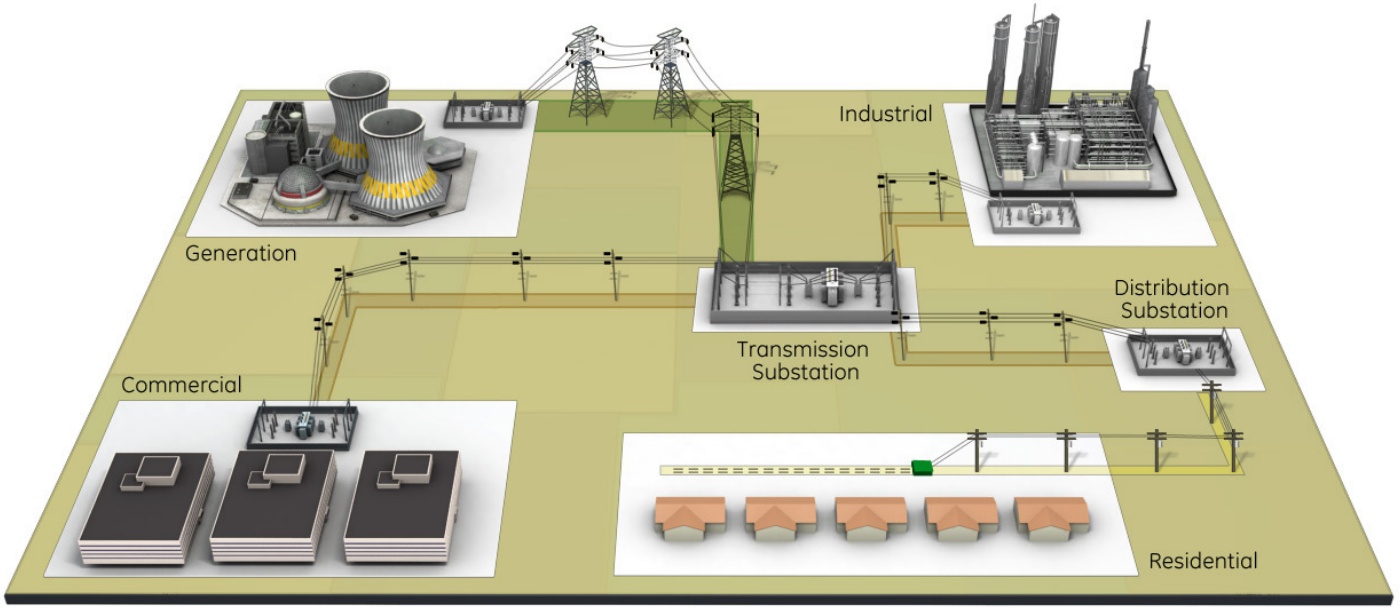
Transmission Line Protection

Transmission Line Fundamentals:

Characteristics of Lines:

- A “line” is a circuit used to transmit power
- Lines are supported by insulators, which are connected to structures
    - structures, which can be made of wood, metal or concrete keep the lines above the ground.
- Electrical properties of the line are affected by material of the structure, the physical arrangement of the components, and the geography plus location of the conductors and towers.

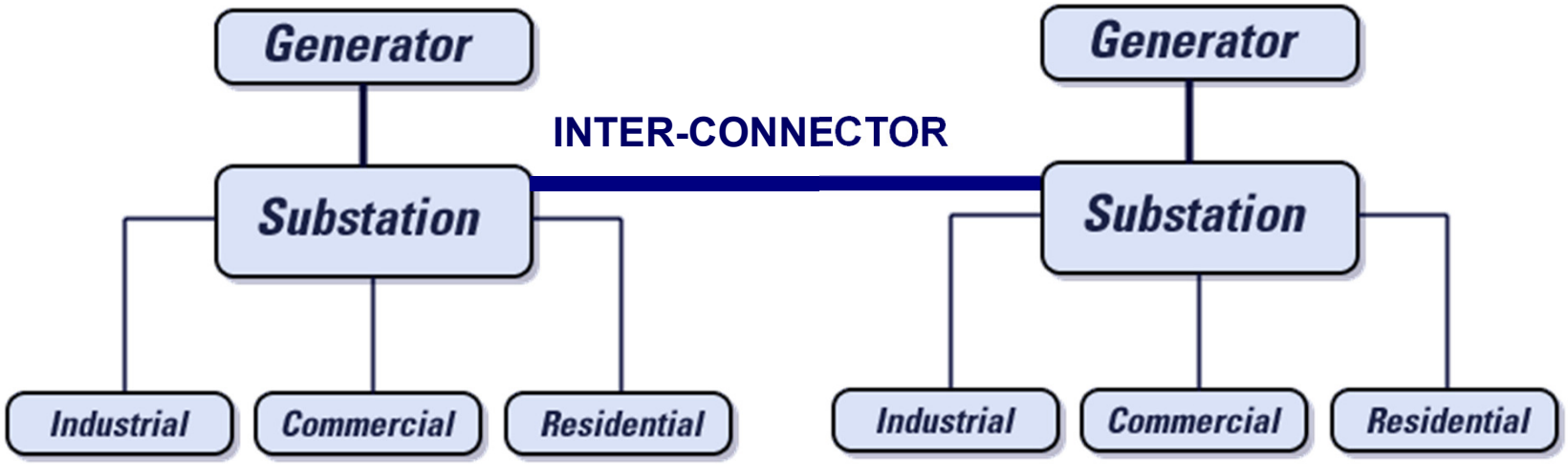
Transmission Line Fundamentals – Line Classification:



Terminal:

- physical location of a line boundary
- switch, breaker, bus or transformer defines the end of a transmission line

Transmission Line Fundamentals – Line Classification:



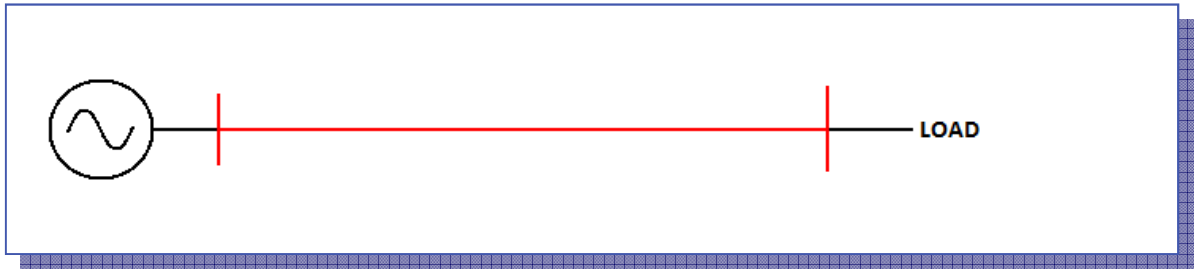
Transmission Line Classifications to describe the configuration, function and location in the system:

- Parallel Lines
- Inter-connector Lines
- Generator Export Lines
- Process Plant Load Lines

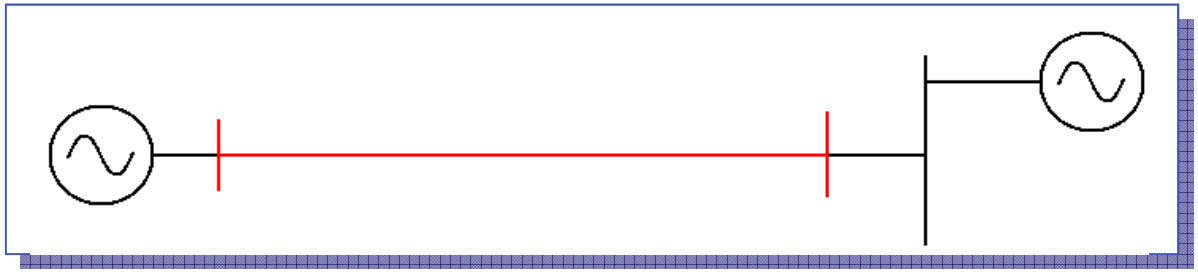
Transmission Line Fundamentals – Line Classification:

SINGLE-FEED

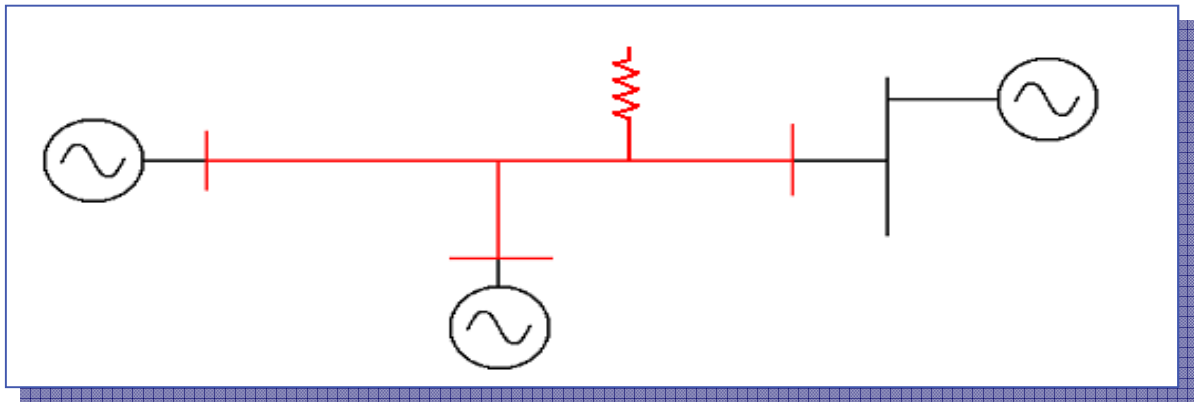
(Radial Line)



DOUBLE-ENDED



MULTI-ENDED



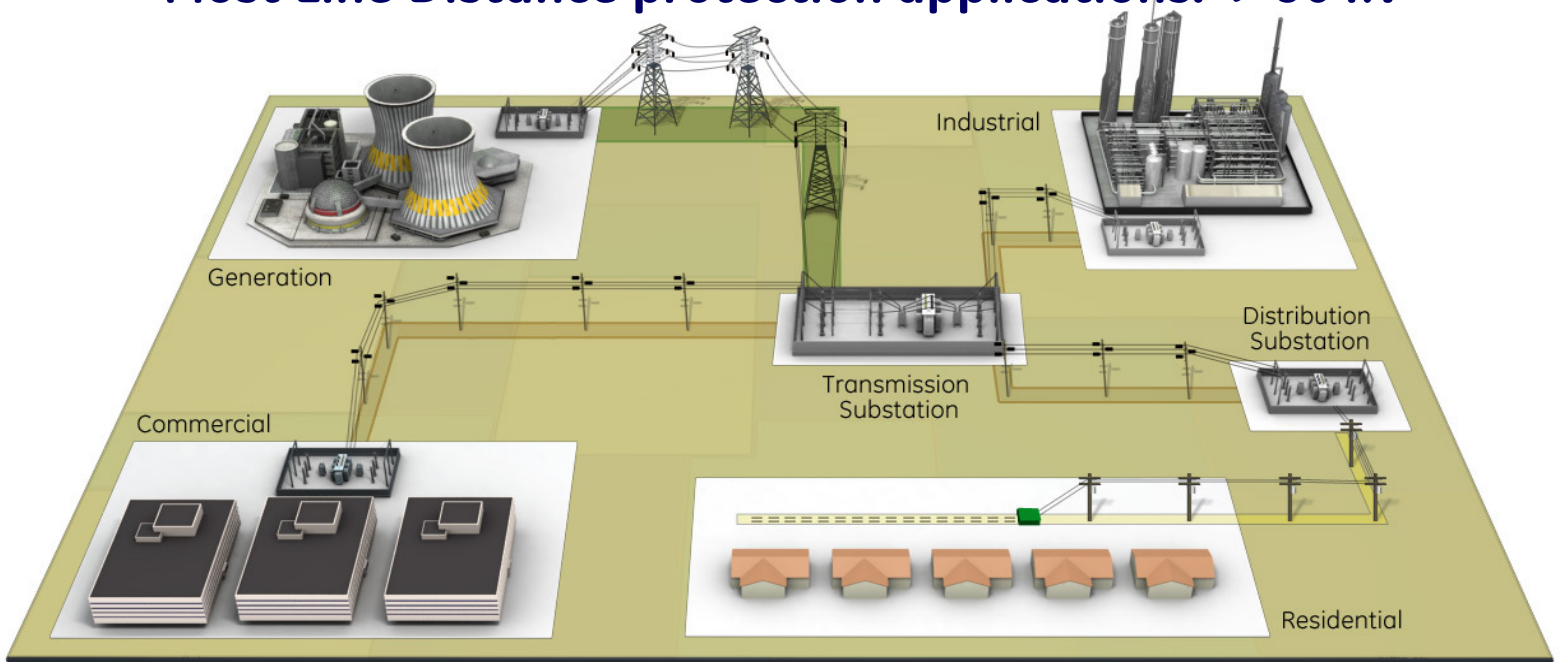
Transmission Line Fundamentals – Line Voltage Classification:

Distribution: **~ 2kV - 50 kV**

Sub-transmission: **~ 30 - 150 kV**

Transmission: **~ >100kV**

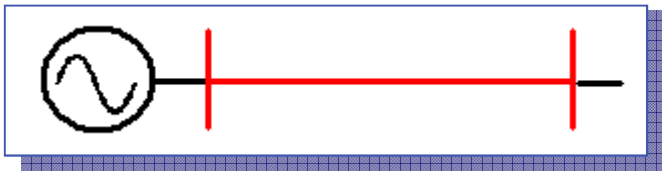
Most Line Distance protection applications: > 50 kV



Transmission Line Fundamentals – Line Classification by Length:

SHORT LINES

< 80 km (SIR > 4)

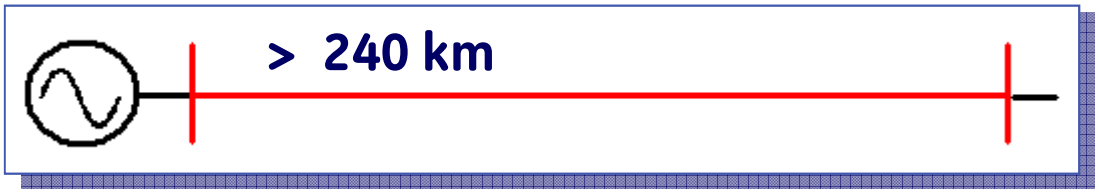


MEDIUM LINES

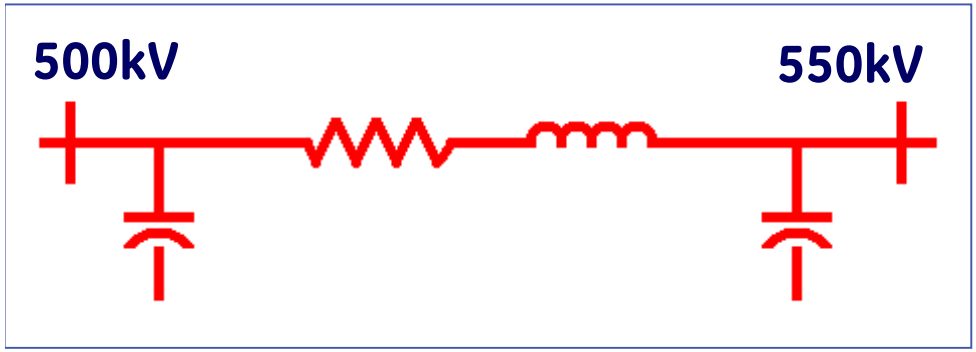
80 km – 240 km (0.5 > SIR < 4)

LONG LINES

> 240 km (SIR < 0.5)

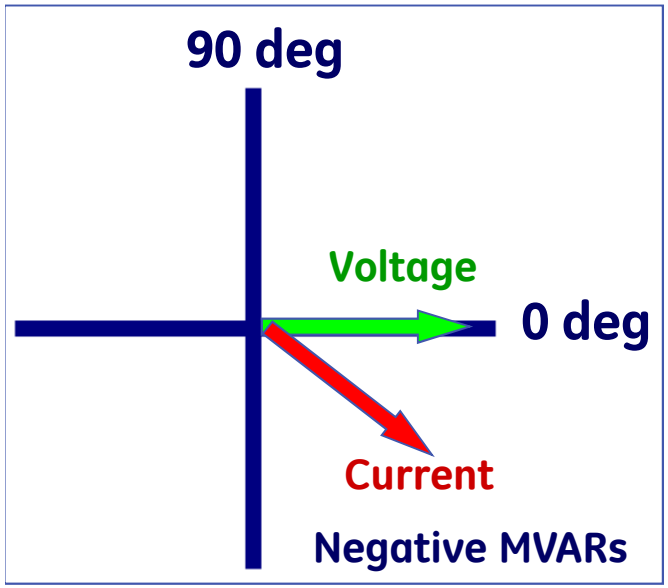


Transmission Line Fundamentals – Shunt Capacitance:

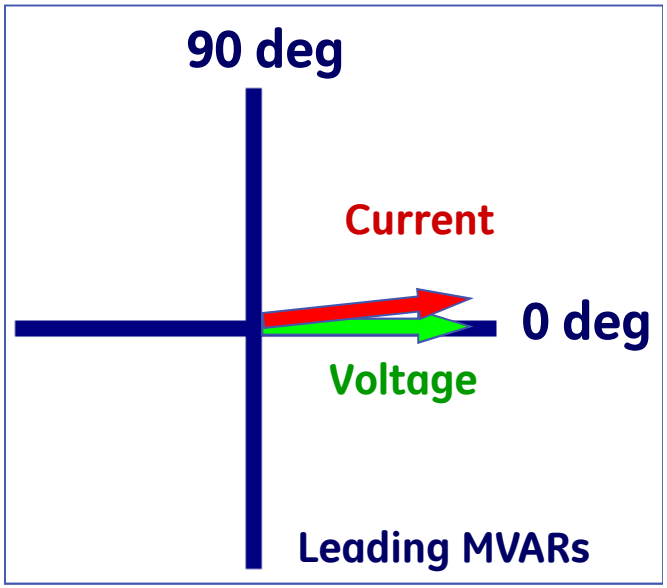


Typical 3-Phase MVAR values:

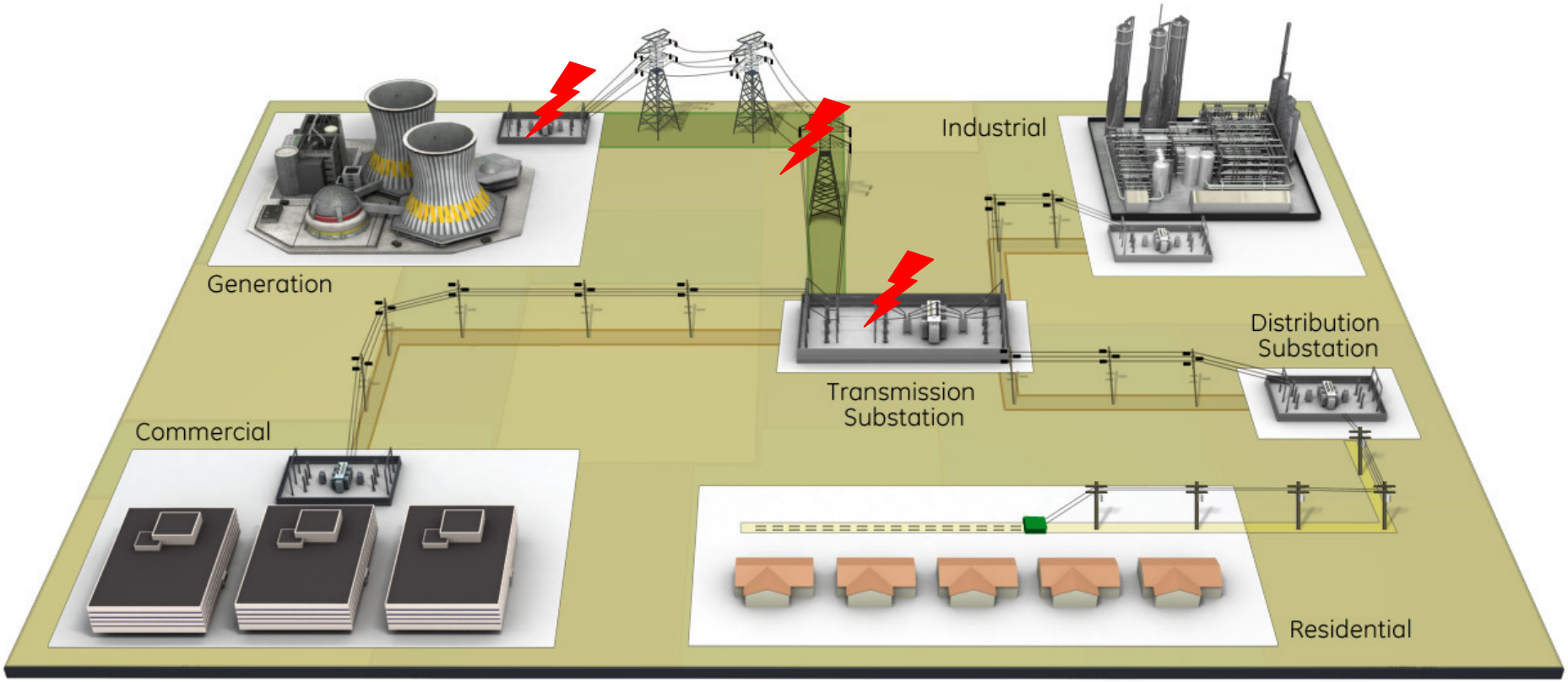
- 500kV lines 1.3 to 1.5 MVAR per km
- 230kV lines 0.15 to 0.4 MVAR per km



Capacitance adds leading MVARs on the line to bring current and voltage back to unity power factor.



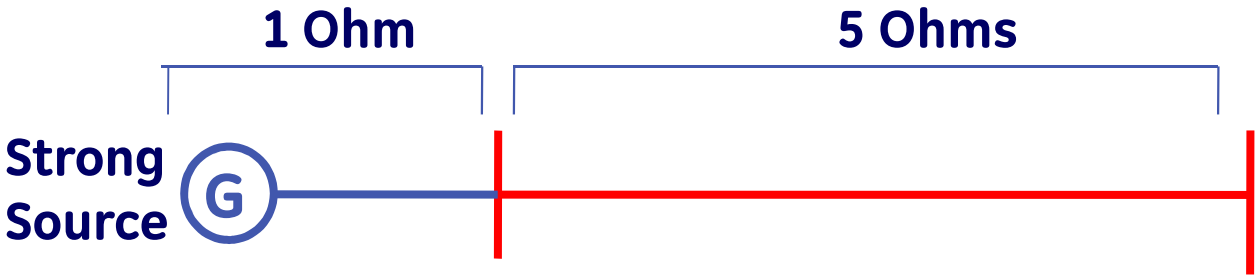
Transmission Line Fundamentals – Fault Protection:



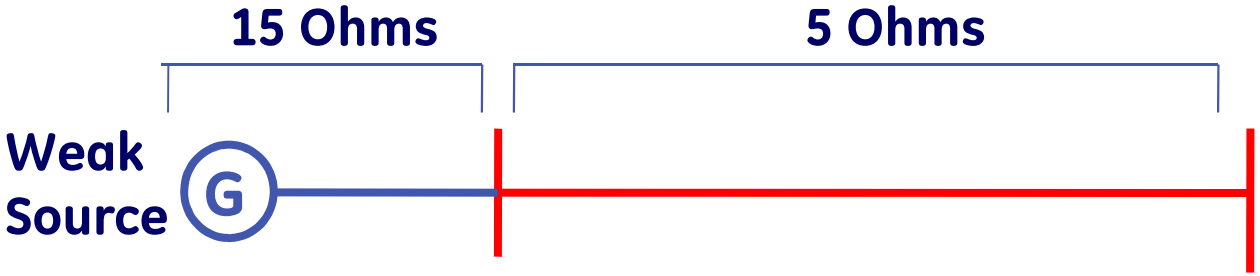
Transmission Line Fundamentals – Fault Protection:

Source to Line Impedance Ratio (SIR):

SIR = Source Impedance / Line Impedance



SIR = 1 Ohm / 5 Ohms = 0.2



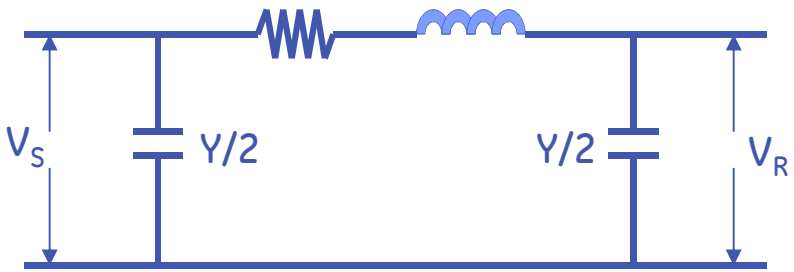
SIR = 15 Ohms / 5 Ohms = 3

Transmission Line Fundamentals – Fault Protection:

Computer-aided Software:

Equivalent Line Model:

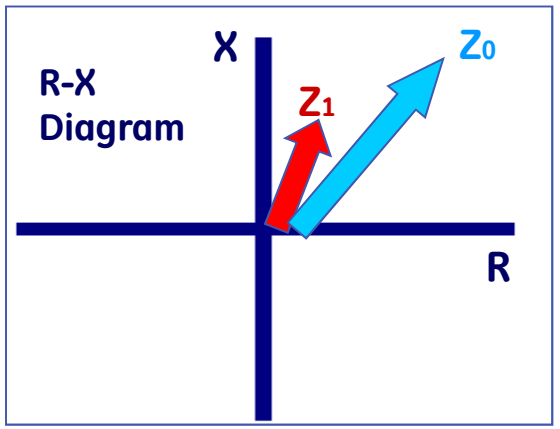
e.g. π-model for Medium Lines



Transmission Line Categories:

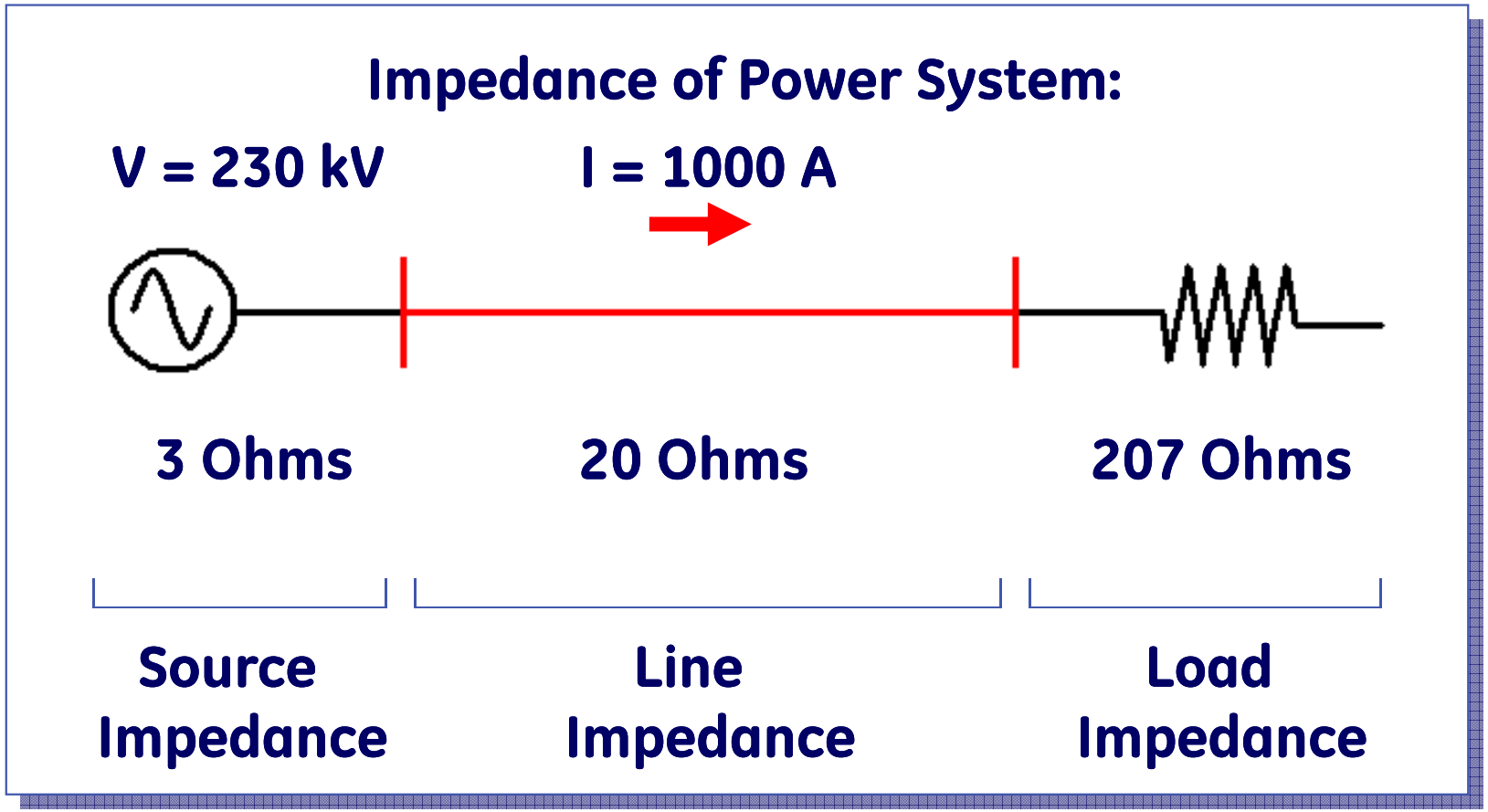
- **Short Lines**
- **Medium Lines**
- **Long Lines**

Sequence Components:



Positive and Zero Sequence Impedances

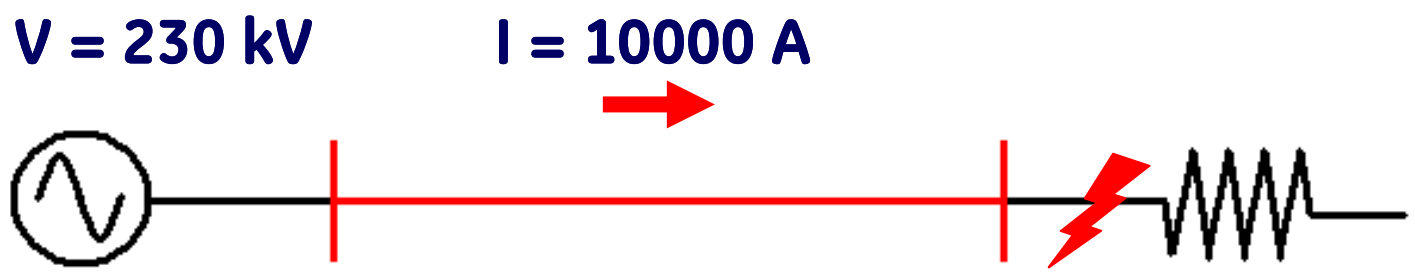
Distance Protection:



Z_{Total} = 3 Ohms + 20 Ohms + 207 Ohms = 230 Ohms

Distance Protection:

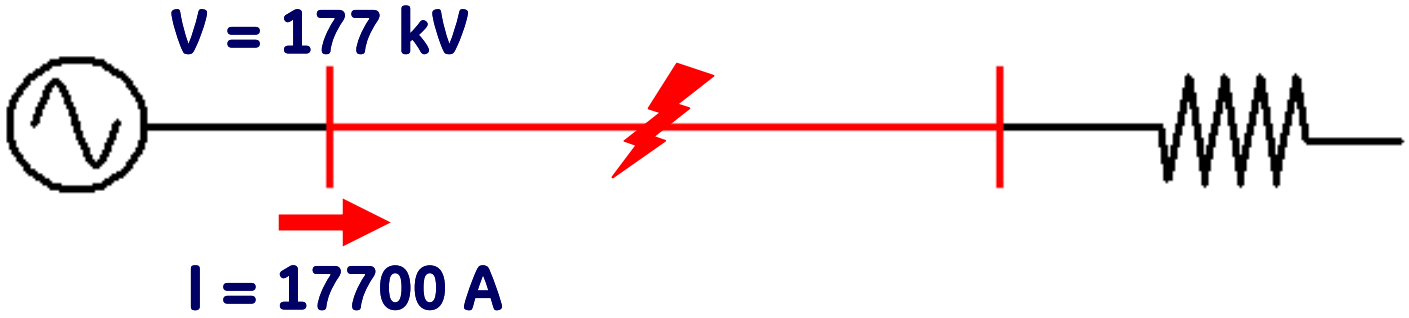
Impedance of Power System with Fault:



$$Z_{Total} = 3 \text{ Ohms} + 20 \text{ Ohms} = 23 \text{ Ohms}$$

Distance Protection:

Fault Distance calculated based on the Ratio of Impedance of Fault to Transmission Line

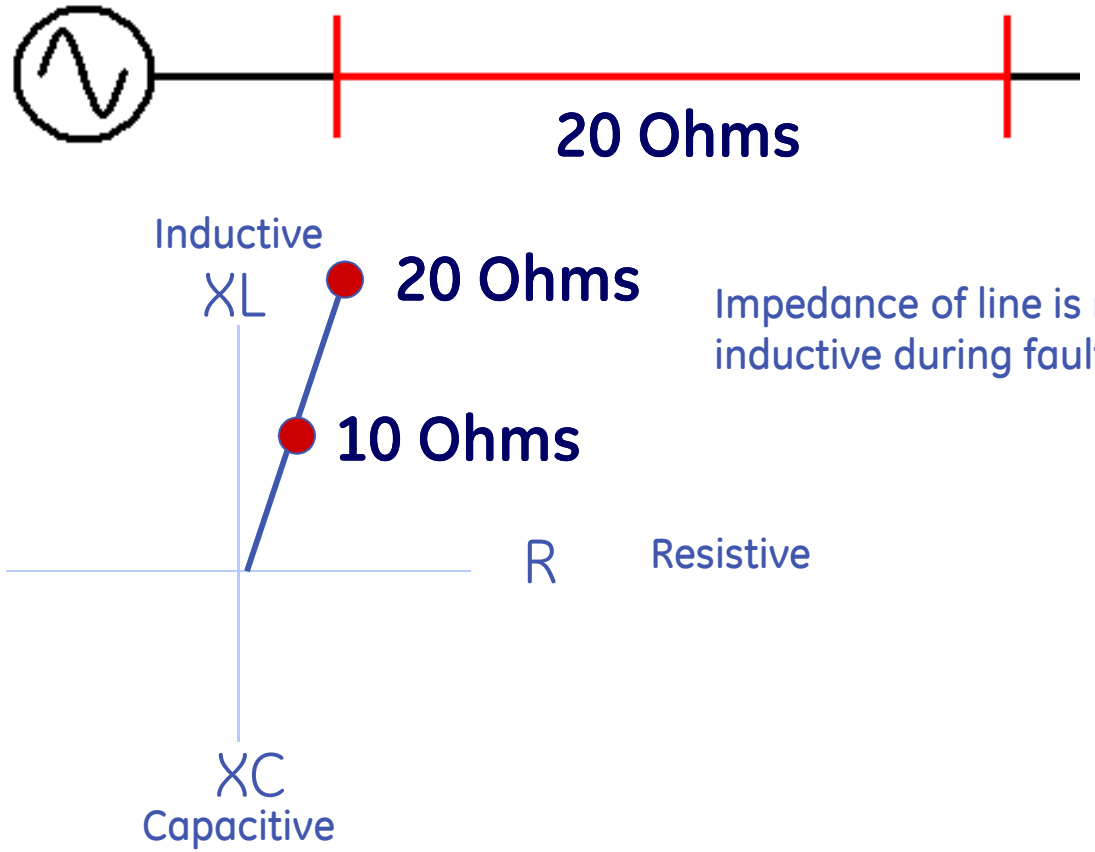


$$Z_{Fault} = \frac{V}{I} = \frac{177\ kV}{17.7\ kA} = 10\ Ohms$$

$$\frac{Z_{Fault}}{Z_{TL}} X\ 100\% = \frac{10\ Ohms}{20\ Ohms} X\ 100\% = 50\%$$

Distance Protection:

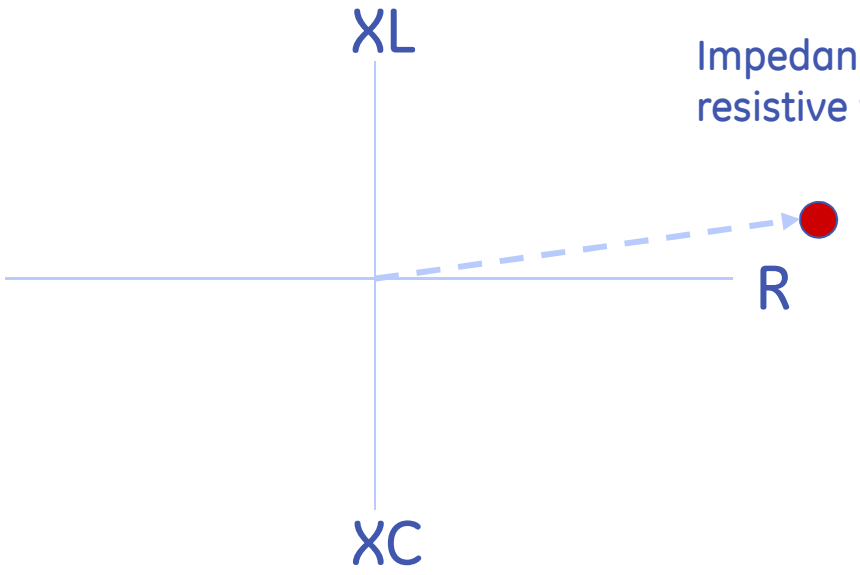
Impedance of Transmission Line on R-X Diagram:



Impedance of line is mostly inductive during fault.

Distance Protection:

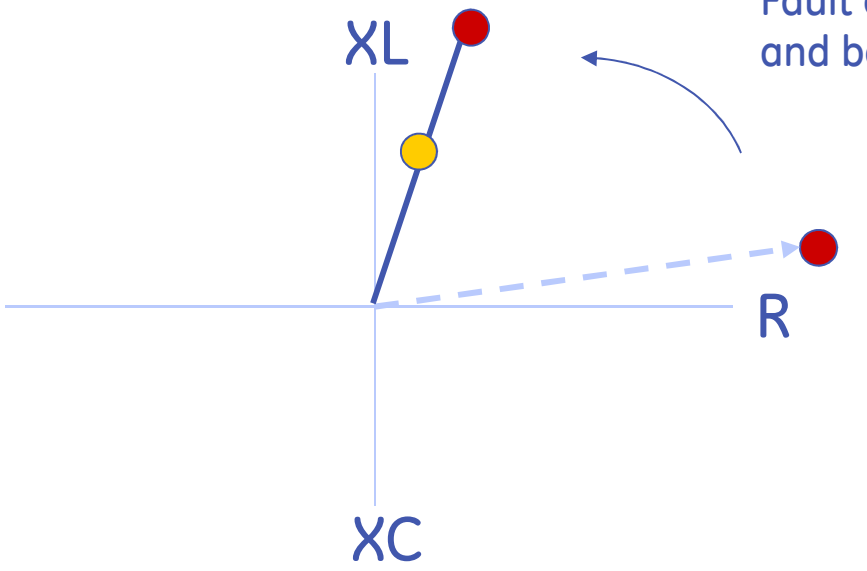
Impedance of Transmission Line on R-X Diagram:



Impedance of line is mostly resistive with load.

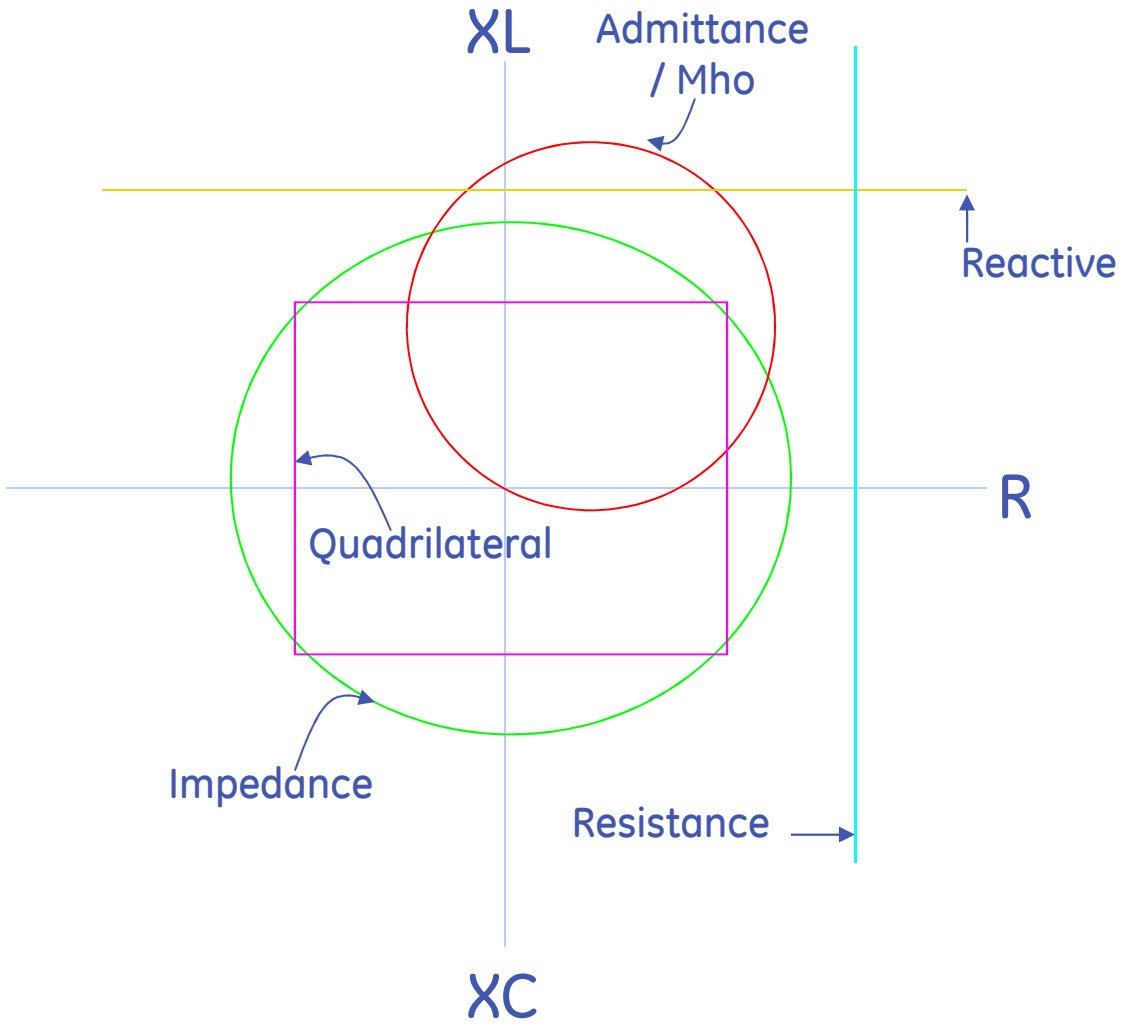
Distance Protection:

Impedance of Transmission Line on R-X Diagram:

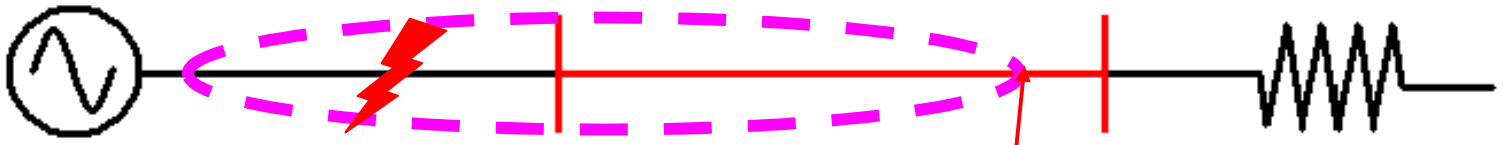


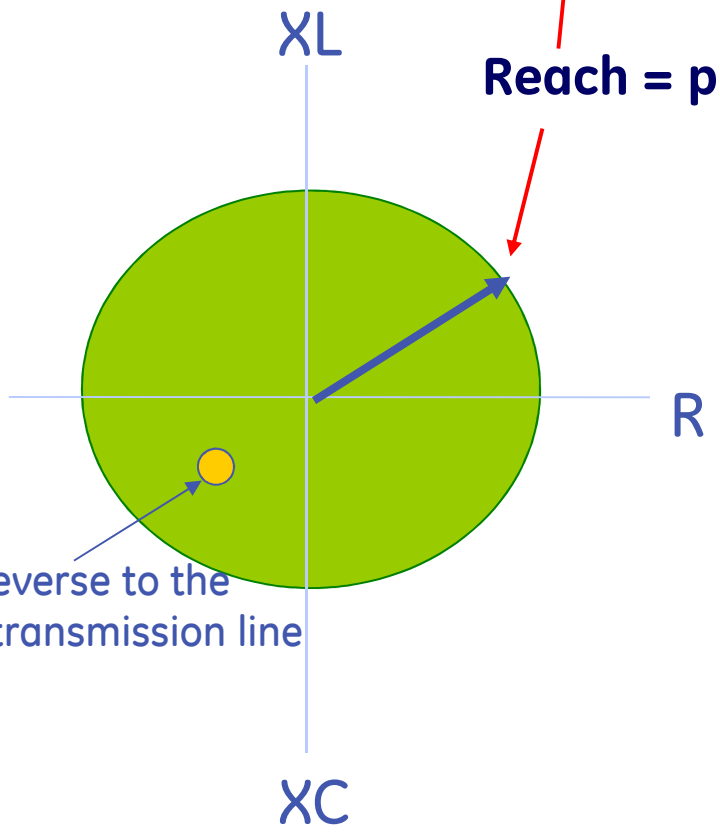
Fault on line causes the loss of load and becomes highly inductive.

Distance Zones Characteristics:



Zones of Protection – Impedance Characteristics





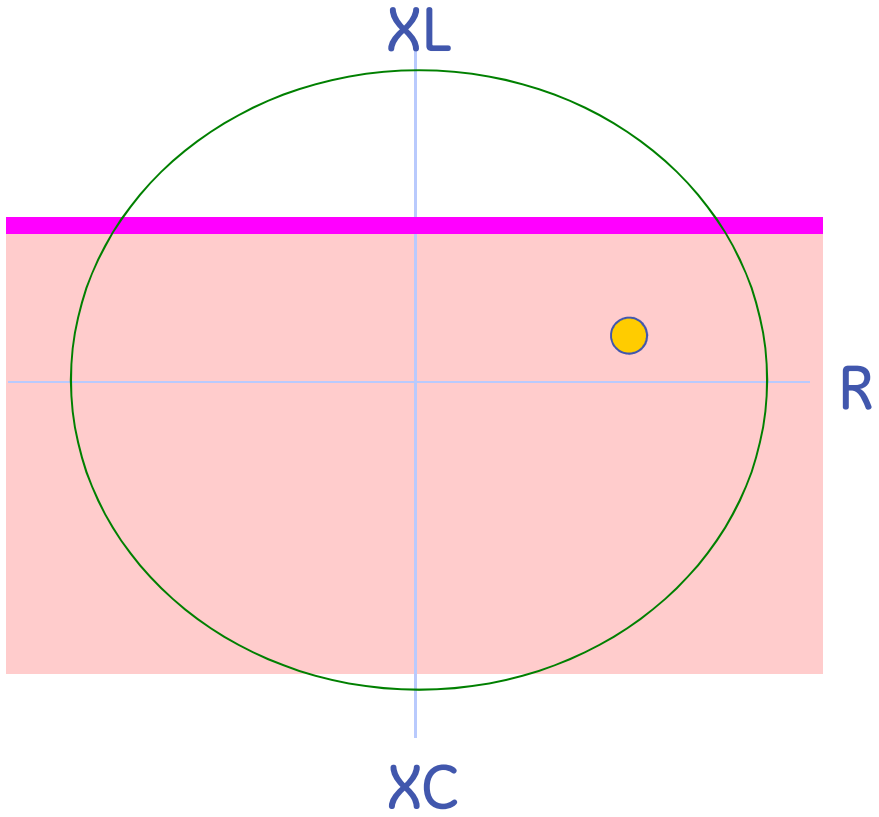
Impedance Characteristics:

- **non-directional**
- **generator backup protection**

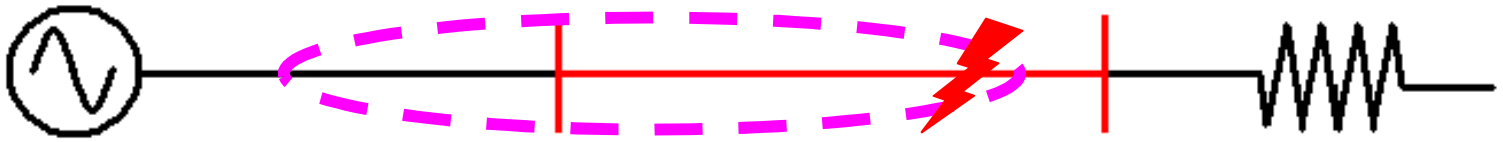
Zones of Protection – Reactance Characteristics :

Reactance Characteristics:

- **fault is highly resistive**
- **supervise another distance zone of protection**

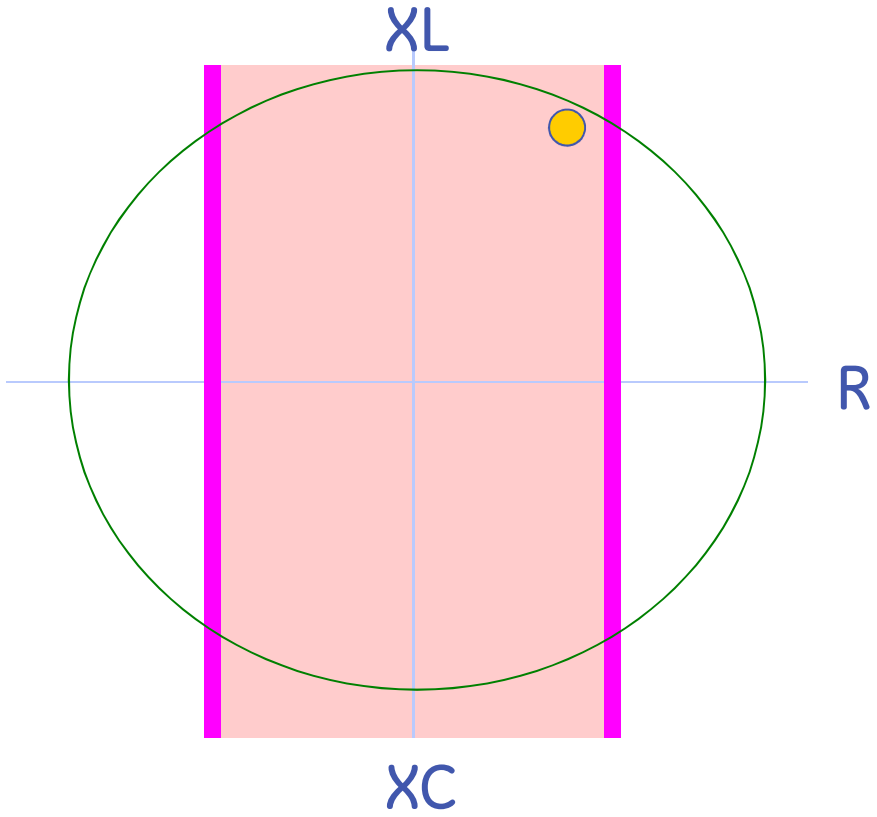


Zones of Protection – Resistance Characteristics:

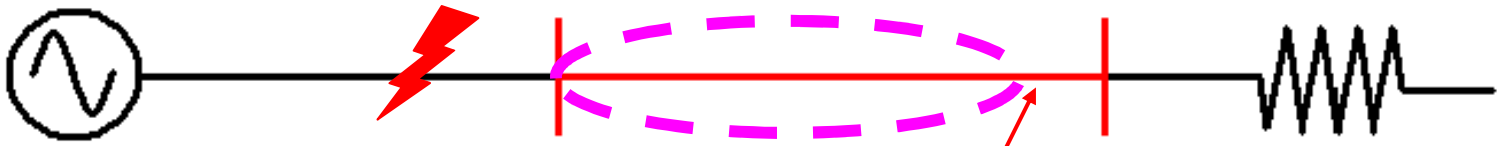


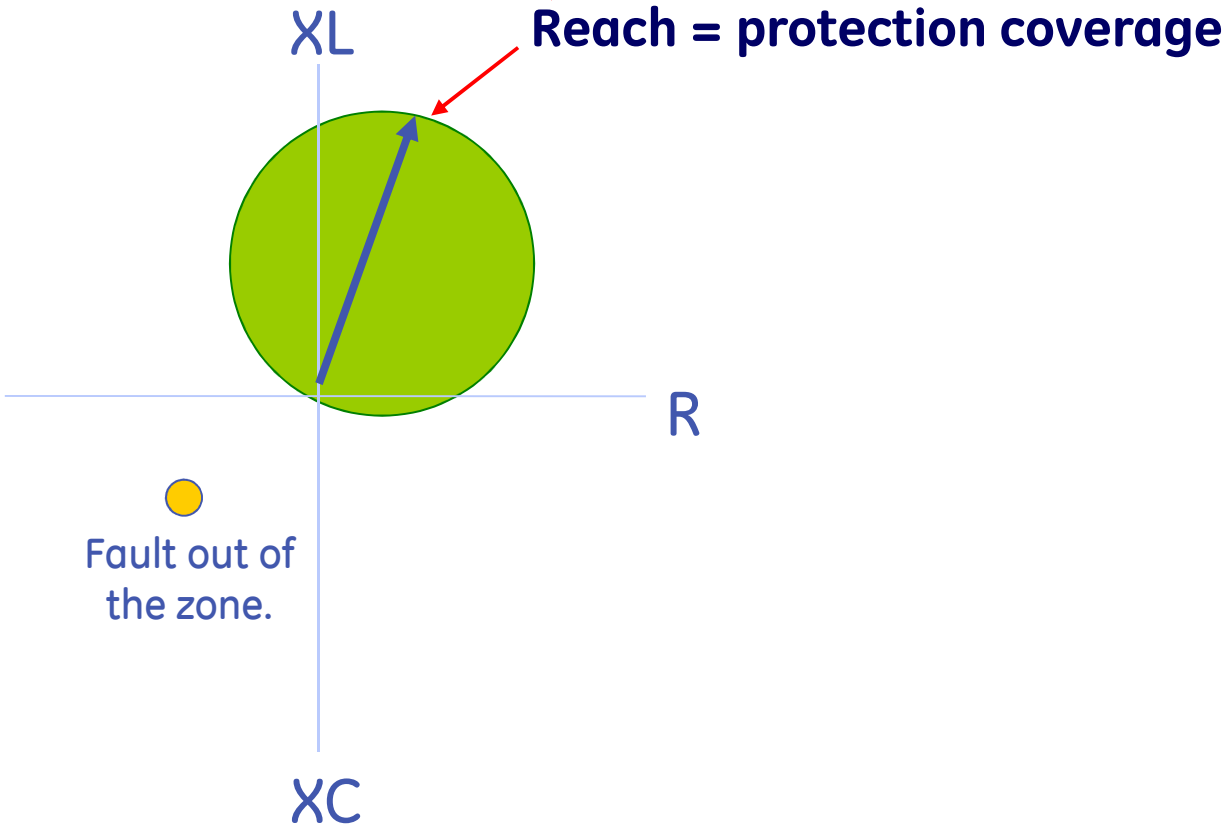
Resistance Characteristics:

- **fault is highly inductive**
- **supervise another distance zone of protection**



Zones of Protection – Admittance / Mho Circle:



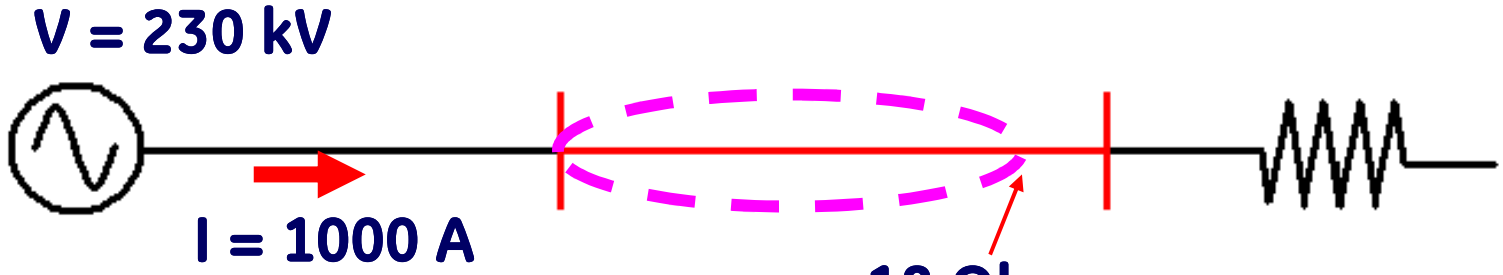


Admittance / Mho Characteristics:

- **directional**
- **most common transmission line distance protection**

Zones of Protection – Admittance / Mho Circle:

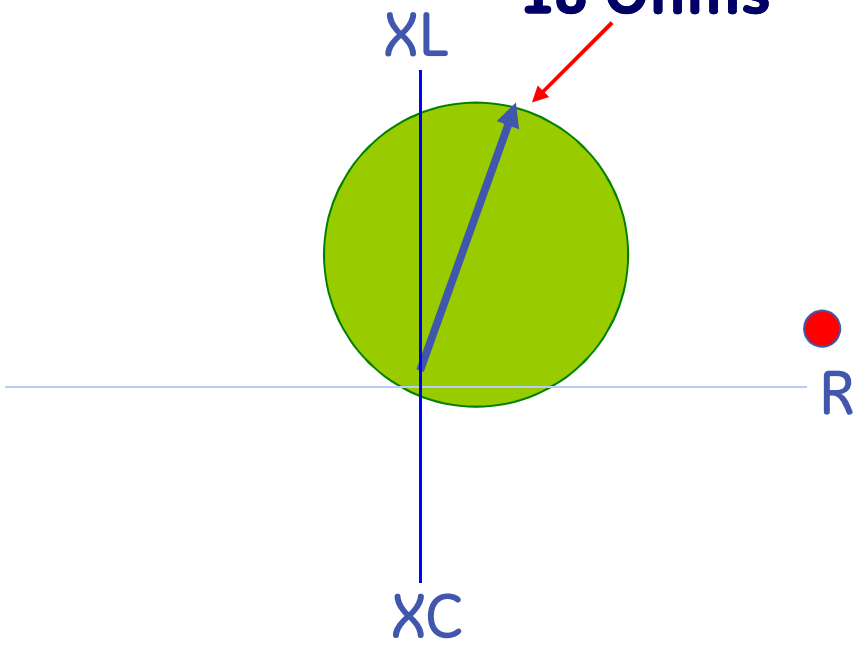
Example:



$$Z_{TL} = \frac{V}{I}$$

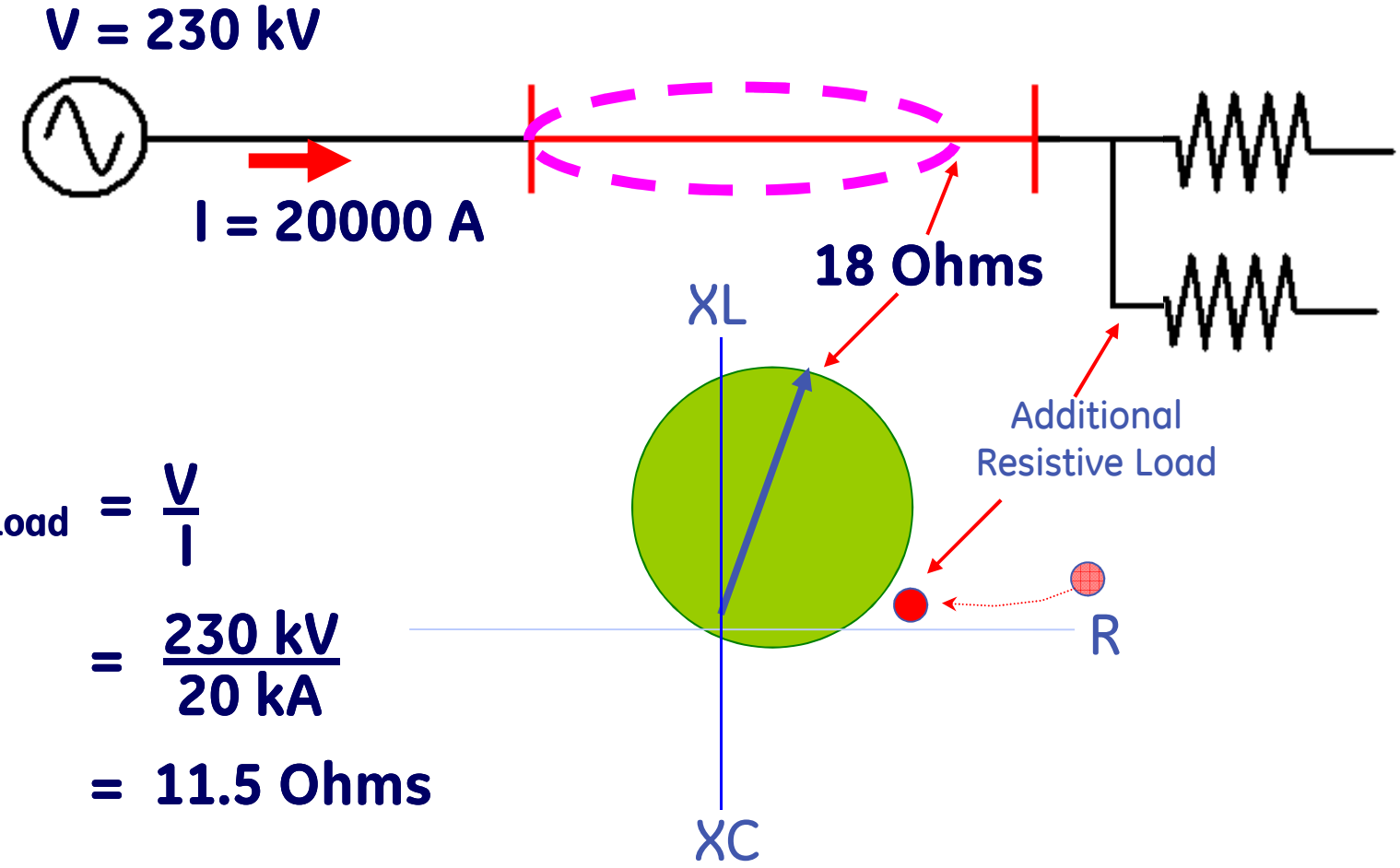
$$= \frac{230\ kV}{1\ kA}$$

$$= 230\ Ohms$$



Zones of Protection – Admittance / Mho Circle :

Example:

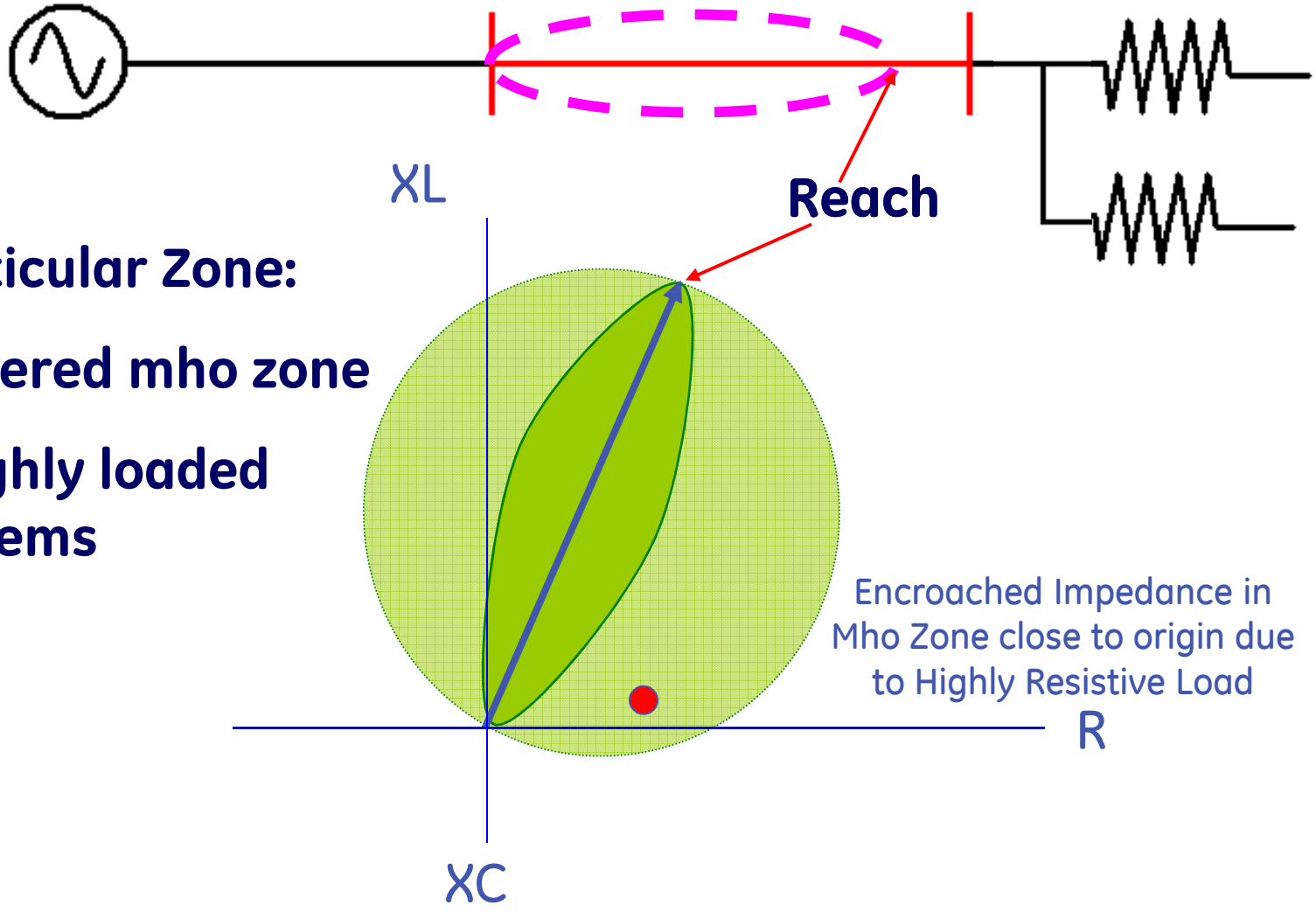


$$Z_{TL + Load} = \frac{V}{I}$$

$$= \frac{230\ kV}{20\ kA}$$

$$= 11.5\ Ohms$$

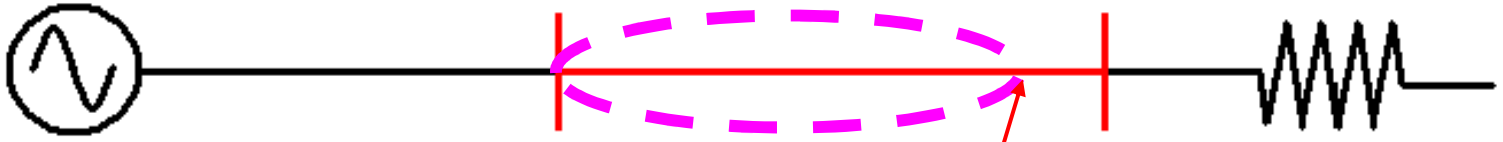
Zones of Protection – Lenticular Zone:

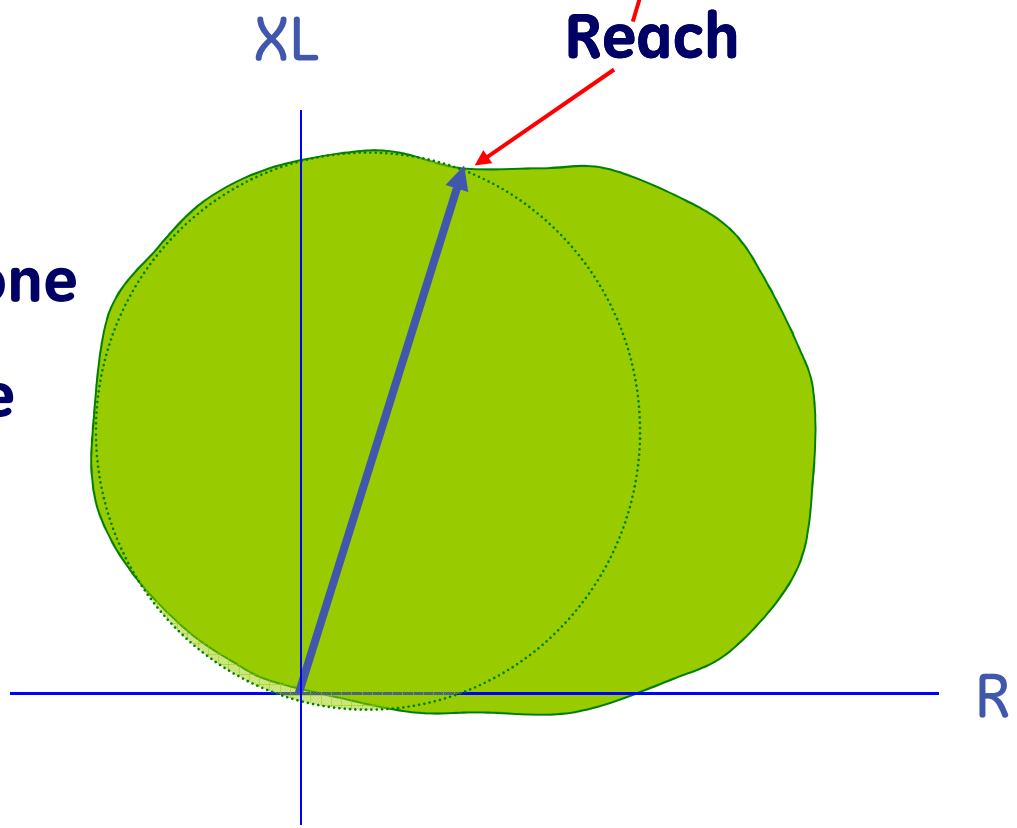


Lenticular Zone:

- **altered mho zone**
- **highly loaded systems**

Zones of Protection – Tomato Characteristics:





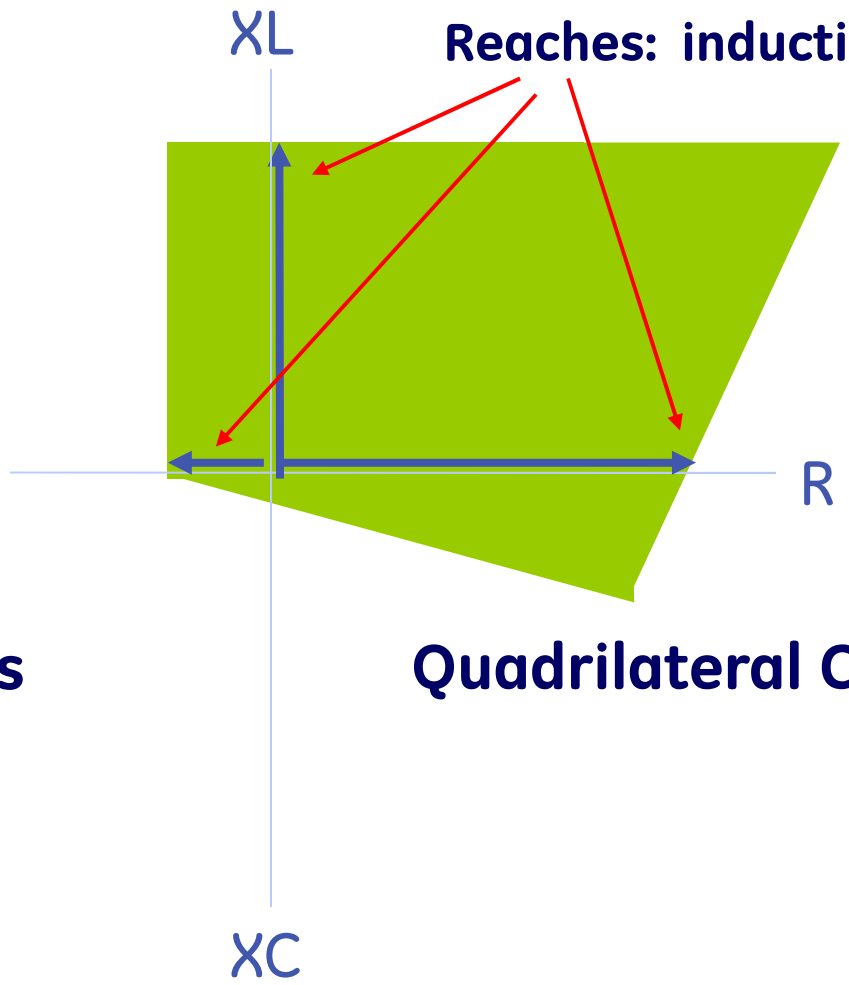
Tomato Characteristics:

- **altered mho zone**
- **highly resistive faults**

Zones of Protection – Quadrilateral Characteristics:

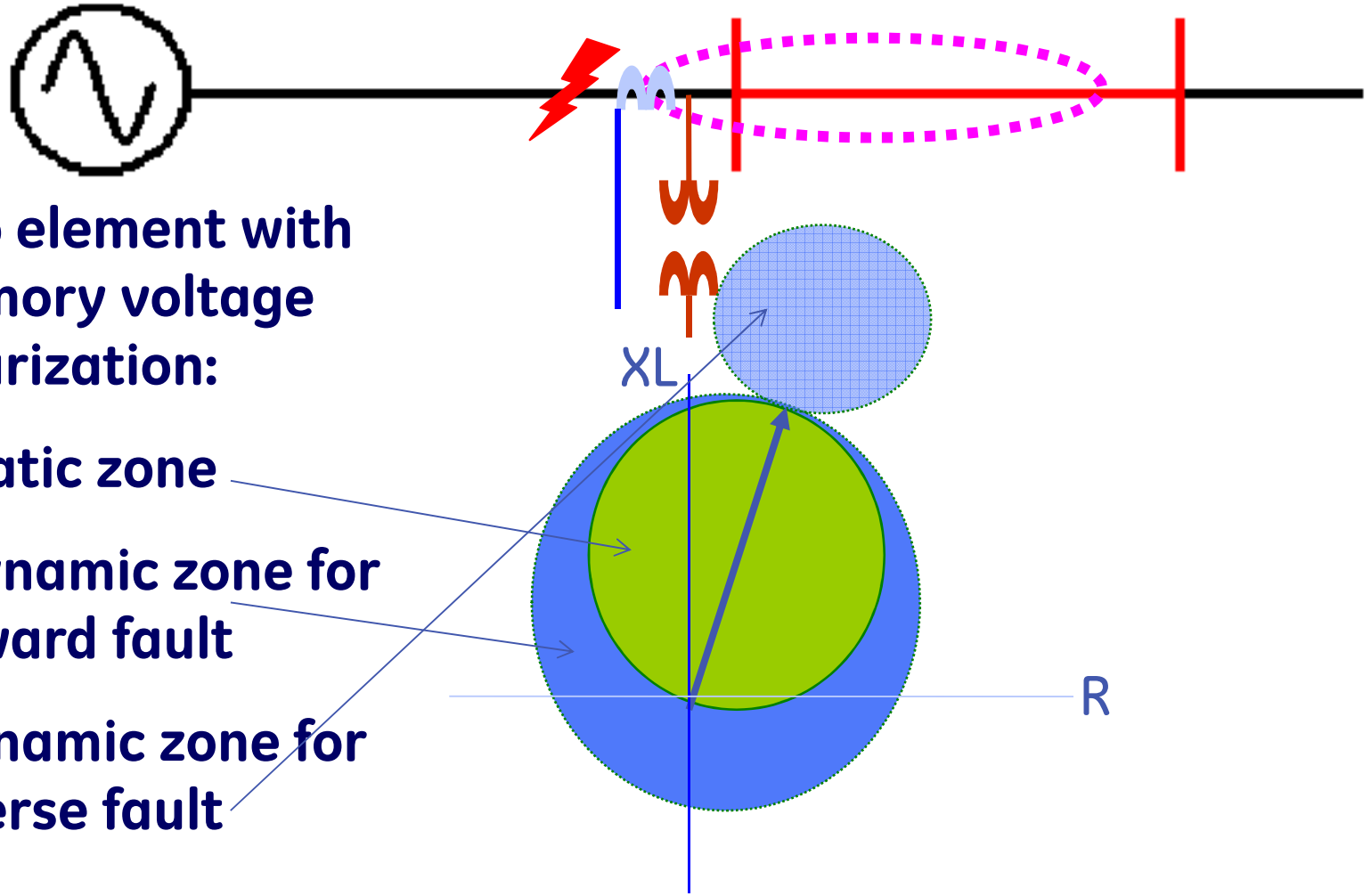
Quadrilateral Characteristics:

- **custom zone**
- **set reactance and resistive boundaries**



Quadrilateral Characteristics

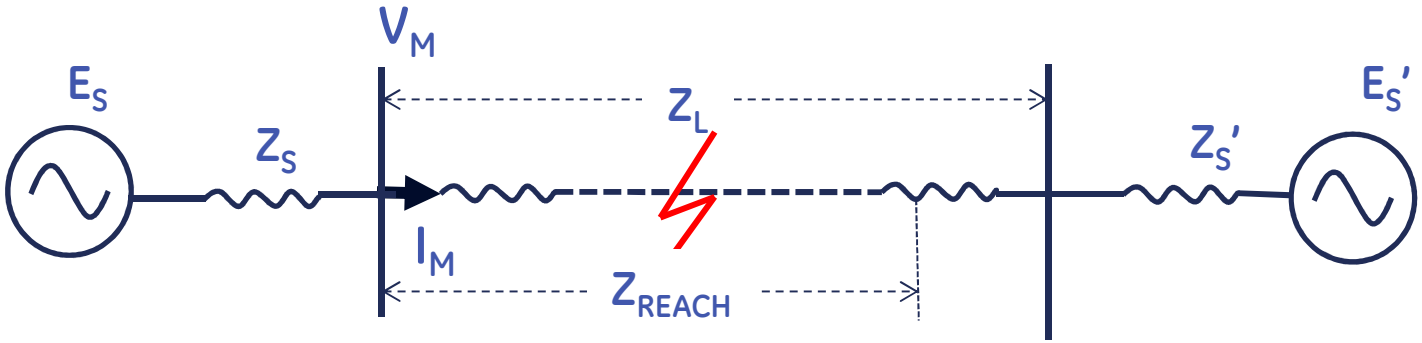
Zones of Protection – Enhanced Mho Element:



Mho element with memory voltage polarization:

- **Static zone**
- **Dynamic zone for forward fault**
- **Dynamic zone for reverse fault**

Zone expanded dynamically for Forward Fault

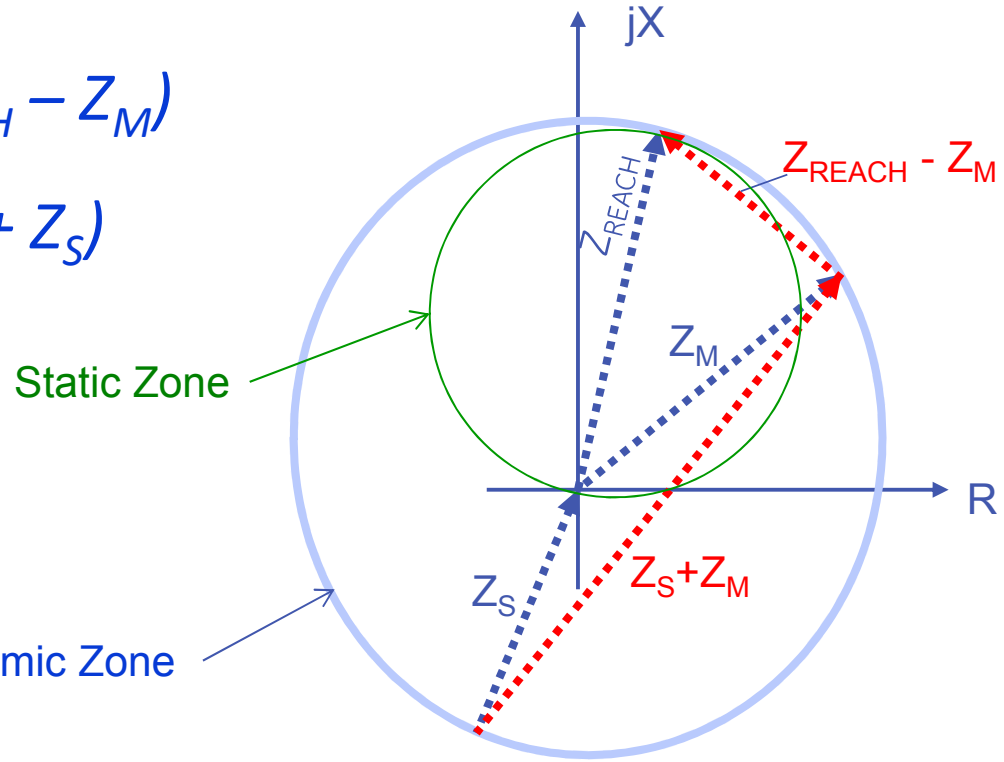


$$V_M = I_M * Z_M$$

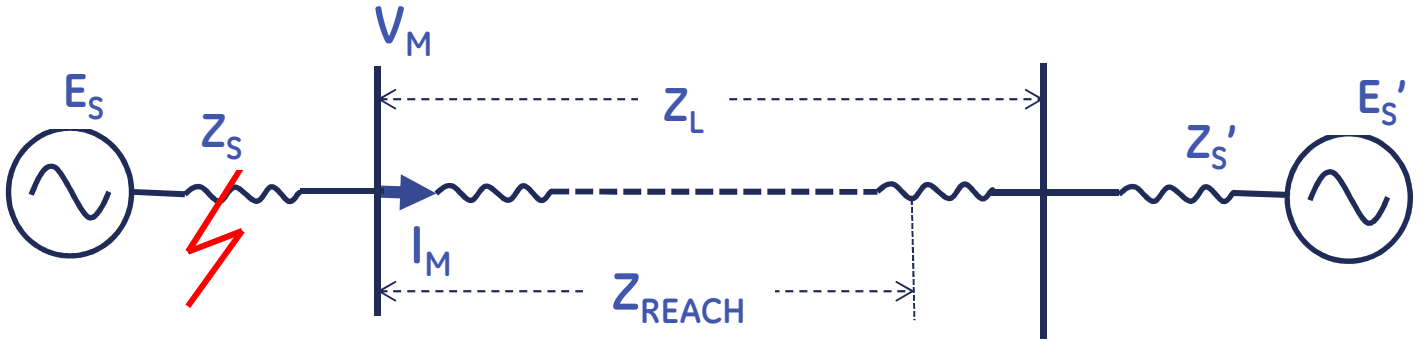
$$V_{OP} = I_M * Z_{REACH} - V_M = I_M * (Z_{REACH} - Z_M)$$

$$V_{POL} = E_S = V_M + I_M * Z_S = I_M * (Z_M + Z_S)$$

Where V_M, I_M and Z_M are the measured voltage, current and apparent impedance at the relay location



Zone shifted up dynamically for Reverse Fault



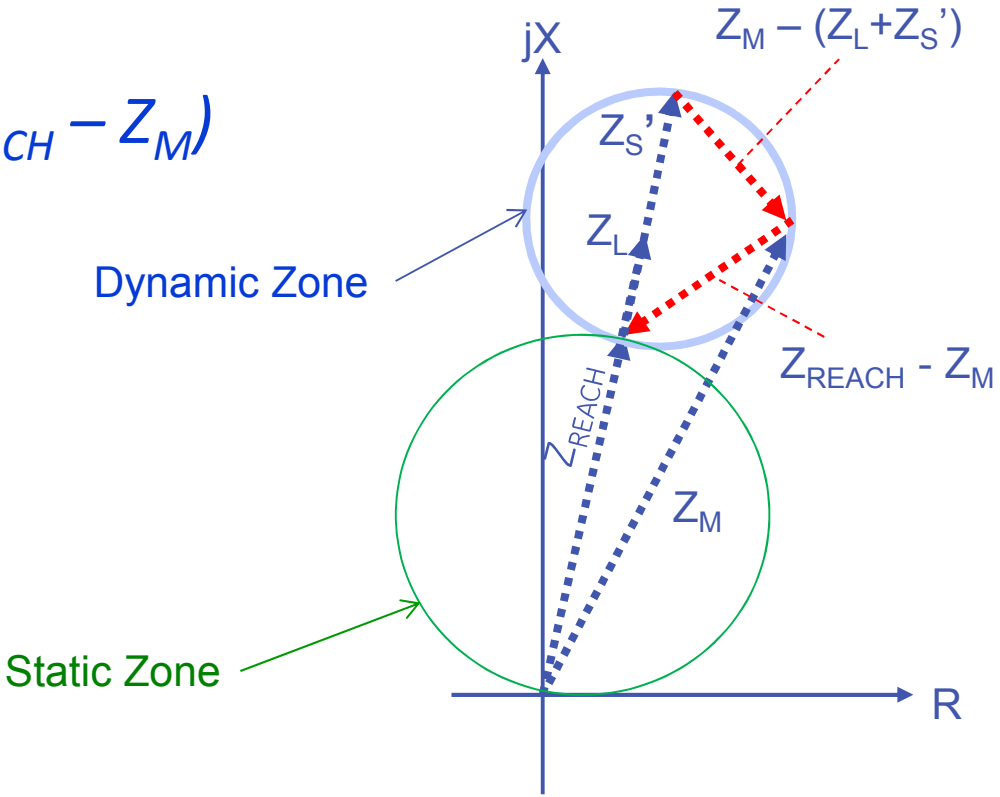
$$V_M = I_M * Z_M$$

$$V_{OP} = I_M * Z_{REACH} - V_M = I_M * (Z_{REACH} - Z_M)$$

$$V_{POL} = E_S' = V_M - I_M * (Z_L + Z_S')$$

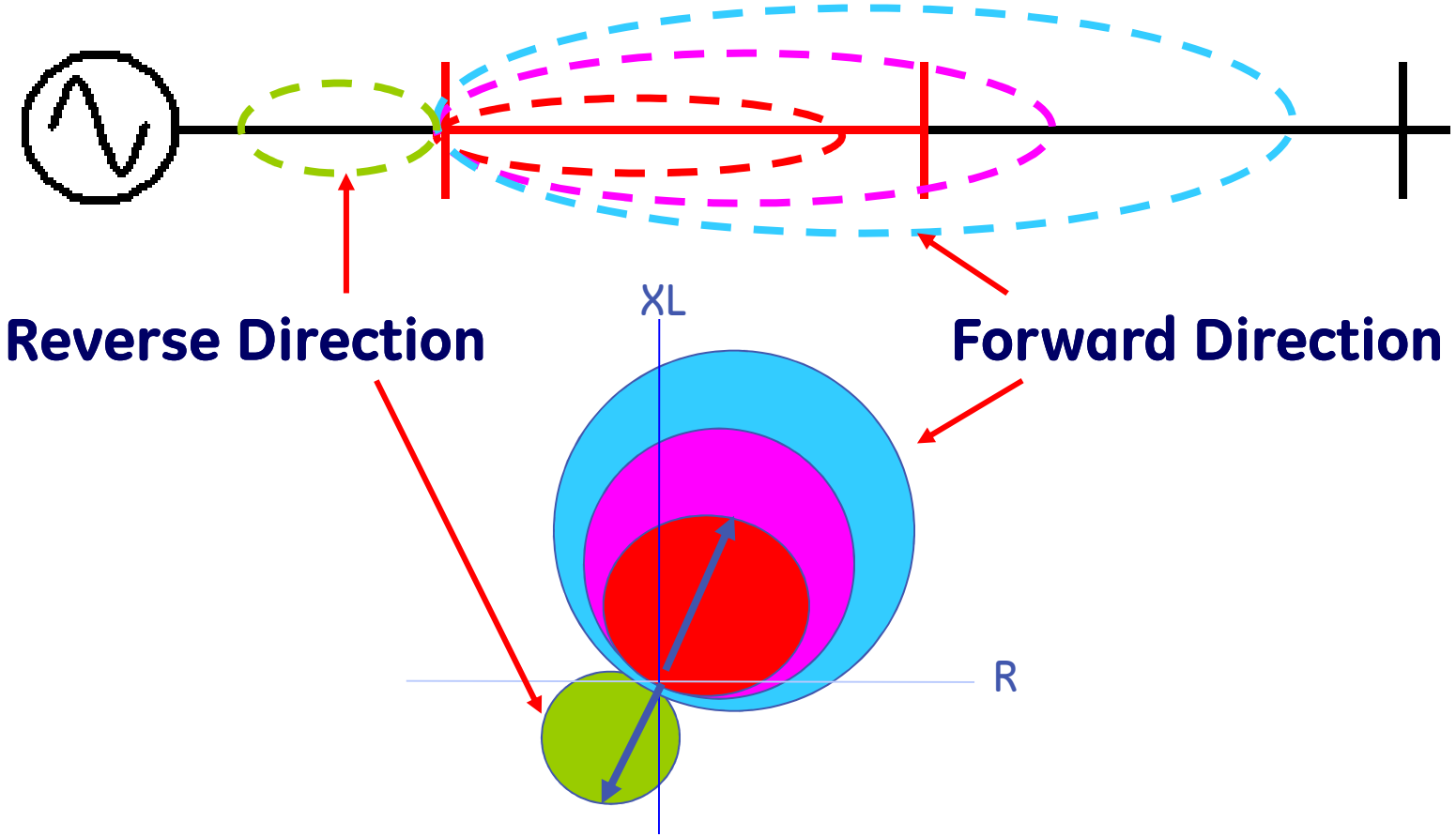
$$= I_M * (Z_M - (Z_L + Z_S'))$$

Where V_M, I_M and Z_M are the measured voltage, current and apparent impedance at the relay location

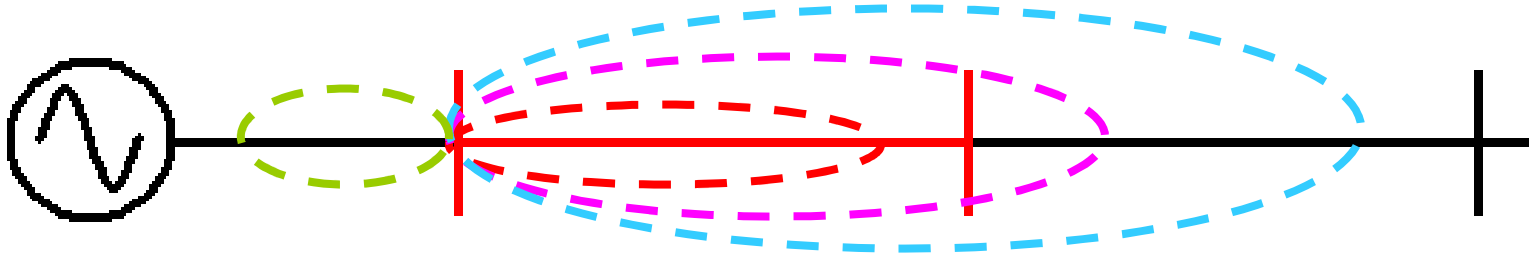


Modern Distance Protection:

- **Phase Distance element - detects phase-to-phase faults**
- **Ground Distance element - detects phase-to-ground faults**



Modern Distance Protection:

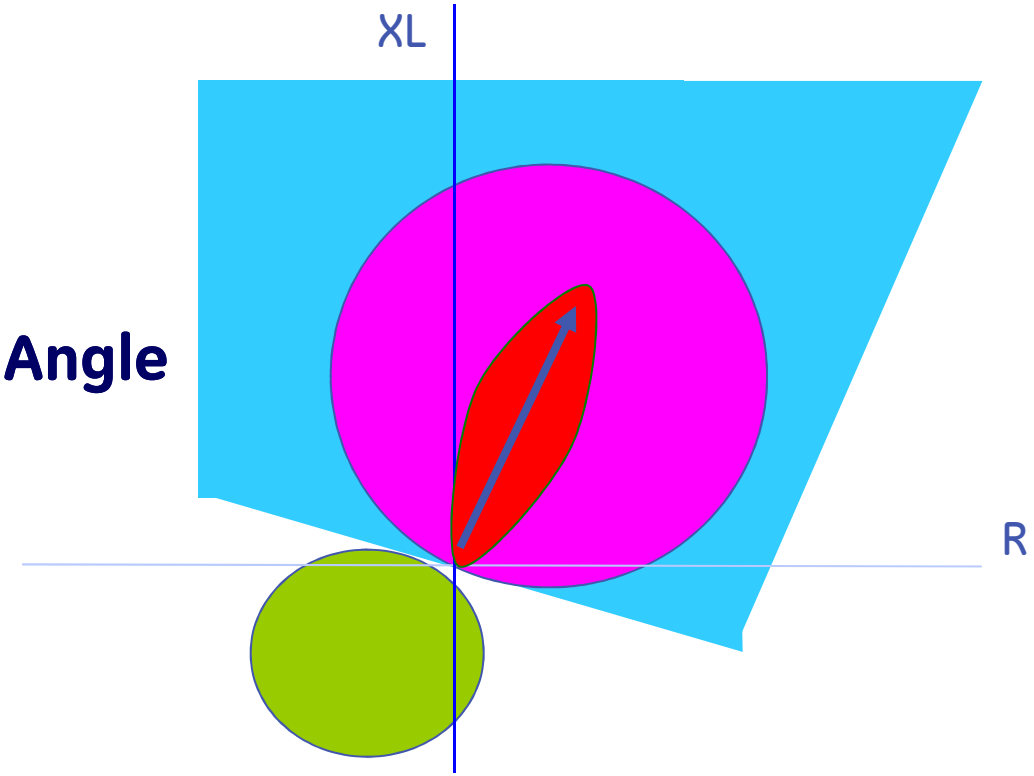


Max Torque Angle

Blinders

Directional Angle

Comparator Limit Angle



Life is not really that simple!

Relays are simple comparators – An actual distance relay compares the angle of two voltages

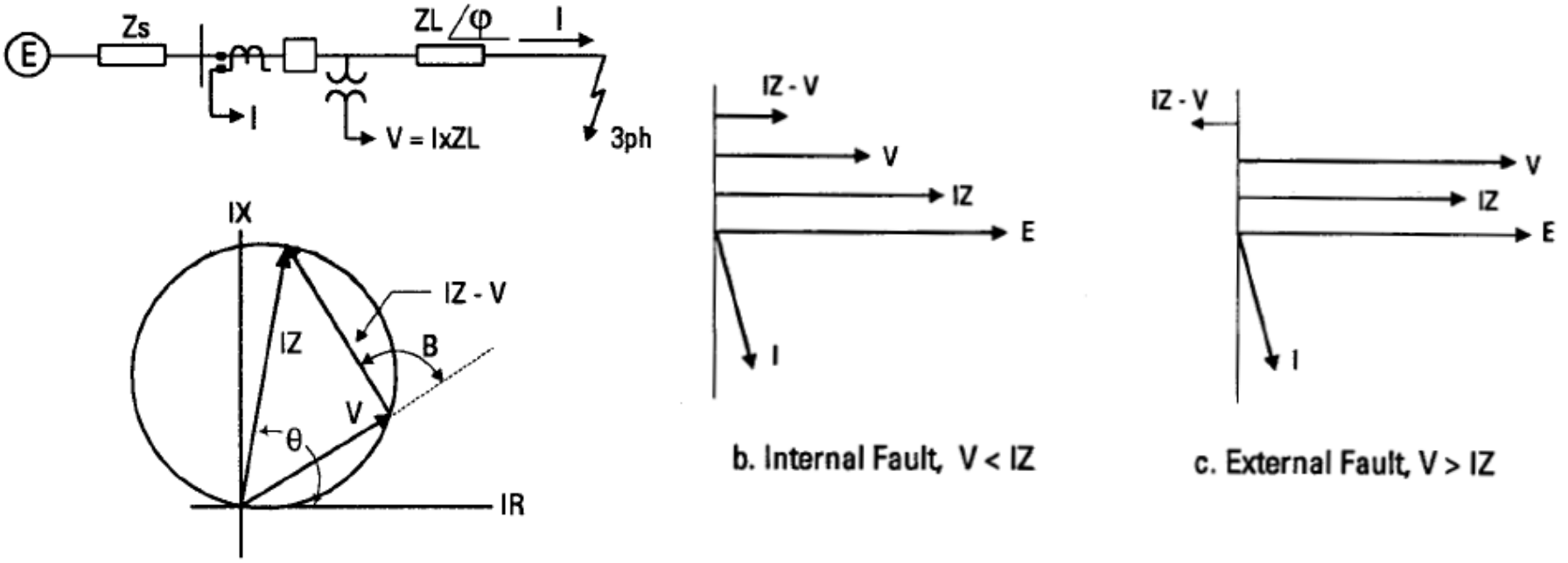
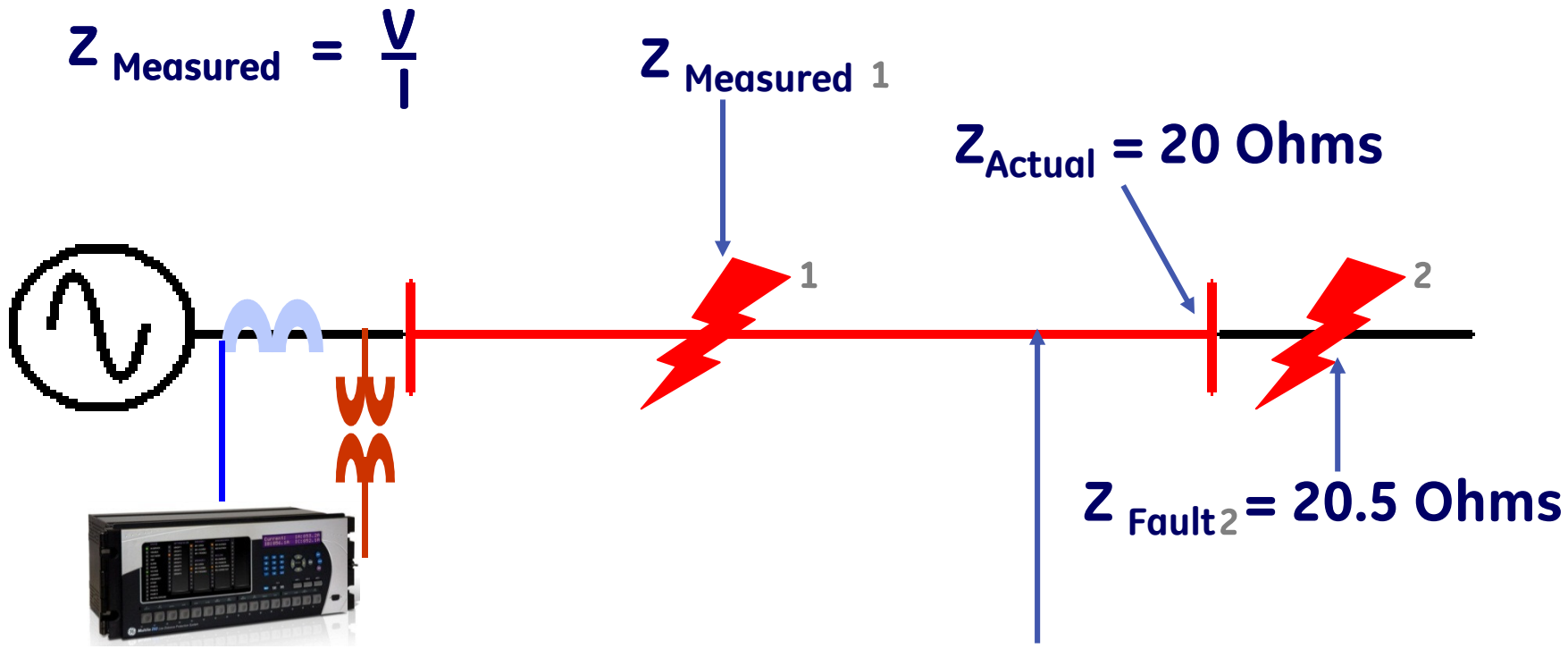


Figure 1 - Simple Mho Function

Distance Zones Protection:

$$Z_{Measured} = \frac{V}{I}$$

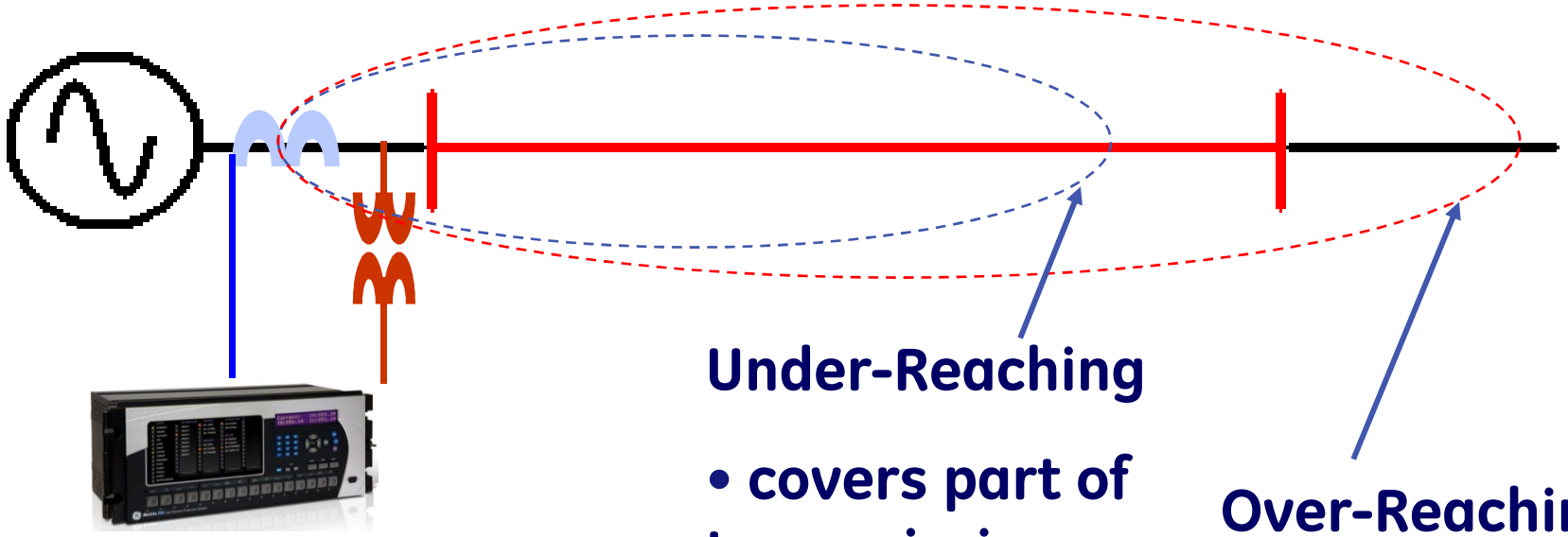


If $Z_{Measured} < Z_{Actual}$,

then Line is Shorter indicating a Fault

- due to inaccuracies of CTs, VTs and transient effects.

Distance Zones Protection:



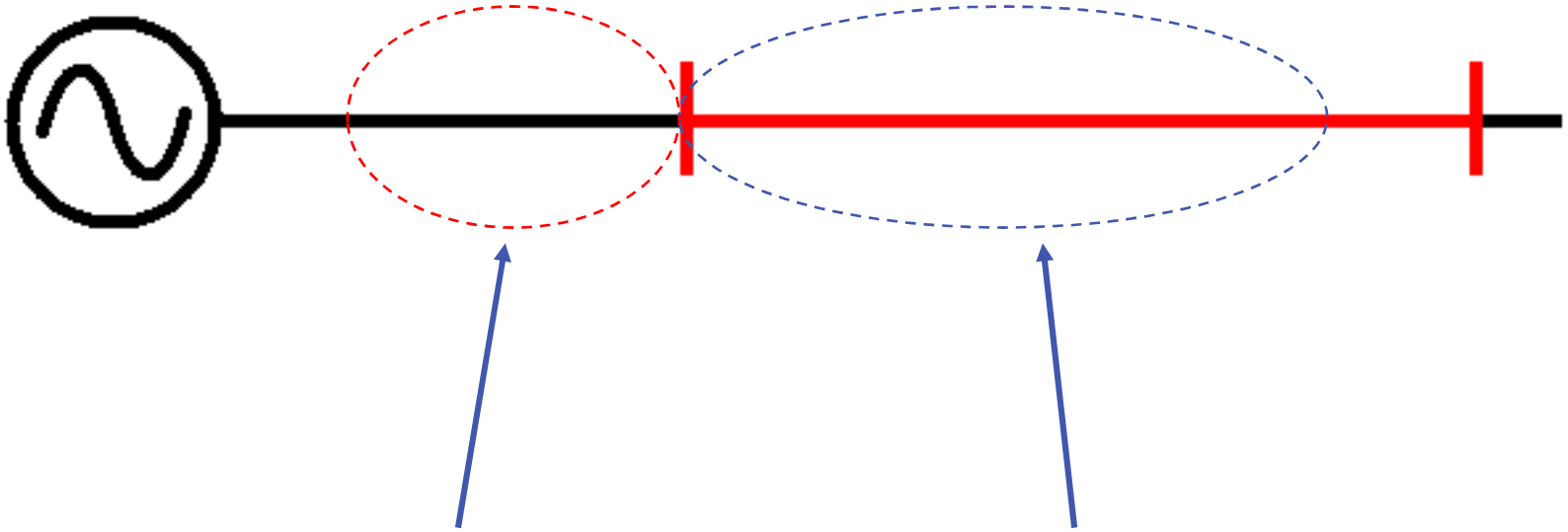
Under-Reaching

- **covers part of transmission line**

Over-Reaching

- **covers transmission line and part of next adjacent line**

Distance Zones Protection:



Out Of the Line

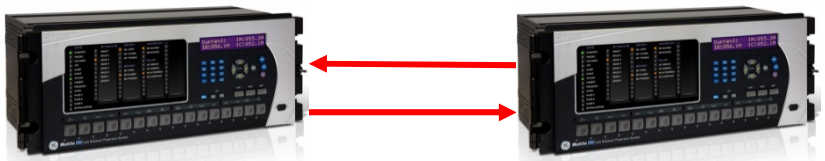
- protects in the reverse direction

Into the Line

- protects in the forward direction

Distance Schemes:

Pilot Aided Schemes



- Communication

Non-Pilot Aided Schemes

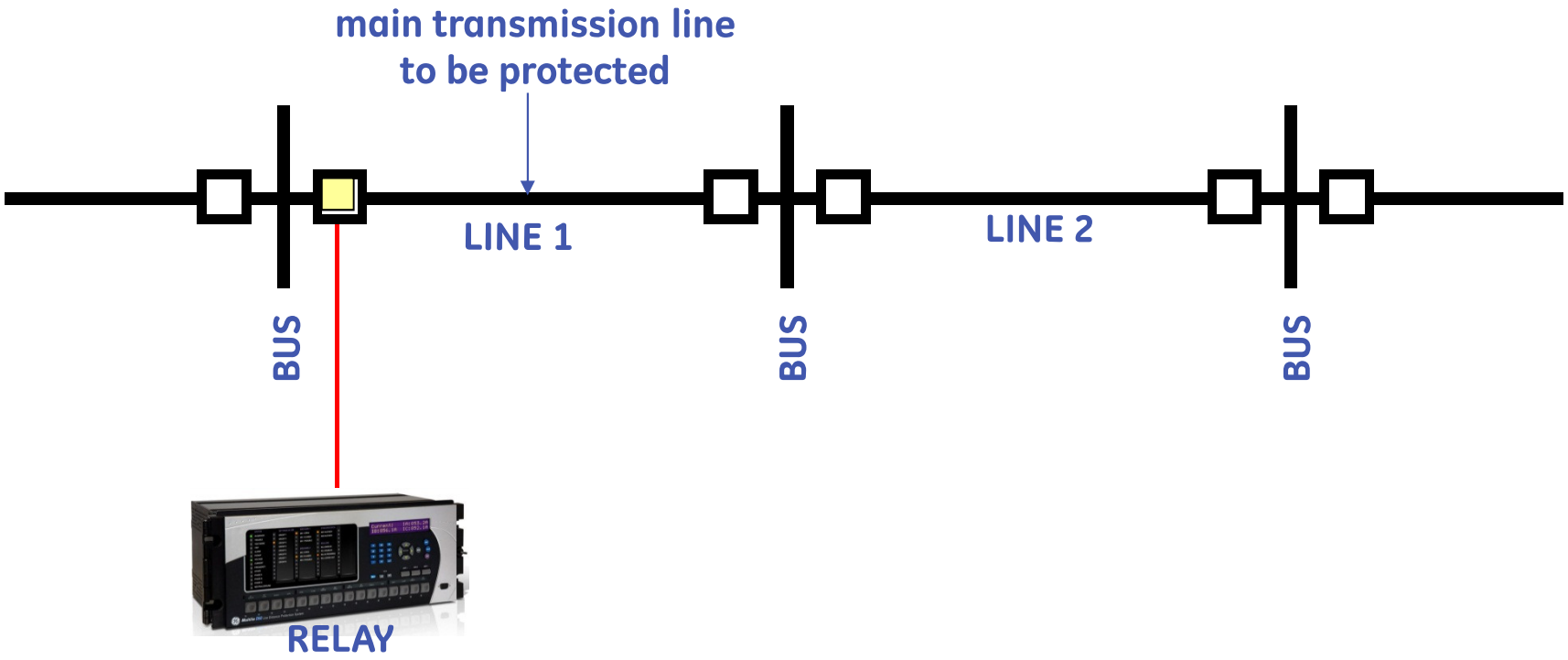
- No Communication
- Delays and Coordination

Non-Pilot Aided Distance Schemes:


- **Stepped Distance**
- **Zone 1 Extension**

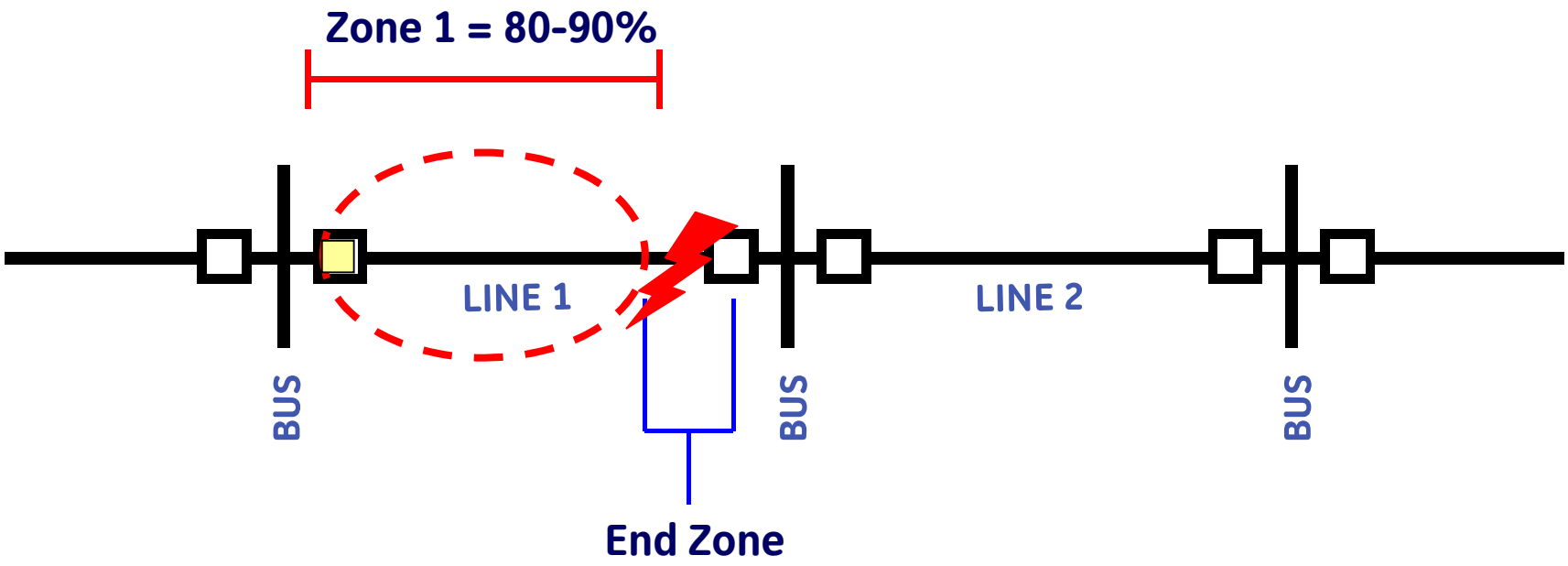
Non-Pilot Aided - Stepped Distance Schemes:

Example:



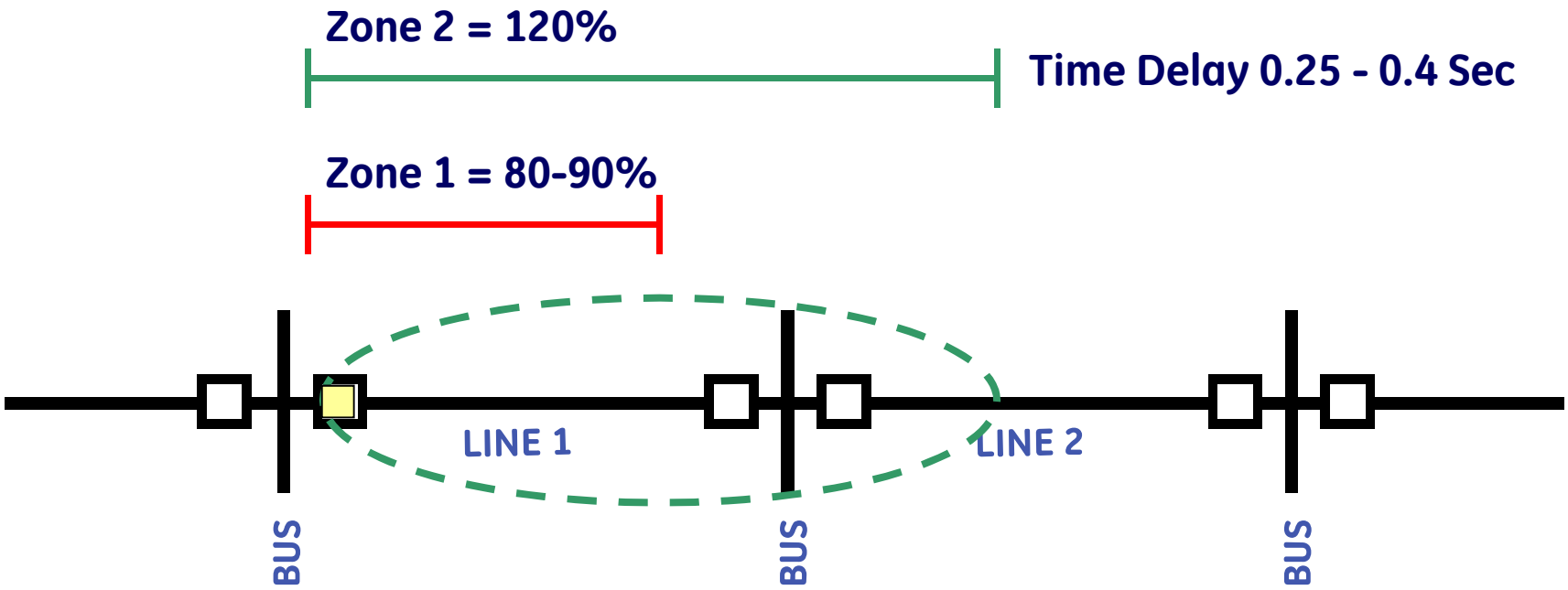
Non-Pilot Aided - Stepped Distance Schemes:

Zone 1 - Under-reaching:



Non-Pilot Aided - Stepped Distance Schemes:

Zone 2 - Over-reaching:

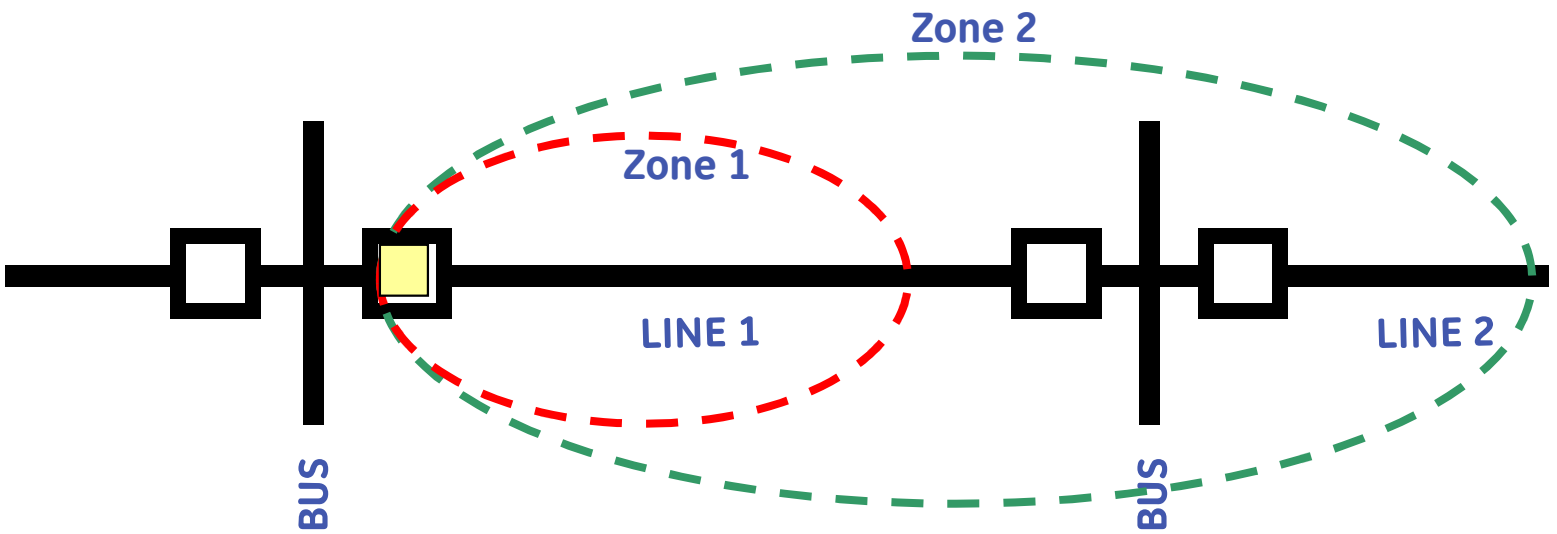


Non-Pilot Aided - Stepped Distance Schemes:

Example:

Zone 1 - Pickup – OFF
- Operate - OFF

Zone 2 - Pickup – OFF
- Operate - OFF

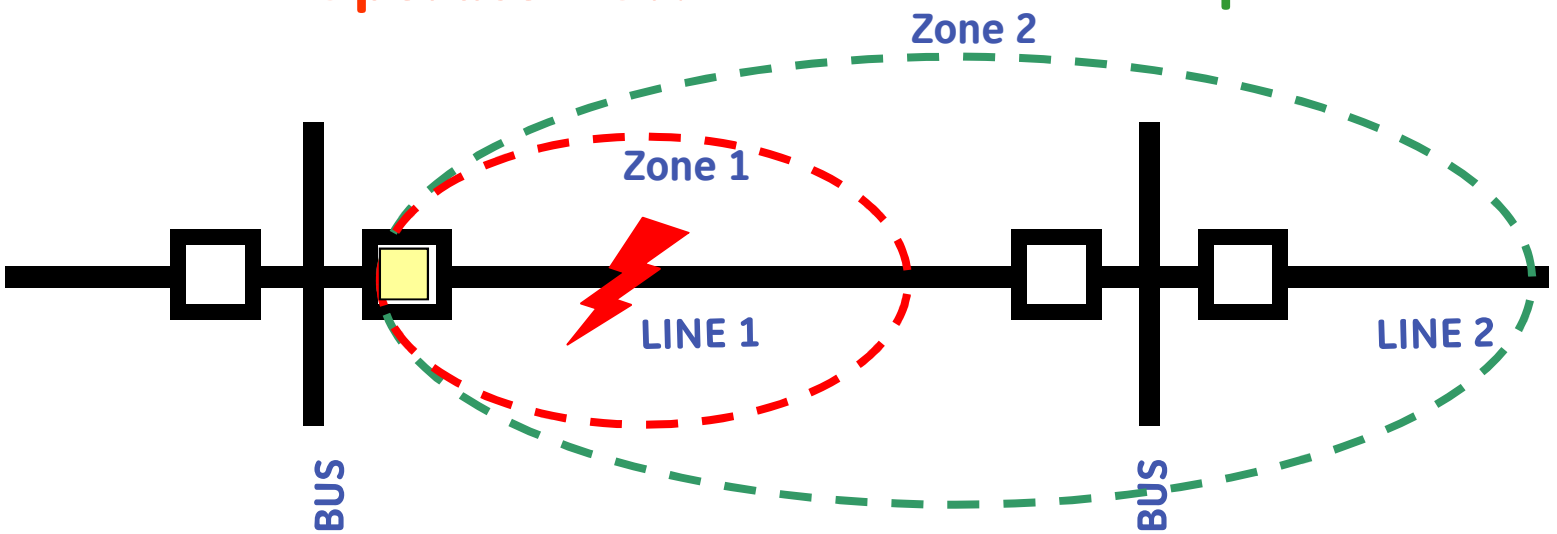


Non-Pilot Aided - Stepped Distance Schemes:

Example 1: Fault on Transmission Line 1 within Zone 1

Zone 1 - Pickup – ON [1]
- Operate - ON [2]

Zone 2 - Pickup – ON [1]
- Operate - OFF



- When Fault Cleared:

Zone 1 - Pickup – OFF [3]
- Operate - OFF [3]

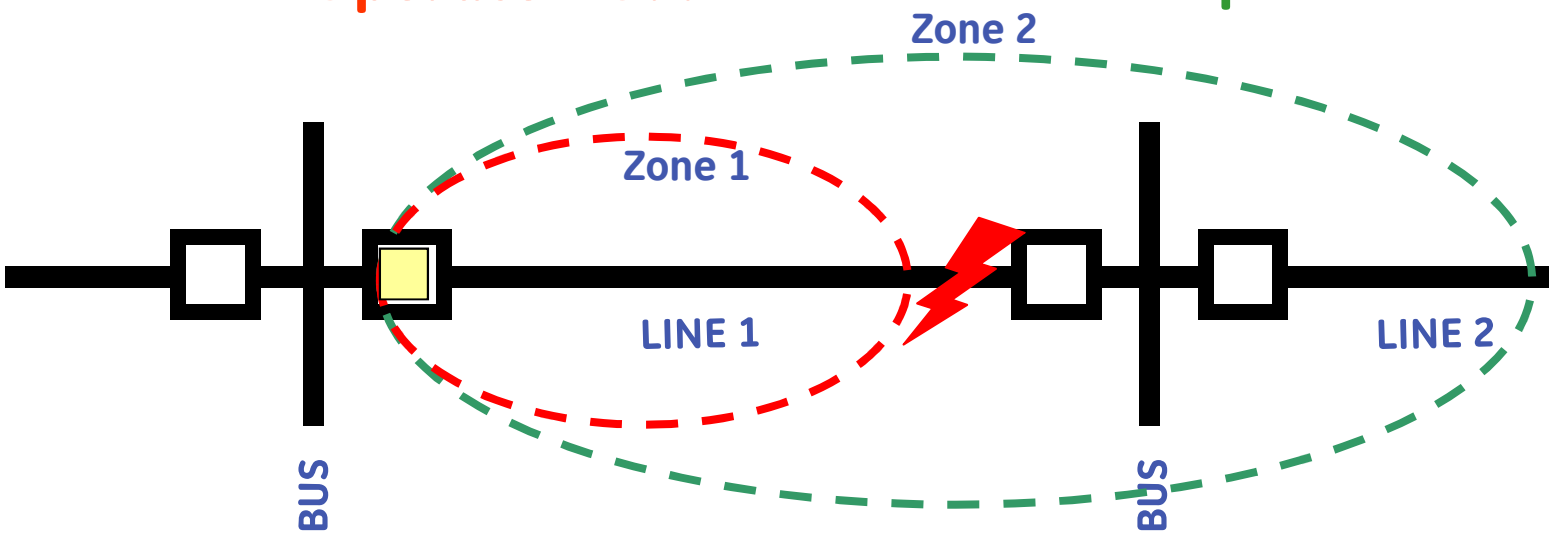
Zone 2 - Pickup – OFF [3]
- Operate - OFF

Non-Pilot Aided - Stepped Distance Schemes:

Example 2: Fault on Transmission Line 1 outside Zone 1

Zone 1 - Pickup – OFF
- Operate - OFF

Zone 2 - Pickup – ON [1]
- Operate - ON [2]



- When Fault Cleared:

Zone 1 - Pickup – OFF
- Operate - OFF

Zone 2 - Pickup – OFF [3]
- Operate - OFF [3]

Non-Pilot Aided - Stepped Distance Schemes:

Example 3: Fault on Transmission Line 2 within Zone 2 of Relay 1 and Zone 1 of Relay 2

Distance Relay 1

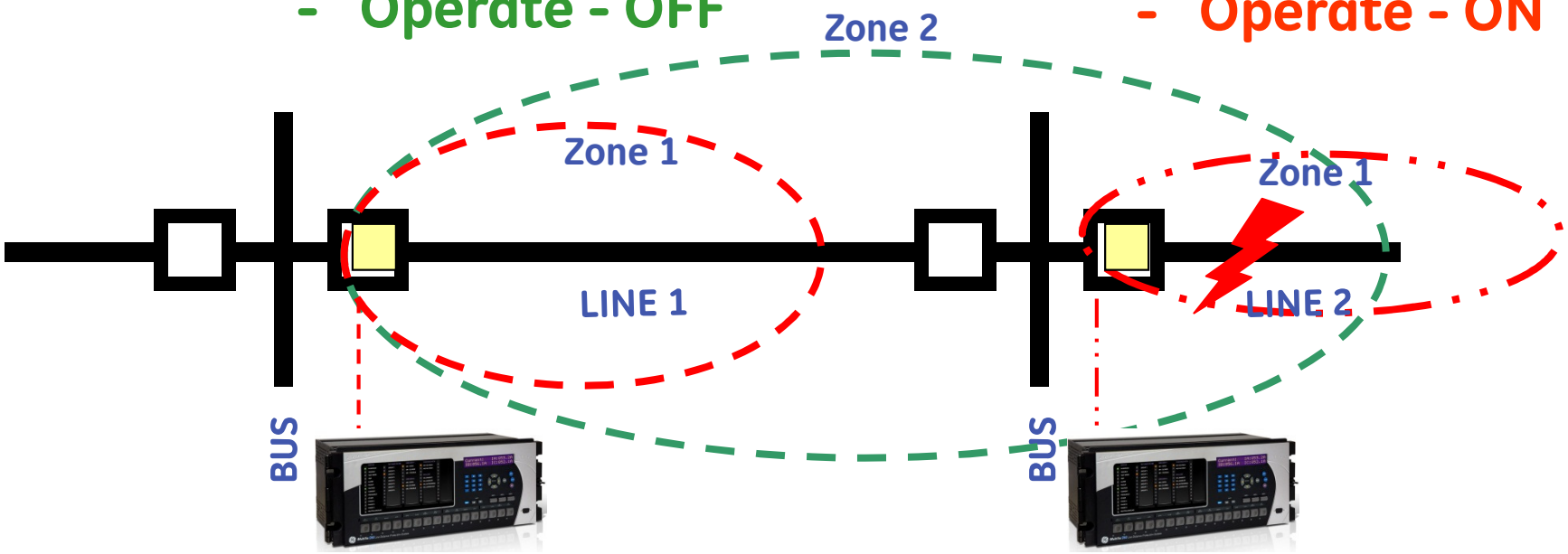
Zone 2 - Pickup – ON [1]

- Operate - OFF

Distance Relay 2

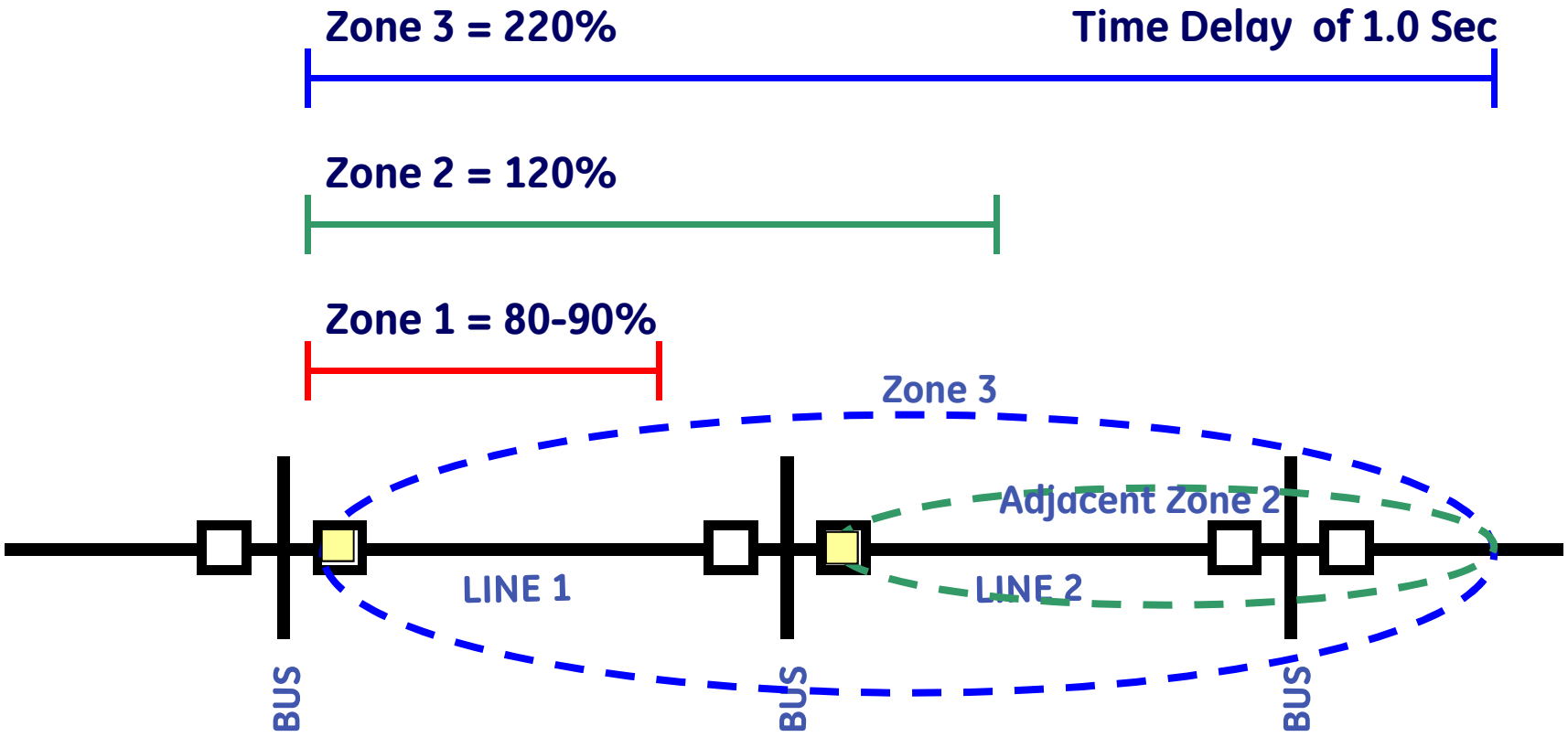
Zone 1 - Pickup – ON [1]

- Operate - ON [2]



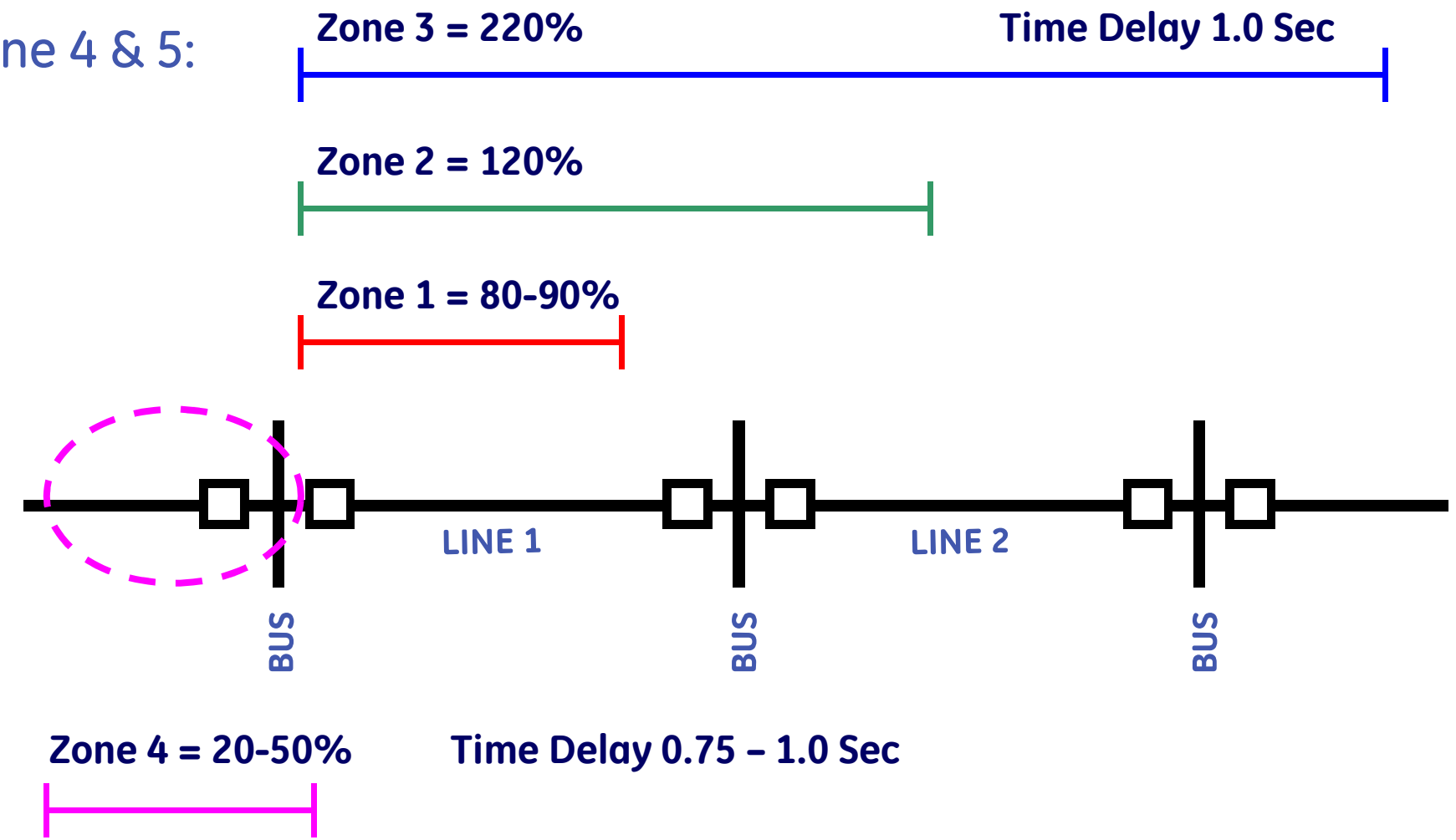
Non-Pilot Aided - Stepped Distance Schemes:

Zone 3:

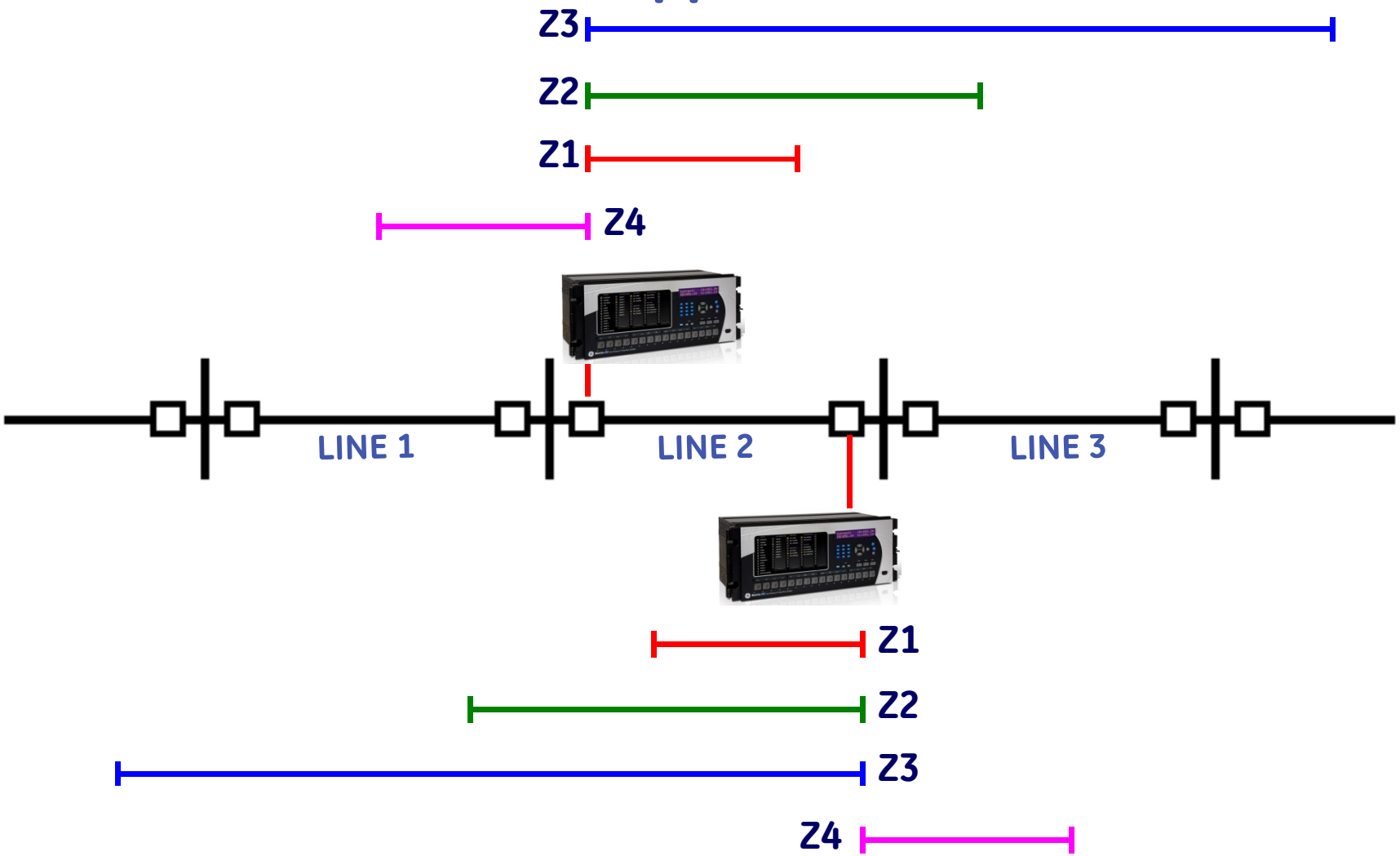


Non-Pilot Aided - Stepped Distance Schemes:

Zone 4 & 5:



Non-Pilot Aided - Stepped Distance Schemes:

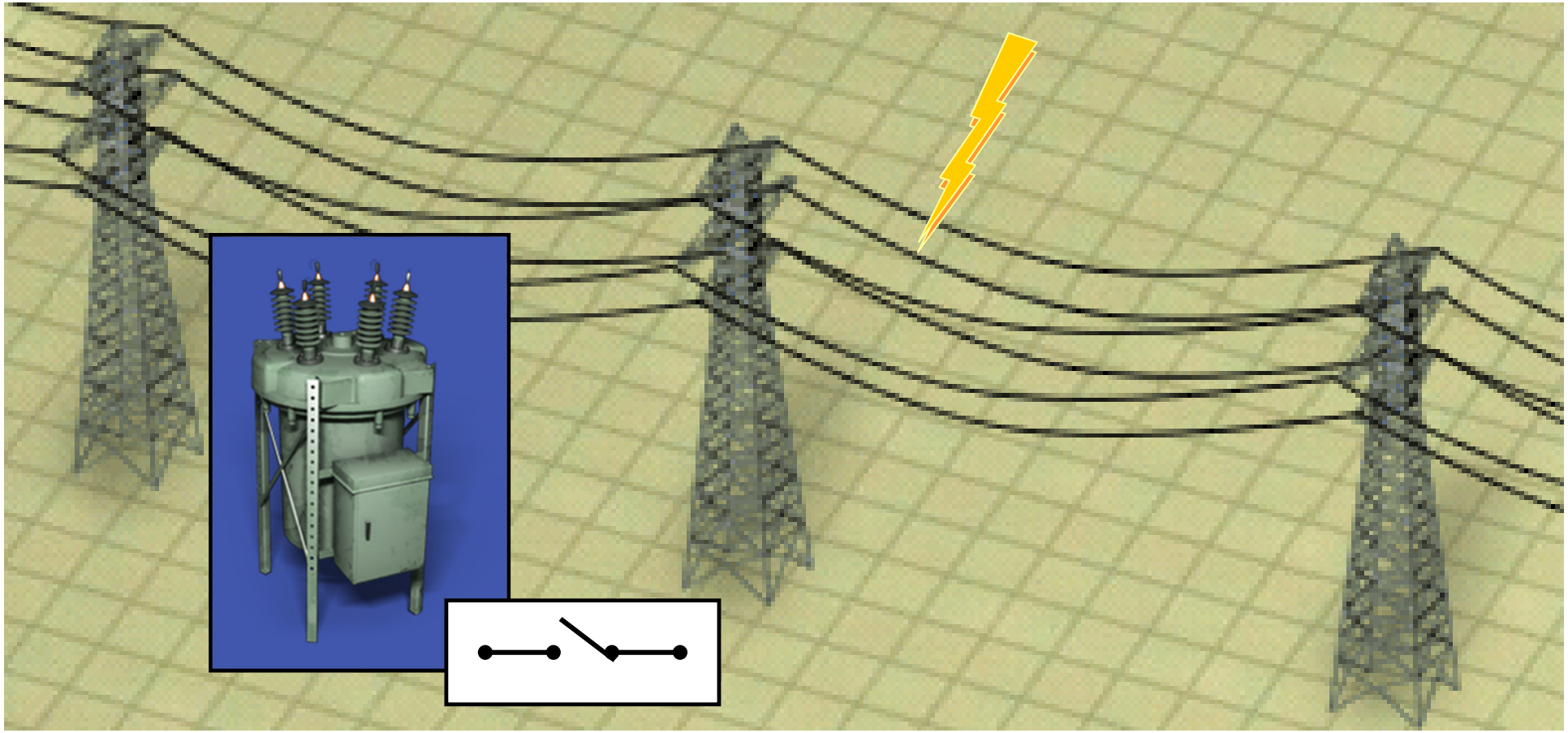


Non-Pilot Aided - Zone 1 Extension Schemes:

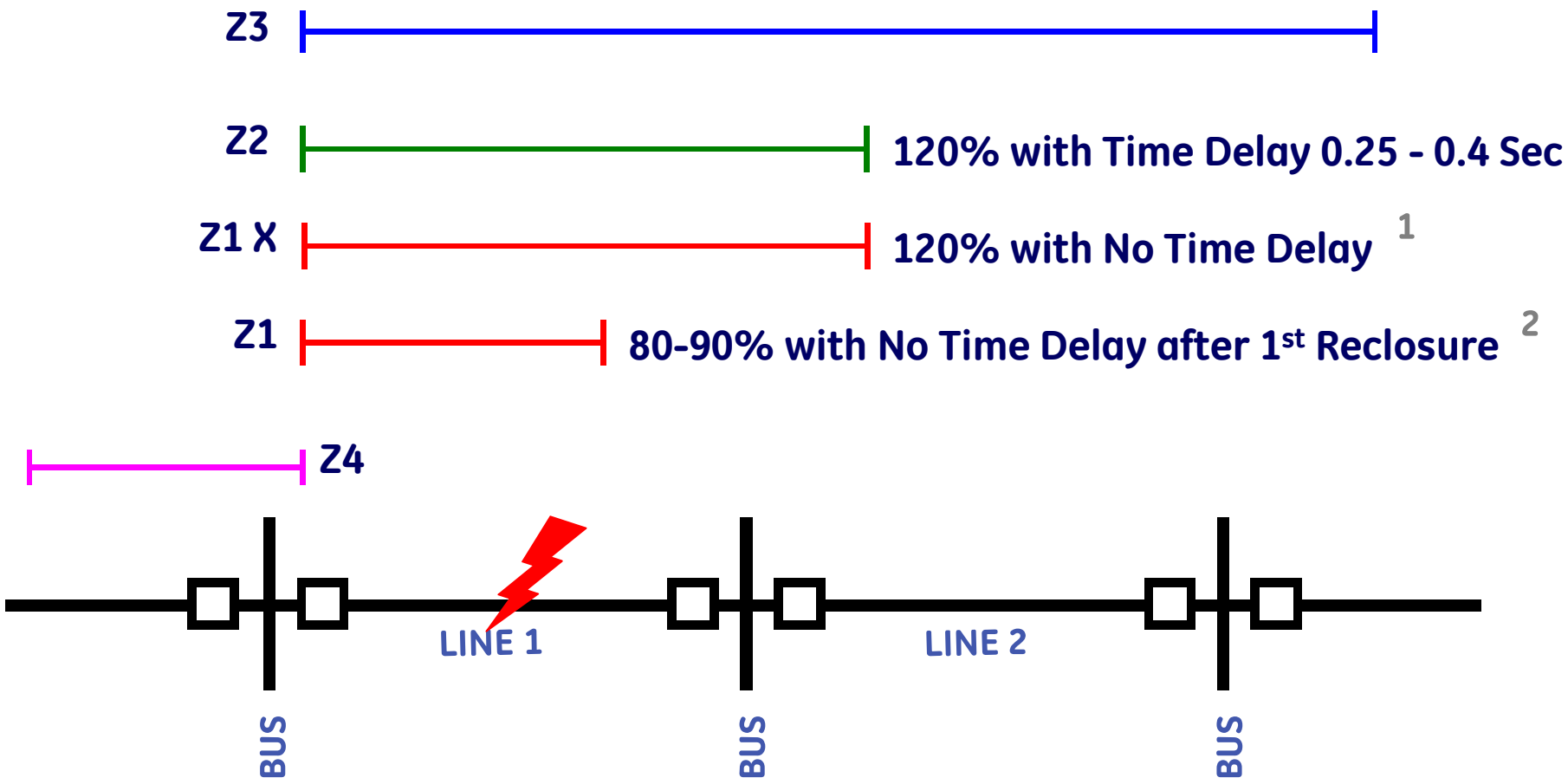
- based on Stepped Distance Scheme
- based on principle that transmission line faults are typically transient

Non-Pilot Aided - Zone 1 Extension Schemes:

Example: transient fault cleared by tripping circuit breaker

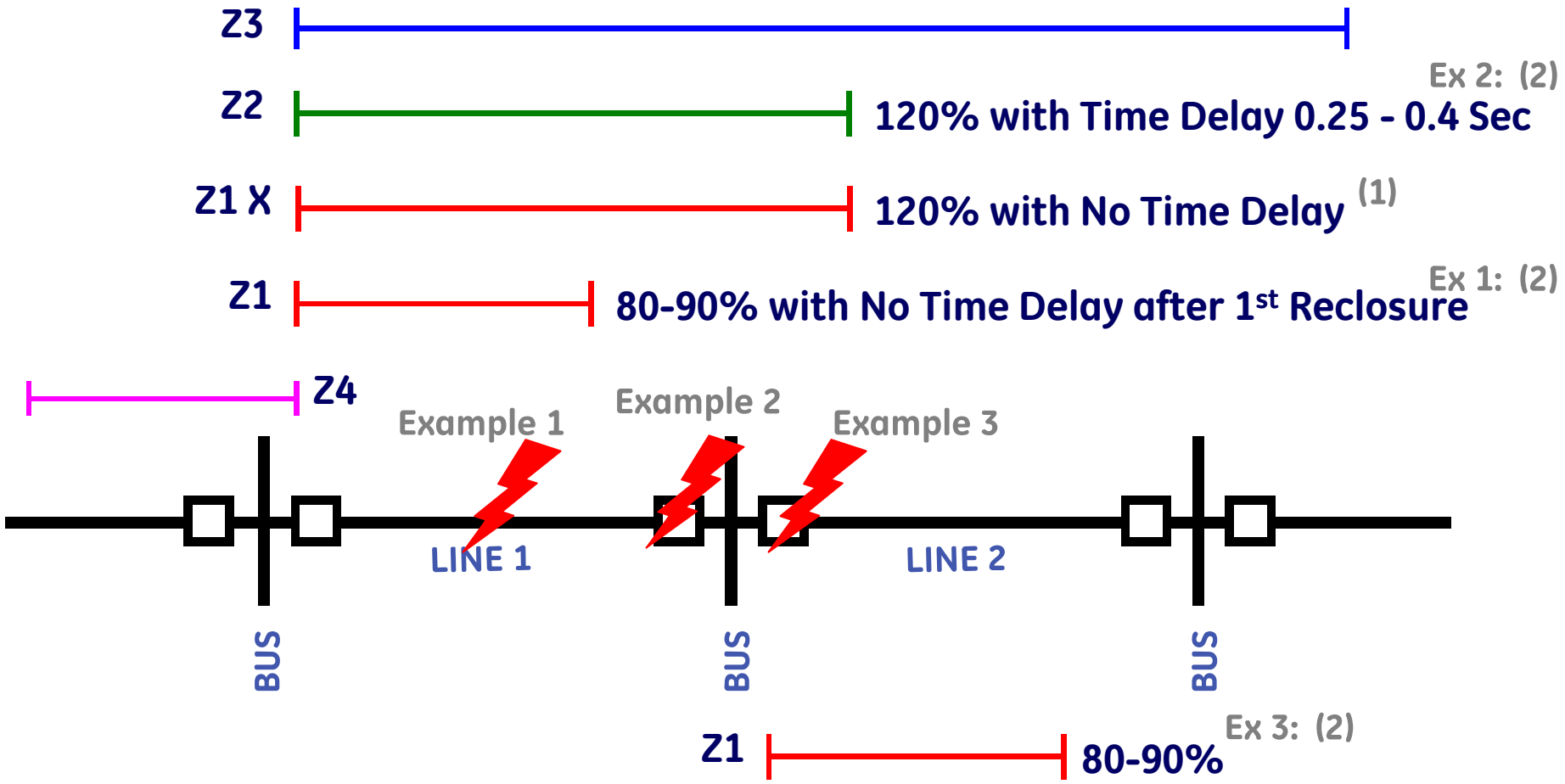


Non-Pilot Aided - Zone 1 Extension Schemes:

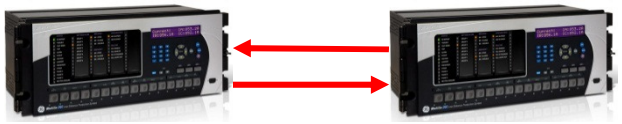


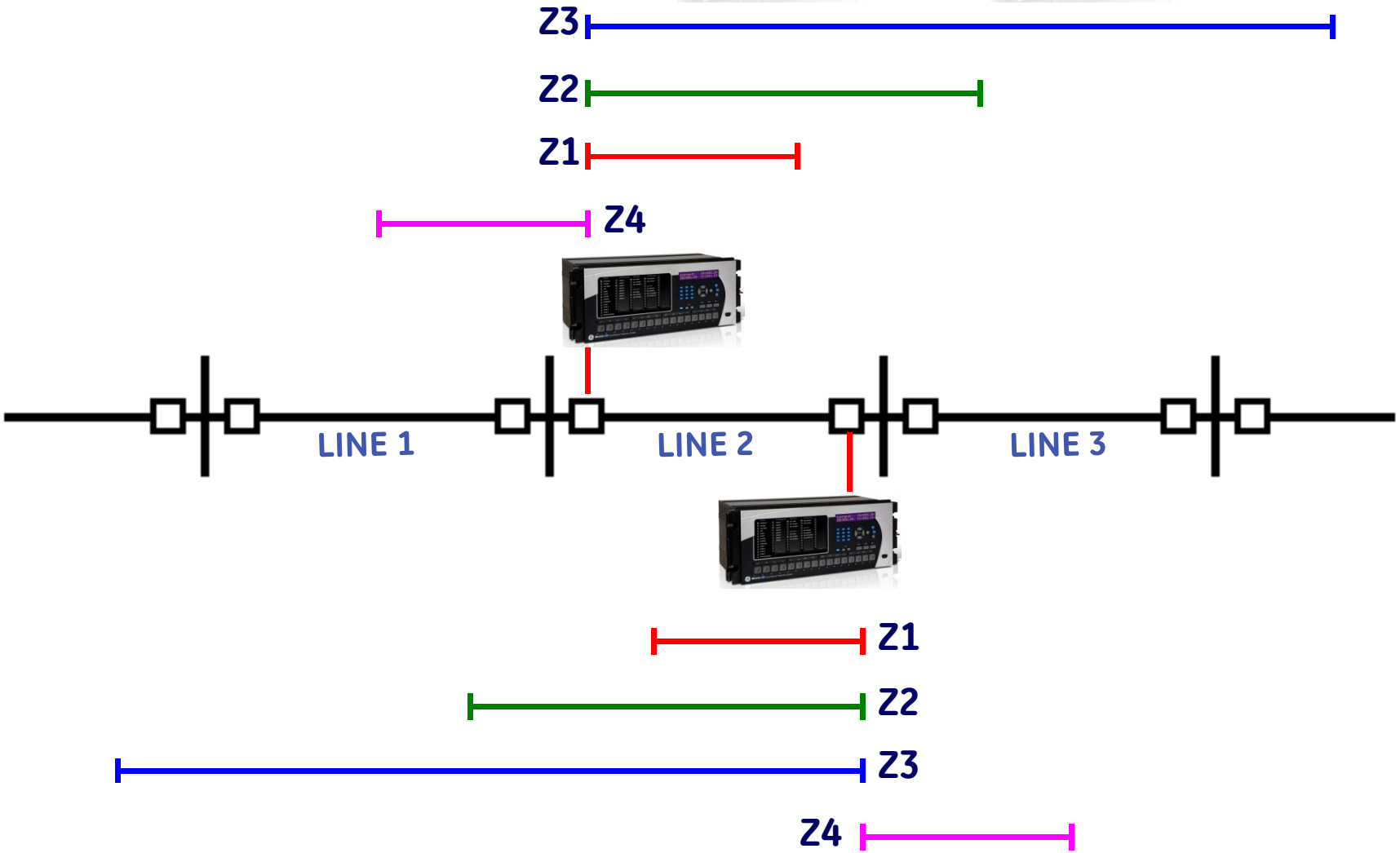
Non-Pilot Aided - Zone 1 Extension Schemes:

Examples:



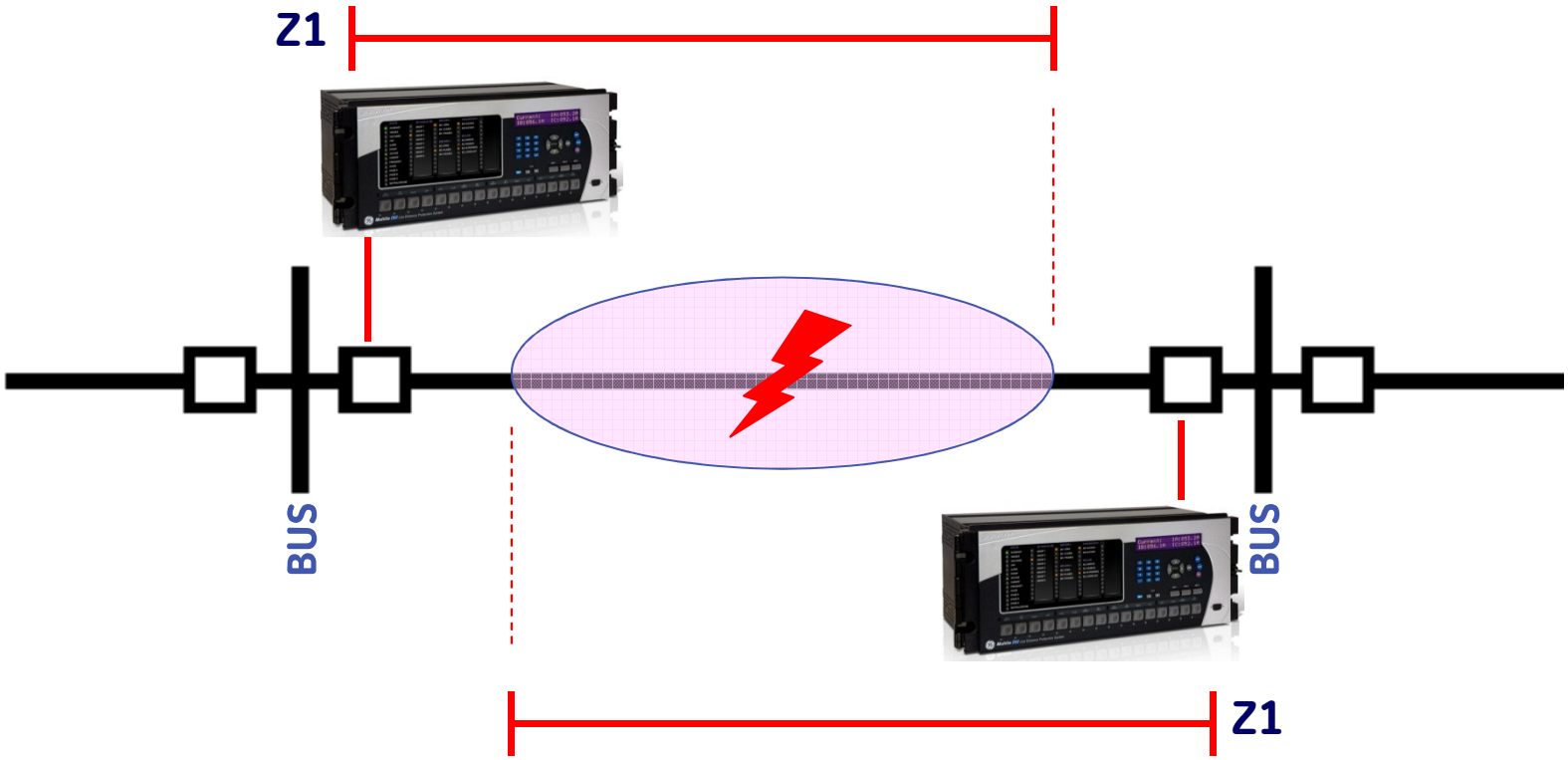
Pilot Aided Schemes:





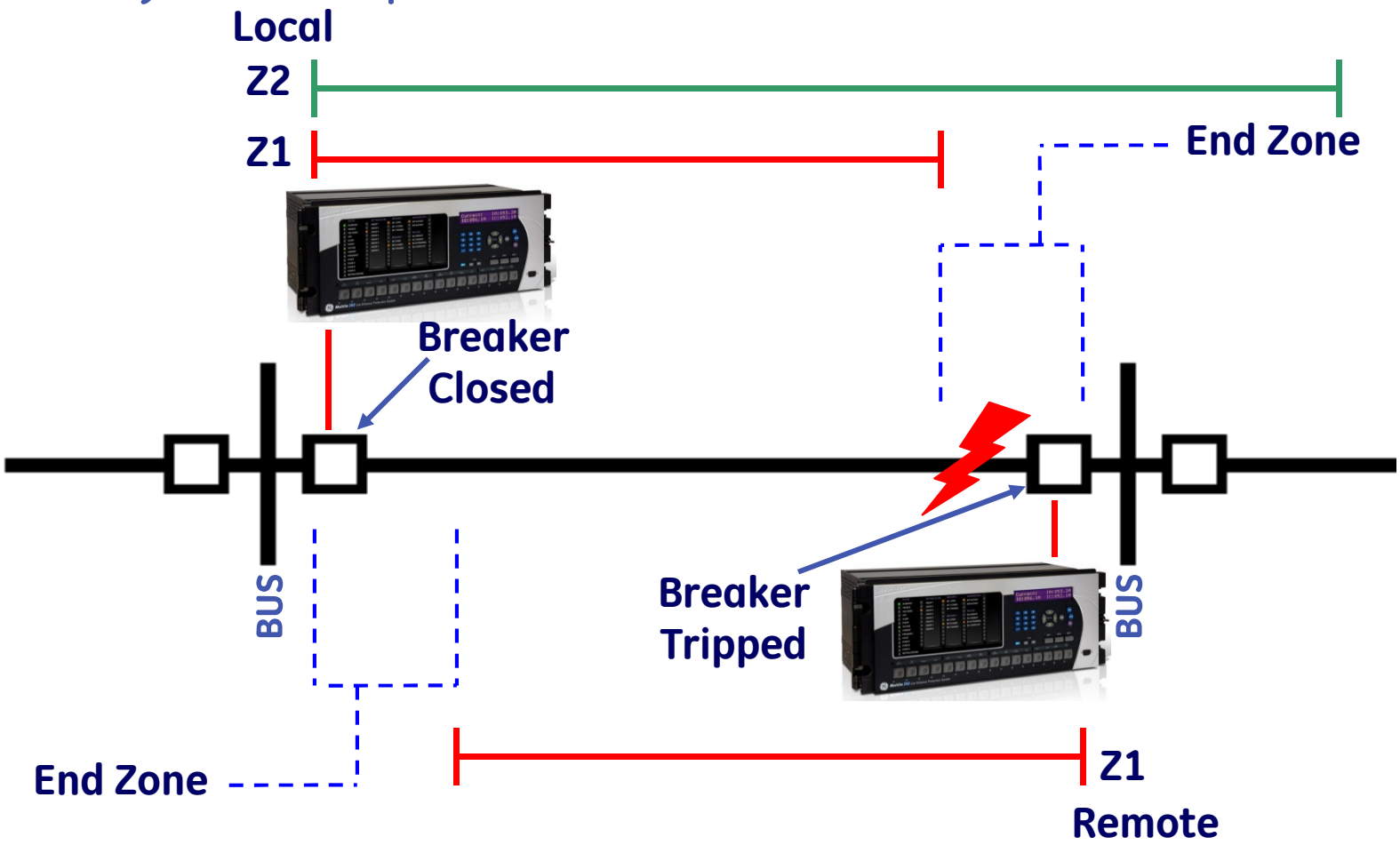
Pilot Aided Schemes:

- Fault in Zone 1 of both relays cleared instantly by local and remote relays



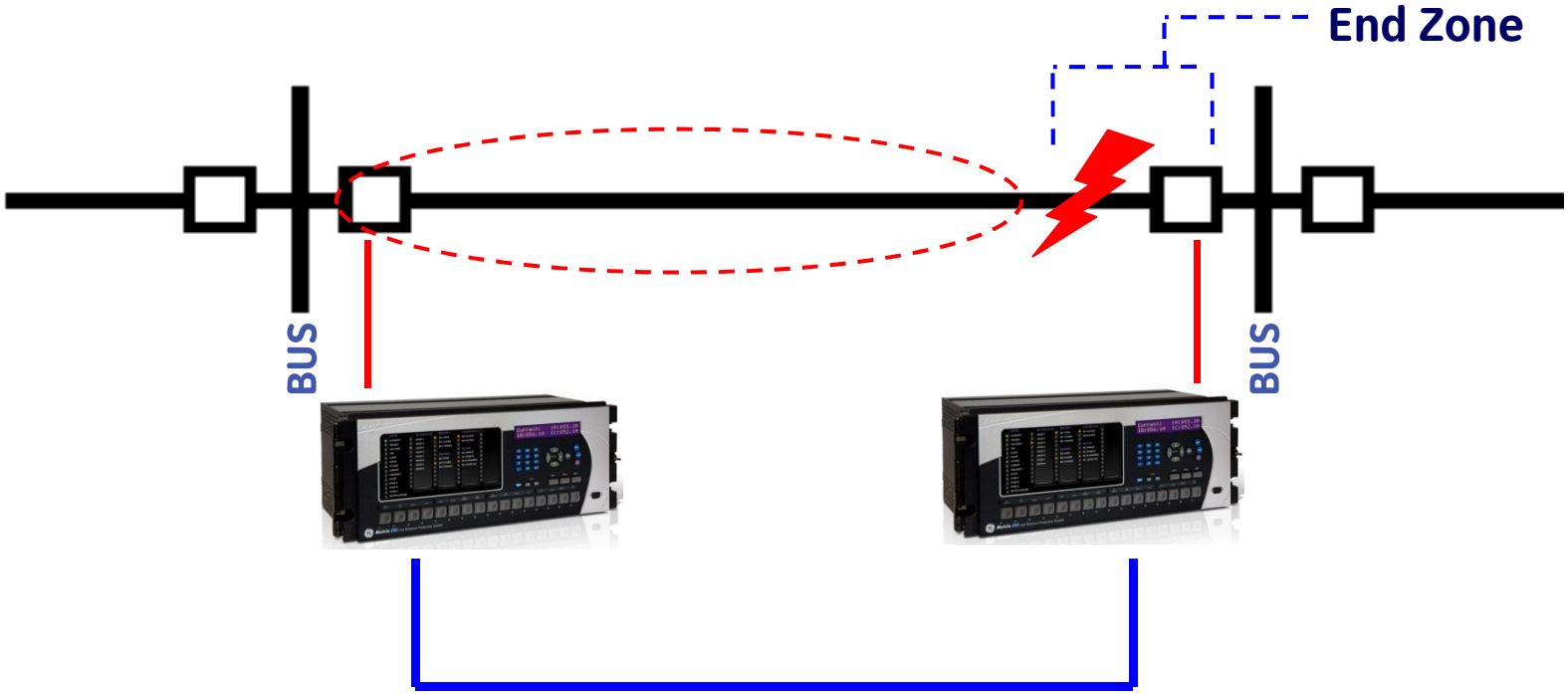
Pilot Aided Schemes:

- Fault in end zone only cleared instantly by the Remote relay without pilot scheme



Pilot Aided Schemes:

- Communication Channel speeds up clearing faults on transmission lines and in the end zones



- power line carriers, microwave radio channels, SONET channels, etc.

Pilot Aided Schemes:

- Communication Channels make all the difference
  - Fiber Optic tends to be very high speed and have high availability and high bandwidth. NOT AFFECTED DURING FAULT!
  - Microwave channels tend to be fairly high speed, but can be affected by weather conditions, vegation growth, etc. Fairly high bandwidth
  - Power line carrier is low bandwidth and can be severely affected during faults.

Pilot Aided Schemes:

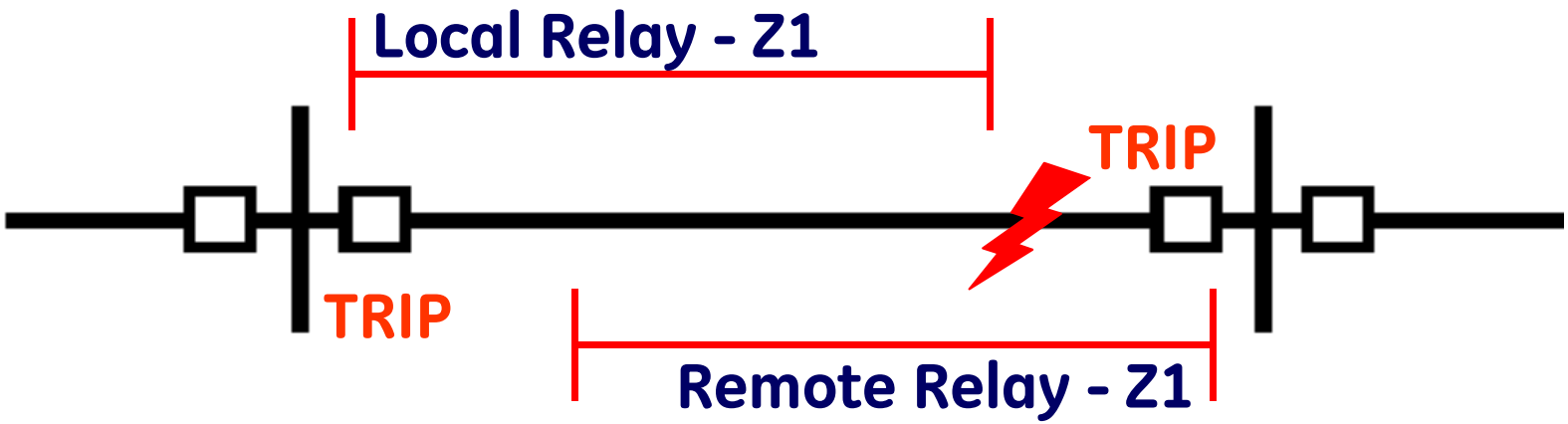
- Power Line Carrier
  - On-Off Keying –
    - Carrier signal is either on or off
    - You don't know if you have a good comm channel
  - Frequency Shift Keying (FSK) –
    - Two Frequencies called Guard and Trip
    - Loss of channel can be detected

Pilot Aided Schemes:

- DUTT – Direct Under-reaching Transfer Trip
- PUTT – Permissive Under-reaching Transfer Trip
- POTT – Permissive Over-reaching Transfer Trip
- Hybrid POTT – Hybrid Permissive Over-reaching Transfer Trip
- DCB – Directional Comparison Blocking Scheme
- DCUB – Directional Comparison Unblocking Scheme

Pilot Aided Schemes – DUTT:

DUTT – Direct Under-reaching Transfer Trip



TRIP

DUTT KEY

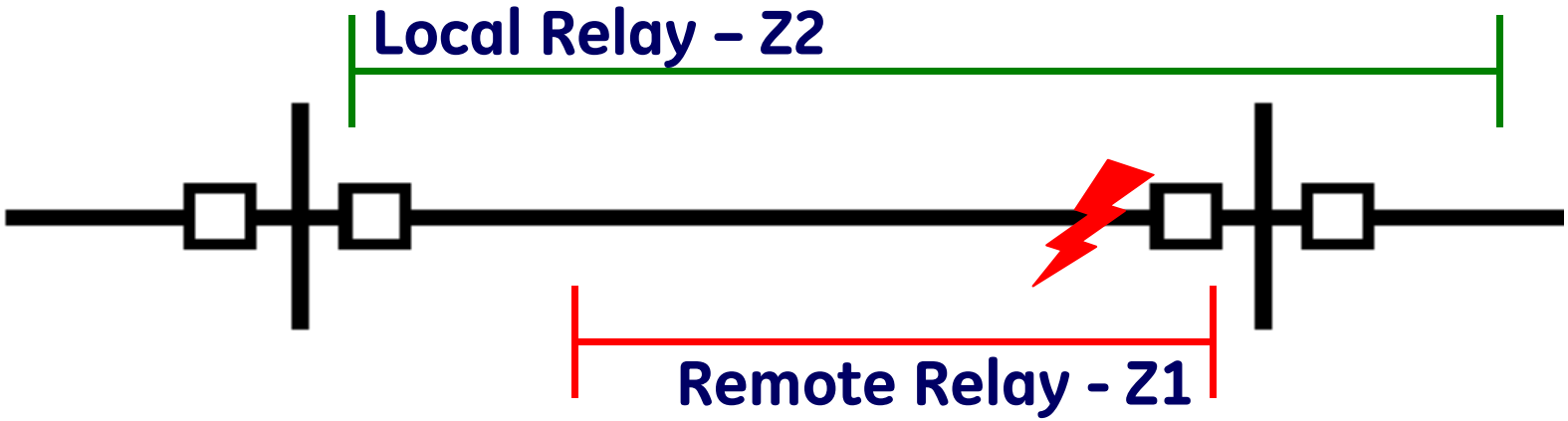
Local Relay

Remote Relay

Zone 1 - OP

Pilot Aided Schemes – PUTT:

PUTT – Permissive Under-reaching Transfer Trip



Local Relay

TRIP

PUTT Key

AND

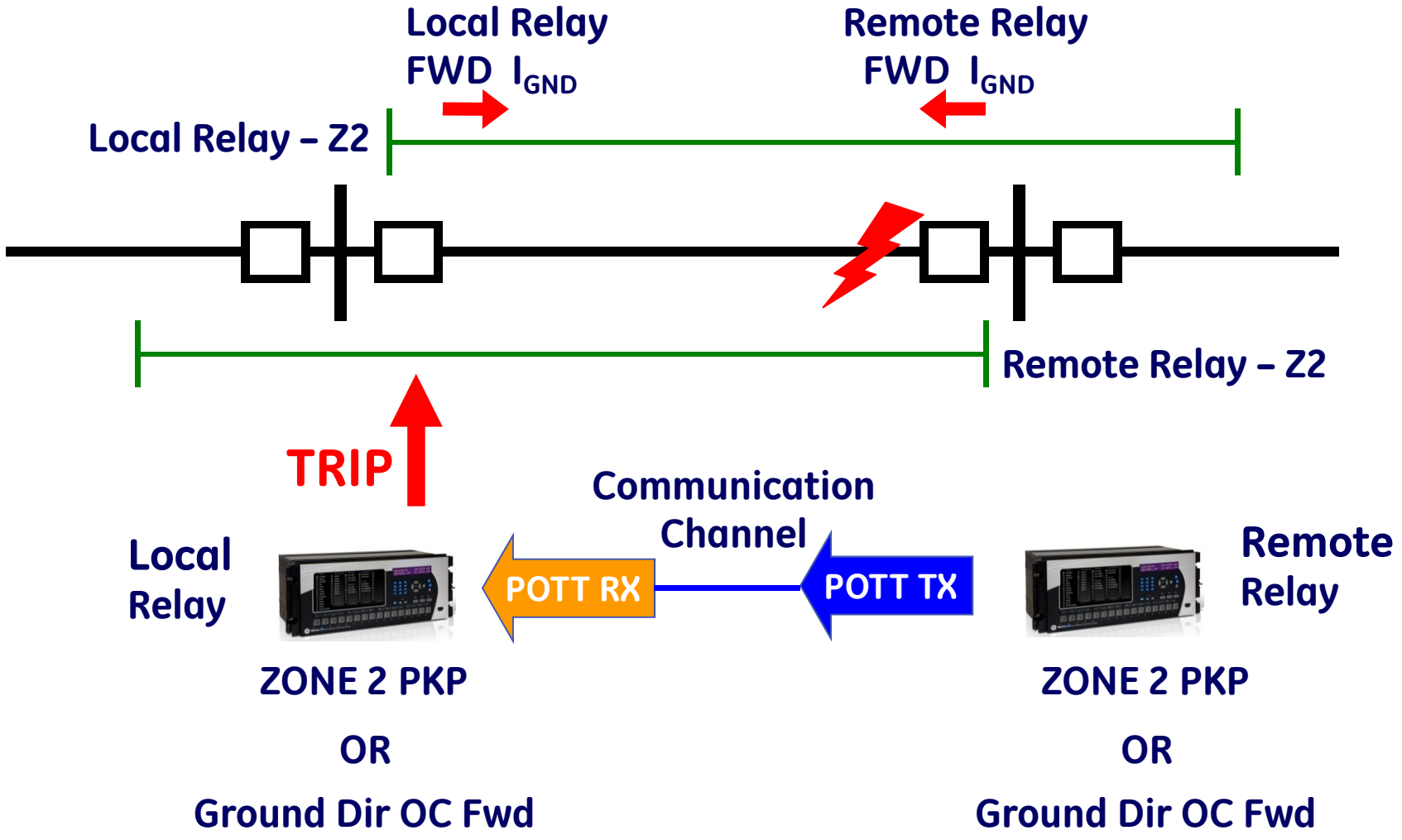
Zone 2 PKP

PUTT KEY

Remote Relay

Pilot Aided Schemes – POTT:

POTT – Permissive Over-reaching Transfer Trip



Pilot Aided Schemes – POTT:

- Conditions to cause relays to trip under the POTT scheme

Diagram 1:

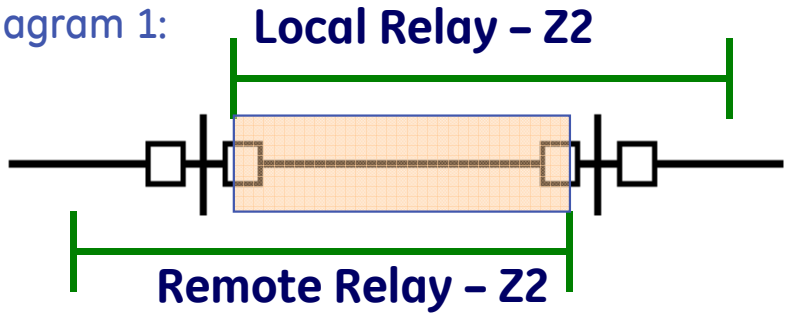


Diagram 2:

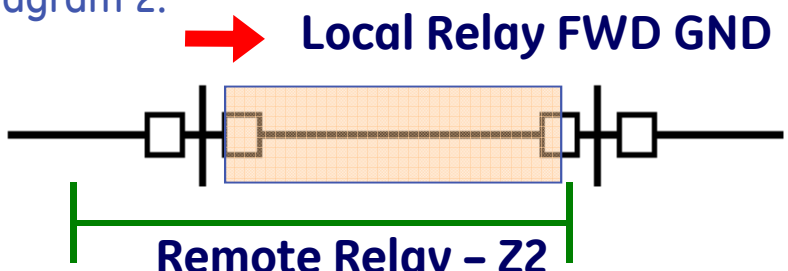


Diagram 3:

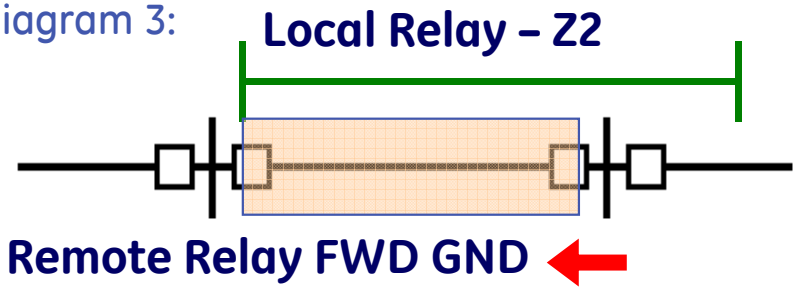
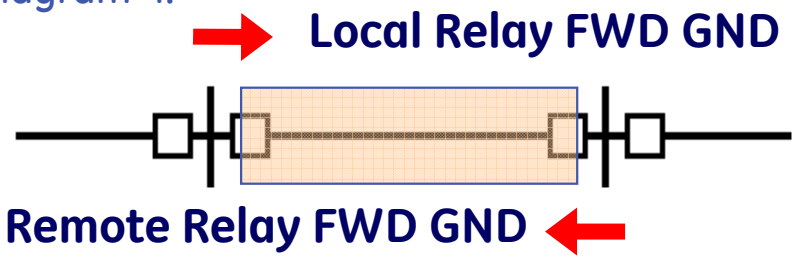


Diagram 4:



Pilot Aided Schemes – POTT:

- distance elements can also determine which phases of the transmission line are faulted

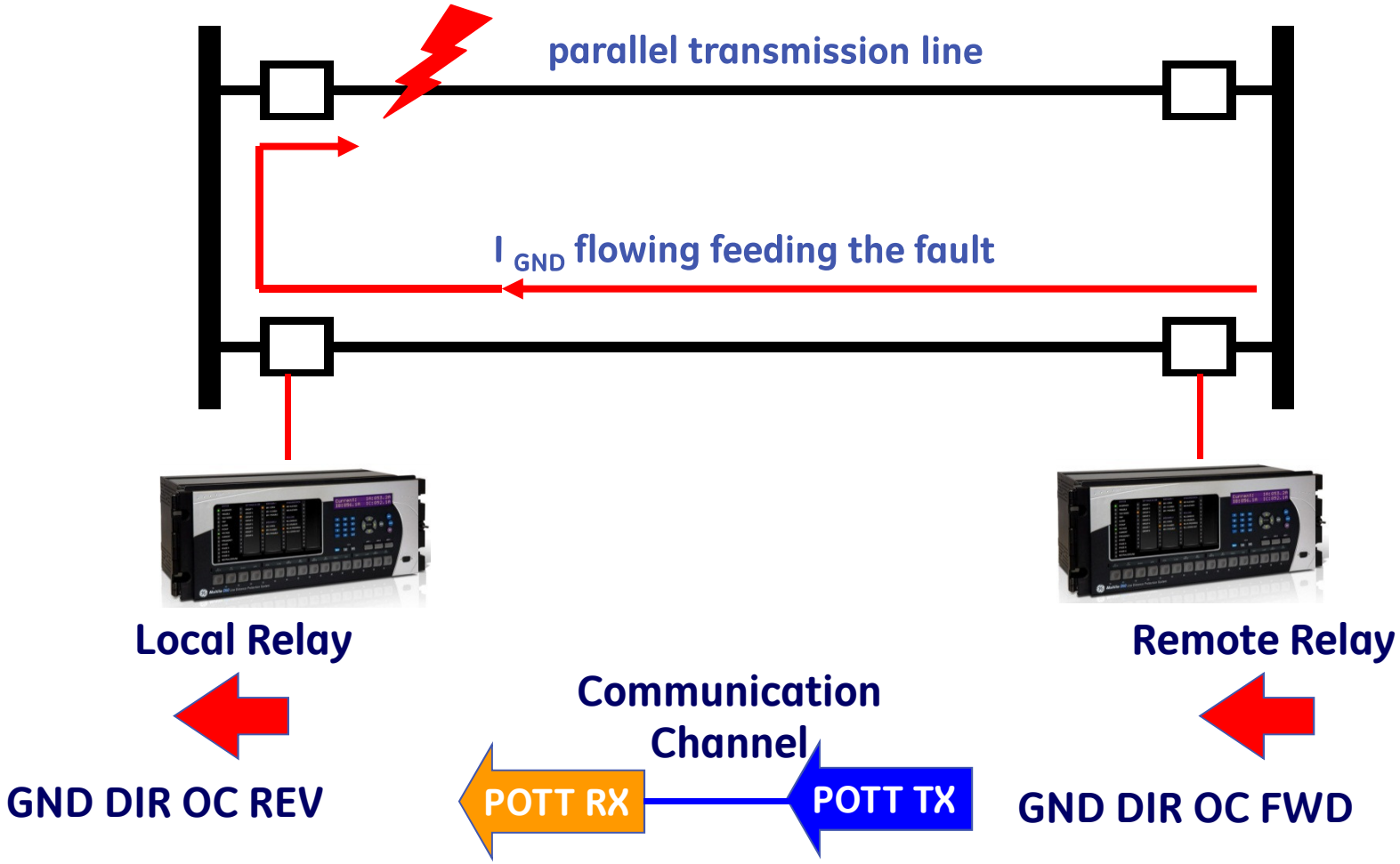
POTT RX 1
POTT RX 2
POTT RX 3
POTT RX 4

Communications Channel(s)

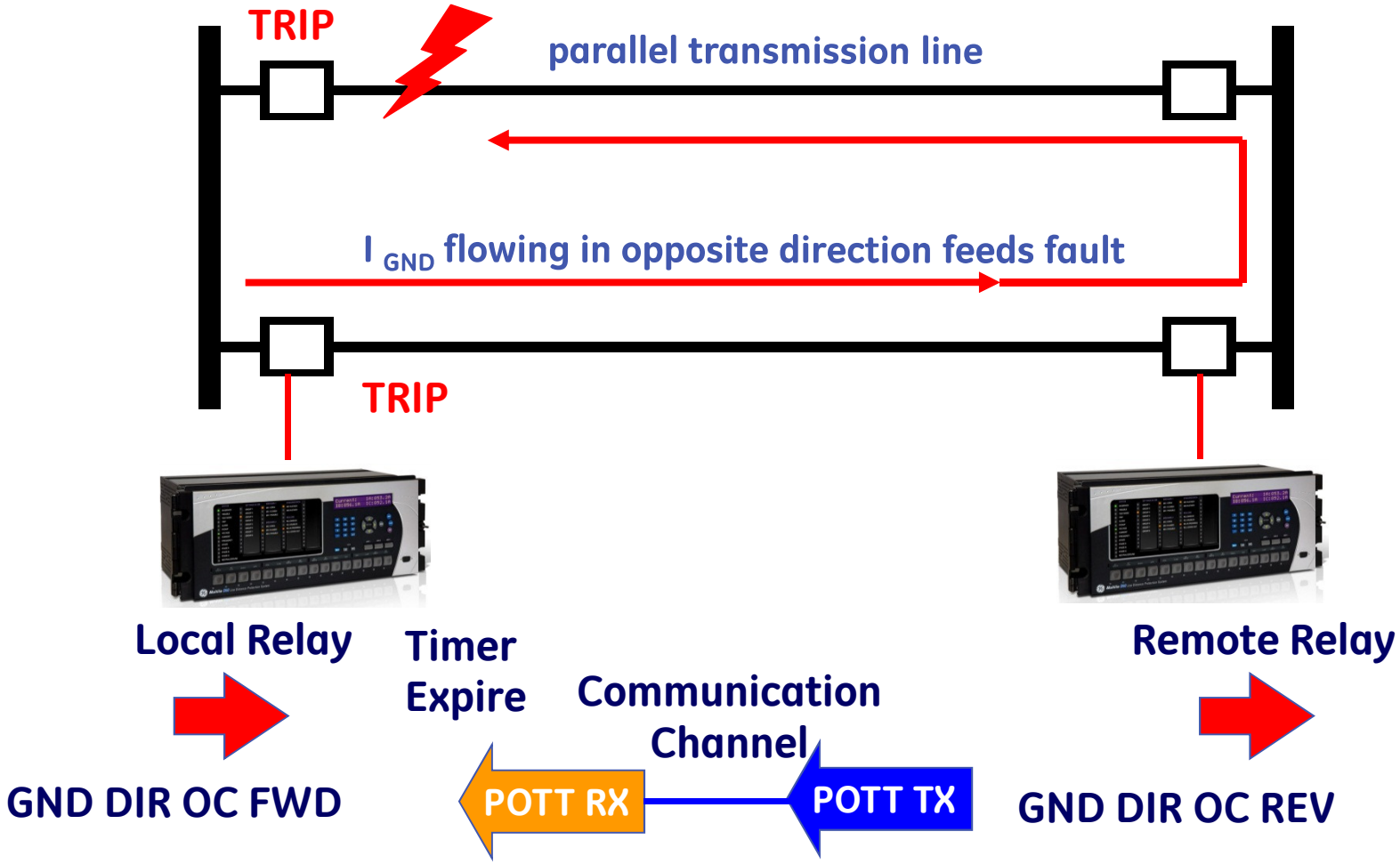
POTT TX 1 A to G
POTT TX 2 B to G
POTT TX 3 C to G
POTT TX 4 Multi Phase

Local Relay **Remote Relay**

Pilot Aided Schemes – POTT:
Example: Current Reversal

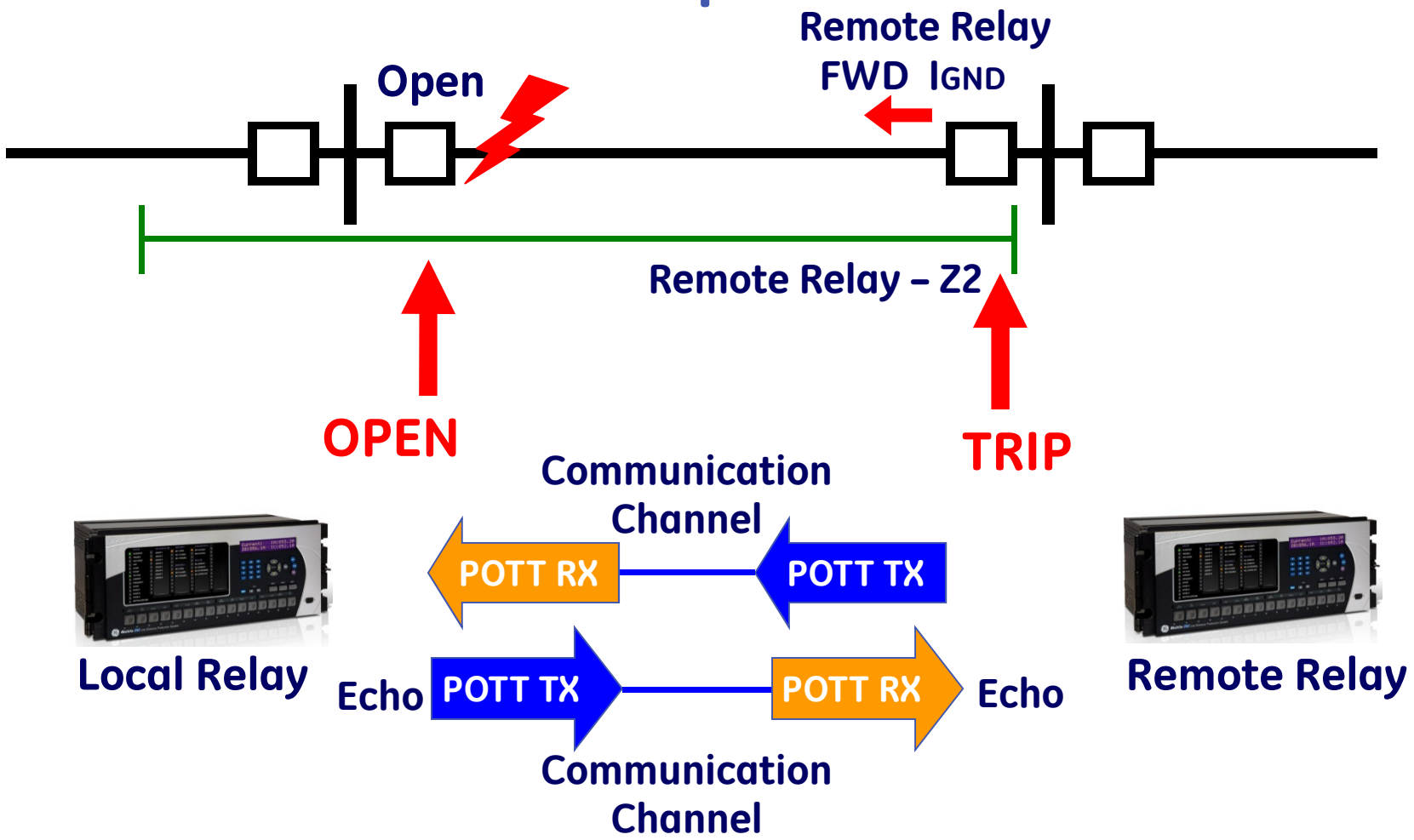


Pilot Aided Schemes – POTT:
Example (cont'd): Current Reversal

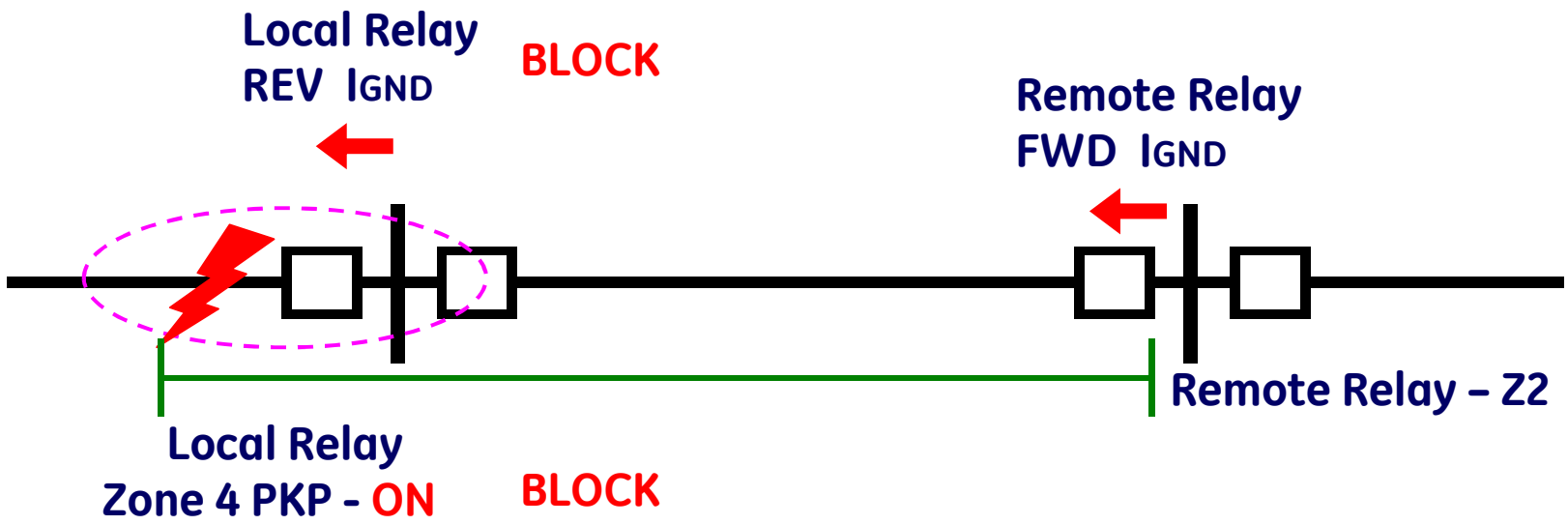


Pilot Aided Schemes – POTT:

Example: Echo



Pilot Aided Schemes – Hybrid POTT:



BLOCK

Local Relay

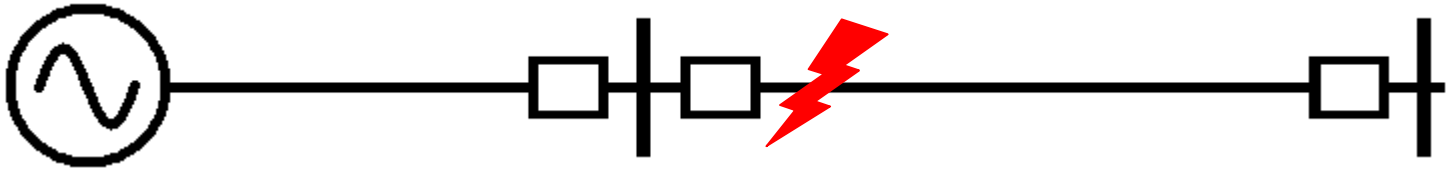
Hybrid POTT Key

Remote Relay

Pilot Aided Schemes – Hybrid POTT:

High Source Impedance

V = LOW



I = LOW

I_{GND} = LOW

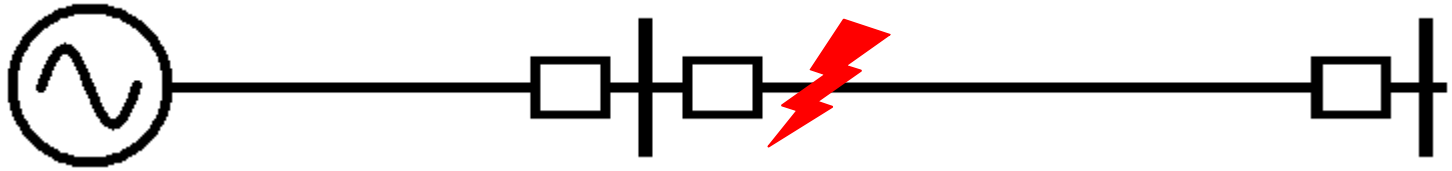
Local Relay

Remote Relay

Pilot Aided Schemes – Hybrid POTT:

- D60 Hybrid POTT scheme and Weak Infeed feature

High Source Impedance



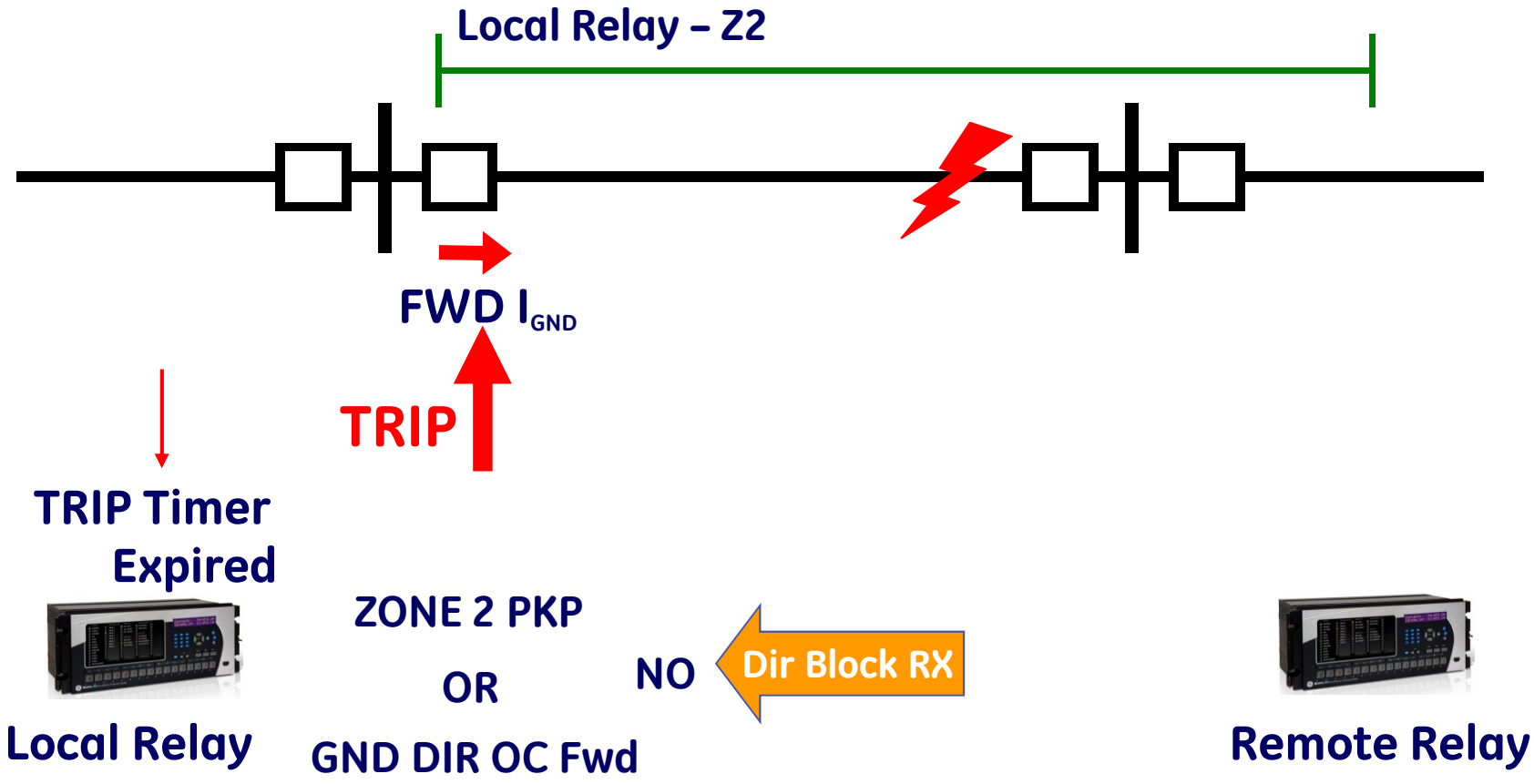
Local Relay

TRIP

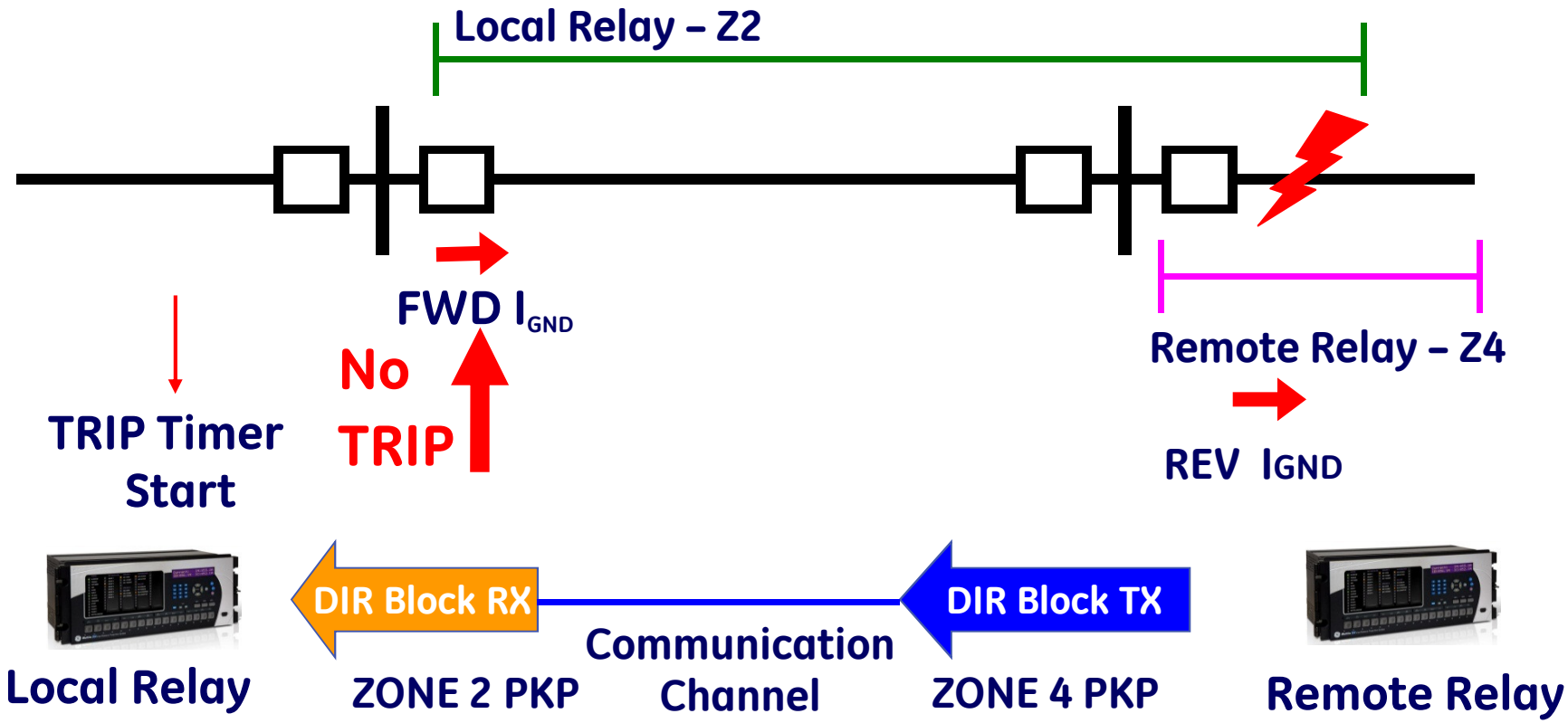
- **Voltage = LOW**
- **Neutral/Neg Seq Dir OC FWD = OFF**
- **Neutral/Neg Seq Dir OC REV = OFF**
- **ZONE 2 PKP = OFF**
- **ZONE 4 PKP = OFF**

Pilot Aided Schemes – DCB: (Internal Faults)

DCB - Directional Comparison Blocking Scheme

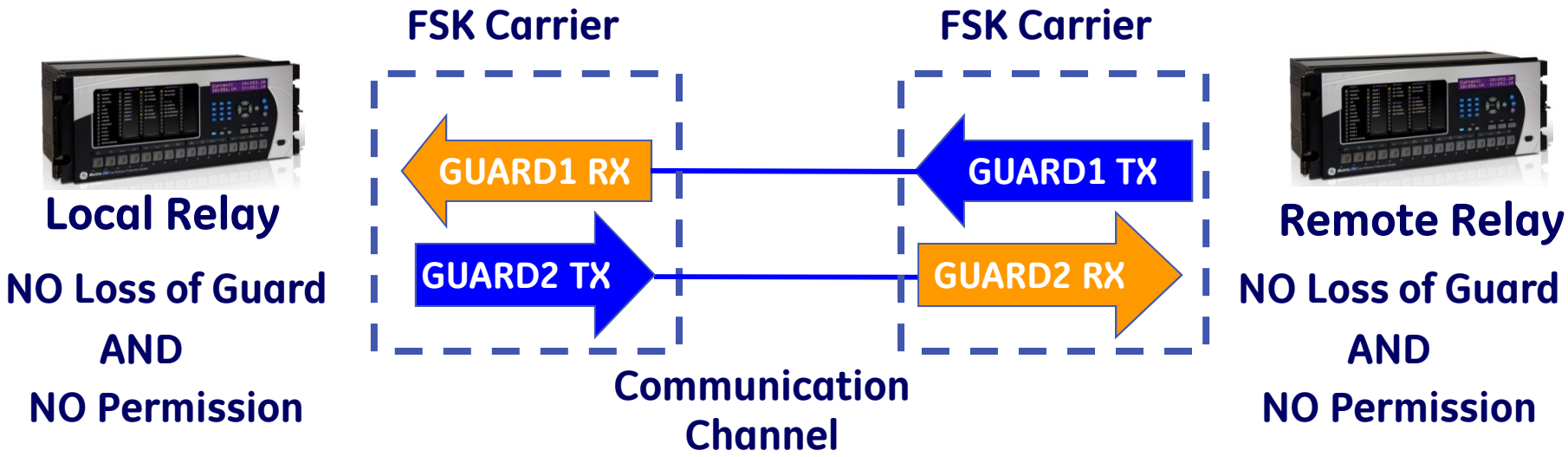


Pilot Aided Schemes – DCB:
(External Faults)



Pilot Aided Schemes – DCUB:
(Normal Conditions)

DCUB - Directional Comparison UnBlocking Scheme



Pilot Aided Schemes – DCUB:
(Normal Conditions, Channel Fails)

Loss of Channel

FSK Carrier

FSK Carrier

Local Relay

No RX

GUARD2 TX

GUARD1 TX

No RX

Remote Relay

Loss of Guard
AND
Block Timer Expired

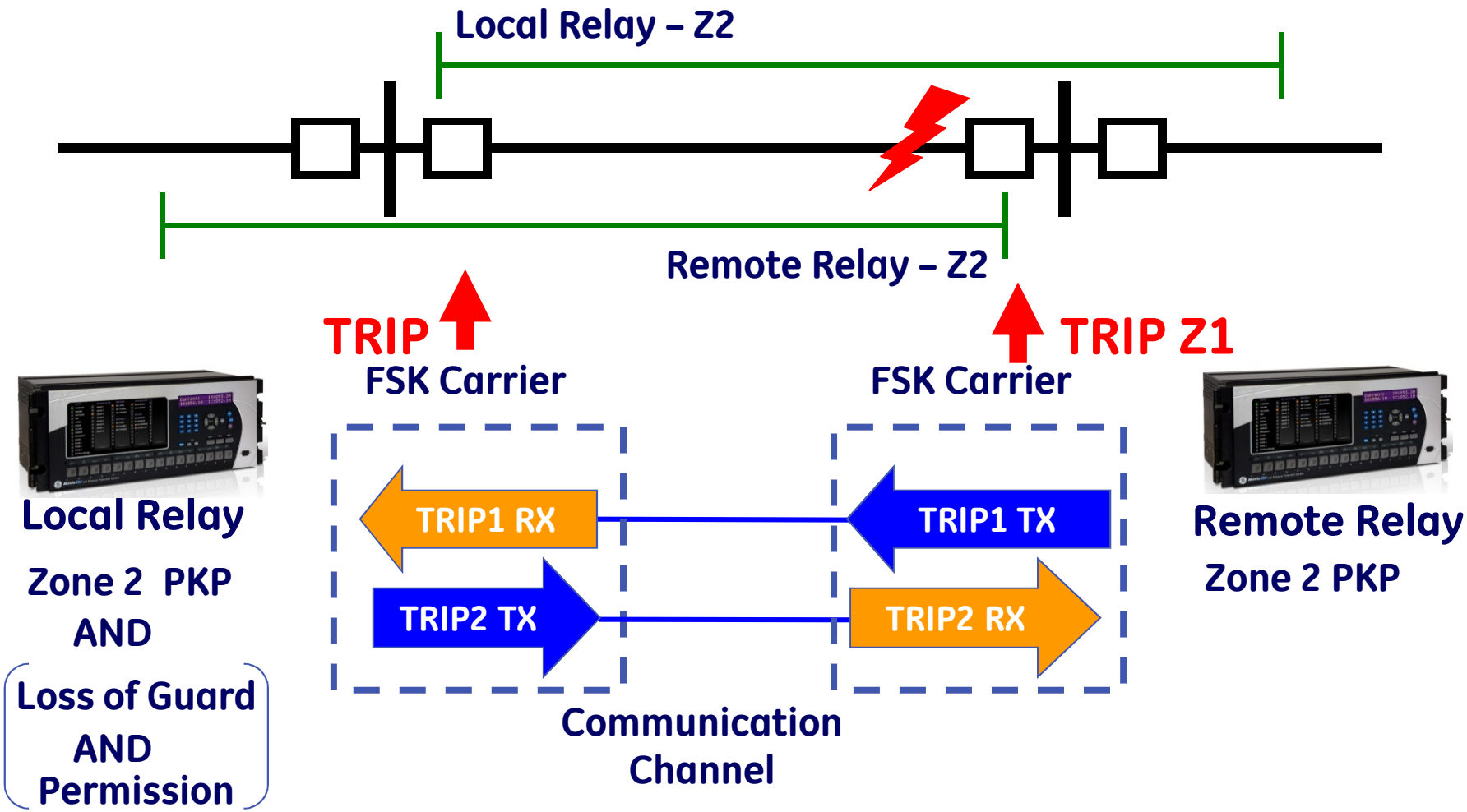
Communication
Channel

Loss of Guard
AND
Block Timer Expired

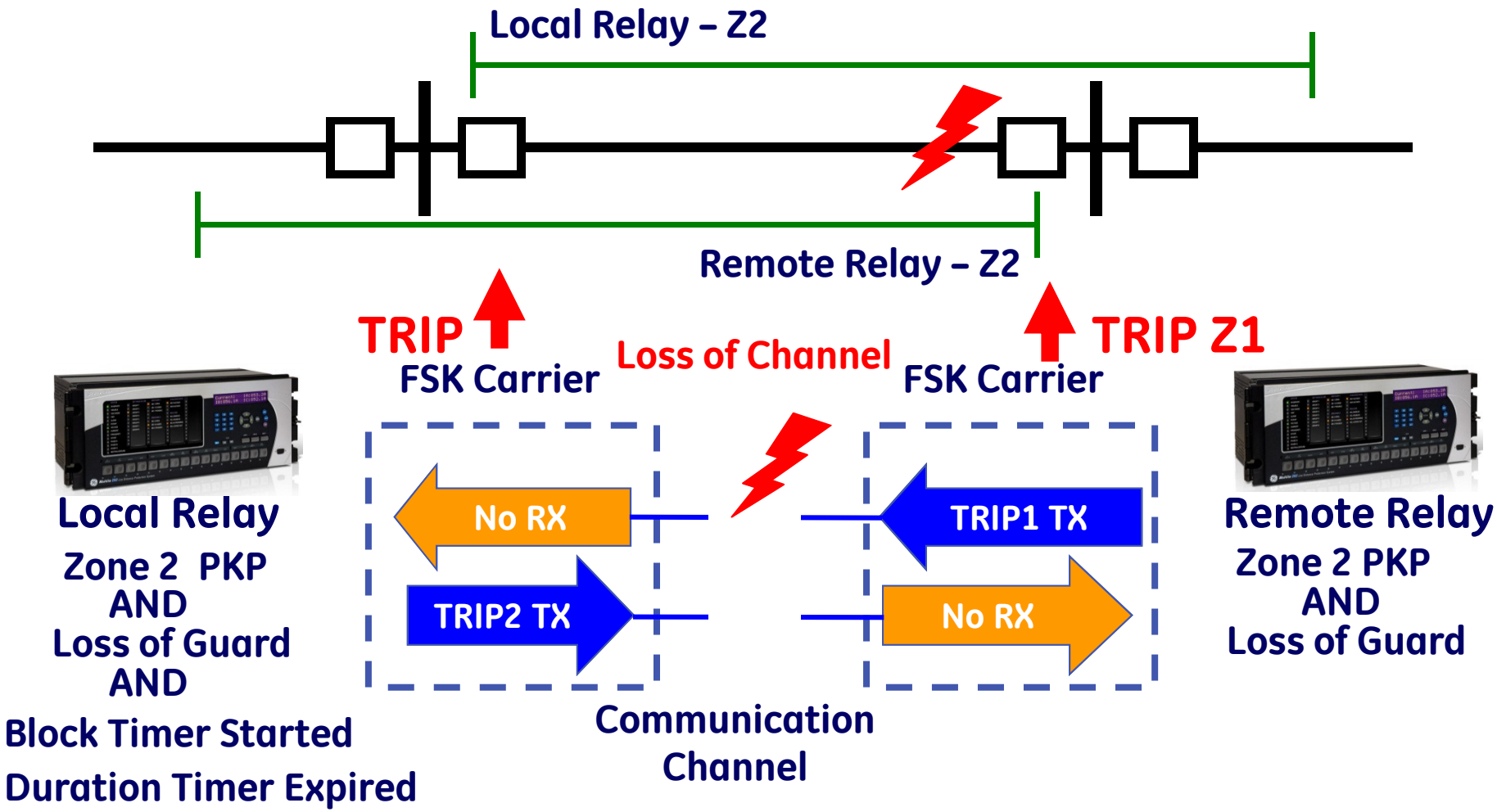
Block DCUB
until Guard OK

Block DCUB
until Guard OK

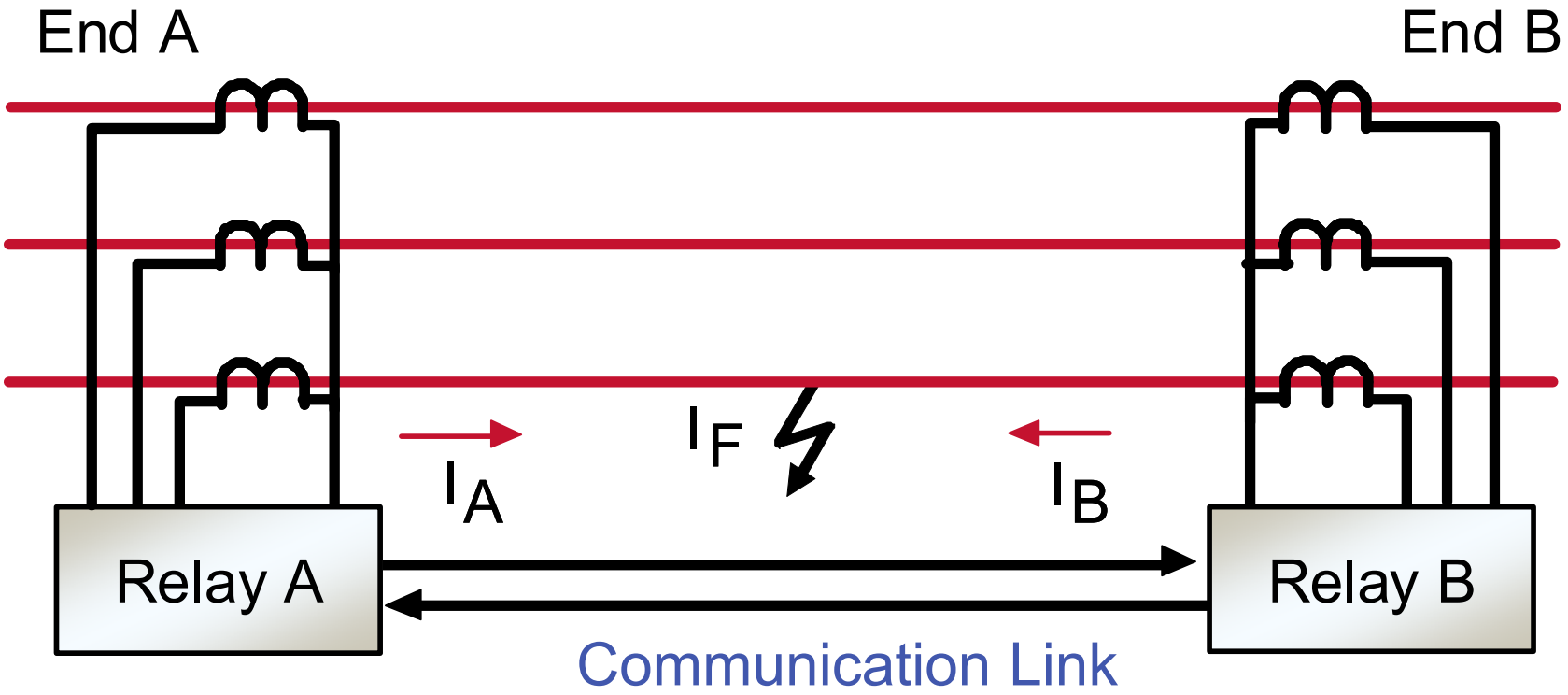
Pilot Aided Schemes – DCUB (POTT Mode): (Internal Fault, Normal Channel)



Pilot Aided Schemes – DCUB (DCB Mode): (Internal Fault, Channel Fail)



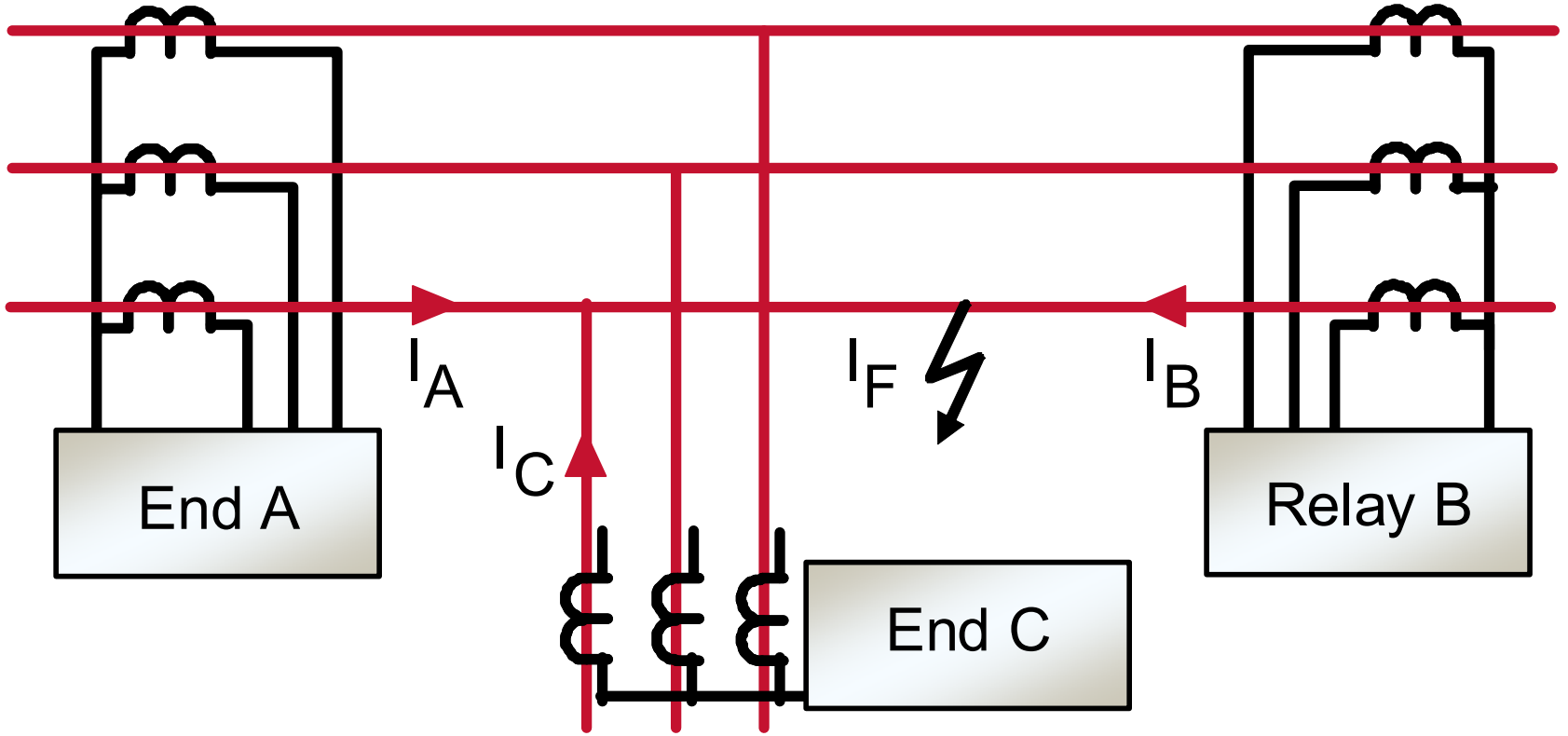
Current Differential Principle



$I_A + I_B = 0$ Healthy

$I_A + I_B \neq 0 (= I_F)$ Fault

Three Ended Line Protection



$I_A + I_B + I_C = 0$ Healthy

$I_A + I_B + I_C \neq 0$ (= I_F faulty)

Current Differential - Advantages

No voltage transformers needed

Good for multi-ended lines

Detect very high resistance faults

Immune to power swings

Uniform trip time

No problems with series compensation

Simple to set with no coordination problems

References

- ANSI/IEEE Device Numbers, C37.2
- ANSI Device Numbers, Publication No. GER-3977
- IEEE CT Burdens (5 Amps), C57.13
- Required information to apply protection
- IEEE Protective Relaying Standards
- "The Art of Protective Relaying," Publication No. GET-7201
- "Protective Relaying Principles and Applications" by J. Lewis Blackburn and Thomas J. Domin

ANSI / IEEE C37.2 Device Numbers:

1	Master Element	26	Apparatus Thermal Device
2	Time Delay or Closing Relay	27	Undervoltage Relay
3	Checking or Interlocking Relay	28	Flame Detector
4	Master Contactor	29	Isolating Contactor
5	Stopping Device	30	Annunciator Relay
6	Starting Circuit Breaker	31	Separate Excitation Device
7	Rate of Rise Relay	32	Directional Power Relay
8	Control Power Disconnect	33	Position Switch
9	Reversing Device	34	Master Sequence Device
10	Unit Sequence Switch	35	Brush Operating or Slip Ring Shorting
11	Multifunction Device	36	Polarity or Polarizing Voltage Device
12	Overspeed Device	37	Undercurrent or Underpower Relay
13	Synchronous-Speed Device	38	Bearing Protective Device
14	Underspeed Device	39	Mechanical Condition Monitor
15	Speed or Frequency Matching	40	Field Relay
16	Reserved for Future Use	41	Field Circuit Breaker
17	Shunting or Discharge Switch	42	Running Circuit Breaker
18	Accel or Decel Device	43	Manual Transfer or Selector Device
19	Start to Run Transition Contactor	44	Unit Sequence Starting Relay
20	Electrically Operated Valve	45	Atmospheric Condition Monitor
21	Distance Relay	46	Reverse Phase or Phase Balance Relay(I)
22	Equalizer Circuit Breaker	47	Phase Sequence Voltage Relay
23	Temperature Control Device	48	Incomplete Sequence Relay
24	Volts/Hz Relay	49	Machine or Transformer Thermal Relay
25	Synch Device or Synch Check	50	Instantaneous Overcurrent Relay

ANSI / IEEE C37.2 Device Numbers:

51	AC Time Overcurrent Relay	71	Level Switch
52	AC Circuit Breaker	72	DC Circuit Breaker
52a	Contacts Open when Main Contacts Open	73	Load Resistor Contactor
52aa	High Speed a contacts	74	Alarm Relay
52b	Contacts Open when Main Contacts Closed	75	Position Changing Mechanism
52bb	High Speed b contacts	76	DC Overcurrent Relay
53	Exciter or DC Generator Relay	77	Telemetering Device
54	Turner Gear Engaging Device	78	Phanse Angle Measuring Relay
55	Power Factor Relay	79	Reclosing Relay
56	Field Application Relay	80	Flow Switch
57	Shorting or Grounding Device	81	Frequency Relay
58	Rectification Failure Relay	82	DC Load Measuring Reclosing Relay
59	Overvoltage Relay	83	Automatic Selective Control or Transfer Relay
60	Voltage or Current Balance Relay	84	Operating Mechanism
61	Density Switch or Sensor	85	Carrier or Pilot Wire Relay
62	Time Delay Stopping or Opening Relay	86	Lockout Relay
63	Pressure Switch	87	Differential Protective Relay
64	Ground Detector Relay	88	Auxiliary Motor or Motor Generator
65	Governor	89	Line Switch
66	Notching or Jogging Device	90	Regulating Device
67	AC Directional Overcurrent Relay	91	Voltage Directional Relay
68	Blocking or Out-of-Step Relay	92	Voltage and Power Directional Relay
69	Permissive Control Device	93	Field Changing Contactor
70	Rheostat	94	Tripping or Trip-Free Relay

ANSI Device Numbers:

Publication No. GER-3977
C37.2 Partial Listing

No.	DESCRIPTION
2	Time-delay
21	Distance
25	Synchronism-check
27	Undervoltage
30	Annunciator
32	Directional power
37	Undercurrent or underpower
38	Bearing
40	Field
46	Reverse-phase
47	Phase-sequence voltage
49	Thermal
50	Instantaneous overcurrent
51	AC time overcurrent
59	Overvoltage
60	Voltage balance
63	Pressure
64	Apparatus ground
67	AC directional overcurrent
68	Blocking
69	Permissive
74	Alarm
76	DC overcurrent
78	Out-of-step
79	AC reclosing
81	Frequency
85	Carrier or pilot-wire
86	Lock out
87	Differential
94	Tripping

IEEE C57.13 CT Burdens (5 Amps):

Application	Burden Designation	Impedance (Ohms)	VA @ 5 amps	Power Factor
Metering	B0.1	0.1	2.5	0.9
	B0.2	0.2	5	0.9
	B0.5	0.5	12.5	0.9
	B0.9	0.9	22.5	0.9
	B1.8	1.8	45	0.9
Relaying	B1	1	25	0.5
	B2	2	50	0.5
	B4	4	100	0.5
	B8	8	200	0.5

Required Information to apply Protection:

1. One-Line Diagram of the system or area involved
2. Impedances and Connections of Power Equipment, System Frequency, Voltage Level and Phase Sequence
3. Existing Schemes
4. Operating Procedures and Practices affecting protection
5. Importance of Protection required and maximum allowed Clearance Times
6. System Fault Studies
7. Maximum Load and System Swing Limits
8. CTs and VTs Locations, Connections and Ratios
9. Future Expected Expansion
10. Any special considerations for application

IEEE Protective Relaying Standards:

IEEE Standard	Description
C37-91	IEEE guide for protective relay applications to power transformers
C37.96	IEEE Guide for AC Motor Protection
C37.97	IEEE guide for protective relay applications to power system buses
C37.99	IEEE guide for the protection of shunt capacitor banks
C37.101	IEEE guide for generator ground protection
C37.102	IEEE Guide for AC Generator Protection
C37.110	IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes
C37.113	IEEE guide for protective relay applications to
C37.119	IEEE Guide for Breaker Failure Protection of Power Circuit Breakers
PC37.230	IEEE (draft) Guide for Protective Relay Applications to Distribution Lines
C37-94	IEEE standard for N times 64 kilobit per second optical fiber interfaces between teleprotection and multiplexer equipment