

# **Power System Fundamentals**

## **Relay Applications**

**PJM State & Member Training Dept.**

At the end of this presentation the Student will be able to:

- Describe the purpose of protective relays
- Identify relay protection scheme characteristics and components
- Describe the impact of the loss of components on system protection
- Identify the types of transmission line protection and their characteristics
- Identify the types of transformer protection and their characteristics
- Identify the types of bus protection and their characteristics
- Identify the types of generator protection and their characteristics

# **Basic Concepts in Protection**

# Purpose of Protective Relaying

- To detect and isolate faulted or malfunctioning equipment in order to:
  - 1) limit the extent of the system disturbance and
  - 2) maintain system reliability

## The Source

Utility Distribution System

Main Service Entrance Panel

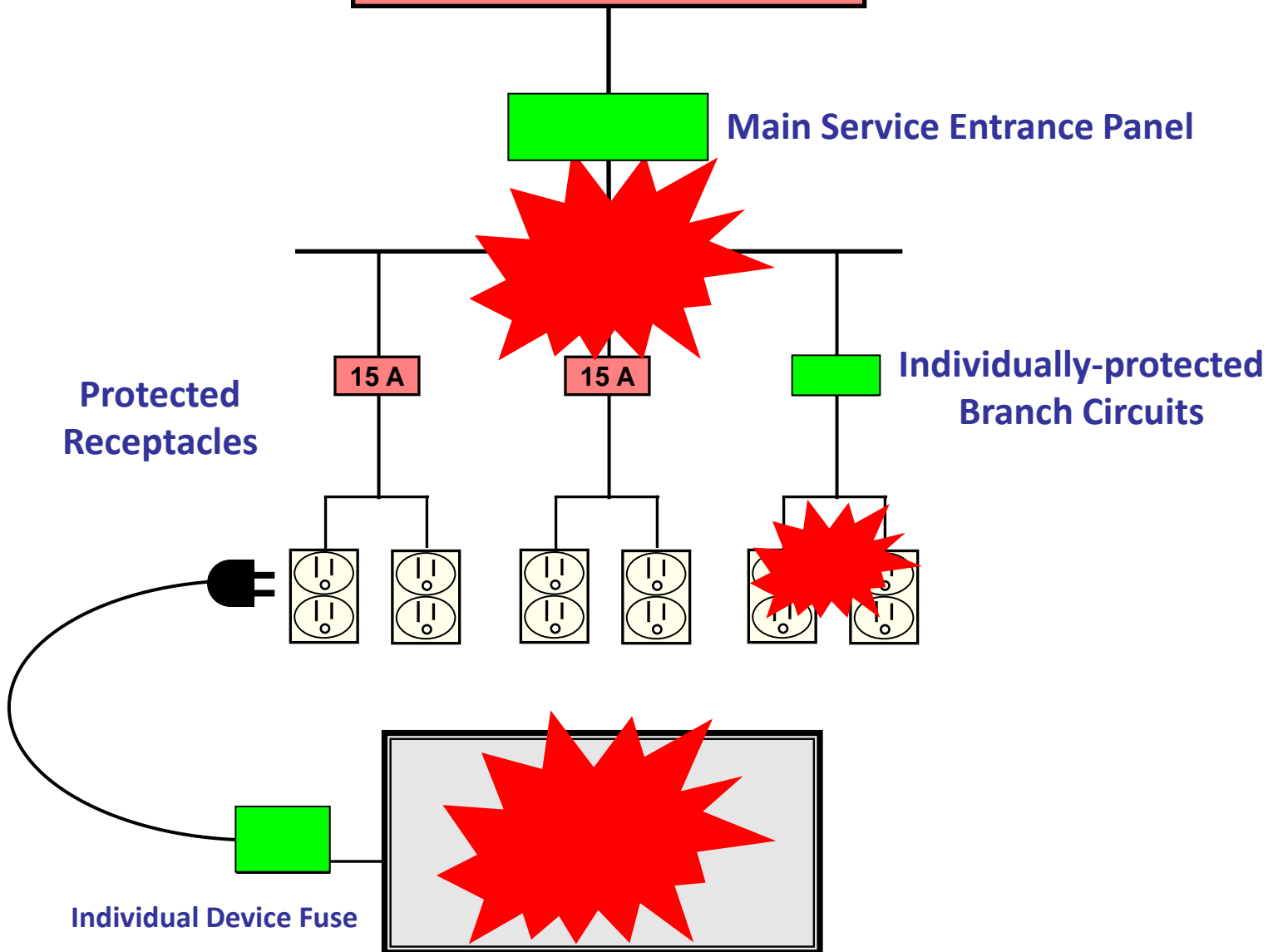
Protected  
Receptacles

15 A

15 A

Individually-protected  
Branch Circuits

Individual Device Fuse



# Basic Concepts

- Relays are the intelligence in a Protective Scheme
  - They monitor system “inputs” and operate when the monitored quantity exceeds a predefined limit
  - Relay response will initiate a desirable system event that will aid in maintaining system reliability (i.e. trip a circuit breaker, throttle back a unit, etc)

# Basic Concepts

- Other devices which are used in conjunction with Protective Relays are:
  - Current Transformer (CTs)
  - Potential Transformers (PTs)
  - Other Sensing Devices (e.g. Temperature, Oil Level, Pressure, etc.)
  - Logic Circuits (Analog or Microprocessor)
  - Three Pole Interrupting Devices (CBs, Circuit Switchers, Motor Operated Disc)

# Basic Concepts

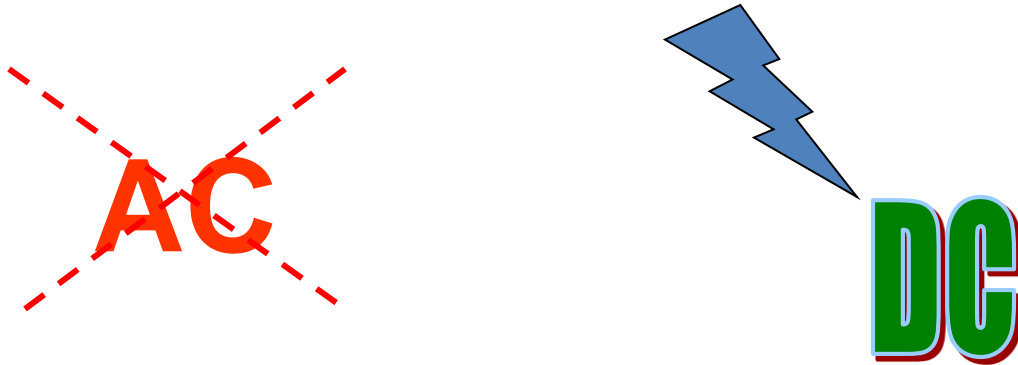
- Most Relay schemes work to control a DC system
  - DC System usually has rack of Batteries and a battery charger
  - Generally controls the tripping of CBs
  - This why NERC compliance includes DC Control Circuitry and Batteries as part of the Relay Standards



# Relay Scheme Components

# DC Control Systems

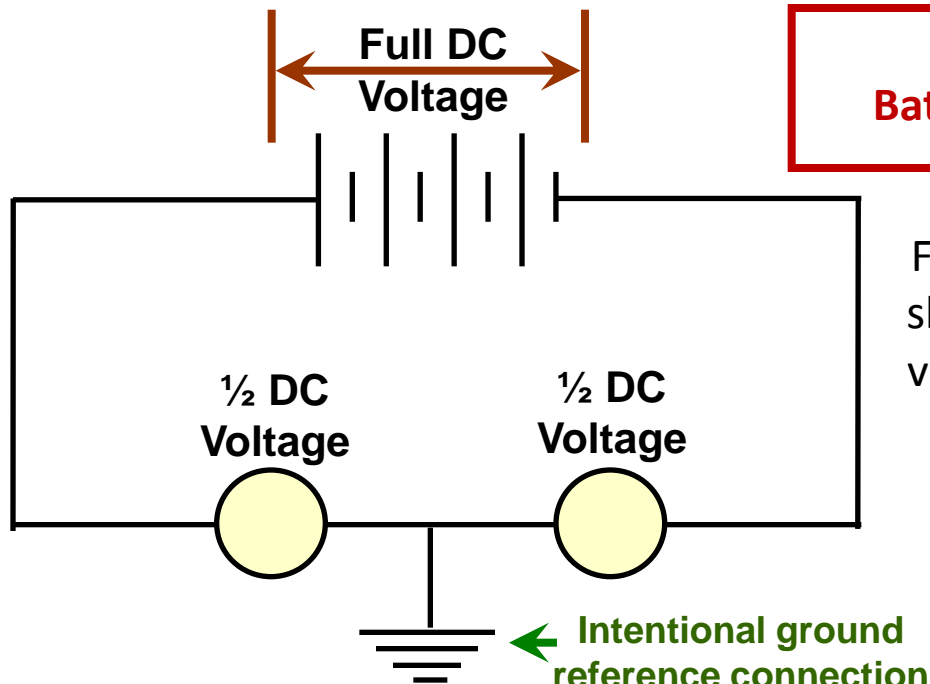
- The power source used for controlling power system equipment must be highly reliable and **not subject to interruption by power system transients or outages**



- Protection and control circuits are individually fused to guard against disrupting the entire DC system for problems on a particular branch circuit
- Amber lights** often monitor the DC supply to individual branch circuits, giving a visual indication that the circuit is energized

# DC Control Systems

- With few special exceptions, DC systems operate ungrounded
- Power plants and most substations have some battery ground detection, very often including *ground indicating lamps* that visually alert personnel to inadvertent DC system grounds

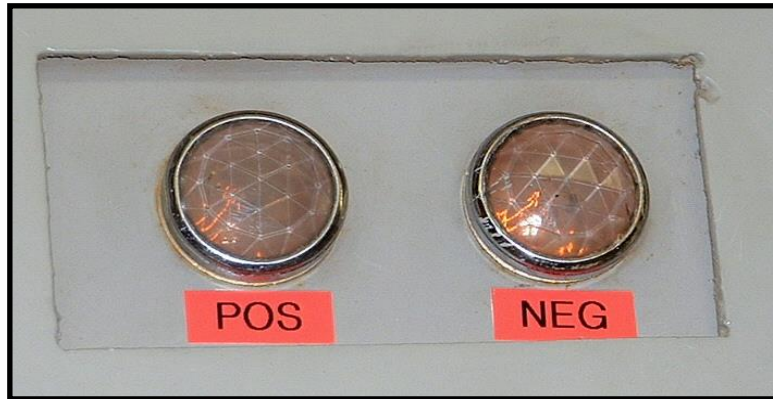


## Illustration Of Battery Ground Detection Lamps

For the normal, ungrounded condition shown, the two lamps each have equal voltage dropped across them and glow with equal brilliance

# DC Control Systems

## Illustration Of Actual Battery Ground Indicating Lamps



**Normal Battery Ground Lamps  
Approximately Equal Brilliance**



**Battery Ground Lamps Indicate A Solid Ground  
On The Positive Side Of The DC System**

- This same principal of DC ground detection is used in more sophisticated devices that provide an alarm contact instead of just a visual indication
- A single inadvertent ground on an ungrounded DC system is not catastrophic...the danger is that a second inadvertent ground could occur on the *opposite side of the DC supply* and short out the battery!

# DC Control Systems

- **COMMON CAUSES OF BATTERY GROUNDS**



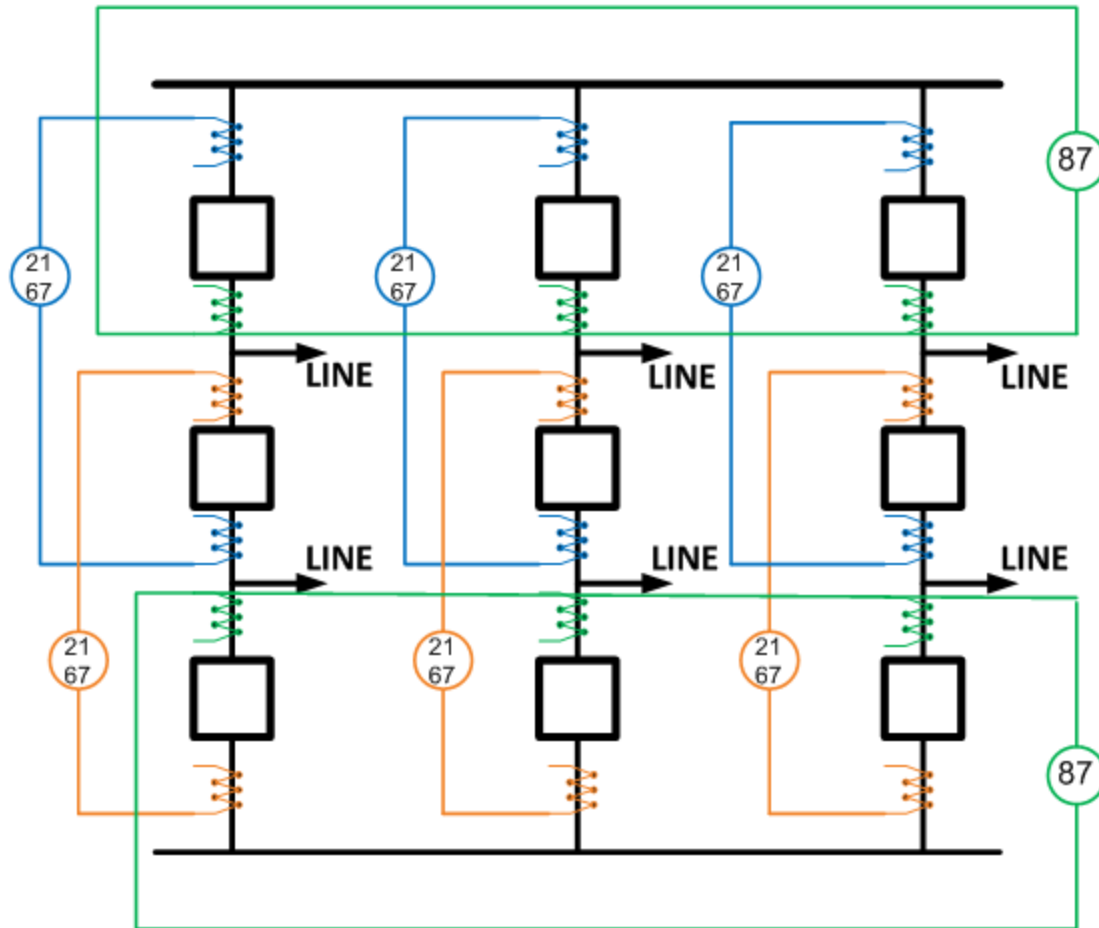
# Overview of Power System Protection

# Overview of Power System Protection

- Key element to remember
  - Protective Schemes are designed to have:

**OVERLAPPING ZONES  
OF PROTECTION!**

# Overlapping Zones of Protection



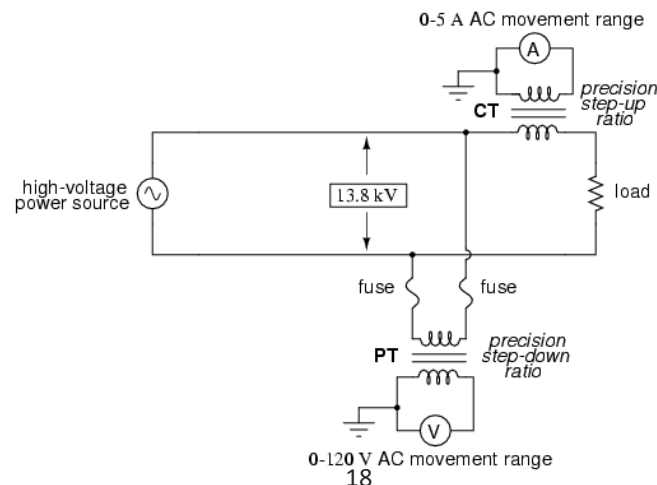


# Overview of Power System Protection

- Critical elements of the power system are protected by “Primary” and “Backup” relay systems
  - Primary Schemes are generally high speed schemes (operate speed = 1 cycle)
  - Backup Schemes can also be high speed but don’t have to be. System conditions dictate if this scheme has to be as fast as the primary scheme

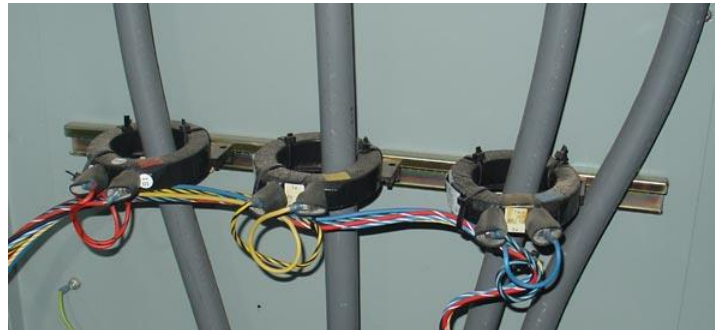
# Instrument Transformers

- Instrument Transformers change *primary* voltages and currents into *secondary* quantities having proportional magnitudes and identical phase angle relationships
  - Primary current is transformed by CTs (Current Transformers) and LCs (Linear Couplers)
  - Primary voltage is transformed by PTs (Potential Transformers) and CCVTs (Coupling Capacitor Voltage Transformers)



# Current Transformers (CTs)

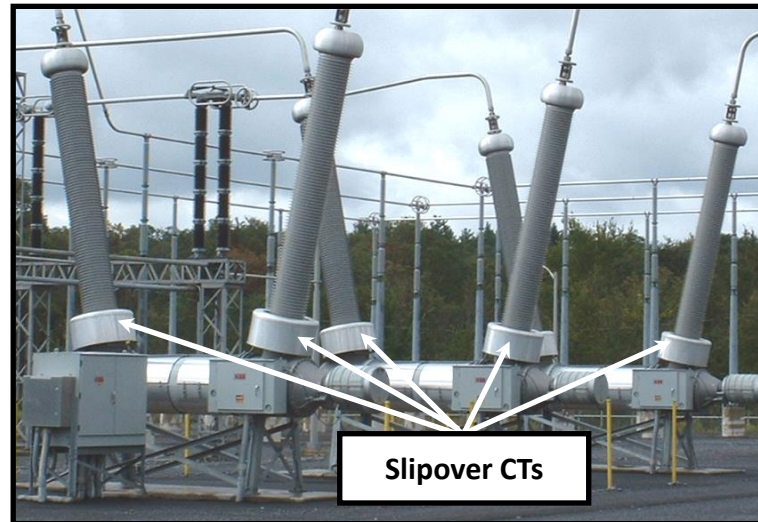
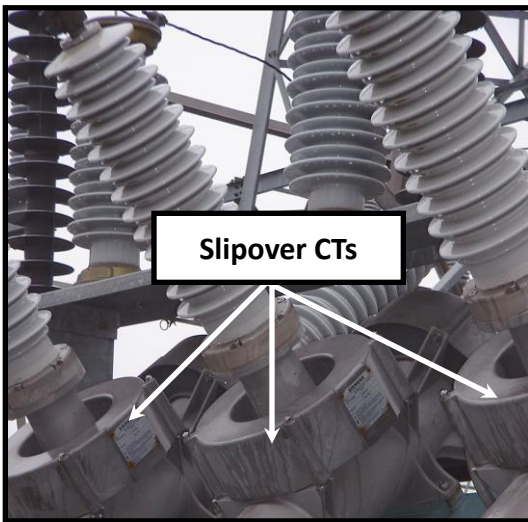
- CTs transform high magnitude primary amps to secondary amp quantities within the current ratings of relays and meters
- CT ratios are typically expressed as Primary Amps/5
  - For example, a generator CT ratio expressed as  $25000/5$  means that **5000 amps** flowing in the **primary circuit** results in **1 amp** flowing in the **secondary circuits**
  - CTs that fit around breaker, generator, or transformer bushings are called bushing CTs; these are the most common type of CTs



# Current Transformers (CTs)

- A CT is a nearly ideal current source...within the limits of its construction, a CT produces as much voltage as necessary to push secondary current proportional to the primary current through a connected load, no matter how large the load impedance
- Ohm's Law,  $V = Z \times I$ , describes how much voltage,  $V$ , a CT must produce to drive its current,  $I$ , through connected load impedance,  $Z$ ...as  $Z$  gets bigger,  $V$  must also increase to satisfy the equation!

**If the secondary circuit of a load-carrying CT is open-circuited, the CT can produce high enough voltage to injure or kill personnel**



## Illustrations Of Externally Applied Current Transformers

### ABOVE LEFT

Slipover CTs installed on a 69kV circuit breaker

### ABOVE RIGHT

Slipover CTs installed on a 500kV circuit breaker

### BELOW

Similar to the bushing CTs pictured above, the window CTs below have a single turn primary winding comprised of the primary current conductor passing through the center of the CT



## Linear Couplers (LCs)

- LCs transform high magnitude primary amps to secondary voltages within the voltage ratings of relays and meters
- Linear Couplers can be *thought of* as having an air core instead of iron, like a CT. This conceptualization isn't *technically* correct, but unless you plan to actually build a linear coupler it's good enough to distinguish between CT and LC construction

# Potential Transformer (PTs)

- PTs transform primary voltages to the 115 VAC or 69 VAC secondary voltages used in relay and metering circuits
- Large generators usually have two sets of PTs, sometimes referred to as the **metering PTs** and the **regulator PTs**. These designations don't necessarily identify function, since both sets of PTs provide voltage to various protective relays and meters
- Although one set of PTs (the **regulator PTs**) is the preferred source of voltage to the generator voltage regulator, either set is usually capable of serving this function
- With a few exceptions, PTs aren't used at transmission voltage levels...most higher voltage applications use a derivative of the PT, the **Capacitance Potential Device**

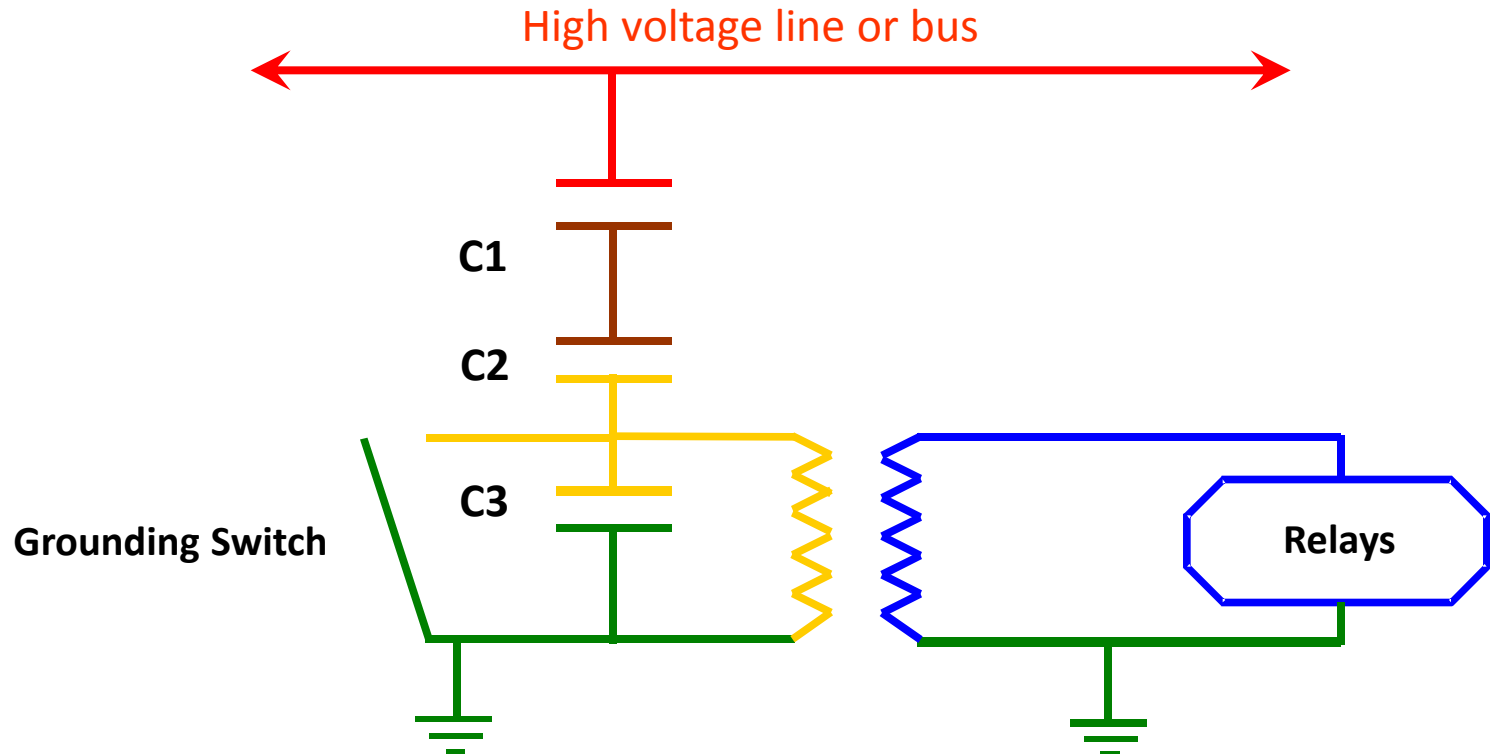
# Capacitance Potential Devices

- Known as CCPDs (Coupling Capacitor Potential Devices) or CCVTs (Coupling Capacitor Voltage Transformers)
- These devices use voltage division to reduce primary voltages to the 115 or 69 VAC needed by relays and metering equipment:
  - Primary voltage divides across porcelain capacitance stacks, the higher the voltage the more units in the stack. A transformer in the CCVT base does the final transformation from several thousand volts to 115/69 VAC
- Due to voltage division, a failure in one stack can act as a row of dominoes resulting in more failures



# Diagram Of CCVT Construction

- Primary voltage divides across capacitance stacks C1, C2, and C3
  - Voltage across C3 equals approximately 20 kV

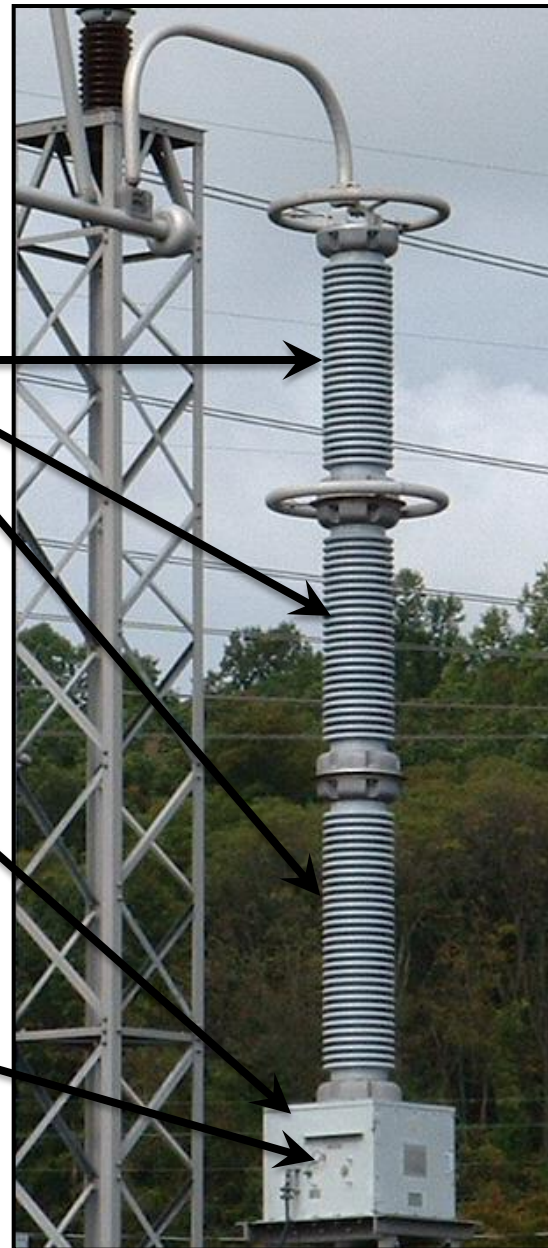


**Illustration Of 230kV CCVT**



**Notice that the 230kV CCVT has 2 capacitor stacks, while the 500kV CCVT needs 3 stacks to divide the higher primary voltage**

**Illustration Of 500kV CCVT**



**Capacitor  
Stacks**

**Transformer  
Enclosure**

**Grounding  
Switch**

# Overview of Power System Protection

- As with most things, there is a balance between preserving system reliability and economics
- Must review the cost of the protective scheme against the probability of a particular event occurring



# Relay Scheme Design Considerations

- **Sensitivity** - can scheme detect all “events” that it is supposed to?
- **Selectivity** - will it remove only the “faulted” piece of equipment?
- **Speed** - can the scheme clear the fault fast enough to maintain or insure system integrity?
- **Reliability** - will the scheme be secure and dependable?
  - Security** - no misoperations
  - Dependability** - operate when it should
- **Economy** - Provide the desired level of protection for the least cost
- **Simplicity** - Attempt to keep designs straightforward

# Relay Devices

# Definition

- A relay is a device that will change its output contact status due to the excursion of a monitored system input beyond a preset value
- Examples:
  - Current exceeds preset value
  - Oil level below required spec
  - Temperature above required spec

# General Functions:

- Protective
  - remove a system disturbance from the power system
- Regulating
  - insures system is operated within proper guidelines
- Auxiliary
  - Other less critical functions (i.e. alarms, reclosing. etc.)





**Electromechanical**



**Solid State**



**Microprocessor**



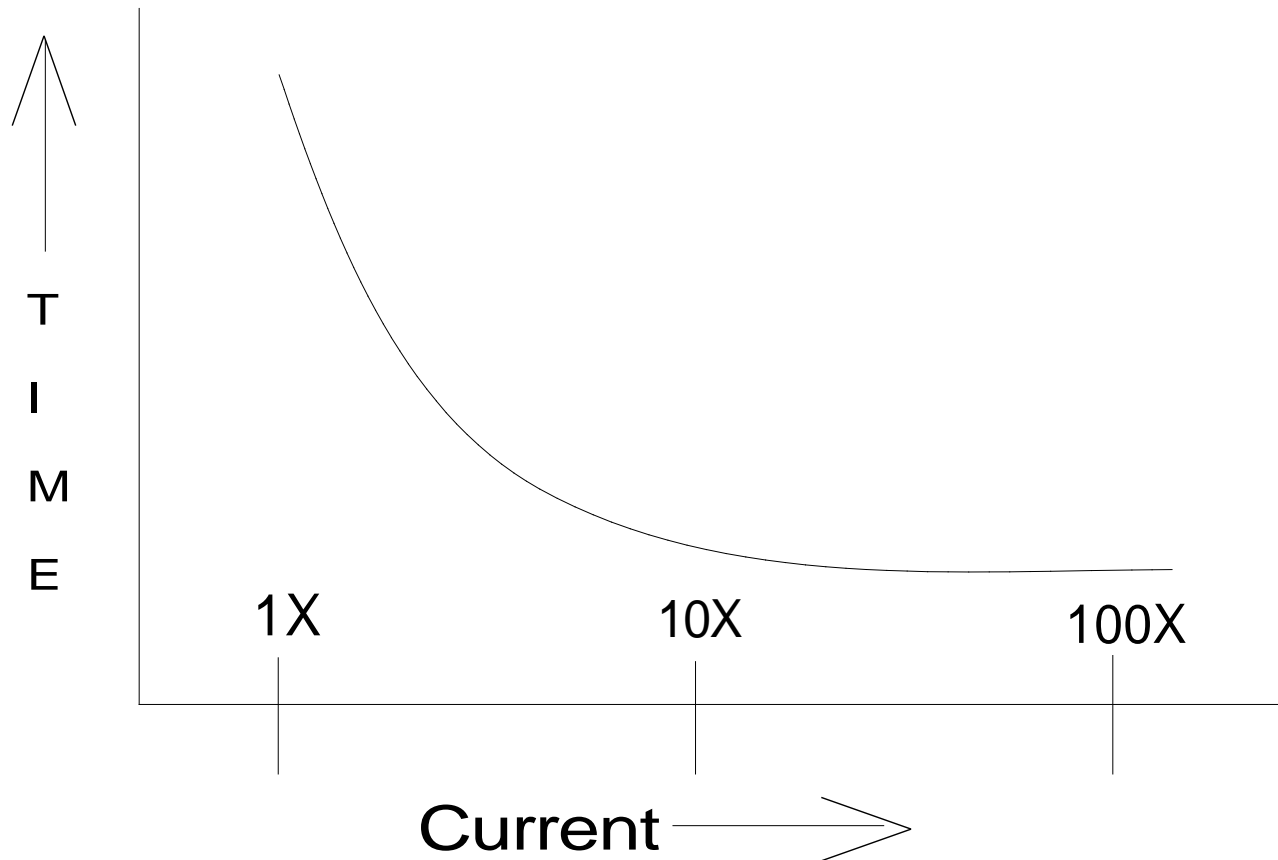
# Universal Numbering System for Protective Relays

IEEE #	Device	Relay Function	IEEE #	Device	Relay Function
21	Distance Relay	Requires a combination of high current and low voltage to operate. The various zones of the distance scheme (Z1, Z2, etc.) assist with determining the location of the fault	63	Pressure Relay	Operates on low or high pressure of a liquid or gas (oil or SF6) or on a rate-of change of pressure (sudden pressure)
25	Synchronizing Relay	Checks voltage magnitude, phase angle, and frequency to verify synchronism across a CB before allowing a close	67	Directional Overcurrent	Operates if current is above a set value and flowing in the designated direction
27	Undervoltage Relay	Operates when voltage falls below a set value	78	Out-of-Step	Detects loss of synchronism.
49	Thermal Relay	Operates when the temperature (usually a winding) rises above a set level	79	Reclosing Relay	Initiates an automatic closing of a circuit breaker following a trip condition
50	Instantaneous Overcurrent	Operates with no time delay when current rises above a set level	81	Frequency Relay	Operates if frequency goes above or below a set limit
51	Time Overcurrent	Operates on a time-delayed basis depending on the amount of current above a set level	86	Lockout Relay	An auxiliary relay that can perform many functions (including tripping of breakers) and prevents closing of circuit breakers until it is reset either by hand or electrically
52	Circuit Breaker	Circuit Breaker	87	Differential Relay	Senses a difference in currents entering and leaving power system equipment
59	Overvoltage Relay	Operate when voltage exceeds a set limit	94	Tripping Relay	Auxiliary relay which is activated by a protective relay and which initiates tripping of appropriate breakers

# Typical Performance Parameters:

## Overcurrent

- Required input: Current from CTs
- Instantaneous - No intentional time delay
- Time delayed - Inverse time/current curve
- Can protect for both Phase and Ground faults. The physical connection determines what current (phase or ground) the relay will respond to



**Current** →  
**Inverse Curve Characteristic**

# Typical Performance Parameters:

## Over/Under Voltage:

- Required input: Voltage from PTs
- Instantaneous - No intentional time delay
- Time delayed - Generally a fixed delay
- Generally used for automatic sectionalizing control (i.e. auto transfer schemes, etc.)

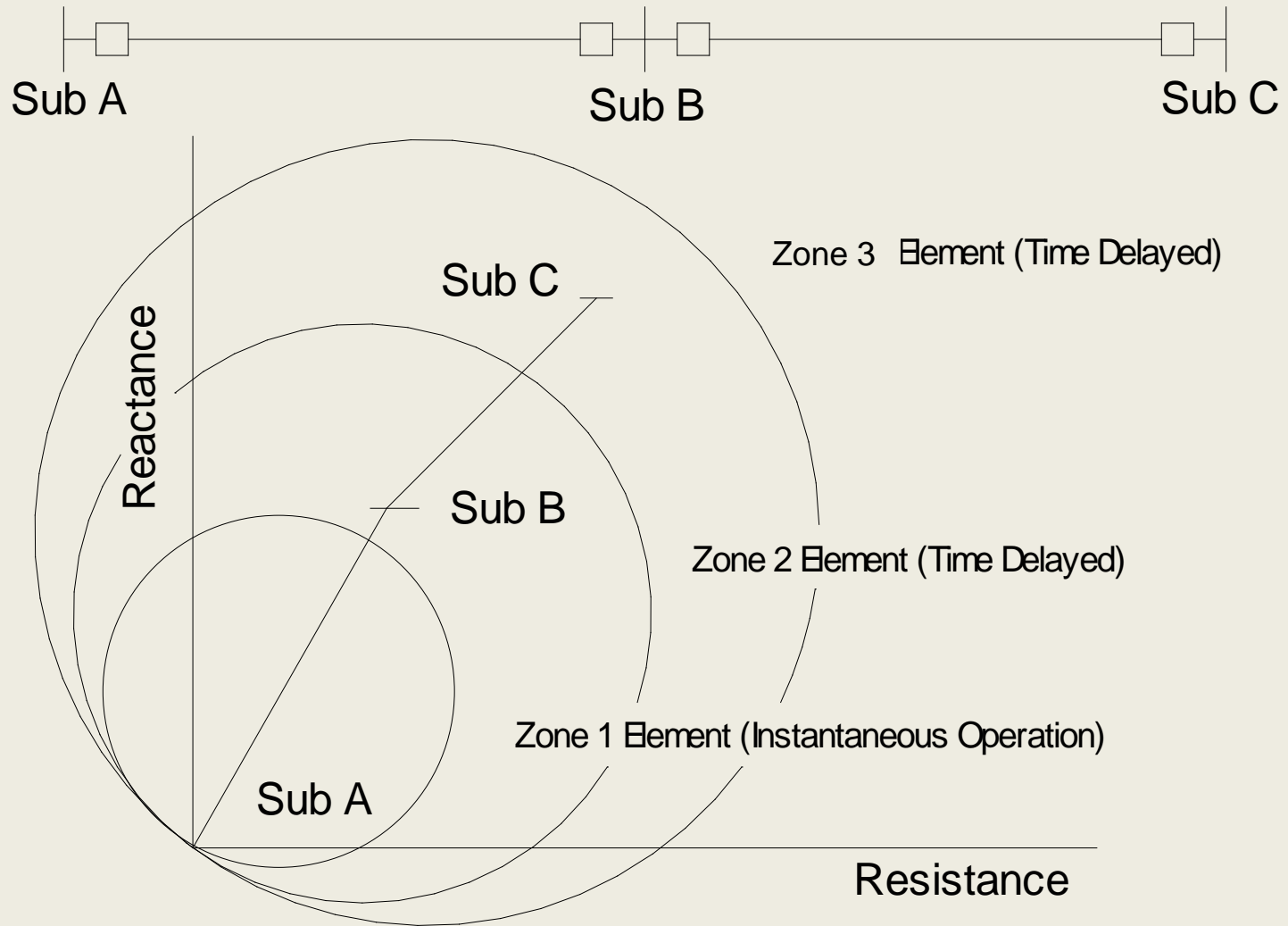
# Typical Performance Parameters:

- Directional Capability
  - Required Inputs: Current and Voltage
  - Can be a stand alone relay or associated with another relay element
  - Directionality makes the life of a protection engineer much easier from a relay coordination point of view

# Typical Performance Parameters

- Stepped Distance Relaying
  - Requires Current and Voltage inputs
  - Operates on the  $V/I = Z$  (impedance) principle
  - Constant reach regardless of system
  - Less susceptible to misoperating on load current (when compared to simple phase overcurrent relays)
  - Usually provides three Zones of Protection:
    - Zone 1 - Instantaneous Operation  
Set for approximately 90% of line
    - Zone 2 - Fixed Time Delay Operation  
Set to see entire line + margin
    - Zone 3 - Fixed Time Delay Operation  
Set greater than Zone 2

## Stepped Zone Distance Protection



# Backup Transmission Line Protection

- Note that Zone 1 can only be set to see, at most, 90% of the protected line
- Cannot be set to see 100% of the line
  - Relay would not be able to distinguish between an internal or external fault
  - Setting relay to see 100% of line to obtain instantaneous clearing would most likely result in an overtrip
- This is the major disadvantage of a Stepped Distance scheme



# Transient Load Limits

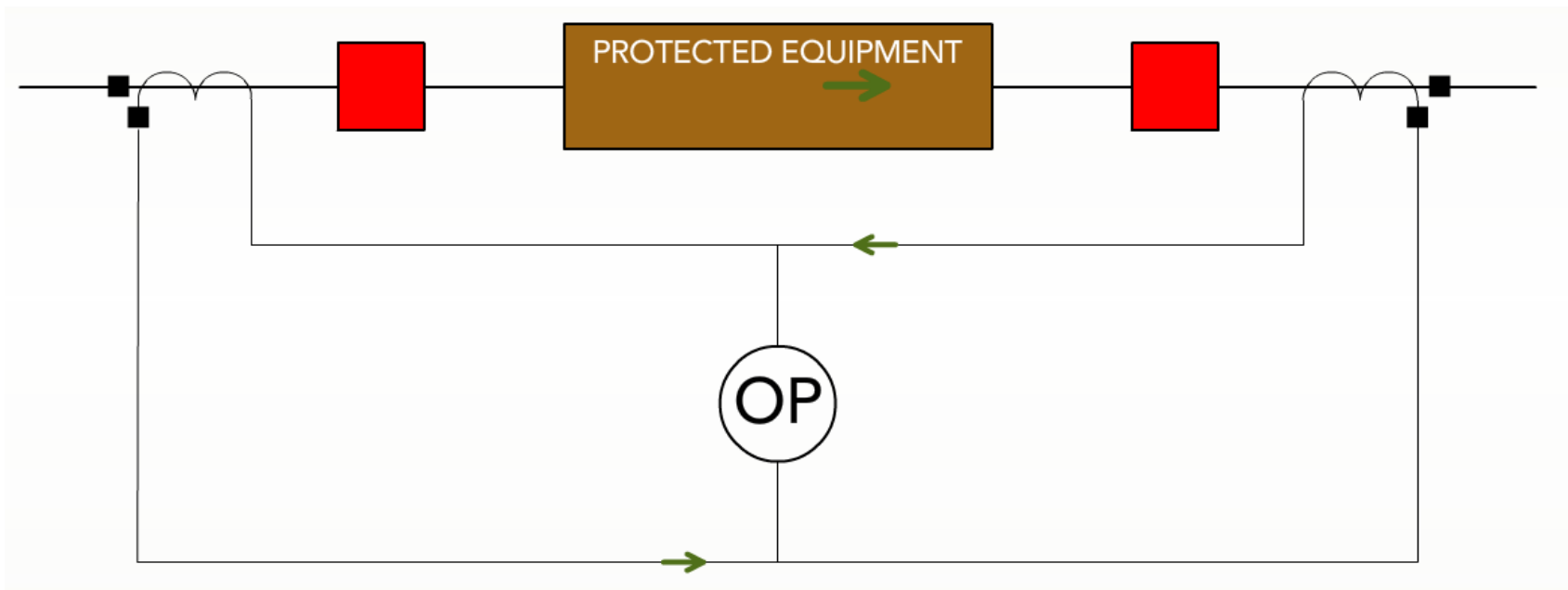
- Load carrying capability is another concern with distance relays
- Transient limit represents the maximum secure load carrying capability of the protective relays during actual operating conditions
- Precise determination is difficult without the use of system stability studies
- An approximate method is used which derates the relays steady state load limit at the “maximum bulge point”

# Typical Performance Parameters:

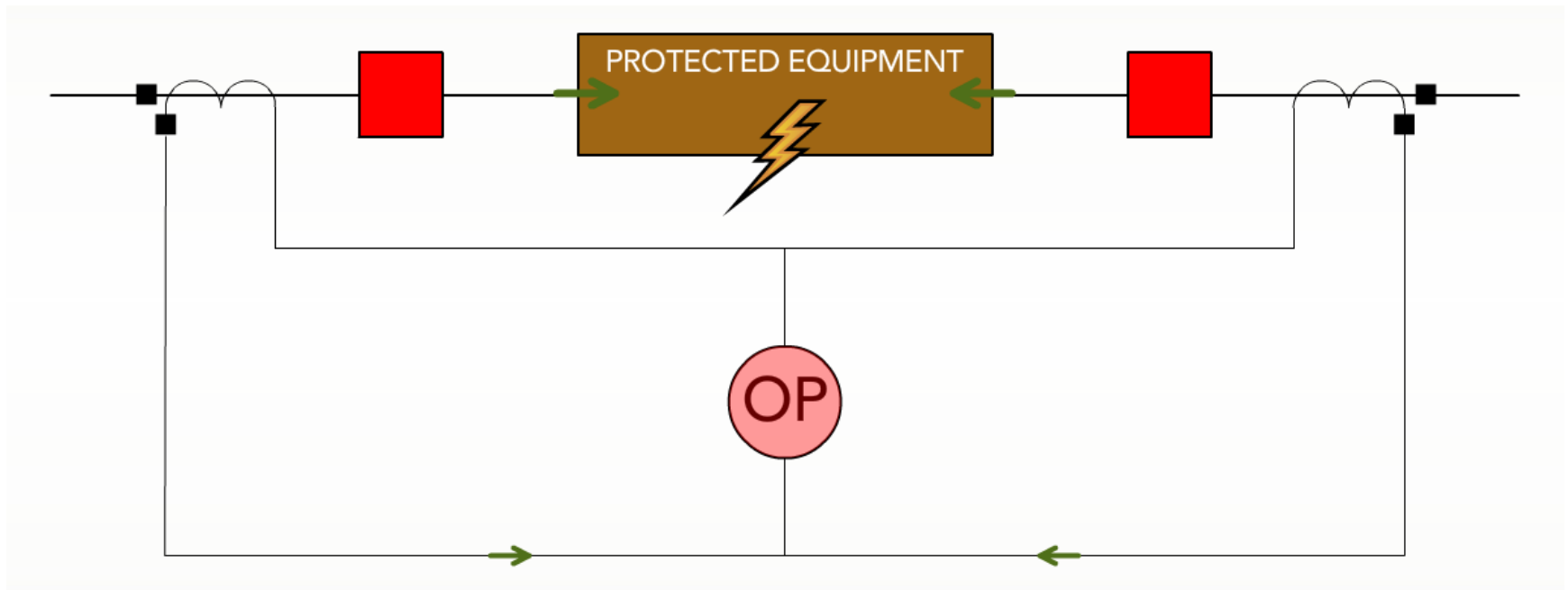
## Differential

- Required input: Current from CTs
- Relay generally operates very fast (1 cycle)
- Normal protection for Generators, Transformers and Bus sections
- CTs supplying the relay should be matched so that currents into the “zone of protection” are equal to those currents that leave
- The difference/mismatch in current is observed in the relays operate coil

# Differential Relay



# Differential Operation



# Typical Performance Parameters:

- Other Types (not all inclusive):
  - Frequency - Typically uses voltage
  - Reclosing - Single or Multi-shot
  - Thermal - Transformer Protection
  - Auxiliary - Master Trip, 52X, etc

# Lockout Relays

- Lockout Relays
  - Special devices operated by dozens of functions that protect generators, transformers, busses and various other pieces of switchyard equipment
  - Relay itself doesn't *protect* anything; instead, it has multiple contacts that cause multiple devices, like circuit breakers, to operate in order to de-energize or isolate failed equipment
  - Serve an important function: if they failed to trip for a fault, for example, the switchyard GCB would stay closed and the equipment would remain energized
  - Because it's so important, the electrical coil that trips the lockout relay is monitored continuously by an amber lamp located immediately above the relay

# Generator Lockouts

- The amber lamp is normally lit to indicate three important things about the **Lockout Relay**:
  - 1) There is DC control power available to the lockout relay
  - 2) The lockout relay operating coil is electrically intact
  - 3) The lockout relay is reset and ready to trip
- If the **lamp isn't lit**, it means there's **no DC power available** or that **the lockout coil has burned** open...in either case the lockout wouldn't be able to trip, making this a very serious situation that has to be resolved **immediately**
- The **Lockout Relay** target is an **orange semaphore** directly above the relay handle. When the lockout operates, the amber light goes out and this colored target appears
- The Lockout relay handle being at an angle instead of being perpendicular to the floor is another indicator of lockout operation

# Illustrations Of A Lockout Relay

## CAUTION

***NEVER HOLD THESE RELAYS IN THE  
RESET POSITION...  
this can burn up the operate coil and  
make the relay useless!***

## RESET



## TRIPPED





# Transmission Line Protection

# Transmission Line Protection

- A typical power system utilizes three types of lines to deliver power to the end user. They are:
  - 1) Transmission Lines
  - 2) Sub-transmission Lines
  - 3) Distribution Lines
- We will be focusing on the Transmission lines which are defined as lines operating at 100kv and above

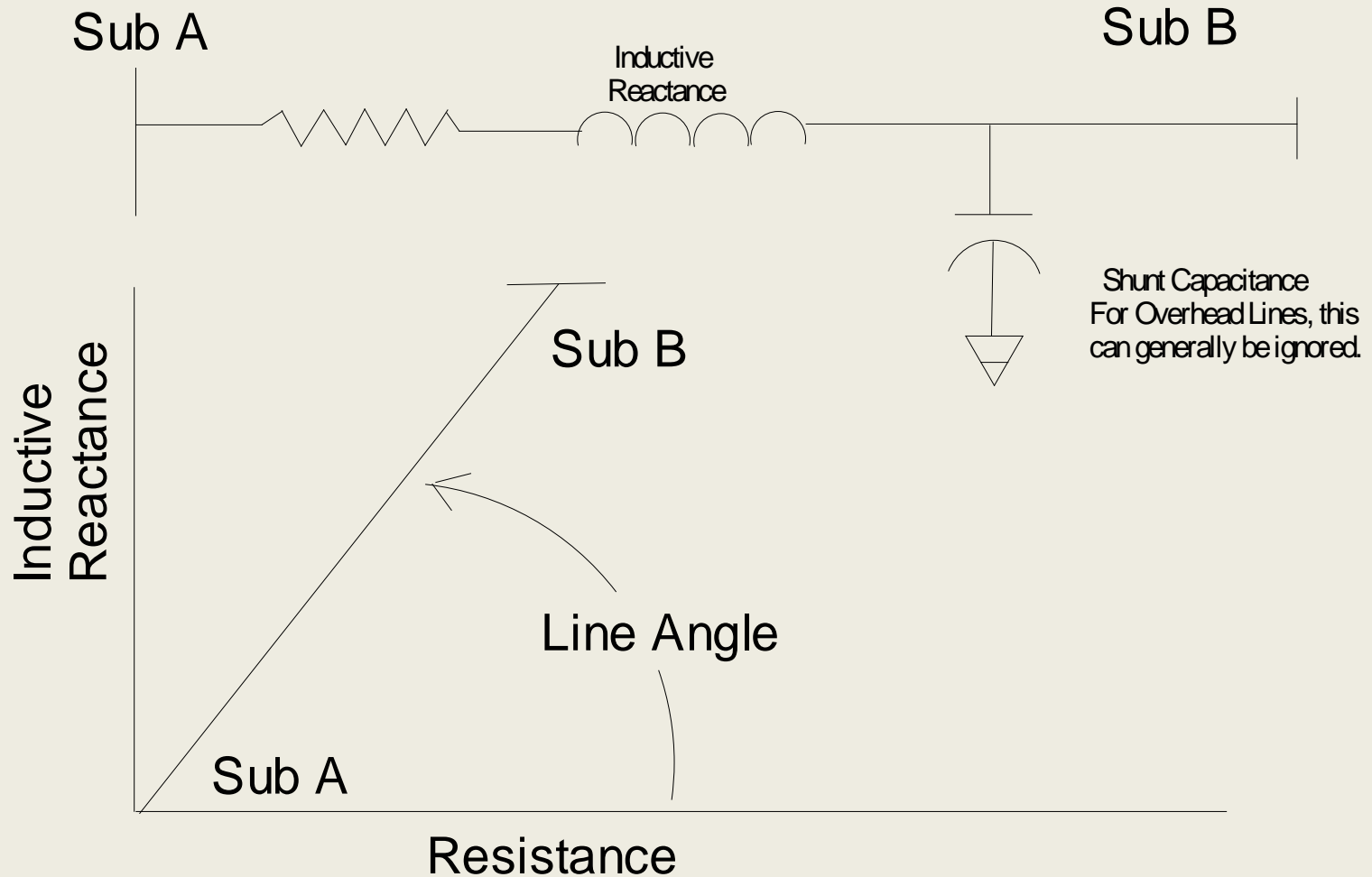
# Transmission Line Protection

- Because these lines carry large amounts of energy and are extremely important to the operation of a power system, it is necessary to use the most advanced relaying methods to insure their integrity
- Being that important, it is desirable to have instantaneous clearing for all faults on the transmission line under normal operating conditions

## Quick Review

- A Transmission Line has Impedance (**Z**) that is composed of resistance (**R**) and Reactance (**X**)
- It can symbolically be represented as:  **$Z = R + jX$**
- Consequently, on an R-X impedance diagram, any line can be graphically represented
- See example

# Graphical Representation of a Line Impedance



# Transmission Line Protection

- For reliability, transmission lines utilize **Primary** and **Backup** protective schemes
- The criticality of each line is evaluated to determine if backup protection should be equivalent to primary protection. The factors which influence the decision are:
  - System Stability Concerns
  - Relay Coordination Concerns

# Transmission Line Protection

## System Stability

- If stability studies indicate that delayed clearing of faults on a transmission line cause a Generator to go unstable, it indicates that both the primary and backup protective schemes must clear all faults instantaneously
- These studies are done as part of the initial engineering process

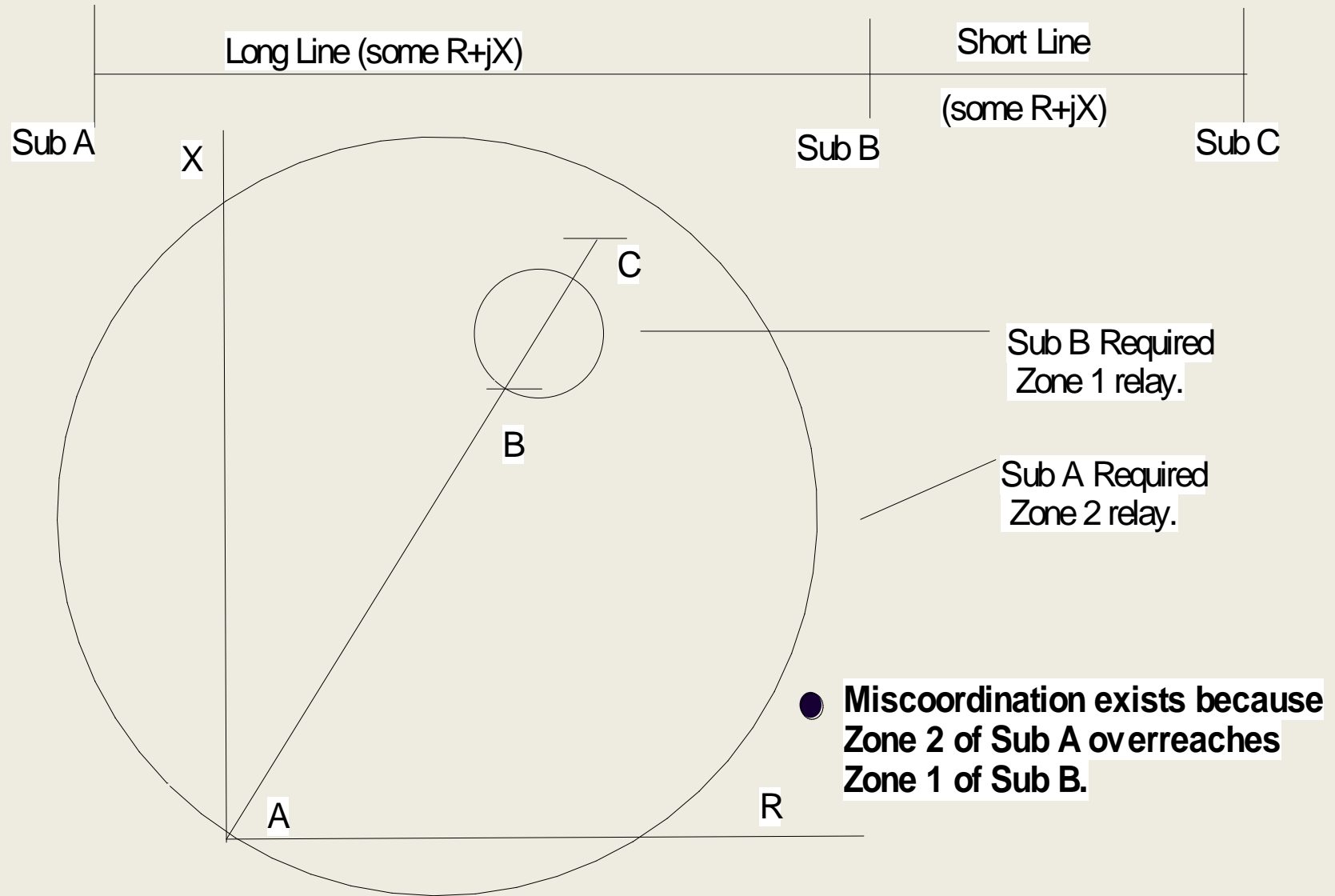
# Transmission Line Protection

## Relay Coordination:

- If protection studies determine that coordination of backup relay schemes can not be achieved, dual **pilot protection** schemes must be employed on the line to be protected
- Typically happens on Long Line/Short Line situations.  
See example



# Relay Coordination: Long Line/Short Line



# Primary Transmission Line Protection

- To obtain instantaneous clearing for all faults, **Pilot Relaying** is utilized
  - The term “pilot” implies that a communication channel exists between all terminals of the protected line
    - Power Line Carrier
    - Telephone pair
    - Fiber Optic
    - Microwave

# Primary Transmission Line Protection

- Several types of “pilot” protection schemes exist. The ones we will review are:
  - 1) Directional Comparison
  - 2) Direct Under-reaching Transferred Trip
  - 3) Permissive (Over & Under-reaching)
  - 4) Phase Comparison
  - 5) AC Pilot Wire
  - 6) Optical Fiber Differential

# Directional Comparison Blocking

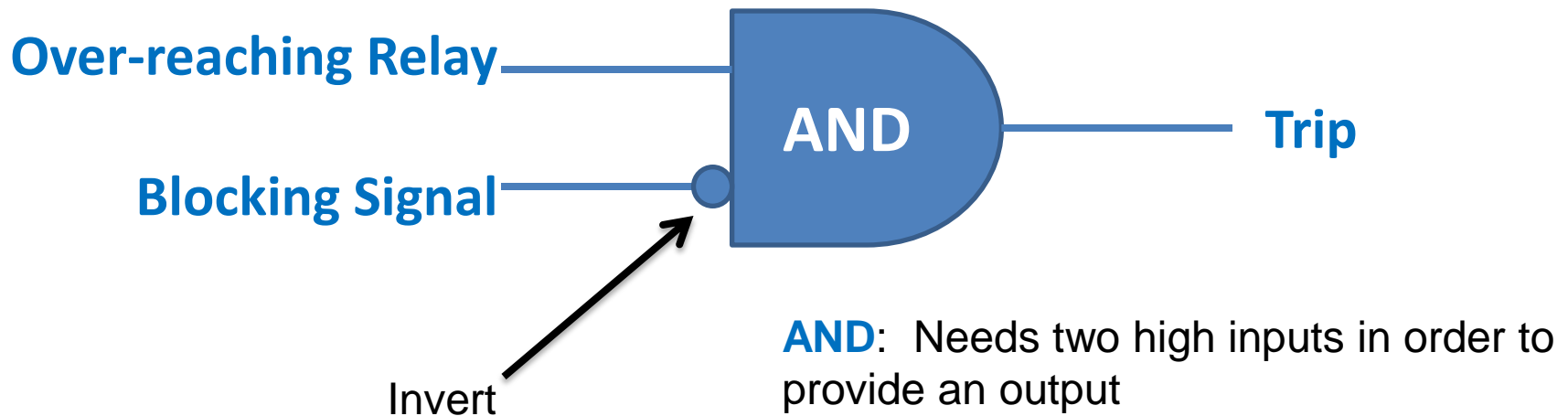
- Relays set to see beyond remote terminals
- Under non-fault conditions, no signal is sent between the terminals of the line
- To initiate a breaker trip, two conditions must be met:
  - Operation of a local tripping relay

**AND**

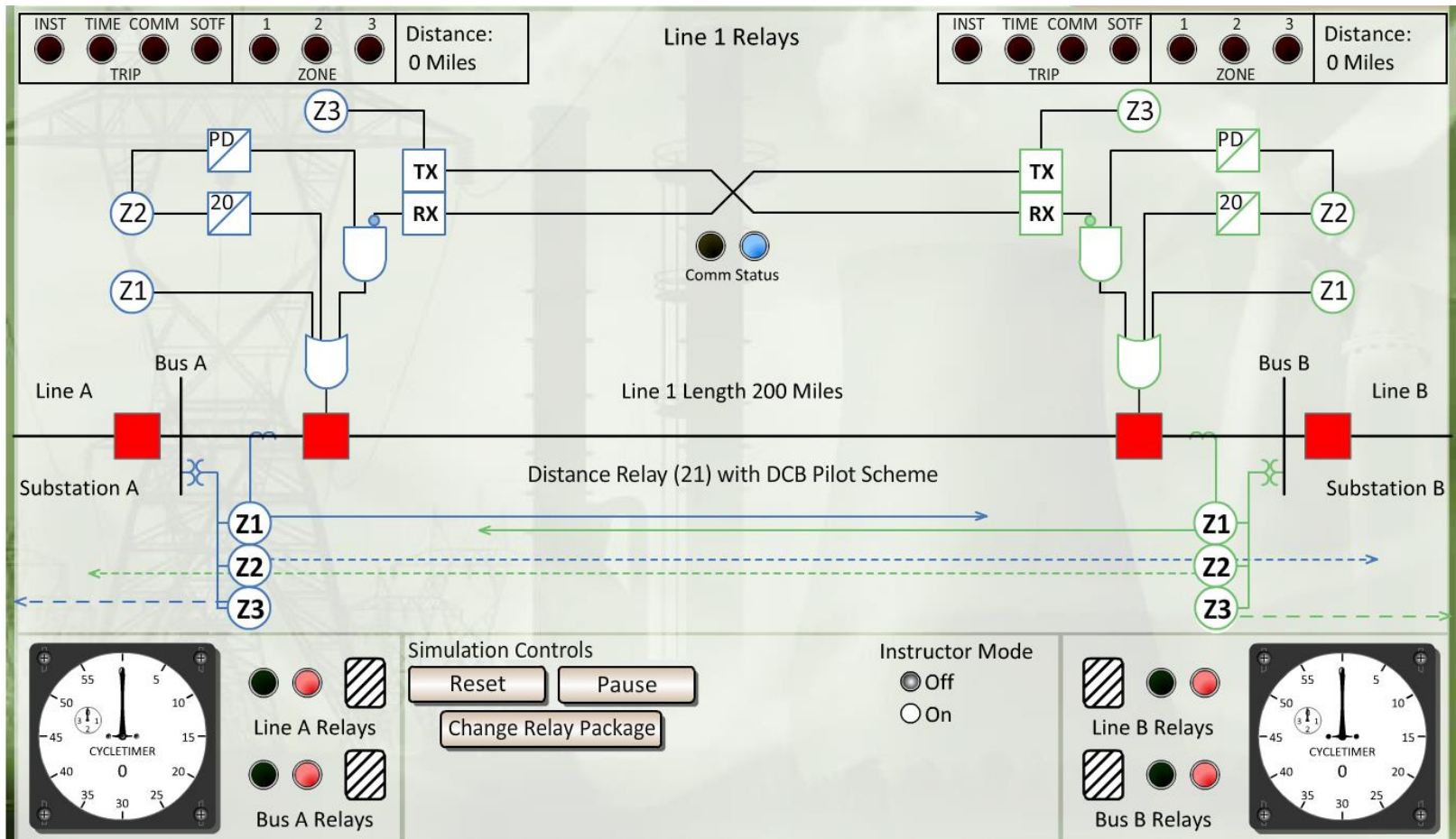
- Absence of a blocking signal from remote end
- Testing of communication path is done by Carrier Checkback Scheme

# Directional Comparison Blocking Scheme

- To Initiate Trip:
  - Over-reaching Relay must operate
  - Absence of Blocking Signal from remote end
- In digital logic:



# Directional Comparison Blocking



# Wave Trap and CCVT

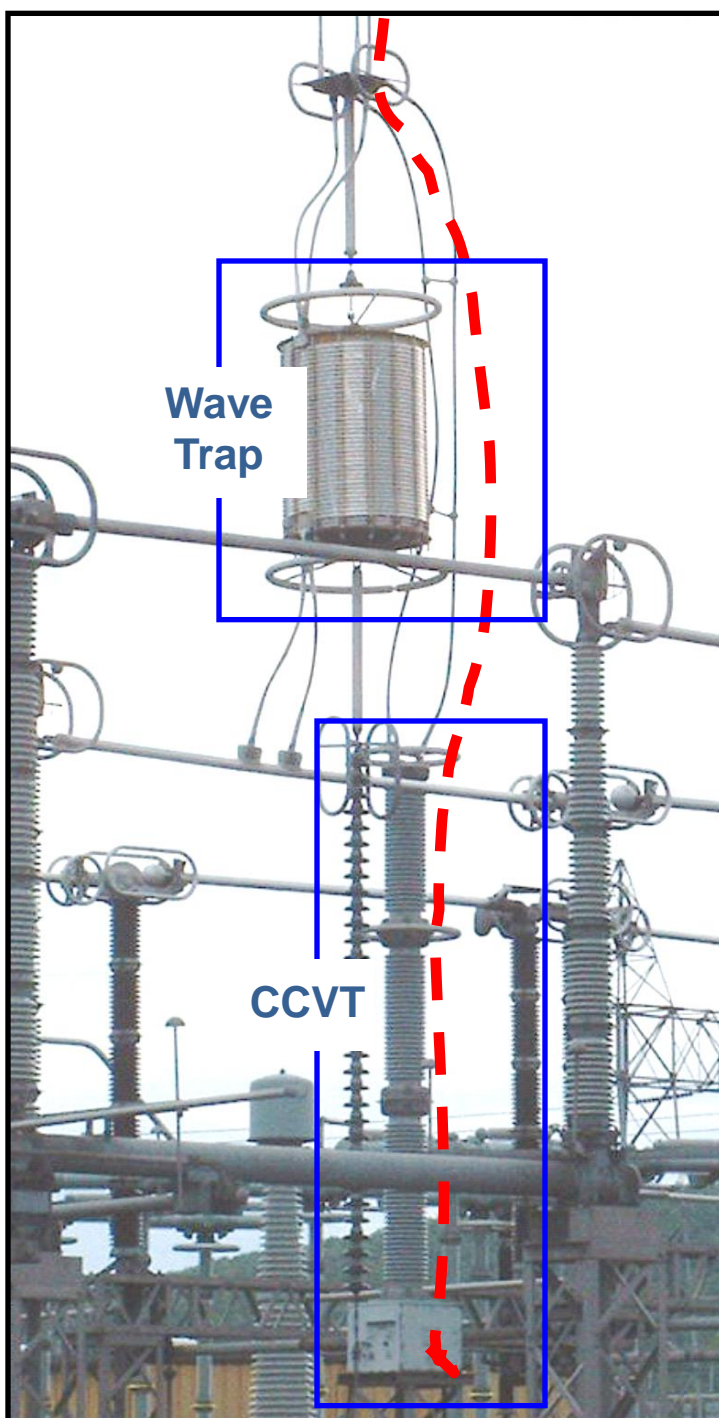
## Illustration Of 500kV Wave Trap & CCVT

The carrier signal couples to the transmission line through the CCVT

The signal enters and exits the base of the CCVT, then connects to a nearby impedance-matching tuning box and then to the transmitter/receiver equipment located inside the substation control house

The carrier signal traffic is bi-directional: the local terminal both transmits a signal to the remote terminal and receives a signal from it, all through the same path shown in the illustration

The wave trap blocks the carrier signal from exiting the transmission line through any path other than through the CCVT





# Typical Blocking Carrier Controls

Carrier Test Switch



Received Signal Meter



Carrier Blocking Switch



Note the **red-yellow-green** segments on the Received Signal Meters... the received carrier signal is **strong enough** if it appears in the **green** region, **so-so** in the **yellow** region, and **bad** enough to warrant blocking the carrier relaying if in the **red** region





## Direct Under-reaching Transfer Trip

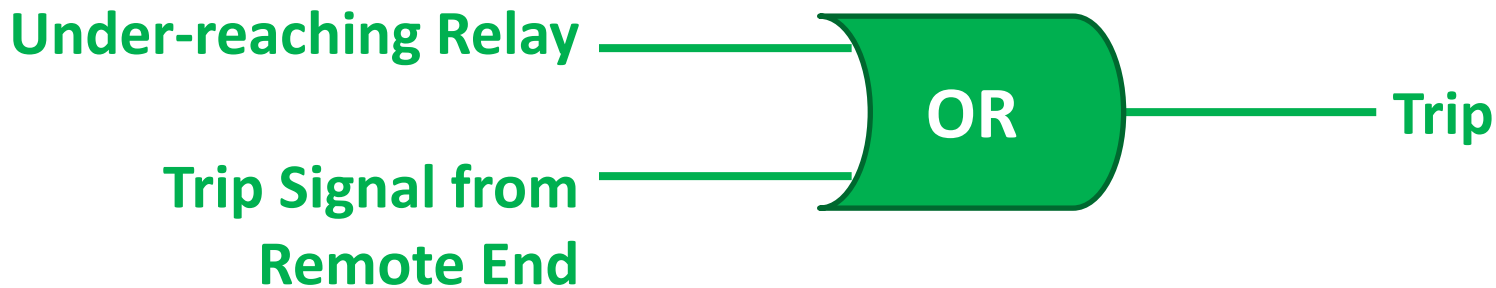
- Relays set to under reach the remote terminal
- Under non-fault conditions, a continuous GUARD signal is sent by the local transmitter and monitored by the remote receiver
- To initiate a breaker trip, one of the following must occur:
  - Local under-reaching relay must operate

**OR**

- Reception of a TRIP signal from the remote end must be received
- Testing of communication path is continuous via GUARD signal. Loss of guard will generate alarm

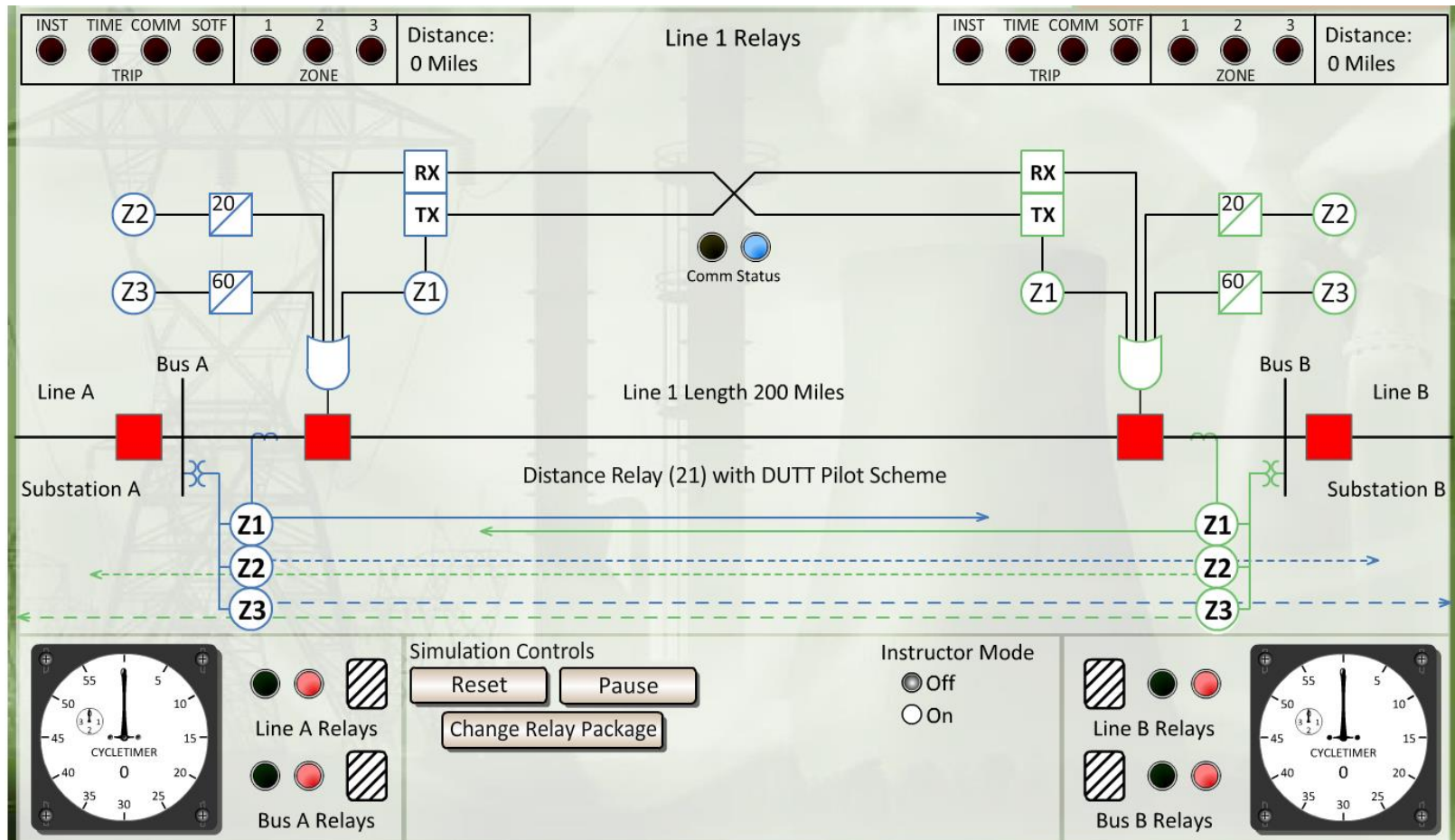
# Direct Under-reaching Transfer Trip Scheme

- To Initiate Trip:
  - Under-reaching Relay must operate
- In digital logic:



**OR:** Needs one high input in order to provide an output

# Direct Under-reaching Transfer Trip

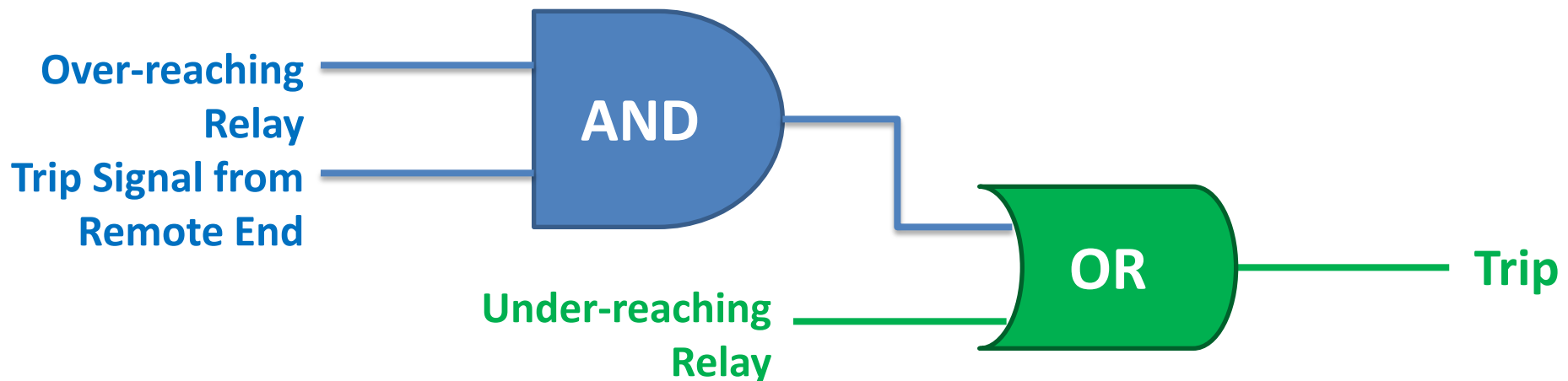


## Permissive Under-reaching Transfer Trip

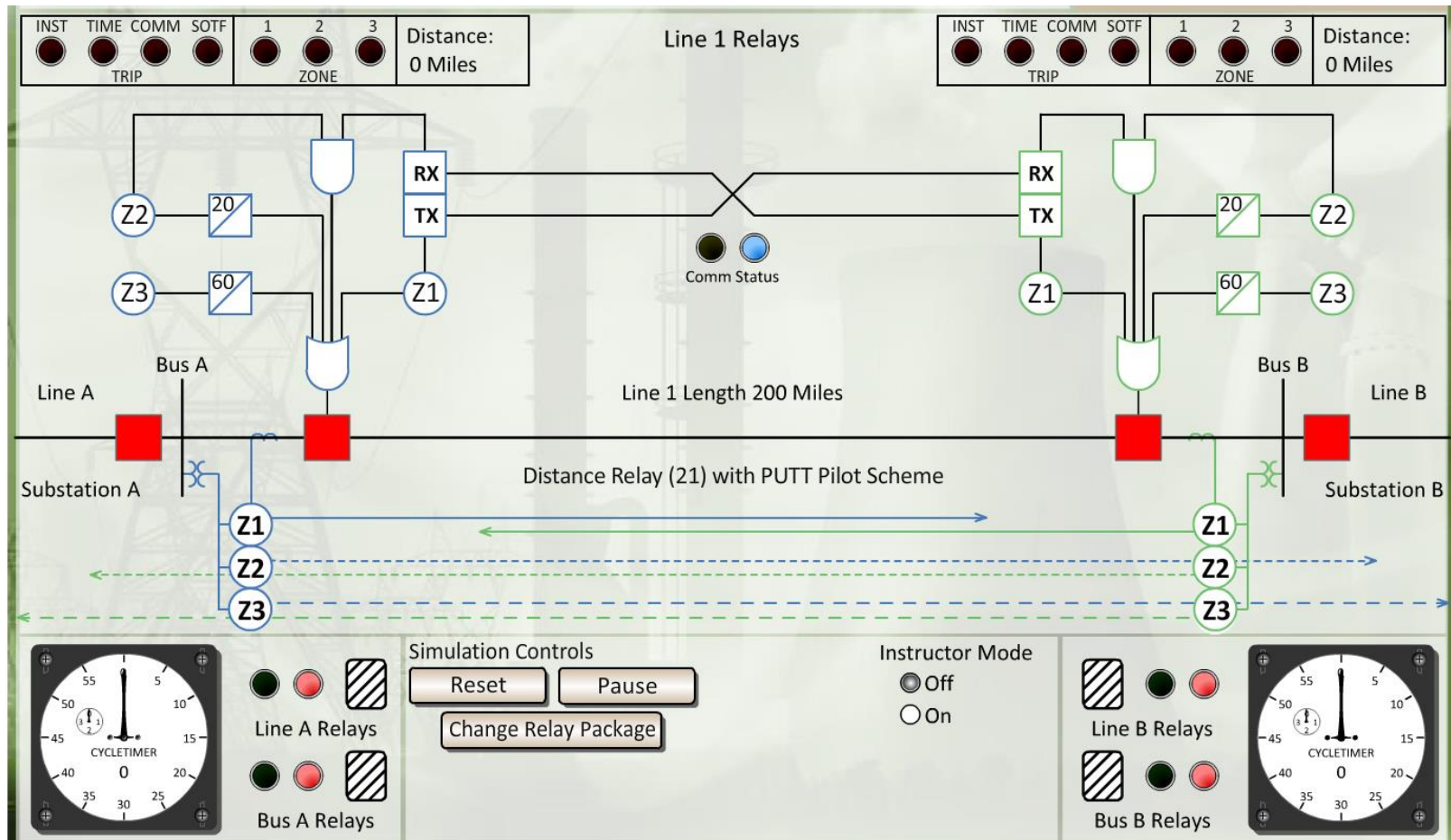
- Direct tripping relays set to under reach remote end
  - Fault detector relays set to overreach remote end
  - Under non-fault conditions, continuous GUARD signal is sent to remote end
  - To initiate a breaker trip, one of the following must occur:
    - The under-reaching relay must operate
- OR**
- The overreaching relay must respond **AND** a TRIP signal must be received from remote end
  - Communication path testing is continuous via GUARD signal. Loss of Guard will generate an alarm

# Permissive Under-reaching Transfer Trip Scheme

- To Initiate Trip:
  - Under-reaching Relay must operate
- **OR**
- Over-reaching relay must operate **AND** receive a trip signal from the remote end
- In digital logic:



# Permissive Under-reaching Transfer Trip



# Permissive Over-reaching Transfer Trip

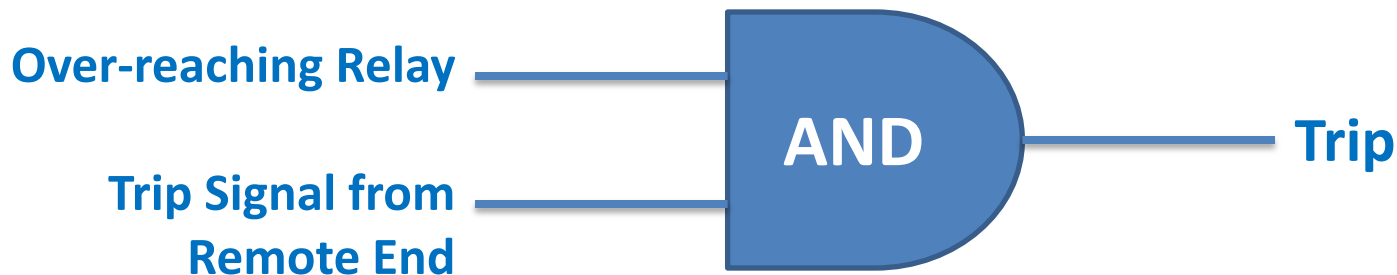
- Relays set to see beyond remote terminals
- Under non-fault conditions, a continuous GUARD signal is sent
- To initiate a breaker trip, two conditions must be met:
  - Operation of local tripping relay

**AND**

- Receipt of TRIP signal from remote end
- Testing of communication path is continuous via GUARD signal. Loss of Guard generates alarm

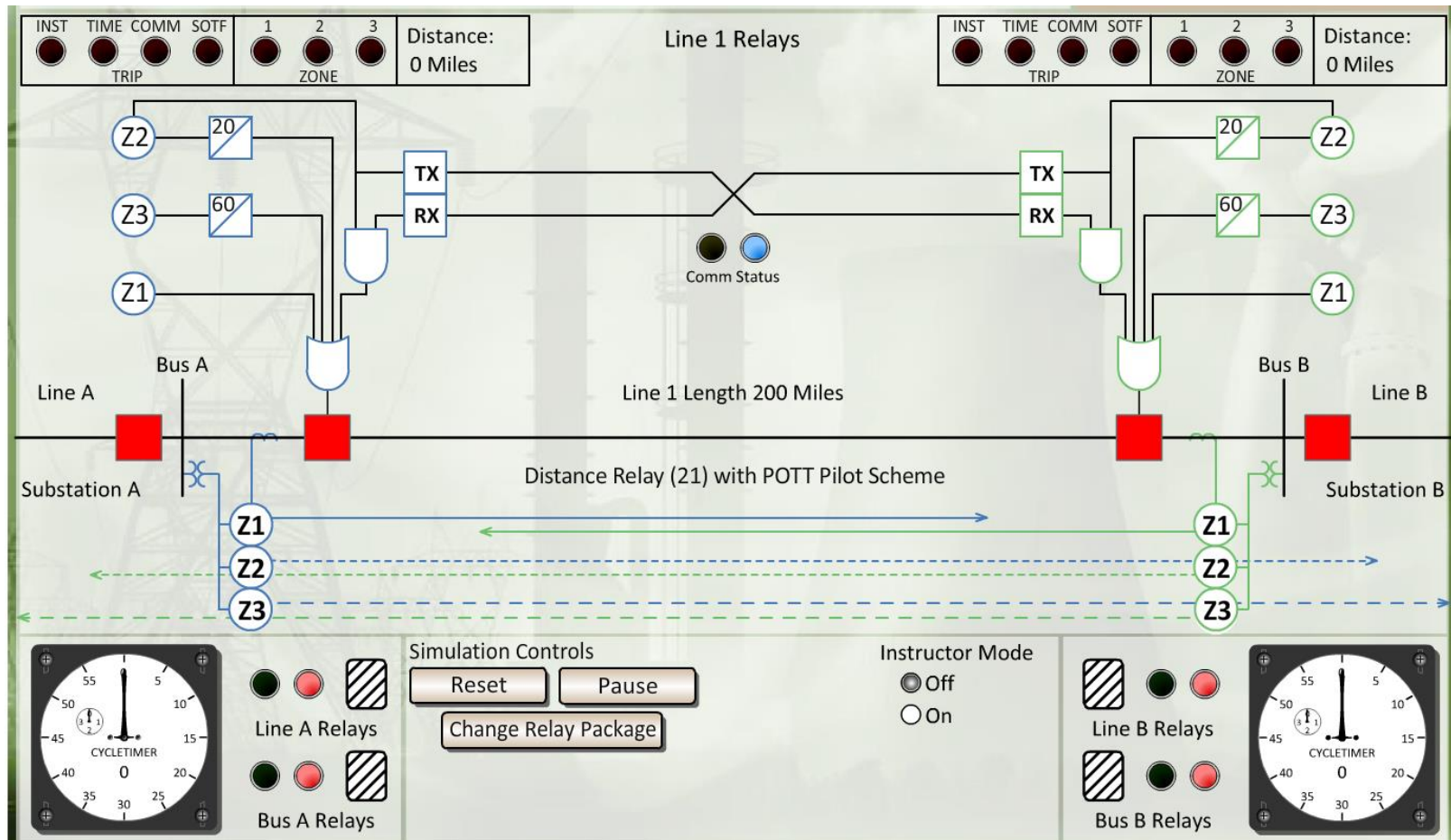
# Permissive Over-reaching Transfer Trip

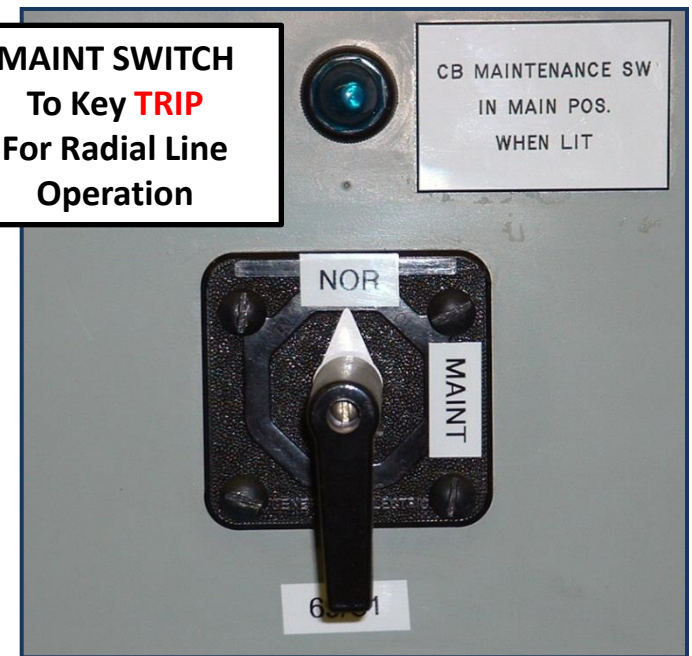
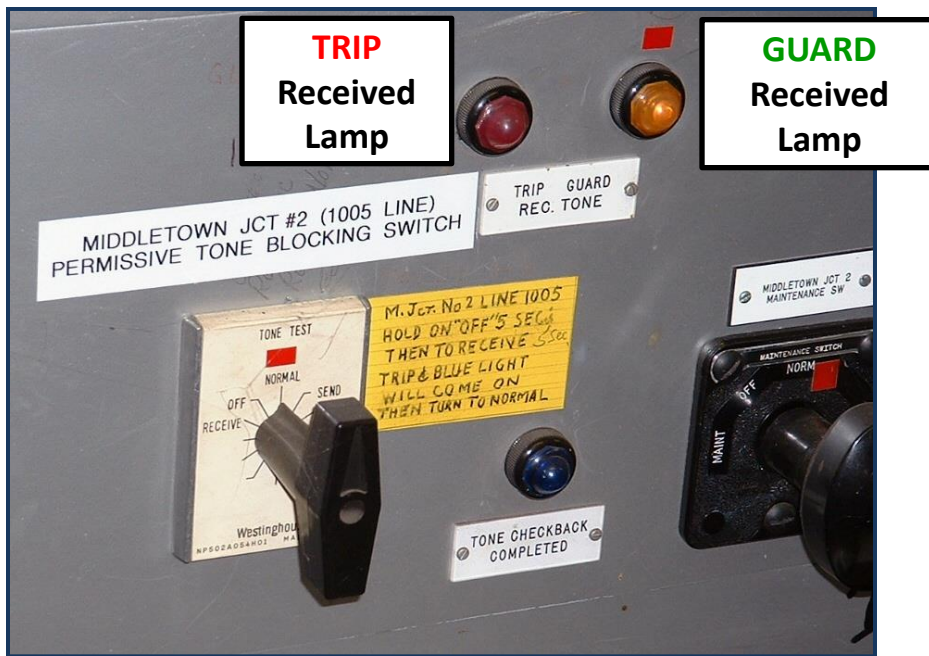
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- In digital logic:



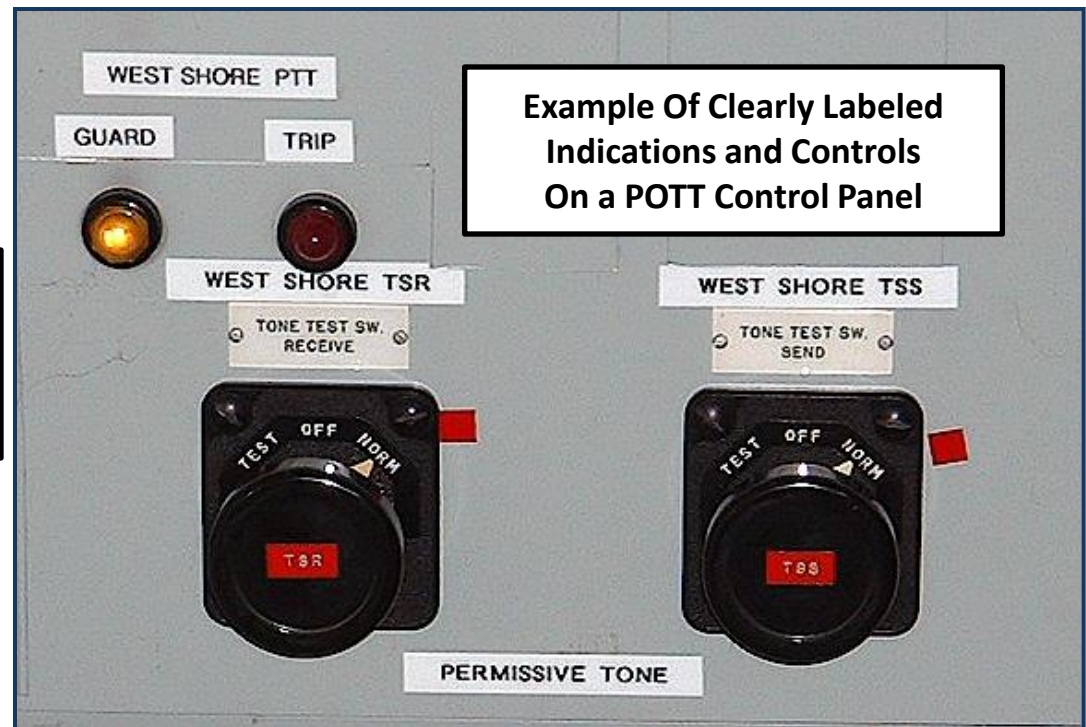


## Permissive Over-reaching Transfer Trip





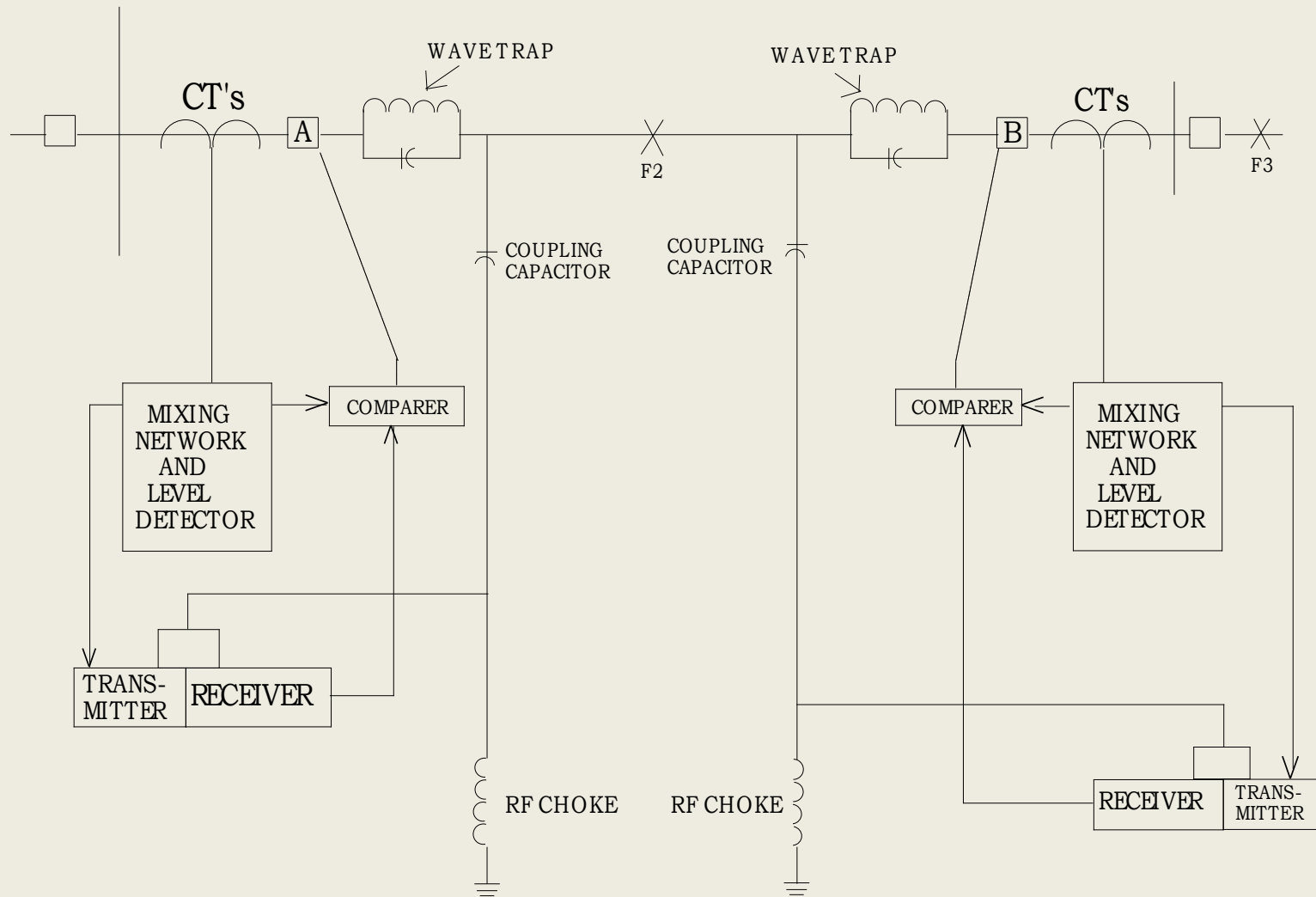
## Illustrations Of Typical POTT Scheme Indications and Controls



## Phase Comparison

- This is a differential scheme that compares the phase angle difference between the currents at the terminals of a transmission line
- If currents are “in-phase”, no fault is present on this line section
- If currents are “out-of-phase” by about 180 degrees, an internal fault is present
- Equipment used is same as Directional Comparison scheme
- Scheme was typically used on the 500 kV system

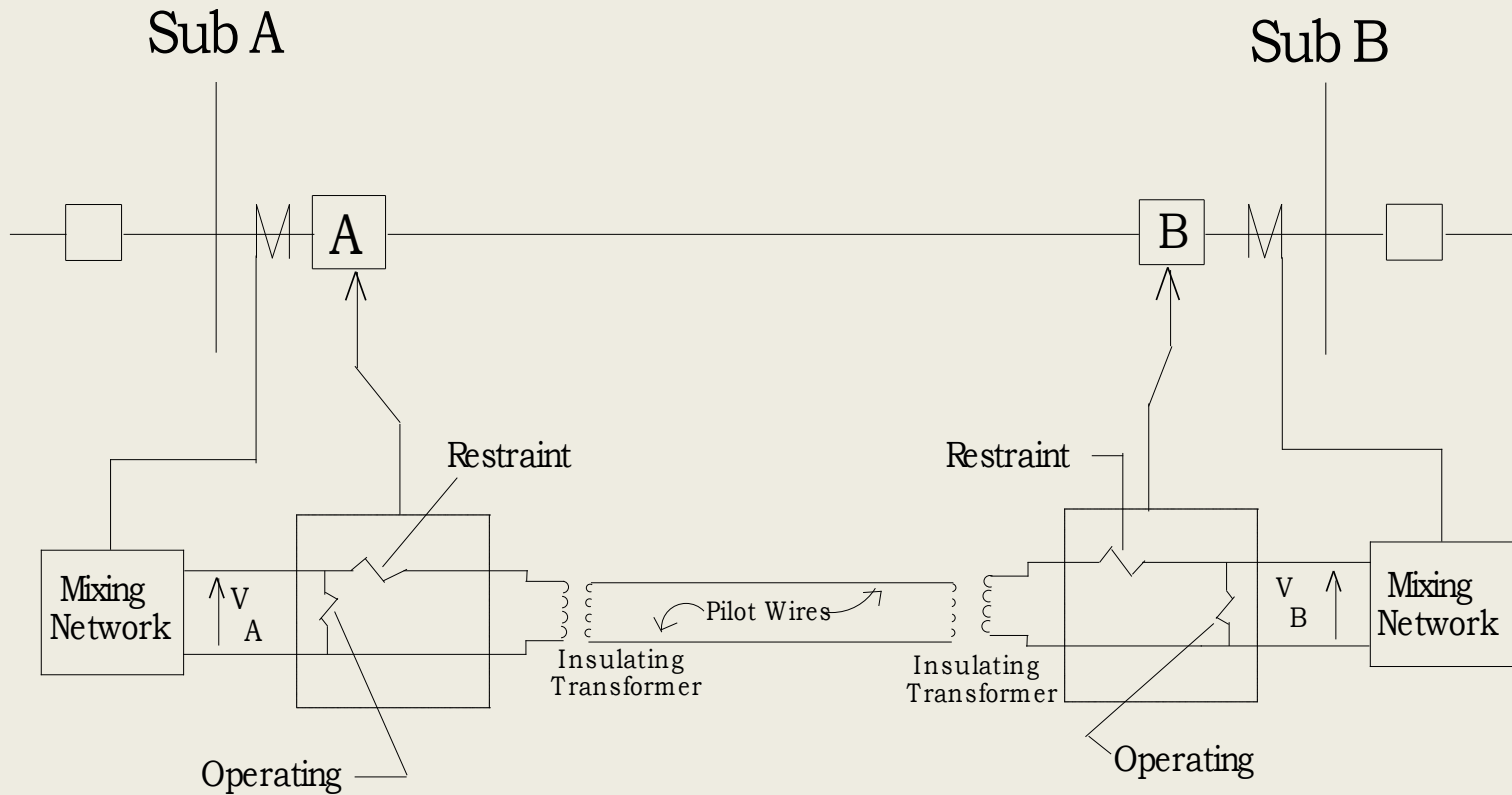
# Phase Comparison Relaying



## AC Pilot Wire

- Form of differential line protection where phase currents are compared to determine if a fault is internal or external to the protected line segment (similar to phase comparison)
- Requires a pair of wires between terminals to operate. Economical for short lines
- Operation is similar to a bus or transformer differential scheme
- Loss of two wire pair will defeat tripping scheme. No automatic testing of P.W. exists

## Pilot Wire Relaying (Current Differential)



# Optical Fiber Differential

- Relays operate on a current differential basis
- Requires the use of optical fiber to transit digital information
- The digital information contains the current magnitudes and other diagnostic parameters and is transmitted continuously between connected stations
- Tripping is initiated when differential relay exceed the relays restraint characteristic
- Failure of the fiber communication path will automatically block the scheme and initiate an alarm

# Backup Transmission Line Protection

- Can be exactly like primary protection. Depends upon stability or coordination concerns
- If stability and coordination are not a concern, non-pilot relaying can be applied as a backup scheme



# Backup Transmission Line Protection

- In non-pilot applications, line protection generally consists of the following:
  - Stepped Distance for Phase Protection
  - Directional Time and Instantaneous Overcurrent for Ground Protection
- Due to the recent introduction of microprocessor based relays, additional relay functions are available for use. The more common functions include:
  - Ground Stepped Distance elements
  - Negative Sequence Overcurrent elements

# Backup Transmission Line Protection

- Directional Overcurrent Ground Relay
  - Equipped with Time & Instantaneous elements
  - Time Element must be coordinated with other ground relays in the system
  - Instantaneous relays must be set short of remote terminal (just like Zone 1 phase relays)
  - Non-directional relays can also be applied if they can be coordinated. However, with the new microprocessor relays, directionality is available - so might as well use it
  - Aids in coordination

# Backup Transmission Line Protection

- Directionality - how is it achieved?
  - The directional unit of a relay uses the current from the line being protected (i.e. phase current for a phase relay and residual current for a ground relay) in conjunction with a “polarizing” quantity to determine “power” flow direction
    - The polarizing quantity is typically voltage

## Other Functions Performed:

- When either a primary or backup relay responds, the relay scheme will initiate:
  - 1) Tripping of the line terminal CB(s)
  - 2) Stop sending carrier blocking, send trip signal, etc. Depends upon relay scheme
  - 3) Initiate Breaker failure relay scheme/DTT
  - 4) Automatic reclosing (if applicable)

## Breaker Failure Relaying - Short Discussion

- If a stuck breaker condition occurs, a breaker failure scheme will be initiated that will trip the necessary local CBs needed to isolate the failed CB
- In addition, Direct Transfer Trip may be initiated to trip any remote CBs that could supply the fault. DTT will temporarily block auto-reclosing
- If the failed CB can be automatically isolated by the opening of motor operated disconnects, this will occur and allow reclosing of remote CBs. If there are no MOD's, reclosing remains blocked

# Breaker Failure Relaying-Short Discussion

## Direct Transfer Trip

- Can be used for the following purposes:
  - Insure tripping of remote terminal for transformer faults
  - Clear the remote terminal for stuck breaker condition at the local station
- Generally, high security is achieved by using two transmitter/receiver pairs
- To initiate a trip, both receivers must detect their unique trip signal from the respective transmitter

# Reclosing Practices

- Just as it is advantageous to clear a fault as fast as possible to minimize the shock to the electrical system, it is also advantageous to return the transmission path to service as soon as possible
- Since most faults on transmission lines are transient in nature (i.e. disappear when circuit is de-energized), automatic reclosing provides the means for returning the power system to a more stable state

## Reclosing Practices

- On the 230 kV system, multi-shot reclosing may be employed. However, this can differ among PJM member companies
- On the 500 kV system, it is a standard policy to utilize single shot reclosing for lines. The reclosure attempt will take place 5 seconds after the line trips



# Reclosing Practices

- Where is automatic reclosing not desirable?
  - 1) If protected line is an underground cable
  - 2) If line has a tapped transformer that cannot be automatically disconnected from the line
  - 3) If line is just being returned to service and trips
- All situations are usually taken care of by the control scheme during design stage

# Reclosing Practices

- Manual Reclosing
  - This includes supervisory (SCADA) control in addition to control handle closures
  - Used when switching equipment in or out of service. (SCADA is typically used instead of control handle in order to confirm its availability)
  - Should fault occur as soon as a CB energizes a piece of equipment, no automatic reclosing will take place

# Reclosing Practices

- Manual Reclosing
  - Also used for “Try Back” (testing) of a line after a fault
  - Company policy should be followed when fault testing is being considered
  - The operator should consider the effects that testing may have on the electrical system (shocking the system again)
  - If possible, it is always better to request a patrol of line before trying to restore it to service

# Reclosing Practices

- In general, reclosing of transmission line CBs is supervised by **Synchro-check relays**
  - Insures that the two systems being ties together are in synchronism with each other (or close to it)
  - If the systems are synchronized such that the angle between the two are within defined limits, reclosing will occur. If they are outside the predefined limits, the relay will block reclosing

# Protective Relay Alarms Via SCADA

- Depending upon design, receiving of an alarm could mean:
  - 1) Low signal levels on Power Line Carrier Equipment
  - 2) Loss of Guard on one or more Permissive or DTT schemes

# Risks Involved

## Directional or Phase Comparison Schemes

- With low signal levels, there is a good chance that the protected line could overtrip for a fault

## Permissive Transferred Trip Schemes

- With a continuous loss of guard, the scheme will shut itself down. Little risk of overtripping exists
- With a sporadic loss of guard, noise is being introduced into communication channel. Fair chance of incorrect tripping exists
- Momentary loss of guard and return to normal has little risk of overtripping

# Risks Involved

## Direct Transfer Tripping Schemes

- A continuous loss of guard will shut down scheme. Little risk of overtripping exists
- Sporadic loss of guard is indication of noisy communication channel. There is a good chance that an overtrip will occur
- Momentary loss of guard and return to normal is of little concern. Low risk of overtripping

## Ranking of Risks (Most to Least Critical)

- 1) Sporadic Loss of Guard - Direct Transferred Trip Schemes
- 2) Low Signal Levels - Directional or Phase Comparison
- 3) Sporadic Loss of Guard - Permissive Transferred Trip Schemes
- 4) Continuous Loss of Guard - Direct Transferred Trip Schemes
- 5) Continuous Loss of Guard - Permissive Transferred Trip Schemes
- 6) Momentary Loss of Guard - Direct Transferred Trip Schemes
- 7) Momentary Loss of Guard - Permissive Transferred Trip Schemes



# Special Relay Schemes

- Load Shedding via Underfrequency
- Close-In Fault Protection

# Underfrequency Load Shed

- Used to match load with available generation
- In this program, PJM Member companies must shed 30% of their base load. Done in 10% steps
- UF load shedding is coordinated with UF relays at generating stations

## Close in Fault Protection

- In service for a short period of time after a transmission line has been re-energized (i.e. one terminal closed)
- Simple instantaneous overcurrent relays are utilized to trip the line if a fault (i.e. grounds) exist on the line. The relays are removed from service after a short time delay

# **Transmission Line Protection Exercises/Review**

# Relay Testing

- Relay testing is important to insure Relays and Relay Schemes are functioning as designed
- Because testing is usually done when primary equipment is energized, there is a risk that unwanted operation of relay schemes may occur

## Why can tripping occur?

- Close working conditions
- Wiring errors
- Improper “Blocking” or “Isolating” of equipment
- Inexperience (lack of training)
- Accidental (bump panel or relay)

## Considerations and Concerns for S.O.'s:

- When a request is received from a person doing testing, think about:
  - What could it do to the system? Is the system being operated in a manner that the loss of the equipment protected by the relay scheme will cause serious problems (stability, voltage, overloads etc.)
  - Would the removal of relay scheme go beyond the setting criteria for other relay schemes

## Protection Practice:

- Protection and Coordination are typically based upon the electrical system being **normal** or altered by any **single contingency**
- A single contingency is the outage of a piece of equipment such as a line, transformer or relay scheme
- If more than one piece of equipment is outaged at a station, protection or coordination can be compromised
- The relay engineers should be contacted to insure protection and coordination will still exist



# **General Considerations for Dispatchers Following a Relay Operation**

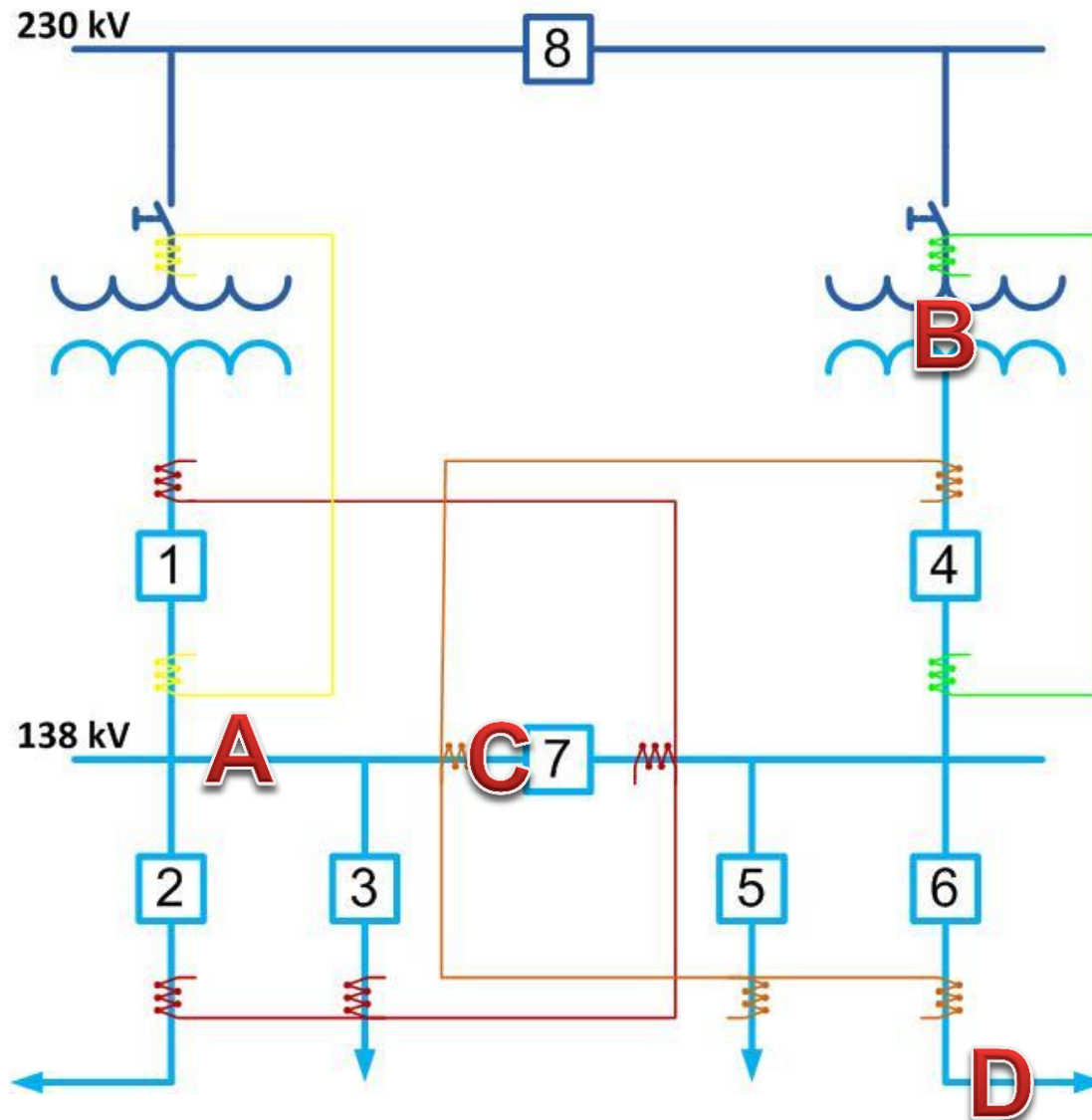
## **Know your companies policy regarding Dispatcher response to a relay trip**

- Who do you notify?
- Who to call to initiate repairs
- Who to call to perform line patrols, substation inspections, etc.
- Inter-company response & notifications

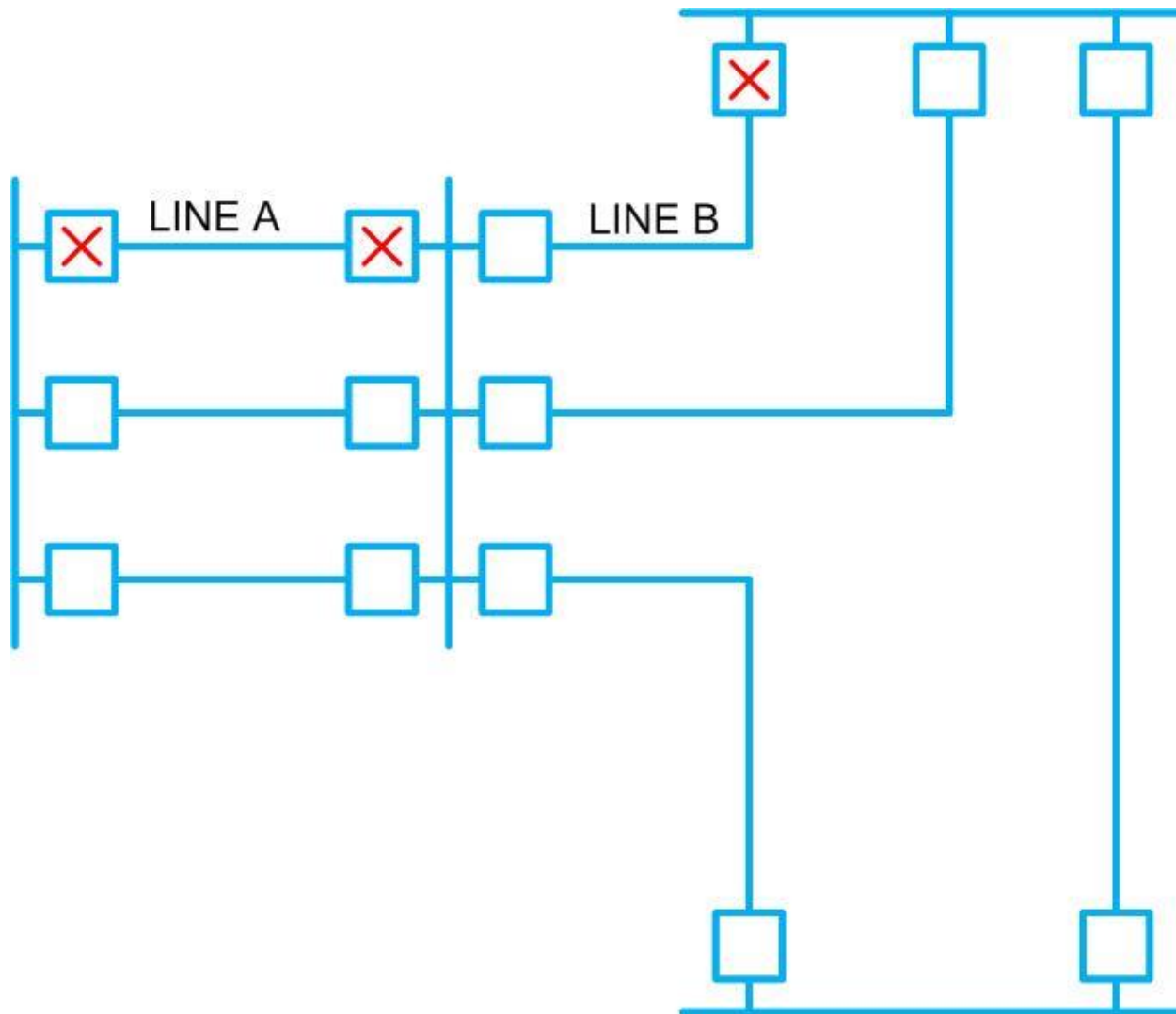
- Data collection and fault analysis
  - Try to obtain as much data as possible for future detailed analysis (i.e. relay targets, Digital fault recorder information, system conditions)
  - Real time analysis comes with experience
  - Often knowing what has tripped may lead to a determination of the faulted piece of equipment or potential relay problem
  - (See examples)

# Fault analysis

Breakers 1 thru 7 trip open. Where is the likely fault location?



# Fault analysis



## Exercise prudence before “Trying Back”

- 500 kV lines have a single shot reclosing attempt after 5.0 seconds
- Testing after 5 minutes is possible with concurrence from PJM and others
- No “Try Back” should occur on:
  - 1) Generator SU transformers
  - 2) Underground Cable (Bus Work)
  - 3) Indoor equipment

# Transformer Protection

## Transformers:

- At the heart of the Transmission System
- They make the transport of large amounts of electrical energy economically possible
- Because of their criticality to the Bulk Power System, high speed clearing for faults is desirable



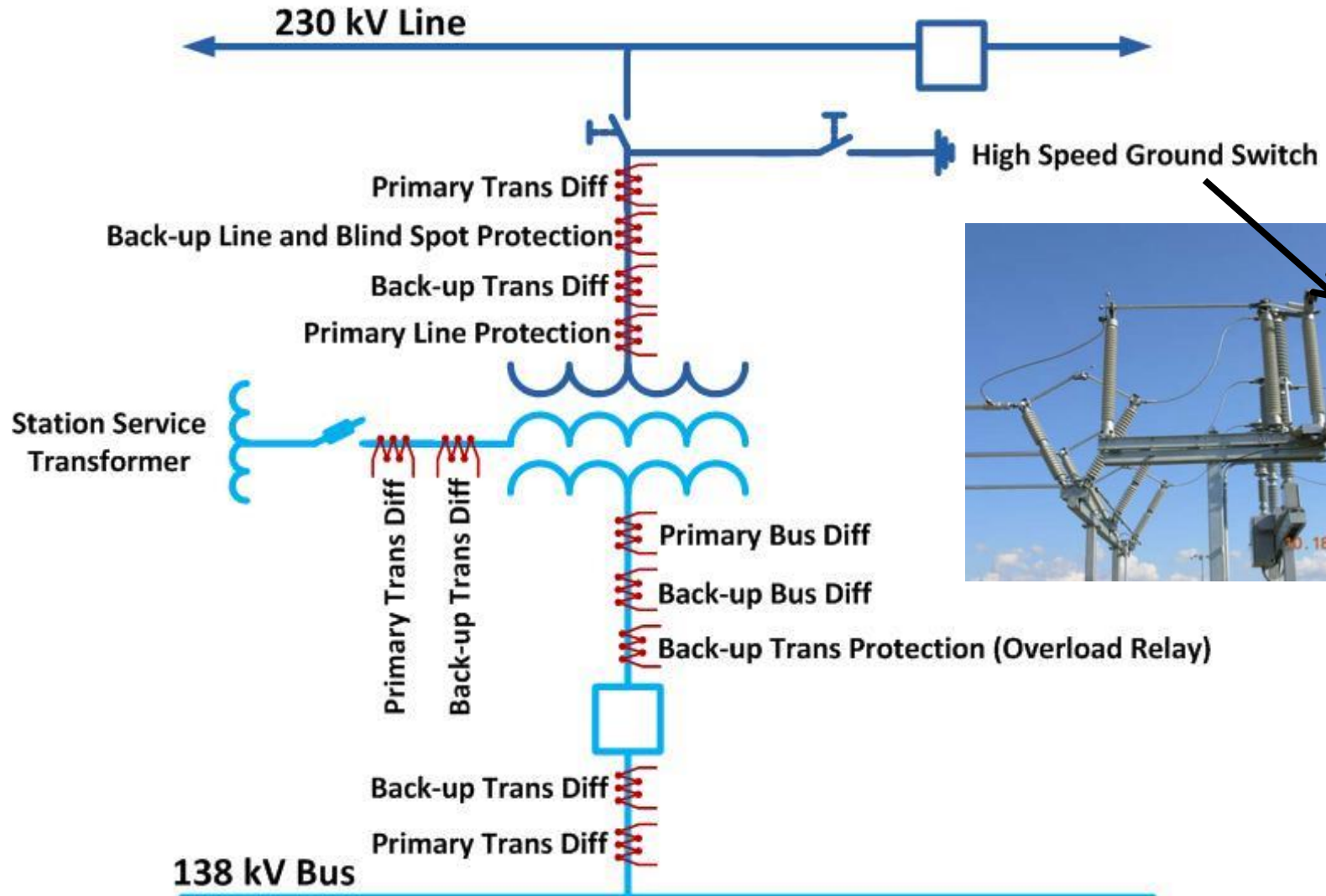
# Transformer Protection

- Typical Problems that can occur:
  - Inside the Tank
    - 1) Winding Faults to Ground
    - 2) Winding Turn to Turn Shorts
    - 3) Excessive Winding and/or Oil Temperature
    - 4) Overloads (i.e. winding/oil temperature
  - External to Tank
    - 1) Bushing Lead Failure
    - 2) Bushing Flashover
    - 3) Lightning Arrester Failure
    - 4) “Through Faults”

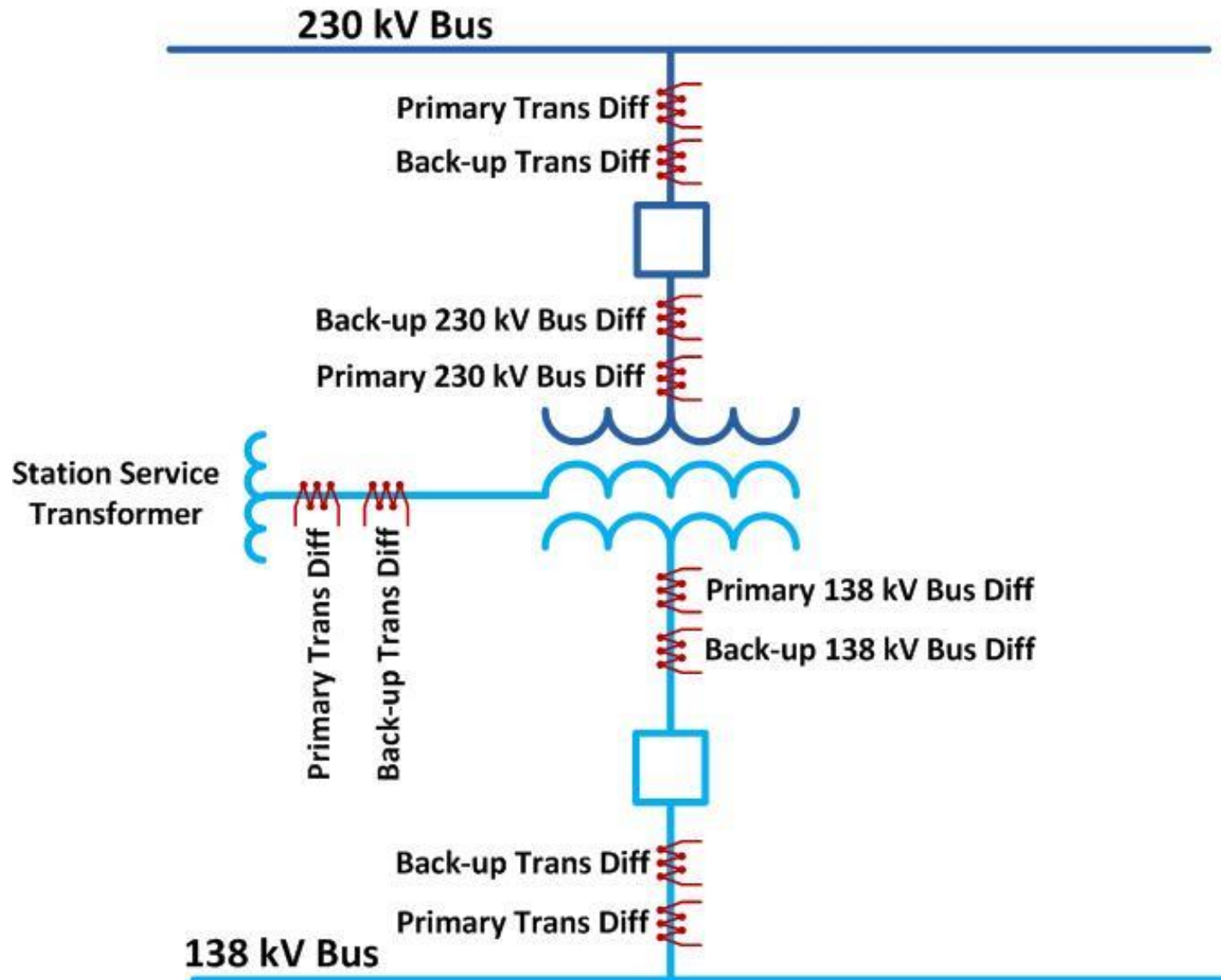
# Transformer Protection

- Transformer Protection is typically provided by **differential relaying**
- Transformers provide unique problems for differential relaying that must be accounted for:
  - 1) Different voltage levels (i.e. different current magnitudes)
  - 2) Automatic Tap Changers (LTC's or TCUL's) associated with transformers cause further mismatch between high side and low side currents
  - 3) Energizing a transformer causes magnetizing inrush current which appears as an internal fault to the differential relay
  - 4) Because of Delta-Wye connections, the transformer introduces a 30 degree phase angle shift that must be accounted for

# CT Connections for Tapped Transformer



# CT Connections for Bus Connected Transformer

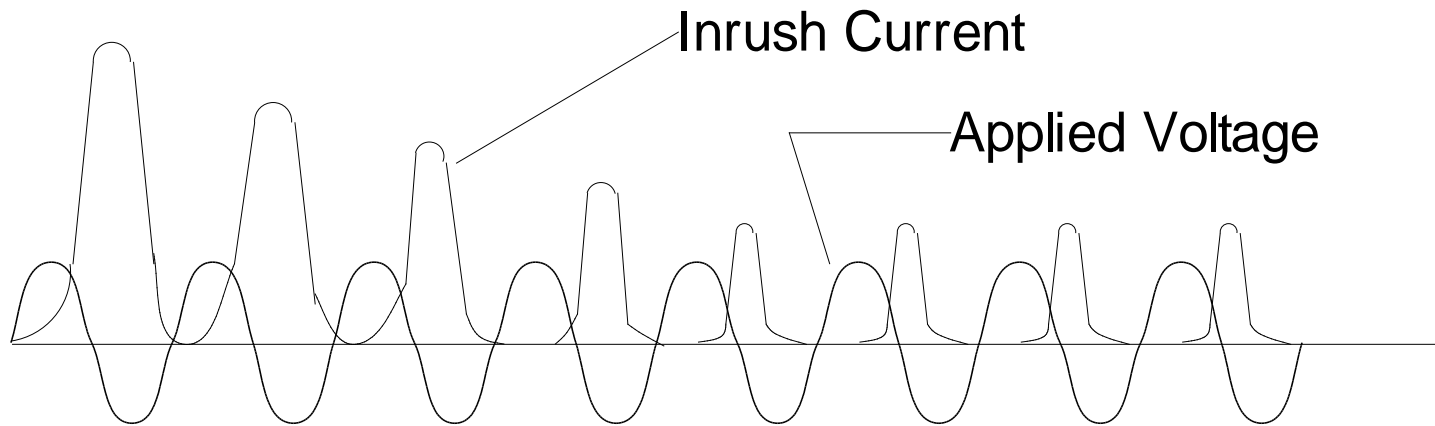


# Transformer Protection

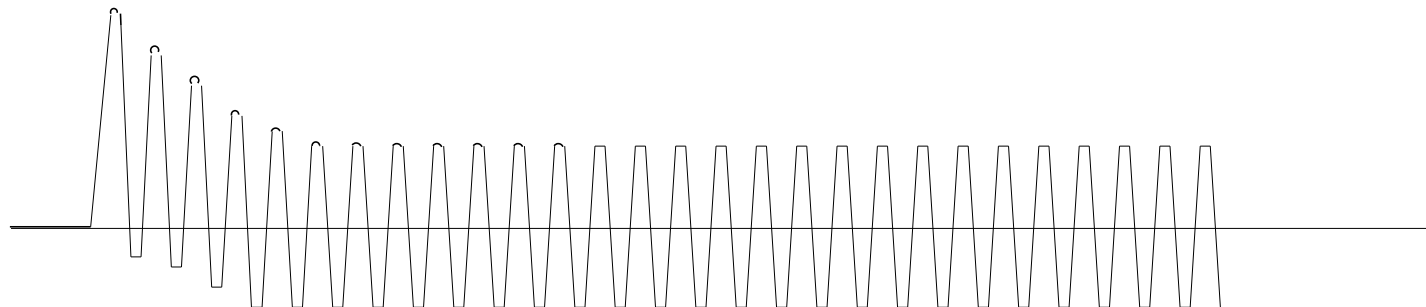
- It was recognized early that a perfect match of CT ratios, necessary for the differential relay, was practically impossible
- Mismatch of CT secondary currents can be overcome with a **Percentage Differential Characteristic** relay
- This type of relay has **operate** and **restraint** coils which are connected in a manner that allows for a certain amount of CT mismatch

# Transformer Protection

- The inrush current that exists when a transformer is energized is high in harmonics, particularly the second harmonic
- The use of a **Harmonic Restraint** element can de-sensitize the differential relay to these harmonics and provide the necessary security required



Typical Magnetizing Inrush Current Wave



Typical Offset Fault Current Wave

# Transformer Protection

- The 30 degree phase shift that is introduced when protecting wye-delta transformer banks can be overcome with the proper connection of the CTs supplying the differential relay
- The general rule of thumb:
  - CTs on wye side of transformer should be connected in delta, while CTs on the delta side should be connected in wye



# Transformer Protection

- Bottom Line:
  - The differential relay is the ideal device for transformer protection in that it takes advantage of the zone type of protection to provide sensitive high speed clearing of transformer faults

# Transformer Protection

- Since high voltage transformers are critical to the Bulk Power System, generally primary and back-up differential relays are used for protection
- Beyond using two discrete differential relays, additional devices are used to protect the transformer

# Transformer Protection

## Sudden Pressure Relays:

- If an arcing fault occurs inside the transformer tank, gases are generated which can be detected by a pressure relay
- Operation of this relay will initiate tripping of the transformer
- This protection provides back up to the differential relays

# Transformer Protection

- Gas Analyzers (Combustible Gas Relay):
  - Low magnitude faults produce gases as they breakdown the oil and insulation in the transformer tank
  - The gas analyzer relay constantly monitors the gas space above the transformer oil and will actuate an alarm if gas levels exceed a predetermined level
  - An Alarm provides warning of a possible internal fault which could be catastrophic

# Transformer Protection

## Winding Temperature Relays:

- Winding Temperature (referred to as “Hot Spot” protection) inside the transformer is simulated by using a CT to drive a heating element under oil
- As the transformer becomes loaded, the heating element produces more heat
- As the heat increases and predetermined temperature levels are reached, a temperature sensing device will:
  - 1) Start additional cooling groups (if possible)
  - 2) Alarm if temperature continues to increase
  - 3) Trip the transformer

# Transformer Protection

## Oil Temperature Relays:

- Oil temperature is monitored by a “Top Oil” device inside the tank.
- Similar to the “Hot Spot” protection, when predetermined temperature levels are reached, a temperature sensing device will:
  - 1) Start additional cooling groups (if possible)
  - 2) Alarm
  - 3) Trip the transformer



**Illustrations Of Analog Gauge Style Winding Temperature and Liquid Temperature Thermal Devices**





Illustration Of  
Microprocessor Based  
Thermal Device

**Liquid Temperature**  
is the upper unit

**Winding Temperature**  
is the lower unit



# Transformer Protection

## Transformer Neutral Overcurrent Relay:

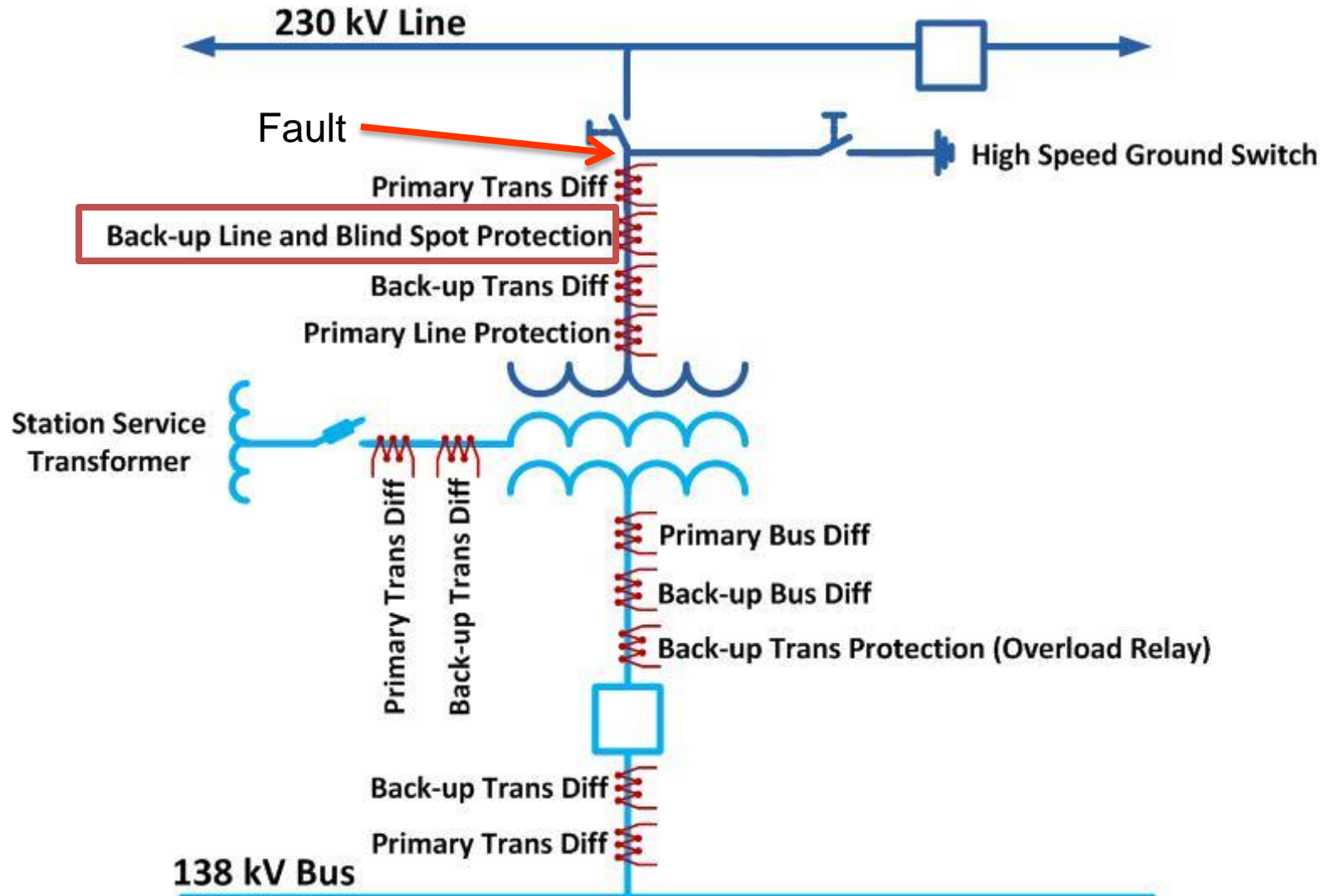
- Relay is connected to a CT located on the neutral connection of a WYE-Grounded transformer
- Used as Back-Up protection for “Through Faults”
- Must be coordinated with other system ground relays
- Operation of this relay will trip the transformer

# Transformer Protection

## Blind Spot Overcurrent Relay:

- On occasion, tapped transformers are energized from the low side only (i.e. high side MOAB is open). This is typically done to maintain station service
- Line Relaying may not respond to a fault that could occur between the Transformer Diff. CTs and the MOAB
- A Blind Spot relay is used to detect this condition
- It is in service only when the high side MOAB is open
- Will trip the low side circuit breakers to isolate the fault

# CT Connections for Tapped Transformer



# Transformer Protection

- Other Protective Devices:
  - Loss of Cooling Relay - If all fans and/or oil pumps are lost for any reason, the transformer will be tripped if temperature is above a predetermined level
  - Low Oil Level - Lack of proper oil level compromises transformer cooling. This device will alarm and eventually trip the transformer if oil level drops below a certain threshold

# Transformer Protection

- Operation of any of the above relay schemes will initiate other protective functions
- The physical design of the electrical system will define what additional actions are taken
- Some actions include:
  - 1) Initiate Direct Transferred Trip to remote terminals
  - 2) Initiate breaker failure relaying
  - 3) Block reclosing of CBs that are tripped (until transformer is isolated)
  - 4) Close the high speed ground switch
  - 5) Initiate permissive trip/stop sending blocking signal, etc

# Transformer Protection

- Turn to Turn shorts (non-fault condition)
  - Have not discussed this abnormal condition much
  - In general, this condition is very difficult to detect - initially
  - As more and more insulation deteriorates, this condition may cause the gas analyzer relay to respond
  - Otherwise, could go undetected until winding flashes over to ground. At that point, normal transformer protection will respond to clear the fault

# Transformer Protection

- Because a Bulk Power Transformer is a high cost piece of equipment, automatic testing of the transformer is generally not included in the control scheme design
- If the differential relay responds, a master trip auxiliary relay will trip and block closing of devices which could re-energize the transformer
- To reclose the locked out devices, this master trip relay must be hand reset

# Operator's role if Transformer Protection Operates

- Know your company policy!
  - Alert all that need to be informed of the operation
  - Be aware of steps required to alleviate possible system overloads, low voltage concerns, etc.
- In general, do not test (try-back) the transformer until it is inspected by qualified individuals

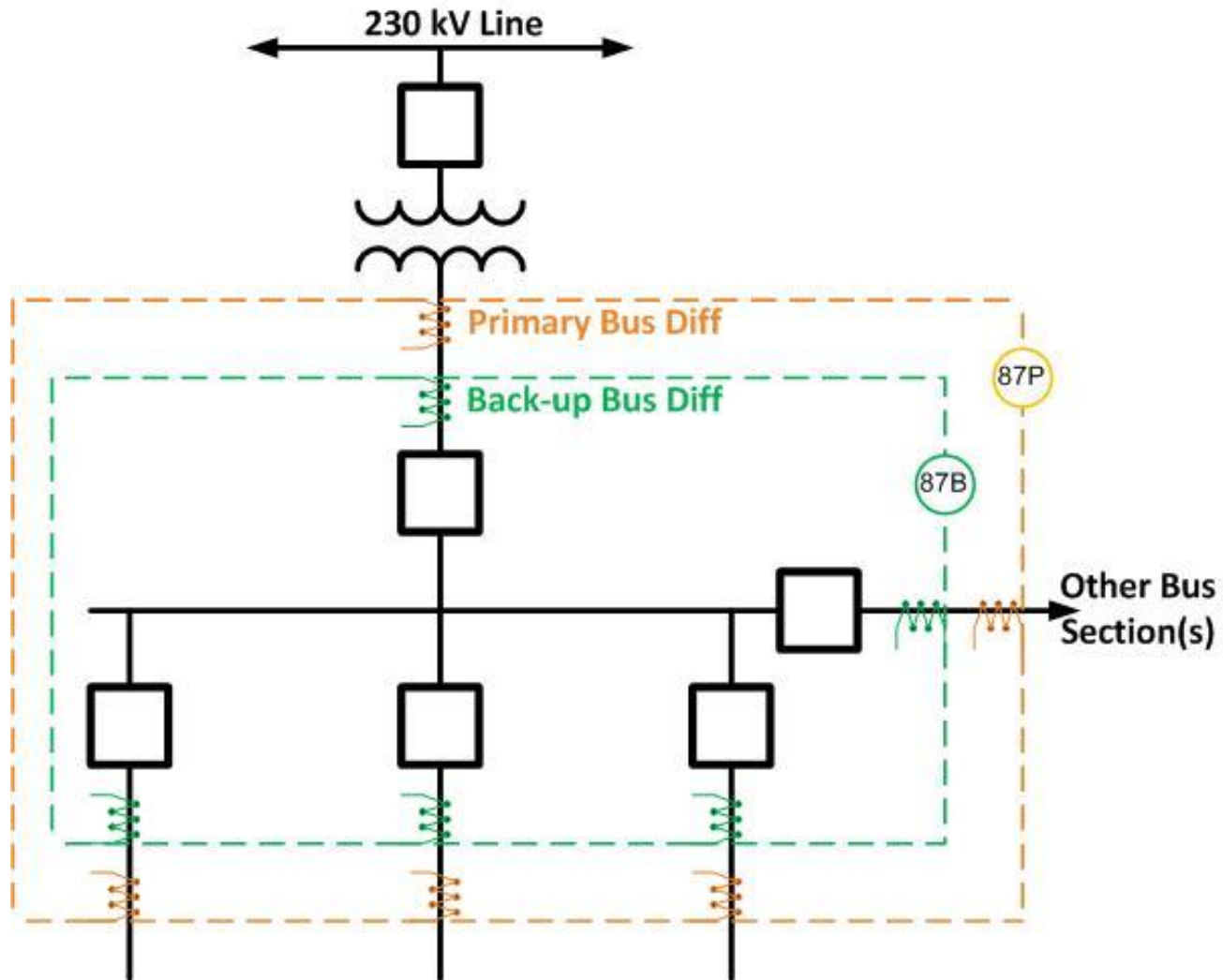


# Bus Protection

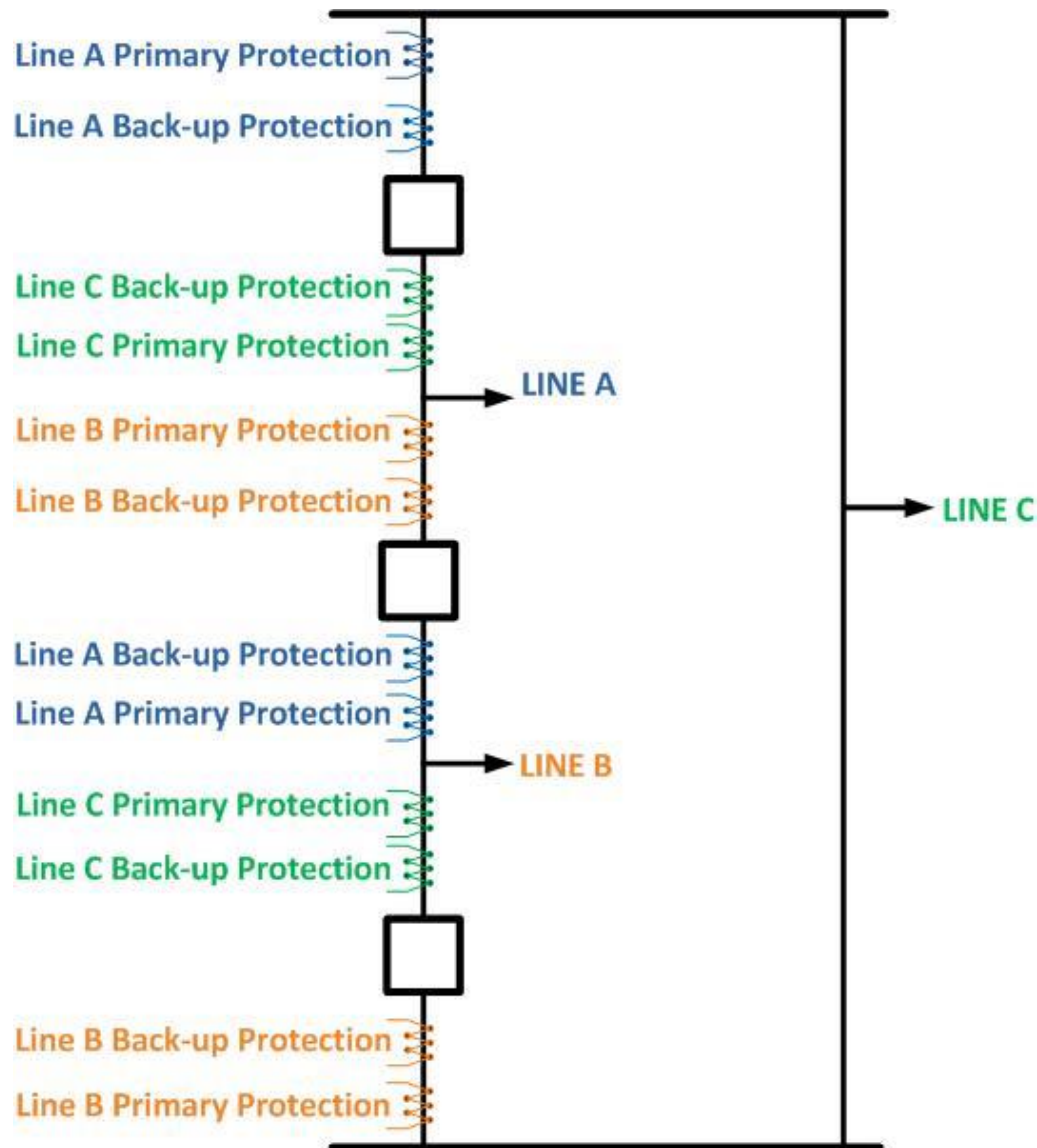
# Typical Bus Designs

- Single Bus - Single Breaker
  - Least flexible of sub designs, but low cost
- Ring Bus
  - Improved Flexibility, may be difficult to relay.
- Breaker and a Half
  - Offers most flexibility, but more expensive
- Double Bus-Double Breaker
  - Similar to Breaker and a Half

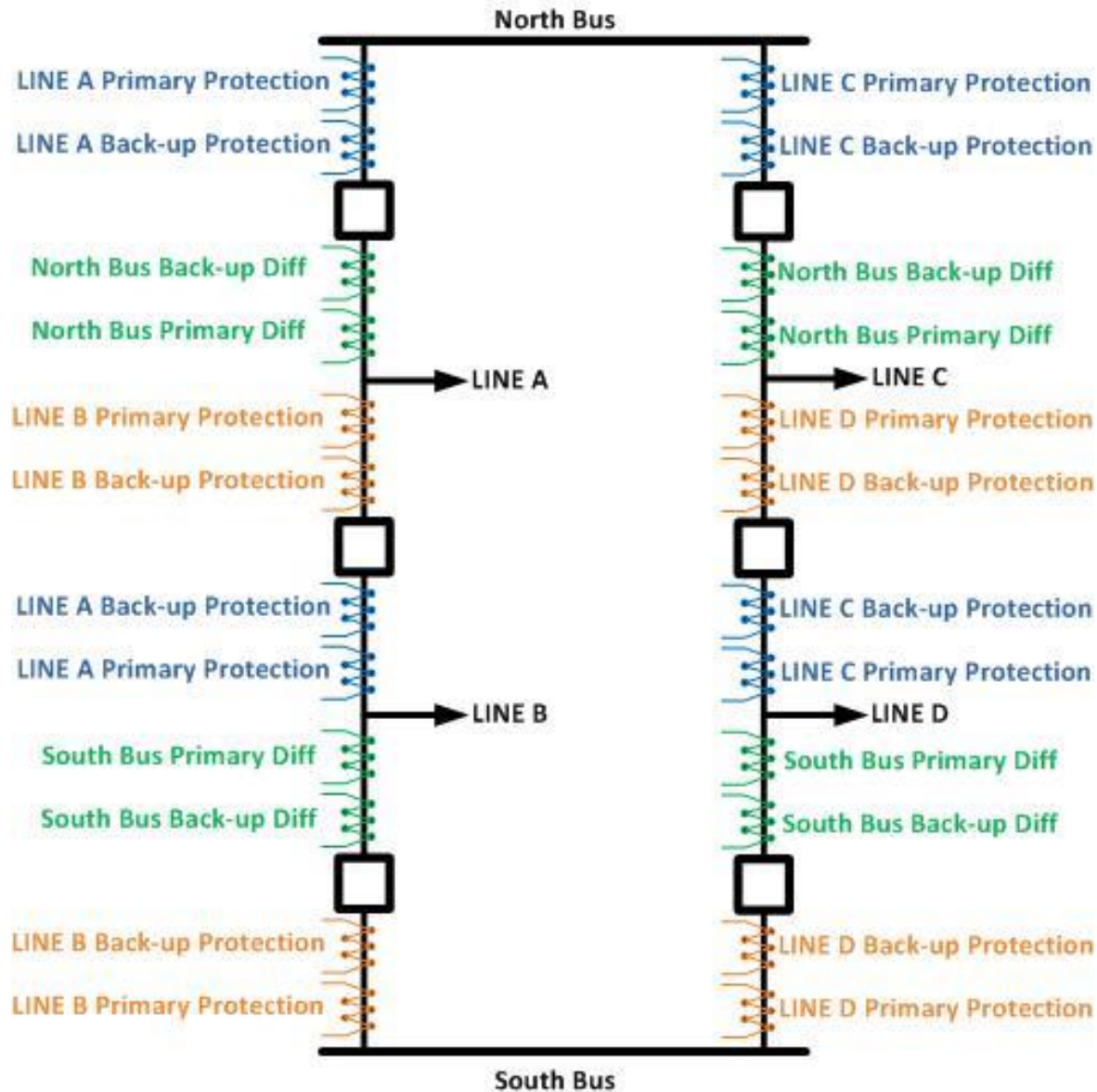
# Single Bus – Single Breaker Arrangement



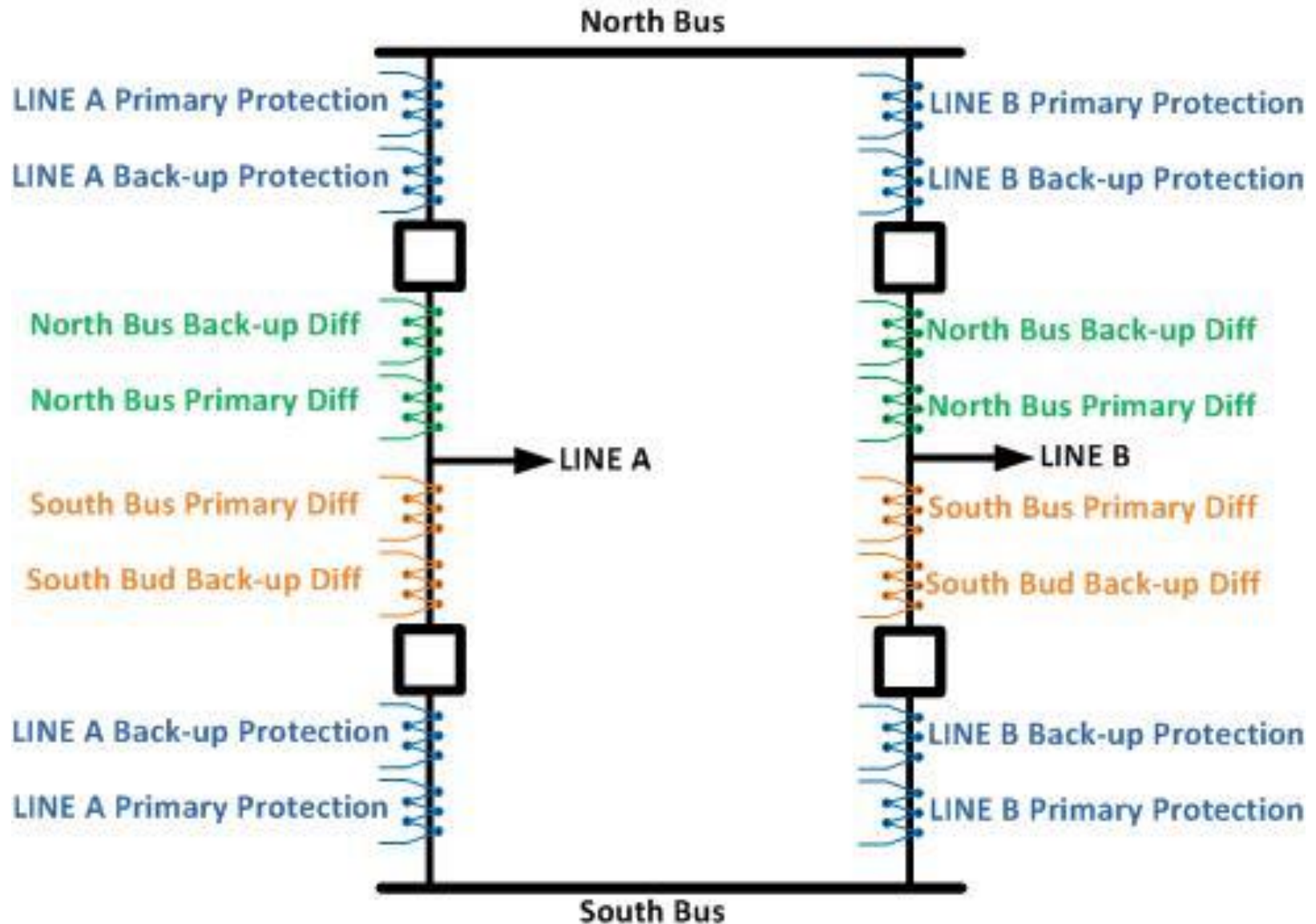
# Ring Bus Arrangement



# Breaker-and-a-Half Bus Arrangement



# Double Breaker – Double Bus Arrangement



# Bus Protection

- On the Bulk Power System, the most common protection practice to insure high speed clearing of faults on bus work is to use **Differential Relays**
- Older, less critical stations may employ Time and Instantaneous Overcurrent relays connected in a differential scheme. These schemes can be less sensitive, slower or both

# Bus Protection

- Generally, the CTs used for Bus Protection are located on the line or equipment side of the circuit breaker. Consequently, the CB is within the protection zone of the bus differential and the line or piece of equipment (**overlapping zones of protection**)
- CTs that are connected in the differential scheme should be of an accuracy class that can withstand maximum expected fault currents (i.e. CTs should not saturate). Failure of application engineers to insure this could lead to a misoperation



# Bus Protection

- If a bus differential relay operates, the relay will typically do the following:
  - 1) Energize a Master Trip Auxiliary Relay
  - 2) Trip all sources to that bus section (via the Master Trip)
  - 3) Setup the Reset of the Master Trip Relay if bus testing is to occur
  - 4) Block reclosing of all CBs except that of the automatic testing source (if so equipped)
  - 5) Initiate Breaker Failure
  - 6) Initiate an Alarm

# Bus Protection

- On the 500kv System, automatic bus testing does not occur
- In general, on voltage levels below 500kv, a single automatic test of the bus might occur. This can vary across the PJM territory

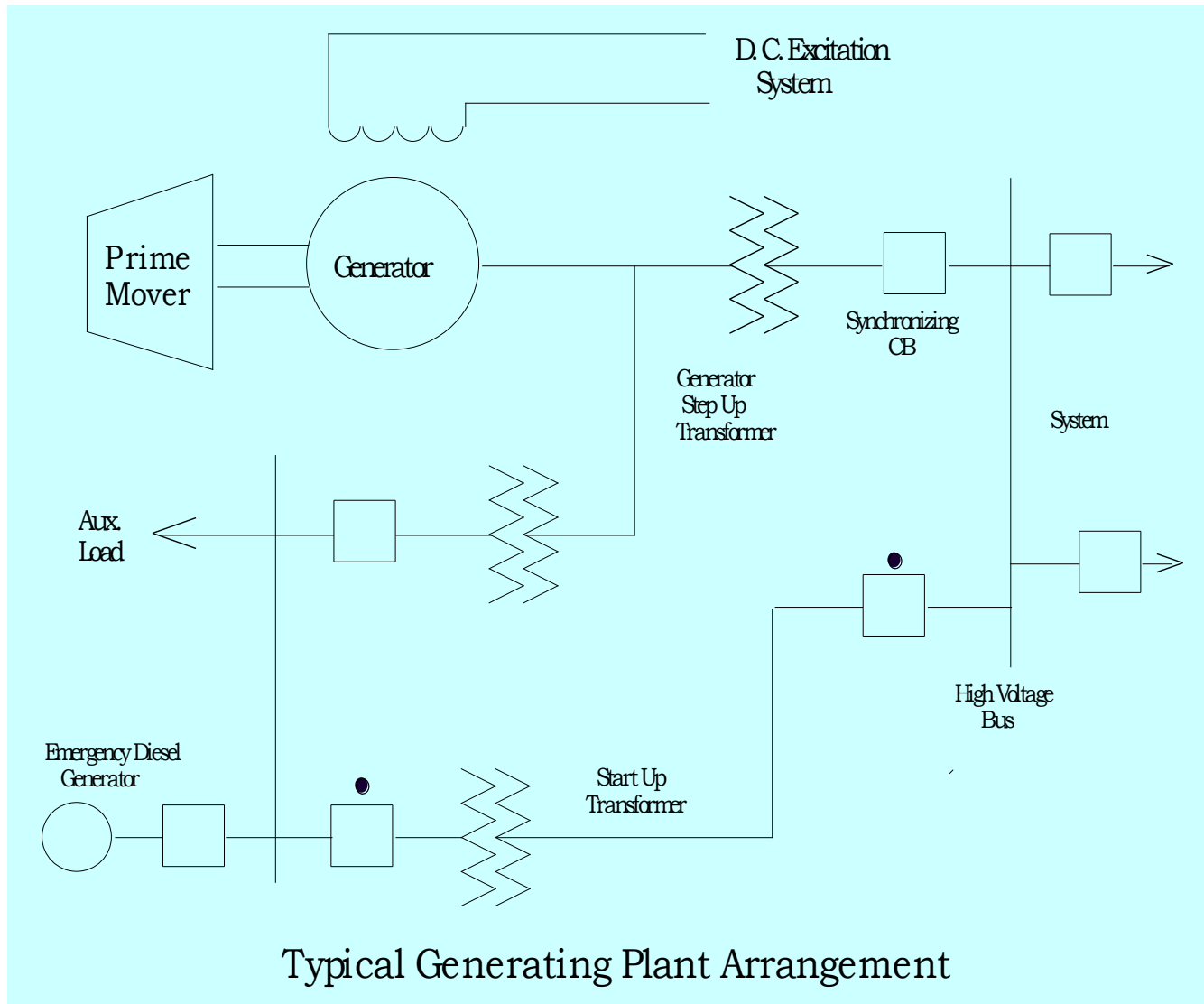
# Bus Protection

- If the particular station is equipped with bus testing and a successful test occurs, all remaining CBs that were tripped will automatically reclose
- If the bus test was unsuccessful, all CBs, including the testing CB, will be locked out
- Although automatic reclosing is blocked, the operator may have the ability to close a CB via supervisory control (SCADA)

# Operator Role is Bus Protection Operates to de-energize a Bus

- Know your company policy!
  - Alert all that need to be informed of operation
  - Be aware of steps required to alleviate possible system overloads, low voltage concerns, etc. (sound familiar?)
- If the bus trips and locks out, no testing via SCADA should occur until the station is inspected by authorized personnel

# Generator Protection



# Station Arrangement

- A Generator is usually connected to the power system through a wye-delta transformer (wye on the high voltage side, delta on the generator side)
- Generator itself is connected wye with its neutral grounded through a high impedance
- Purpose of this generator connection is to limit the high magnitude currents which could flow for a ground fault

# Station Arrangement

- Generator In-Service
  - Startup Transformer is out of service
  - Plant auxiliary loads are supplied from the station service transformer
- Generator Out of Service
  - Since Generator is off line, the station service transformer is out of service
  - Plant auxiliary loads are supplied from the Startup Transformer



# Station Arrangement

- Station Blackout
  - Generator has just tripped or was already off line
  - The startup transformer can provide no help because this portion of the high voltage system is interrupted
  - Emergency generators (diesel) are used to supply the plant auxiliary load until the system is restored

# Generator Unit Tripping

# Generator Unit Tripping:

- The frequency of failures in Rotating Machines is low, however failures can and do occur
- Beyond actual failures, certain abnormal conditions can cause generator failure if not corrected quickly
- Some of these harmful conditions are:
  - Winding Faults
  - Overheating
  - Loss of Field
  - Single Phasing
  - Overloading
  - Overspeed
  - Motoring (turbine)
  - Overexcitation

## Generator Unit Tripping:

- Not all of the problems mentioned necessarily have to cause a unit trip. If detected quickly, measures can be taken to mitigate the problem
- Consequently, some relay schemes will first produce an alarm to alert operators of the problem. If the problem worsens before corrective action can be taken, the scheme will initiate a unit trip

## Generator Unit Tripping:

- If protective devices do cause a unit trip, the following actions will occur:
  - 1) Generator Synchronizing CB is tripped and locked out
  - 2) Normal Station Service supply CB is tripped
  - 3) Generator DC field CB is tripped
  - 4) Prime Mover is tripped

## Generator Unit Tripping:

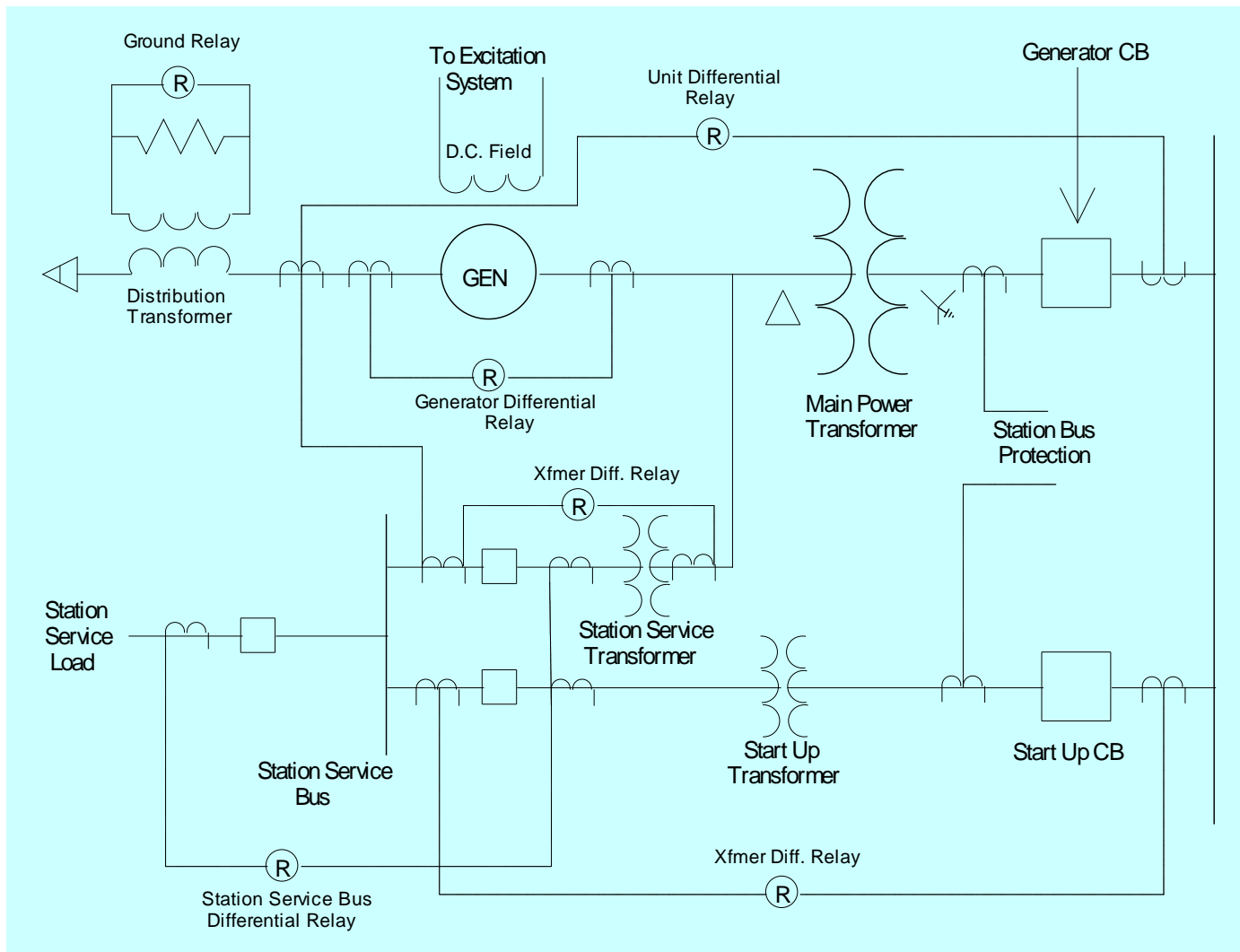
- When a unit trips, the function of the plant operator is to stabilize the prime mover and auxiliary systems to insure a controlled shut down
- The generation dispatcher's purpose is dependent upon individual company procedures. This could involve negotiation for additional generation or notifying that company's energy marketing function

# Overall Unit Protection

## **Areas to be protected and concerns:**

- 1) Generator - Winding Fault, Overloading, Overheating, Overspeed, Underfrequency, Loss of Excitation, Motoring, Phase Unbalance, Out of Step
- 2) Turbine - Overspeed, Underspeed, Vibration, Temperature
- 3) Auxiliaries - Cable Faults, Grounds on System
- 4) Station Service - Transformer Faults, Lead faults, etc

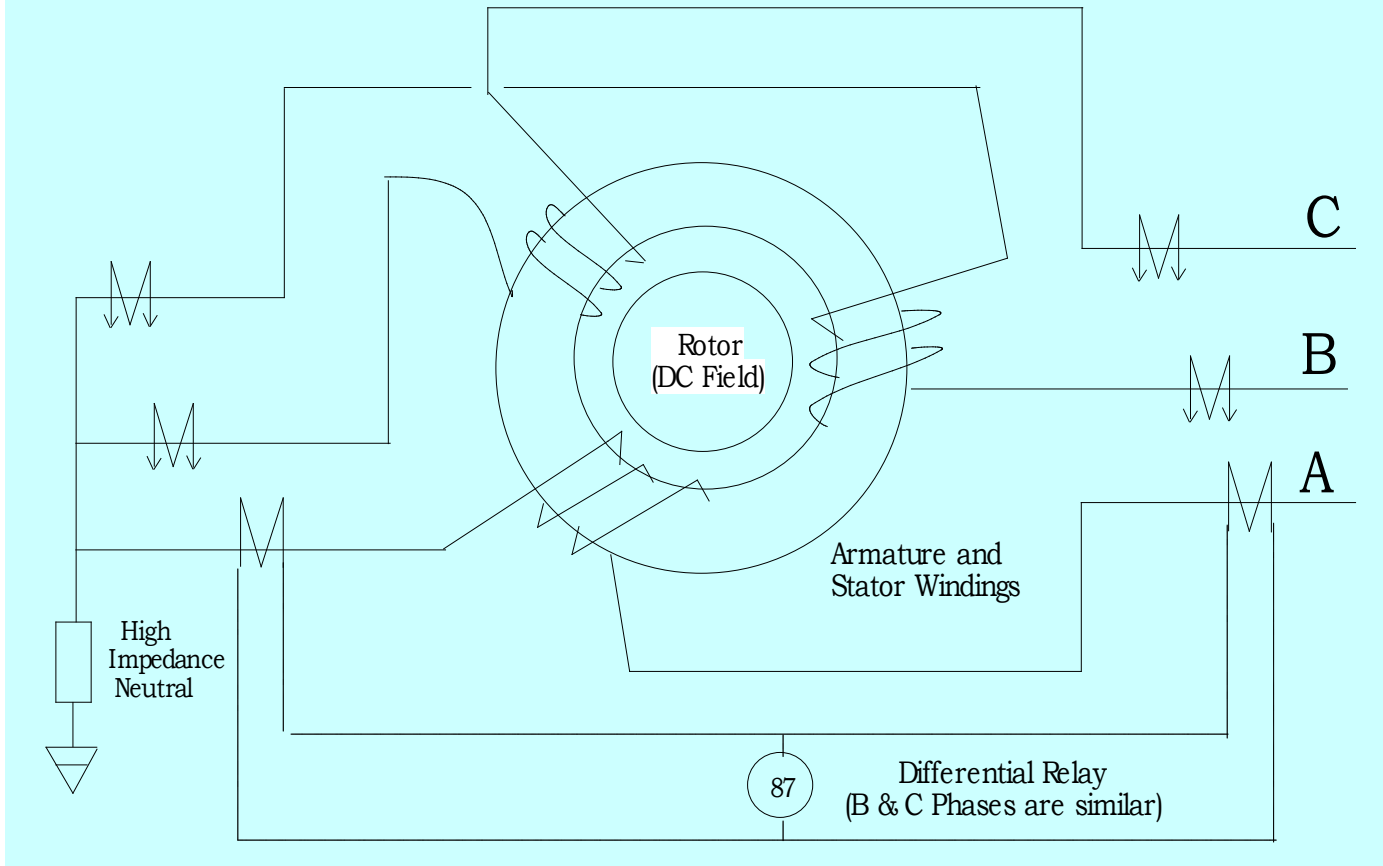




# Protective Relay Schemes for the Generator:

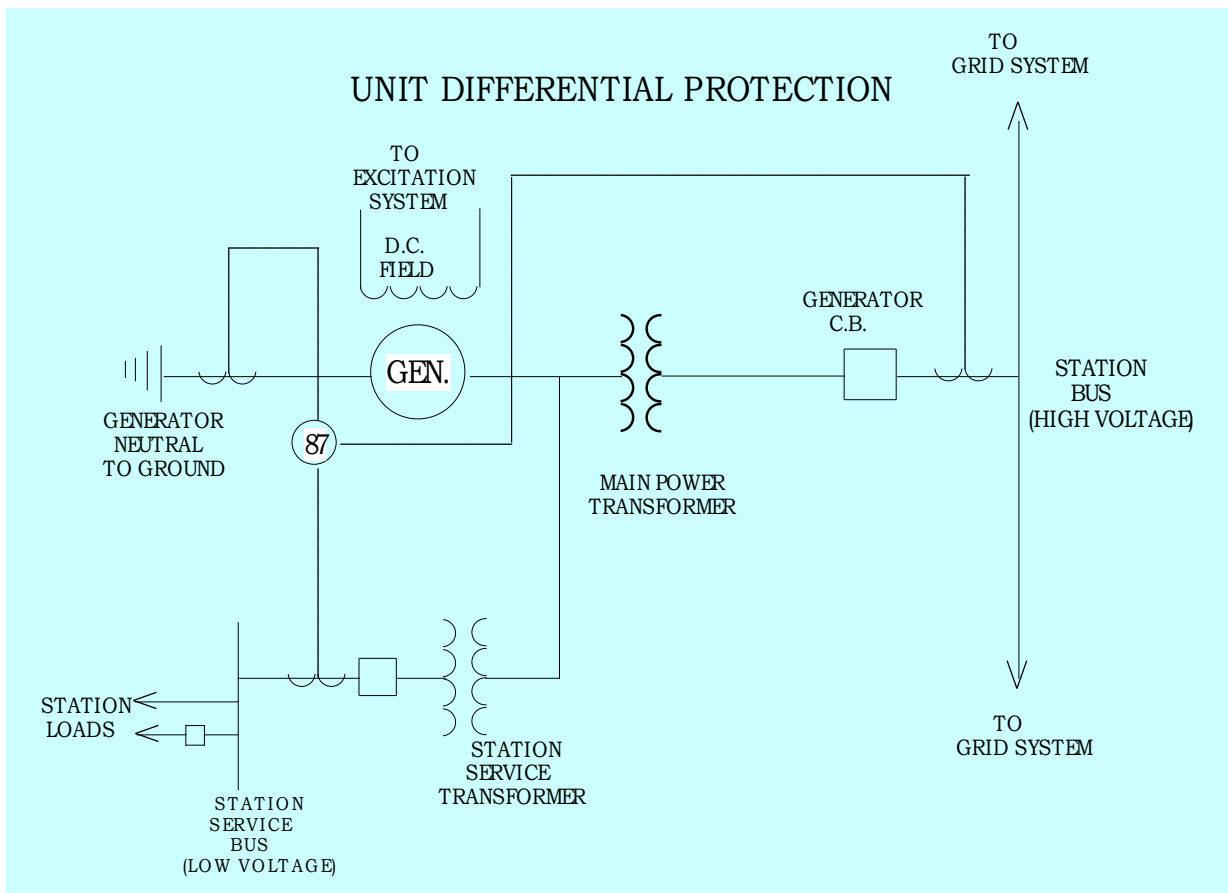
- Generator Differential
  - Wraps only the Stator Windings of the Generator
  - Sensitive to phase and some ground faults
  - Operation of this relay will initiate a unit trip

## Generator Differential



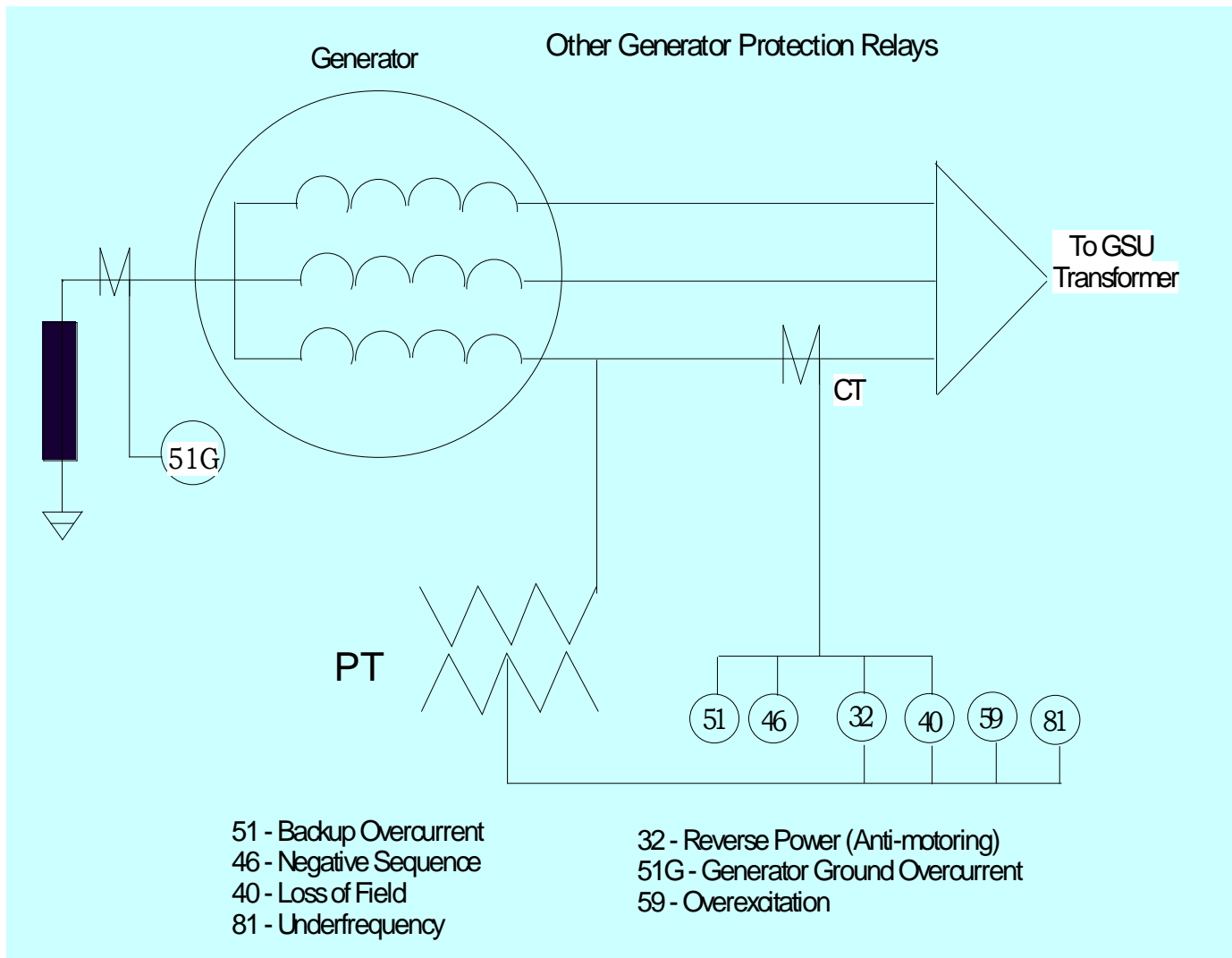
# Protective Relay Schemes for the Generator:

- Overall Differential
  - Wraps the Generator, Gen. Step-up Transformer & Station Service Transformer
  - Sensitive to phase & some ground faults
  - Backs up the Gen. Diff, GSU Diff., Station Service Diff, etc
  - Less sensitive than the Gen. Diff
  - Operation of this relay will initiate a unit trip



# Protective Relay Schemes for the Generator:

- Overcurrent Protection
  - Provide Backup Protection for Gen. Diff Scheme
  - Protects the generator from system faults that are not cleared within a predetermined time interval
  - Coordinated with System Overcurrent schemes
  - Usually time delayed to minimize tripping for transient surges or synchronizing
  - Will initiate a unit trip



# Protective Relay Schemes for the Generator:

- Anti-motoring or Reverse Power Protection:
  - Actually used to protect the Turbine instead of the generator
    - When Generator takes in power, it is essentially a synchronous motor (non-harmful to generator)
    - This mode of operation, if sustained could lead to turbine blade failure
  - This is one standard method for taking unit off line
  - May cause alarm, but will initiate a unit trip



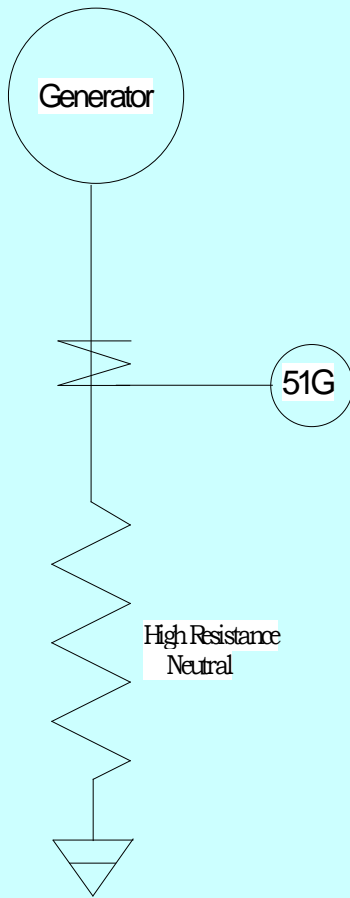
# Protective Relay Schemes for the Generator

- Negative Sequence Protection
  - During unbalanced faults, “Negative Sequence” currents will flow
    - Physically, 120 cycle rotor currents are induced in the solid rotor forgings, non-magnetic rotor wedges and retaining rings.
    - The  $I^2R$  loss quickly raises temperature of the rotor and would eventually cause serious rotor damage
  - Will initiate an alarm and trip unit

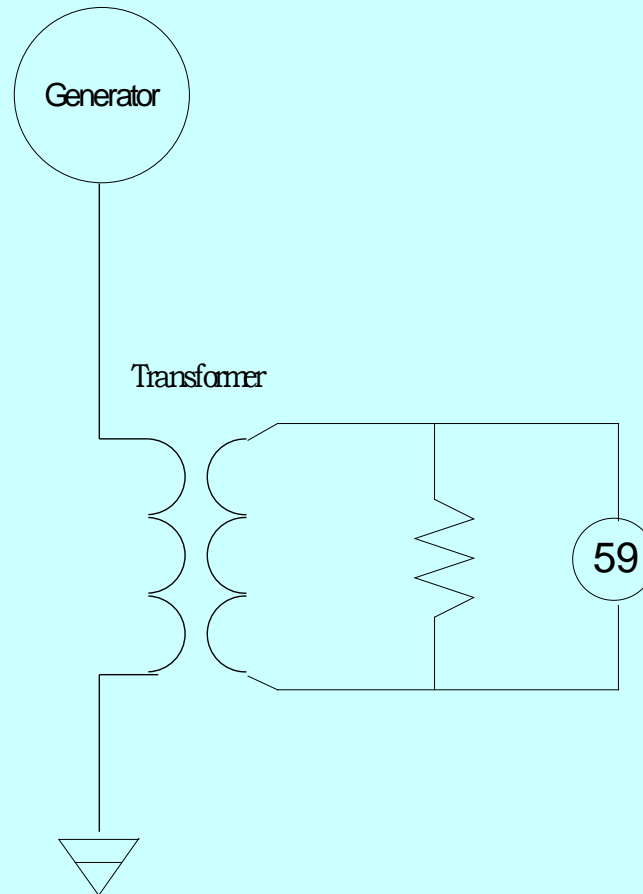
# Protective Relay Schemes for the Generator:

- Generator Ground Fault Protection
  - Method of Generator Grounding affects the protection provided by the differential relays
    - The higher the grounding impedance, the lower the ground fault current magnitude
  - To detect these low magnitude faults, Neutral Overcurrent or an Overvoltage relay scheme is employed
  - Operation of this relay scheme will initiate a unit trip

## Types of Generator Grounding Used



Resistored Neutral with  
an Overcurrent Relay



High Impedance Neutral  
with Overvoltage Relay

# Protective Relay Schemes for the Generator:

- Loss of Field Protection
  - When loss of field occurs in a synchronous machine, reactive power flows from the system into the machine
  - The reactive flow can be 2 to 3 times the generators rated load (i.e. thermal damage)
  - Relays monitor reverse var flow or low voltage
  - Operation of this relay will alarm and initiate a unit trip

# Protective Relay Schemes for the Generator:

- Loss of Field Protection
  - Loss of Field indicates that trouble exists in:
    - 1) Main Exciter
    - 2) Field Winding
    - 3) Operating Error when machine is in Manual mode

# Protective Relay Schemes for the Generator:

- Overexcitation Protection
  - Concern is for the Generator Field and main GSU transformer since overexcitation can cause damaging overheating due to core saturation in a very short time
  - For GSU transformer protection, a Volts/Hertz relay is applied
    - Operation of relay will trip unit
  - For Field Overexcitation, Voltage or Current relays are employed
    - Relay will alarm or automatically reduce field to allowable limits

# Protective Relay Schemes for the Generator:

- Underfrequency Protection
  - If System Load exceeds the capability of the machine, the frequency will decay
  - In PJM, machines are typically set for 57.5 hz with a 5.0 second time delay
  - System load shedding schemes are used to dump load as required
    - If not enough load is disconnected and frequency drops, relay will initiate a unit trip
  - If unit tripping occurs, pull out your “Black Start Restoration” guide because it will be needed!

# **Generator Protection Exercises/Review**



List the associated actions that typically occur when a generator trips:

- Field Breaker Opens
- Generator Synchronizing Breaker Opens
- Normal Station Service Transformer Opens
- Energy source to Prime Mover is removed
- Other devices may operate in order to safely shut down the unit

# Summary

- Describe the purpose of protective relays
- Identify relay protection scheme characteristics and components
- Describe the impact of the loss of components on system protection
- Identify the types of transmission line protection and their characteristics
- Identify the types of transformer protection and their characteristics
- Identify the types of bus protection and their characteristics
- Identify the types of generator protection and their characteristics

# Questions?

## Disclaimer:

PJM has made all efforts possible to accurately document all information in this presentation. The information seen here does not supersede the PJM Operating Agreement or the PJM Tariff both of which can be found by accessing:

<http://www.pjm.com/documents/agreements/pjm-agreements.aspx>

For additional detailed information on any of the topics discussed, please refer to the appropriate PJM manual which can be found by accessing:

<http://www.pjm.com/documents/manuals.aspx>

## Resources and References

- PJM. (2013). *PJM Manual 3: Transmission Operations (rev 43)*. Retrieved from <http://www.pjm.com/~media/documents/manuals/m03.ashx>
- PJM. (2011). *PJM Manual 7: PJM Protection Standards (rev 0)*. Retrieved from <http://www.pjm.com/~media/documents/manuals/m07.ashx>
- Miller, R. & Malinowski, J. (1994). *Power System Operation*. (3<sup>rd</sup> ed.). Boston, MA. McGraw-Hill.