Power System Elements

Relay Applications

PJM State & Member Training Dept.

Objectives

- At the end of this presentation the Learner will be able to:
- Describe the purpose of protective relays, their characteristics and components
- Identify the characteristics of the various protection schemes used for transmission lines
- Given a simulated fault on a transmission line, identify the expected relay actions
- Identify the characteristics of the various protection schemes used for transformers and buses
- Identify the characteristics of the various protection schemes used for generators
- Describe the purpose and functionality of Special Protection/Remedial Action Schemes associated with the BES
- Identify operator considerations and actions to be taken during relay testing and following a relay operation

Basic Concepts in Protection

Purpose of Protective Relaying

- Detect and isolate equipment failures
  - Transmission equipment and generator fault protection
- Improve system stability
- Protect against overloads
- Protect against abnormal conditions
  - Voltage, frequency, current, etc.
- Protect public

Purpose of Protective Relaying

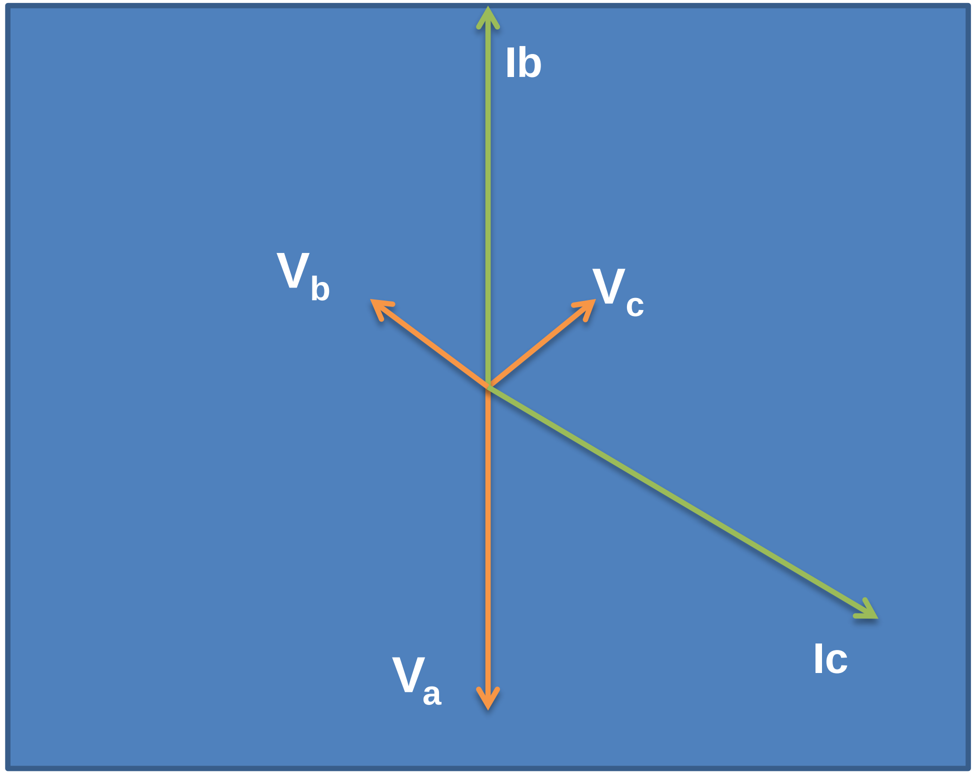
- Intelligence in a Protective Scheme
  - Monitor system “inputs”
  - Operate when the monitored quantity exceeds a predefined limit
    - Current exceeds preset value
    - Oil level below required spec
    - Temperature above required spec
  - Will initiate a desirable system event that will aid in maintaining system reliability (i.e. trip a circuit breaker, throttle back a unit, etc.)

Fault Causes

- Lightning
- Wind and ice
- Vandalism
- Contamination
- External forces
  - Cars, tractors, balloons, airplanes, trees, critters, etc.
- Equipment failures
- System disturbances
  - Overloads, system swings

Fault Types

- Single phase to ground (most common)
- Three phase (rare but most severe)
- Phase to phase
- Phase to phase to ground



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)

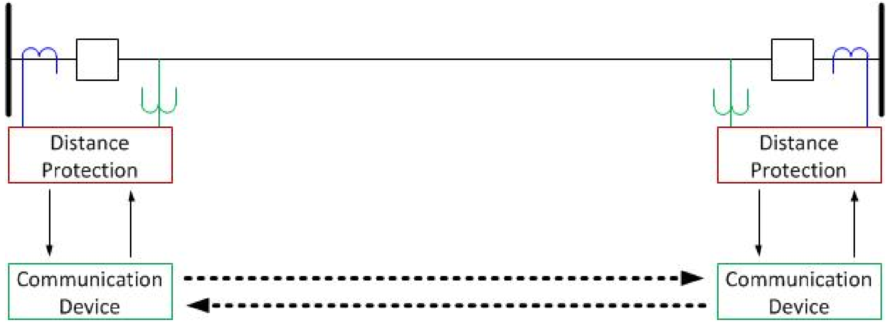
Relay Scheme Components

Components

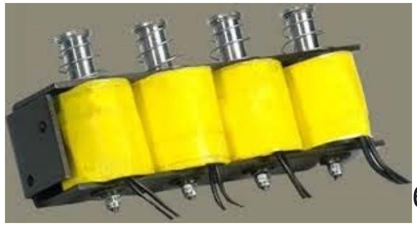
Components That Could Impact System Protection				
Current Transformers	Potential Transformers	Battery Bank	Control Wiring	Operating Coils
Communication Circuits	Relays	Vandalism	Critters	Humans











Effects

- Loss of CTs or PTs
  - Main source of inputs to protection schemes
  - Failure would render scheme inoperable if no redundant source
- Battery Bank
  - Substation equipment uses DC to operate
  - Loss of the DC would prevent devices from operating
- Control Wiring
  - Damaged control wiring could prevent operation of isolating devices or relays
    - Protection and control circuits are individually fused

Effects

- Communication Circuits
  - Could result in an over-trip or no trip at all
- Relays
  - Could result in miss-operation or no operation of the scheme and the devices it is to operate
- Operating Coils
  - Part of breaker mechanism and would prevent operation if failed
- Critters
  - Mice can chew through control wires that could affect the operation of a protection scheme

Effects

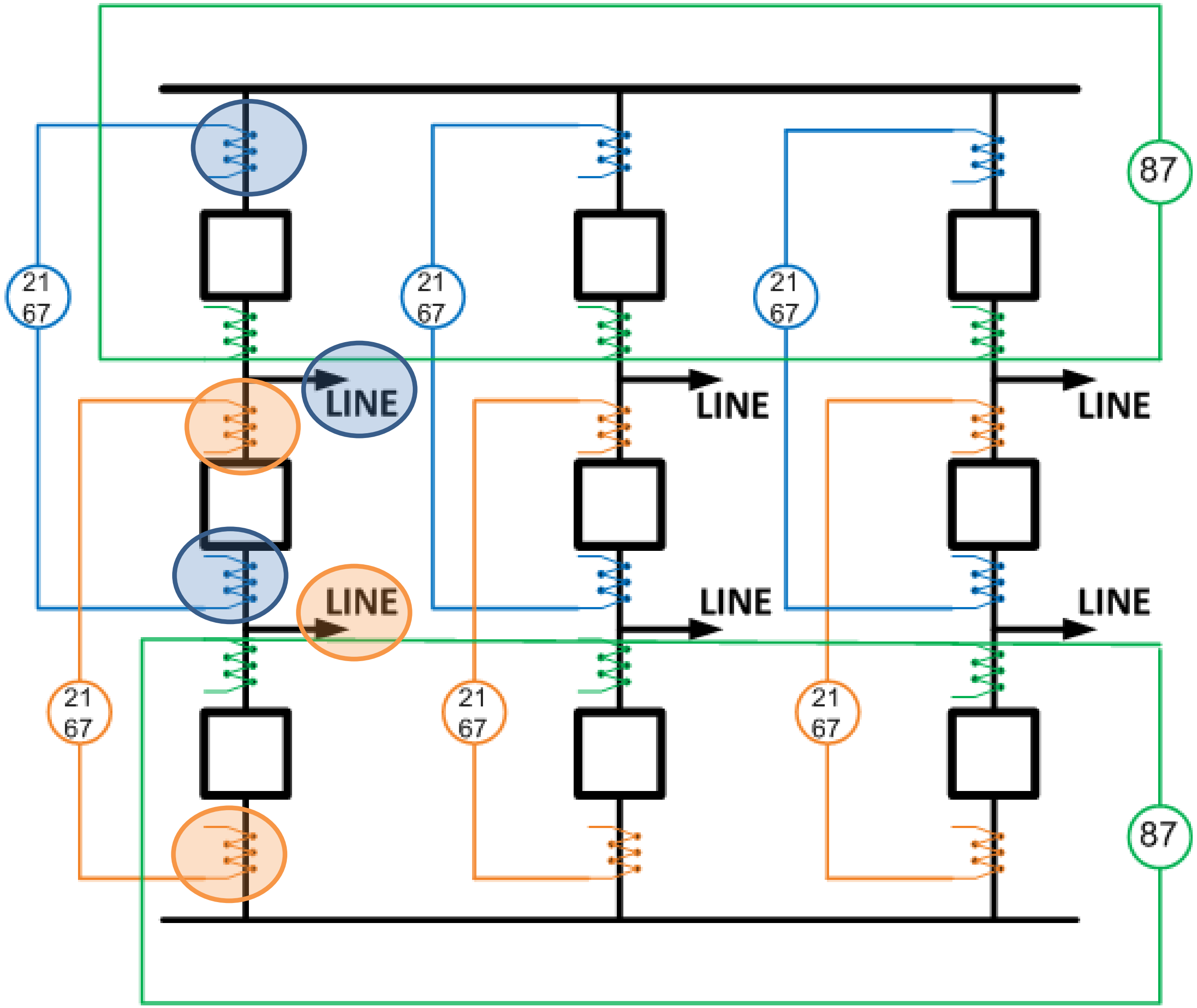
- Humans
  - Vandalism
    - Copper theft could render schemes inoperable
  - Incorrect settings
    - Scheme not operating when it should, or operating when it shouldn’t
  - Scheme not completely isolated during testing
    - Equipment tripping for non-fault condition
  - Isolation links left open after testing
    - Equipment not tripping for a fault condition

Overview of Power System Protection

Key Element to Remember:
Protective Schemes Are Designed to Have:

Overlapping Zones of Protection!

Overlapping Zones of Protection

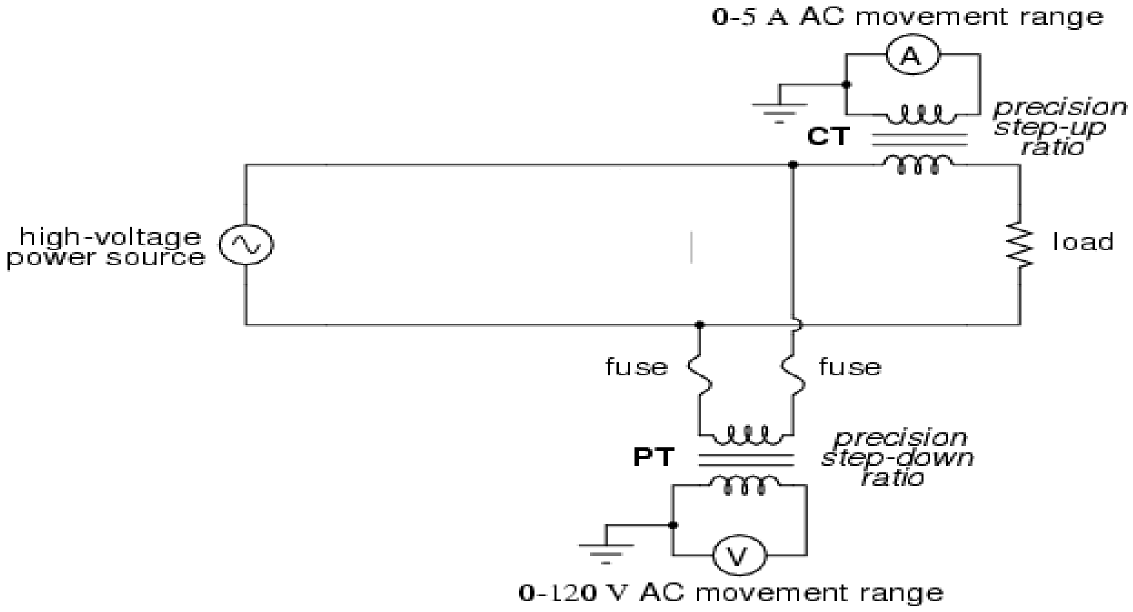


Overview of Power System Protection

- Critical elements of the power system are protected by "Primary" and "Backup" relay systems
  - Primary Schemes
    - 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

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

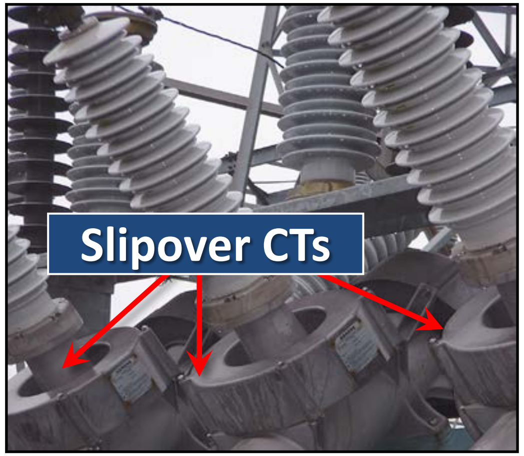


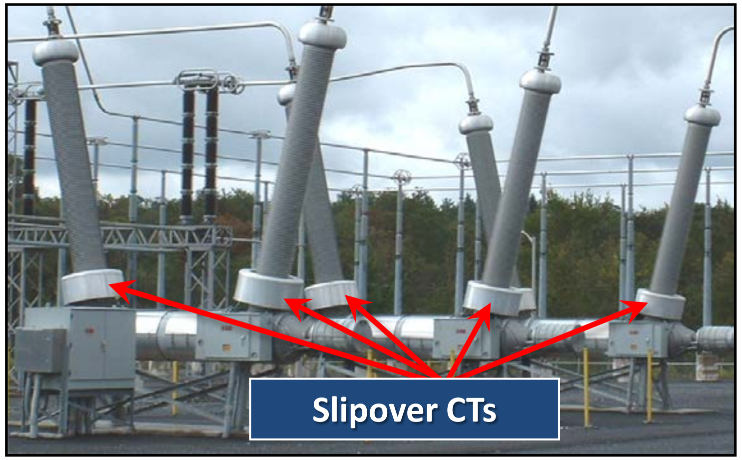
Current Transformers (CTs)

- 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
    - Most common type of CTs

Current Transformers (CTs)

- 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 x 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



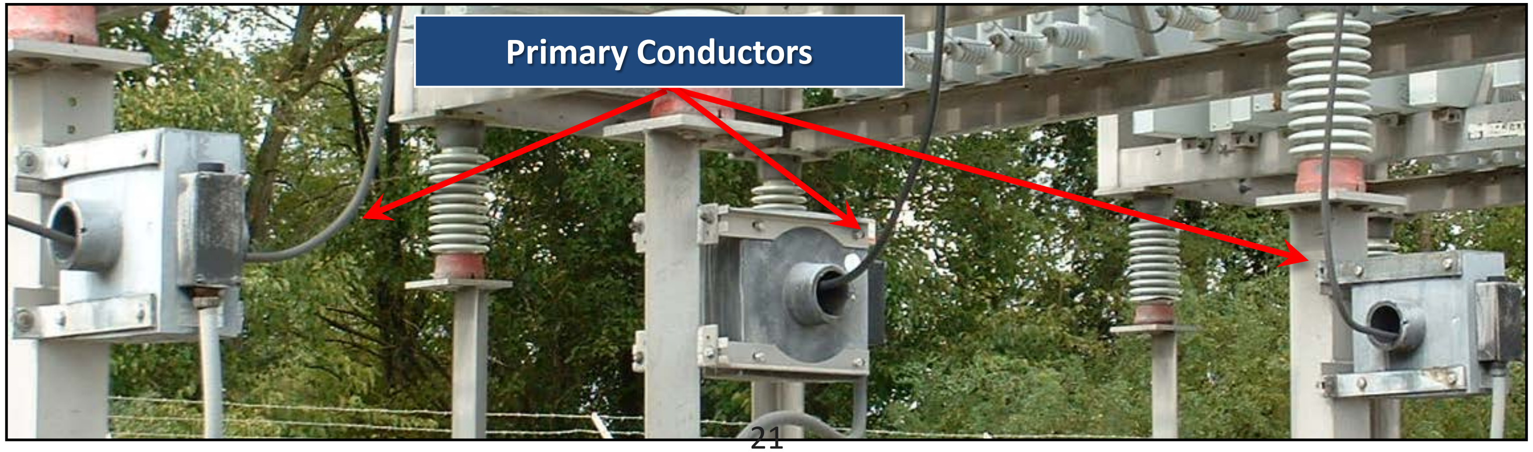


Illustrations of Externally Applied Current Transformers

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**



Potential Transformer (PTs)

- PTs transform primary voltages to 115 VAC or 69 VAC secondary voltages used in relay and metering circuits
- Large generators
  - Usually have two sets of PTs,
    - **Metering PTs** and the **Regulator PTs**
- PTs aren't usually used at transmission voltage levels
- Most higher voltage applications use a derivative of the PT, the **Capacitance Potential Device**

Capacitance Potential Devices

- **CCPD** *(**C**oupling **C**apacitor **P**otential **D**evice)* or
  CCVT *(**C**oupling **C**apacitor **V**oltage **T**ransformer)*
  - Use **voltage division** to reduce primary voltages
  - Primary voltage divides across porcelain capacitance stacks, T
  - The higher the voltage the more units in the stack
  - Transformer in CCVT base does final transformation
  - 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, C3 and C4
- Voltage across C4 equals approximately 20 kV

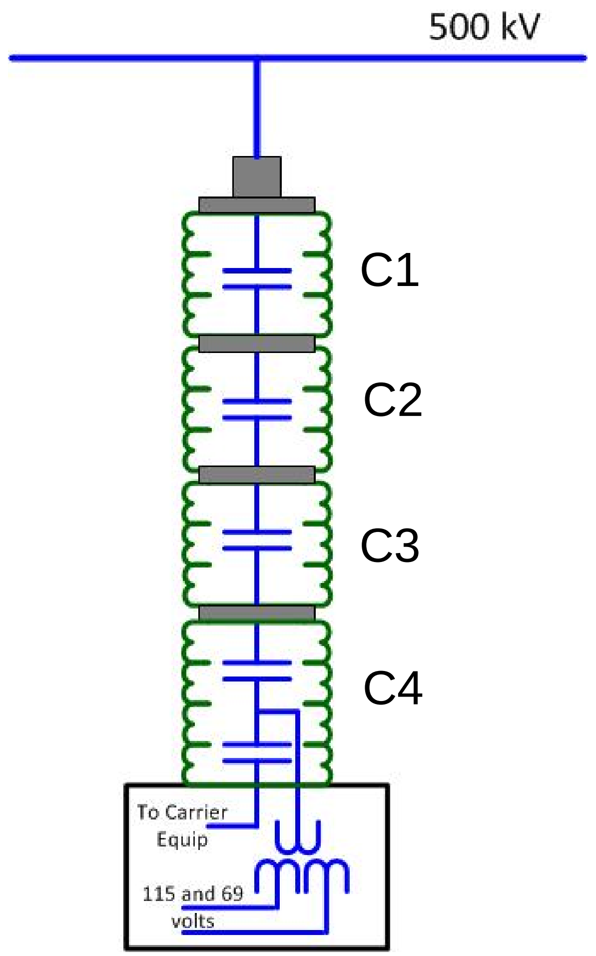


Illustration of 230kV CCVT

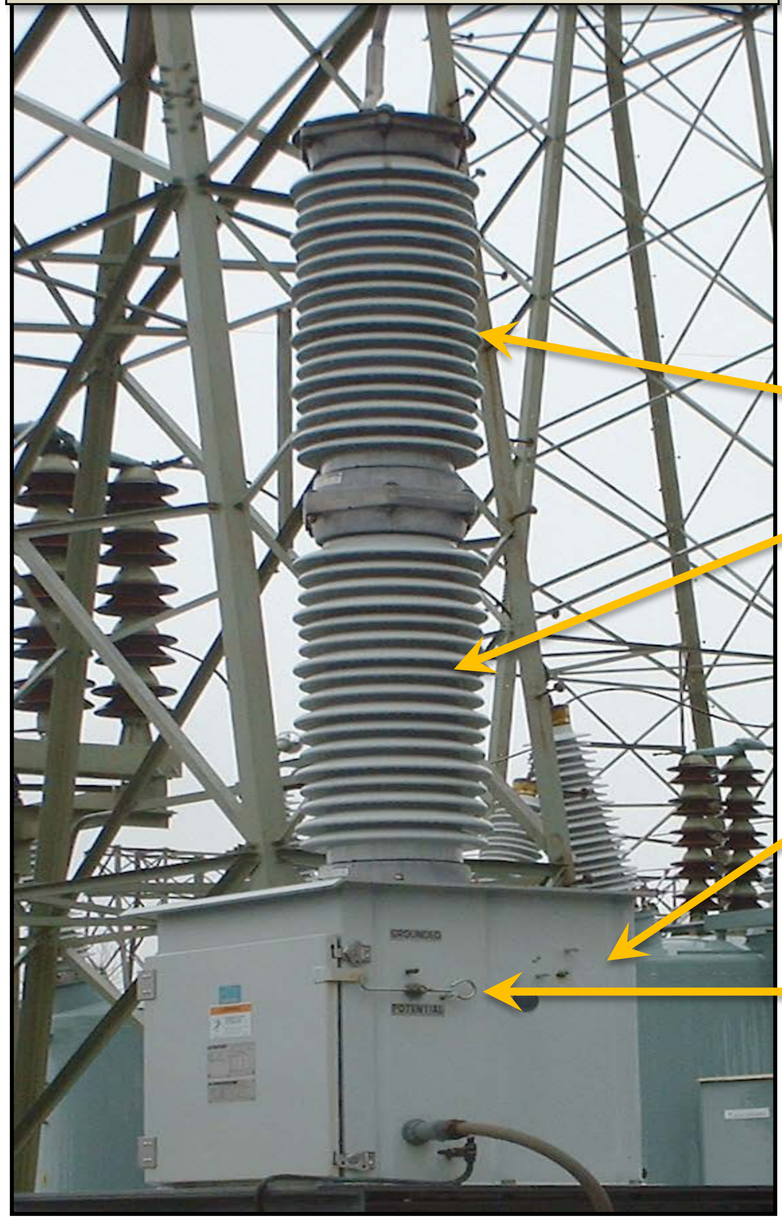
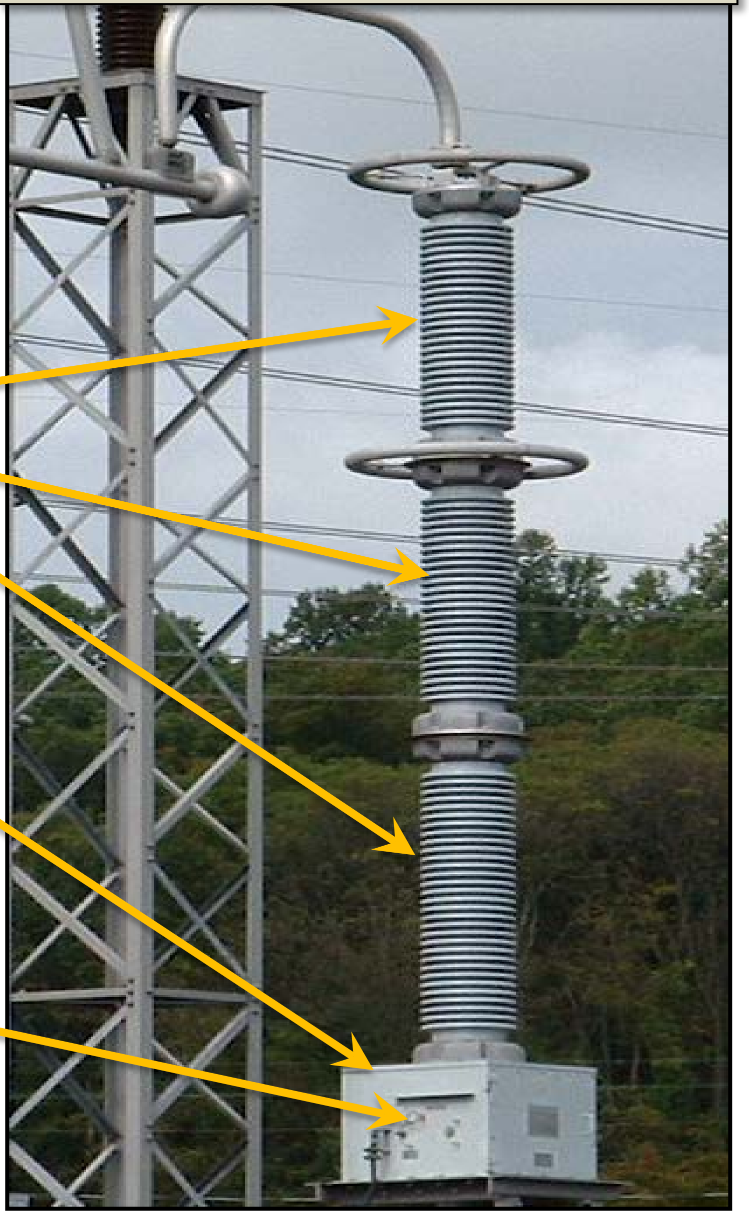


Illustration of 500kV CCVT



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

Capacitor Stacks

Transformer Enclosure

Grounding Switch

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

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

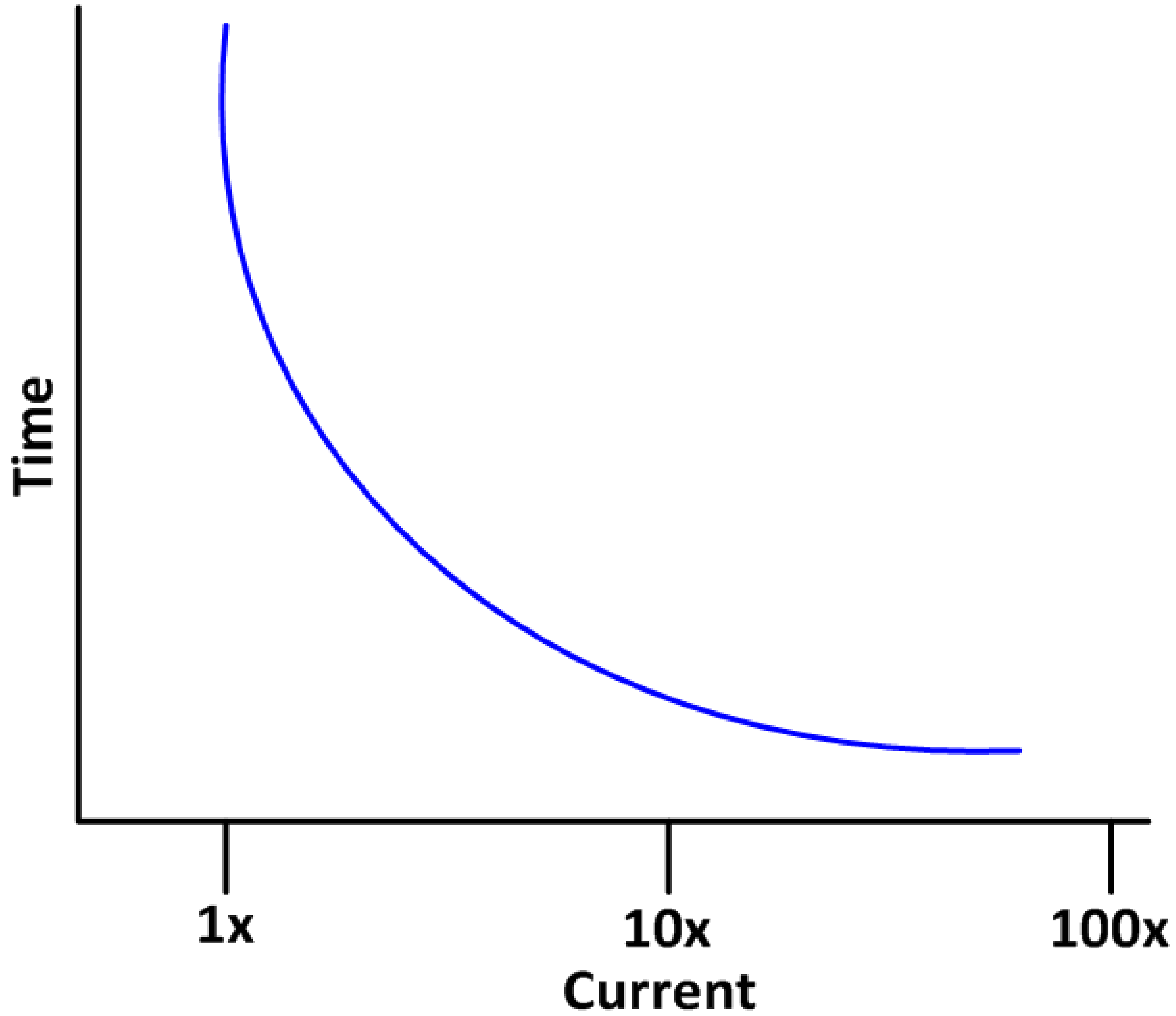
IEEE #	Device	Relay Function	IEEE #	Device	Relay Function
21	Distance Relay	Requires a combination of high current and low voltage to operate. The various zones of the distance scheme (Z1, Z2, etc.) assist with determining the location of the fault	63	Pressure Relay	Operates on low or high pressure of 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

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

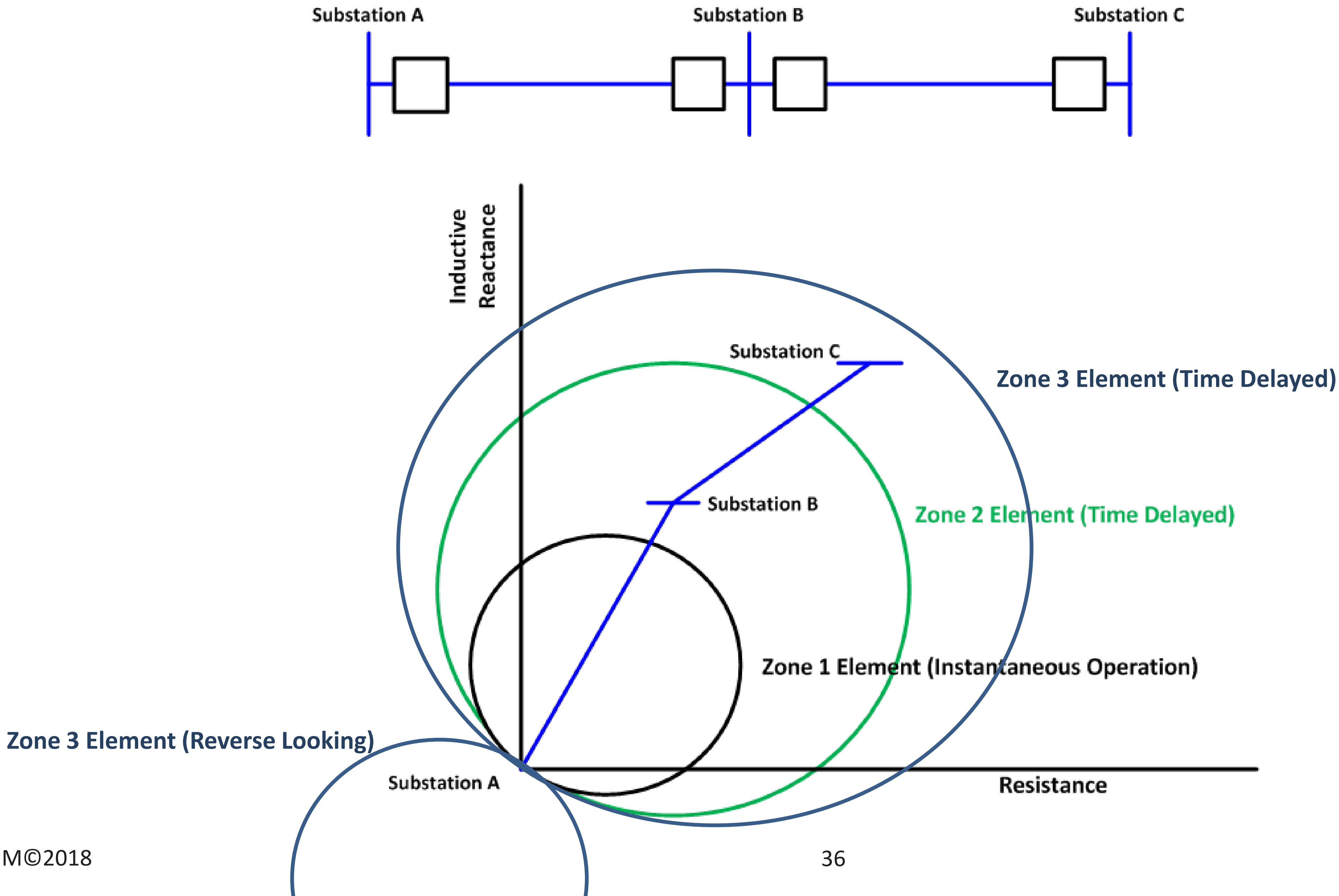
- Required Inputs: Current and Voltage
- How is it achieved?
  - Directional relays require polarizing quantities
    - Voltages and/or currents
    - These are converted into proportional magnetic forces acting on an induction cup that spins either clockwise or counter-clockwise towards a trip or non-trip position
  - As a rule of thumb:
    - Voltage restrains the induction cup from spinning in the trip direction
    - Current tends to spin the cup such that its electrical contact operates and trips
  - The rule of thumb makes sense: a power system fault decreases voltage and increases current…less voltage means less restraint and more current means greater torque toward the trip direction

Typical Performance Parameters

Directional 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)
- Can provide three Zones of Protection:
  - Zone 1 - Instantaneous Operation:
    - Set for approximately 90% of line
      - Beyond that relay would not be able to distinguish between internal or external fault
  - Zone 2 - Fixed Time Delay Operation
    - Set to see entire line + margin
  - Zone 3 - Fixed Time Delay Operation (Generally not used for forward faults anymore)
    - Set greater than Zone 2

Directional Distance Protection



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
  - Operators must be aware of any lines that are restricted not due to their thermal capability, but by the relays themselves

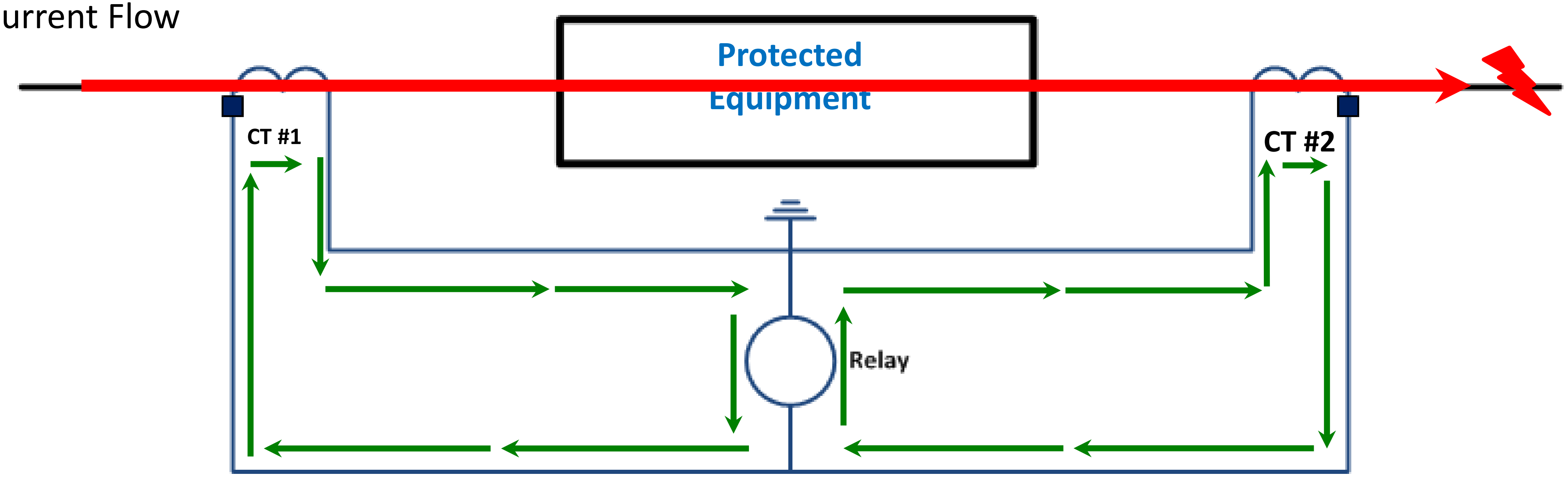
Typical Performance Parameters:

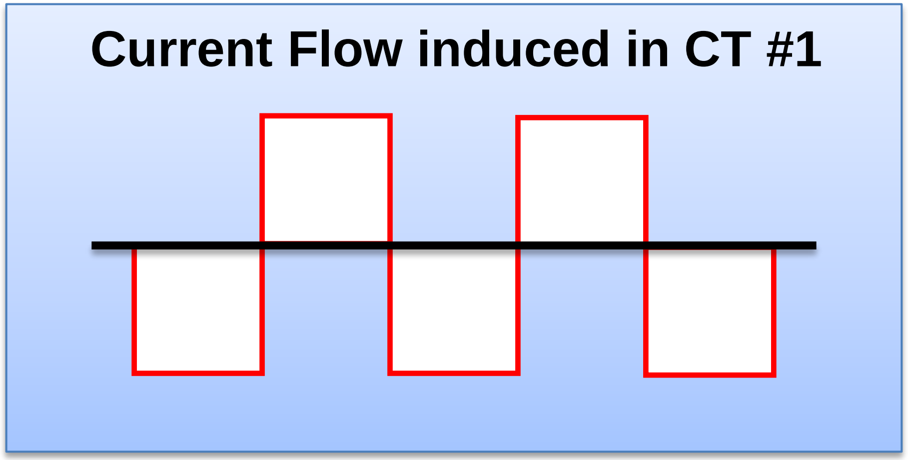
Differential

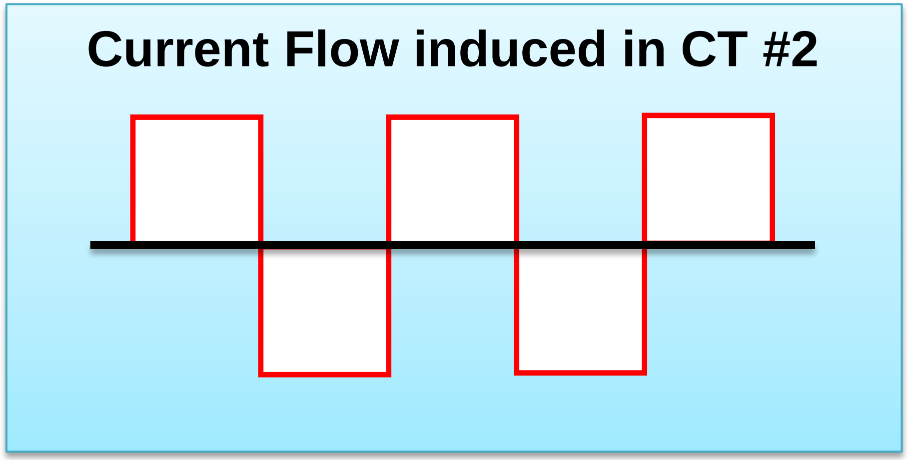
- Required input: Current from CTs
- Relay generally operates very fast (1 cycle)
- Normal protection for Generators, Transformers and Bus sections
- CTs supplying the relay should be matched so that currents into the "zone of protection" are equal to those currents that leave
- The difference/mismatch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

Differential Relay

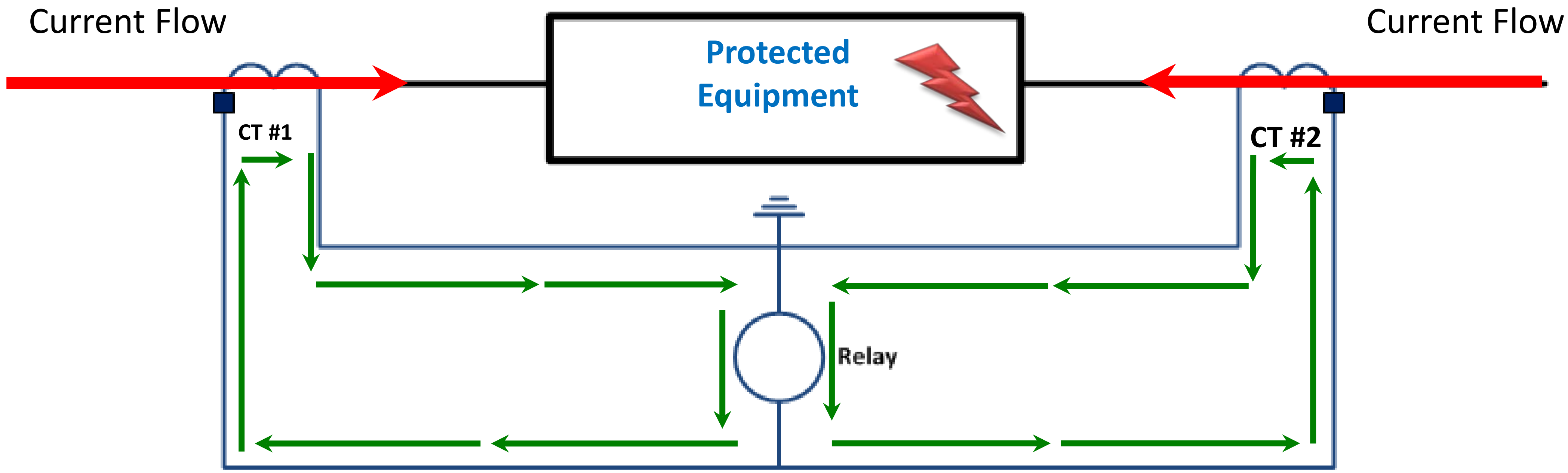
Current Flow

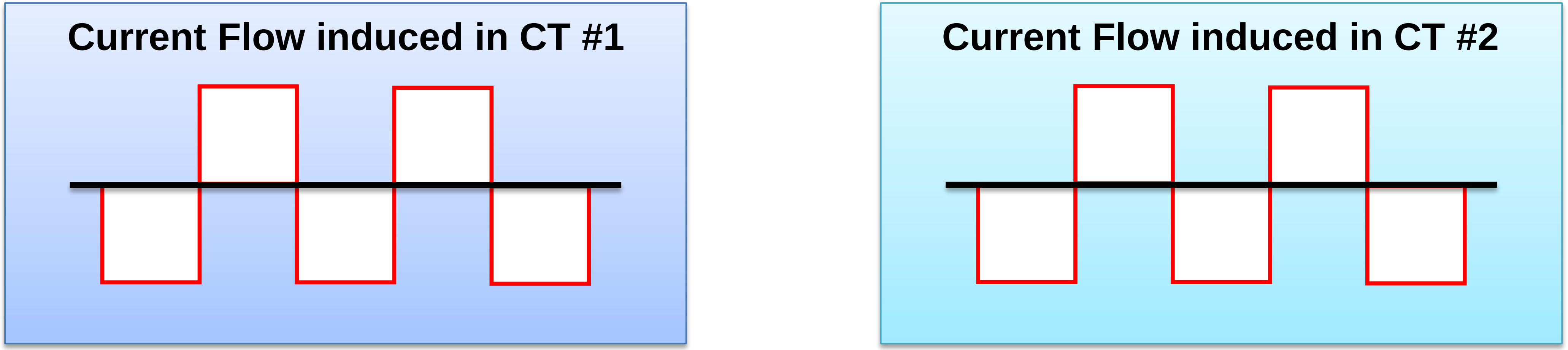






Differential Relay





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

- Part of generator, transformer, bus and other switchyard equipment protection schemes
  - Relay itself doesn't *protect* anything;
    - Has multiple contacts that operate multiple devices
    - If they failed to trip for a fault, the switchyard GCB would stay closed and the equipment would remain energized
    - Electrical coil that trips the lockout relay is monitored
      - Amber light above handle

Lockout Relays

- 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
- Lockout Relay target
  - **Orange semaphore** directly above the relay handle
- When the lockout operates
  - Amber light goes out and colored target appears
  - Lockout relay handle will be at an angle instead of being perpendicular to the floor

Illustrations of a Lockout Relay

RESET

TRIPPED

Relay Basics Exercises / Review

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

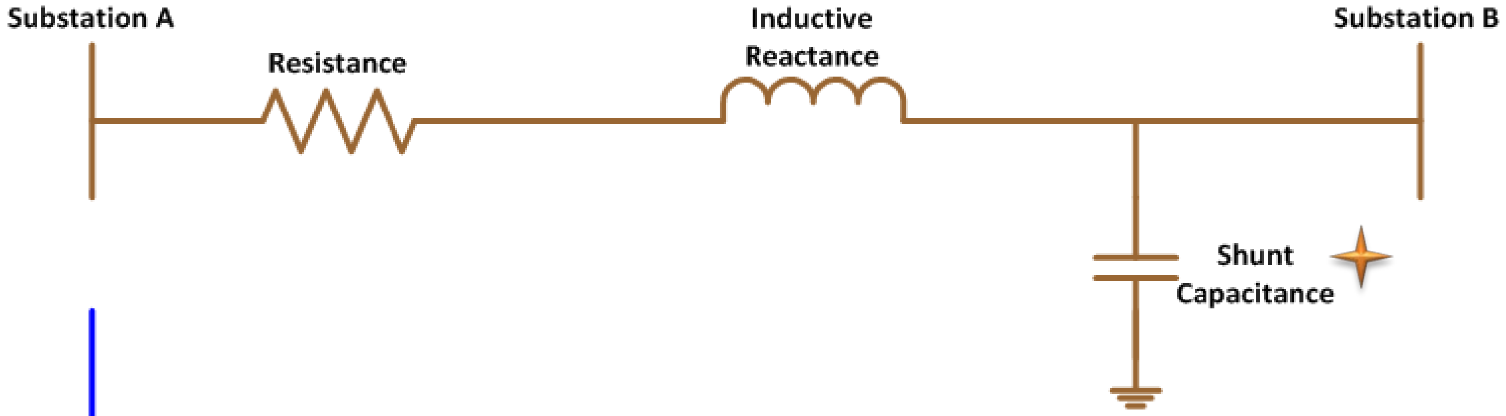
- Because these lines carry large amounts of energy and are extremely important to the operation of a power system, it is necessary to use the most advanced relaying methods to insure their integrity

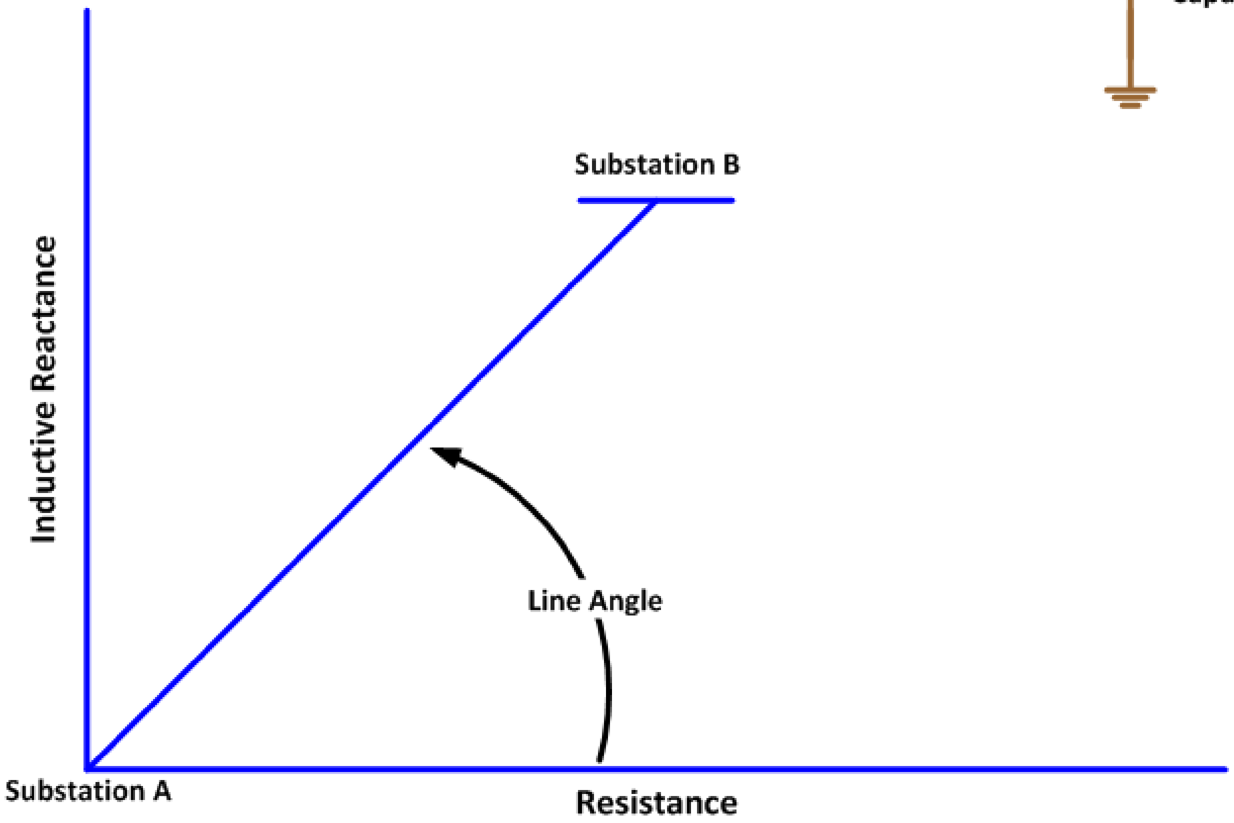
- Being that important, it is desirable to have instantaneous clearing for all faults on the transmission line under normal operating conditions

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 +j X**
- Consequently, on an R-X impedance diagram, any line can be graphically represented

Graphical Representation of a Line





For overhead lines, this can generally be ignored

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

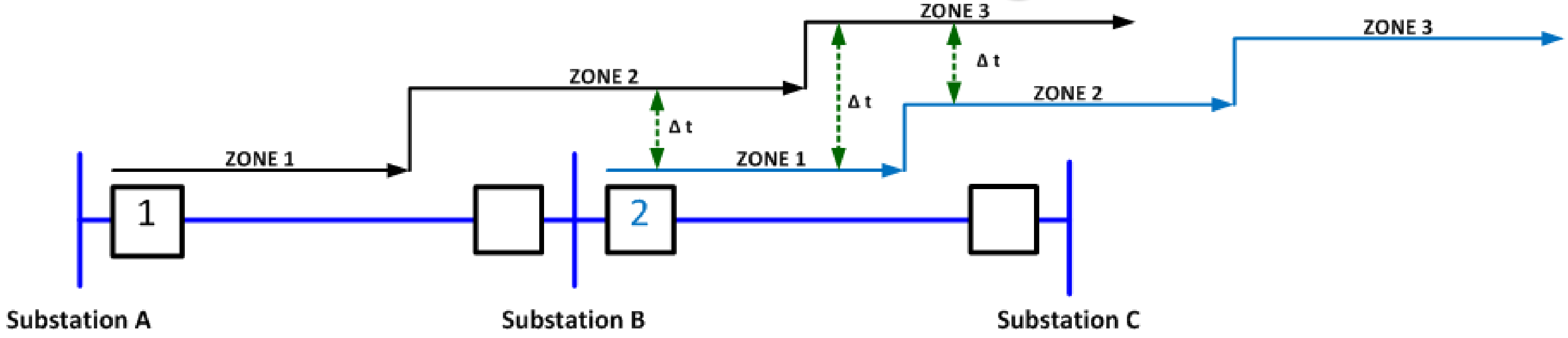
Transmission Line Protection

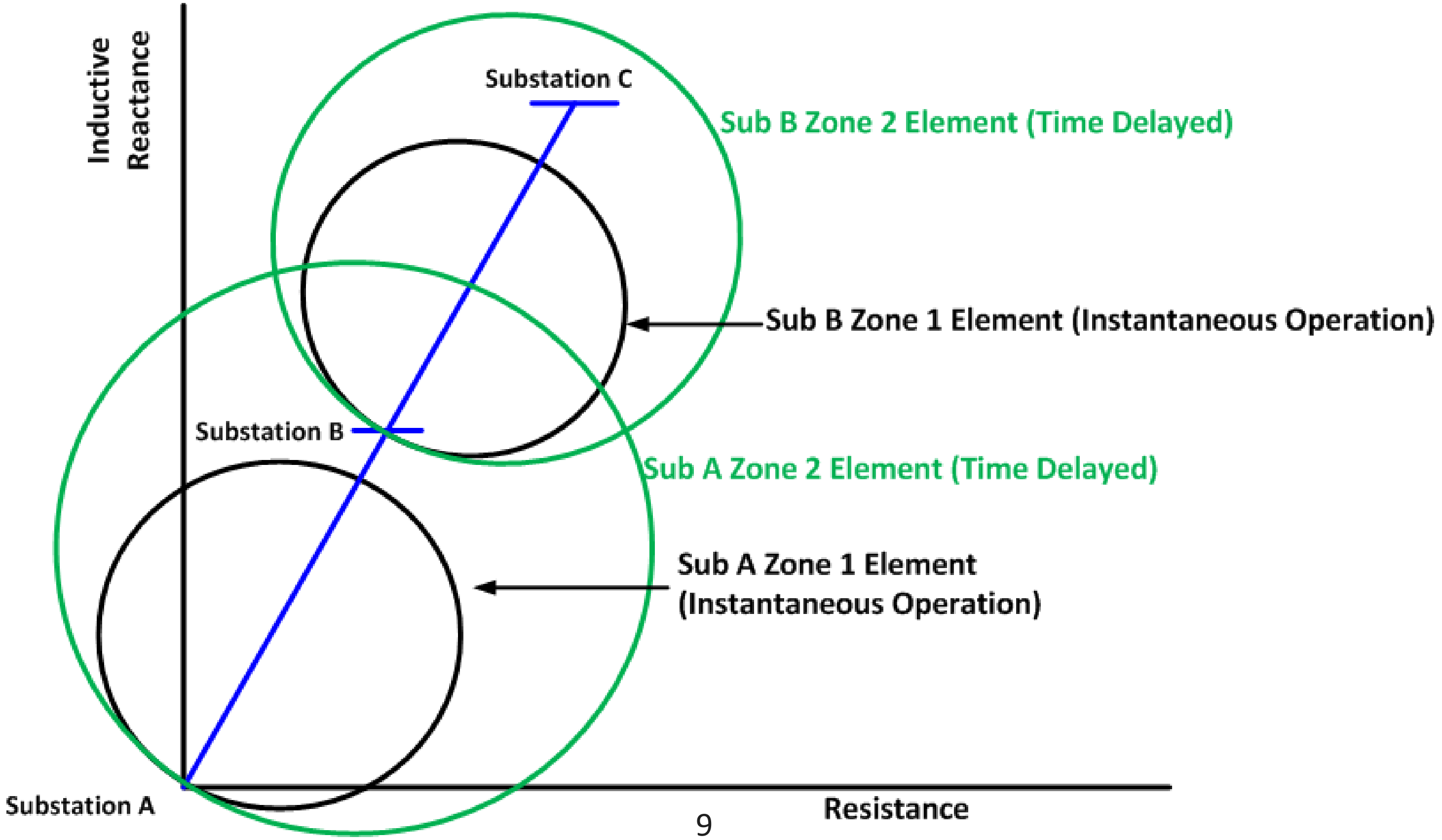
Relay Coordination:

- 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

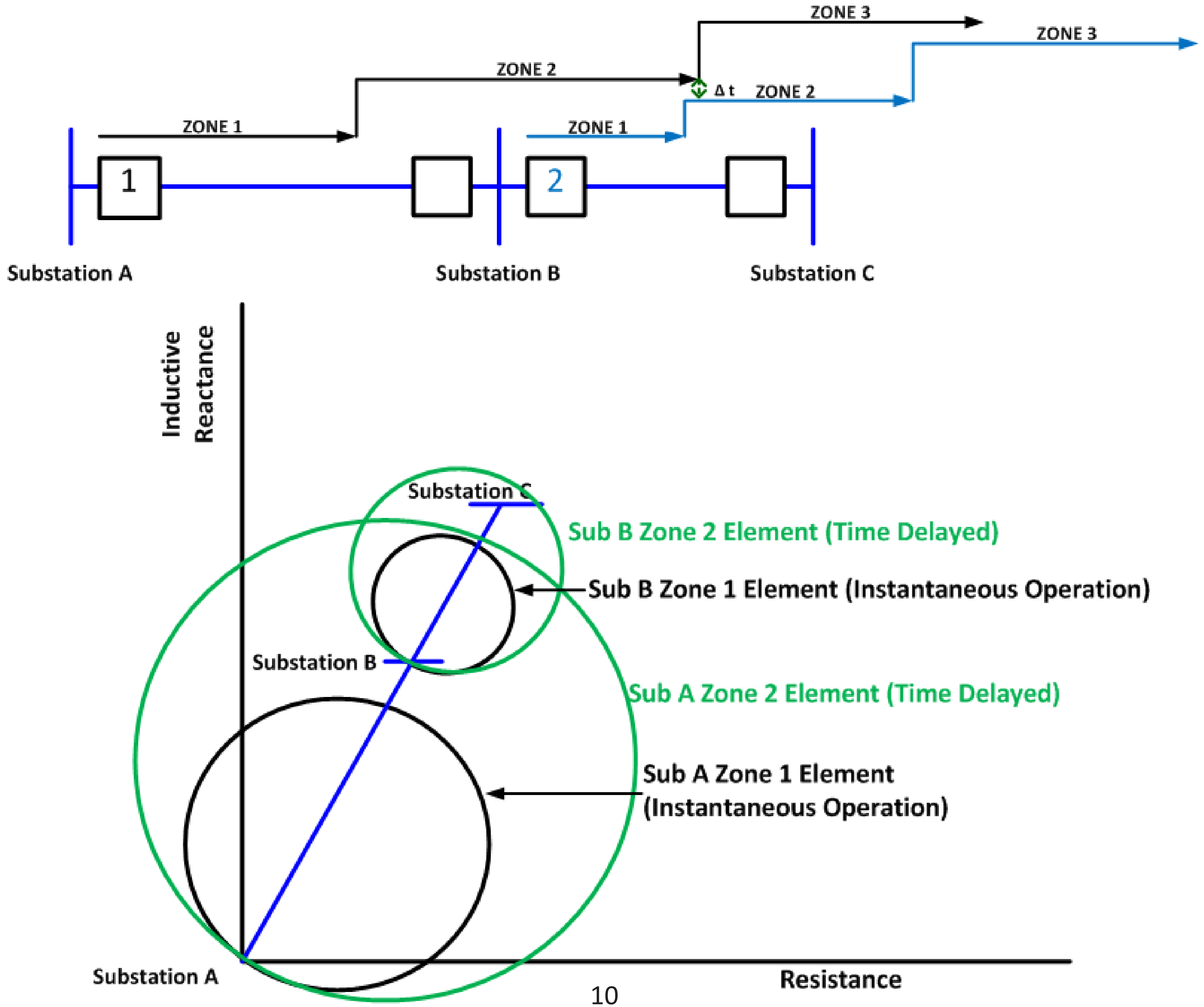
- Typically happens on Long Line/Short Line situations

Relay Coordination – Normal Line Configuration





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.

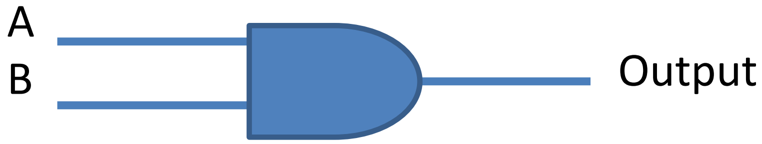
  The ones we will review are:

  - Directional Comparison
  - Direct Under-reaching Transferred Trip
  - Permissive (Over & Under-reaching)
  - Phase Comparison
  - AC Pilot Wire
  - Optical Fiber Differential

Logic Gates Overview

AND Gate

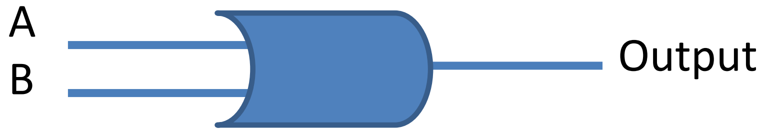
Needs 2 inputs to get an output



A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1

OR Gate

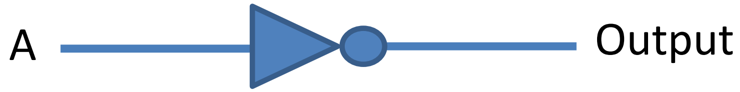
Needs 1 input to get an output



A	B	Output
0	0	0
0	1	1
1	0	1
1	1	1

NOT Gate

Output is the inverse of the input



A	Output
0	1
1	0

Pilot Schemes

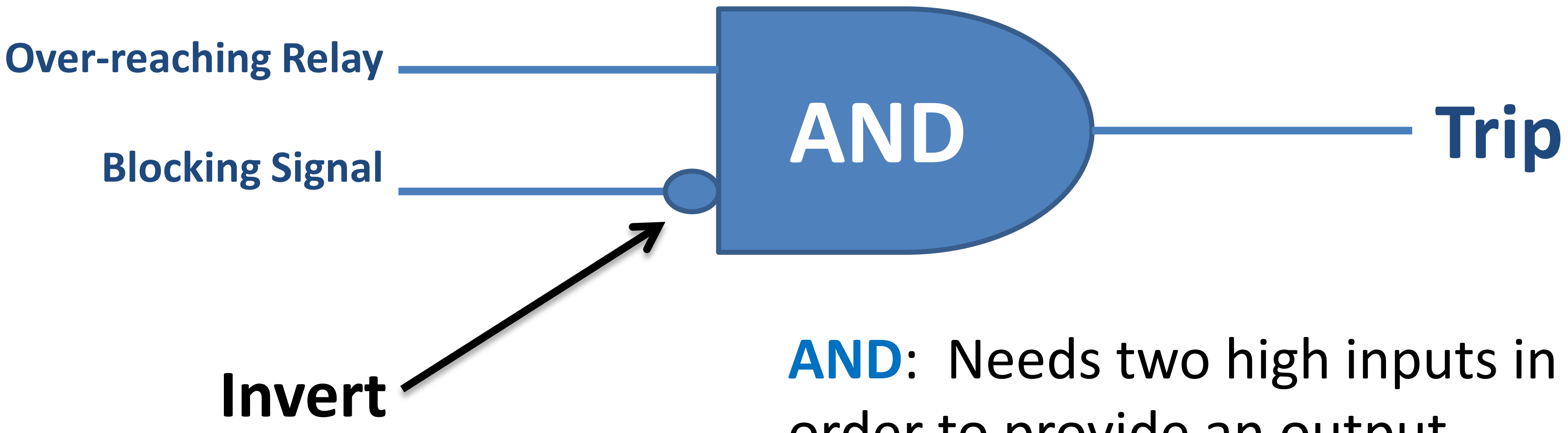
- 3 major components
  - Protective relays set to look:
    - *Beyond*, or *over-reach*, the remote terminal of the protected line
    - *Short of*, or *under-reach* the remote terminal of the protected line
  - A communications channel between the local and remote terminals:
    - Telephone line operating at audio tone frequencies (usually between 1000 and 3000 HZ)
    - Fiber optic link
    - Powerline carrier
  - Transmitting and receiving equipment at all terminals capable of either:
    - *Shifting* between a continuous pilot signal (**GUARD**) and a permissive signal (**TRIP**)
    - Sending/receiving a *blocking* signal

Directional Comparison Blocking

- Relays set to see beyond remote terminals
- Under non-fault conditions, no signal is sent between the terminals of the line
- 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:

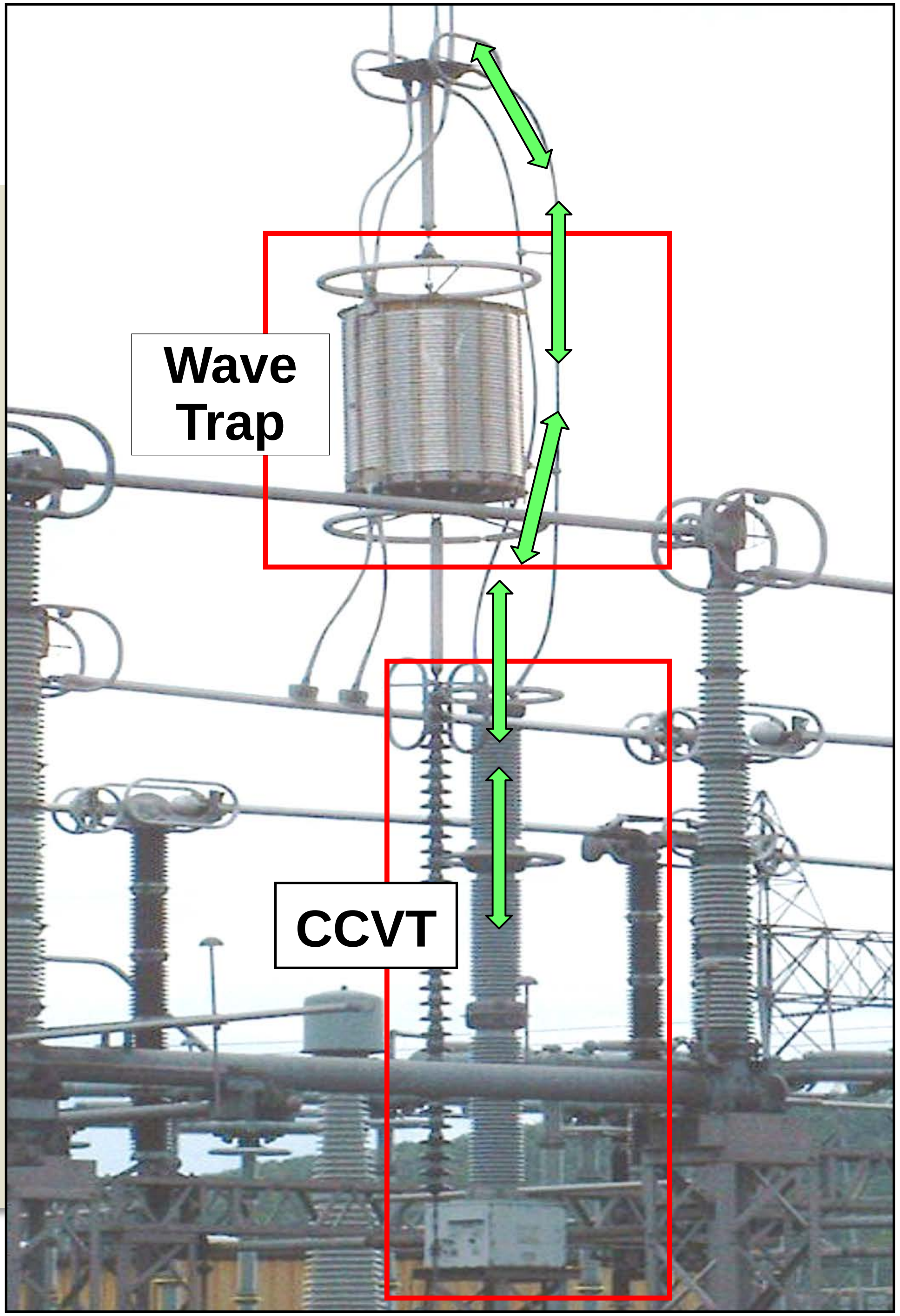


AND: Needs two high inputs in order to provide an output

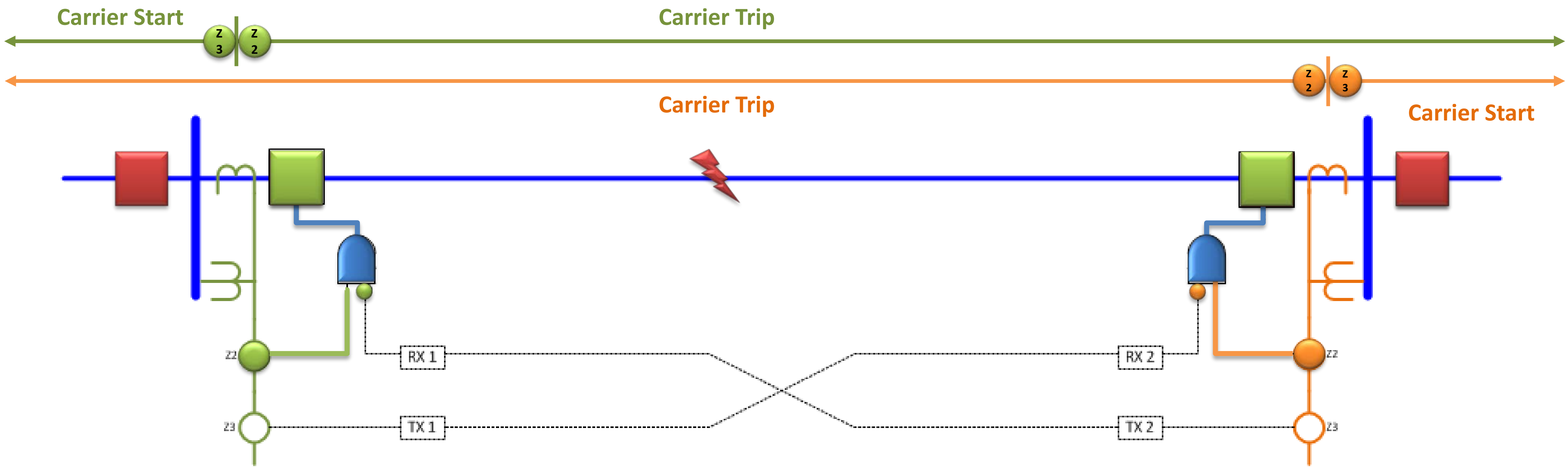
Wave Trap and CCVT

Illustration of 500kV Wave Trap & CCVT

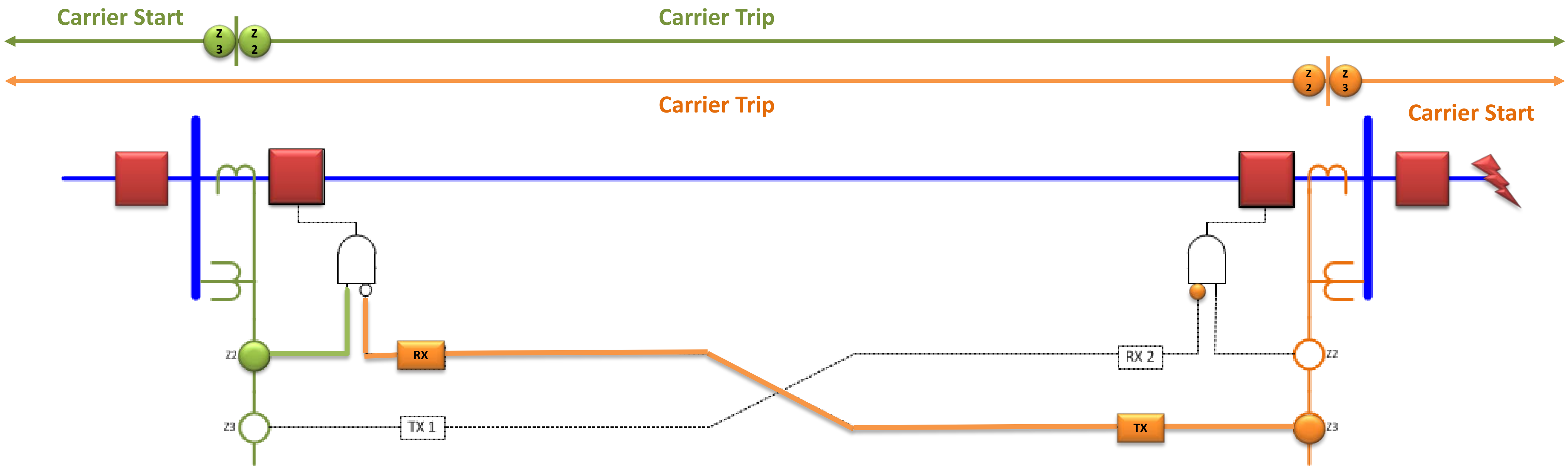
- The carrier signal couples to the transmission line through the CCVT
- The signal enters and exits the base of the CCVT, then connects to a nearby impedance-matching tuning box and then to the transmitter/receiver equipment located inside the substation control house
- The carrier signal traffic is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



Directional Carrier Blocking – Internal Fault



Directional Carrier Blocking – External Fault



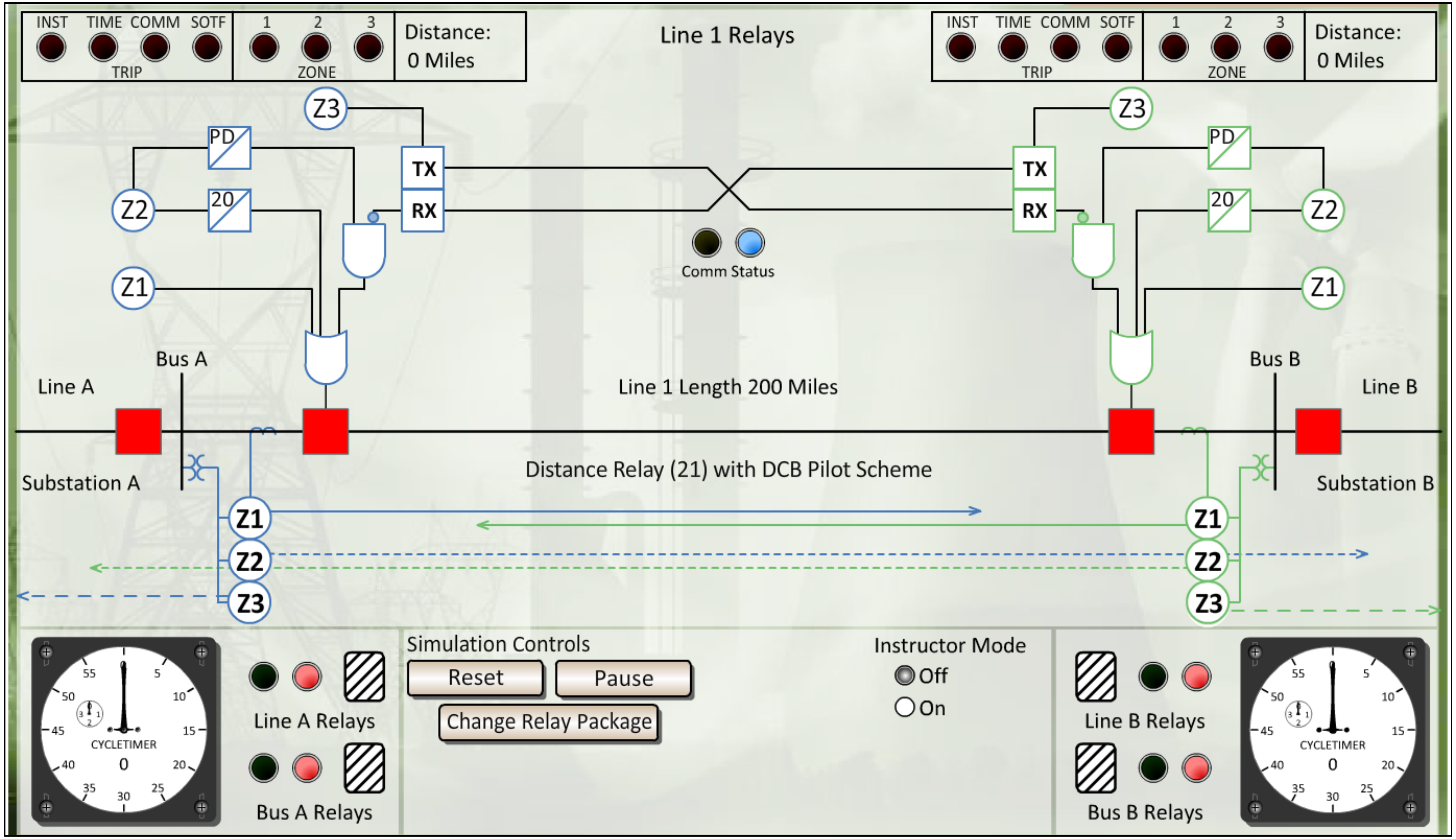
Directional Carrier Blocking

- **Advantages of a Blocking Carrier Scheme**
  - Provides high-speed fault clearing all the way to the end of the line
  - The carrier signal from the remote terminal serves to limit the reach of the local carrier trip relay to the length of the protected line by preventing overtripping
  - Communication between line terminals is across the power line conductors rather than through separate telephone or fiber optic channels
  - Since absence of a carrier signal constitutes permission to trip, scheme is relatively immune to disruption by faults on the protected line
    - A broken or faulted power line actually promotes correct operation by blocking transmission of any spurious carrier signals that might prevent tripping

Directional Carrier Blocking

- **Disadvantages of a Blocking Carrier Scheme**
  - Proper carrier channel tuning is essential to maintain signal levels
    - Improperly tuned carrier channels make the scheme overtrip
  - Switching coordination is necessary to block carrier schemes out of service at all terminals as simultaneously as possible to prevent overtripping
  - Blocking only one terminal of a carrier scheme has the same effect as deteriorated signal strength by preventing transmission of a carrier signal
  - No form of a “guard” signal is continuously present to monitor the carrier channel’s integrity and ensure its viability during an actual fault
    - An external checkback scheme that automatically exchanges carrier signals between line terminals at periodic intervals is the only non-fault of ensuring that the carrier communications channel is operational

Directional Carrier Blocking



DCB Bismarck Sim

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
  - Tests communication path
  - Loss of **GUARD** will generate an alarm

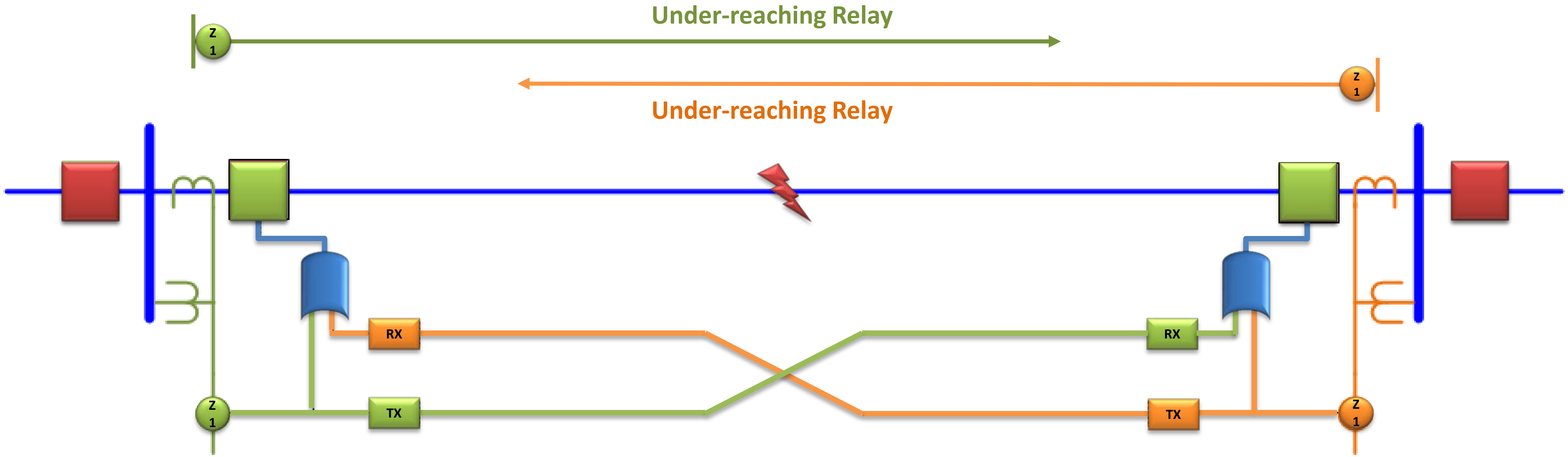
Direct Under-reaching Transfer Trip Scheme

- To Initiate Trip:
  - Under-reaching Relay must operate

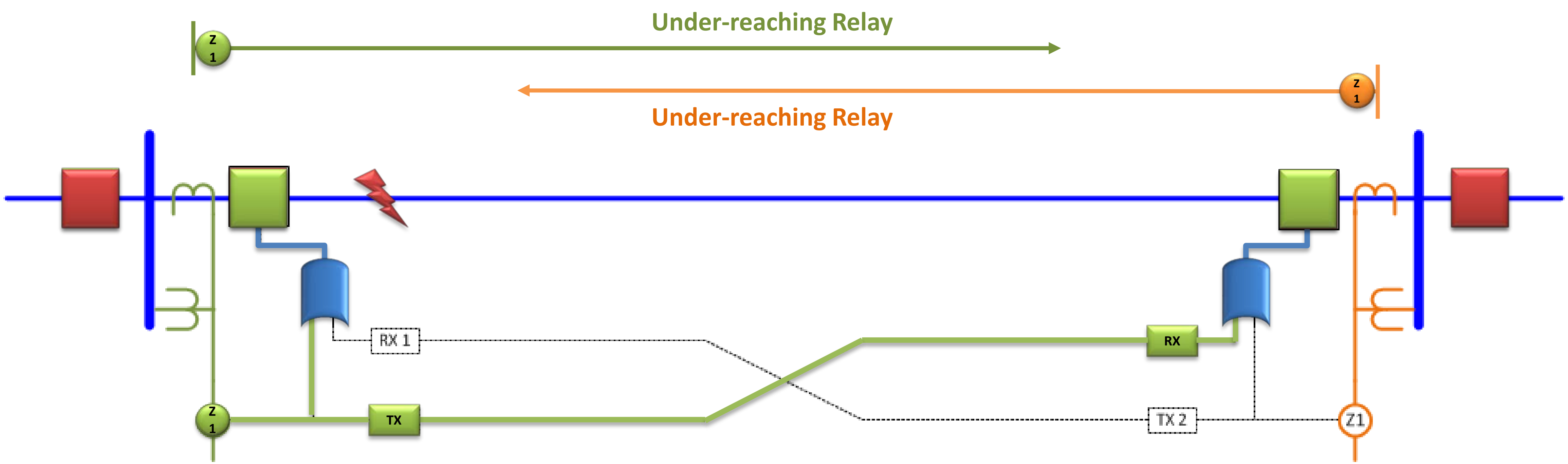
    OR
  - Receive a **TRIP** signal from the remote end
- In Digital Logic:

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

Direct Under-reaching Transfer Trip



Direct Under-reaching Transfer Trip



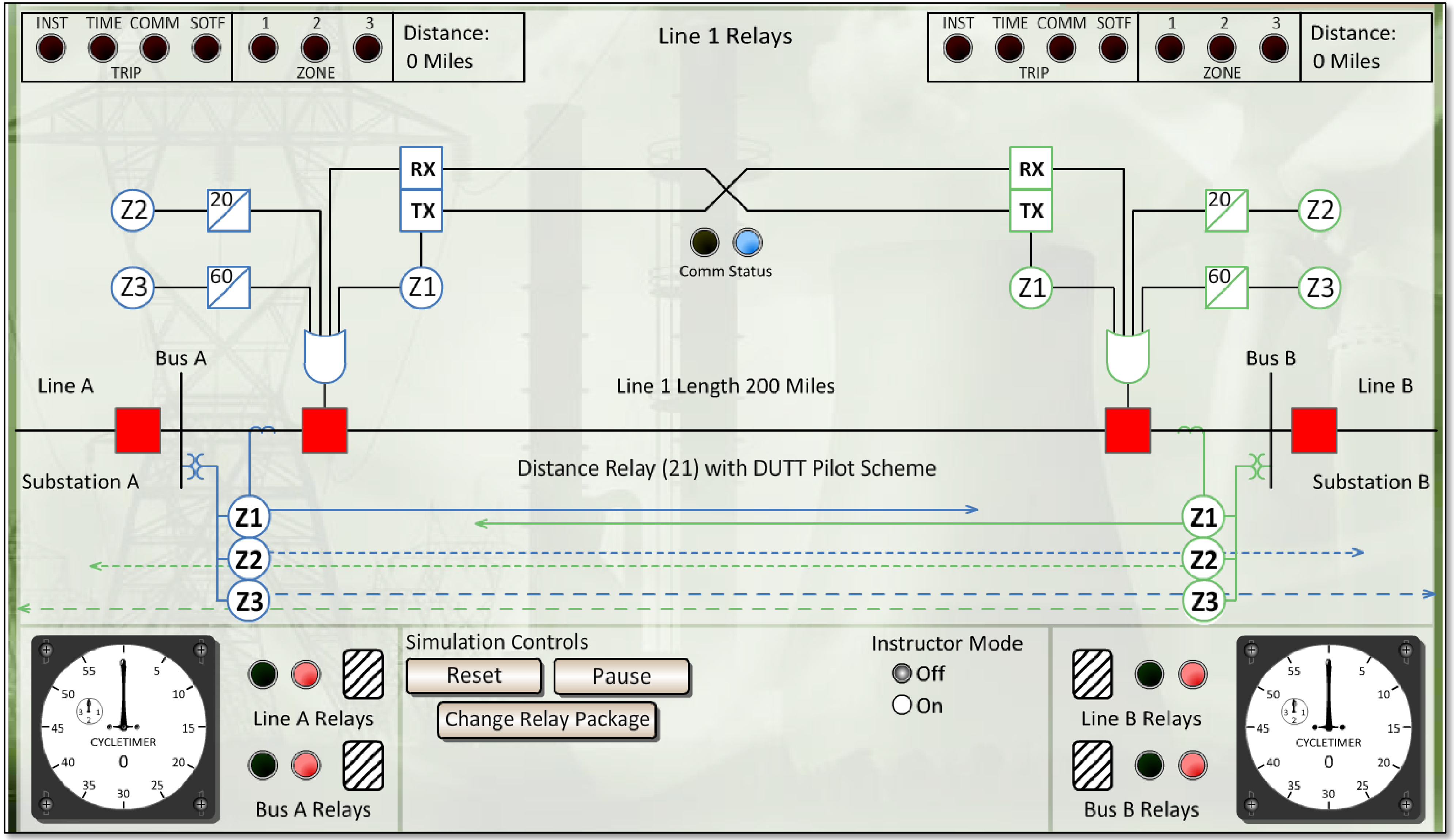
Direct Under-reaching Transfer Trip

- **Advantages of DUTT relaying**
  - Provides *high-speed fault detection for the entire length of the line*
  - Communication between line terminals *is continuously monitored* by the **GUARD** signal or some other form of pilot
  - Immune from disruption *by faults on the protected line* since it uses a separate communications channel rather than the power line itself

Direct Under-reaching Transfer Trip

- **Disadvantages of DUTT relaying**
  - The communications channel is subject to external interruption
  - Possibility of undesired tripping by:
    - Accidental operation
    - Mis-operation of signaling equipment, or
    - Interference on the communications channel

Direct Under-Reaching Transfer Trip



DUTT Bismarck Sim

Permissive Under-Reaching Transfer Trip

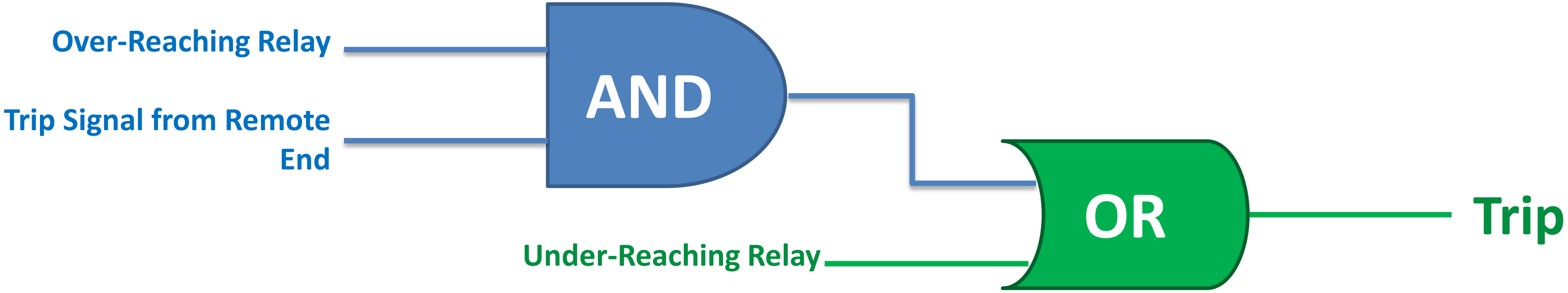
- Direct tripping relays set to under reach remote end
- Fault detector relays set to overreach remote end
- Under non-fault conditions, continuous **GUARD** signal is sent to remote end
  - Tests communication path
  - Loss of **GUARD** will generate an alarm

Permissive Under-Reaching Transfer Trip Scheme

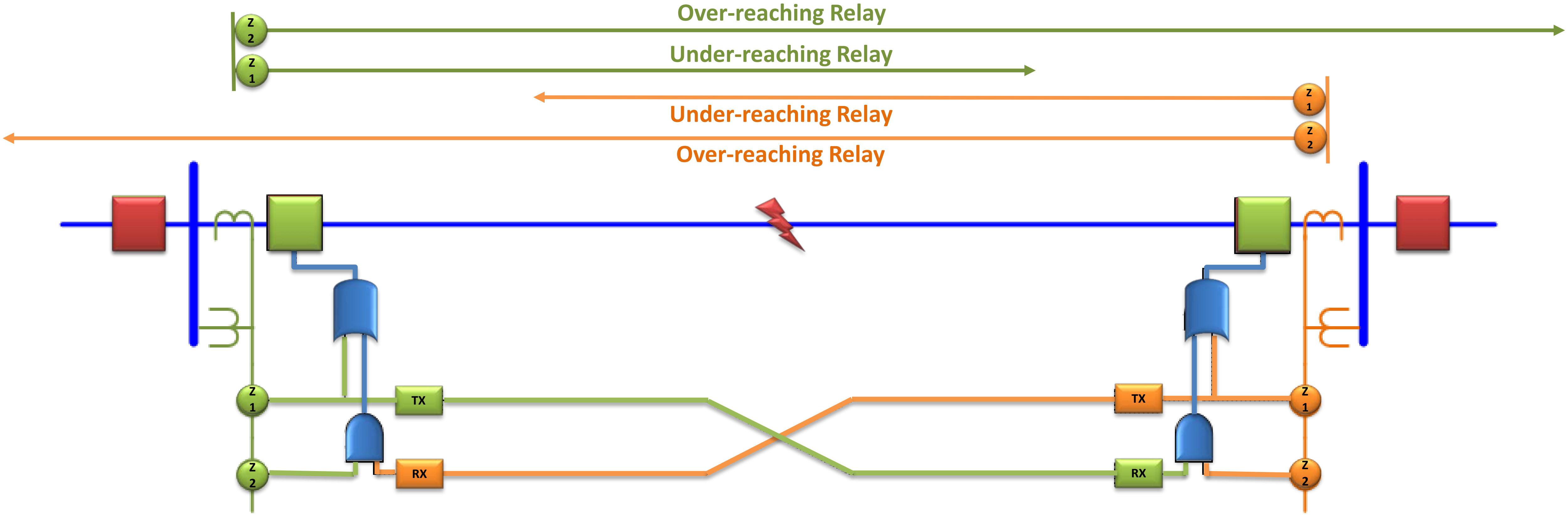
- To Initiate Trip:
  - Under-reaching Relay must operate

    OR

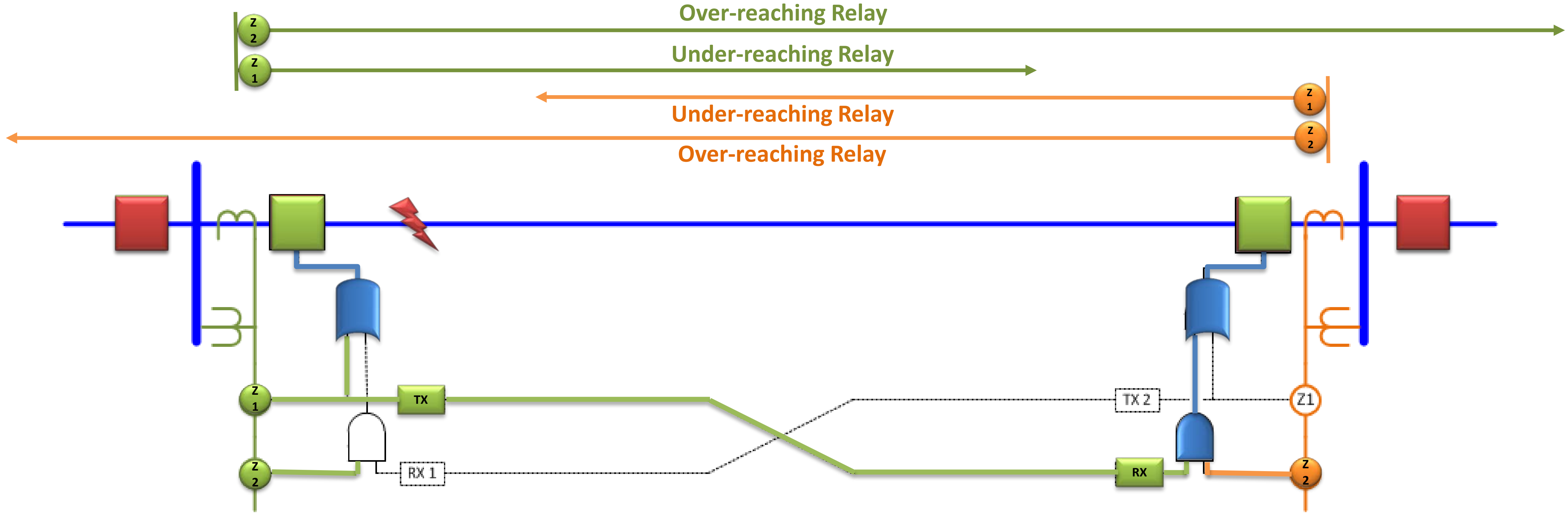
  - Over-reaching relay must operate ***AND*** receive a **TRIP** signal from the remote end
- In digital logic:



Permissive Under-Reaching Transfer Trip



Permissive Under-Reaching Transfer Trip



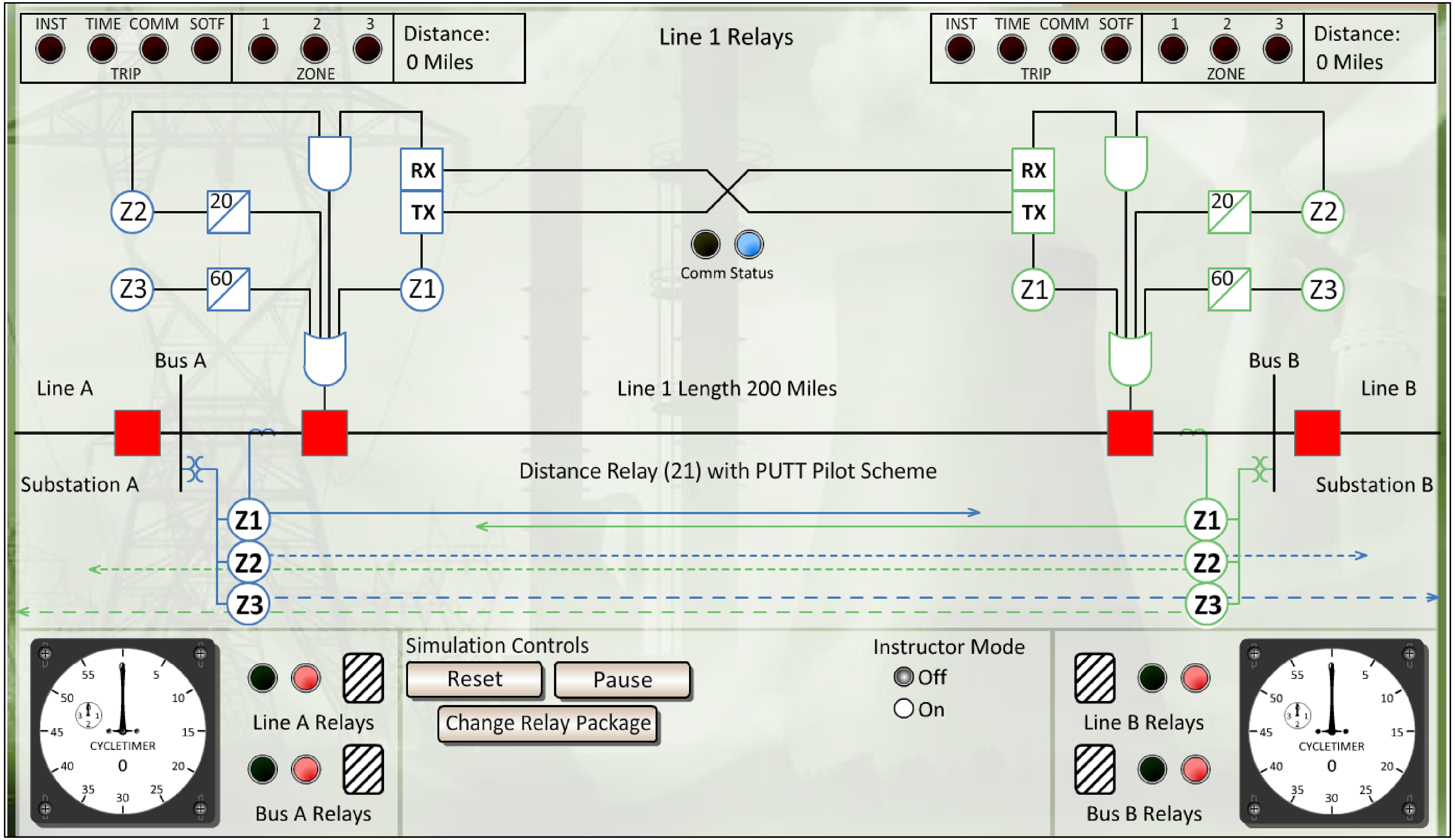
Permissive Under-Reaching Transfer Trip

- **Advantages of PUTT relaying**
  - Provides *high-speed fault detection for the entire length of the line*
  - Communication between line terminals *is continuously monitored* by the **GUARD** signal or some other form of pilot
  - Immune from disruption *by faults on the protected line* since it uses a separate communications channel rather than the power line itself
  - More secure than DUTT, since **TRIP** signal is supervised by overreaching relay

Permissive Under-Reaching Transfer Trip

- **Disadvantages of PUTT relaying**
  - The communications channel is subject to external interruption
  - Special precautions are necessary to ensure PUTT will operate for faults on radially energized lines
    - Since PUTT requires **TRIP** permission from the Local terminal, “b” switch keying and maintenance or PUTT TEST switches must be implemented and manually operated
  - Failure of PUTT transmitters to shift from **GUARD** to **TRIP** or failure of PUTT receivers to recognize that shift can completely disable a PUTT relay scheme

Permissive Under-Reaching Transfer Trip



PUTT Bismarck Sim

Permissive Over-Reaching Transfer Trip

- The nature of a POTT relay scheme requires two things to happen before tripping is allowed:
  - The protective relays must ***sense a fault***, and
  - The protective relays must ***receive a valid TRIP signal from the remote terminal***

Permissive Over-Reaching Transfer Trip

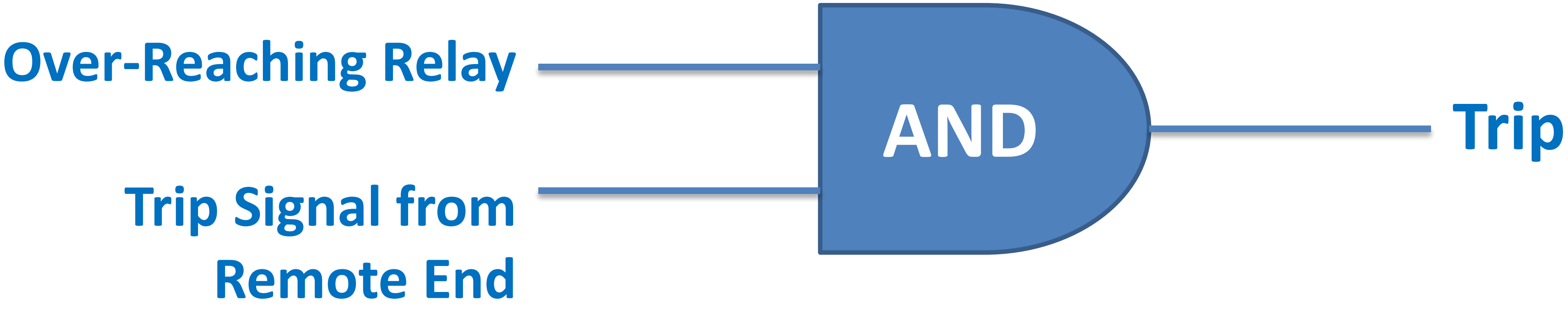
- A **GUARD** tone or other pilot signal is continuously sent between terminals for two purposes:
  - To monitor integrity of the communications channel
  - To enhance security of the POTT scheme:
    - The **GUARD** signal must be present and recognized by the local receiver prior to receipt of a **TRIP** signal from the remote transmitter in order to permit a local trip output;
    - In an audio tone POTT scheme the local receiver will not produce a trip output unless the shift from **GUARD** to **TRIP** is accomplished within several hundred milliseconds…this is GUARD-BEFORE-TRIP logic

Permissive Over-Reaching Transfer Trip

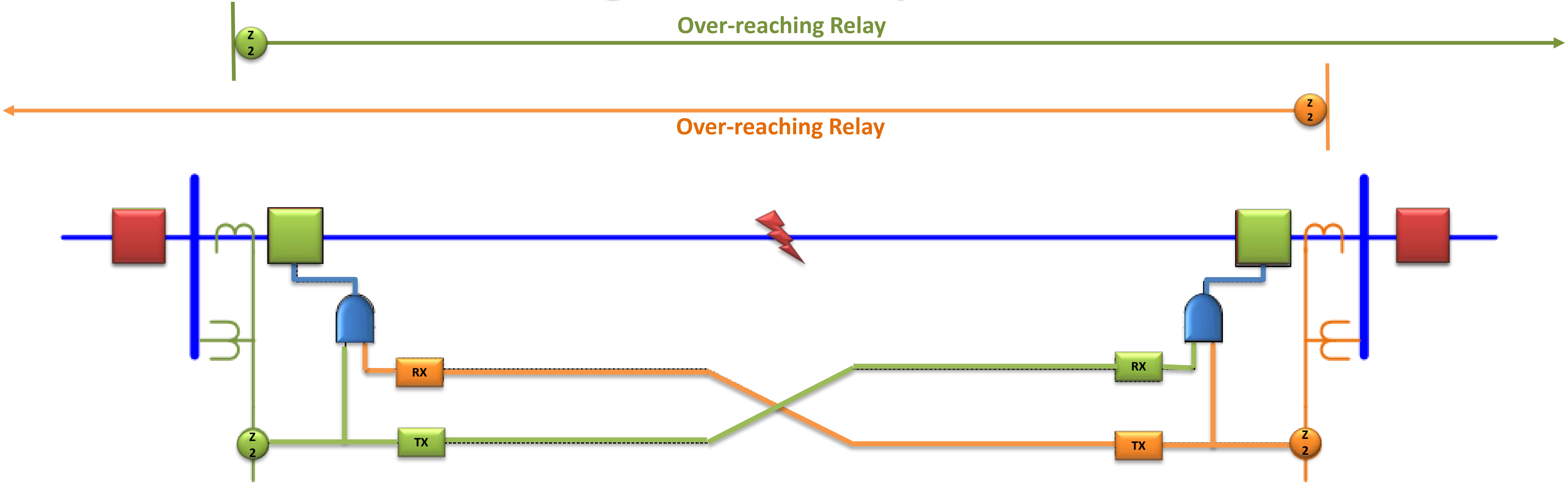
- To Initiate Trip:
  - Over-reaching Relay must operate

    AND

  - Receive a trip signal from the remote end
- In digital logic:



Permissive Over-Reaching Transfer Trip



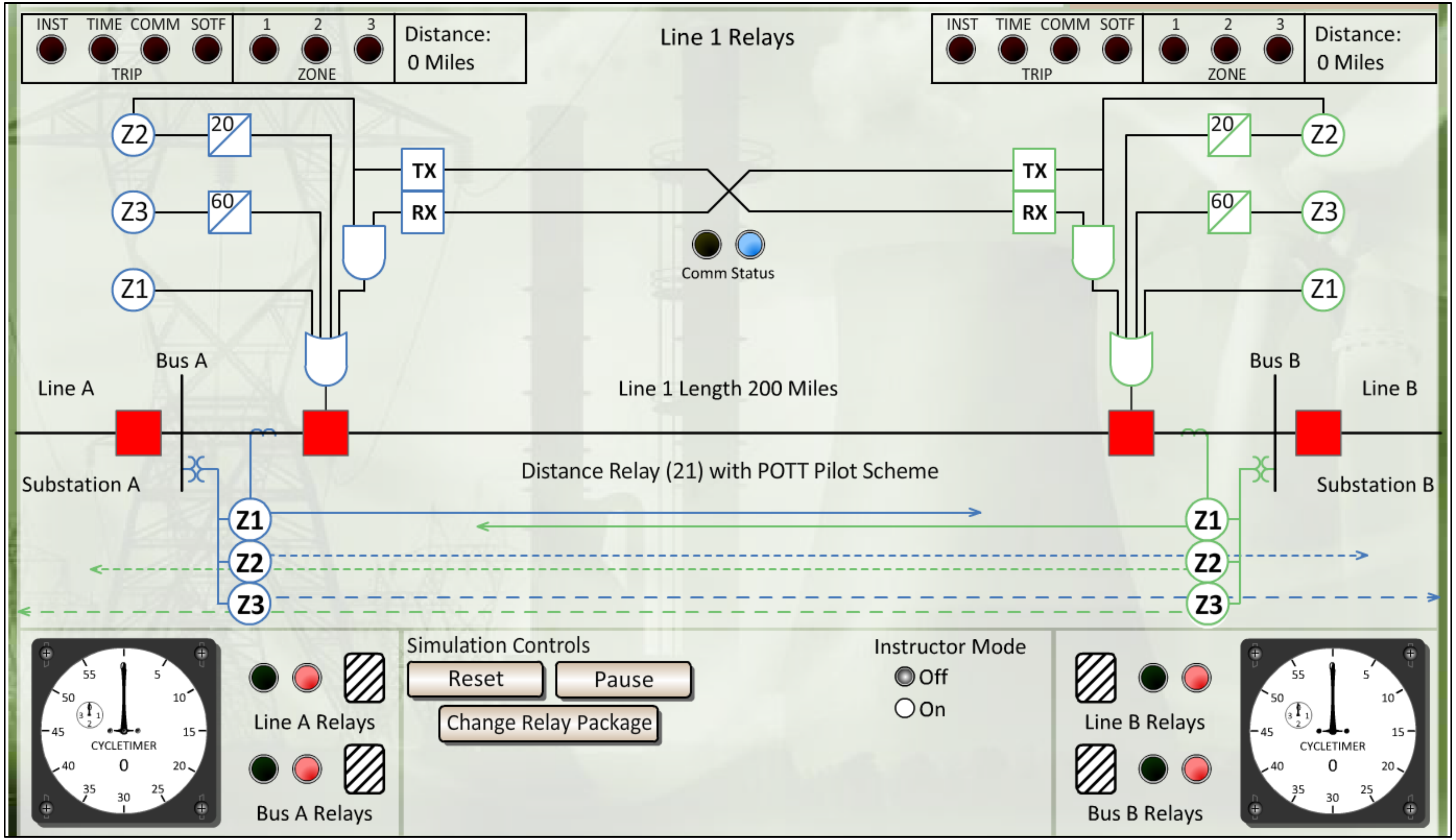
Permissive Over-Reaching Transfer Trip

- **Advantages of POTT Relaying**
  - Overreaching characteristic provides *high-speed fault detection all the way to the end of the line*
  - Communication between line terminals *is continuously monitored* by the **GUARD** signal or some other form of pilot
  - Immune from disruption *by faults on the protected line* since it uses a separate communications channel rather than the power line itself

Permissive Over-Reaching Transfer Trip

- **Disadvantages of POTT Relaying**
  - The communications channel is subject to external interruption
  - Special precautions are necessary to ensure POTT will operate for faults on radially energized lines
    - Since POTT requires **TRIP** permission from the remote terminal, "b" switch keying and maintenance or POTT TEST switches must be implemented and manually operated
  - Failure of POTT transmitters to shift from **GUARD** to **TRIP** or failure of POTT receivers to recognize that shift can completely disable a POTT relay scheme

Permissive Over-Reaching Transfer Trip



POTT Bismarck Sim

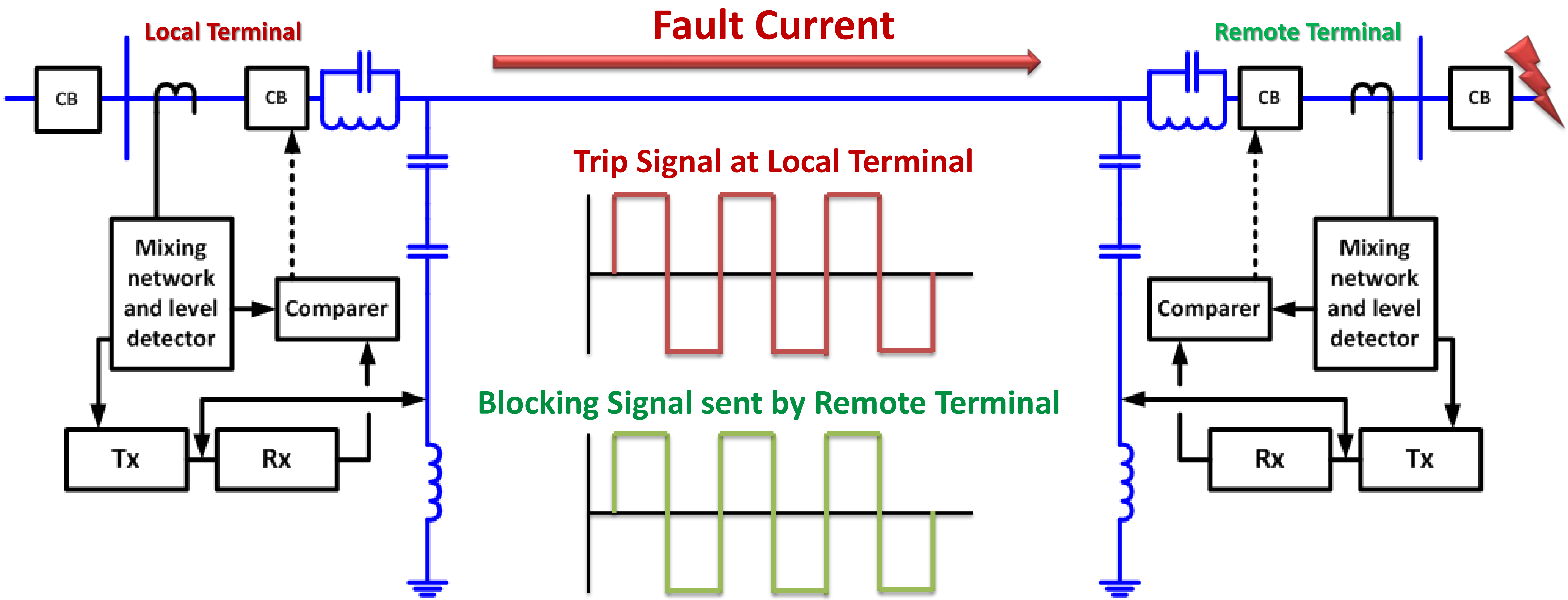
Phase Comparison Blocking

- Scheme was typically used on 500 kV system
- Relays at each line terminal compare the direction of the neutral current flow they see
- This intelligence is exchanged with the remote terminal by pulsing the blocking carrier signal in a square wave pattern that corresponds to the positive and negative cycles of the 60 HZ line current sine wave

Phase Comparison Blocking

- **For a Ground Fault External to the Line:**
  - Fault current flows ***INTO*** the line at the **LOCAL TERMINAL** and ***OUT OF*** the line at the **REMOTE TERMINAL**
    - The relay currents seen at each terminal are thus 180^{o} apart
  - The BLOCKING CARRIER signal pulse trains *received* at each terminal are in-phase with the TRIP signal pulse trains *generated* at each terminal… each time the TRIP signal goes to full value, the CARRIER signal does likewise and BLOCKs tripping of either terminal

Phase Comparison Blocking

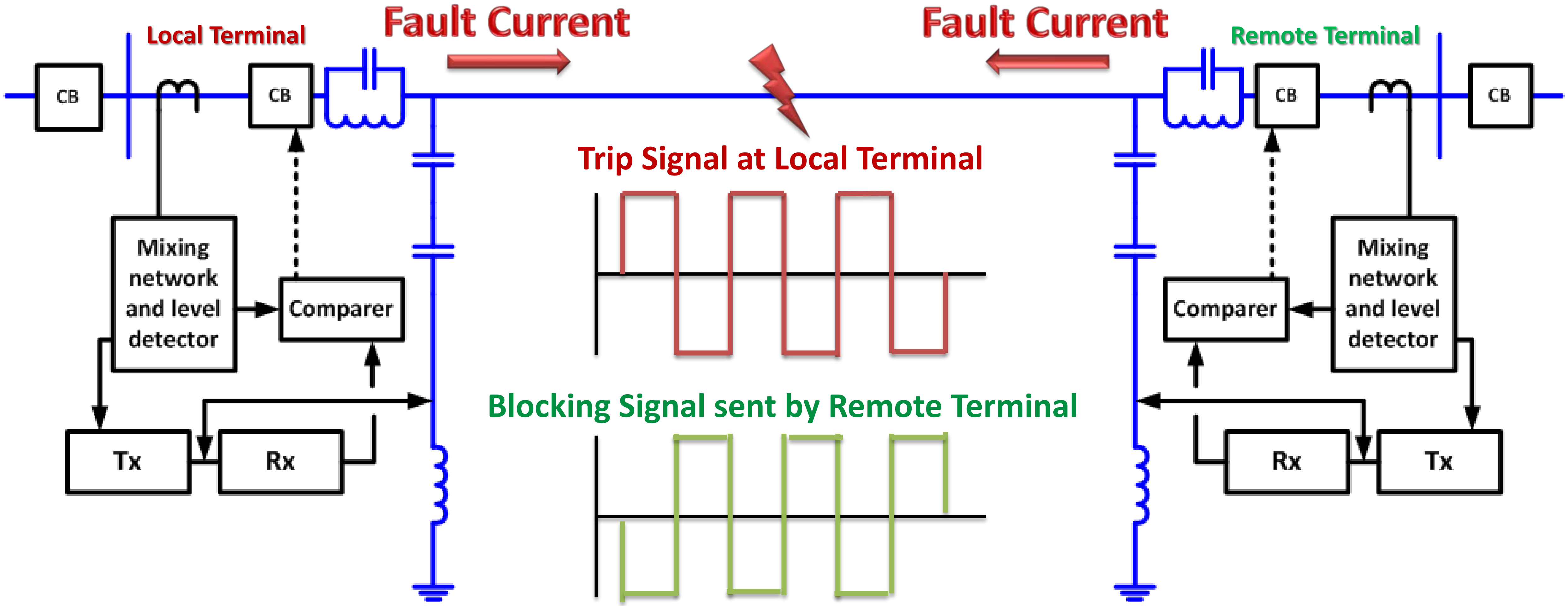


External Fault

Phase Comparison Blocking

- **For a Ground Fault Internal to the Line:**
  - Both the **LOCAL TERMINAL** and the **REMOTE TERMINAL** see fault current flowing ***INTO*** the line…the relay currents seen at each terminal are thus *in-phase*
  - The BLOCKING CARRIER signal pulse trains *received* at each terminal now are *out-of-phase* with the TRIP signal pulse trains *generated* at each terminal… each time the TRIP signal goes to full value, the CARRIER signal is at a low value and is unable to block, thus both terminals TRIP

Phase Comparison Blocking

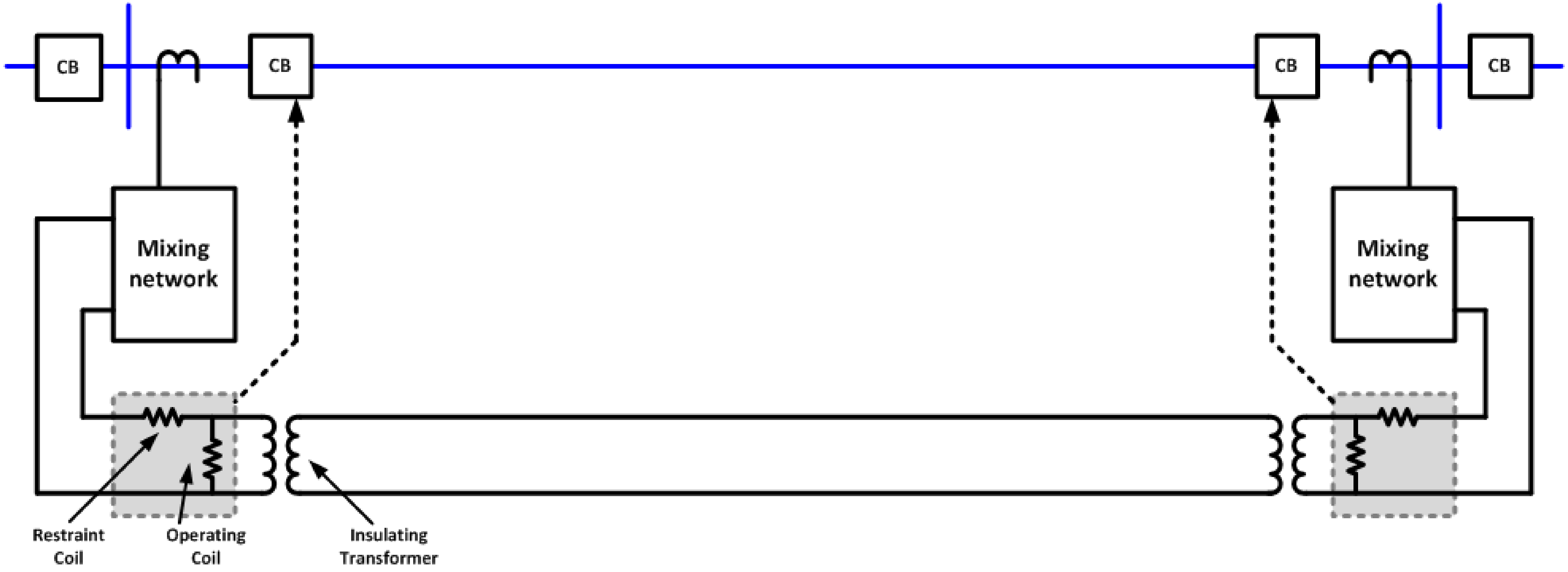


Internal Fault

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 Scheme



Line Differential Relaying

- 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
- Failure of the fiber communication path will automatically block the scheme and initiate an alarm

Line Differential Relaying

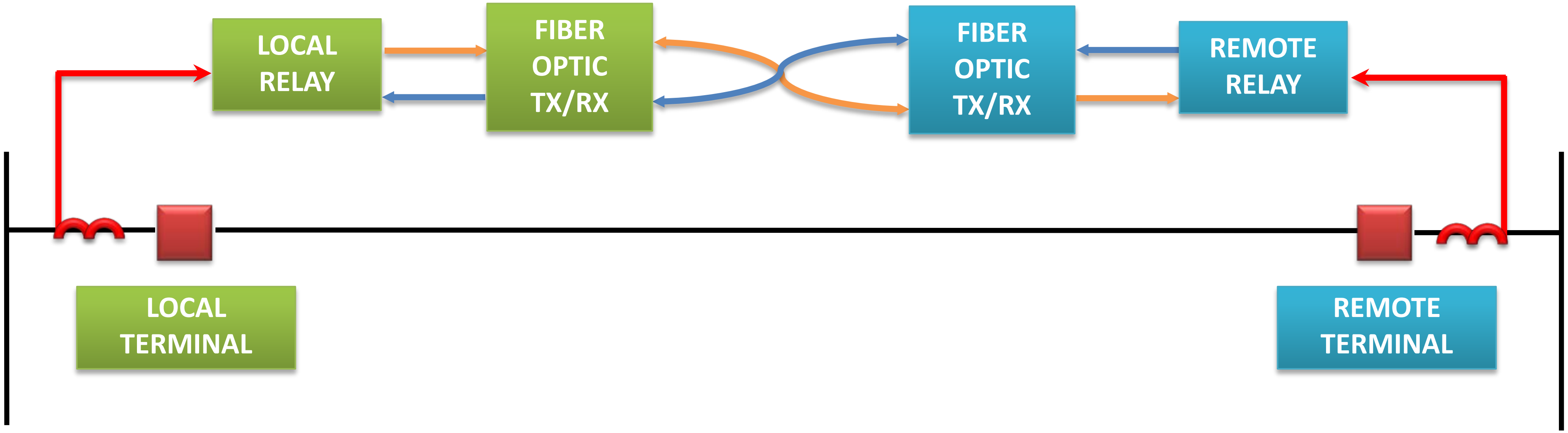


Illustration of a Line Differential Relay Scheme

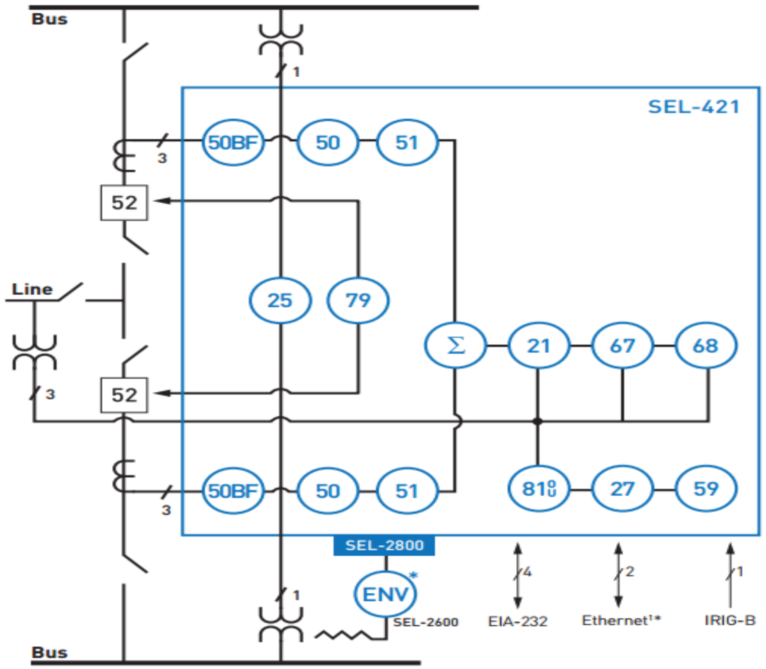
Each line differential relay directly measures line current at its own terminal and, via the fiber optic communications link, instantaneously receives from its counterpart a measurement of the line current at the remote terminal. The sum of the local and remote line currents seen by each relay is normally zero; a non-zero result indicates a line fault and causes both relays to trip.

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
- With microprocessor based relays, additional 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)

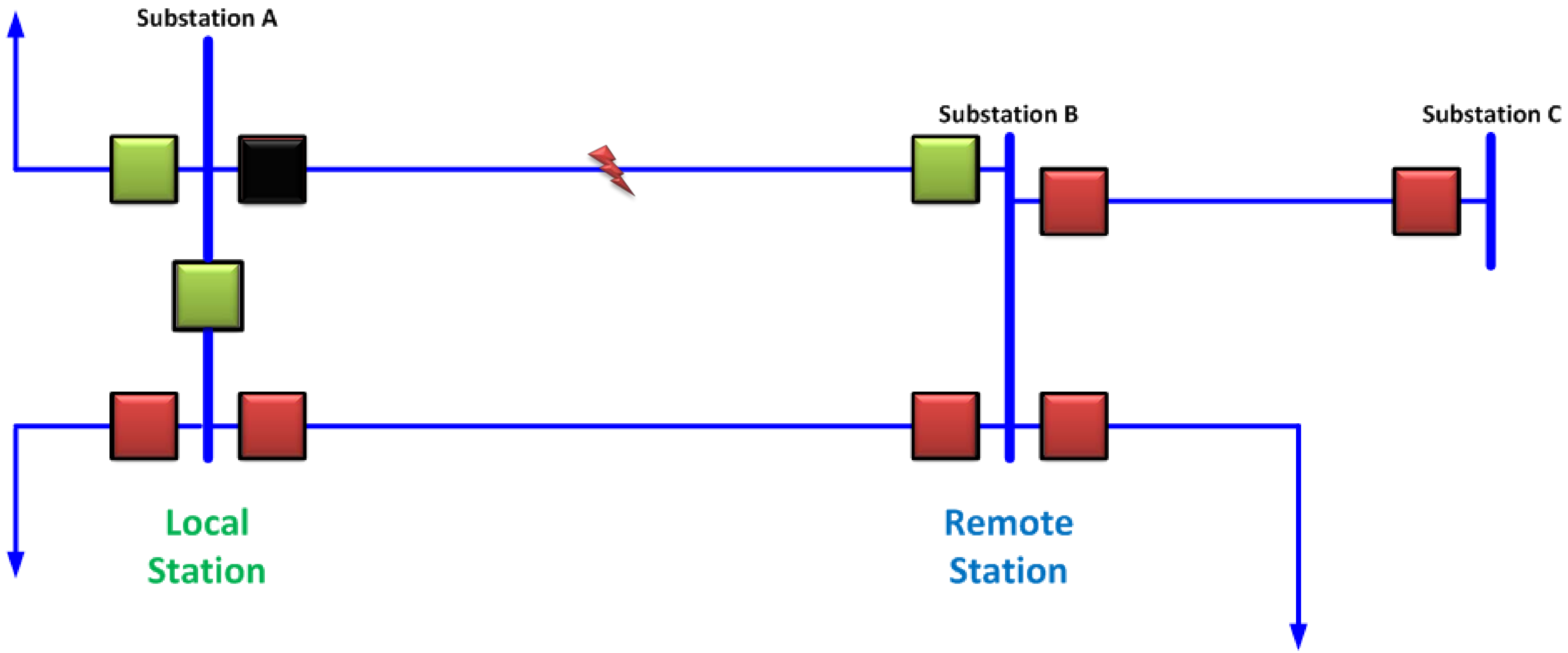
Other Functions Performed:

- 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)

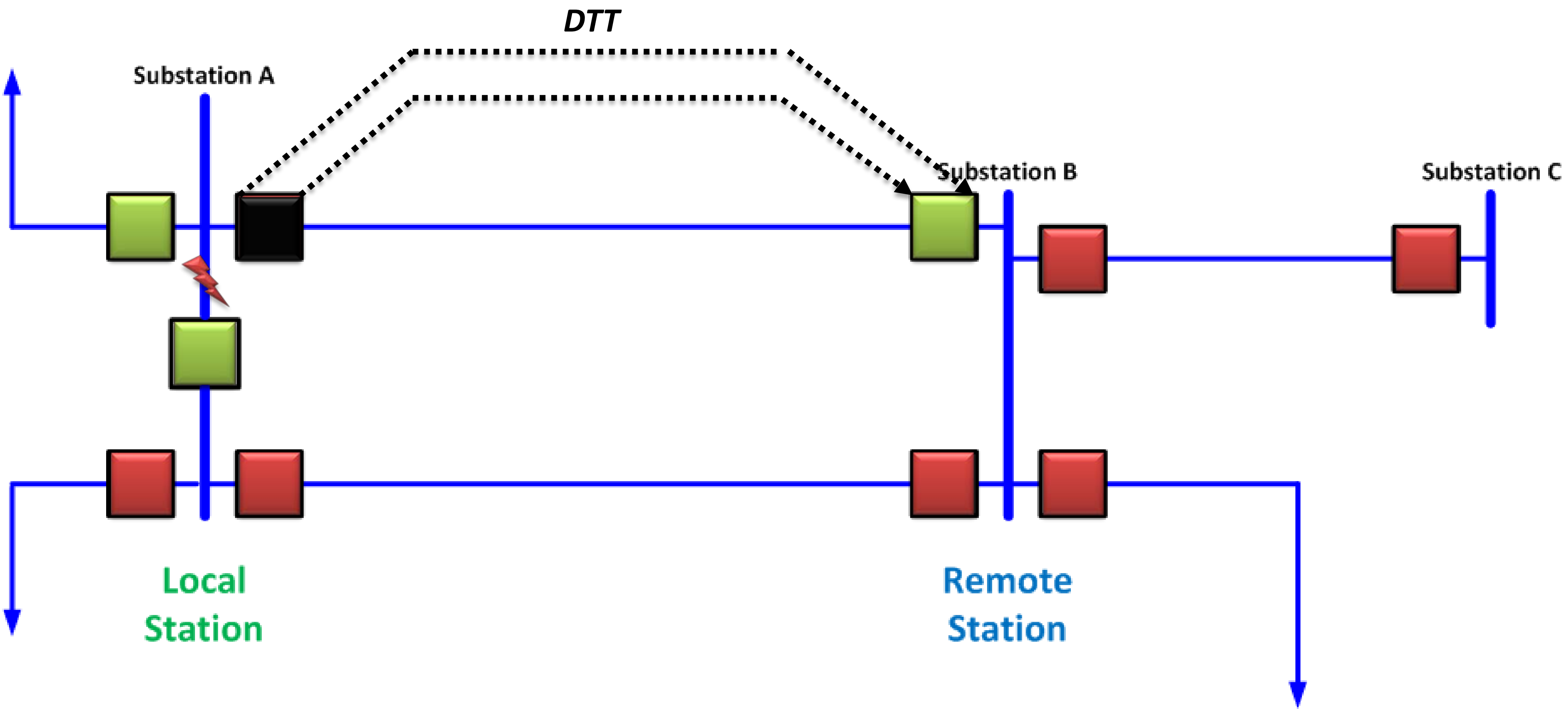
Breaker Failure Relaying

- Breaker Failure protection clears a fault even if the circuit breaker that's called upon to trip fails to operate or fails to interrupt the fault
- Every function that sends a TRIP signal to a transmission line circuit breaker also initiates its breaker failure scheme
  - Except manual and SCADA TRIP commands
- If a breaker has not interrupted fault current within 7 to 10 cycles
  - Breaker failure scheme operates to trip all adjacent circuit breakers, and
  - Remote line terminals via DTT
- After a breaker failure operation, all tripped breakers generally stay locked open until the master trip relay is hand reset
  - Some locations have automatic restoration schemes that allow adjacent breakers to reclose once the failed circuit breaker has been isolated by its MODs

Breaker Failure Relaying



Breaker Failure Relaying



Under-frequency Load Shed Relays

- Used to match load with available generation
- PJM Member companies must shed 25 - 30% of their peak load
  - Done in either 5 or 10% steps
  - Relays are set to shed load at predefined levels of frequency decay
    - Load shedding is the most expedient way to stabilize the power system and to halt further decay of the system frequency during a shortage of generation capacity
- 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

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
  - Reclosure times may vary across the PJM footprint, but could take place up to 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
    - Little risk of overtripping exists

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

Transmission Line Protection

Exercises/Review

Transformer Protection

Transformers:

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

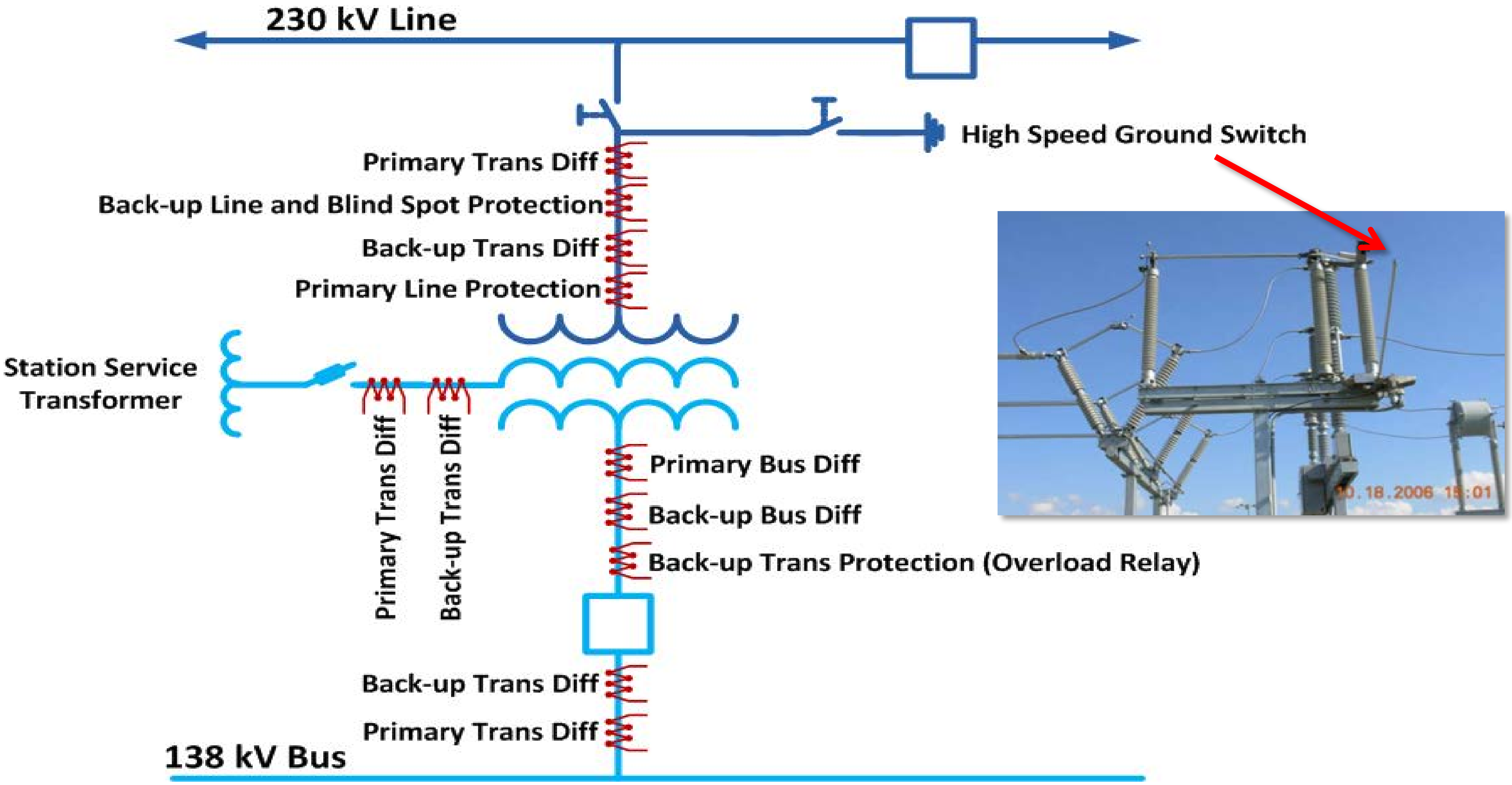
Transformer Protection

- 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”

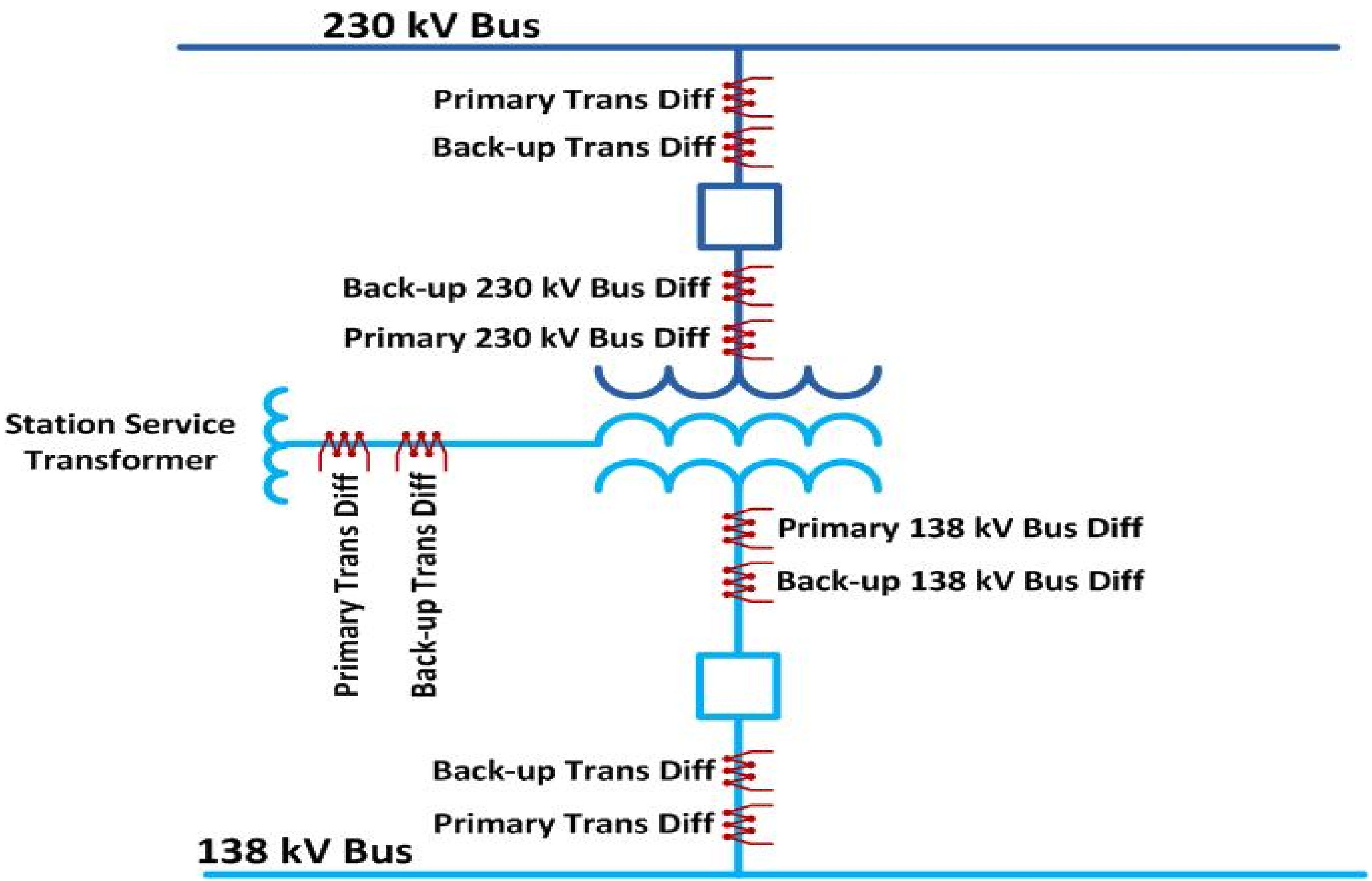
Transformer Protection

- 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

- 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
- 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

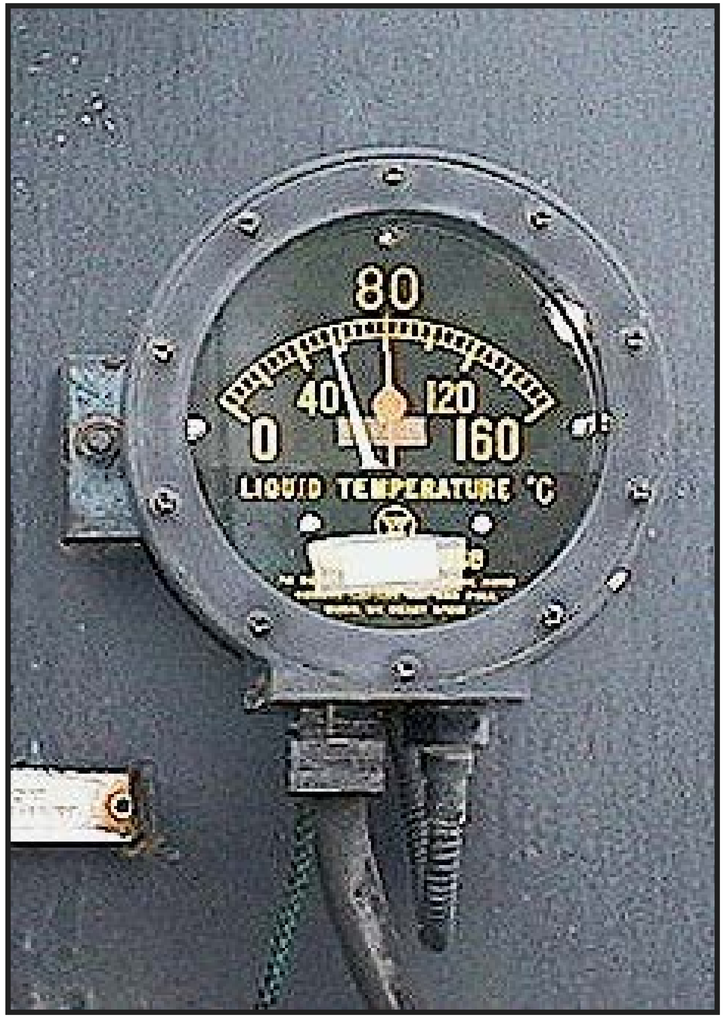
Winding Temperature Relays:

- 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

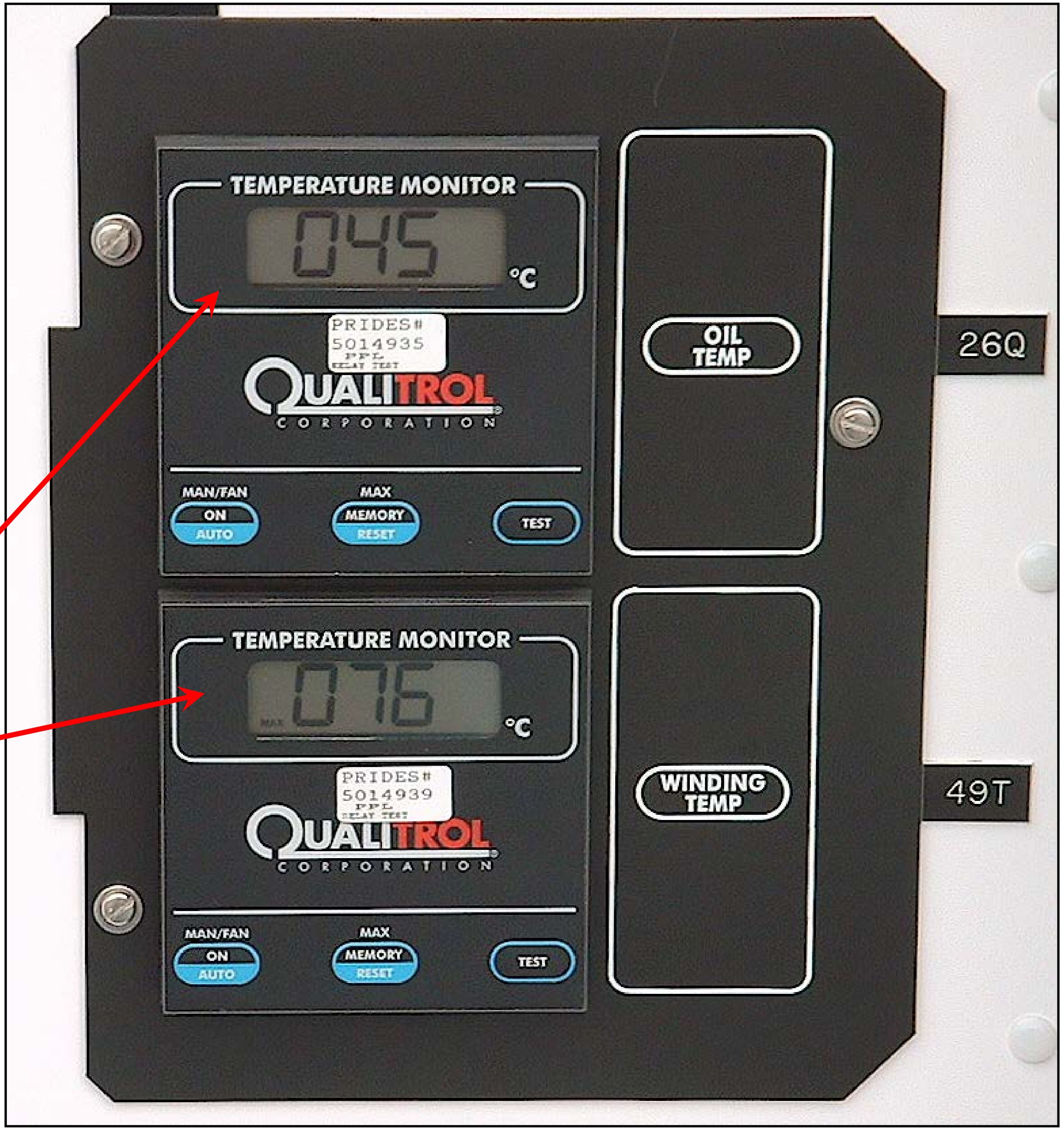


Illustrations of Analog Gauge Style Winding Temperature and Liquid Temperature Thermal Devices

Illustration Of Microprocessor Based Thermal Device

Liquid Temperature
is the upper unit

Winding Temperature
is the lower unit



Transformer Protection

Transformer Neutral Overcurrent Relay:

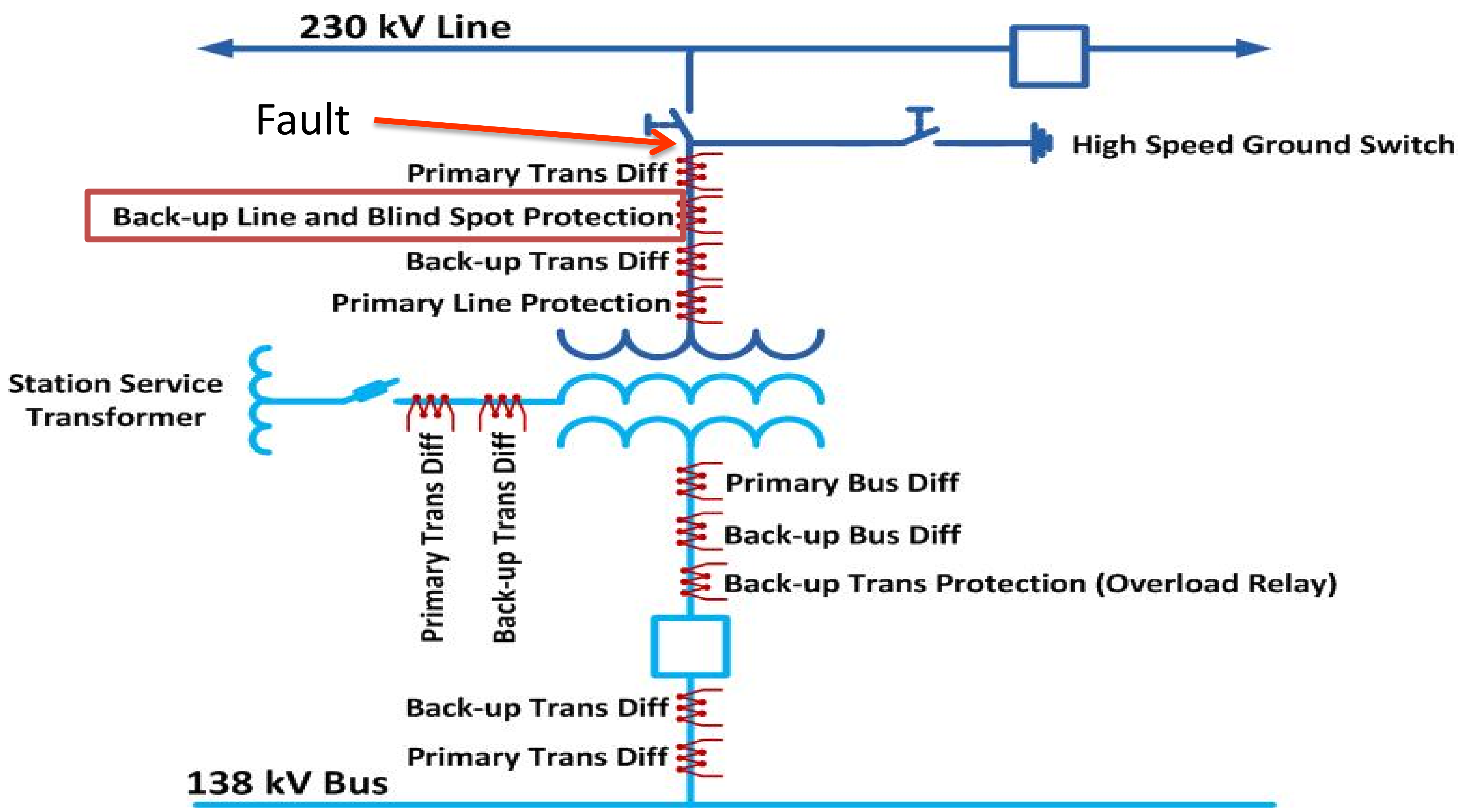
- Relay is connected to a CT located on the neutral connection of a WYE-Grounded transformer
- Used as Back-Up protection for “Through Faults”
- Must be coordinated with other system ground relays
- Operation of this relay will trip the transformer

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

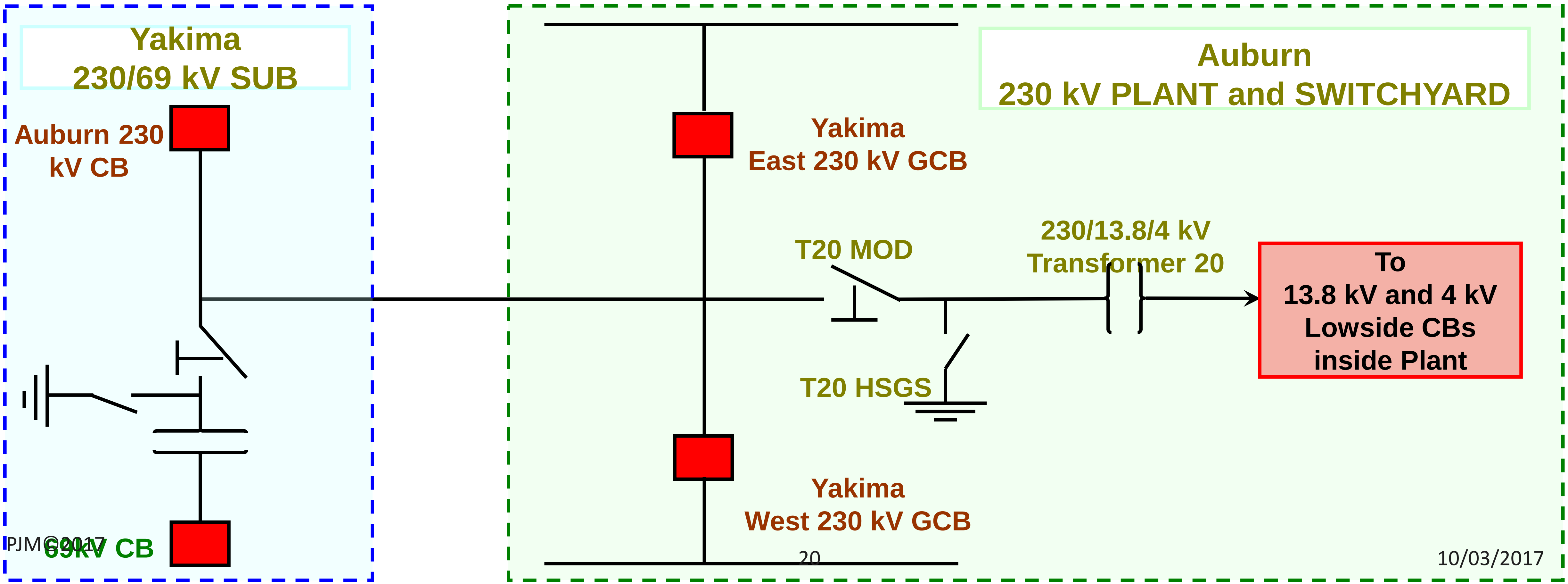
- **Other Protective Devices:**
  - Loss of Cooling Relay - If all fans and/or oil pumps are lost for any reason:
    - The transformer will trip if temperature is above a predetermined level
  - Low Oil Level - Lack of proper oil level compromises transformer cooling
    - This device will alarm and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

Transformer Protection

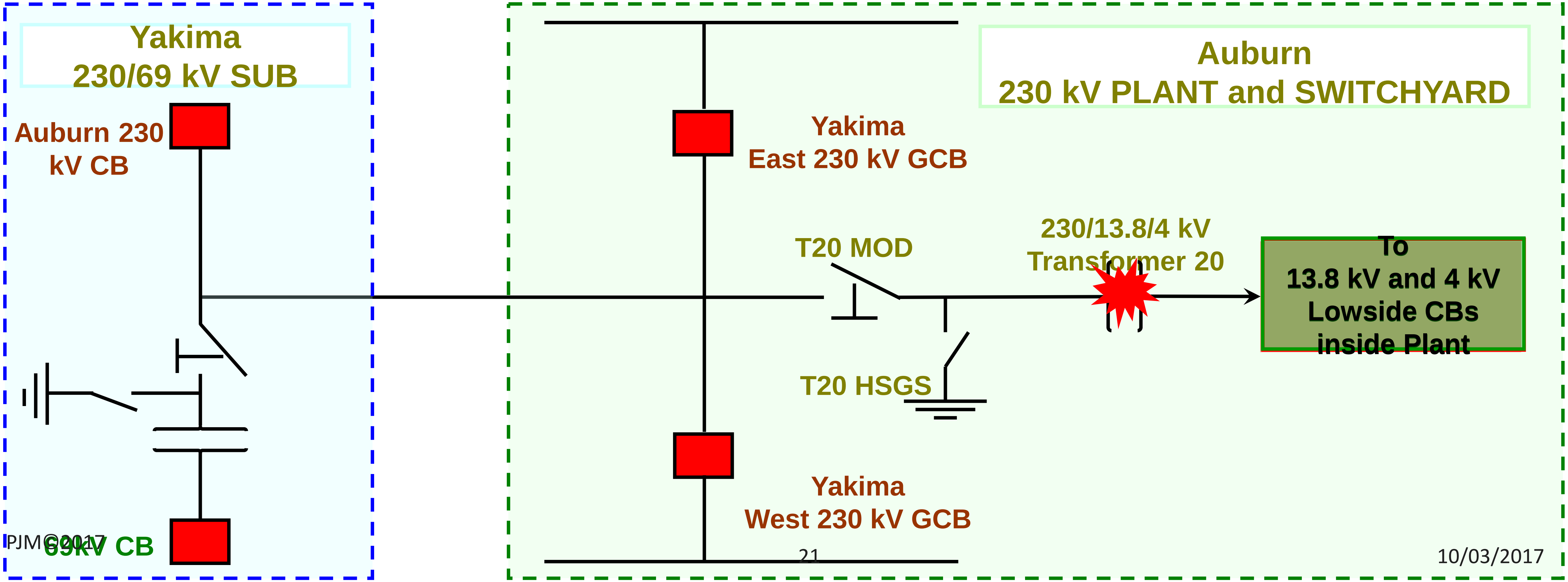
- Operation of any of the above relay schemes will initiate other protective functions
- The physical design of the electrical system will define what additional actions are taken
- Some actions include:
    1) Initiate Direct Transferred Trip to remote terminals
    2) Initiate breaker failure relaying
    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.

Direct Transfer Trip (DTT) Relaying for Transformer Protection

Clearing Sequence For A Fault On Auburn Transformer 20

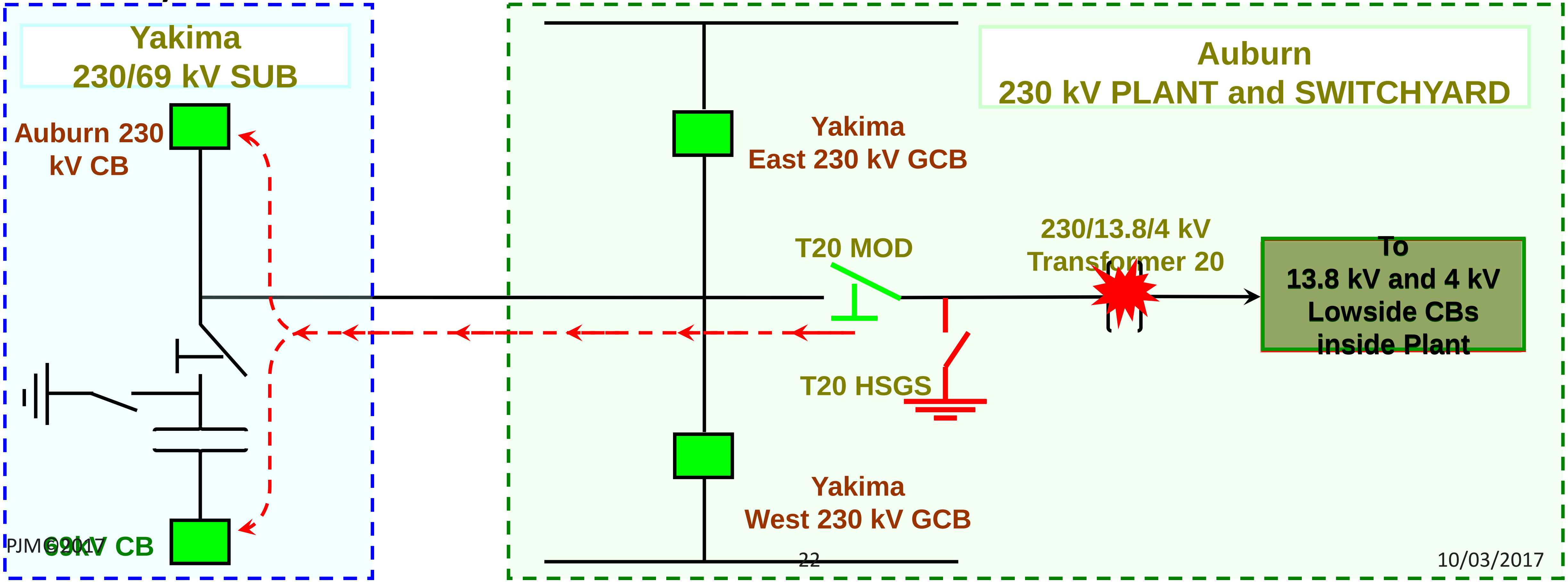


1) A fault occurs inside Transformer 20 at Auburn

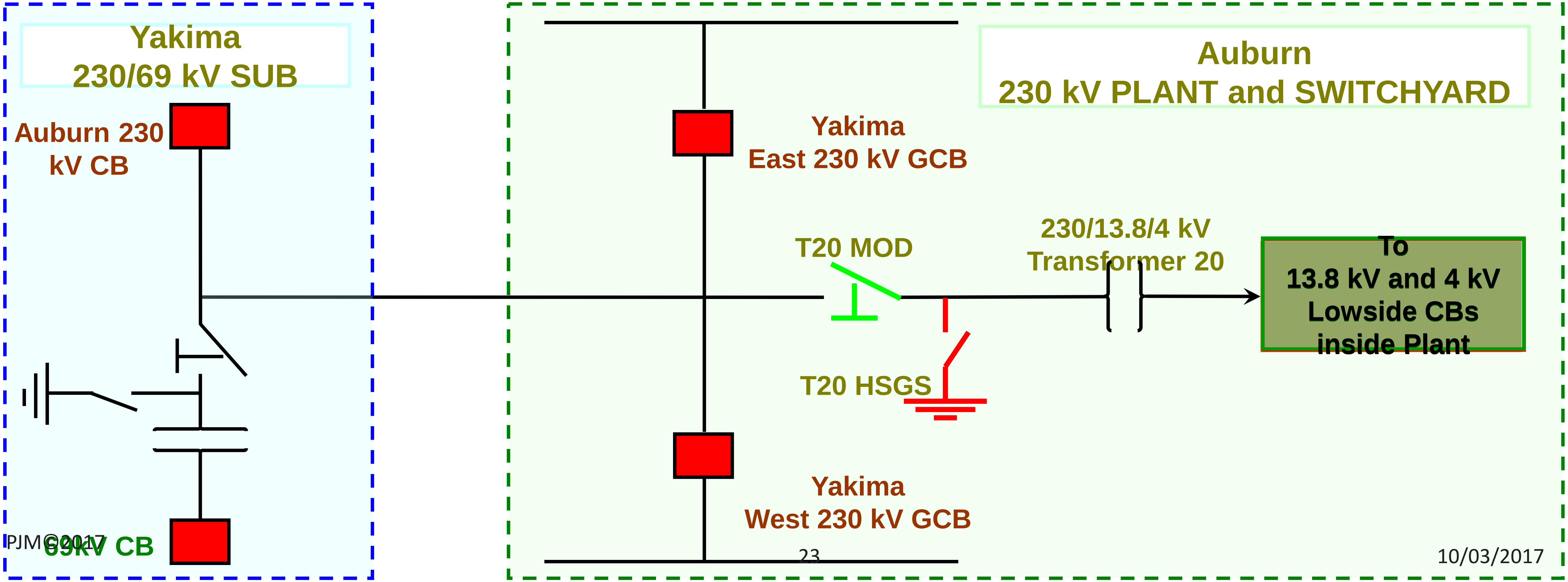


2) At Auburn, Transformer 20 protection operates to immediately trip the Yakima East and West 230kV circuit breakers and the 13.8kV and 4kV Transformer 20 lowside circuit breakers. Simultaneously, a DTT TRIP signal is initiated to Yakima Sub, the T20 HSGS closes and the T20 MOD starts to open

3) At Yakima, the 230kV line and 69kV transformer lowside breakers open immediately upon receipt of the DTT TRIP signal…all circuit breakers at Yakima are open before the HSGS at Auburn closes fully into the transmission line



4) At Auburn, the T20 MOD opens fully to physically isolate the fault and stops the DTT TRIP signal to Yakima…all circuit breakers at Yakima reclose automatically. The transmission line breakers at Auburn also reclose automatically after the failed transformer is isolated, but the T20 lowside breakers are designed to stay open.



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

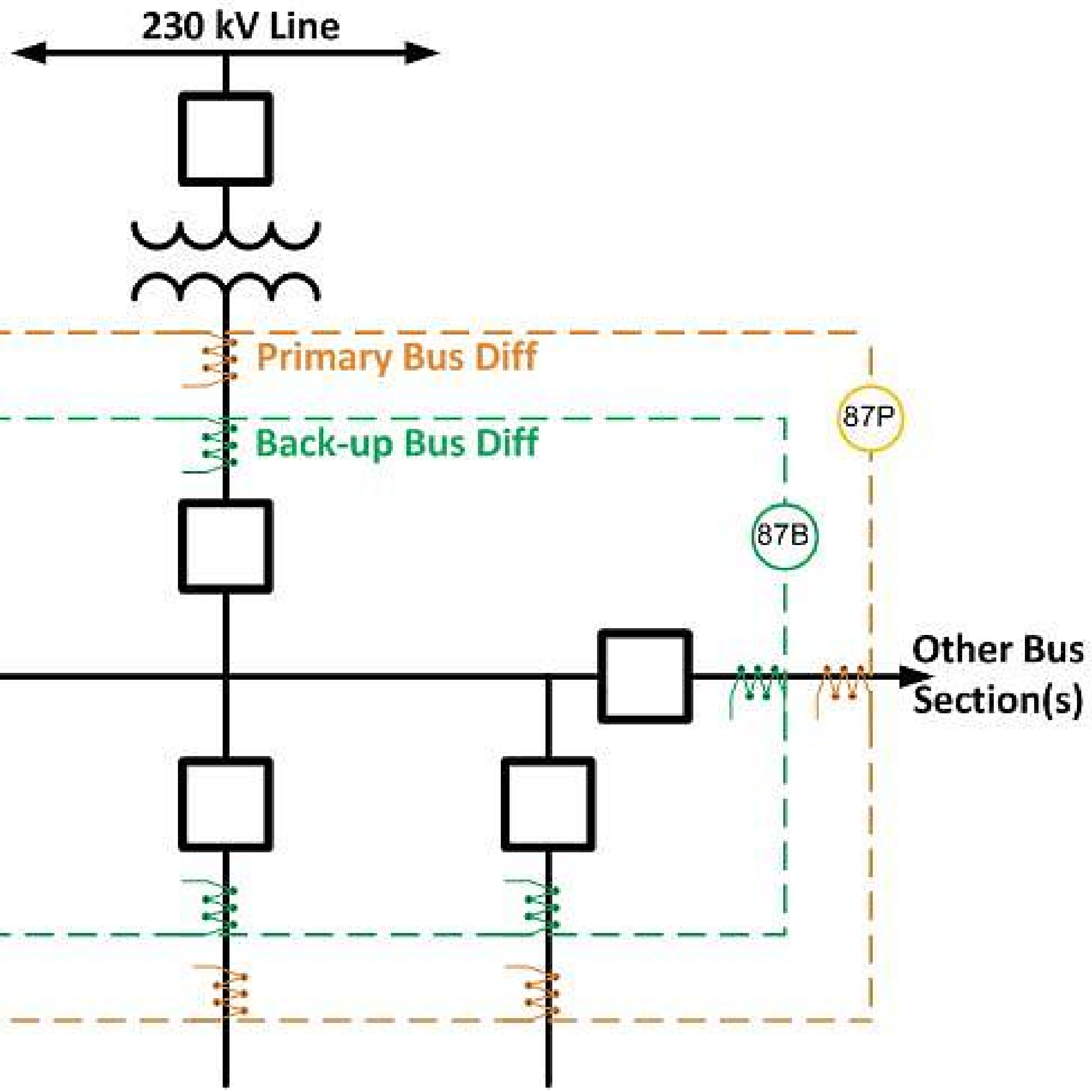
- Know your company's policy!
  - Alert all that need to be informed of the operation
  - Be aware of steps required to alleviate possible system overloads, low voltage concerns, etc.
- In general, do not test (try-back) the transformer until it is inspected by qualified individuals

Bus Protection

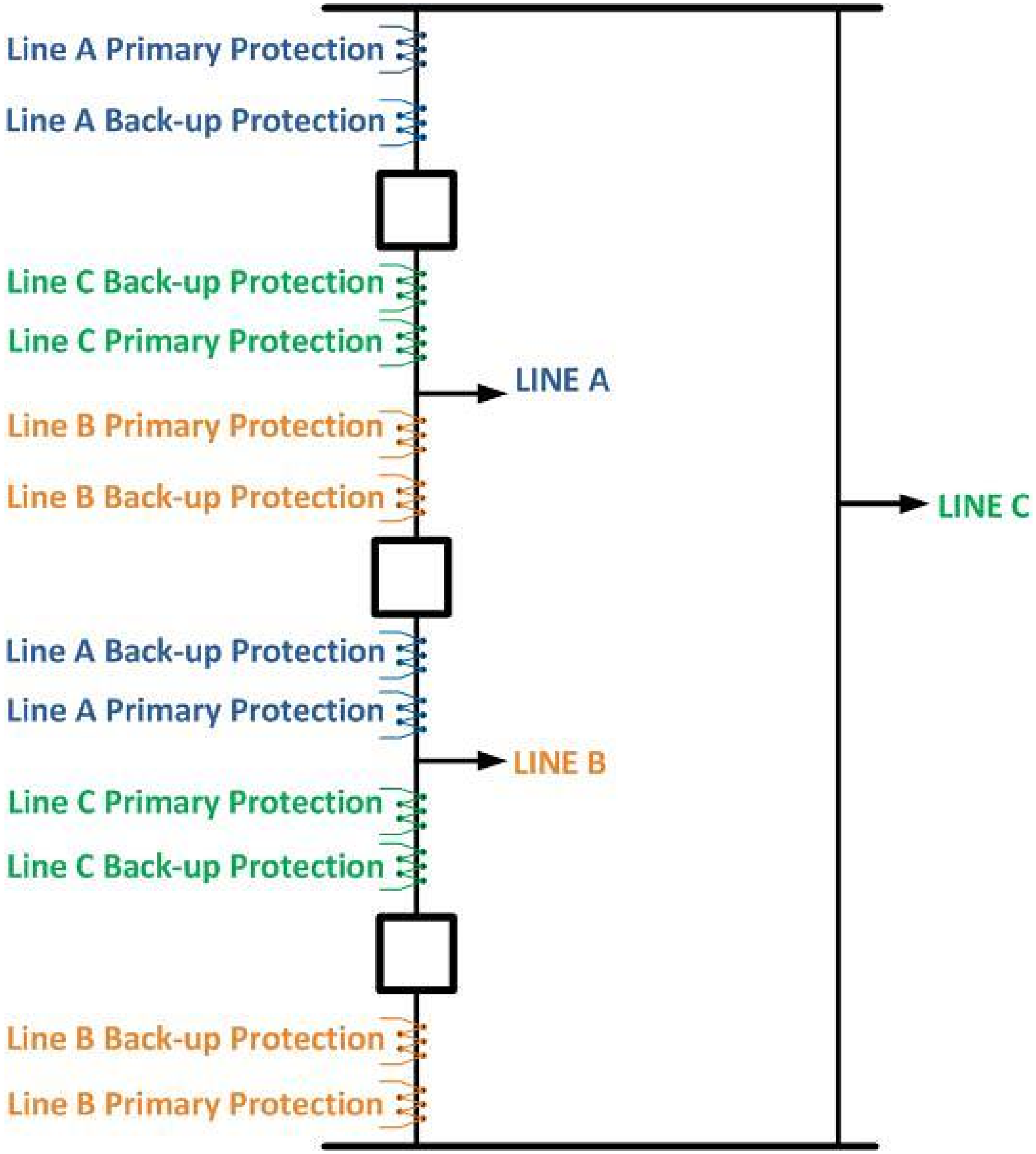
Typical Bus Designs

- **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

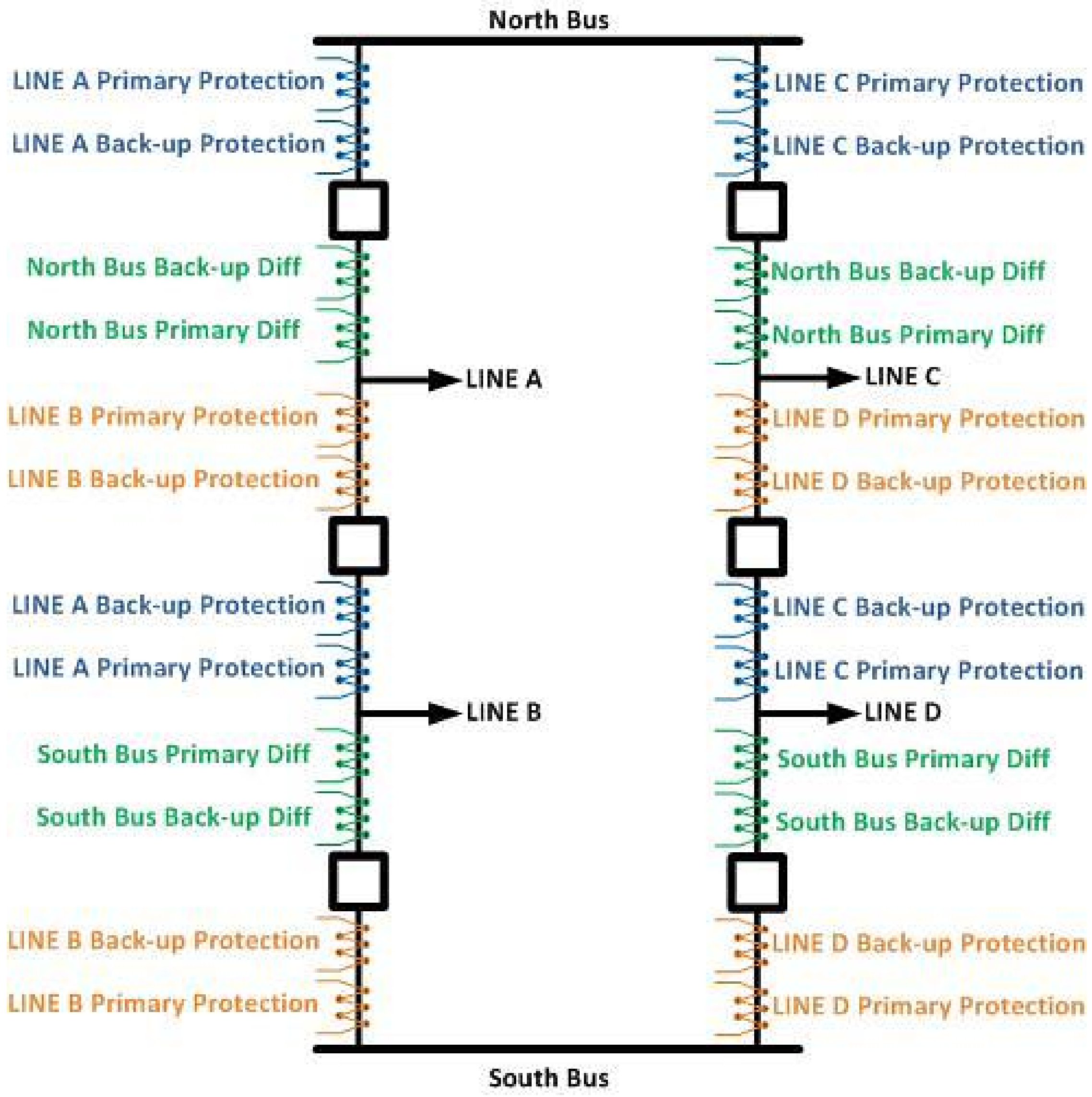
Single Bus – Single Breaker Arrangement



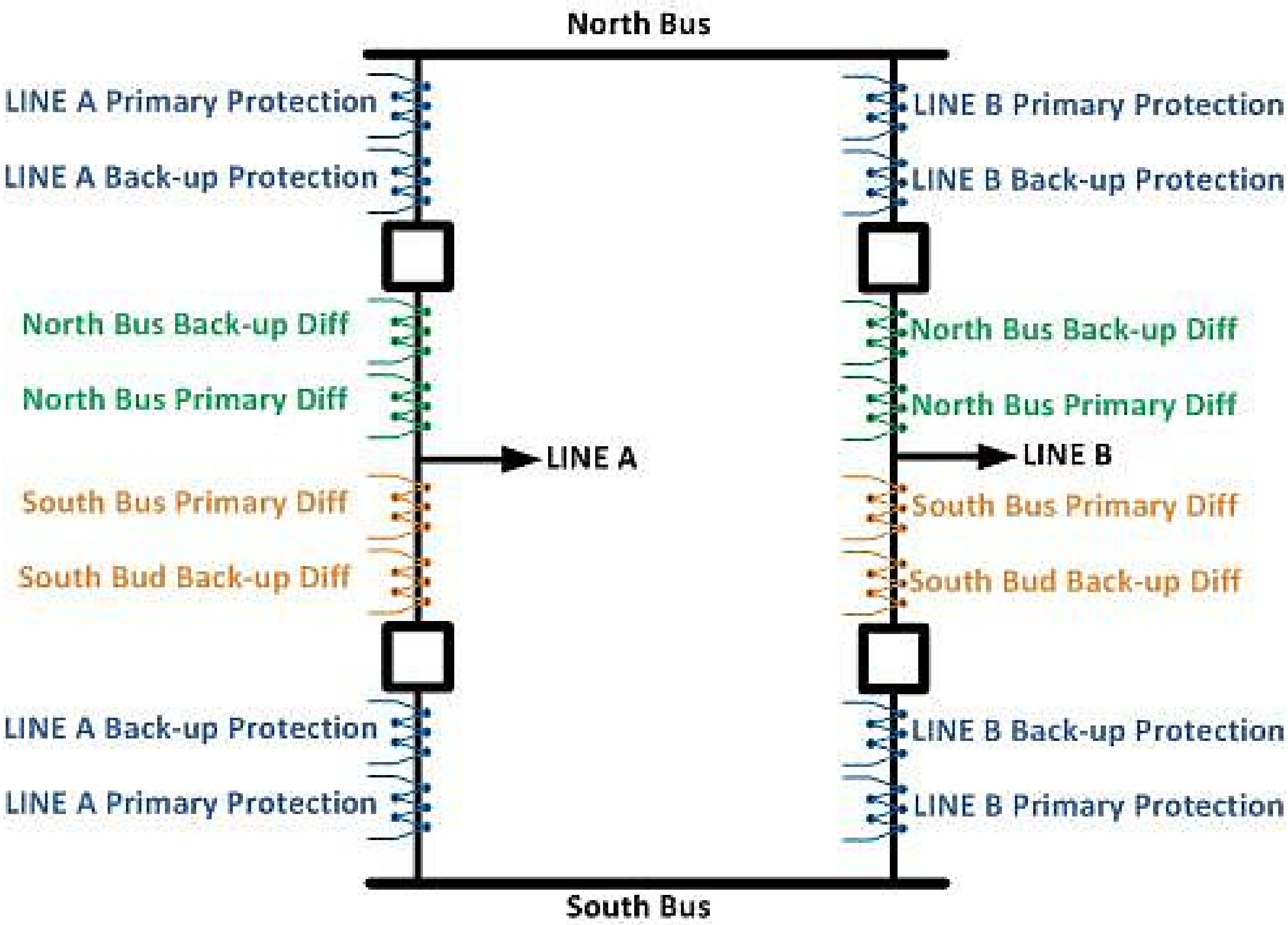
Ring Bus Arrangement



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)**

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 <u>may</u> have the ability to close a CB via supervisory control (SCADA)

Operator's Role is Bus Protection - De-Energize a Bus

- Know your company's 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

Bus Differential with Automatic Testing

Illustration of Automatic Bus Testing in a Transmission Switchyard

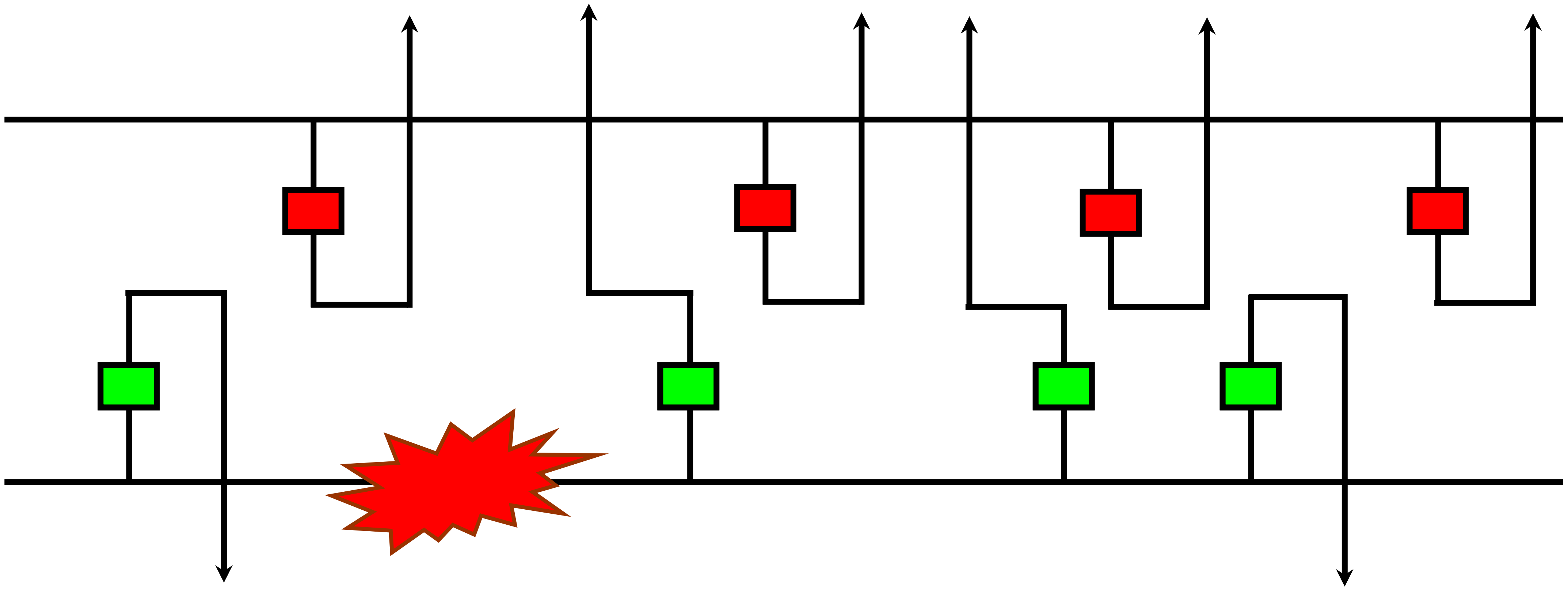
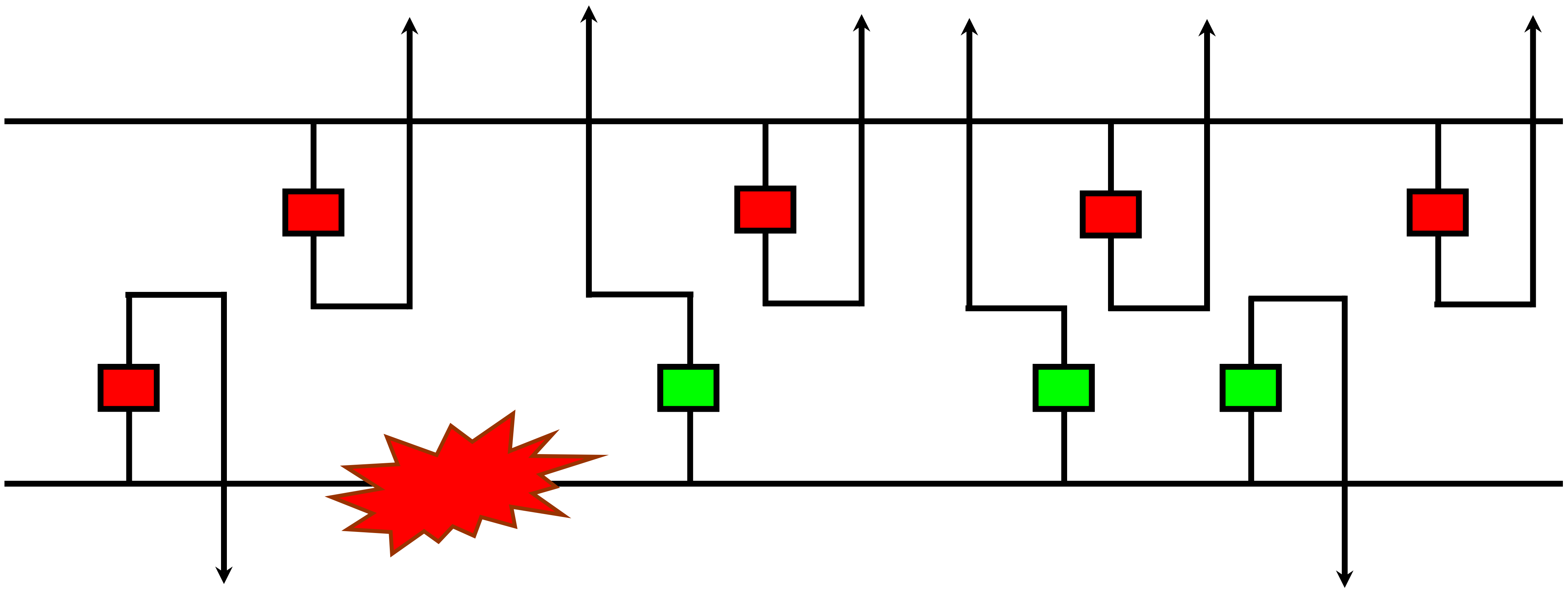
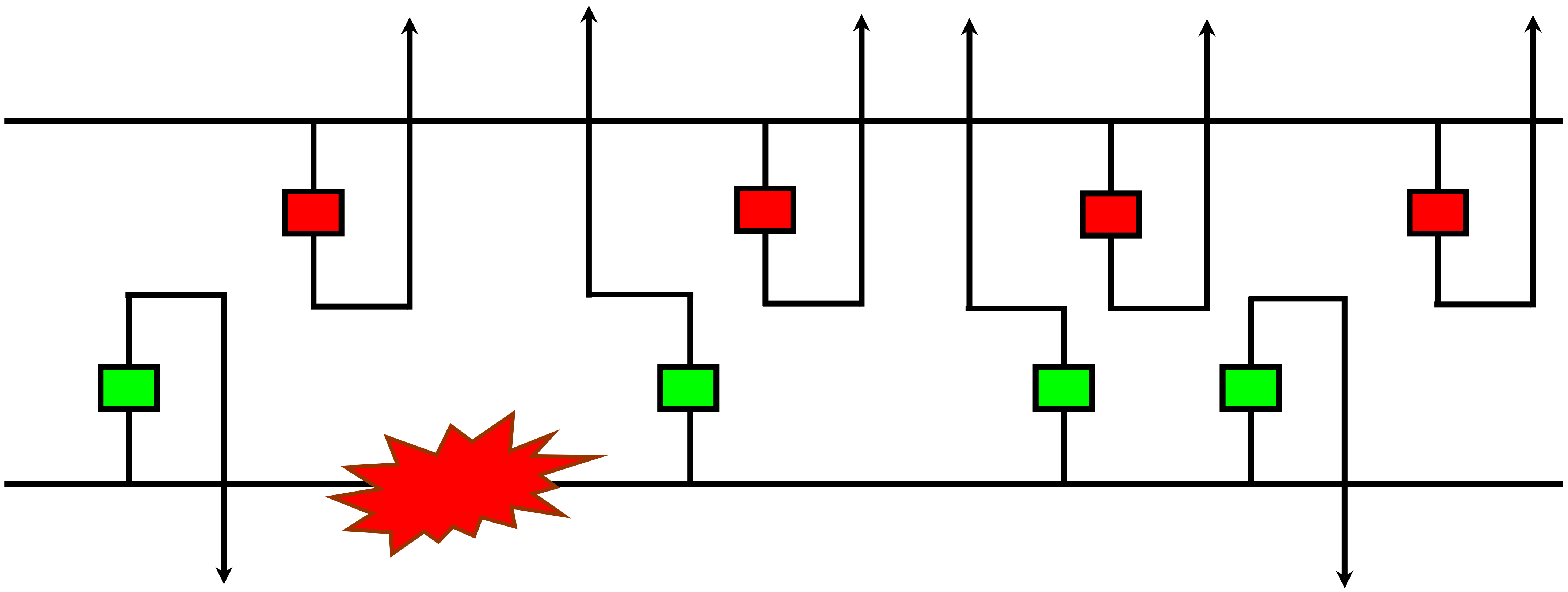


Illustration Of Automatic Bus Testing In a Transmission Switchyard



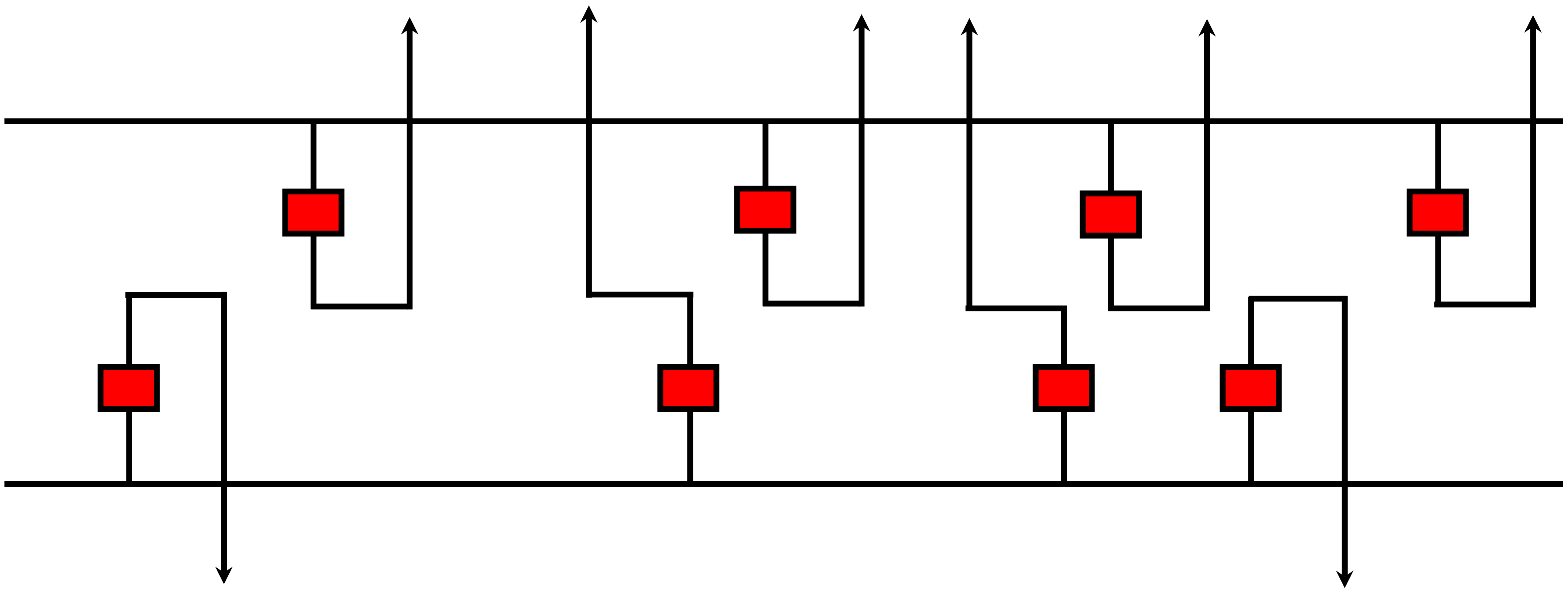
Following a bus differential operation, a preselected circuit breaker automatically recloses to test the bus

Illustration Of Automatic Bus Testing In a Transmission Switchyard



If the bus test is unsuccessful, all circuit breakers lock out and must be closed manually or by SCADA

Illustration Of Automatic Bus Testing
In a Transmission Switchyard



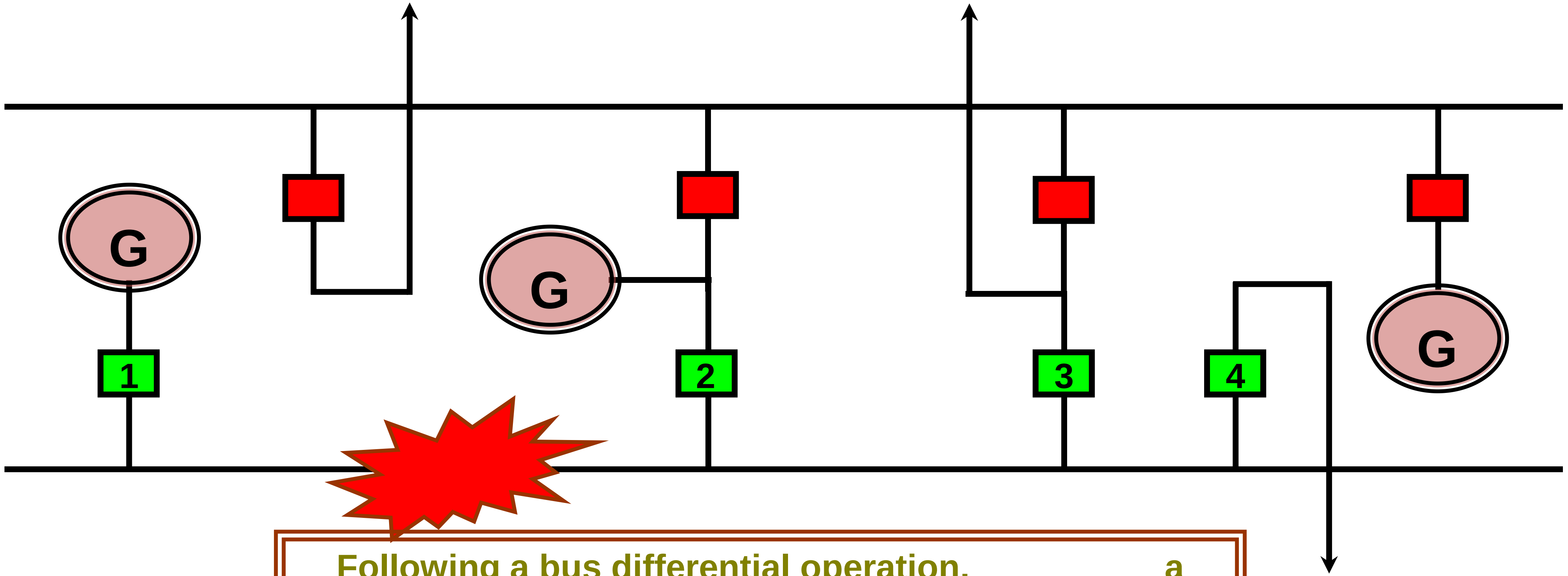
On the other hand, **if the bus test is successful,** all the other circuit breaker automatically reclose after a time delay to ensure the bus is stable.

Bus Testing at Generating Stations

Following a bus differential operation at a **generating station**, special consideration on the testing method is important to avoid severe mechanical stresses on turbine-generator:

- Normally impedance between generator terminals and fault on power line "cushions" the mechanical impact on the turbine-generator
- Bus fault is right at terminals of GSU transformer
  - Want to limit exposure of generator to close-in faults
- Tripped bus at generating station should be tested with transmission line energized from remote substation
- Impedance of transmission line limits current available to bus fault
  - Minimizes stress on the local generators

Illustration Of Automatic Bus Testing At a Generating Station



Following a bus differential operation, a preselected circuit breaker must be closed to test the bus… which one is preferred here and why?

Transformer and Bus Protection Exercises/Review

Generator Protection

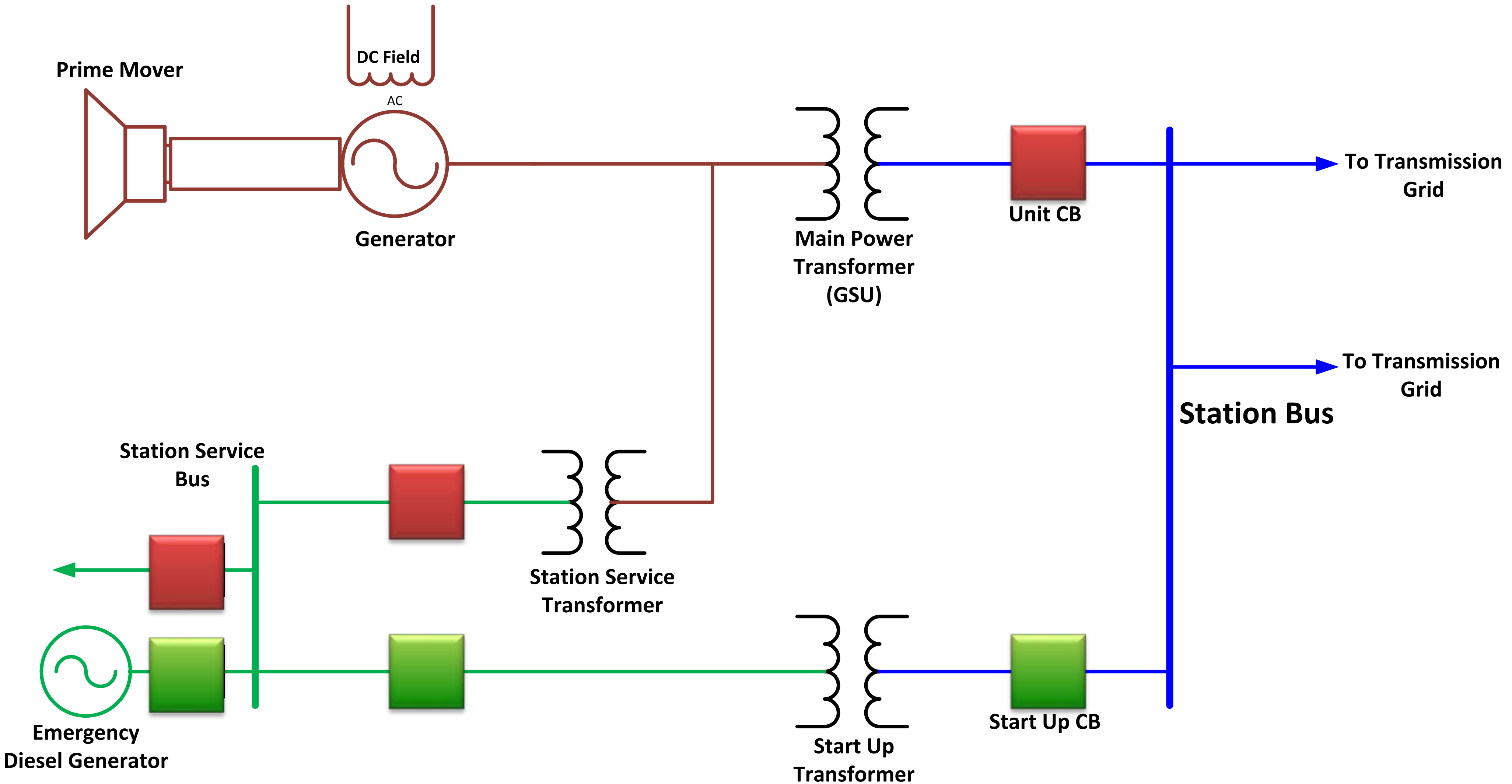
Station Arrangement

- 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)

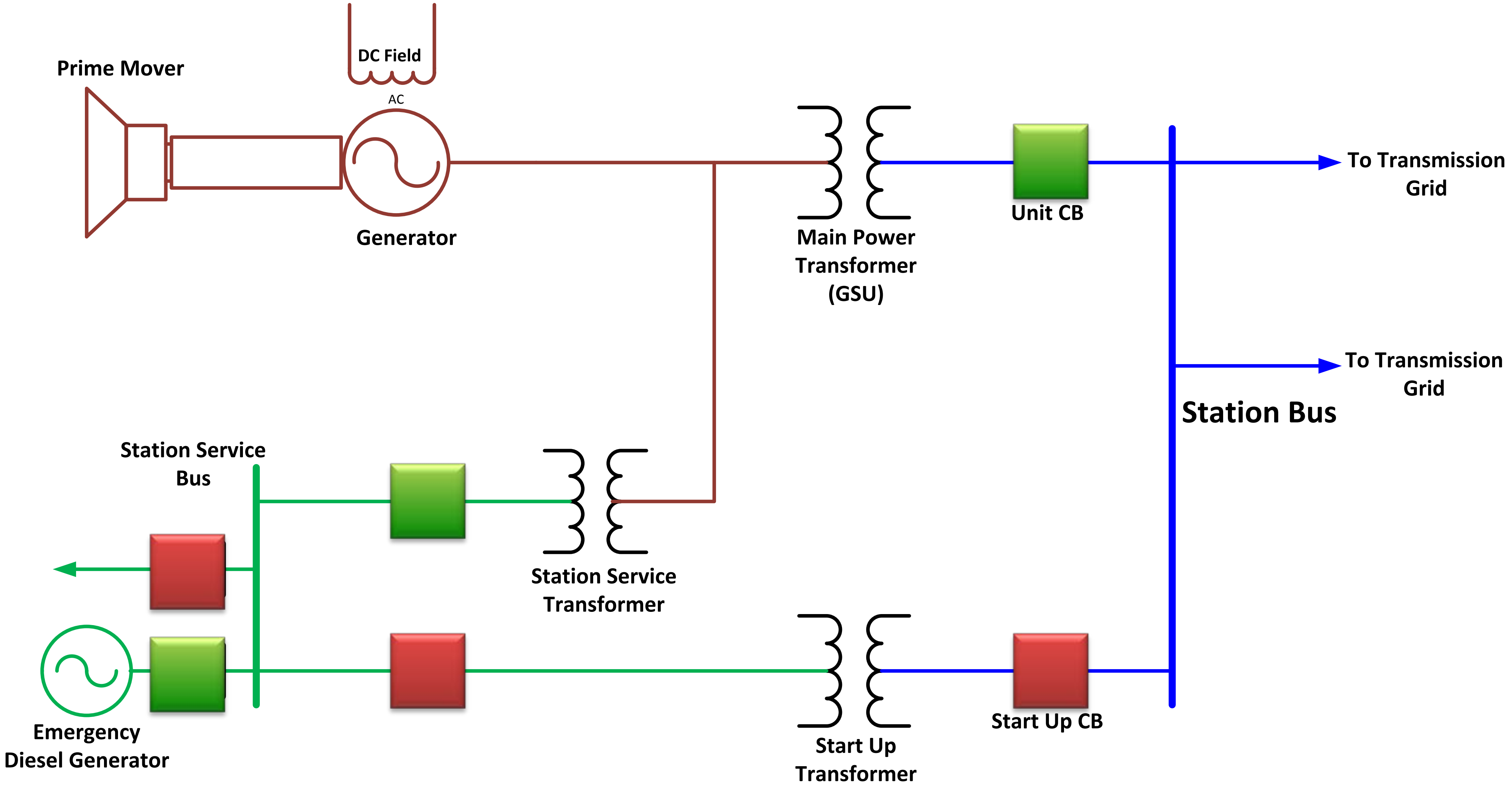
- Generator itself is connected wye with its neutral grounded through a high impedance

- Purpose of this generator connection is to limit the high magnitude currents which could flow for a ground fault

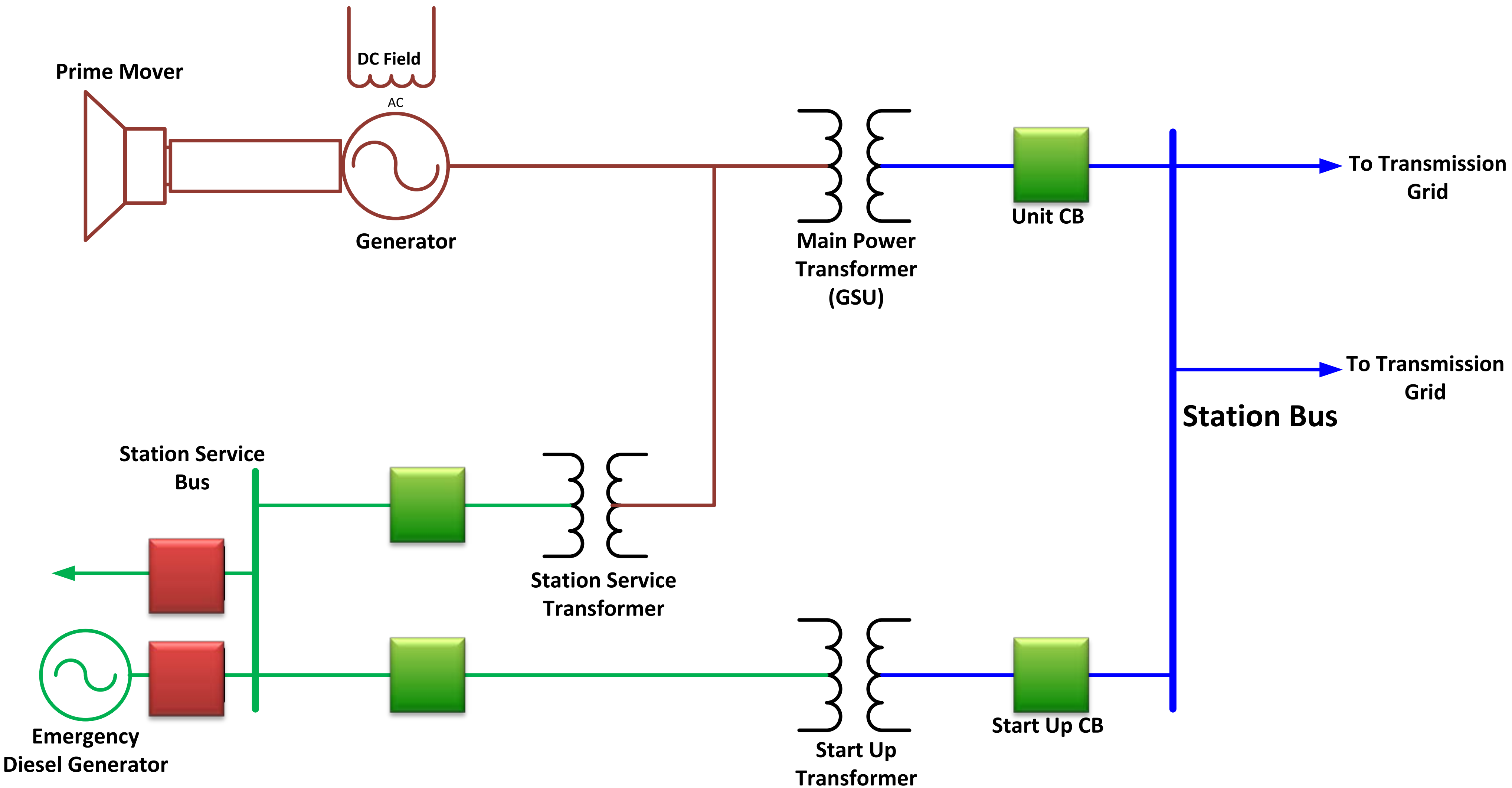
Station Arrangement – Unit in Service



Station Arrangement – Unit Out of Service



Station Arrangement – Station Blackout



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 their company’s procedures
  - This could involve negotiation for additional generation or notifying that company’s energy marketing function

Overall Unit Protection

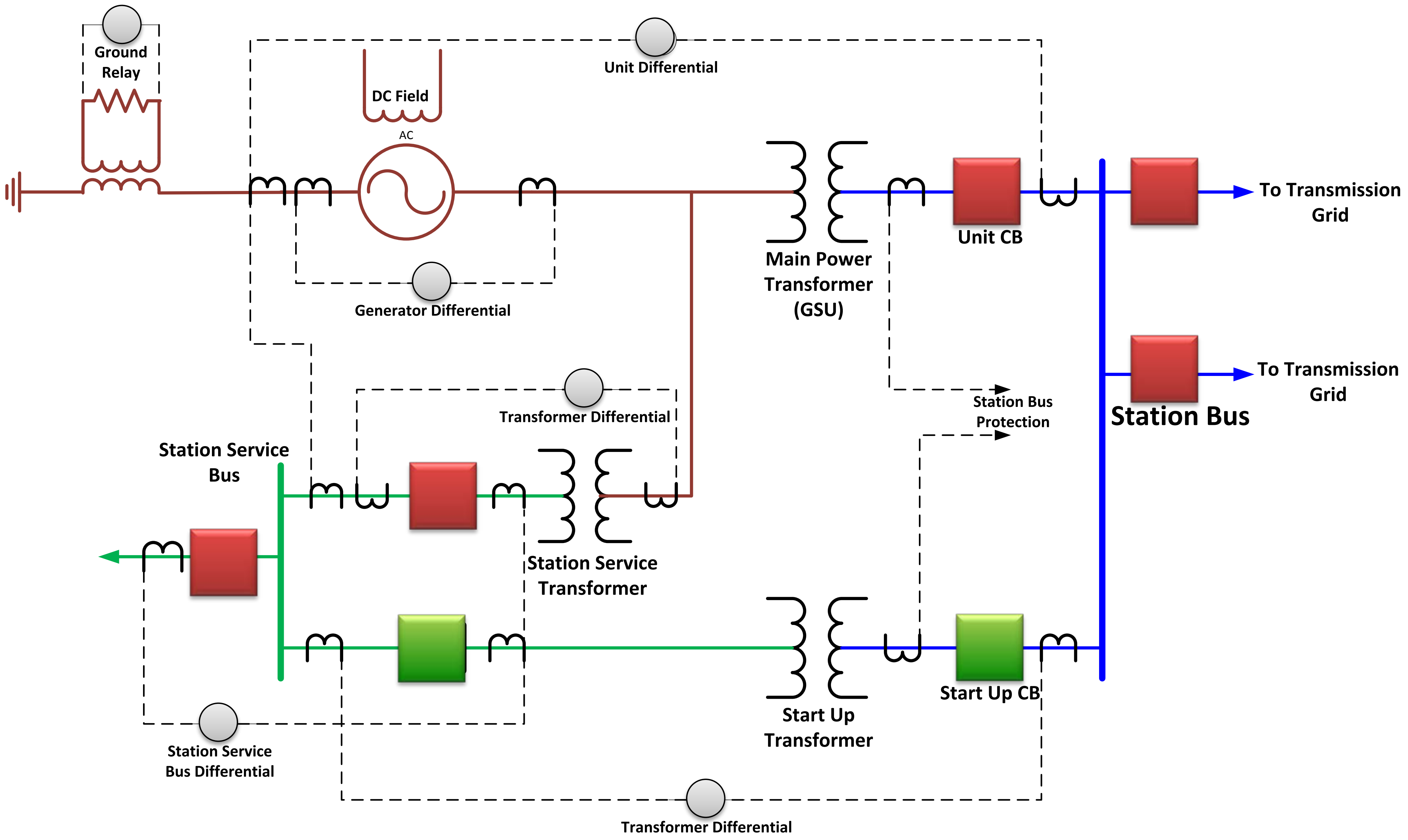
Areas to be Protected and Concerns

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.

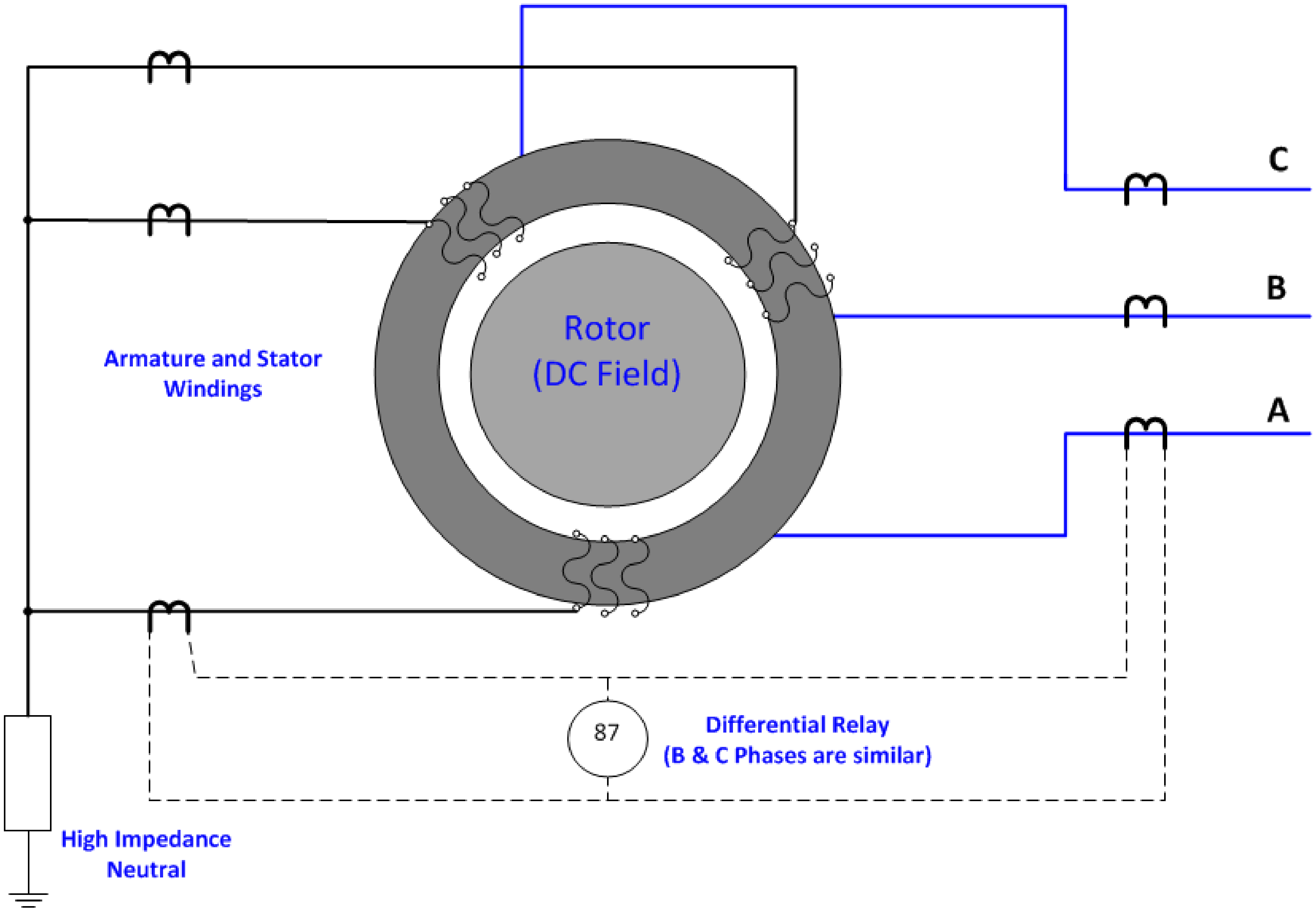

Ground
Relay
DC Field
AC
Unit Differential
Main Power
Transformer
(GSU)
Unit CB
To Transmission
Grid
Generator Differential
To Transmission
Grid
Station Bus
Protection
Station Bus
Transformer Differential
Station Service
Bus
Station Service
Transformer
Start Up
Transformer
Start Up CB
Station Service
Bus Differential
Transformer Differential

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

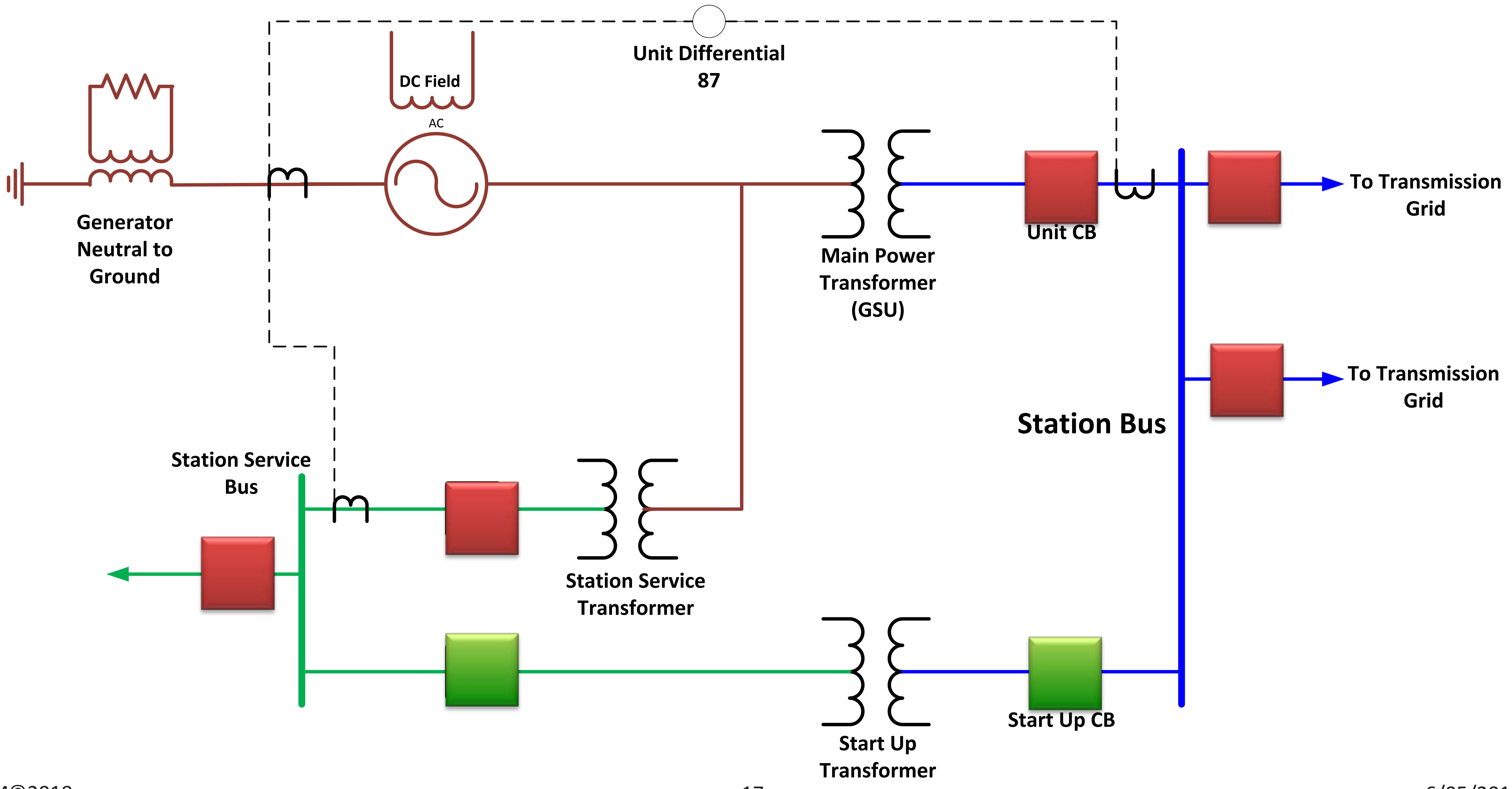


Protective Relay Schemes for the Generator

Overall Differential

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

Unit Differential Protection

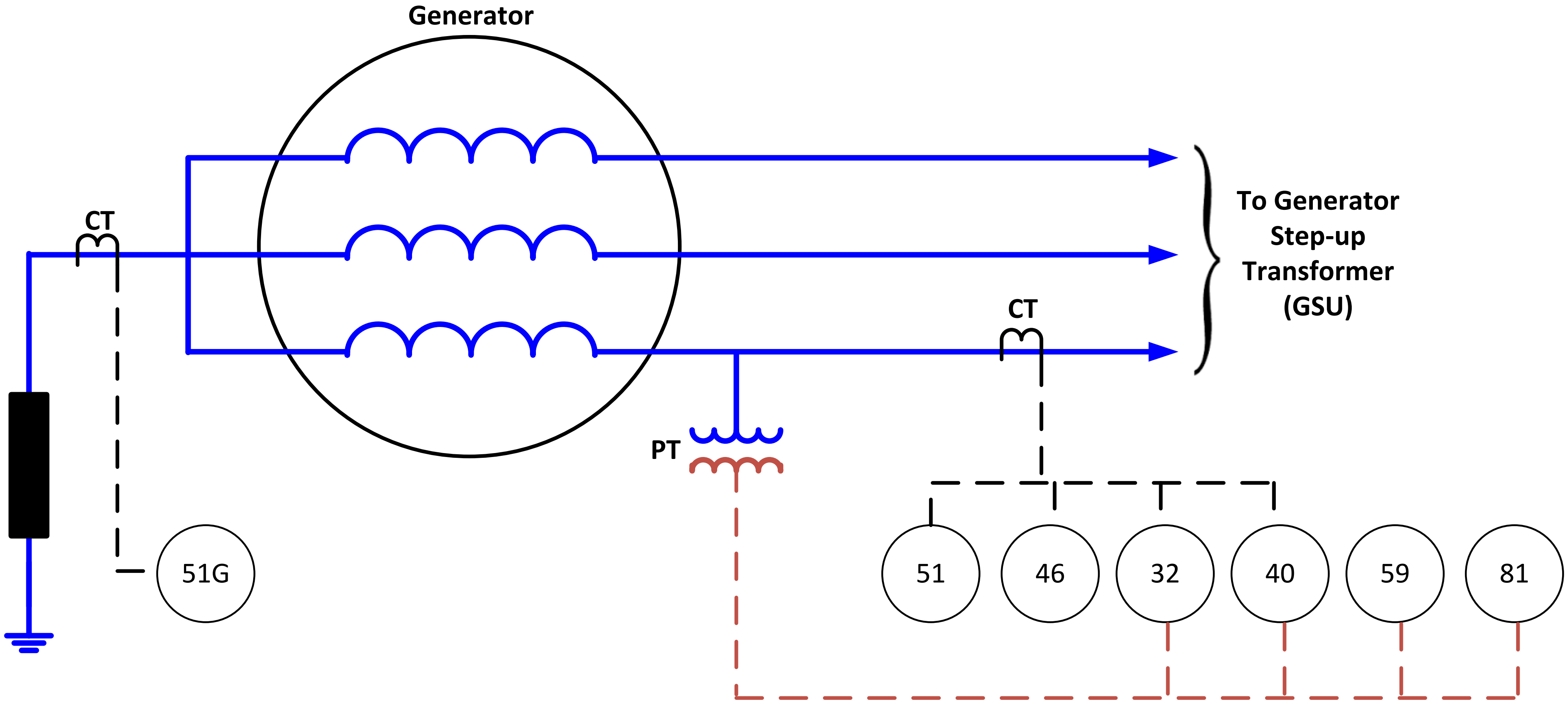


Protective Relay Schemes for the Generator

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

Other Generator Protection Relays



51 – Back-up Overcurrent
46 – Negative Sequence
32 – Reverse Power (Anit-motoring)
40 – Loss of Field

59 – Over-excitation
81 – Under-frequency
51G- Neutral Over-current

Protective Relay Schemes for the Generator

Negative Sequence Protection

- During unbalanced faults, "Negative Sequence" currents will flow
  - Caused by open circuits in the system (Downed conductors, stuck breakers and pole-top switches
  - 120 cycle currents are induced in the solid forgings, non-magnetic rotor wedges and retaining rings of the rotor caused by the "negative sequence" current in the stator
  - 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

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 based ventilation being greatly reduced
- 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

Loss of Field Protection

- Generator Effects
  - Synchronous generator becomes induction motor
  - Induced eddy currents heat rotor surface
  - High reactive current drawn by generator overloads stator (2 to 3 times the generator rating)
- System Effects
  - Loss of reactive support
  - Creates a reactive drain
  - Can trigger system/area voltage collapse

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
- 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

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
- Volts/Hertz, or Voltage or Current relaying is employed
  - Typically "stair-step" operation
    - One relay will alarm or automatically reduce field to allowable limits
    - One relay will trip unit

Protective Relay Schemes for the Generator

Overexcitation Protection

- Generator issues:
  - Voltage regulator problems
    - Operating error during manual operation
    - Control failure
    - Loss of sensing signal

Protective Relay Schemes for the Generator

Overexcitation Protection

- System issues:
  - Unit load rejection: full load, partial rejection
  - Power system islanding during major disturbances
  - Ferranti effect
  - Reactor out of service
  - Capacitors in service
  - Faulty LTCs

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!

Protective Relay Schemes for the Generator

Underfrequency Protection

- Turbine blades are designed and tuned to operate at rated frequencies
  - Operating at frequencies different than rated can result in blade resonance and fatigue damage
  - Accumulated operation, for the life of the machine, not more than:
    - 10 minutes for frequencies between 56 and 58.5 Hz
    - 60 minutes for frequencies between 58.5 and 59.5 Hz

Protective Relay Schemes for the Generator

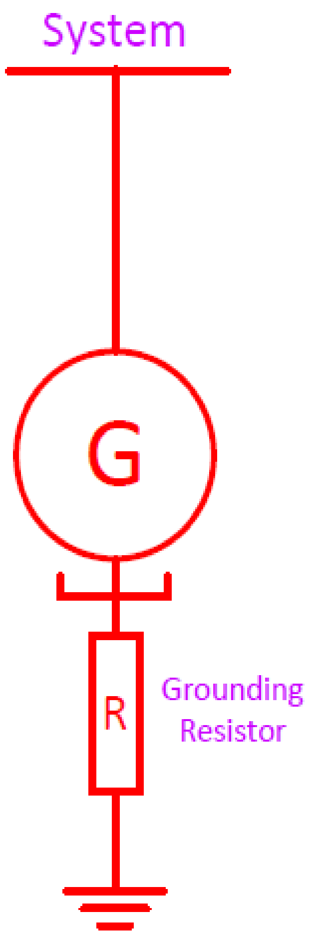
Generator Ground Fault Protection

- 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

Protective Relay Schemes for the Generator

Generator Ground Fault Protection

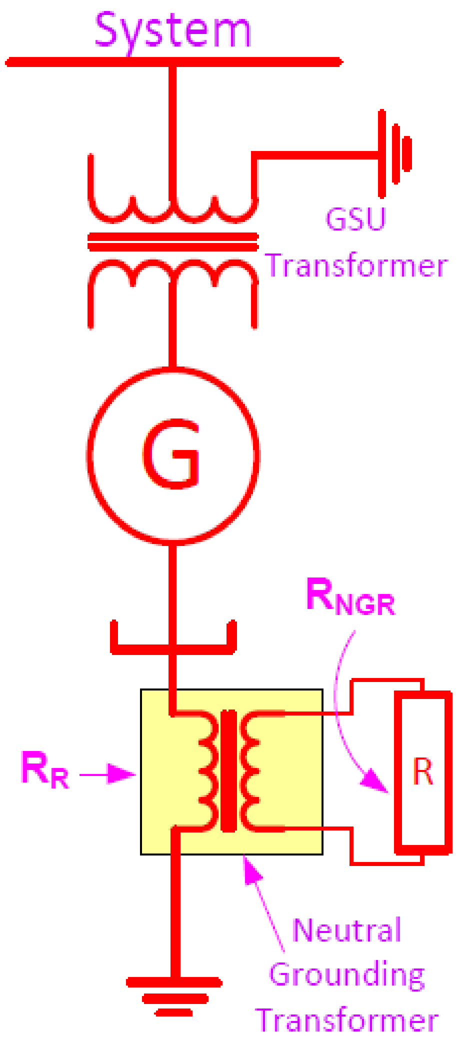
- Low Impedance
  - Good ground source;
    - The lower the R, the better the ground source
    - The lower the R, the more damage to the generator on internal ground fault



Protective Relay Schemes for the Generator

Generator Ground Fault Protection

- High Impedance
  - Creates “unit connection”
  - System ground source obtained from GSU



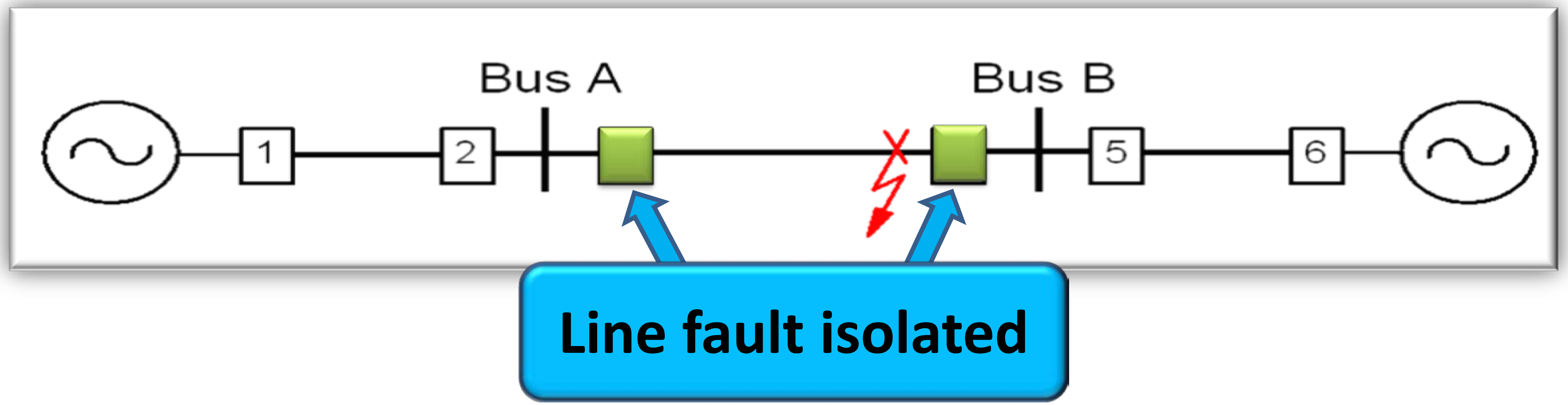
Generator Protection Exercises/Review

Remedial Action Scheme (RAS)

Disclaimer

- This presentation explains the types of RAS that can be found on transmission and distribution systems
- Examples of RAS will be provided for schemes that are used in the PJM RTO. Each individual scheme on the PJM system is not covered in this presentation
- Further information regarding specific RAS in PJM can be located in **Section 5 of PJM Manual 3**

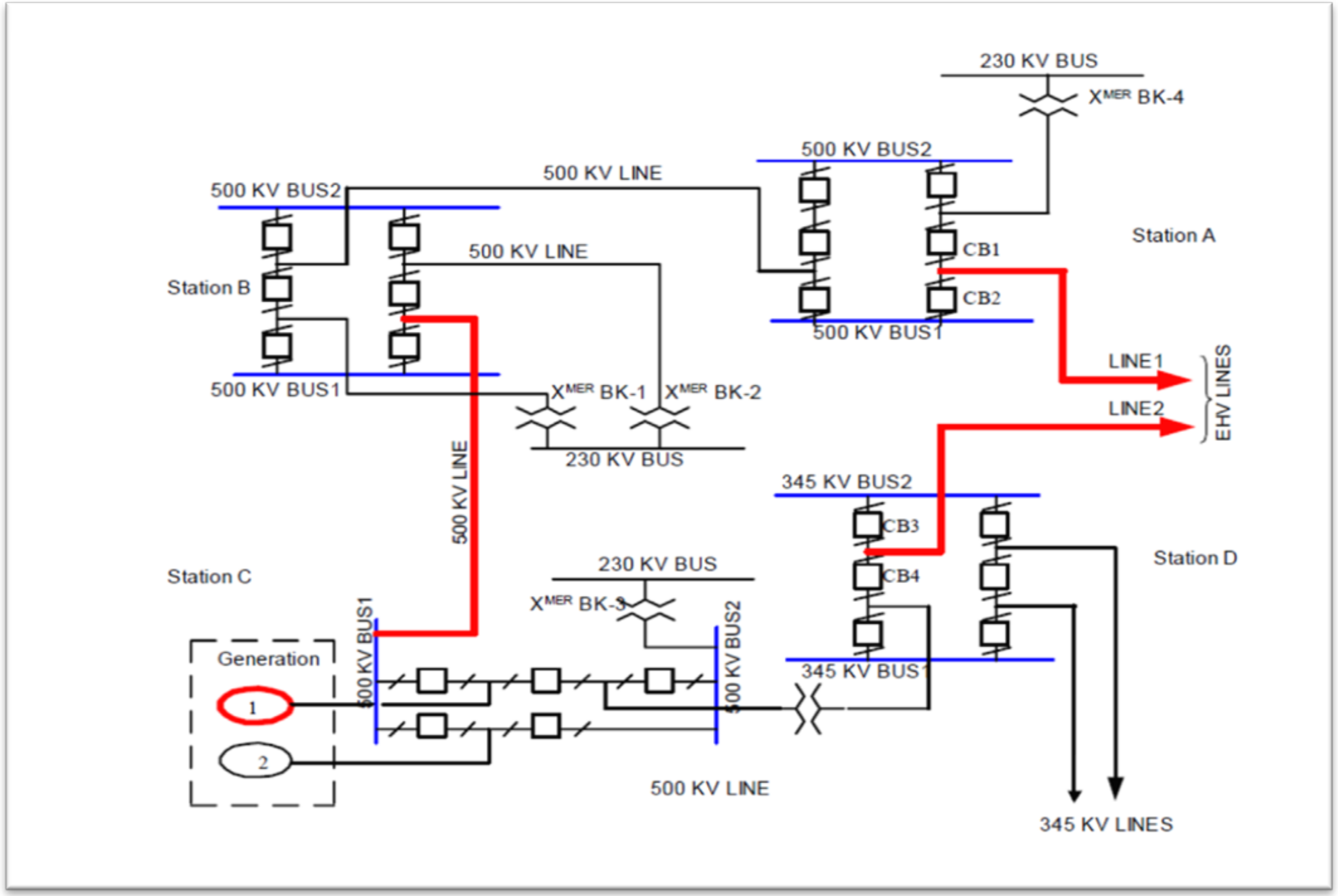
Introduction



- Basic power system protection is designed to protect system equipment by isolating faulted equipment
- Examples include: generators, lines, transformers and busses

Problem Statement

- The size and complexity of the power grid makes the bulk electric system vulnerable to:
  - Congestion
  - Over/underfrequency
  - Over/undervoltage
  - Power system instability



www.gedigitalenergy.com (2013)

Problem Statement

- Unaddressed system vulnerabilities could result in:
  - Multiple contingencies
  - Equipment damage
  - Power system collapse

Solution: Use Remedial Action Schemes (RAS)

- Remedial Action Scheme (RAS) is designed to **detect abnormal system conditions and initiate predetermined actions** to maintain the reliability of the Bulk Electric System (BES)
- Actions include:
  - Changes in demand
  - Changes in generation output
  - Changes in system configuration
- Goals of an RAS:
  - Maintain system stability
  - Maintain acceptable system voltages
  - Maintain all facilities within acceptable thermal limits

Criteria

- **Dependability:**
  - Certainty that the scheme operates when required to avoid a collapse
- **Security:**
  - Certainty that the scheme does not operate when not required
- **Selectivity:**
  - Ability to select the correct and minimum amount of action
- **Robustness:**
  - Ability of the scheme to provide dependability, security, and selectivity over the full range of dynamic and steady state operating conditions

NERC Standards

- As the Reliability Coordinator, Transmission Operator and Balancing Authority, PJM is responsible to monitor the status of all schemes in the RTO

PRC-001.1(ii) R.6

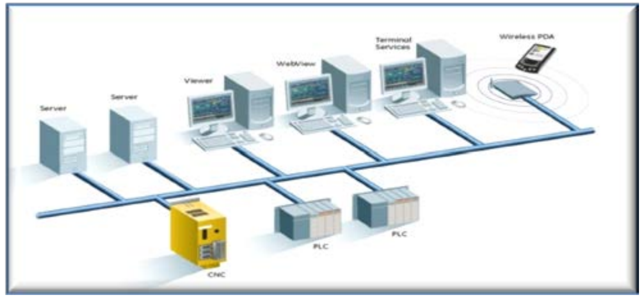
> **R6.** Each Transmission Operator and Balancing Authority shall monitor the status of each Special Protection System in their area, and shall notify affected Transmission Operators and Balancing Authorities of each change in status.

IRO-002-4 R.3

> **R3.** Each Reliability Coordinator shall monitor Facilities, the status of Special Protection Systems, and non-BES facilities identified as necessary by the Reliability Coordinator, within its Reliability Coordinator Area and neighboring Reliability Coordinator Areas to identify any System Operating Limit exceedances and to determine any

RAS Requirements

Communication Network



Relays

Scheme Logic

IF circuit breaker X trips ***THEN*** circuit breakers Y and Z will____?

PJM RAS Review Process

- PJM Manual 3: Section 1.7
  - PJM receives proposal for RAS
    - Must meet NERC RAS definition
  - PJM and TO review scheme and system impacts
    - PJM provides recommendation and identifies if scheme is needed for reliability purposes including operational performance
  - PJM posts scheme information and document scheme in M-03
  - Owner obtains RRO approval and discusses at various committee meetings

PJM RAS Identification

- PJM will always use the following format to identify RAS:

Facility/Equipment Identifier

RAS Identifier

Black Oak 500/138kV #3 Transformer [RAS]

- NOTE: all existing schemes required to be compliant with RAS definition by 4/1/2019 – SPS has replaced RAS in PJM Manual M-03

RAS Questions for Activation

- Does the scheme require manual activation (communication protocol)?
- What are the conditions that will activate the scheme?
- What conditions make the scheme nonfunctional?
- What procedures are in place should the RAS become unavailable?
- Is my contingency analysis modeled properly based on the relay scheme logic?
- Is the bulk electric system in a reliable posture following the activation of the RAS?

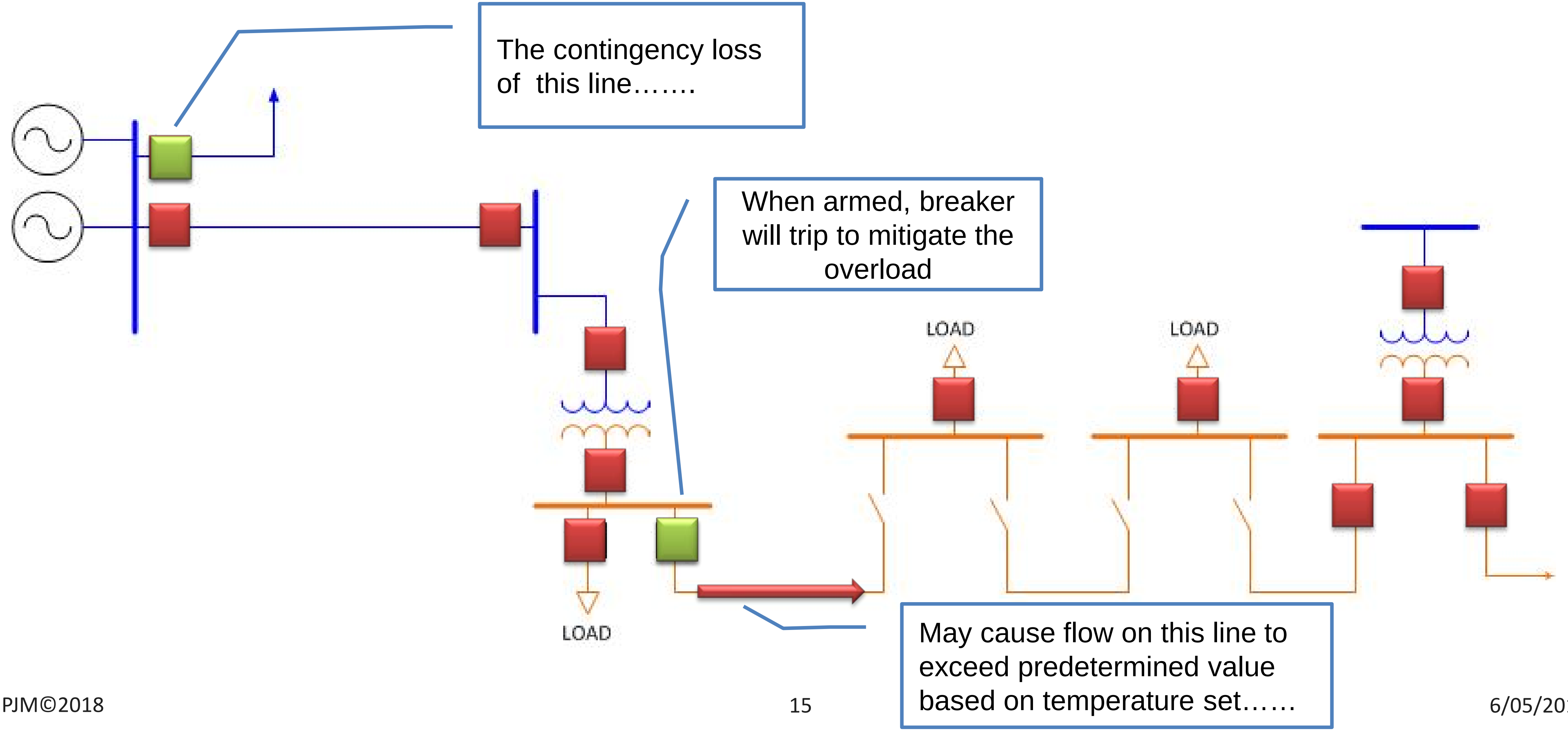
Types of RAS

Types of RAS

- Remedial Action Scheme is designed to perform several functions. These include:
  - Trip or transfer trip a facility
  - Initiate generator run-back/load rejection/fast valving schemes
  - Shed load

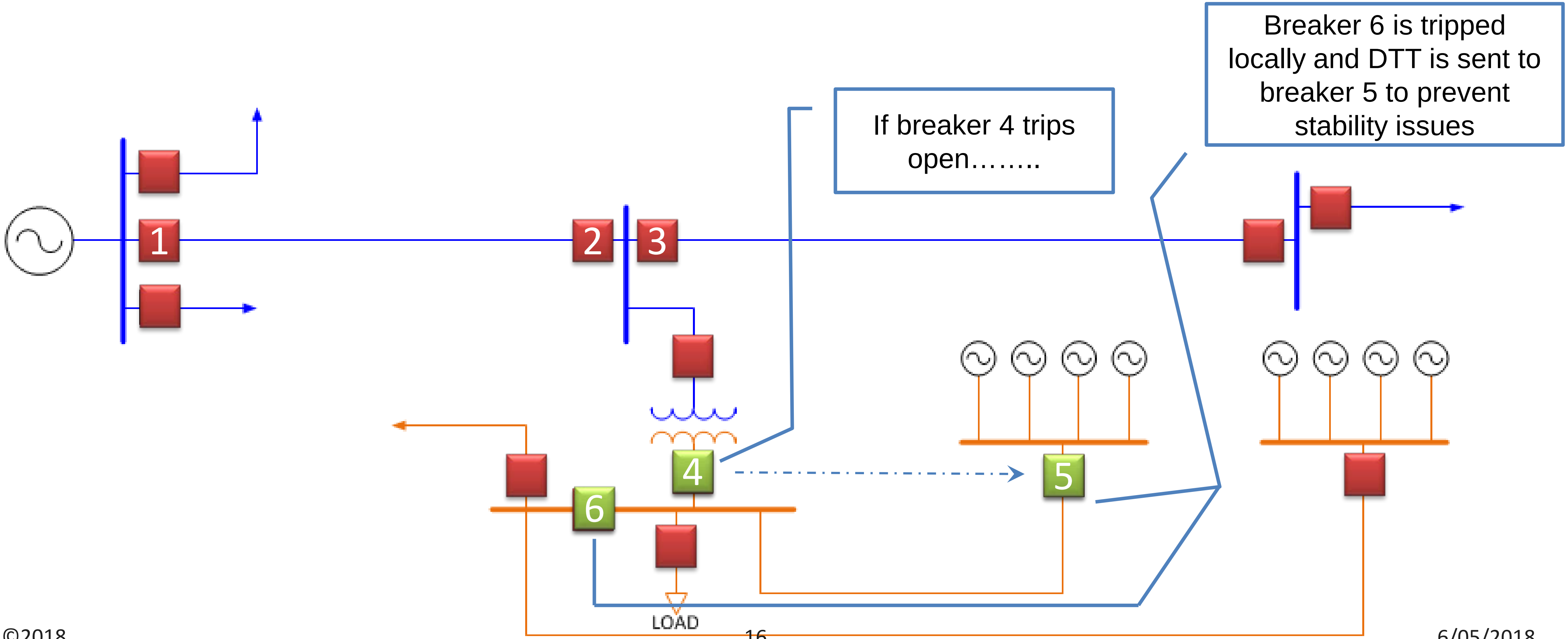
Trip Scheme

- Will initiate breaker operation to mitigate overload



Transfer Trip Scheme

- Will coordinate breaker operations to initiate remote tripping based on a predetermined set of conditions



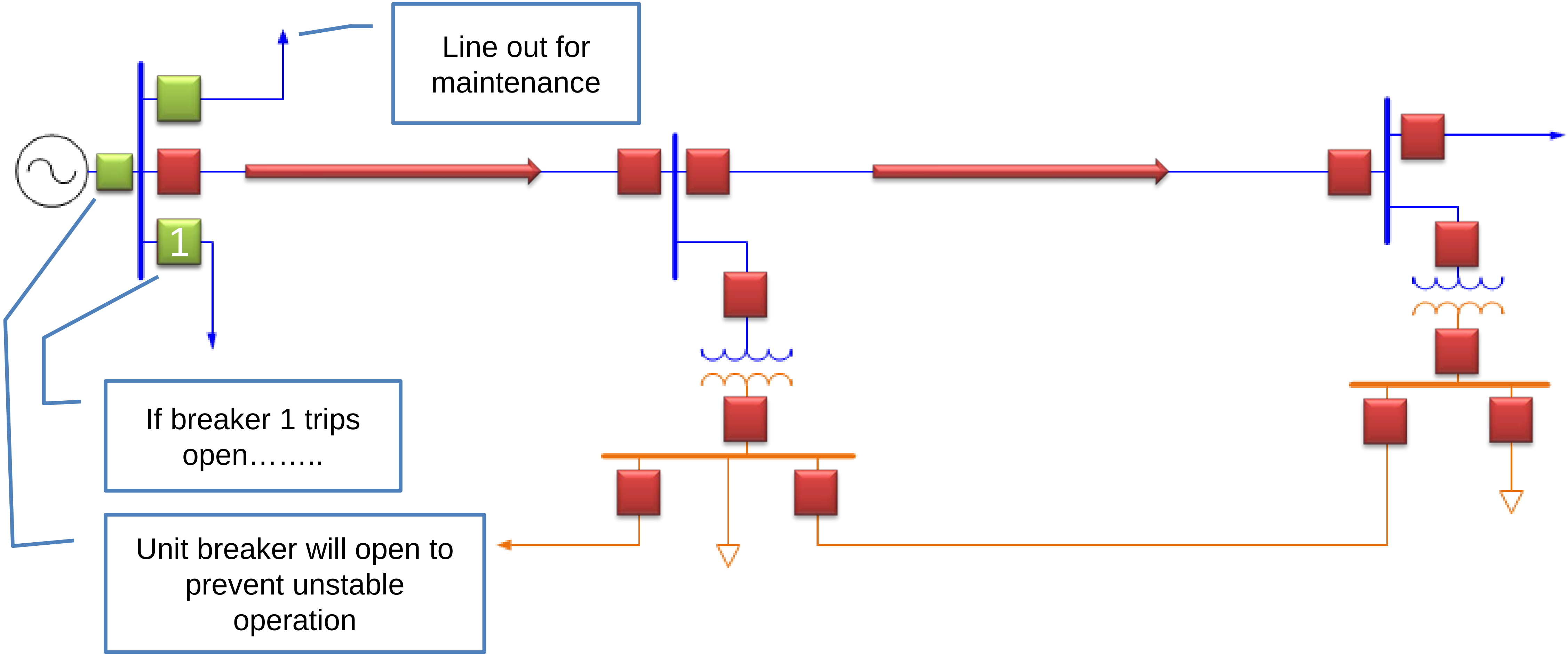
Generation Runback/Load Rejection

- Used to maintain system stability following loss of load events
  - Full Load Rejection (Generator Runback)
  - Partial Load Rejection
  - Fast Valving
- Most PJM generator runback schemes are Full Load Rejection

Generation Runback/Load Rejection

- Full Load Rejection
  - Main generator breakers trip
  - Loss of synchronization and full load
  - Steam generators runback from full load to no-load

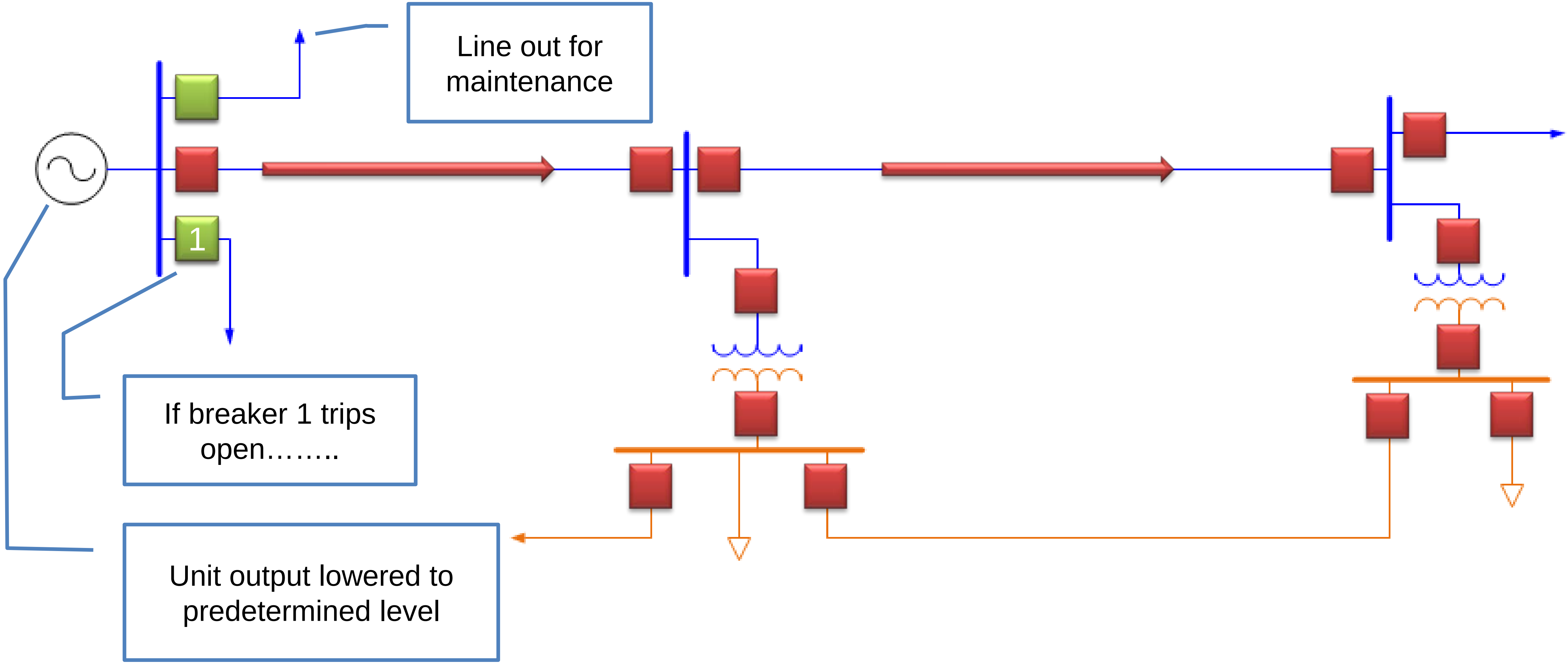
Generation Runback/Load Rejection



Generation Runback/Load Rejection

- Partial Load Rejection:
  - Main generator breakers remain closed
  - Loss of partial load (10% to 50%)

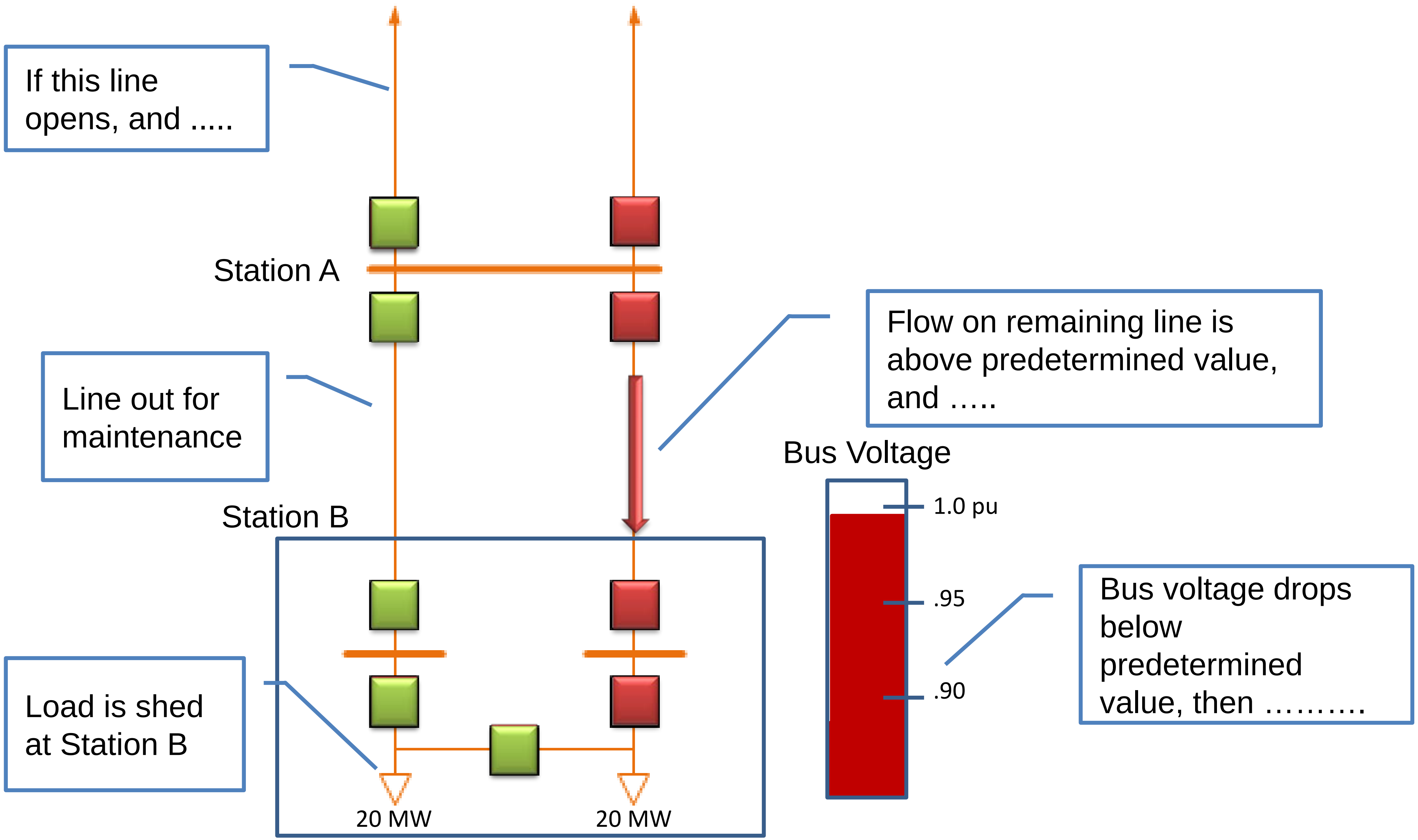
Generation Runback/Load Rejection



Load Shed Scheme

- Reduce system load for a given set of conditions

Load Shed Scheme



PJM RAS Actions

1. PJM will contact the TO to verify EMS results and direct the RAS to be Enabled
2. PJM will modify the contingency definition to simulate the N-1 condition in the EMS with the RAS activated
3. PJM will log the activation/deactivation of the RAS scheme that is a change from its "Normal" status
4. PJM will control all actual facility loadings below the Normal ratings and all contingency loadings below the Emergency rating

committee review unless required for reliability, operational performance, or to restore the system to the state existing prior to a significant transmission facility event, in which case the scheme will be implemented as soon as practicable. PJM will conduct an annual review of automatic sectionalizing schemes to ensure that the results of the initial qualifying analysis remain in effect. A list of accepted Automatic Sectionalizing Schemes is located in Attachment E.

Automatic Special Protection Scheme (SPS) Operating Criteria

Under normal operating conditions, PJM's EMS will perform an N-1 contingency analysis for the loss of each Bulk Electric System line and transformer within the PJM RTO. PJM will then control as indicated in **Manual M-03 Section 3: Thermal Operating Criteria**.

When PJM's EMS indicates that a simulated N-1 contingency will result in an overload on a facility that can be mitigated by a Special Protection Scheme (SPS) that has been documented in **PJM Manual M-03 Section 5: "Index and Operating Procedures for PJM RTO Operation"***, the following actions should be taken:

PJM Actions:

1.) PJM will contact the Transmission Owner based on EMS results and direct the SPS to be changed from its 'Normal Status' (enabled/disabled). PJM will also verify that the SPS is operational and that its status can be changed.

2.) Once the Transmission Owner has changed the SPS status, PJM will modify the contingency definition(s) to simulate the N-1 condition and the subsequent activation of the associated SPS within the PJM EMS System.

3.) PJM will log activation/deactivation for an SPS that is a change from its 'Normal Status'

4.) PJM will control all actual facility loadings below the normal ratings and all subsequent contingency loadings below the emergency limits as indicated in **PJM Manual M-03, Section 3: Thermal Operating Criteria.**

TO Actions:

Upon PJM's direction, for any SPS involving a transmission line, the TO will change the SPS from its 'Normal Status' (enable/disable)

The TO will not place the SPS back in its 'Normal Status' until PJM has directed to do so.

GO Actions:

Upon PJM' direction, for any SPS involving a generating unit, the GO will change the SPS from its 'Normal Status' (enable/disable)

The GO will not place the SPS back in its 'Normal Status' until PJM has directed to do so.

Note: PJM does not receive telemetered status of all SPS schemes (with the exception of Bath County and a few others). Unless a change in status is directed by PJM, the PJM TO and GO notify PJM of any change in status from 'Normal Status' (enabled/disabled). PJM logs all such changes and modifies contingency definitions within the PJM EMS to reflect such changes.

PJM TO/GO RAS Actions

1. TO/GO will change the RAS status upon PJM's direction

2. TO/GO will not change the RAS status back to "Normal" unless directed to do so by PJM

3. TO/GO must report any condition that would prevent the use of the RAS or cause the RAS to become inoperable

pjm

Manual 3: Transmission Operations
Section 5: Index and Operating Procedures for PJM RTO Operation

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When PJM's EMS indicates that a simulated N-1 contingency will result in an overload on a facility that can be mitigated by a Special Protection Scheme (SPS) that has been documented in **PJM Manual M-03 Section 5: "Index and Operating Procedures for PJM RTO Operation"***, the following actions should be taken:

PJM Actions:

1.) PJM will contact the Transmission Owner based on EMS results and direct the SPS to be changed from its 'Normal Status' (enabled/disabled). PJM will also verify that the SPS is operational and that its status can be changed.

2.) Once the Transmission Owner has changed the SPS status, PJM will modify the contingency definition(s) to simulate the N-1 condition and the subsequent activation of the associated SPS within the PJM EMS System.

3.) PJM will log activation/deactivation for an SPS that is a change from its 'Normal Status'

4.) PJM will control all actual facility loadings below the normal ratings and all subsequent contingency loadings below the emergency limits as indicated in **PJM Manual M-03, Section 3: Thermal Operating Criteria.**

TO Actions:

Upon PJM's direction, for any SPS involving a transmission line, the TO will change the SPS from its 'Normal Status' (enable/disable)

The TO will not place the SPS back in its 'Normal Status' until PJM has directed to do so.

GO Actions:

Upon PJM' direction, for any SPS involving a generating unit, the GO will change the SPS from its 'Normal Status' (enable/disable)

The GO will not place the SPS back in its 'Normal Status' until PJM has directed to do so.

Note: PJM does not receive telemetered status of all SPS schemes (with the exception of Bath County and a few others). Unless a change in status is directed by PJM, the PJM TO and GO notify PJM of any change in status from 'Normal Status' (enabled/disabled). PJM logs all such changes and modifies contingency definitions within the PJM EMS to reflect such changes.

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RAS Exercises/Review

Relay Testing - Considerations and Concerns

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 Company's 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 and notifications

Data Collection and Fault Analysis

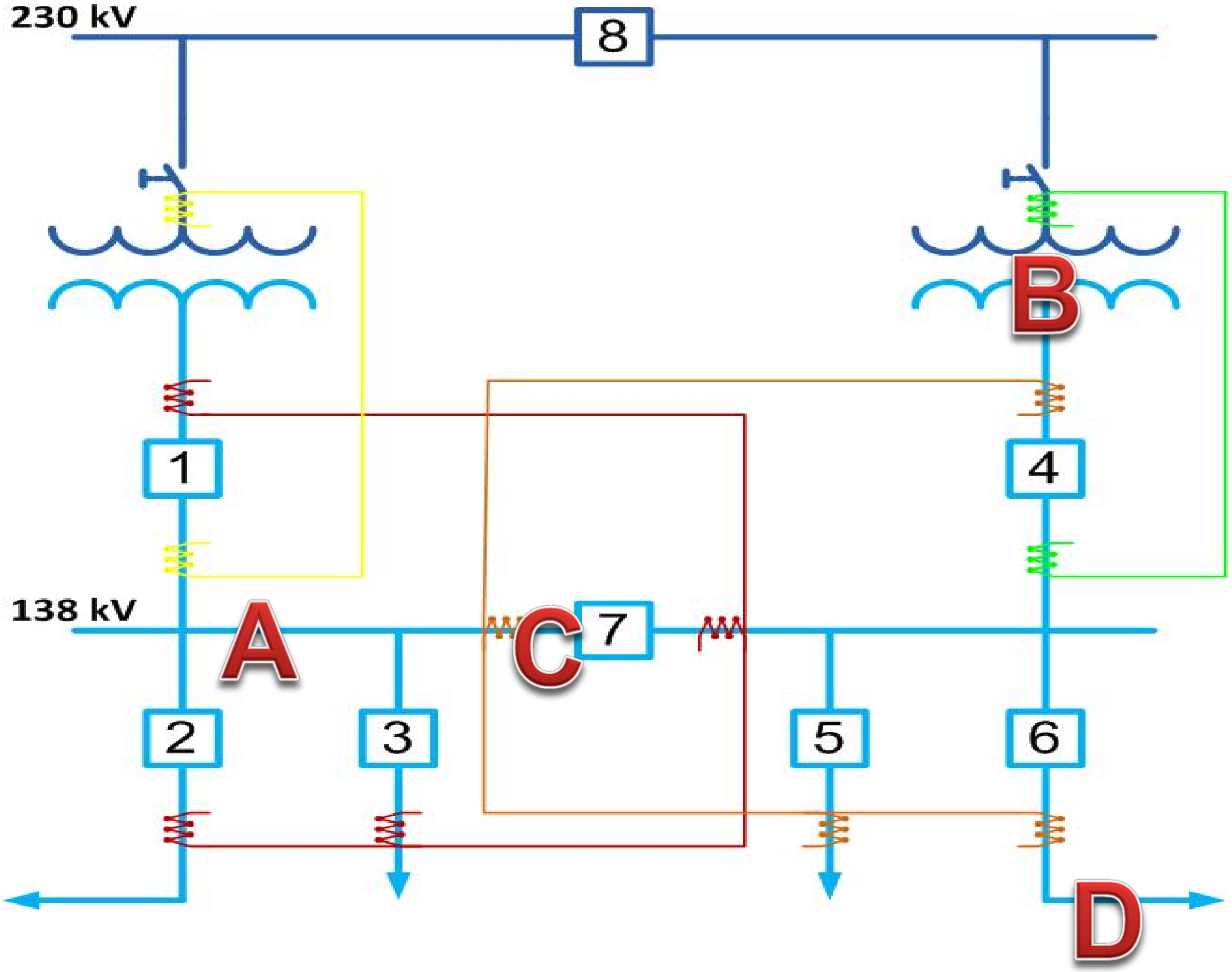
- Try to obtain as much data as possible for future detailed analysis (i.e. relay targets, Digital fault recorder information, system conditions)
- Real time analysis comes with experience
- Often knowing what has tripped may lead to a determination of the faulted piece of equipment or potential relay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

(See examples)

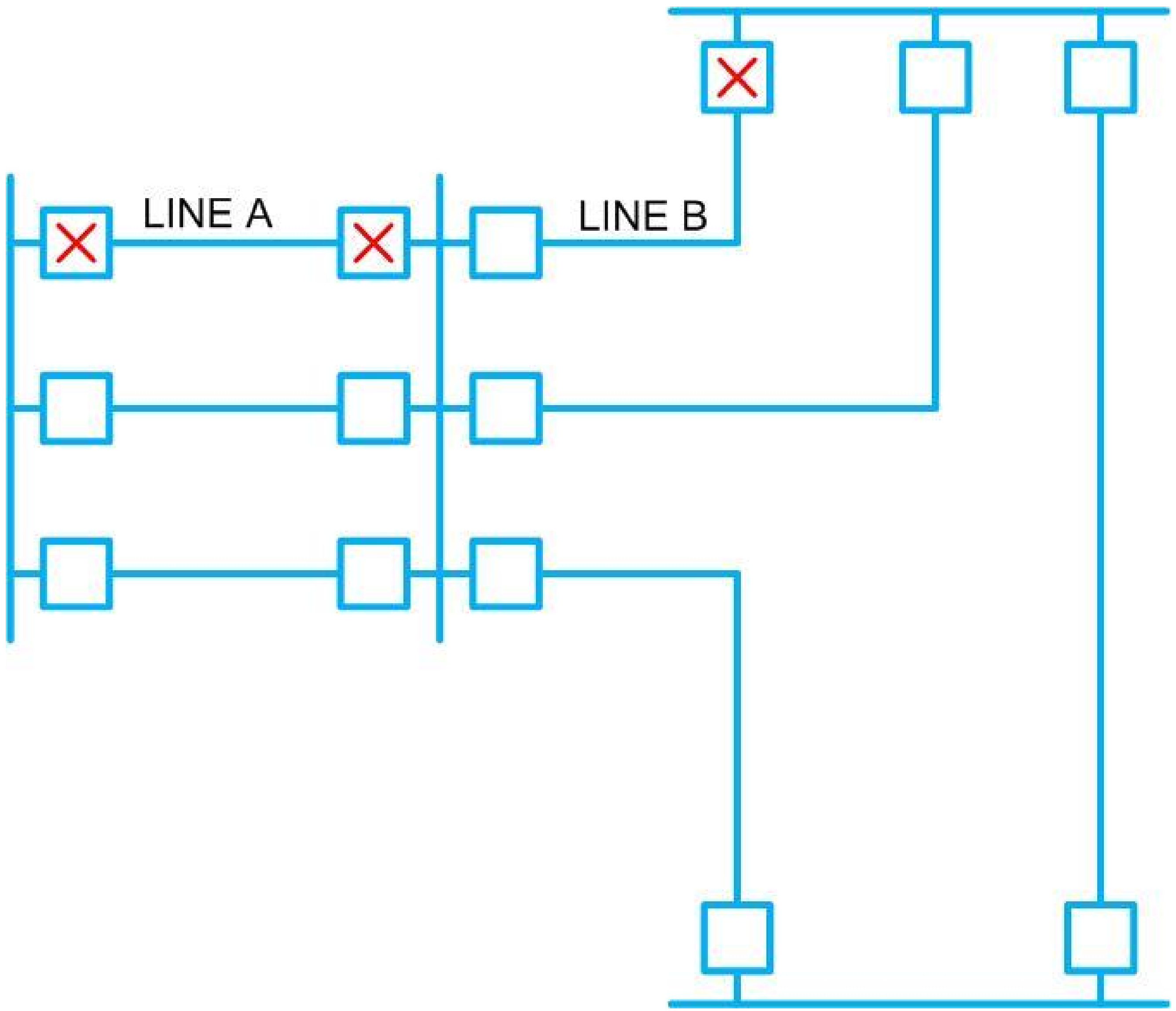
Fault Analysis

Breakers 1 thru 7 trip open

Where is the likely fault location?



Fault Analysis



Summary

- Described the purpose of protective relays
- Identified relay protection scheme characteristics/components and the impact the loss of those components has on protection
- Identified the types of transmission line, transformer, bus and generator protection schemes and their characteristics
- Defined Remedial Action Scheme (RAS)
- Identified several types of special protection schemes used within the PJM RTO

Questions?

PJM Client Management & Services

Telephone: (610) 666-8980

Toll Free Telephone: (866) 400-8980

Website: www.pjm.com

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

Resources and References

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

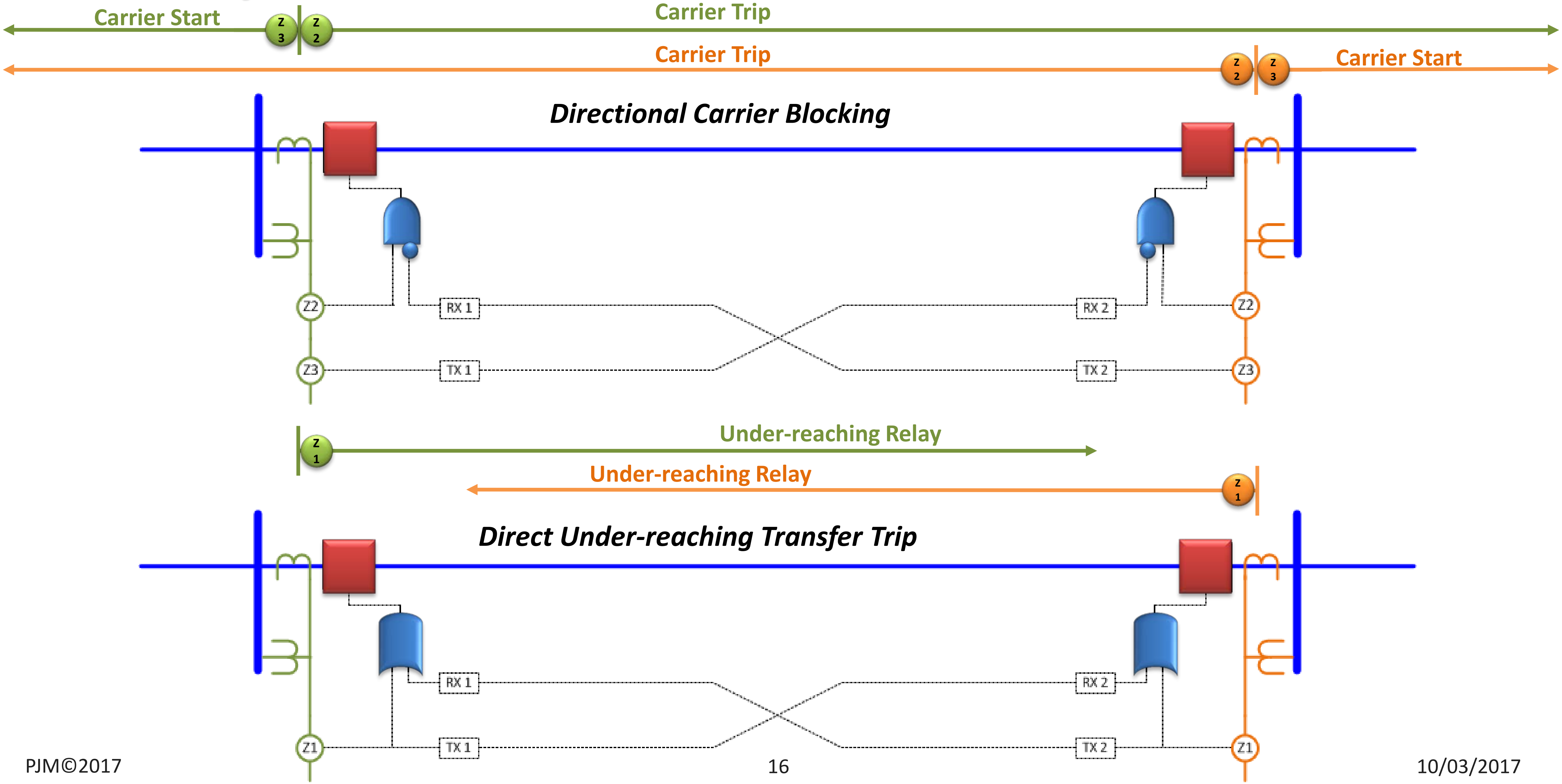
Appendix

Summary of Line Protection Schemes

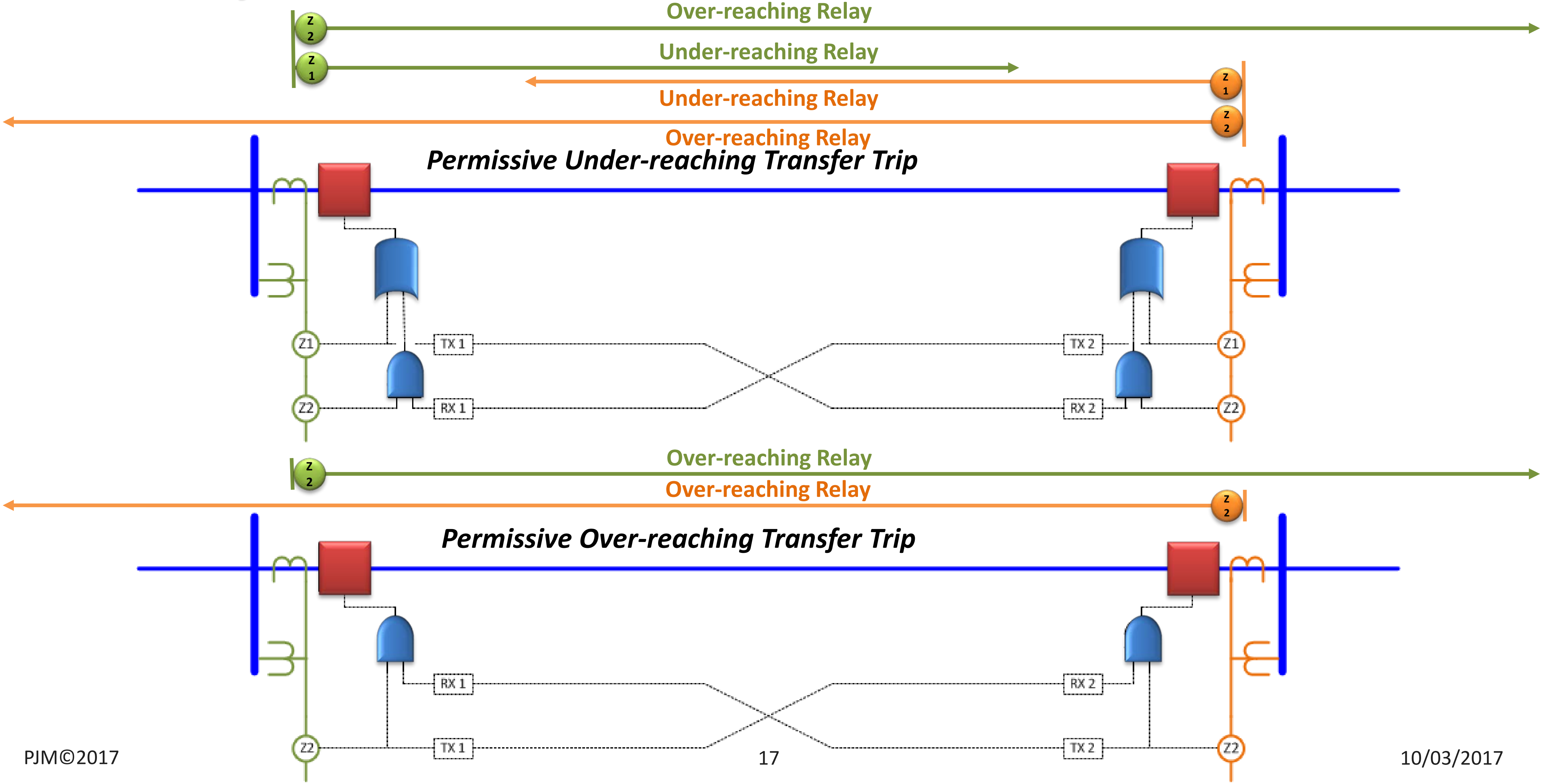
Summary of Line Protection Schemes

Scheme	Will initiate trip when . . .
Directional Carrier Blocking	Local Over-reaching relay operates ***AND*** there is an absence of a **BLOCKING** signal from the remote end
Direct Under-reaching Transfer Trip	Local under-reaching relay operates ***OR*** **TRIP** signal is received from the remote end
Permissive Under-reaching Transfer Trip	Local Under-reaching relay operates ***OR*** Local Overreaching relay operates ***AND*** a **TRIP** signal is received from remote end
Permissive Over-reaching Transfer Trip	Local Over-reaching relay operates ***AND*** a **TRIP** signal is received from the remote end
Phase Comparison	Both the **LOCAL TERMINAL** and the **REMOTE TERMINAL** see fault current flowing ***INTO*** the line and **BLOCKING CARRIER** signal is out-of-phase with the **TRIP** signal
AC Pilot Wire	The current flow induced in the operating coil is less than the current induced in the restraint coil
Line Differential	The sum of the local and remote line currents seen by each relay is a non-zero result

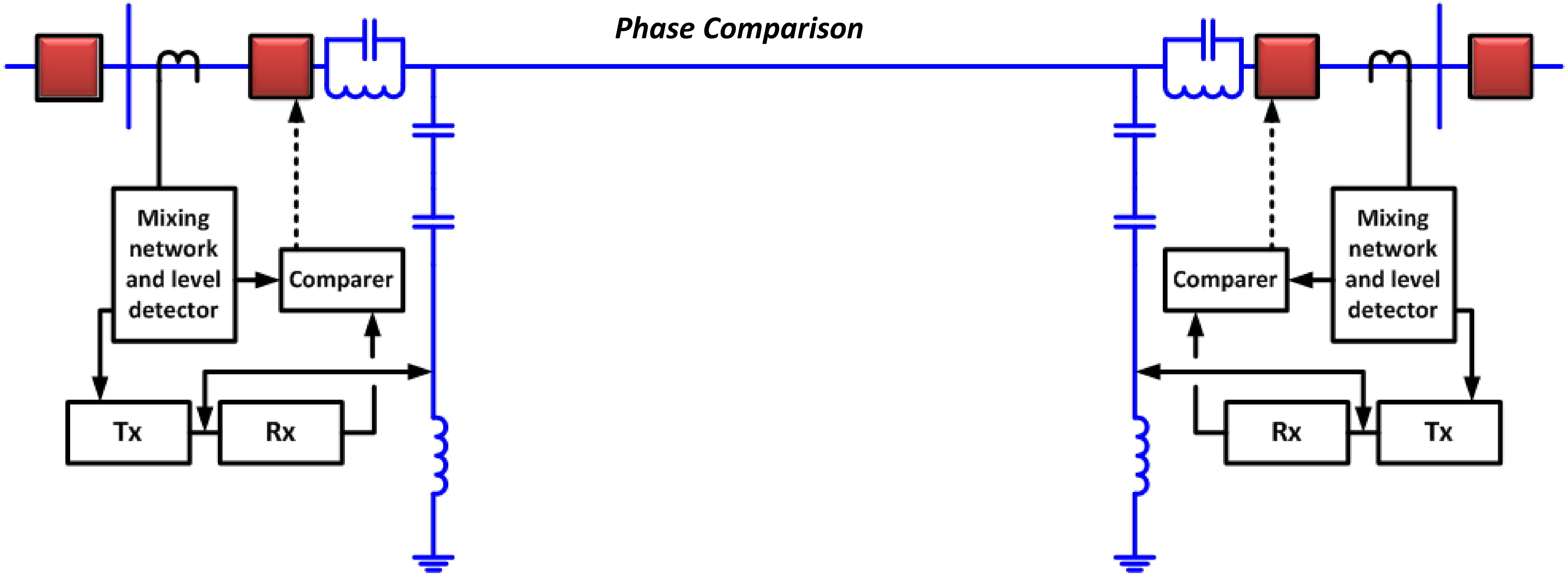
Summary of Line Protection Schemes



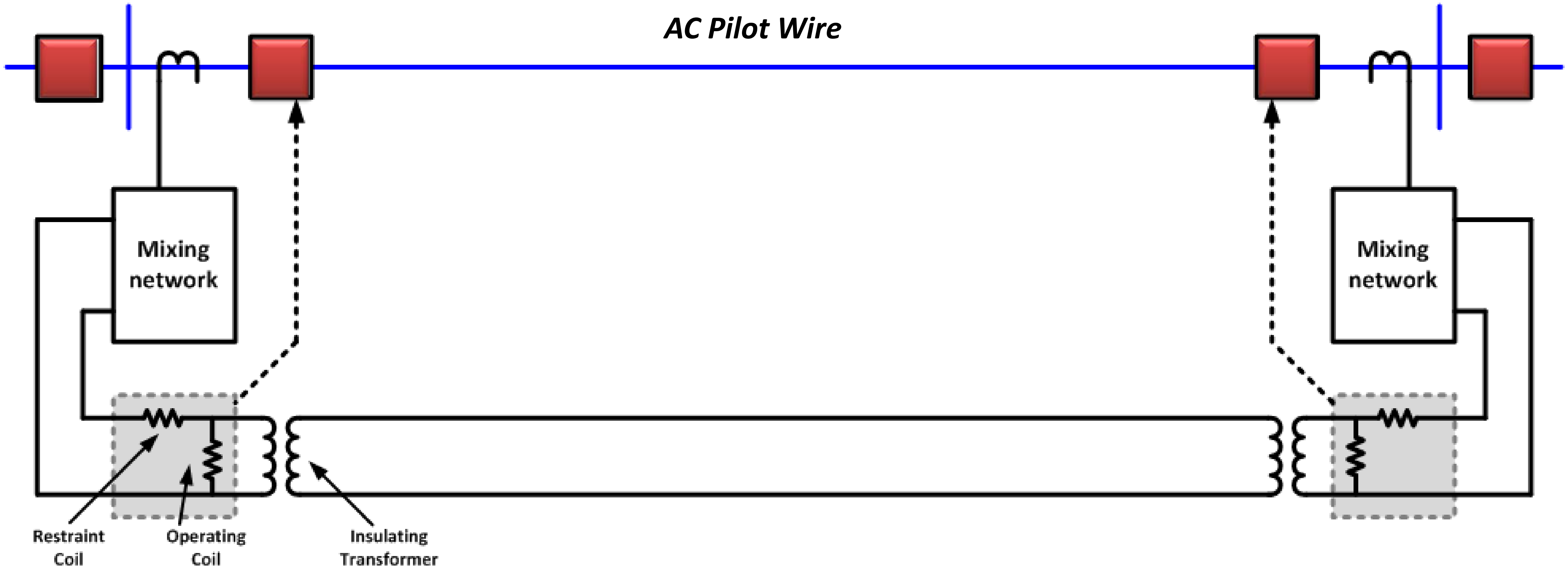
Summary of Line Protection Schemes



Summary of Line Protection Schemes



Summary of Line Protection Schemes



Summary of Line Protection Schemes

Line Differential