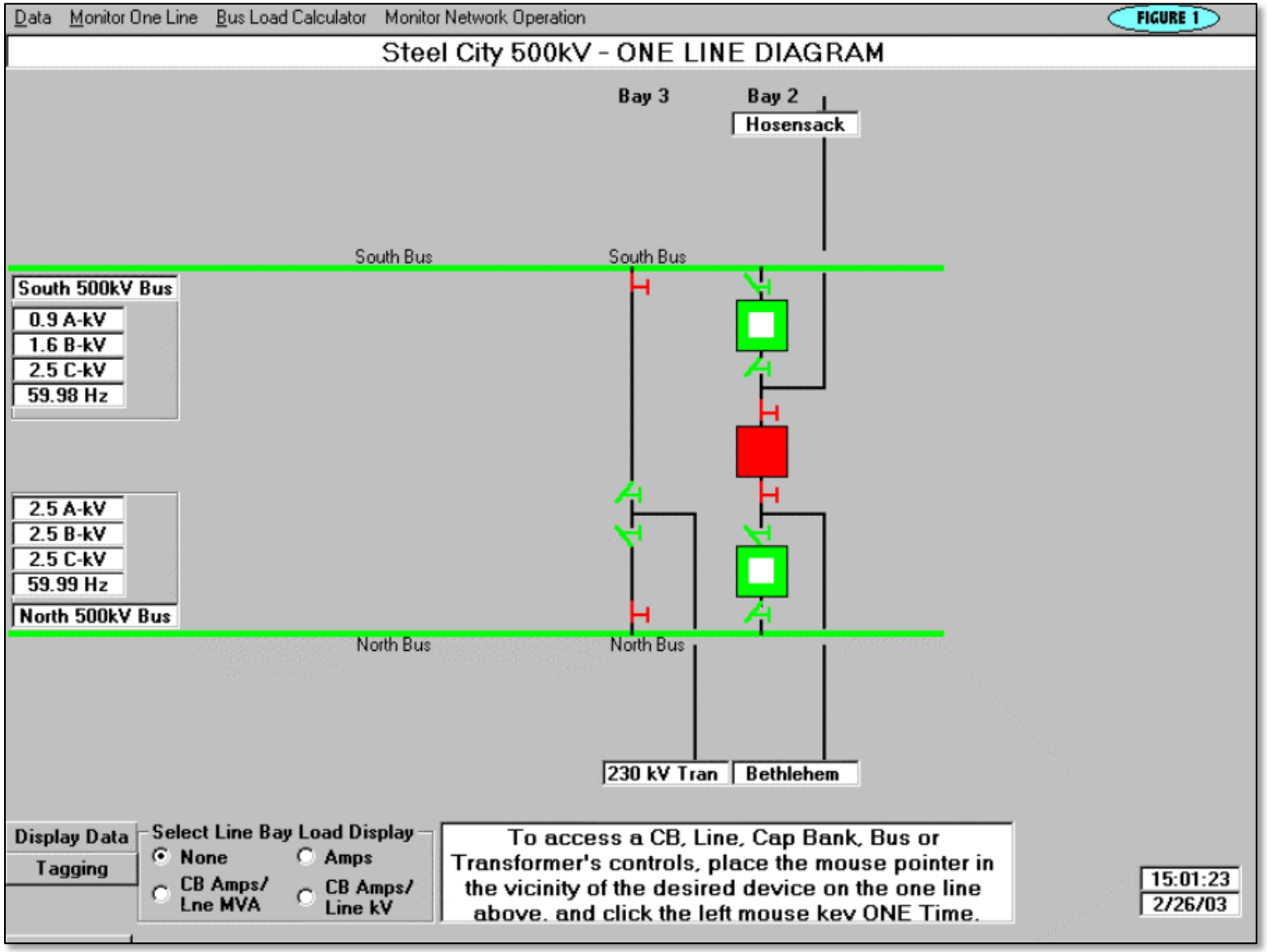
Control Panel with Synchroscope

BES Transmission Substation Equipment

- Newer substations are being placed in service that have no Control Panel. Instead, the remote device controls are operated by a computer system, and a PC display provides the electrical station layout
- This design is known as HMI (Human Machine Interface)
- Typical control panel hardware is replaced with software on local computer
- All control, tagging, and relay functions that would have used the Control Panel are copied in the HMI software

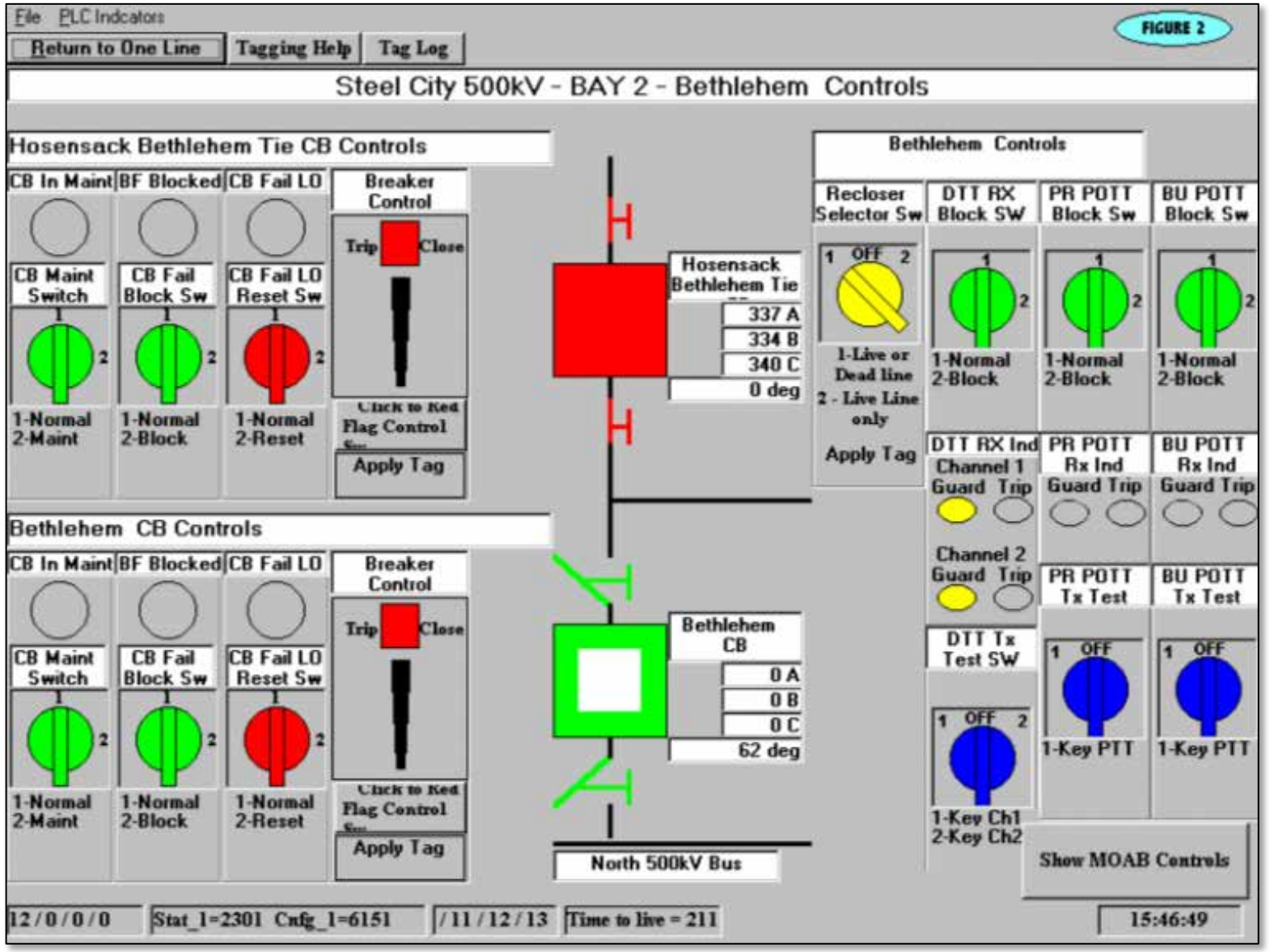
BES Transmission Substation Equipment

Screen Shot of an HMI CB display



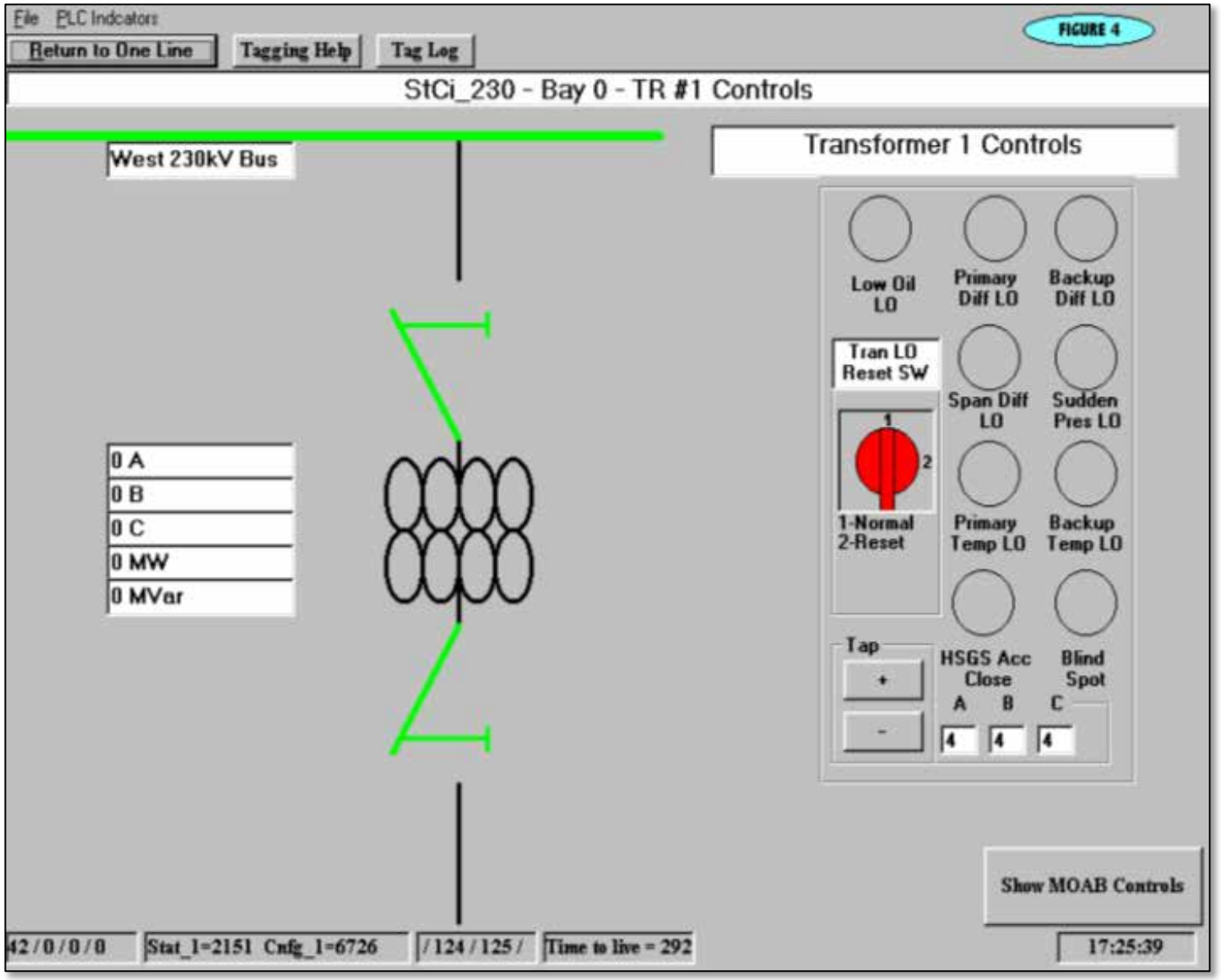
BES Transmission Substation Equipment

Screen Shot of the HMI CB and Relay Control display



BES Transmission Substation Equipment

Screen Shot of the HMI Transformer Control display



BES Transmission Substation Equipment

- **Substation Batteries**
  - Substation Batteries supply DC to relays, indicating lamps, SCADA, and trip coils in circuit breakers
  - Individual batteries are arranged and electrically connected in banks
  - Battery chargers (supplied from AC station service) are provided to maintain the charge on the batteries
  - The charge level on the battery bank is generally monitored and will alarm for high or low voltage levels
  - The continuity of the DC circuit supplied by the batteries is also monitored for the presence of a ground

BES Transmission Substation Equipment

Battery Bank in a 500 kV Substation

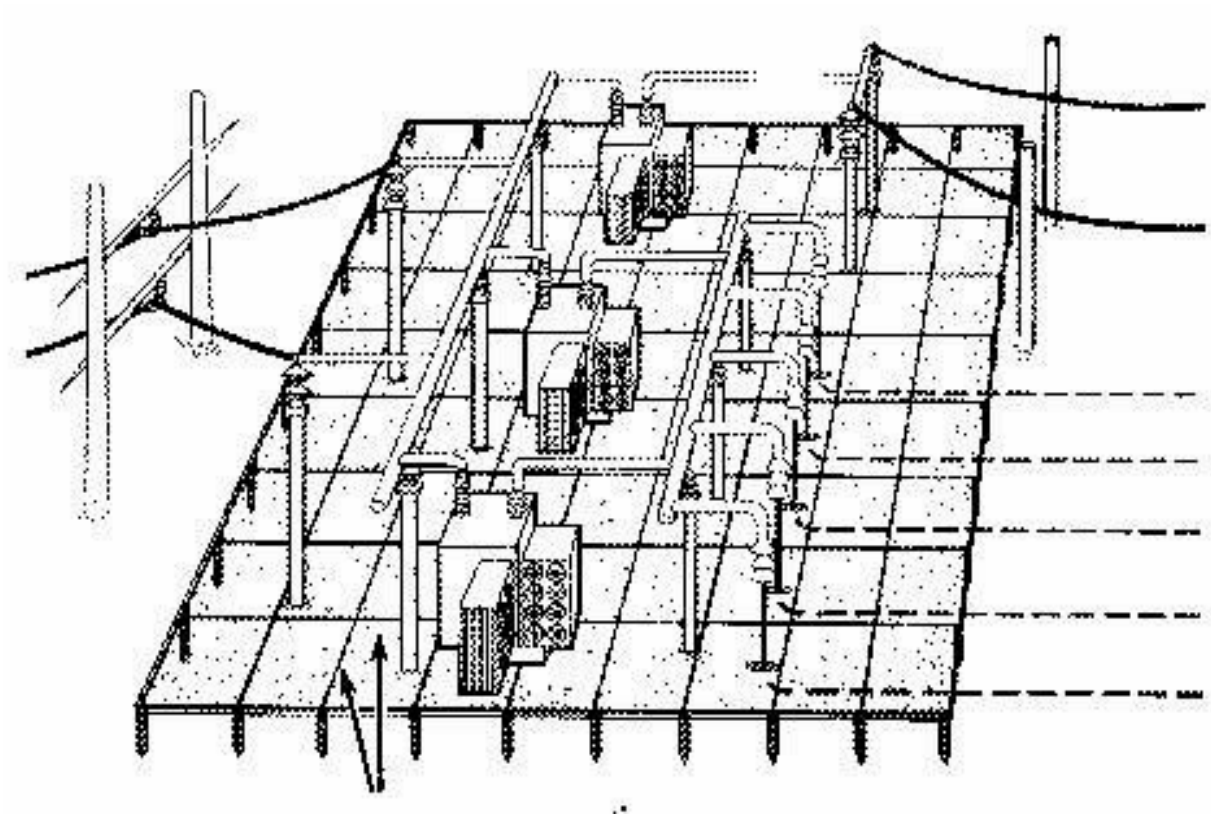


BES Transmission Substation Equipment

Grounding Grid

- The grounding system is a system of conductors laid out in a grid pattern beneath the entire substation
- A good (low resistance) connection to earth is very important for the proper operation of fault detecting relays in the substation
- The grounding grid also provides a location to which to connect the grounding mats, which are used to protect personnel as they operate switches in BES Substations

BES Transmission Substation Equipment



Typical Grounding Grid Layout



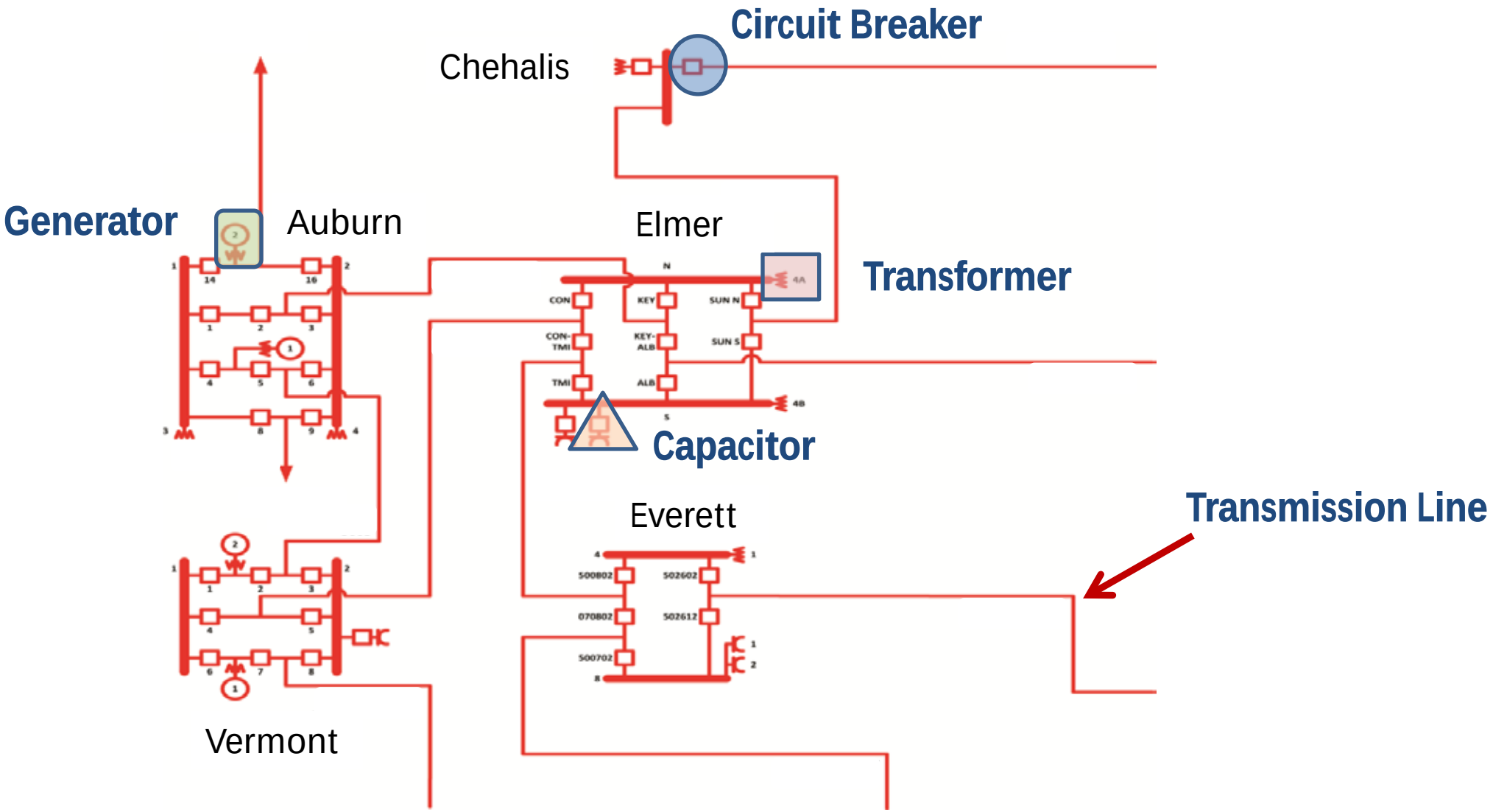
Grounding Mat Installed by a MOD

One-line Diagrams

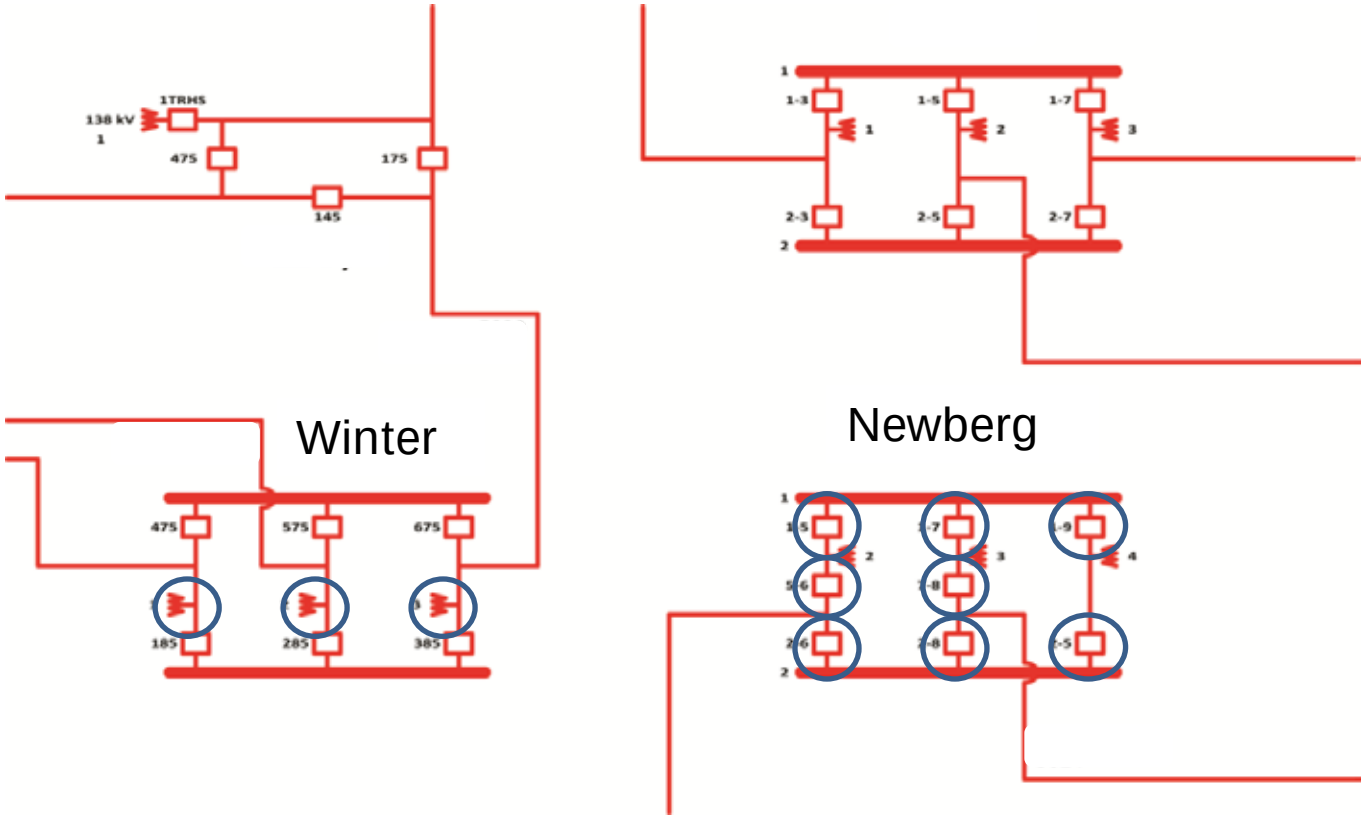
One-Line Diagrams

- One-line diagrams are used to display the equipment installed at substations in a uniform format
- Allows a large, uncluttered overview of large parts of the interconnected system

One-Line Diagrams



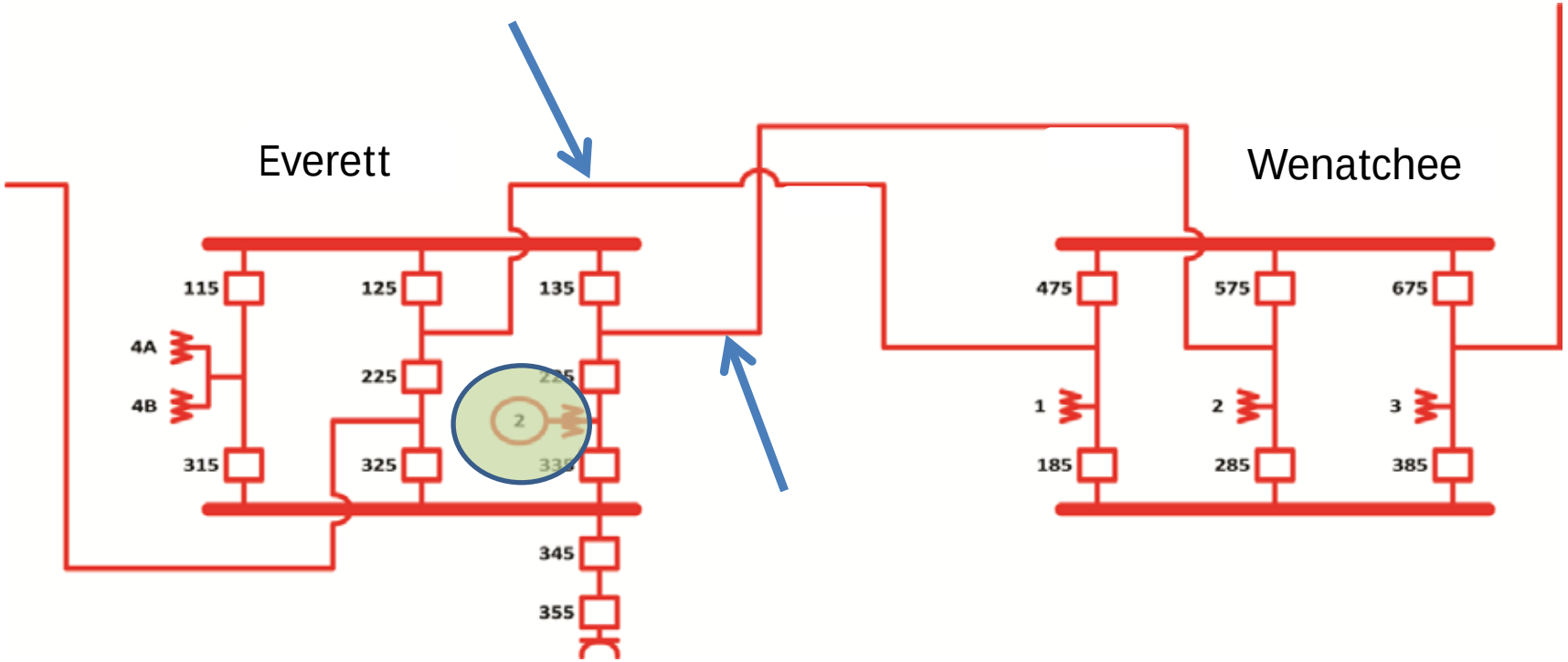
One-Line Diagrams Exercise 1



How many circuit breakers are located at Newberg Substation? **8**

How many transformers are located at Winter Substation? **3**

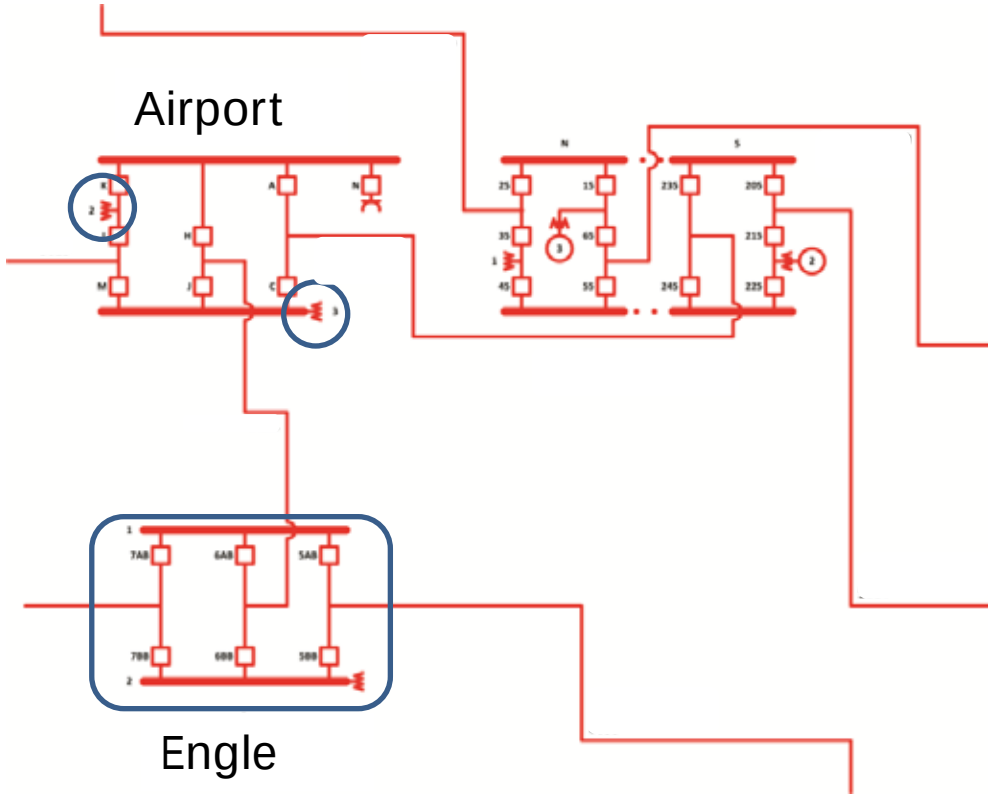
One-Line Diagrams Exercise 2



How many lines connect Everett and Wenatchee? **2**

Which station has a generator? **Everett**

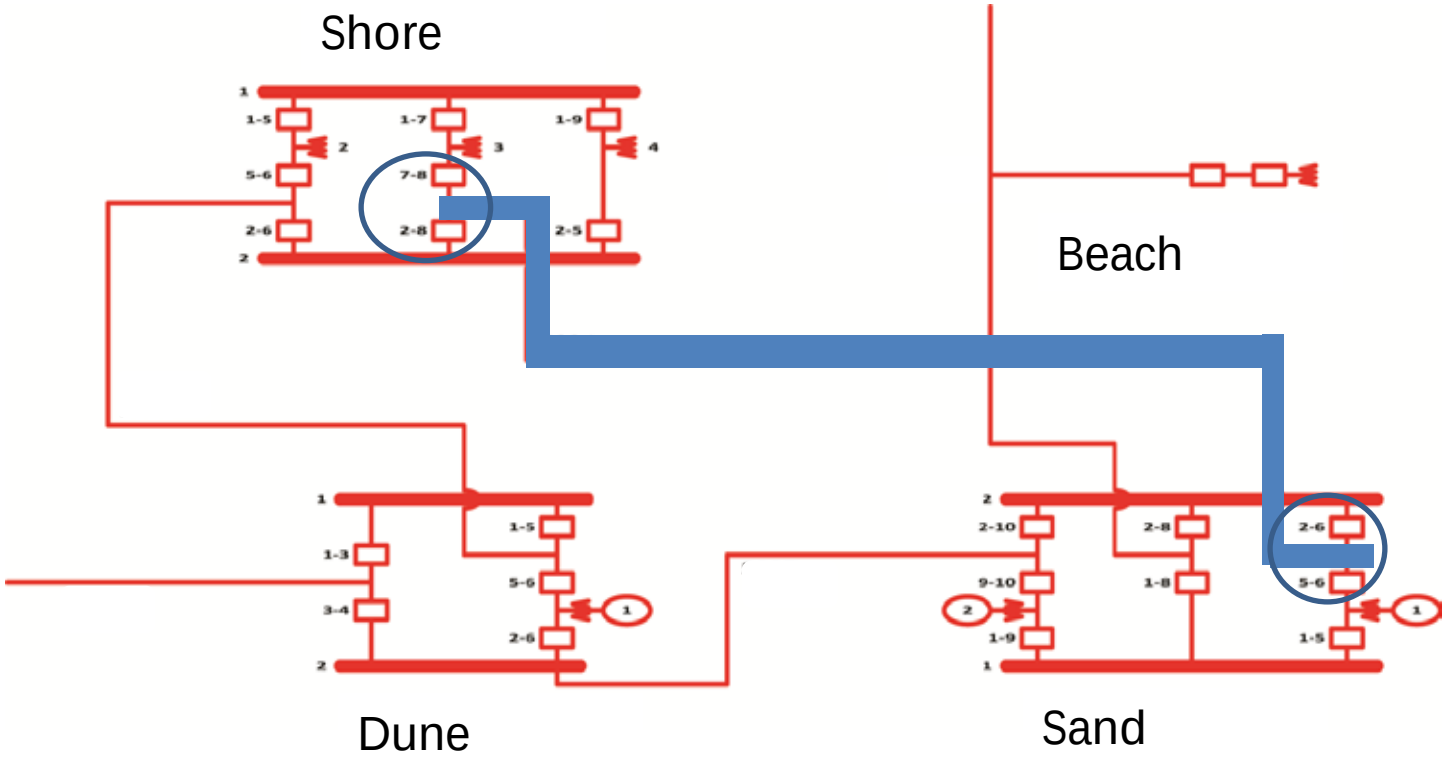
One-Line Diagrams Exercise 3



What type of Station design is Engle? **Double Bus – Double Breaker**

How many transformers are located at Airport? **2**

One-Line Diagrams Exercise 4



If the 500 kV line between Shore and Sand develops a fault, which breakers have to open to isolate that fault?

Questions?

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Website: www.pjm.com



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