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ABB Protective Relay School Webinar Series
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ABB Protective Relay School Webinar Series

Line distance protection fundamentals

Elmo Price

November 5, 2013

Presenter

Elmo Price

Elmo Price received his BSEE from Lamar State College of Technology in Beaumont, Texas and his MSEE degree in Power Systems Engineering from the University of Pittsburgh.

He began his career with Westinghouse in 1970 and worked in many engineering positions. He also worked as a district engineer located in New Orleans providing engineering support for Westinghouse power system products in the South-central U.S.

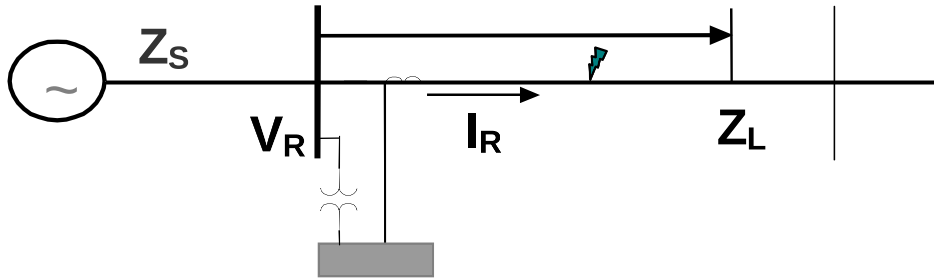
With the consolidation of Westinghouse into ABB in 1988, Elmo assumed regional responsibility for product application for the Protective Relay Division. From 1992 to 2002 he worked in various technical management positions responsible for product management, product design, application support and relay schools. From 2002 to 2008 Elmo was a regional technical manager providing product sales and application support in the southeastern U.S.

Elmo is currently senior consultant for ABB, a registered professional engineer and a Life Senior member of the IEEE. He is a member of the IEEE Power System Relay Committee and the Line Protection Subcommittee, serving as a contributing member to many working groups. He has two patents and has authored and presented numerous industry papers.

Learning objectives

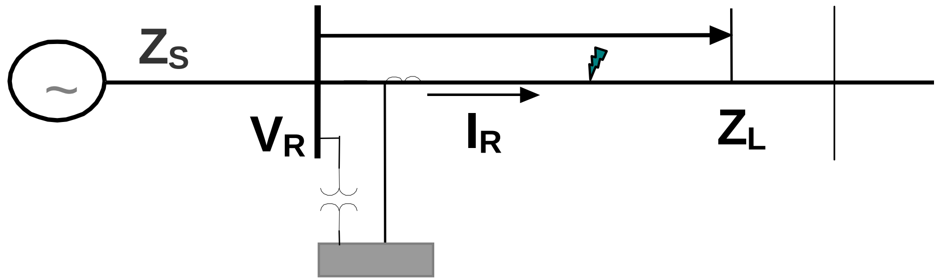
- Line distance measurement methods and characteristics
- Apparent impedance of fault loops and differences in phase and ground measurements
- The importance of faulted phase selection
- Step distance line protection
- Zone acceleration schemes (non-pilot)
- Basics of communications assisted schemes (optional – time permitting)

Distance and impedance relays



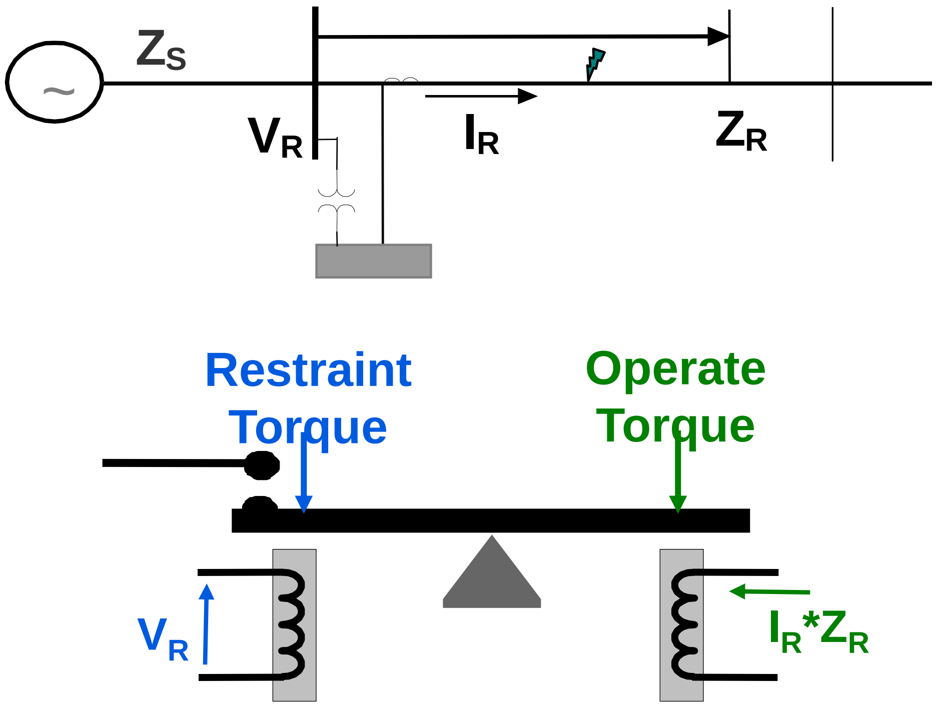
- Uses both voltage and current to determine if a fault is within the relay's set zone of protection
- Settings based on positive and zero sequence transmission line impedance
- Measures phase and ground fault loops

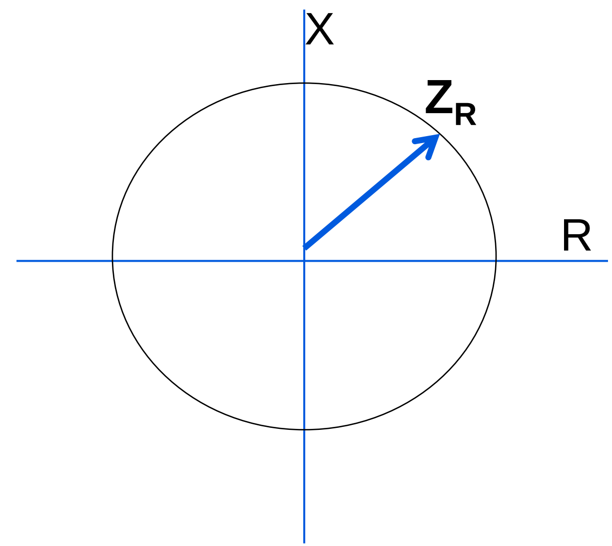
Distance and impedance relays
Brief History



- 1921 – Voltage restrained time overcurrent was first form of impedance relaying
- 1929 – Balance beam impedance relay improved operating speed performance, but was non-directional
- 1950 – Induction cup phase comparator providing mho distance characteristic
- 1965 – Solid-state implementations
- 1984 – Microprocessor implementations

Impedance relay
Simple balance beam



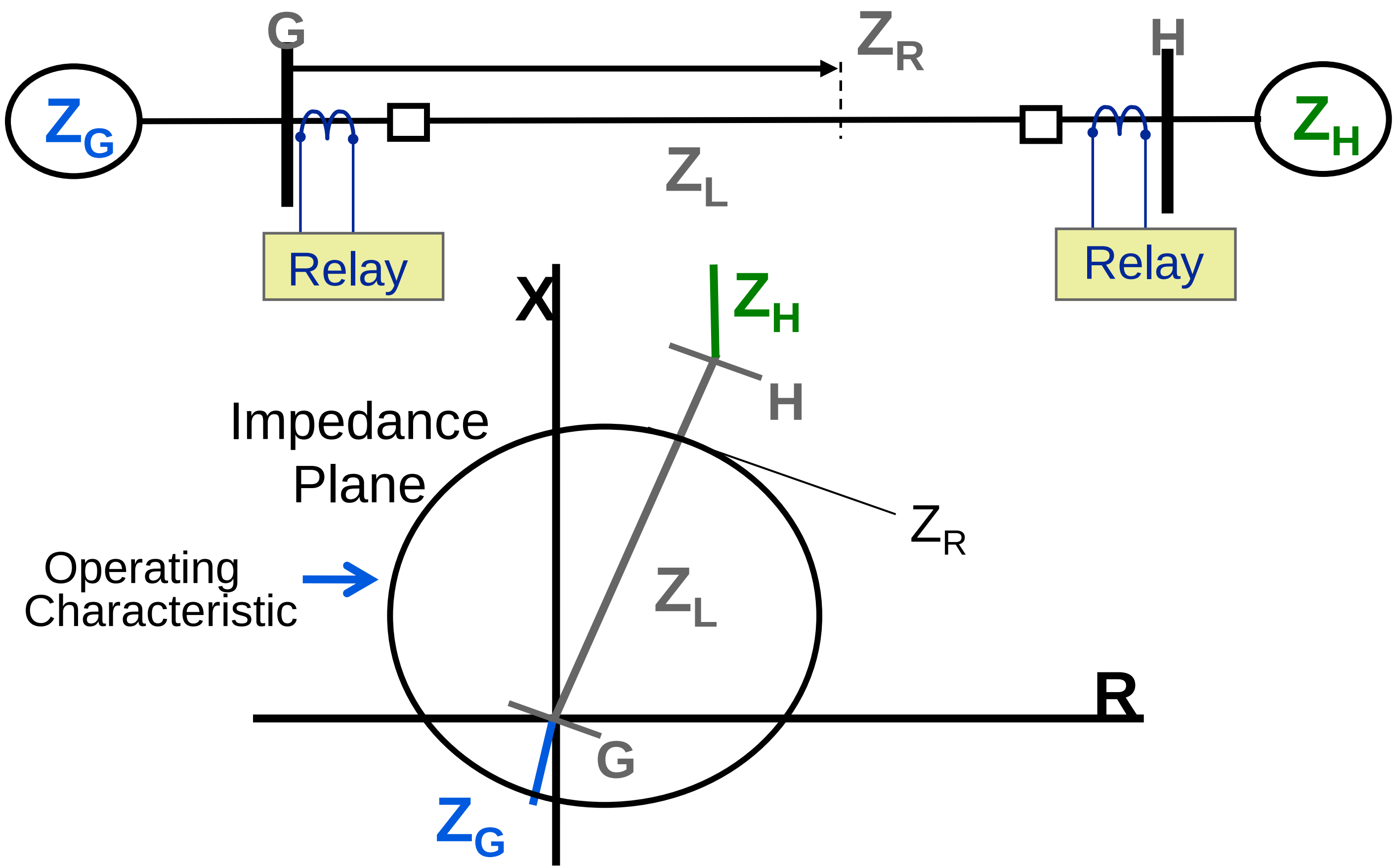


Reach to balance point = $V_R/I_R = Z_R$

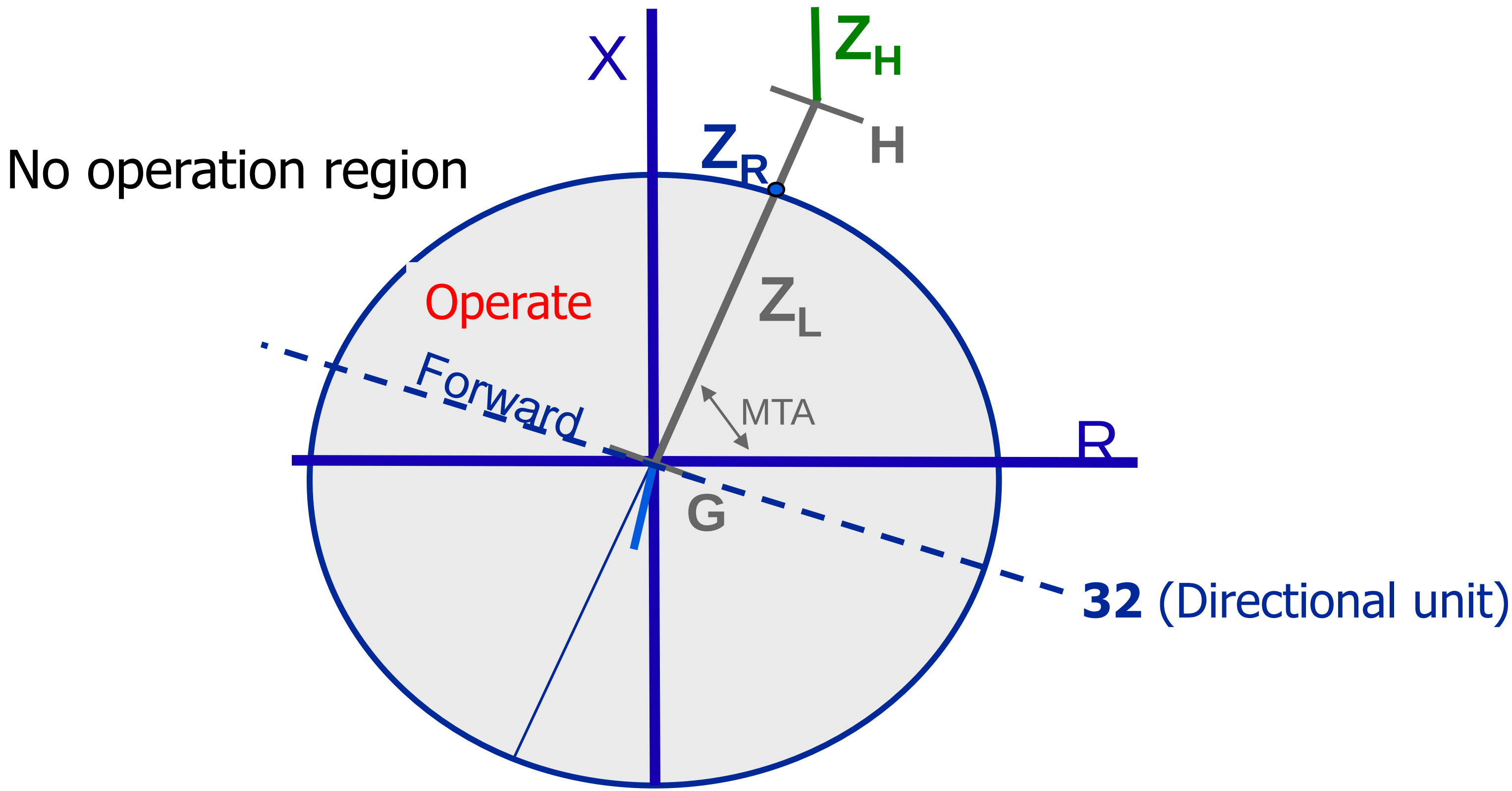
Distance relays

- Need
  - Fault levels are higher on high voltage transmission lines
  - Faults need to be cleared rapidly to avoid instability, and extensive damage
- Advantages
  - The impedance zone has a fixed impedance reach
  - Greater Instantaneous trip coverage with security
  - Greater sensitivity
  - Easier setting calculations and coordination
  - Fixed zone of protection that are relatively independent of system changes
  - Higher independence of load

Distance relay application

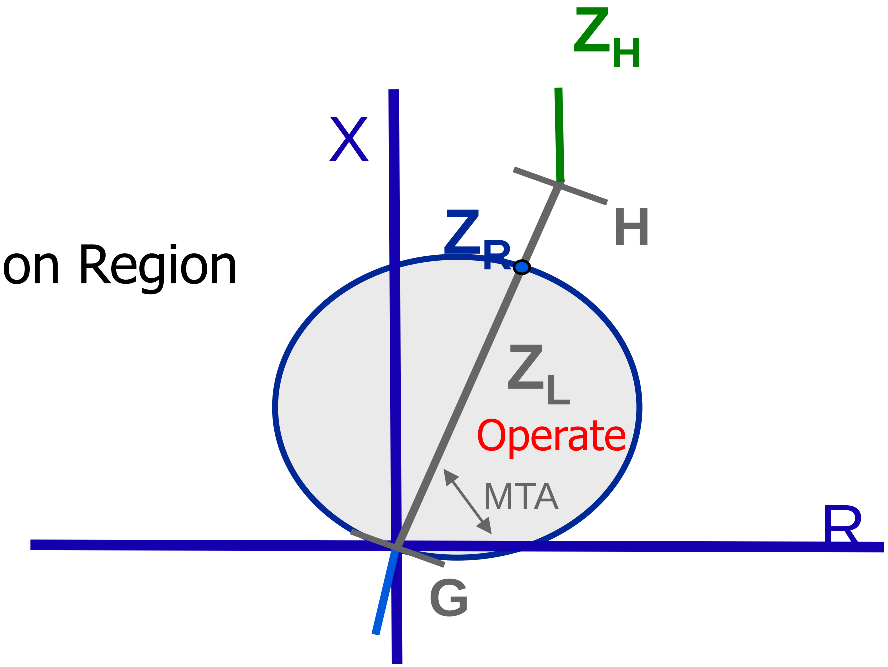


Distance relay characteristics
Impedance

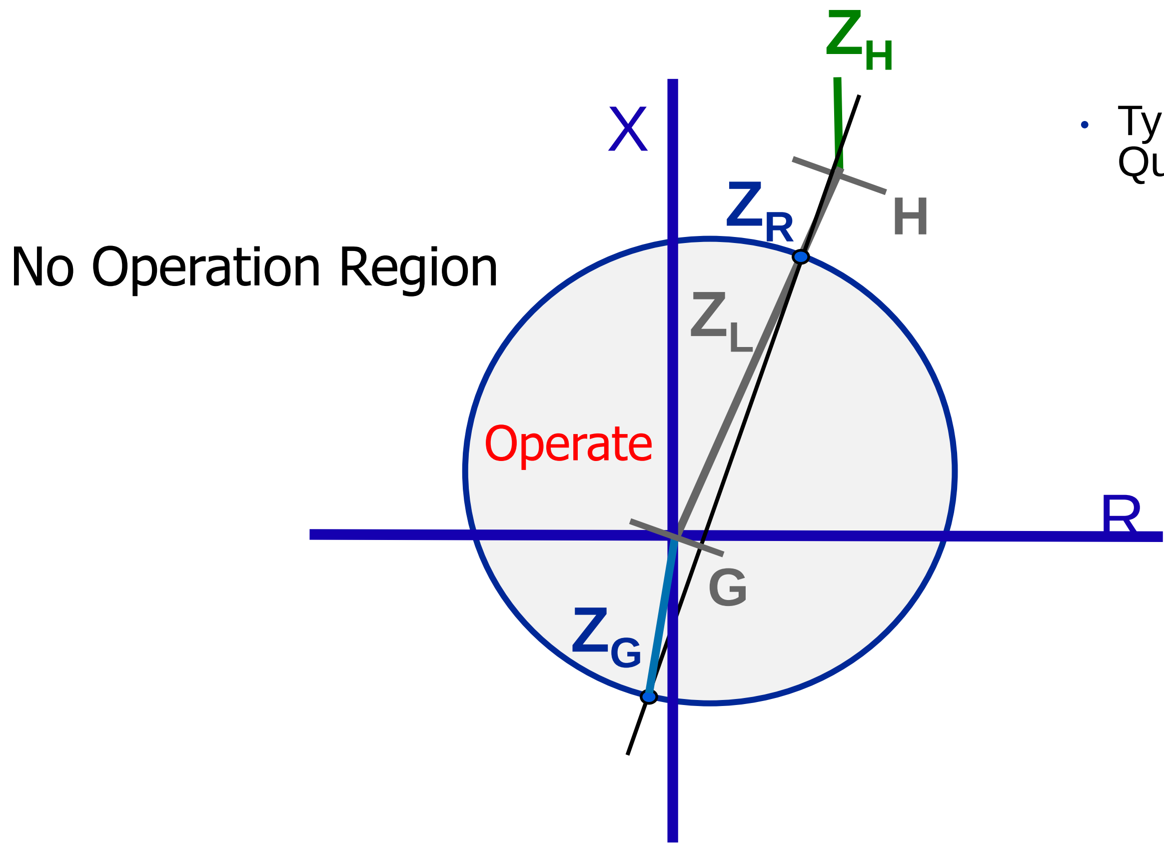


Distance relay characteristics
Mho distance, self (fault voltage) polarized

No Operation Region

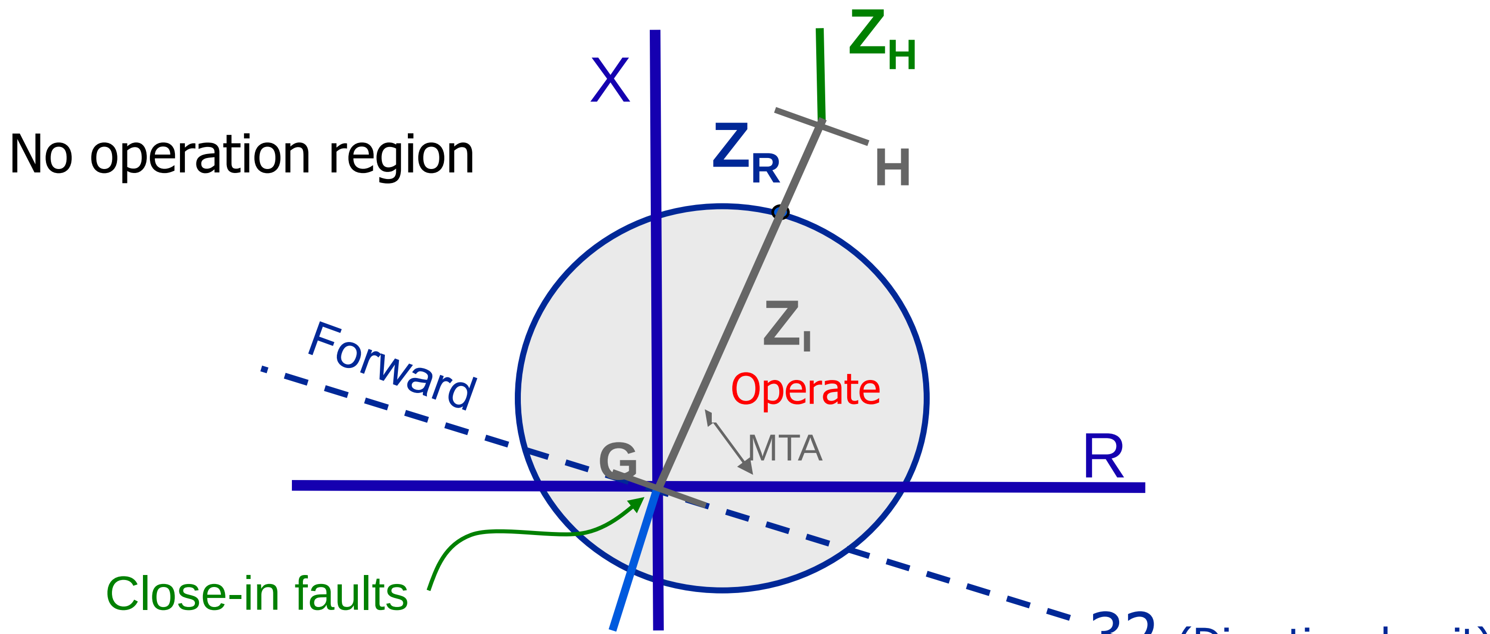


Distance relay characteristics
Mho distance, (healthy) voltage polarized

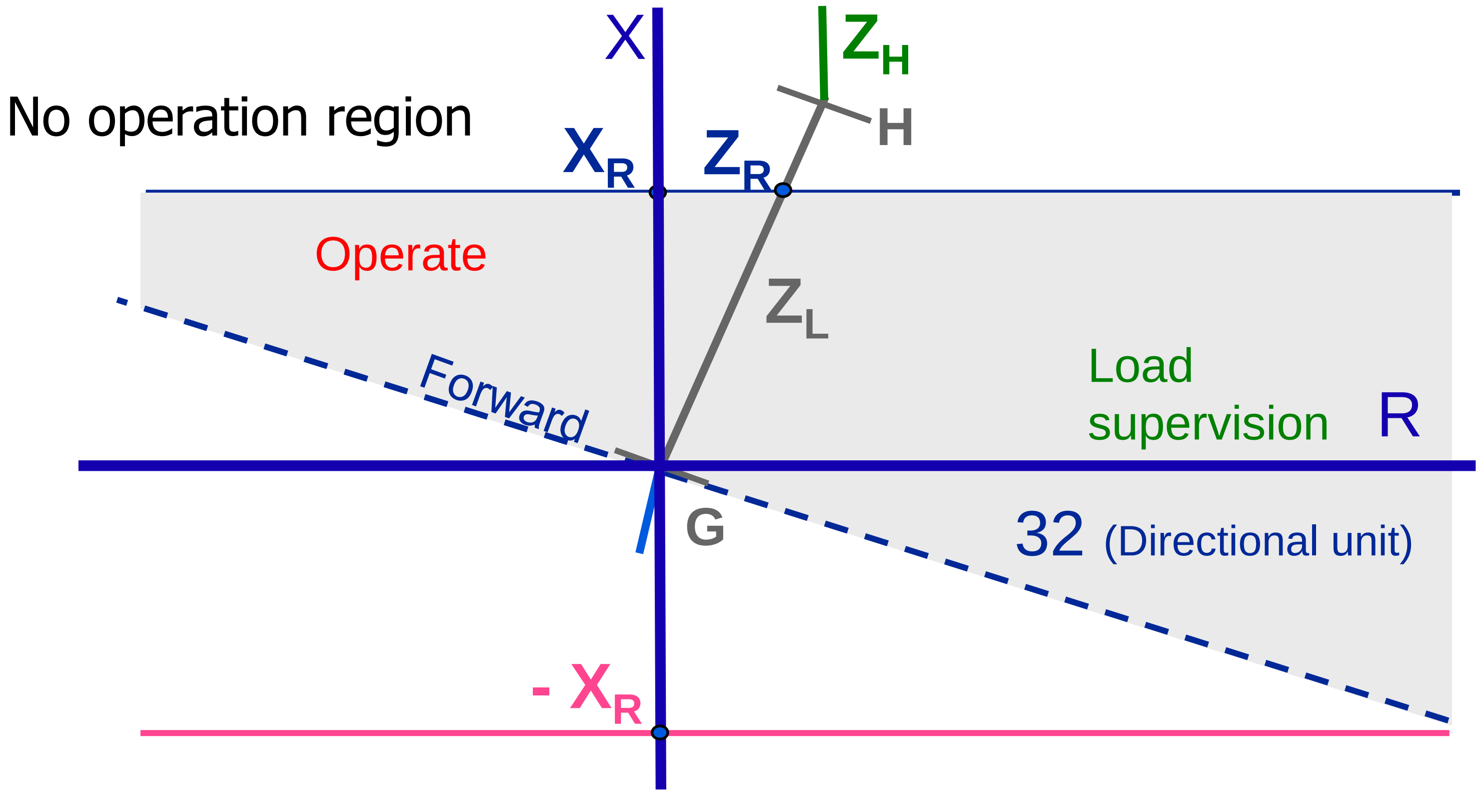


- Typical polarizing Quantities
  - Cross
  - Positive Sequence
  - Memory

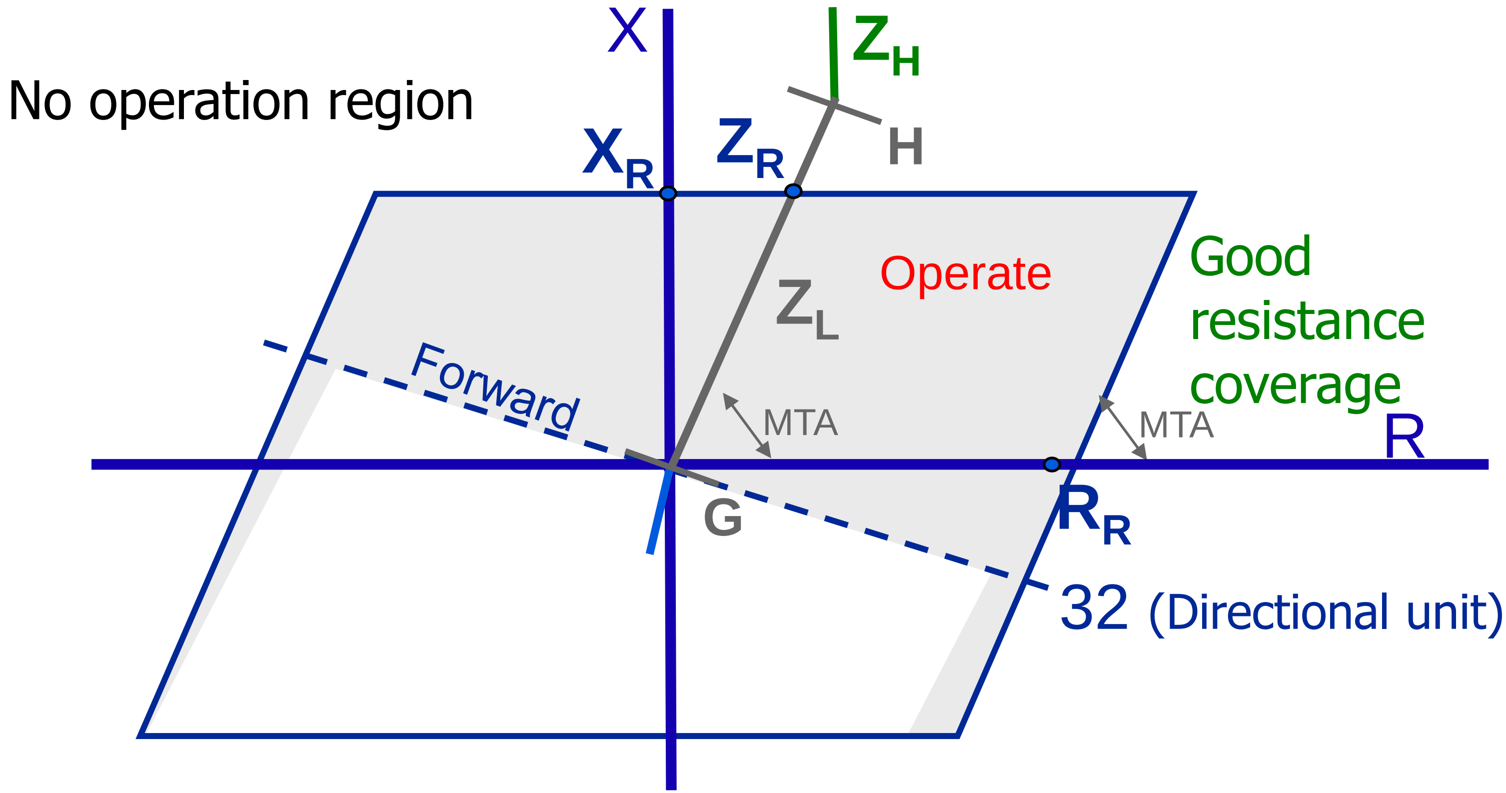
Distance relay characteristics
Offset mho distance



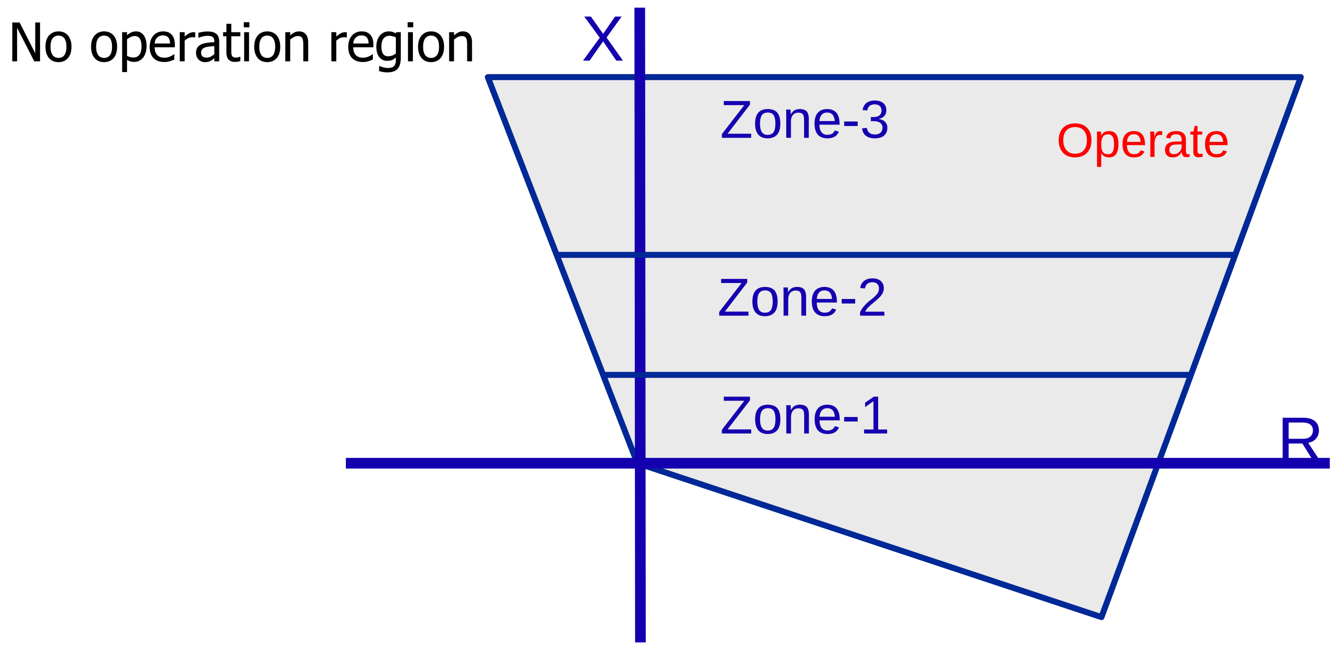
Distance relay characteristics
Reactance



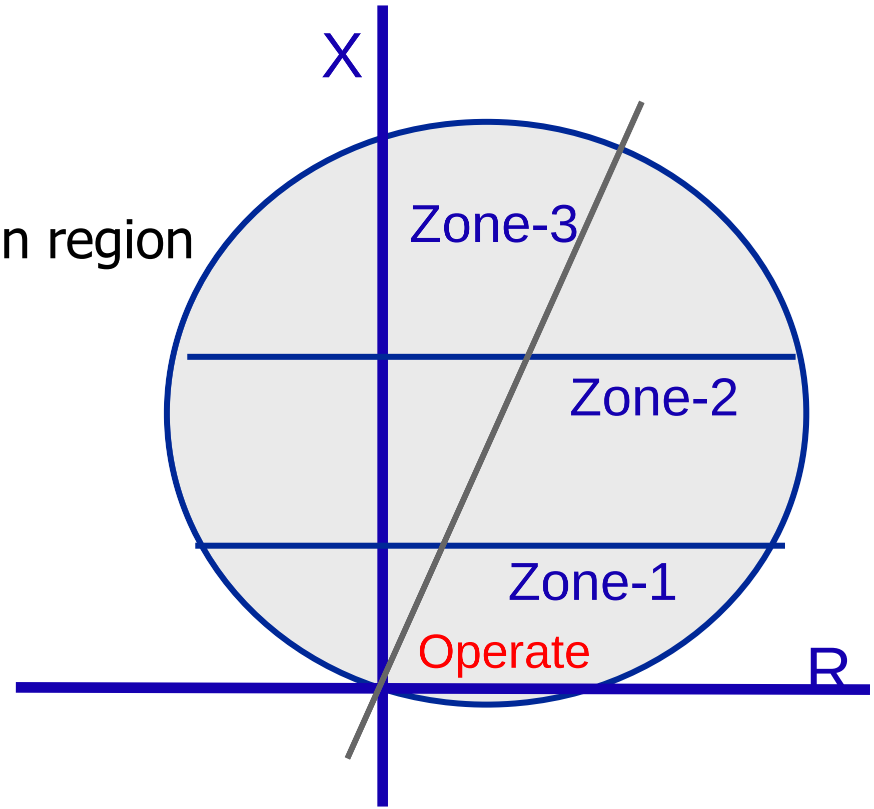
Distance relay characteristics
Quadrilateral



Distance relay characteristics
Switched zone quadrilateral

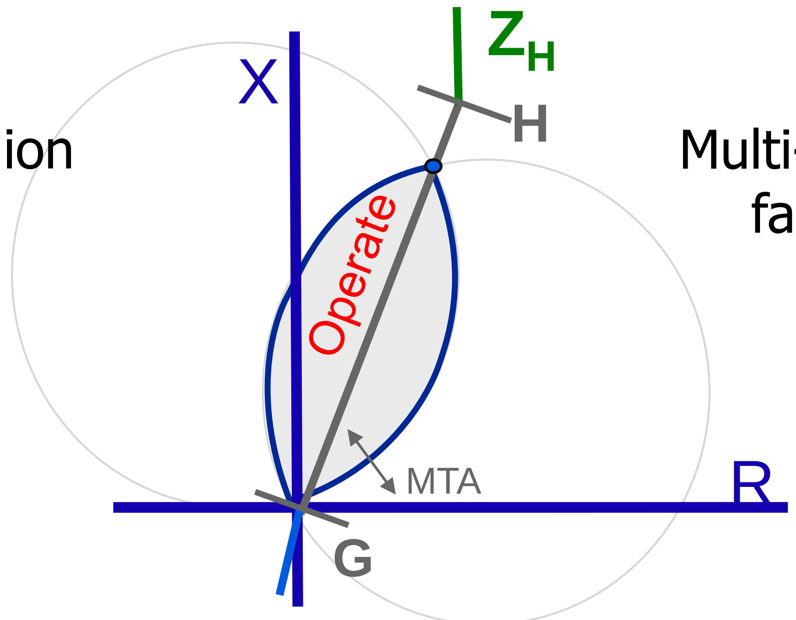


Distance relay characteristics
Mho distance with switched reactance



Distance relay characteristics
Lenticular

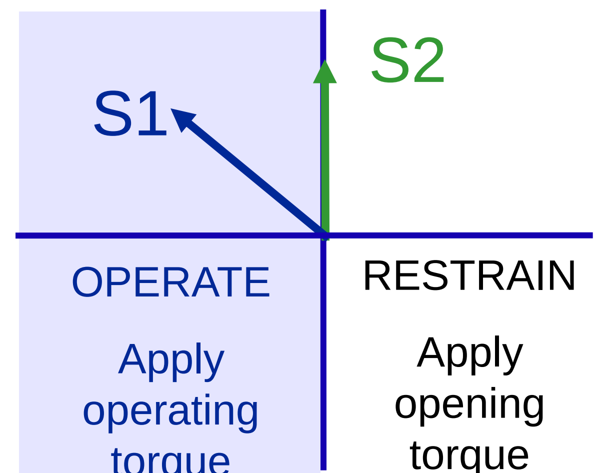
No operation region



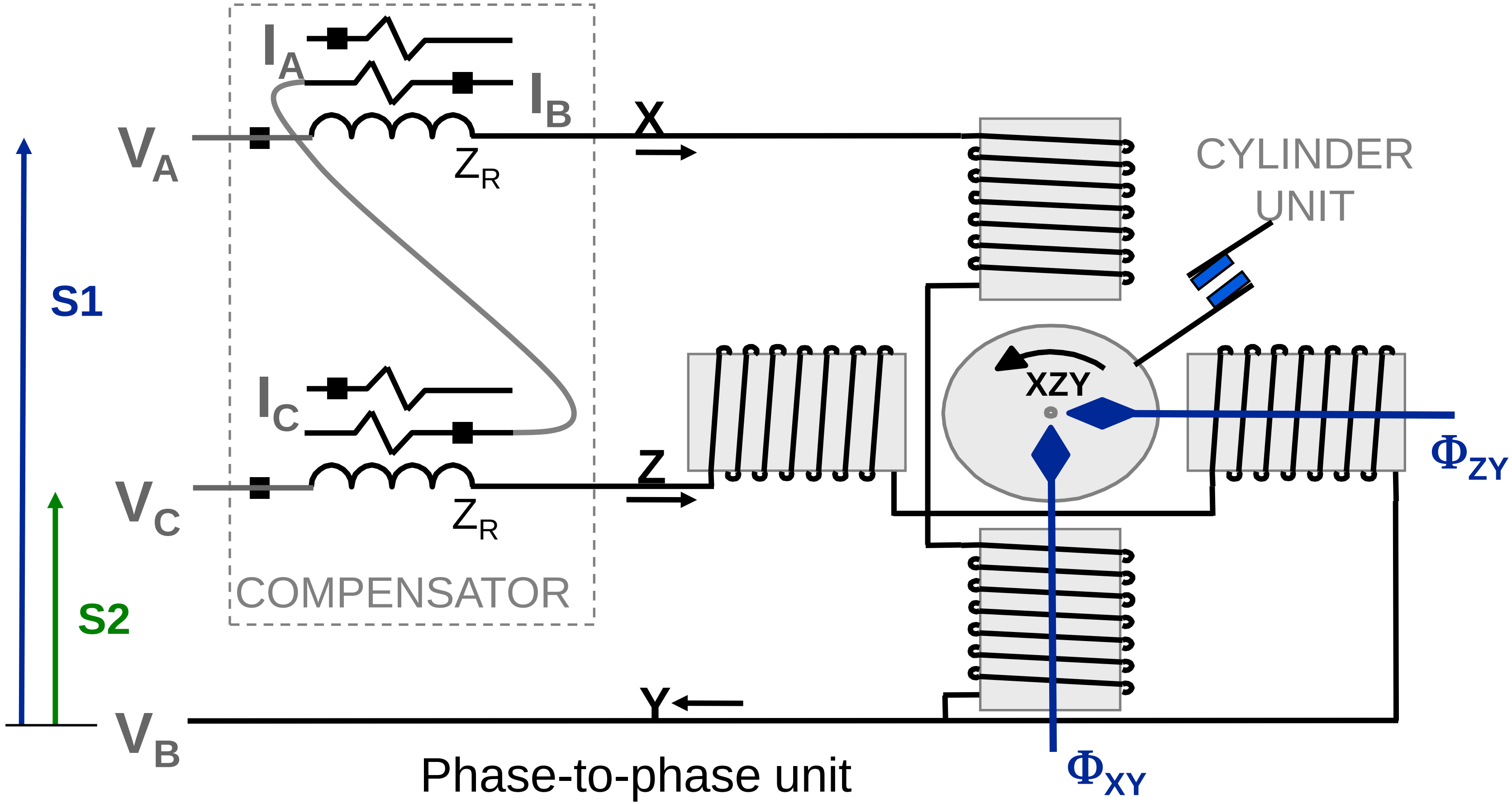
Multi-phase faults

Phase comparators

Compares the phase angle of two phasor quantities to determine operation

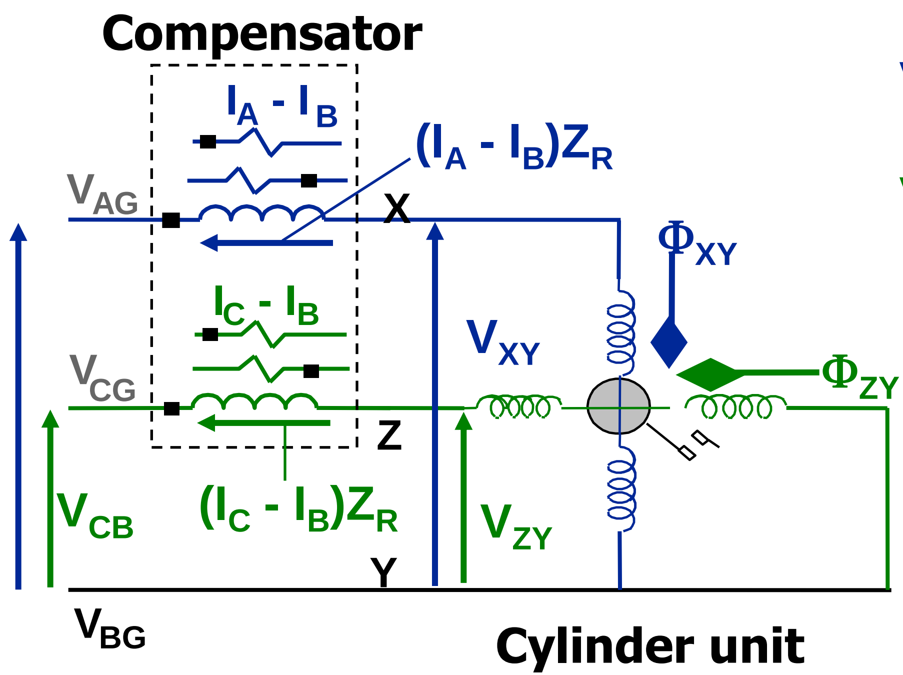


Distance relay characteristics
KD-10 cylinder unit (comparator) and compensator



Phase-to-phase unit

Distance relay characteristics
KD-10 cylinder unit



$V_{XY} = V_{AB} - (I_A - I_B)Z_R$

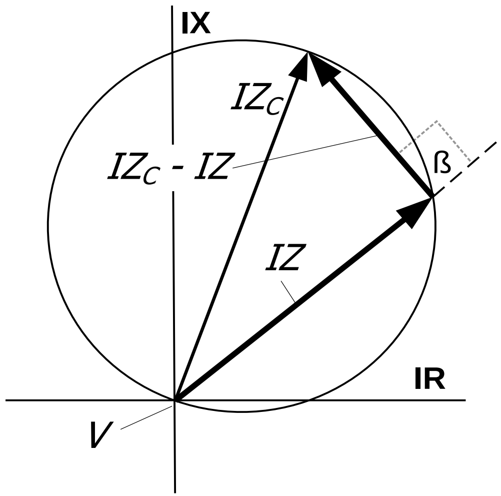
$V_{ZY} = V_{CB} - (I_C - I_B)Z_R$

Trips when V_{XY} leads V_{ZY}

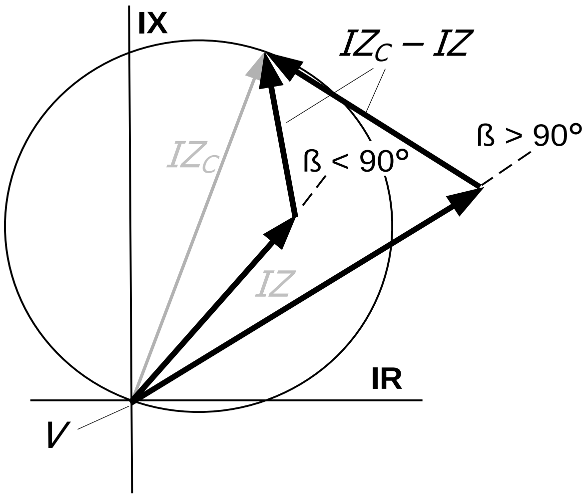
XZY sequence

Distance relay characteristics
Mho distance phase comparator principle

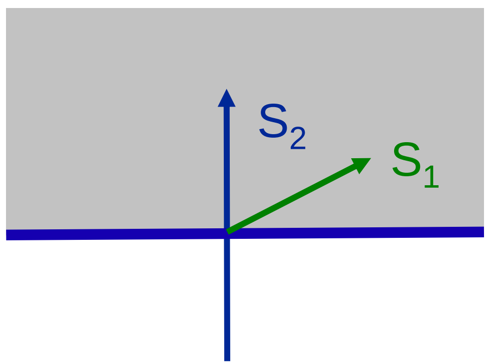
Generic single phase self polarized without zero sequence compensation



(a) Self (faulted phase) Polarized



(b) Internal and External Fault



Trip β < 90°

Z_C = impedance reach setting

Z = fault impedance

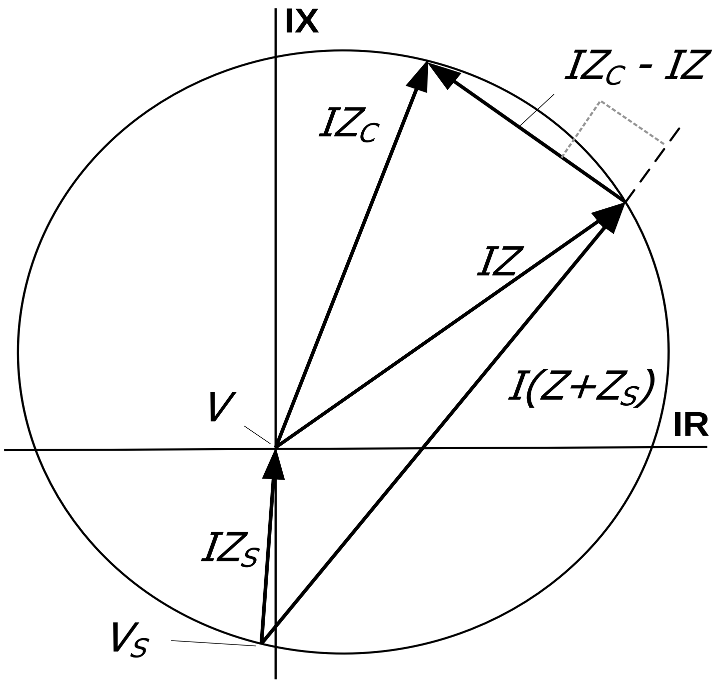
V_f = fault voltage at relay

I = fault current

$$S_1 = V_f = IZ$$

$$S_2 = IZ_C - V_f = IZ_C - IZ$$

Distance relay characteristics
Mho distance phase comparator – cross polarized



Generic single phase (healthy) voltage polarized without zero sequence compensation

$$S_1 = I(Z + Z_S); V_{BC}, V_1, V_{Mem}$$

$$S_2 = IZ_C - IZ$$

$Z+Z_S$ = fault impedance from source

V_S = source voltage

Distance relay characteristics
Mho distance phase comparators

V_{OP}	V_{POL}		Comments
$Z_c*I_{XY} - V_{XY}$	jV_{XY}	XY = AB, BC, CA Z_c = setting	• Three units required for phase-to-phase and three-phase • Self Polarizing • No expansion • Requires directional unit supervision • Requires memory for zero voltage faults • V_{OP} leads V_{POL}
$Z_c*I_{XY} - V_{XY}$	V_Z	XY = AB, BC, CA Z = C, A, B Z_c = setting	• Three units required for phase-to-phase and three-phase • Cross Polarizing • Source Impedance expansion • Requires directional unit supervision • Requires memory for zero voltage faults • V_{OP} leads V_{POL}
$V_{AB} - (I_A - I_B)Z_c$	$V_{CB} - (I_C - I_B)Z_c$	Z_c = setting	• Single unit required for phase-to-phase (AB, BC, CA) • Separate unit required for three-phase faults • Source Impedance expansion • V_{OP} leads V_{POL}

Positive Sequence Polarizing, V_{POL} == sub jV_{ZY} with V_{X1}

Distance relay characteristics
Mho distance phase comparators

V_{OP}	V_{POL}		Comments
V_{XG} – $Z_c*(I_X + K_0 I_0)$	V_{ZY}	X = A, B, C YZ = BC, CA, AB $I_0 = 1/3(I_A+I_B+I_C)$ $K_0=(Z_0 - Z_1)/Z_1$	• Three units required for phase-to-ground (A, B, C) • zero sequence (I_0)compensation • Cross Polarizing • Source Impedance expansion • Requires directional unit supervision • V_{OP} leads V_{POL}
V_{XG} – $Z_c*(I_X + K_N I_R)$	jV_{ZY}	X = A, B, C YZ = BC, CA, AB $I_R = I_A+I_B+I_C$ $K_N = (Z_0 - Z_1)/3Z_1$	• Three units required for phase-to-ground (A, B, C) • Residual ground ($I_r=3I_0$) compensation • Cross Polarizing • Source Impedance expansion • Requires directional unit supervision • V_{OP} leads V_{POL}

Positive sequence polarizing, V_{POL} == sub jV_{ZY} with V_{X1}

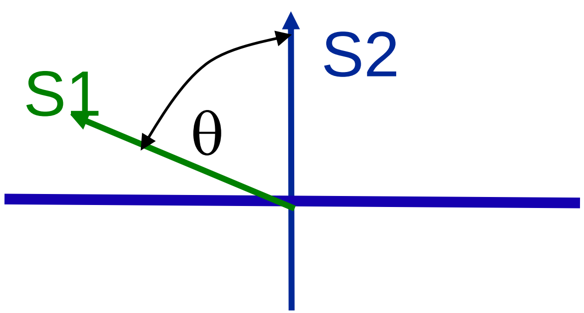
Quadrilateral characteristics
Reactance Lines (current polarization)

Z_C

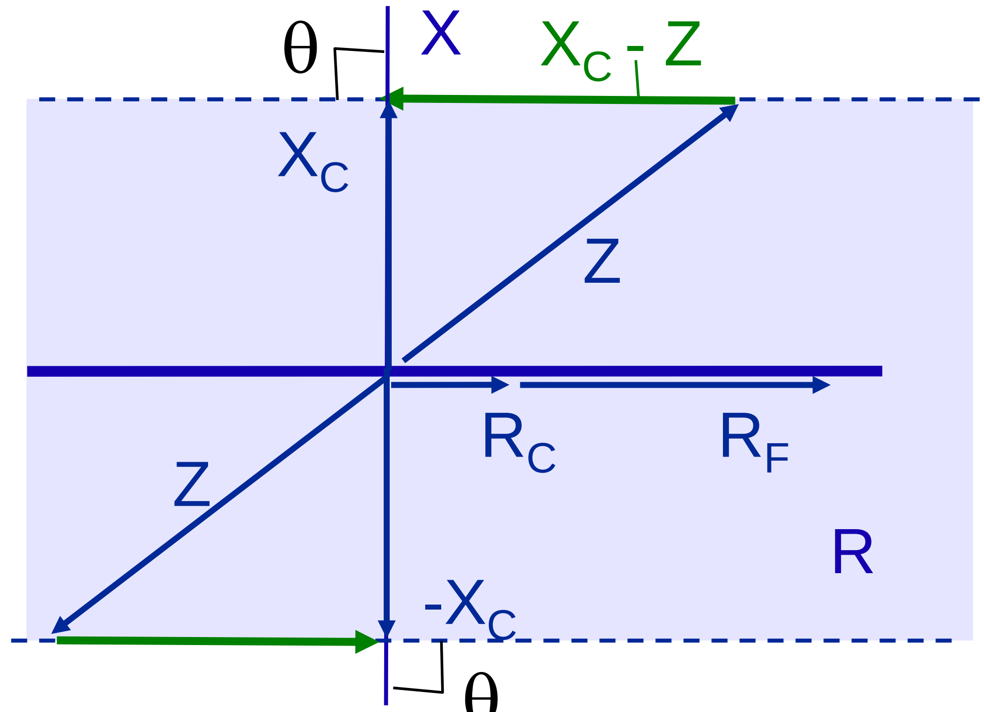
$$S1 = IZ_C - V = (X_C - Z)I$$

$$S2 = V_{POL} = X_C I$$

Only the forward reach line can be defined, therefore, it must be directionally supervised



Operate $\theta < \pm 90^O$

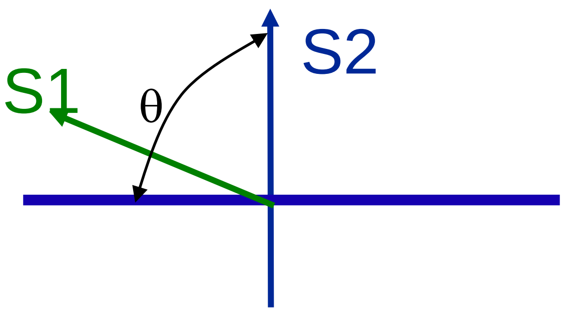


- I_2 used for load compensation

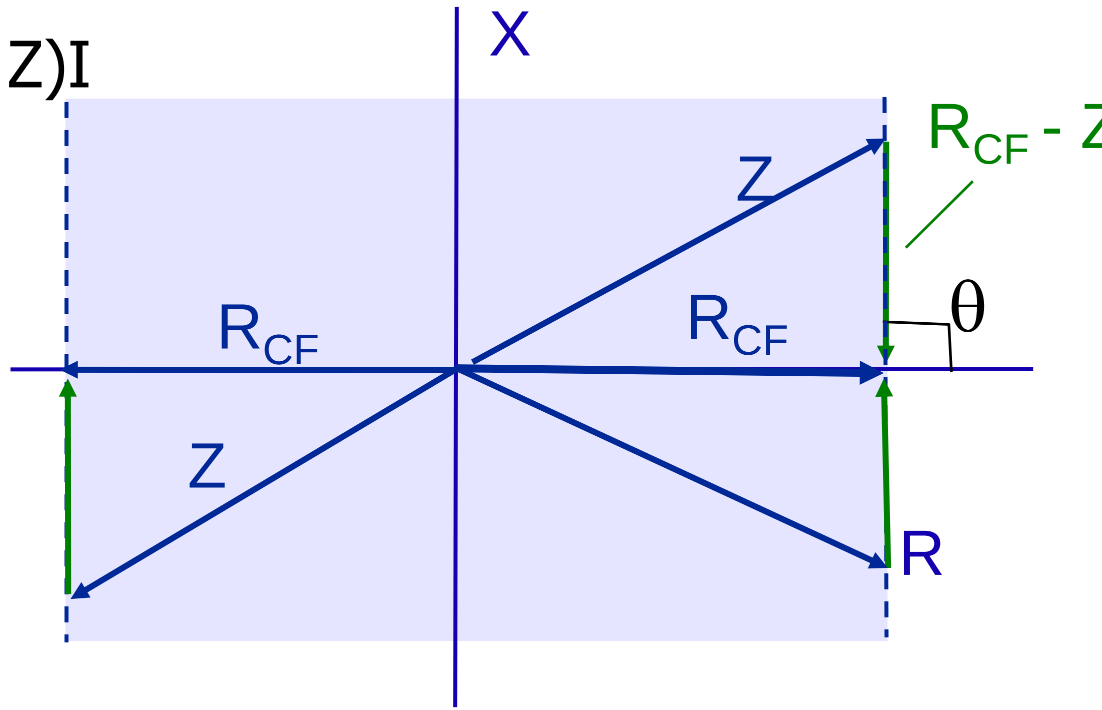
Quadrilateral characteristics
Resistance (current polarized)

$$S1 = IR_{CF} - V = (R_{CF} - Z)I$$

$$S2 = V_{POL} = R_{CF}I$$



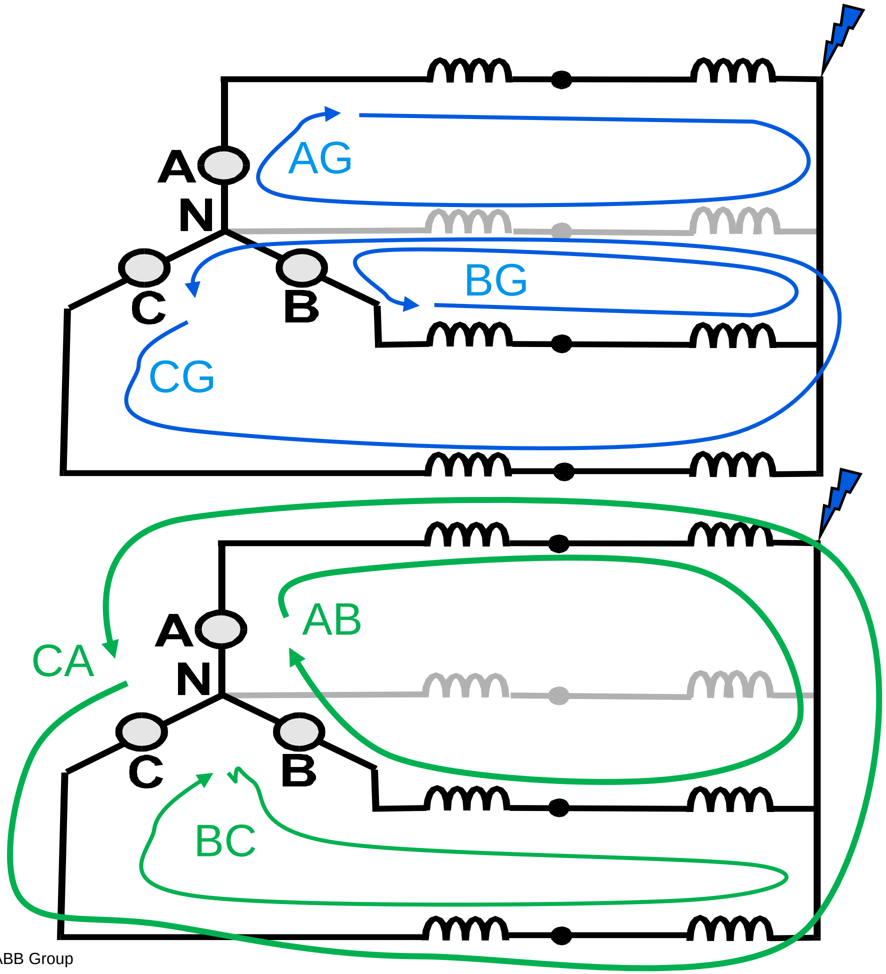
Operate $\theta < \pm 90^{O}$



Distance relay characteristics
Reference

E. Price, T. Einarsson, "Complementary Approach for Reliable High Speed Transmission Line Protection," 62nd Annual Georgia Tech Protective Relaying Conference, Atlanta, Georgia, 2008.

Apparent impedance of fault loops

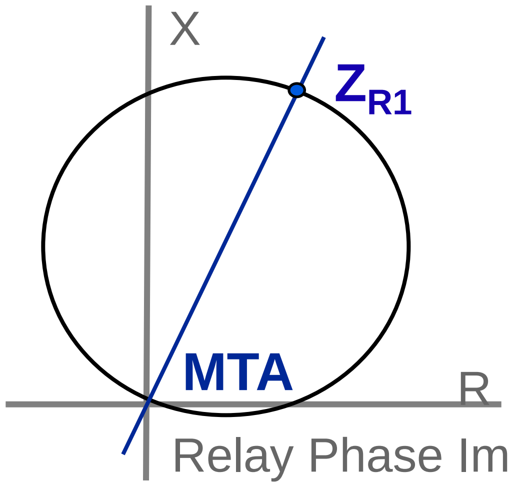


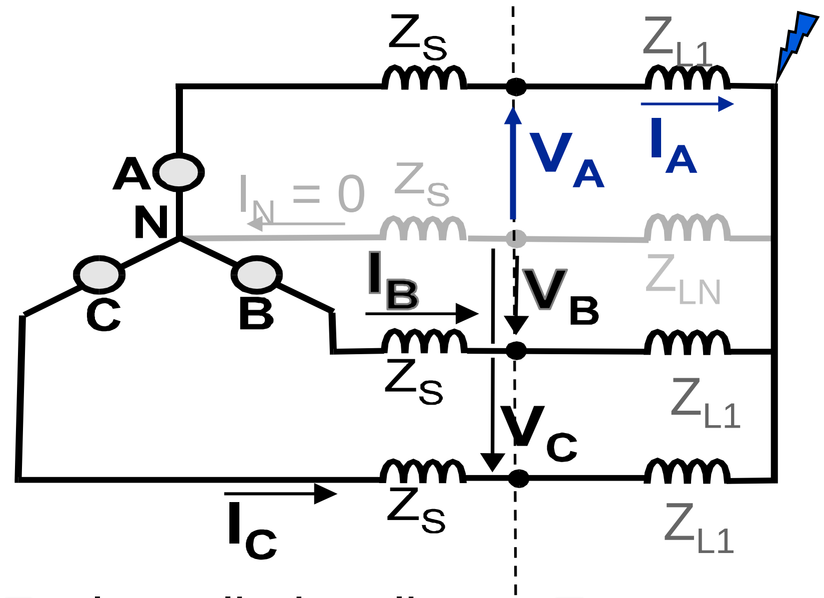
6 fault loops measured for each zone

Fault Types

- Phase-to-ground
- Phase-to-phase
- Two phase-to-ground
- Three phase

Apparent impedance of fault loops
Three phase





Fault applied on line at Z_{L1}

Apparent impedance (per phase)

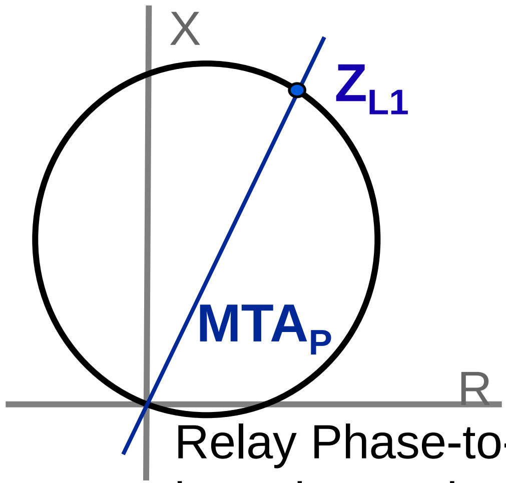
$V_A = I_A Z_{L1}$

$Z_{3P} = Z_{L1} = V_A/I_A$

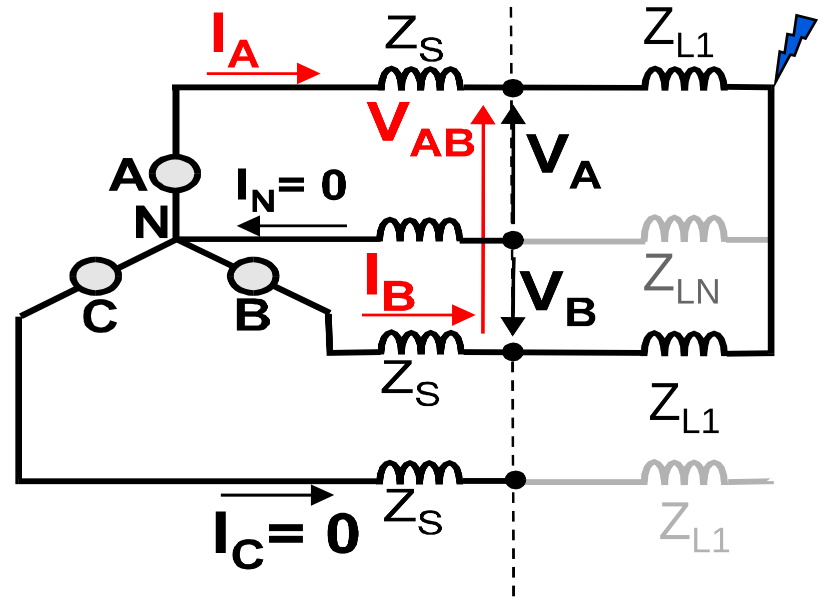
Phase reach is set in terms of positive sequence impedance, Z_{L1}

Apparent impedance of fault loops

Phase-to-phase



Relay Phase-to-phase impedance characteristic

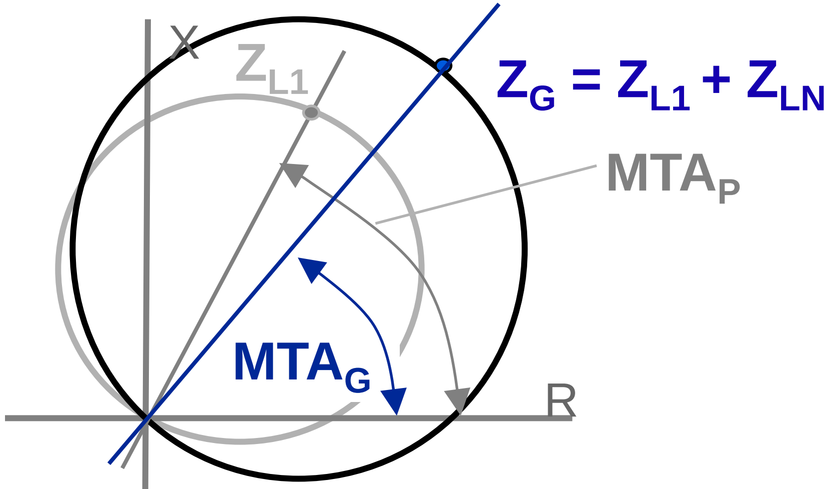


<u>Apparent impedance, Z_{PP}</u>

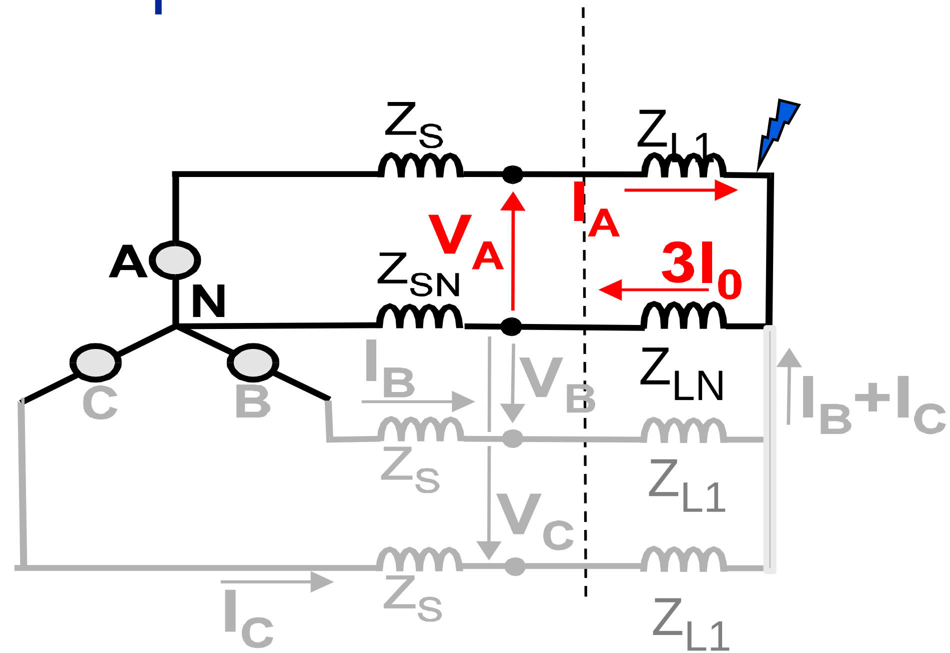
$$V_{AB} = (I_A - I_B)\, Z_{L1} = 2I_A\, Z_{L1}$$
$$Z_{PP} = Z_{L1} = V_{AB}/(I_A - I_B) = (V_A - V_B)/(I_A - I_B)$$

Phase reach is set in terms of positive sequence impedance, Z_{L1}

Apparent impedance of fault loops
Phase-to-ground



Relay Phase-to-ground impedance characteristic



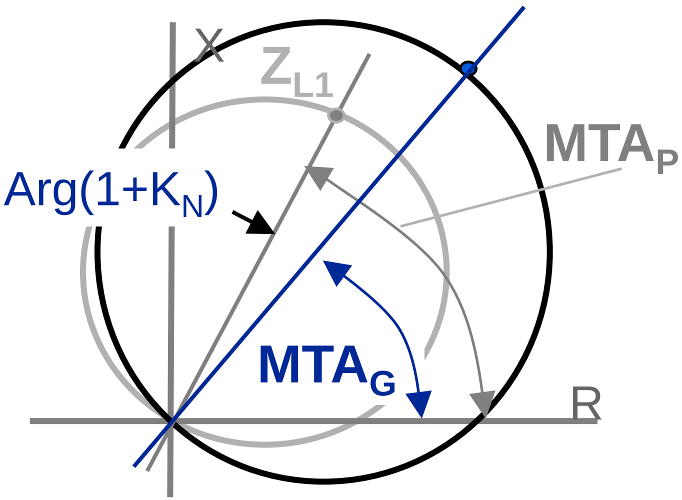
<u>Apparent impedance</u> (no load $I_A = 3I_0$)

$$V_A = I_A Z_{L1} + 3I_0 Z_{LN} = I_A (Z_{L1} + Z_{LN})$$

$$Z_G = V_A / I_A = (Z_{L1} + Z_{LN})$$

$$MTA_G = \text{Argument} (Z_{L1} + Z_{LN})$$

Apparent impedance of fault loops
Phase-to-ground



Relay Phase-to-ground impedance characteristic

Apparent impedance

$Z_G = (Z_{L1} + Z_{LN})$

$Z_{LN} = (Z_{L0} - Z_{L1}) / 3$

$Z_G = (2Z_{L1} + Z_{L0}) / 3$ (ground loop)

Z_{L1} with residual $3I_0$ compensation

$Z_G = Z_{L1} (2 + Z_{L0} / Z_{L1}) / 3$

$Z_G = Z_{L1} (2 + 1 + Z_{L0} / Z_{L1} - 1) / 3$

$Z_G = Z_{L1}(1 + K_N)$; **$KN = (Z_{L0} - Z_{L1})/3Z_{L1}$**

$MTA_G = Arg(Z_G)$

Apparent impedance of fault loops
Phase-to-ground

Two Factors used by different relays and manufacturers

Residual [neutral] current compensation

$$V_A = Z_{L1}\left[I_A + 3I_0\left(\frac{Z_{L0} - Z_{L1}}{3Z_{L1}} \right) \right]$$

K_N compensates for $3I_0$

$$K_N = \frac{Z_{L0} - Z_{L1}}{3Z_{L1}}$$

$$V_A = Z_{L1}\left[I_A + I_0\left(\frac{Z_{L0}}{Z_{L1}} - 1 \right) \right]$$

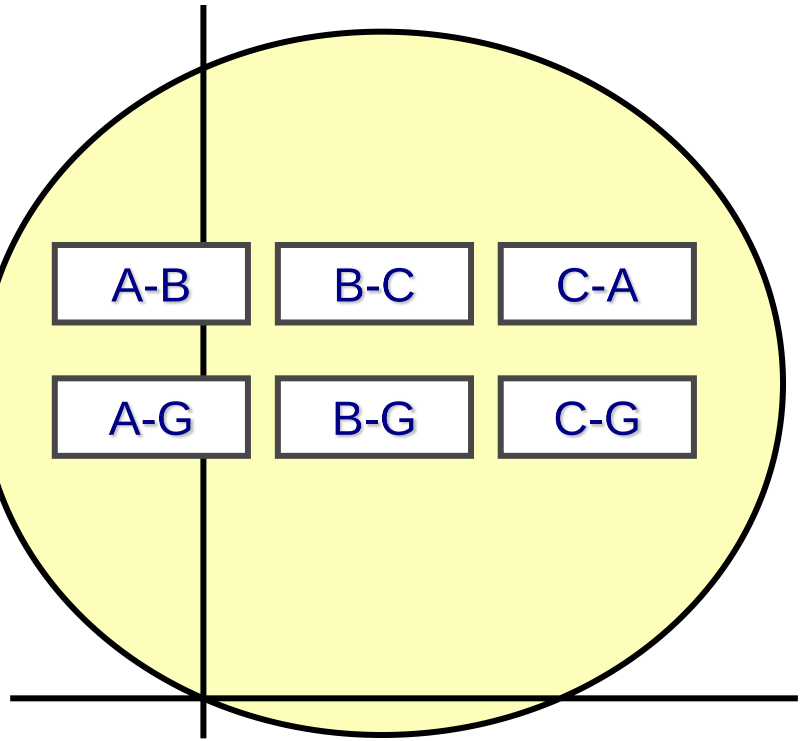
Zero sequence current compensation

K_0 compensates for I_0

$$K_0 = \frac{Z_{L0}}{Z_{L1}} - 1$$

Ground reach is set in terms of Z_{L1} and K_N: $Z_G = \mathbf{Z_{L1}}(1 + \mathbf{K_N})$

Faulted phase selection

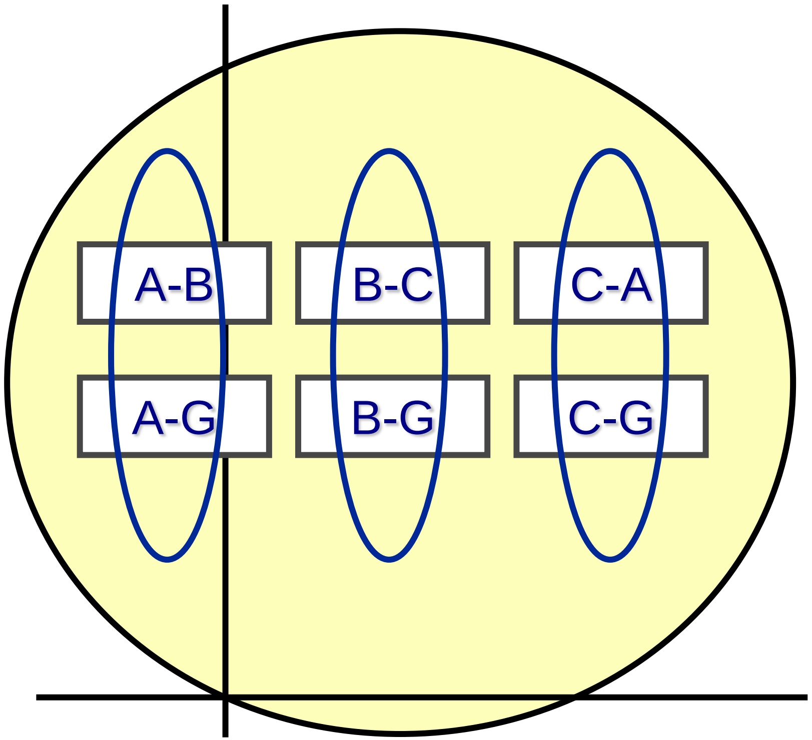


6 fault loops measured in each zone

Release or identify correct impedance loop

- Single pole trip
- Event recording
- Fault location

Faulted phase selection
Issues



Multiple impedance loop operations for a fault event

- Common phases of a fault loop
- Magnitude of fault quantities
- Load
- Fault resistance

Faulted phase selection
Issues

- The ΦΦ unit may operate for close-in reverse ΦΦ, ΦΦG, or ΦG faults
- The ΦΦ unit may operate for close-in forward ΦG faults
- The ΦG units may operate for close-in reverse ΦG faults
- The ΦΦ unit of a non-faulted loop may operate for ΦΦG faults with high fault resistance
  - e.g. CA unit for a BCG fault
  - The CA operation will occur with the expected BC operation giving the appearance of a three phase fault.

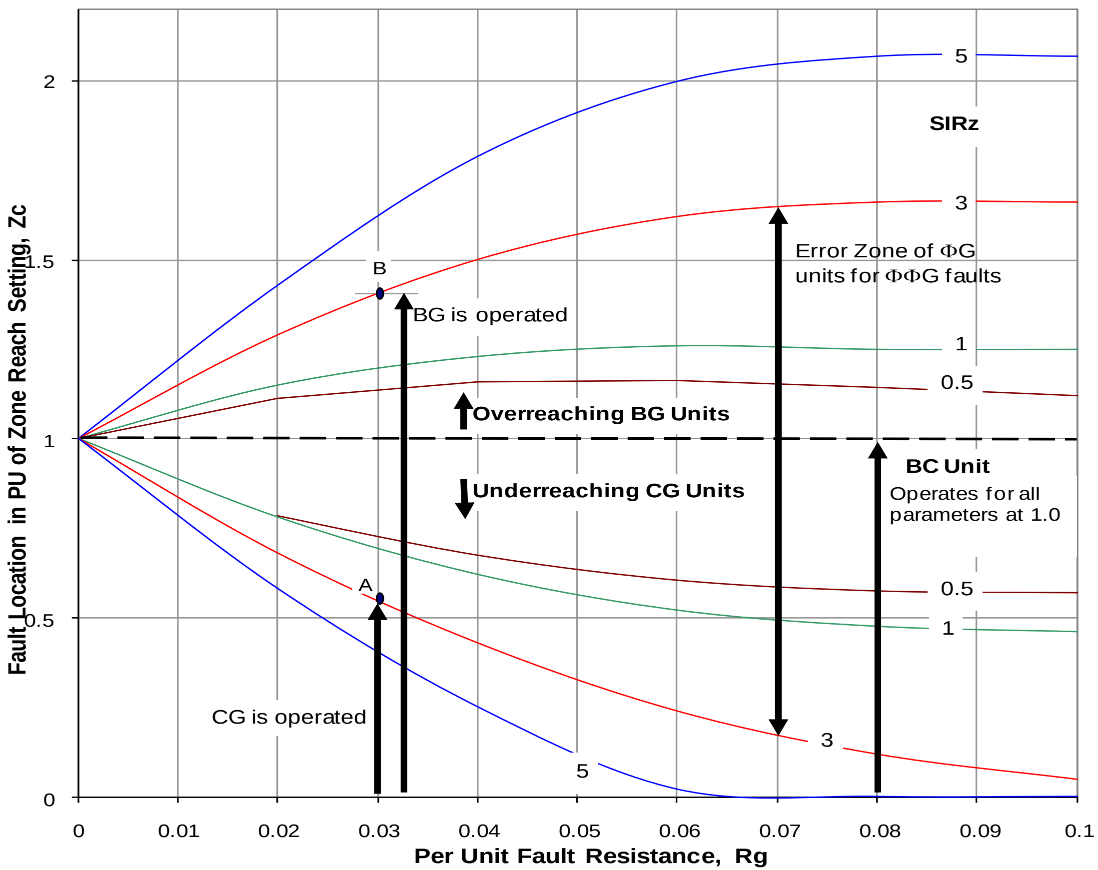
These issues are resolved with directional and/or sequence current supervision.

Faulted phase selection
Issues

- The ΦG unit of the leading phase will overreach for forward external ΦΦG faults with any measurable fault resistance
  - e.g. BG unit for a BCG fault
- The ΦG unit of the lagging phase will underreach for forward internal ΦΦG faults near the reach setting with any measurable fault resistance
  - e.g. CG unit for a BCG fault
  - This is generally of no consequence

These issues are the result of ΦΦG faults and must be resolved by accurate phase selection.

Faulted phase selection
Response of BG, CG and BC units to BCG fault



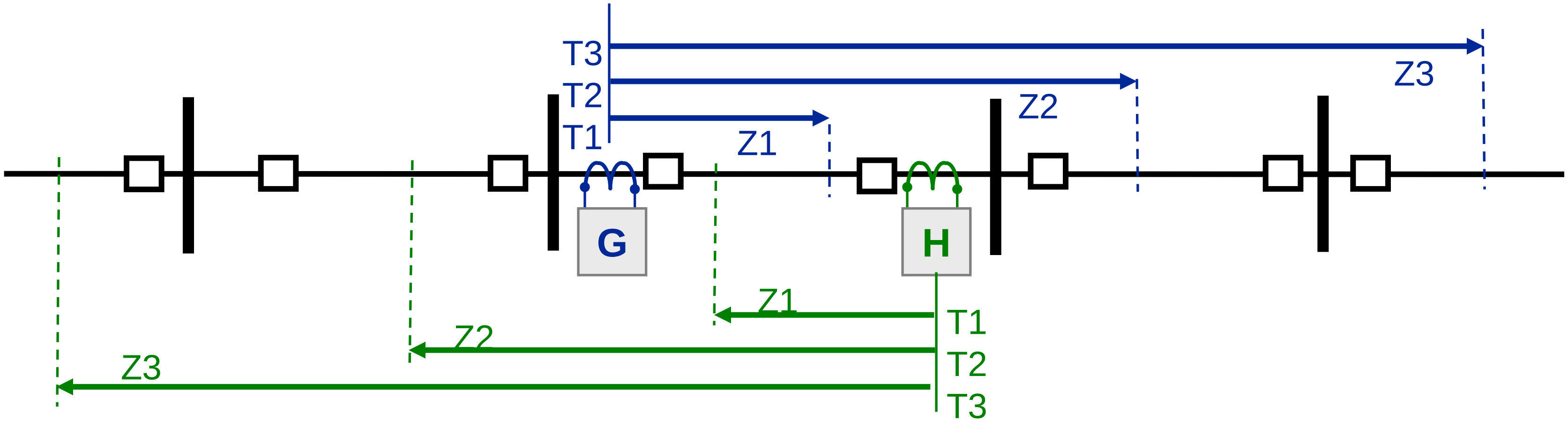
Faulted phase selection
Reference

E. Price, T. Einarsson, "The Performance of Faulted phase Selectors used in Transmission Line Applications," 62nd Annual Georgia Tech Protective Relaying Conference, Atlanta, Georgia, 2008.

Application
Location of cts and vts

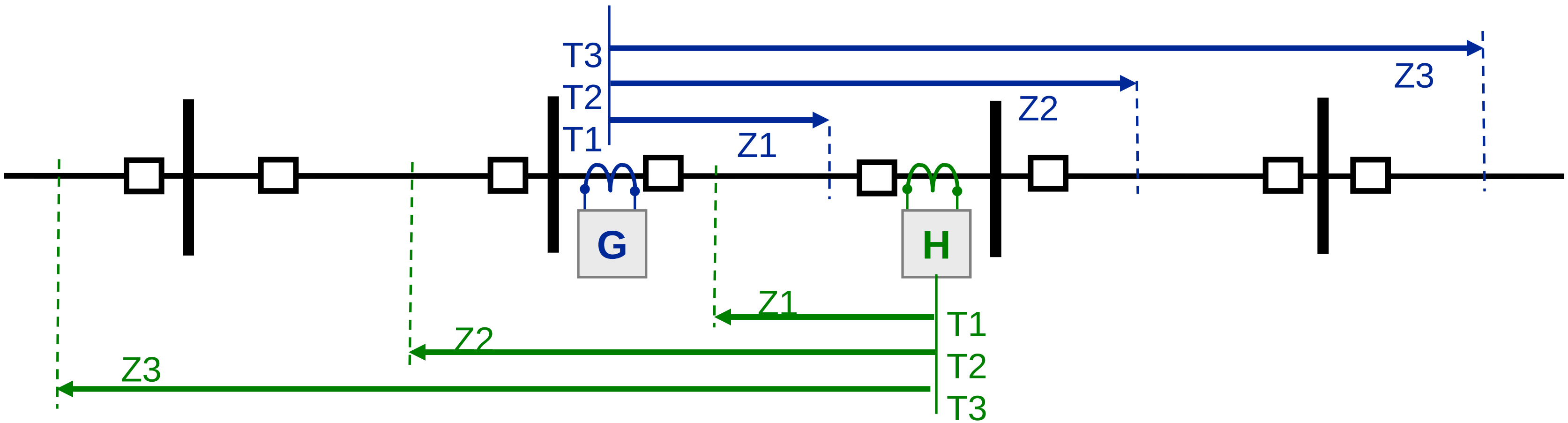
- Reach of a distance relay is measured from the location of the voltage transformer
- Directional sensing occurs from the location of the current transformer
- In most applications vts and cts are usually at same location (no measurable impedance between them)
- Their location should always be considered especially for applications with transmission lines terminated with transformers

Application
Step distance protection



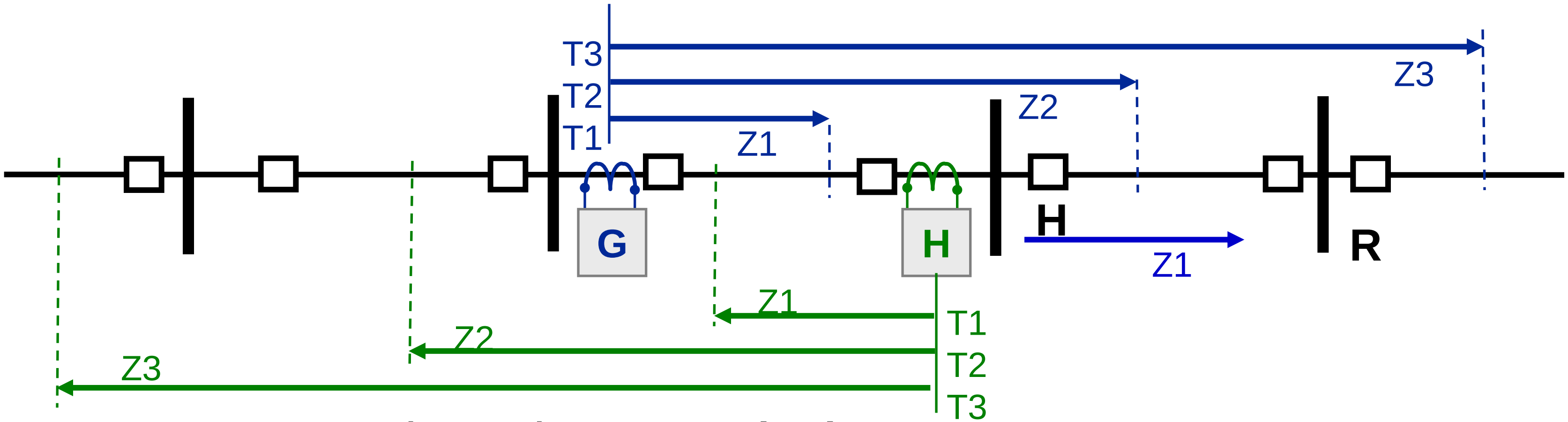
- Zone 1 set for 80 - 90 % of line impedance
- Zone 2 set for 100% of line plus 25 - 50% of shortest adjacent line from remote bus
- Zone 3 set for 100% of both lines plus 25% of adjacent line off remote bus

Step distance protection
Zone 1



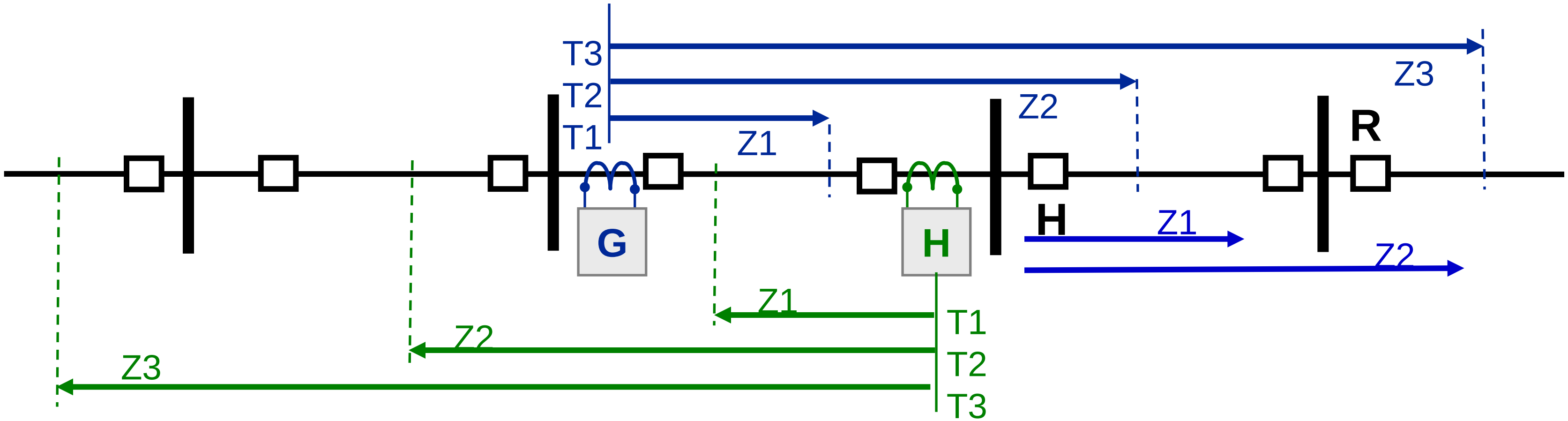
- Do not want Zone 1 to reach beyond remote bus
- 10 to 20% is safety factor
- Inaccuracies
  - Relays
  - Current and potential transformers
  - Line impedances

Step distance protection
Zone 2



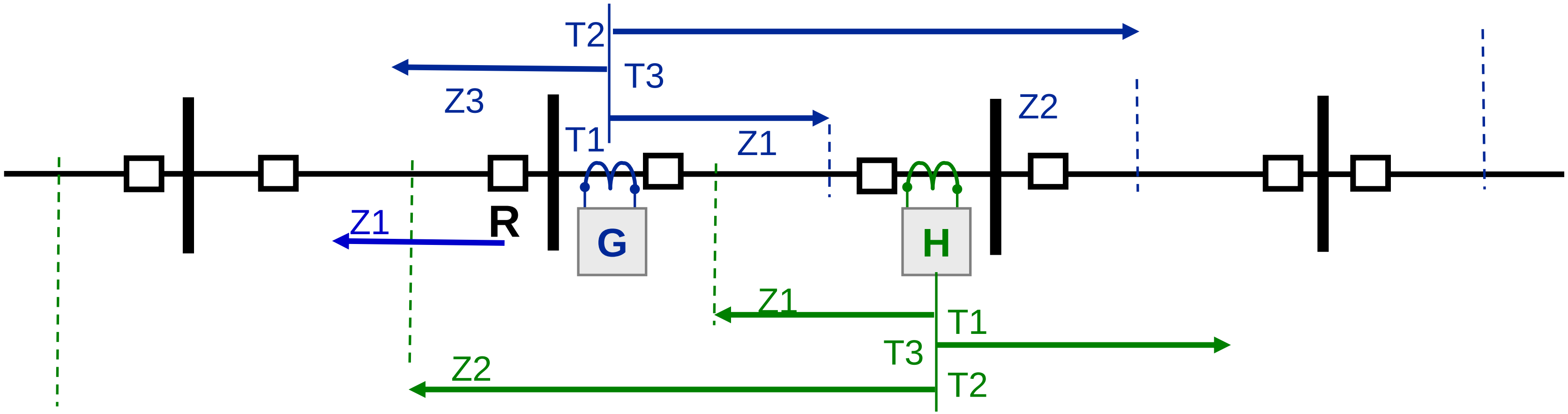
- Operates through a timer (T2)
- Timer set for Coordination Time Interval (CTI) that allows remote relay zone 1 [Z1] and breaker [at **H**] to operate with margin before zone 2 [Z2] relay
- Z2 at G must overreach the remote bus H, but should not overreach the closest far bus at R
- Z2 at G is remote backup to Z1 at H

Step distance protection
Zone 3



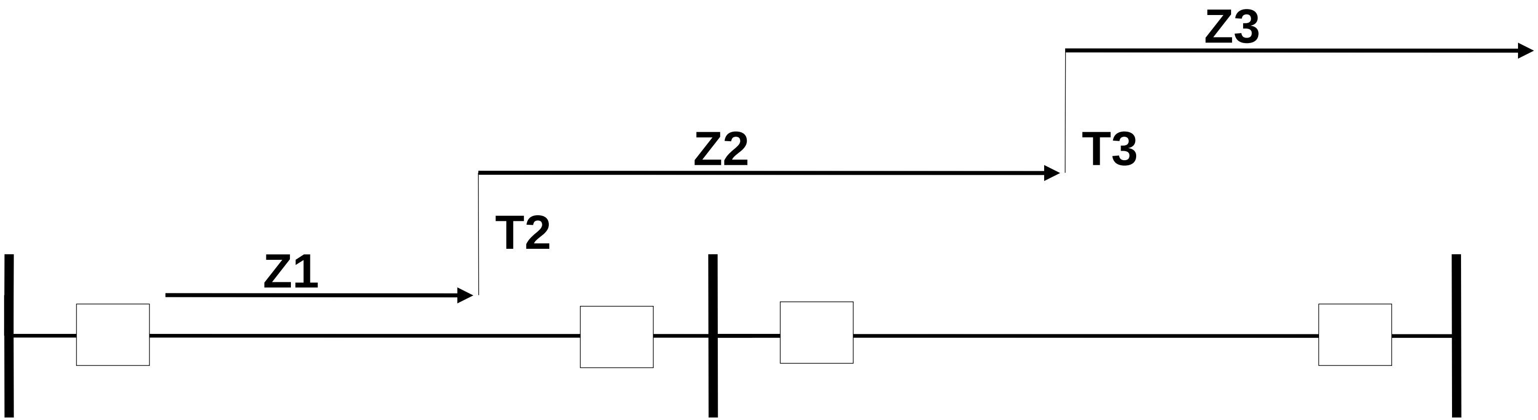
- Operates through a timer (T3)
- Timer set for Coordination Time Interval (CTI) that allows remote relay zone 2 [Z2] and breakers [at **H** and **R**] to operate with margin before the zone 3 [Z3] relay
- Z3 at G is also remote backup to Z1 and Z2 at H

Step distance protection
Zone 3

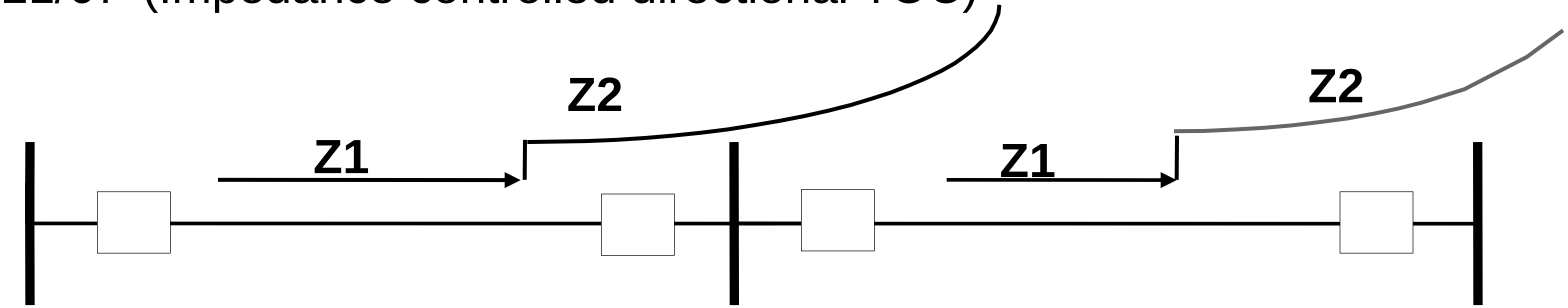


- Zone 3 relay [Z3] may be applied looking reverse for pilot system logic with no timer
- Zone 3 relay [Z3] may be applied looking reverse for reverse [backup] bus protection
  - Timer set to allows reverse zone 1 [Z1] relay and breaker [at **G**] to operate with margin before zone 3 [Z3] relay

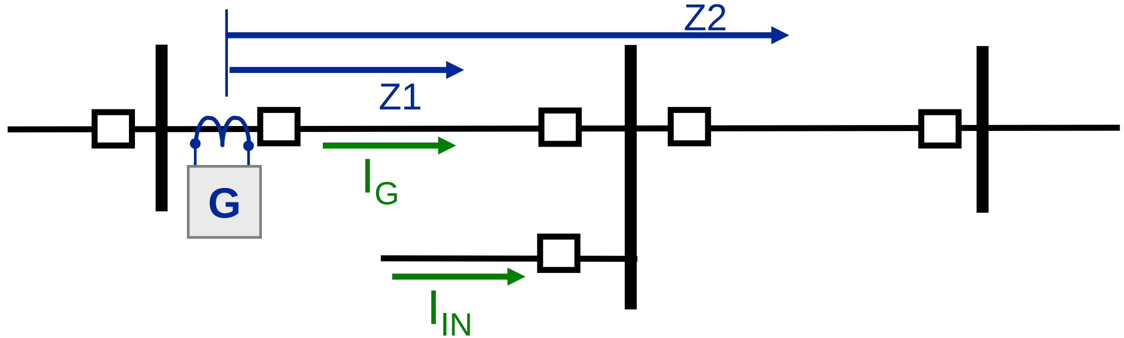
Step distance protection
Operating time profile



21/67 (Impedance controlled directional TOC)

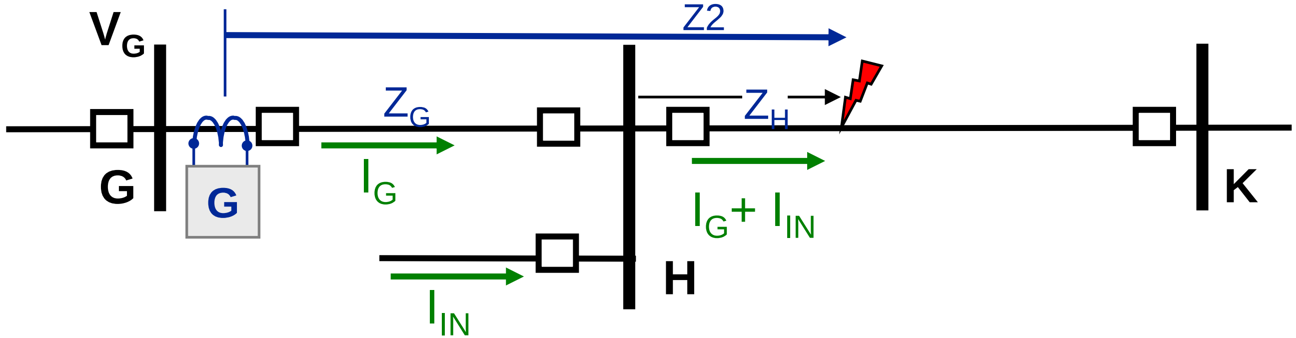


Step distance protection
Infeed [from remote bus]



- Reduces the apparent reach measured by distance relays
- Depends on the ratio between current going through relay (I_G) and current from infeed (I_{IN})
- Usually not a factor on Zone 1 [Z1] relay unless tapped line [or appreciable fault resistance for ground faults]
- Zone 2 may underreach remote bus

Step distance protection
Infeed [from remote bus]



With Zero voltage fault and $\mathbf{Z2 = Z_G + Z_H}$

$$V_G = I_G Z_G + (I_G + I_{IN}) Z_H$$

$$Z_A \text{ (Apparent)} = V_G / I_G$$

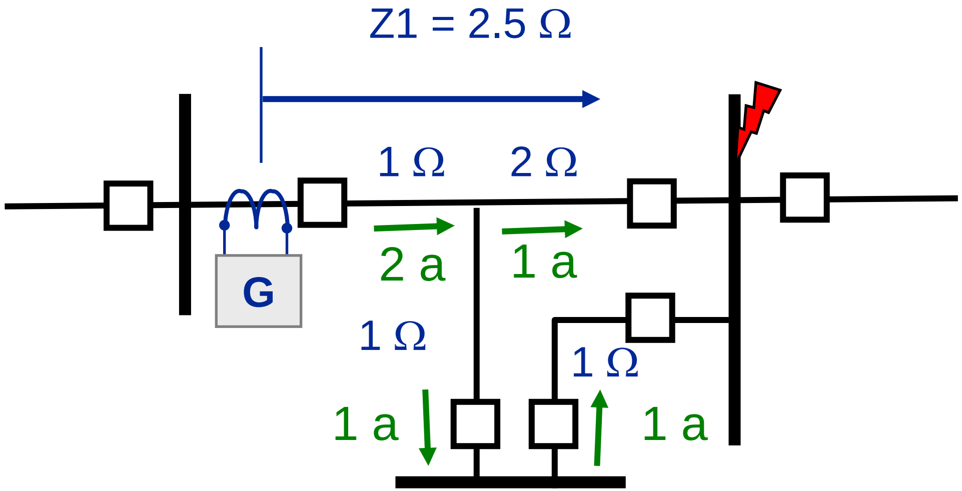
$$Z_A = Z_G + (1 + I_{IN}/I_G) Z_H$$

$$Z_A = Z_G + Z_H + (I_{IN}/I_G) Z_H \text{ (Increase in Apparent Impedance)}$$

Z2 must be set to overreach bus H for infeed at bus H

and not overreach bus K for no infeed at bus H

Step distance protection
Outfeed



Usually associated with three terminal line applications and paralleling of line segment

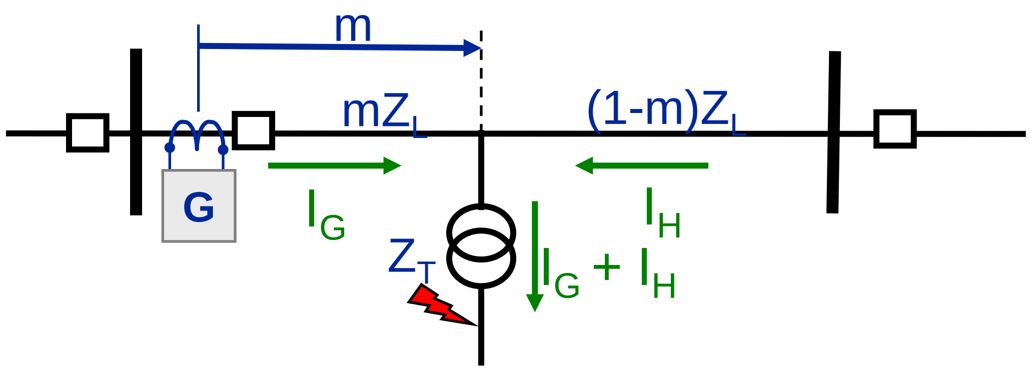
Example: $\mathbf{V_G = 2(1) + 2(1\,) = 4}$

$\mathbf{Z_G}$ (Apparent) $\mathbf{= V_G / I_G}$

$\mathbf{Z_G = 4/2 = 2\,\Omega}$

Z1 will overreach and see the fault

Step distance protection
Tapped transformers and loads



$$V_G = I_G m Z_L + (I_G + I_H) Z_T$$

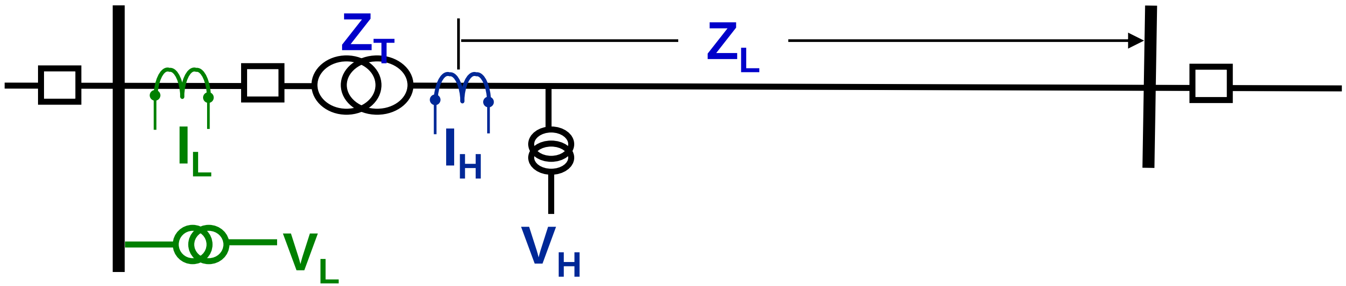
$$Z_G \text{ (Apparent)} = V_G / I_G$$

$$Z_G = mZ_L + (1 + I_H/I_G) Z_T$$

$$Z_G = mZ_L + Z_T + I_H/I_G Z_T$$ (Increase in apparent impedance)

Apparent impedance will always be larger than impedance to fault

Step distance protection
Lines terminated into transformers



- I_H and V_H preferred to provide line protection
- Use of VL and/or IL affects measured impedance and requires ct and/or vt ratio adjustment
- Transformer should always be protected separately

Reference

E. Price, R. Hedding, "Protecting Transmission Lines Terminated into Transformers," 63rd Annual Georgia Tech Protective Relaying Conference, Atlanta, Georgia, 2009.

Source impedance ratio

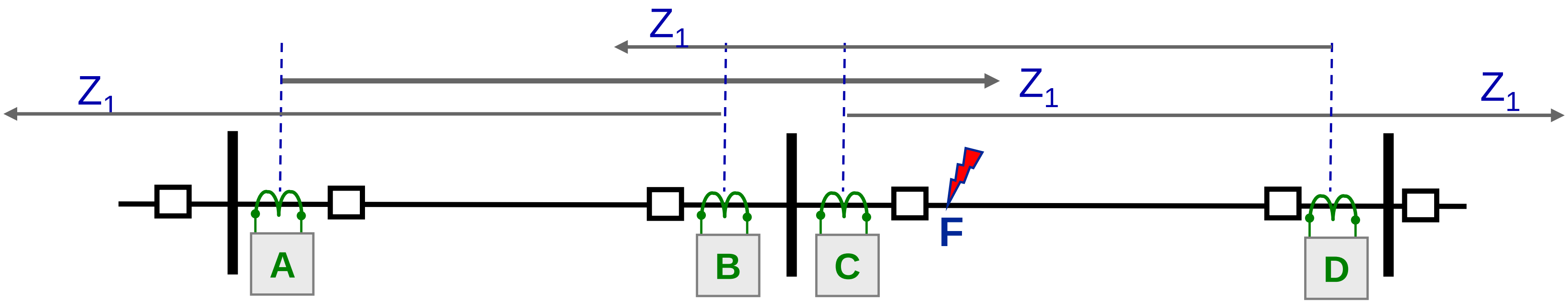
- Ratio of source impedance to the line impedance
- SIR to the relay is the ratio of source impedance to the zone impedance setting
- The higher the SIR the more complex the line protection with zone 1
  - Measurement errors are more pronounced
    - Current and or voltage transformer error
    - CVT transients
  - Zone-1 may not be recommended in many applications
  - Current differential protection preferred

Source impedance ratio
Recommended applications

- Short Line — SIR > 4.0
  - **Current Differential**
  - **Phase Comparison**
  - **Pilot (POTT, DCB**)
- Medium Line — 4.0 > SIR > 0.5
  - **Above**
  - **Step Distance**
- Long Line — 0.5 > SIR
  - **Above**
  - **Step Distance**

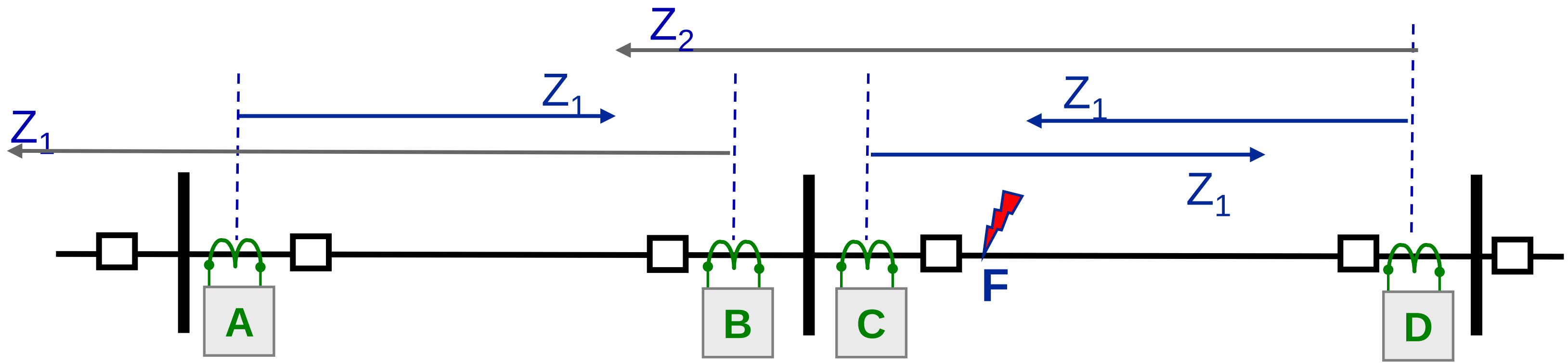
IEEE Guide for Protective Relay Applications to Transmission Lines - IEEE Std C37.113-1999

Non-pilot applications
Zone 1 extension



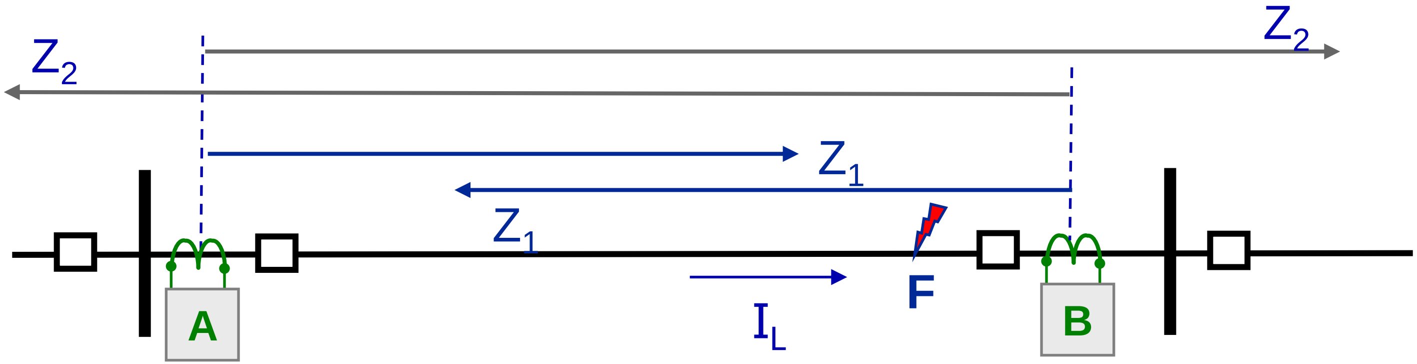
- Z1 reach is initially set to overreach remote bus
- Circuit breakers controlled by relays A, C, & D trip for a fault at F
- Z1 reach is reduced to not overreach remote bus
- High-speed reclose

Non-pilot applications
Zone 1 extension



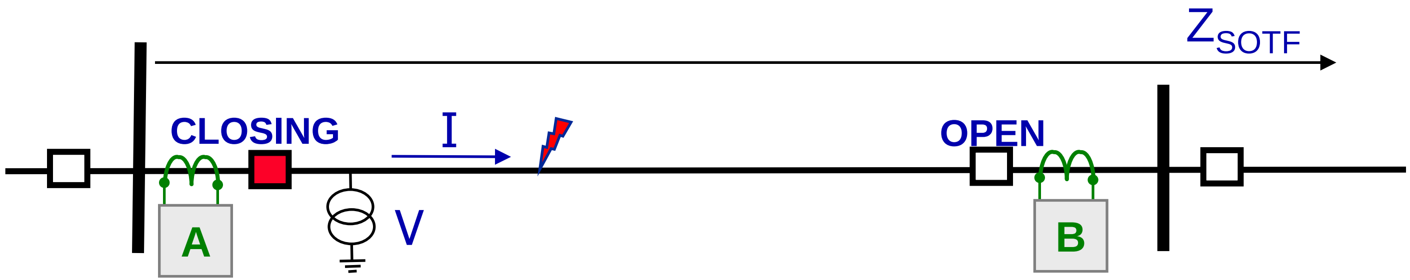
- After high-speed reclose
  - Circuit breaker controlled by relay C trips instantaneously
  - Circuit breaker controlled by relay D trips time-delayed
  - Circuit breaker controlled by relay A does not trip

Non-pilot applications
Load loss trip



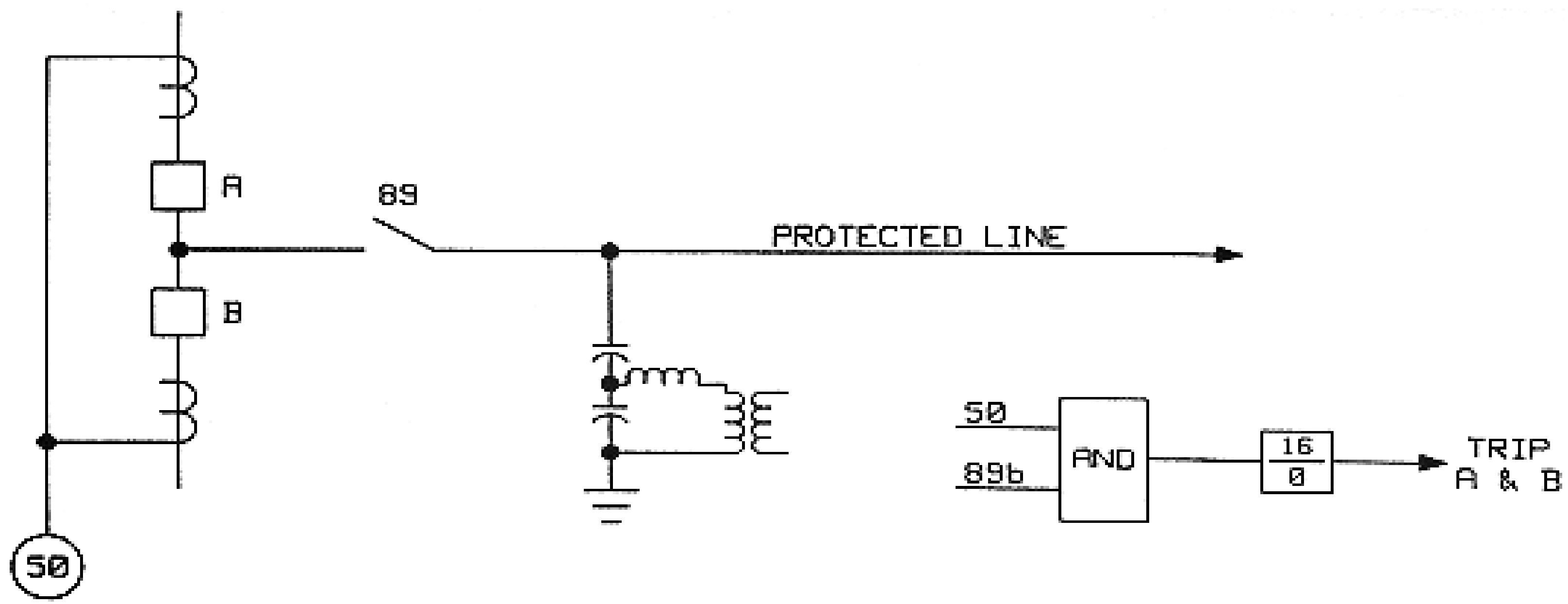
- Unbalanced fault occurs at F
- Breaker controlled by relay B trips instantaneously by Z1
- Balanced load current, IL, is interrupted
- LLT Logic at A
  - Detects loss of balanced (load) current and bypasses Z2 timer to trip
  - Does not operate for three-phase fault

Switch onto fault logic



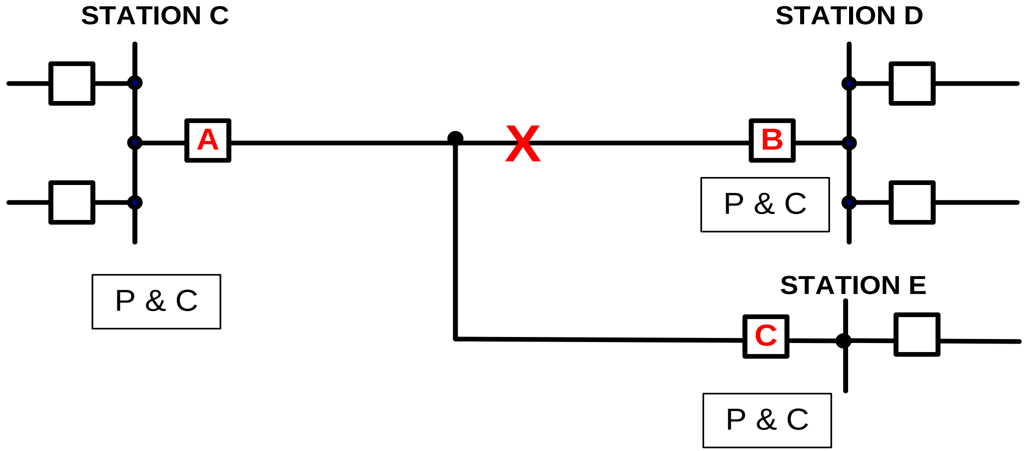
- Logic determines breaker has been open awhile and sets SOTF logic (aka: CIFT, SOFT)
  - Breaker position
  - Dead line logic
- When breaker controlled by relay A closes SOTF asserts when:
  - I and Not V, and/or
  - ZSOTF operates
    - Set ZSOTF offset, overreaching line and below minimum load impedance

Stub bus protection logic



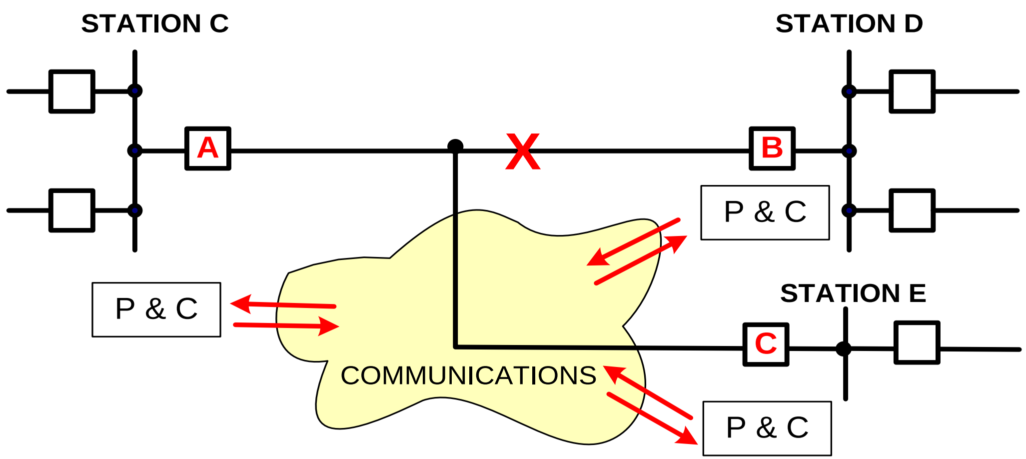
Pilot relaying schemes
Communication assisted schemes

Goal - High speed simultaneous tripping of all line terminals for internal line faults



Pilot relaying schemes
Communication assisted schemes

Goal - High speed simultaneous tripping of all line terminals for internal line faults



Requires reliable high-speed communications between line terminals.

Pilot Communications

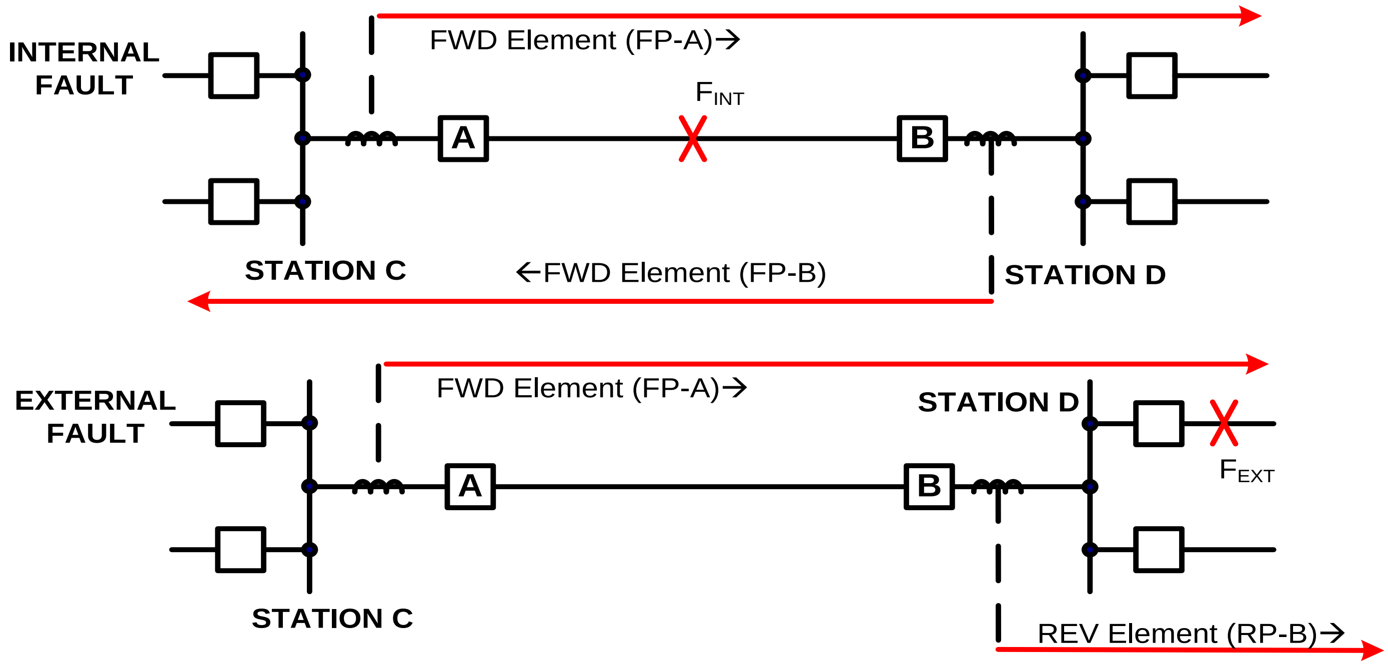
- Power Line Carrier (PLC)
  - The communication signal is coupled to the transmission line being protected requiring additional substation equipment
    - Line traps
    - Line tuners
    - Coupling capacitors
  - On/Off Keying, Frequency Shift Keying (FSK)
  - Generally more available and economical than other forms of pilot communications
  - Communication issues tend to occur when reliable communications is need most – during the fault
  - DCB (On/Off) and DCUB (FSK) developed specifically for PLC

Pilot Communications

- Non Power Line Carrier
  - The communication signal is routed separately from the transmission line conductor
  - Audio tone – FSK over voice (telephone, microwave)
  - Digital – most reliable, particularly with fiber optics, direct connected or multiplexed

Directional Comparison

Directional Comparison relaying determines the fault direction at each line terminal and compares the results to determine the fault to be internal or external to the protected line.

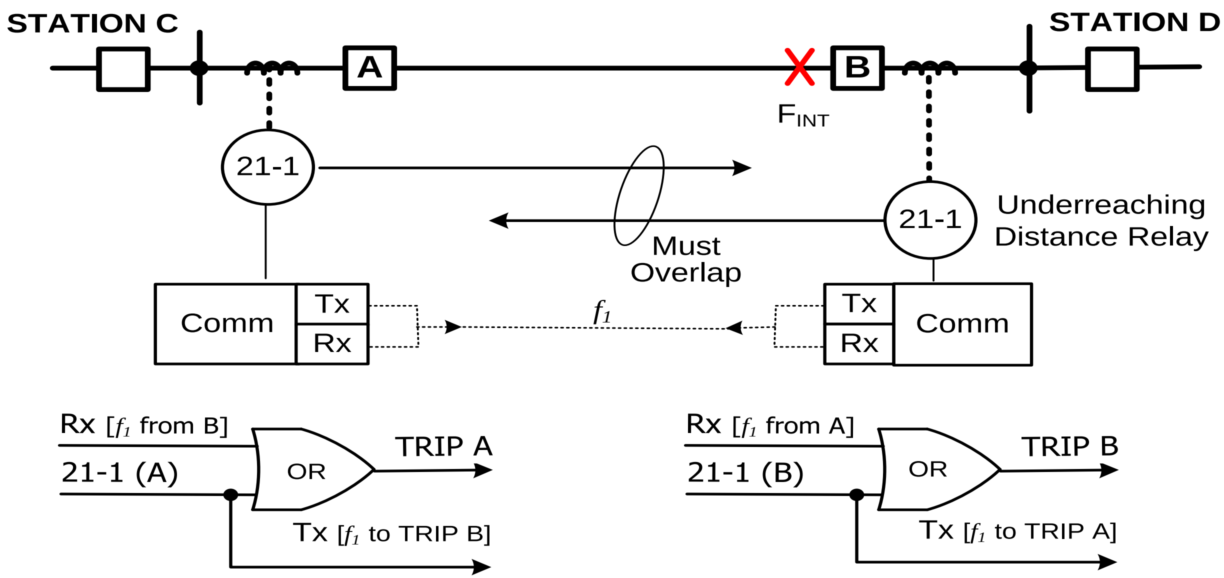


Distance Protection
Directional Comparison Schemes

- Non PLC Channels
  - DUTT* – Direct-underreaching transfer trip
  - POTT – permissive-overreaching transfer trip
  - PUTT – permissive-underreaching transfer trip
- PLC
  - DCB – directional comparison blocking
  - DCUB – directional comparison unblocking

* Although there is no directional comparison between terminals this scheme is usually considered with directional comparison schemes.

DUTT – Direct-underreaching Transfer Trip

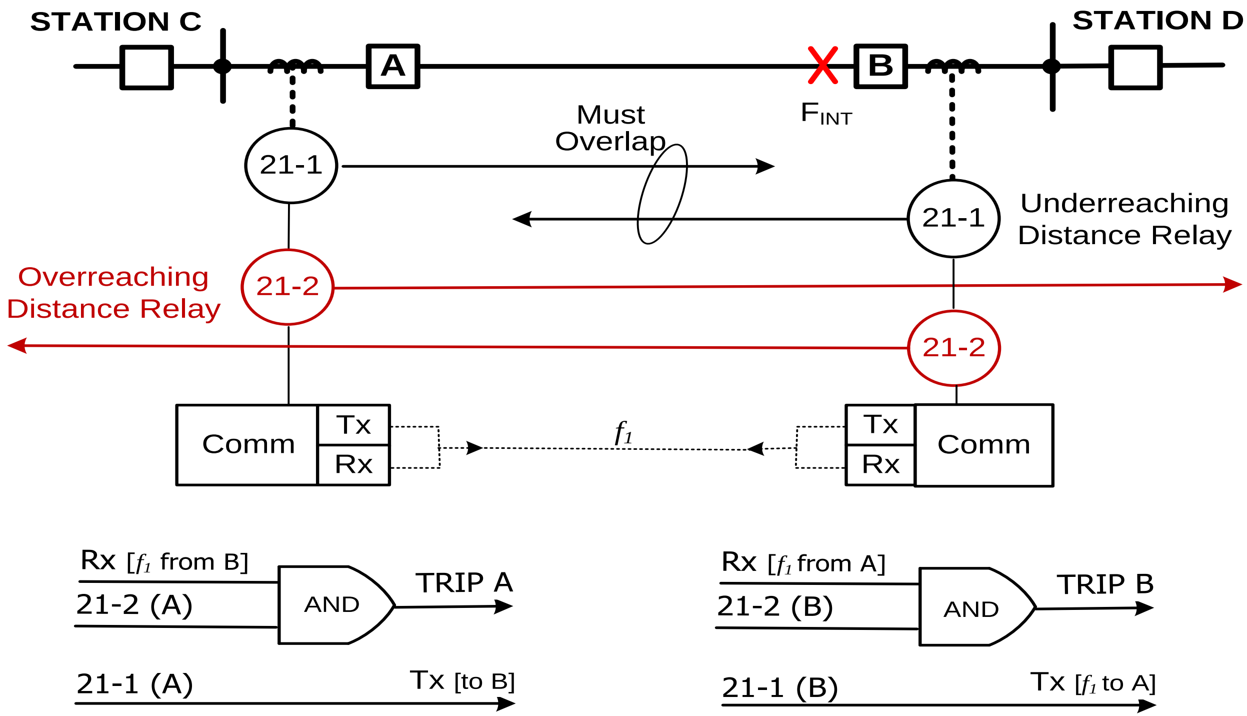


- Also known as an “Intertrip” scheme

DUTT – Direct-underreaching Transfer Trip

- Advantages
  - Fast method for clearing end zone faults
  - Single communications channel
- Disadvantages
  - Cannot protect full line if one terminal is open or has weak infeed
  - Requires ground distance relays for accurate reach on ground faults (no overcurrent)
  - Subject to 21-1 overreaching issues (e.g. ccvt transients)
  - Spurious communication channel noise may cause undesired trip (secure channel desired – FSK, digital)

PUTT – Permissive-underreaching Transfer Trip

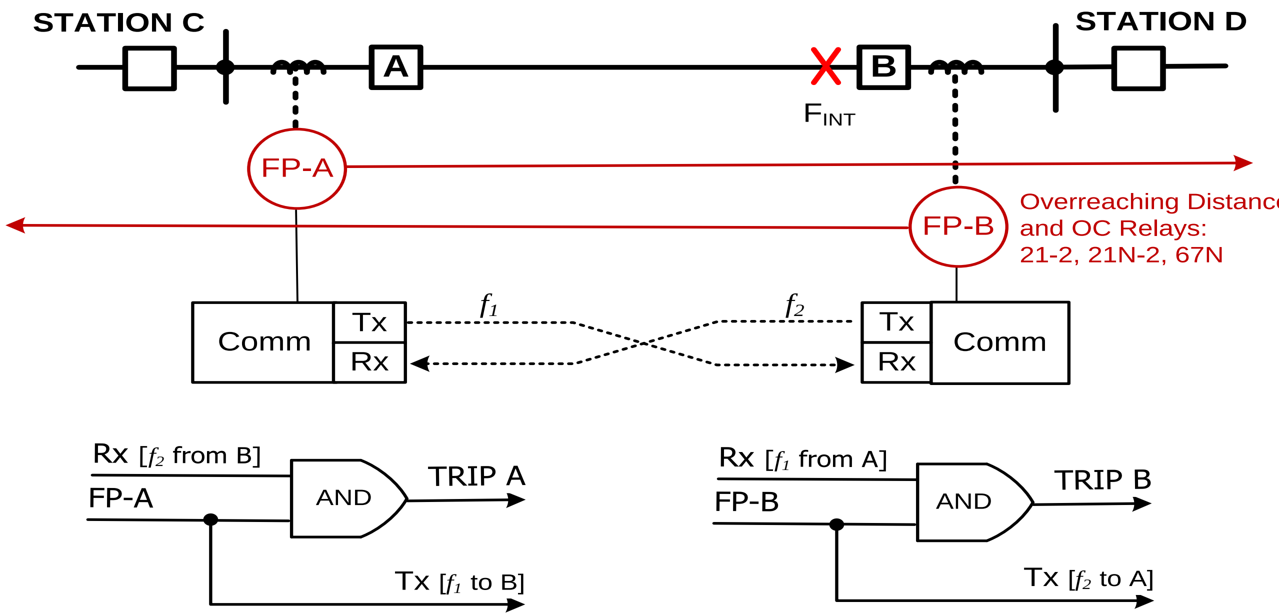


Rx signal should have a minimum receive time to allow operation of 21-2.

PUTT – Permissive-underreaching Transfer Trip

- Advantages
  - More secure than DUTT requiring a 21-2 operation for permission to trip
  - Single communications channel
- Disadvantages
  - Cannot protect full line if one terminal is open or has weak infeed
  - Requires ground distance relays for accurate reach on ground faults (no overcurrent)

POTT – Permissive-overreaching Transfer Trip



Rx signal should have a minimum receive time to allow operation of 21-2.

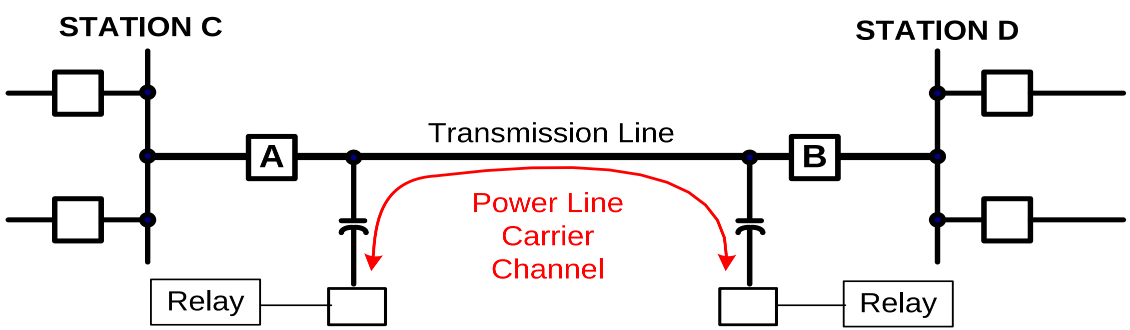
POTT – Permissive-overreaching Transfer Trip

- Advantages
  - More dependable than PUTT because it sees all line faults.
  - Open terminal and weak-end infeed logic can be applied.
  - Forward and reverse ground directional overcurrent relays may be applied for greater sensitivity to high resistance ground faults
- Disadvantages
  - Requires a duplex communications channel (separate frequency/signal for each direction)
  - Will not trip for internal fault with loss of channel (but usually applied with a zone-1/2 step-distance relay)

Directional Comparison Blocking (DCB) and Unblocking (DCUB)

- DCB and DCUB schemes are specifically intended to be used with systems where communications is less secure (likely to be lost) during line fault conditions

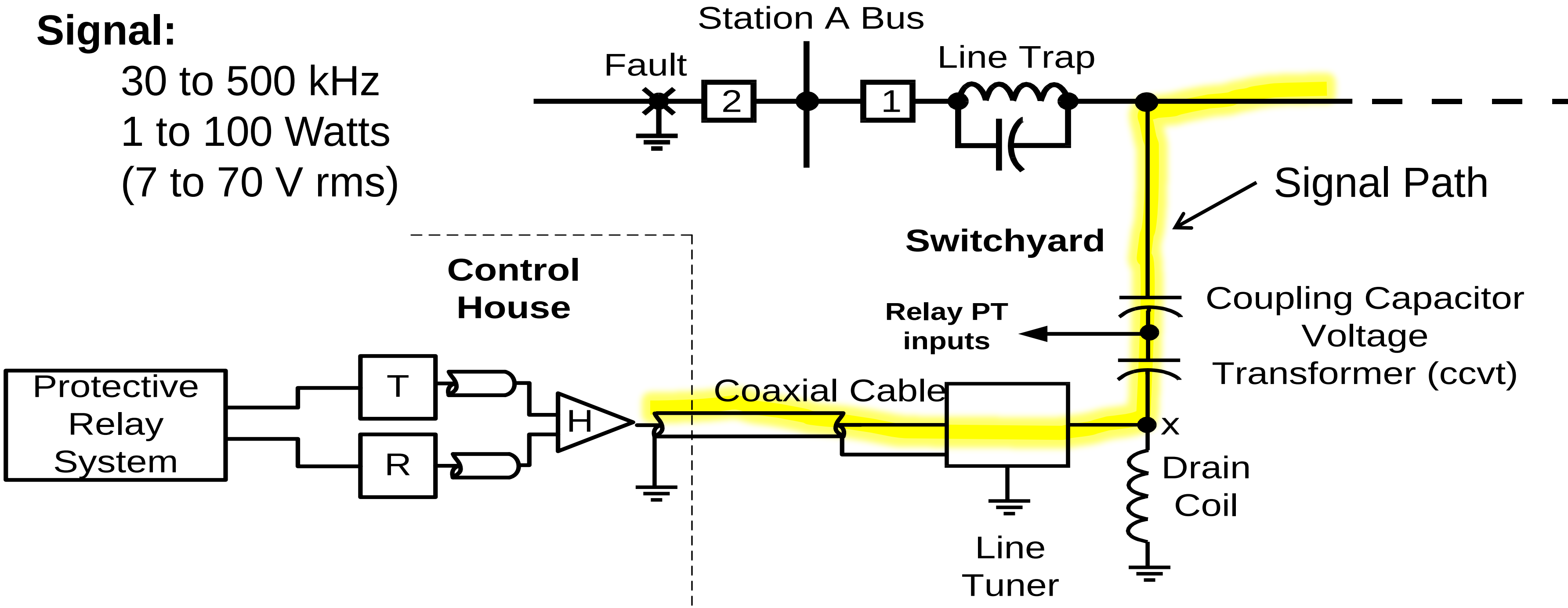
- Power-line carrier – *signal communications is on same conductor that you are protecting*



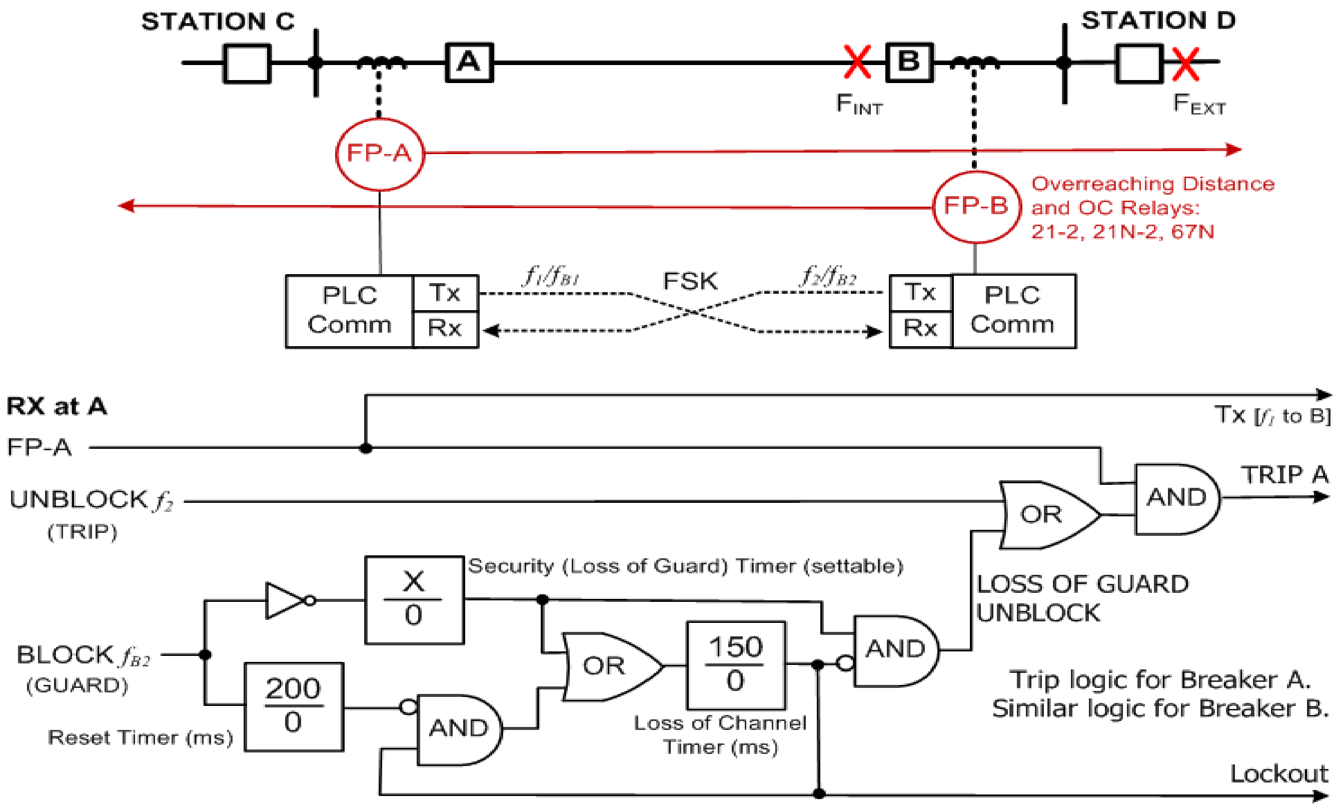
The PLC Channel

Signal:

30 to 500 kHz
1 to 100 Watts
(7 to 70 V rms)



DCUB – Directional Comparison Unblocking

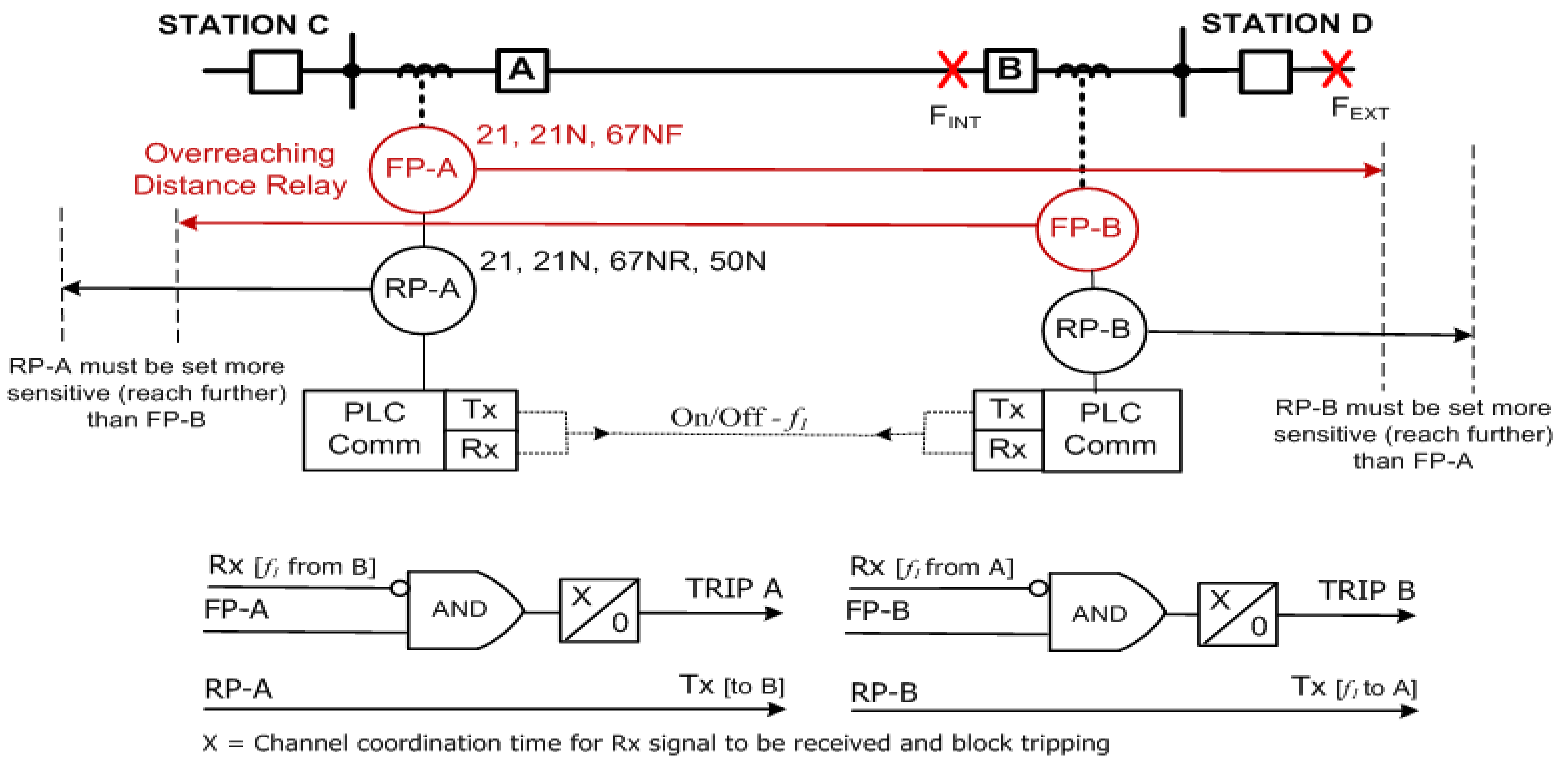


f_{B1} and f_{B2} are continuous **block** signals until a fault is detected and the frequency is shifted to the **unblock** (trip) f_1 and/or f_2.

DCUB – Directional Comparison Unblocking

- Advantages
  - Very secure at it requires receipt of Unblock signal for tripping.
  - Has logic to handle loss of channel during faults.
  - Open terminal and weak-end infeed logic can be applied.
  - Forward and reverse ground directional overcurrent relays may be applied for greater sensitivity to high resistance ground faults
  - Security logic for loss of channel (carrier holes) only delays trip during loss of channel
- Disadvantages
  - Requires a duplex communications channel (separate trip and guard frequencies for each direction)

DCB – Directional Comparison Blocking



DCB – Directional Comparison Blocking

- Advantages
  - Very dependable – does not depend on channel for tripping for internal faults
  - Open terminal and weak-end infeed are handled by scheme
  - Forward and reverse ground directional overcurrent relays may be applied for greater sensitivity to high resistance ground faults
  - Low cost communications channel – single frequency channel On/Off PLC
- Disadvantages
  - Not as secure – tends to overtrip for slow channel or loss of channel
  - Security logic for carrier holes may be required – slows tripping.
  - Channel is normally off so periodic checking is required

References

1. *IEEE Guide for protective Relay Applications to Transmission Lines,* IEEE Std. C37-113, 1999.
2. W. A. Elmore, *Protective Relaying: Theory and Application, Marcel* Decker, Inc., New York,1994.

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