# *Understanding Transmission System Ground Fault Protection*

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# *Premise*

- ***Numerical technology has brought about major changes in the way protective relays are made and applied but the underlying principles have remained the same.***

# Premise

- ***This paper highlights some of the fundamentals that govern system behavior as well as the most important aspects that a protection engineer should look for when applying ground fault protection***

# Outline

- Introduction
- Transmission Line Model
- Sequence Impedances
- Mutual Impedance
- Source Impedance Modeling
- Fault Resistance
- CT and VT Performance
- Distance Relay Characteristics
- Conclusions

# Ground Faults on Transmission Lines

- Phase to ground faults are the most common faults on transmission lines.
- In order to detect such faults and take appropriate tripping action an understanding of the basics that govern such faults is essential

# *Types of Relays Used for Transmission line Ground Fault Protection*

- ***Time Overcurrent***
- ***Directional Overcurrent***
- ***Ground Distance***

# *Ground Distance*

***Since the majority of the relays applied currently for transmission line ground fault protection are ground distance relays, This talk will be limited to ground distance protection***

# Distance Relays

- *One of the most widely applied protection systems for transmission lines is the distance relay*
- *A good understanding of line impedance and its estimation is essential to apply distance protection schemes*

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- *Conclusions*

# Transmission Line Model

- ***Ohm's Law***

$$V_R = R \cdot I$$

***In an AC system***

$$V_R = R \cdot I$$

***Magnetic flux buildup***

$$v = -L_S \, di/dt$$

***V is instantaneous Voltage, i is instantaneous current in conduction, L is Self inductance***

## *Transmission line model*

$$\boldsymbol{V} = \boldsymbol{I} \cdot \boldsymbol{j} L_S \, \omega$$

*Where* ***I*** *is current Phasor*

***V*** *is applied voltage phasor*

$L_S$ *is Self inductance of the conductor*

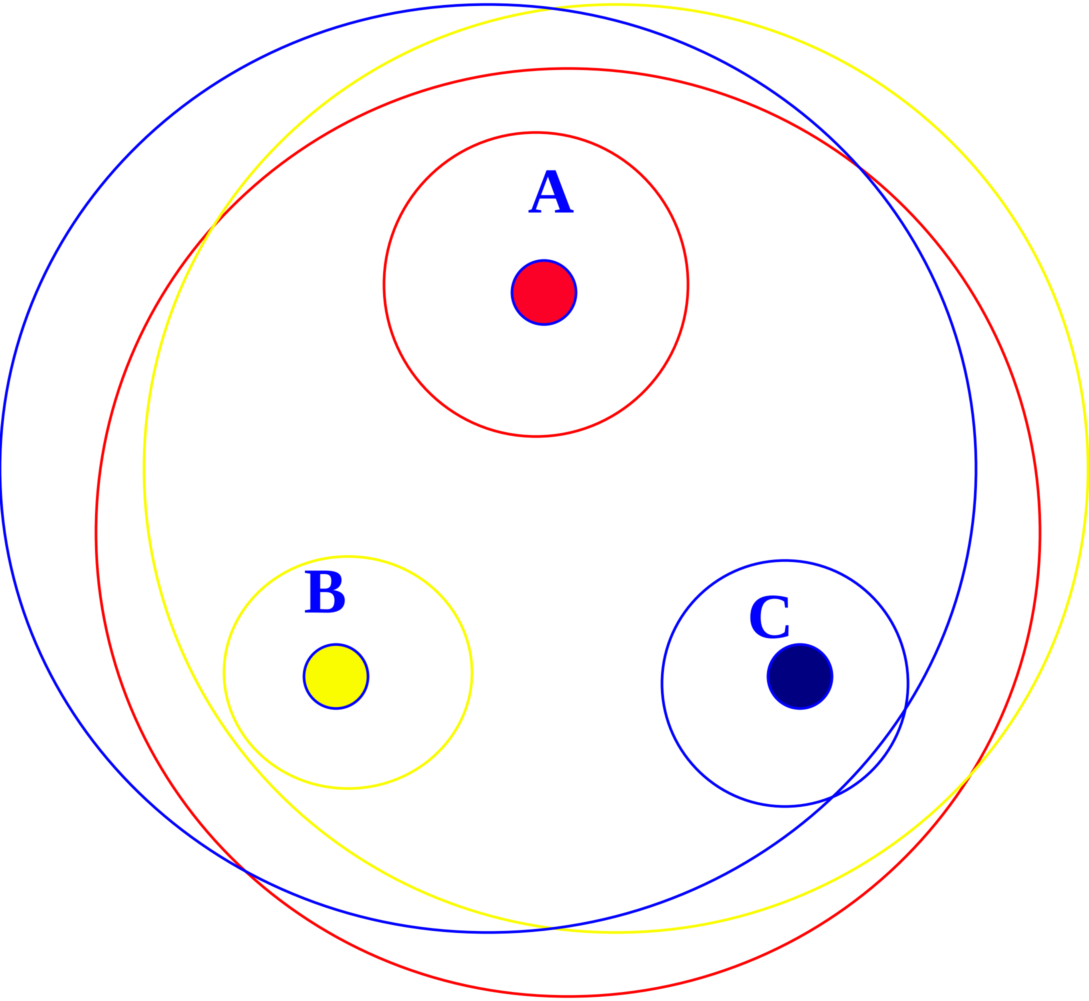
$\omega = 2\pi f$

$X_S = L_S \, \omega$

$\boldsymbol{V}_S = j \, X_S \cdot \mathbf{I}$

$\mathbf{V}_{\mathbf{m}} = \mathrm{j} \, \mathrm{X}_{\mathrm{m}} \cdot \mathbf{I}_{\mathrm{m}}$   m = mutual

# *Voltage in a 3 phase system conductor*




**Volage drop in A phase**
**= A combination of:**
**1. Self reactance A ,**
**2. Mutual react of B**
**3. Mutual react of  C**

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# Positive sequence Impedance

***Vap = XsIA+ XmIB+XmIC***

***= XsIA-XmIA+XmIA+XmIB+XmIC***

***=IA(Xs-Xm) + Xm(IA+IB+IC)***

***=IA. X1+ 0,***

***since IA+IB+IC = 0 for positive sequence currents***

***So X1 = Xs-Xm = Reactance caused by flux linkages between the conductor up to the other two conductors***

# Positive Sequence Impedance

- $X_1 = X_s - X_m$

Or $V_A = I_A ( R + j X_1 )$

simplifying by eliminating the resistance term

$V_{A1} = I_{A1} \cdot j X_1$

# *Negative Sequence Impedance*

- ***Same as the Positive Sequence Impedance!***

$$V_{A2} = I_{A2} \cdot jX_2$$

# Zero sequence Impedance

$Va0 = XsIA0 + XmIB0 + XmIC0$

For zero sequence, $IA0 = IB0 = IC0$

$Va0 = IA0(Xs + 2Xm)$

$= IA0\ X0$

Where,

$X0 = Xs + 2Xm$

This is the reactance caused by own conductor flux + Flux caused by other two conductors enclosing all the conductors

# *Zero Sequence Impedance*

- ***Zero sequence current divide equally among the three conductors***
- ***Common return through earth***
  - ***follows the path of the line***
  - ***non-uniform conductivity***
- ***Return through ground wires, if used***

# *Zero Sequence Impedance*

## *Carsons assumptions (1926):*

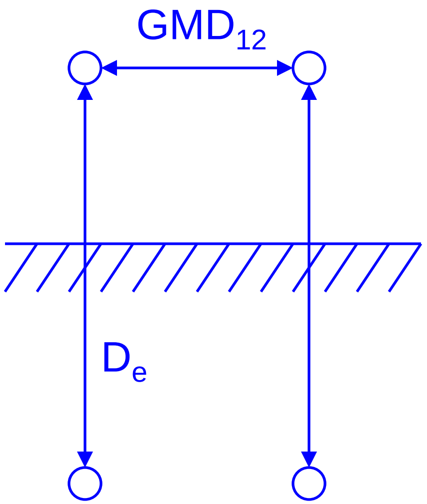
- ***the conductors are parallel to the ground***
- ***the earth is a solid with a plane surface, infinite in extent, and of uniform conductivity***

Self impedance:

$$Z_{11} = r_a + 1.588 f \cdot 10^{-3} + j4.657 f \cdot 10^{-3} \log \frac{D_e}{GMR}$$

Mutual impedance:

$$Z_{12} = 1.588 f \cdot 10^{-3} + j4.657 f \cdot 10^{-3} \log \frac{D_e}{GMD_{12}}$$




$D_e$=equivalent depth of earth return (mathematical fiction)

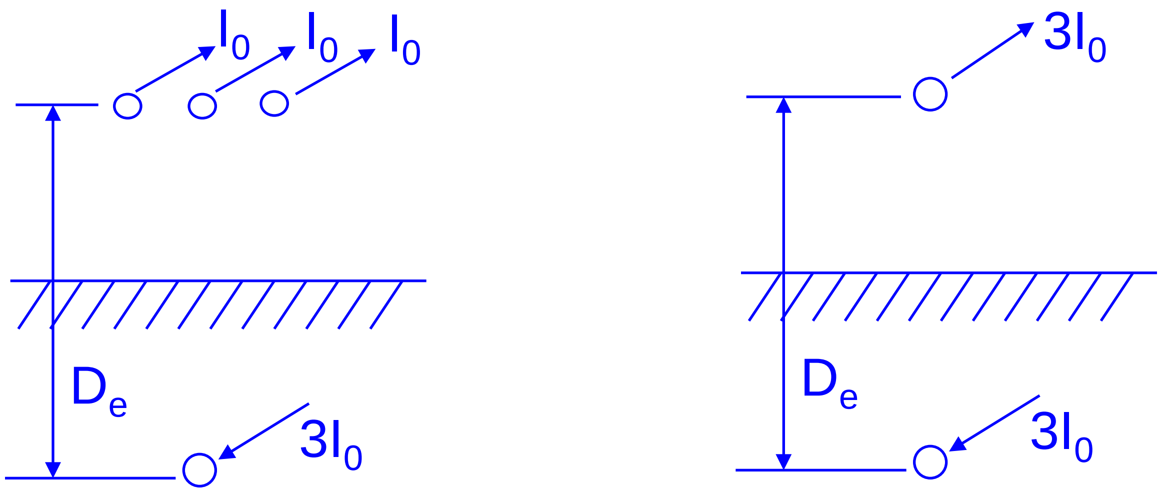
# *Equivalent Depth of Earth Return*

$$D_e = 2160\sqrt{\frac{p}{f}}$$

p = earth resistivity in meter-ohms
f = frequency

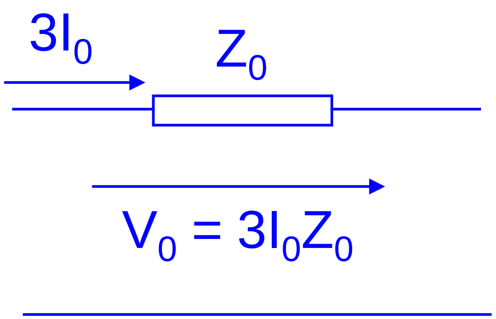
| **Soil** | **p/f** | **$D_e$(ft)** | **Log$D_e$** |
|---|---|---|---|
| Sea water | 1 | 280 | 2.45 |
| Damp earth | 100 | 2800 | 3.45 |
| Dry earth | 1000 | 8840 | 3.95 |
| Pure slate | $10^6$ | $2x10^6$ | 6.33 |
| Sand stone | $10^8$ | $2x10^7$ | 7.33 |

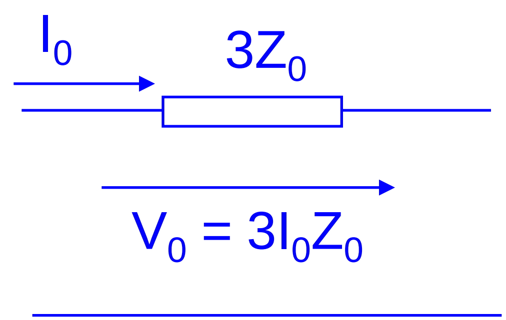
# *Converting Carson's Equations to calculate $Z_0$*




- ***Unit zero sequence current consists of 1 pu current flowing in each phase circuit and 3 pu flowing in the earth or return***
- ***By replacing the three phases by one equivalent conductor, 3 pu current flows in this equivalent***

# *Converting Carson's Equations to calculate $Z_0$*




- ***By definition only 1 pu flows in the zero sequence networks***
- ***The same voltage drop for 1 pu current x 3 pu impedance, as 3 pu current x 1 pu impedance***
- ***Thus, it is necessary to multiply Carson's equations by 3***

# Zero Sequence Impedance

$$Z_{011} = Z_0 = 3Z_{11}$$

$$Z_{012} = Z_{0m} = 3Z_{12}$$

$$Z_0 = r_a + 0.286 + j0.8382 \log \frac{D_e}{GMR}$$

$$Z_{0m} = 0.286 + j0.8382 \log \frac{D_e}{GMD}$$ Ohms/mile at 60 Hz

Note: r for a single conductor gives r/3 for a group of three, hence multiplication by 3 gives 3r/3 = r for $Z_0$

# Transposed 3-Phase Line, No Ground Wires

$$Z_0 = r_a + 0.286 + j0.8382 \log \frac{D_e}{GMR}$$

$$Z_0 = r_a + 0.286 + j0.8283 \log \frac{D_e}{\sqrt[9]{GMR^3 D_{ab}^2 D_{bc}^2 D_{ca}^2}}$$

$$Z_{0m} = 0 \ \text{(single line)}$$

$$Z_0 = r_a + 0.286 + j0.8382(\log D_e + \frac{3}{9}\log\frac{1}{GMR} - \frac{2}{9}\log D_{ab}D_{bc}D_{ca})$$

$$= r_a + 0.286 + j0.8382 \log D_e + \underbrace{j0.2794 \log \frac{1}{GMR}}_{X_a} - j2 \cdot \underbrace{0.2794 \log \sqrt[3]{D_{ab}D_{bc}D_{ca}}}_{X_d}$$

$$Z_0 = r_a + r_e + j(X_a + X_e - 2X_d)$$

$$r_e = 0.286$$

$$X_e = 0.8382 \log D_e$$

# $Z_0$ as a Function of $Z_1$

- ***Z1 is the self impedance of each phase, a one way impedance***
- ***Z0 is a loop impedance, or the sum of the phases and the ground return impedance***

$$Z_1 = r_a + j(X_a + X_d)$$ Ohms/phase

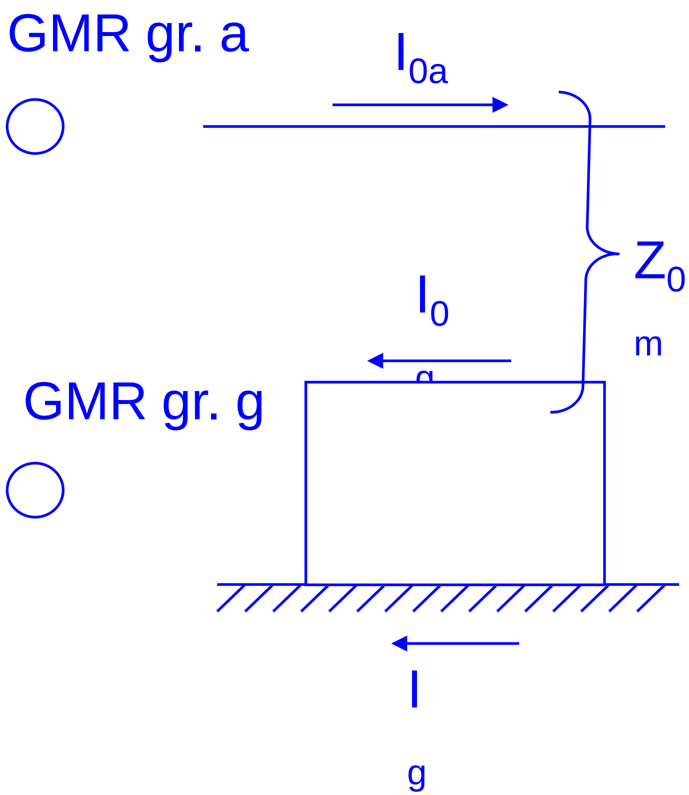
⇨ $$Z_0 = r_a + r_e + j(X_a + X_e - 2X_d)$$ Ohms/loop

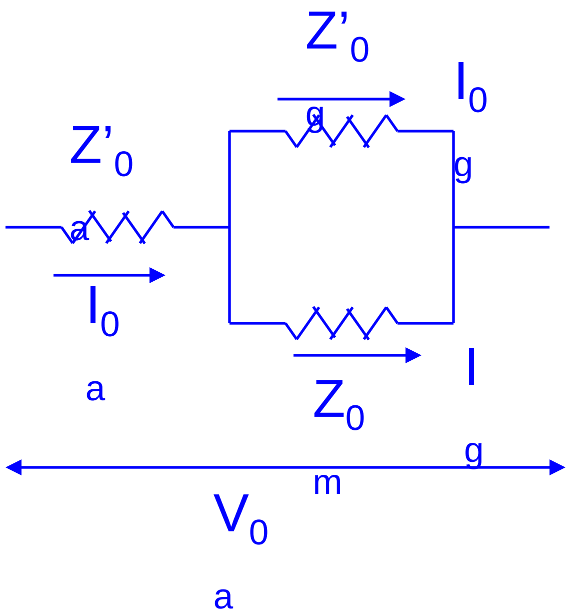
$$Z_0 = Z_1 + r_e + j(X_e - 3X_d)$$

# $Z_0$ for Lines With Ground Wires

- ***The ground wires provide a parallel path to the earth***
- ***The ground wire circuit is tied to earth at each tower***
- ***These connections will have some impedance, mostly resistance, known as tower footing resistance***
- ***In zero sequence line impedance calculations, the tower footing resistance is assumed to be zero, which is practical for fault calculations***

# $Z_0$ for Lines With Ground Wires




Return current divides between earth and ground wire(s)

# $Z_0$ for Lines With Ground Wires

$$V_{0a} = Z_{0a} I_{0a} - Z_{0m} I_{0g} = Z'_{0a} I_{0a} + Z_{0m} I_g$$

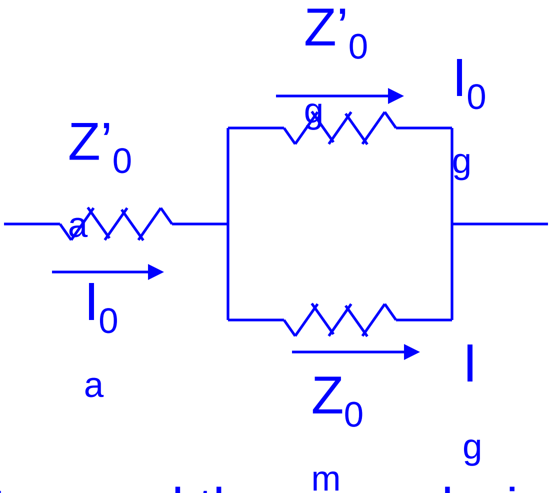
$$Z'_{0a} = Z_{0a} - Z_{0m}$$

$$I_g = I_{0a} - I_{0g}$$

$$V_{0g} = Z_{0g} I_{0g} - Z_{0m} I_{0a} = Z'_{0g} I_{0g} - Z_{0m} I_g = 0$$

$$Z'_{0g} = Z_{0g} - Z_{0m}$$

$$Z_0 = Z'_{0a} + \frac{Z'_{0g} Z_{0m}}{Z'_{0g} + Z_{0m}}$$




$Z'_{0a}$=leakage impedance of the conductors
$Z'_{0g}$=leakage impedance of the ground wires
$Z_{0m}$=mutual impedance between the conductors and the ground wires
$I_g$=current in the earth

# Transposed 3-Phase Line, One Ground Wire

$$Z_{0a} = r_a + 0.286 + j0.8382 \log \frac{D_e}{GMR_{gr.of\,3}}$$

$$Z_{0m} = 0.286 + j0.8382 \log \frac{D_e}{GMD}$$

$$Z_{0g} = 3r_g + 0.286 + j0.8382 \log \frac{D_e}{GMR_g}$$

$$Z'_{0a} = Z_{0a} - Z_{0m} = r_a + j0.8382 \log \frac{GMD}{GMR_{gr.of\,3}}$$

$$Z'_{0g} = Z_{0g} - Z_{0m} = 3r_g + j0.8382 \log \frac{GMD}{GMR_g}$$

# Transposed 3-Phase Line, One Ground Wire

$$Z'_{0a} = r_a + j(X_a + 3X_{d(g)} - 2X_{d(gr.of\,3)})$$

$$Z'_{0g} = 3r_g + j(3X_g + 3X_{d(g)})$$

$$Z_{0m} = r_e + j(X_e - 3X_{d(g)})$$

Use in:

$$Z_0 = Z'_{0a} + \frac{Z'_{0g}\,Z_{0m}}{Z'_{0g} + Z_{0m}}$$

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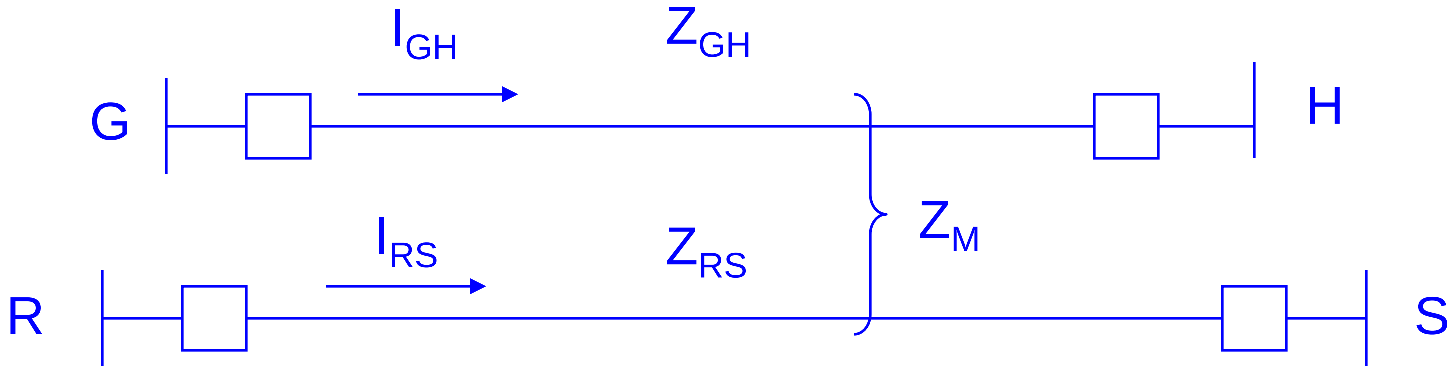
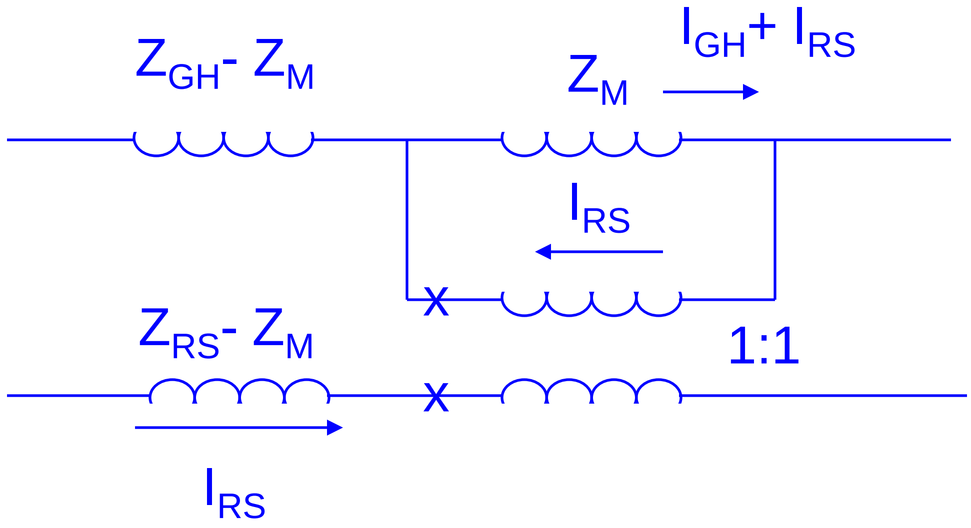
# *Mutual Impedance*

- ***Inductive coupling between lines that are paralleled***
  - ***same or different voltages or communication lines parallel to power lines***
- ***Negligible for positive- and negative-sequence currents (3 - 7%)***
- ***Zero sequence mutual impedance can be 50 - 70% of the self impedance***
- ***Must be considered for ground faults***
  - ***use negative sequence polarizing for directional ground relays***

# *Mutual Impedance*

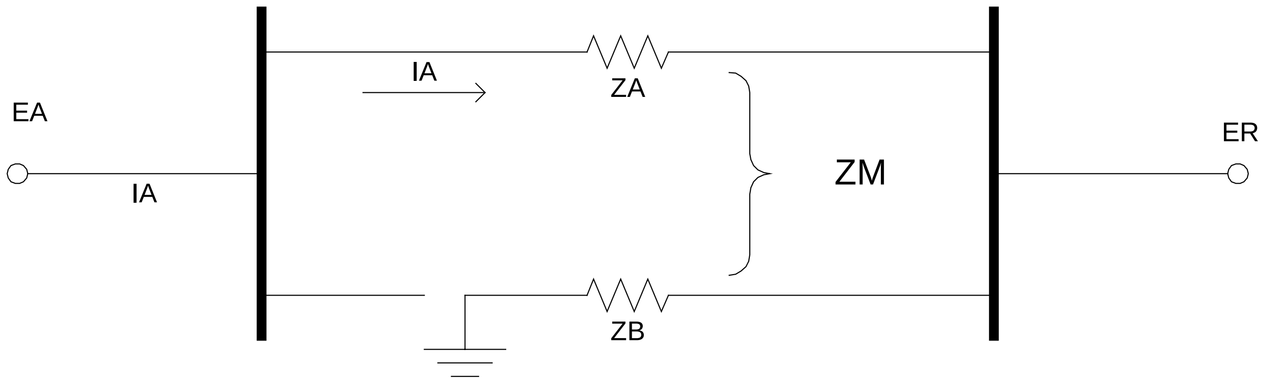


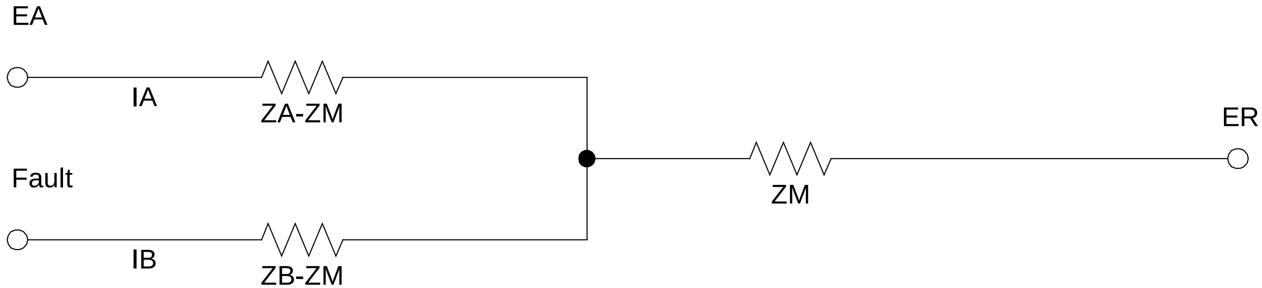




$$V_{GH} = I_{GH} Z_{GH} + I_{RS} Z_m$$

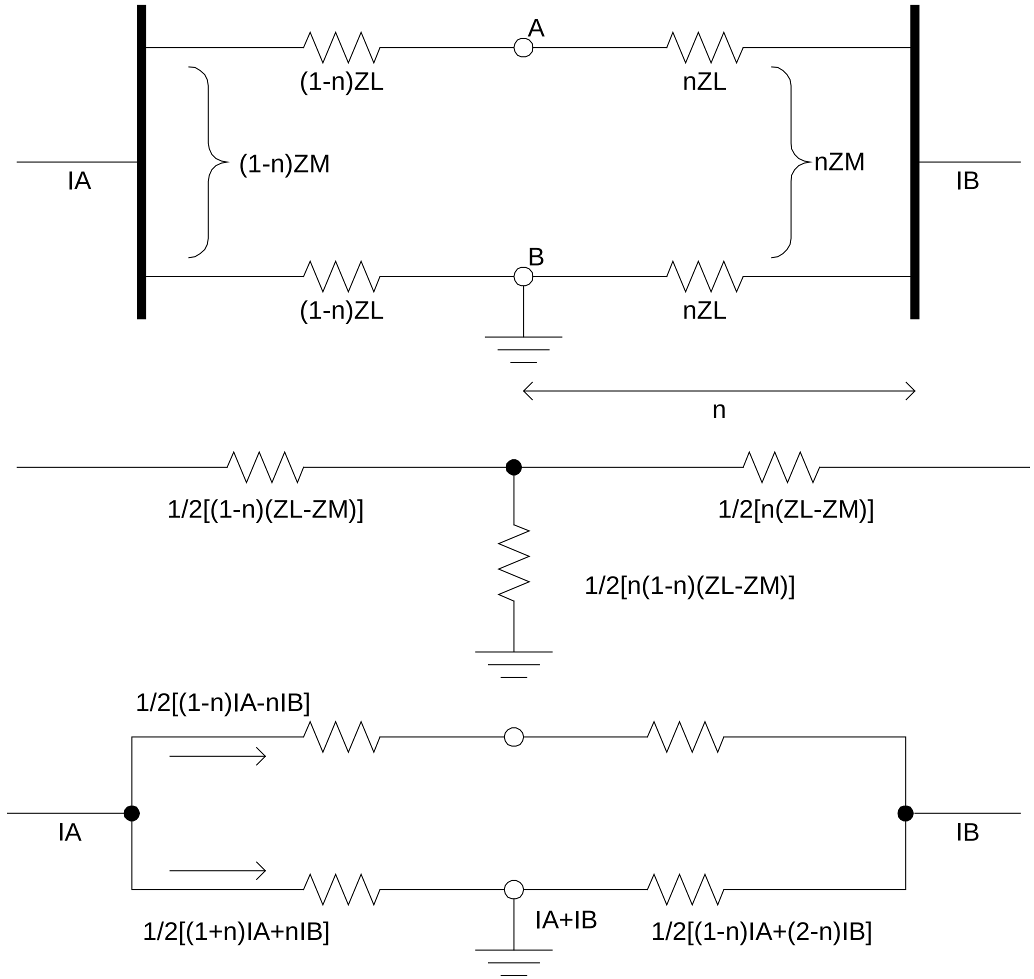
$$V_{RS} = I_{RS} Z_{RS} + I_{GH} Z_m$$

# *Mutual Coupling - Fault at One Line End*

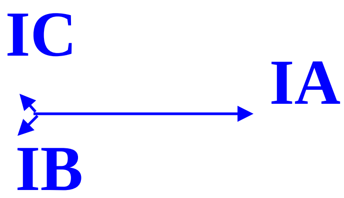


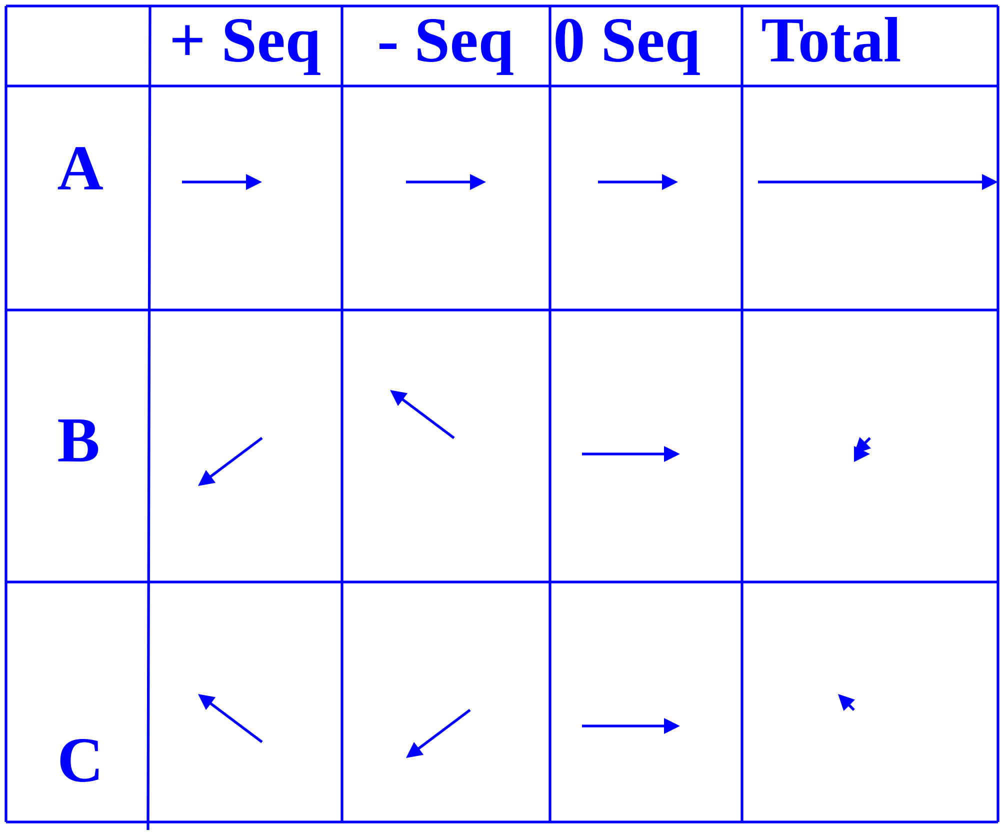



# Mutual Coupling - Fault at n

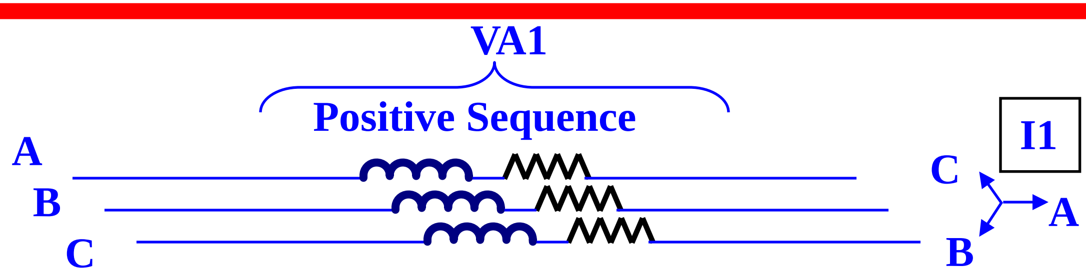


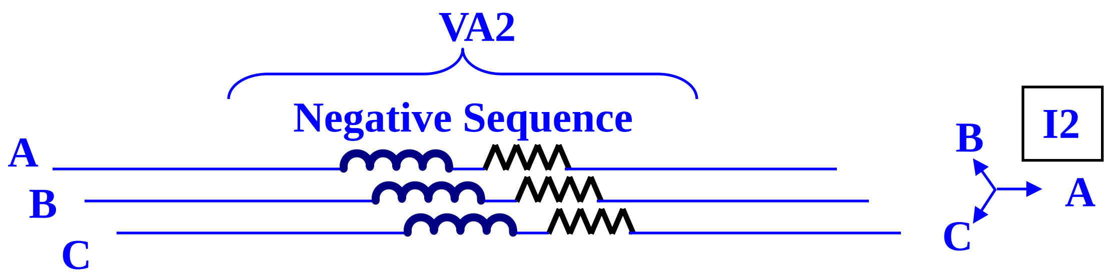
# *Sequence components: Ground Fault current*

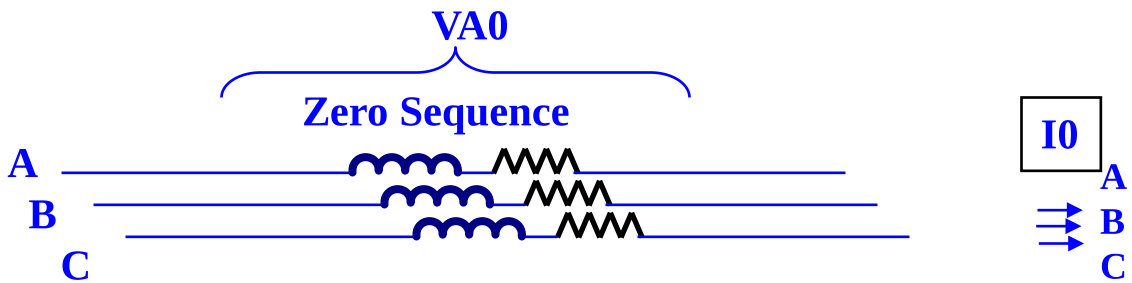


# *Voltage drop along the line = $V_A = V_{A1} + V_{A2} + V_{A0}$*



# Voltage drop for SLG Fault

$$V_A = I_{A1} \cdot jX_1 + I_{A2} \cdot jX_2 + I_{A0} \cdot jX_0$$

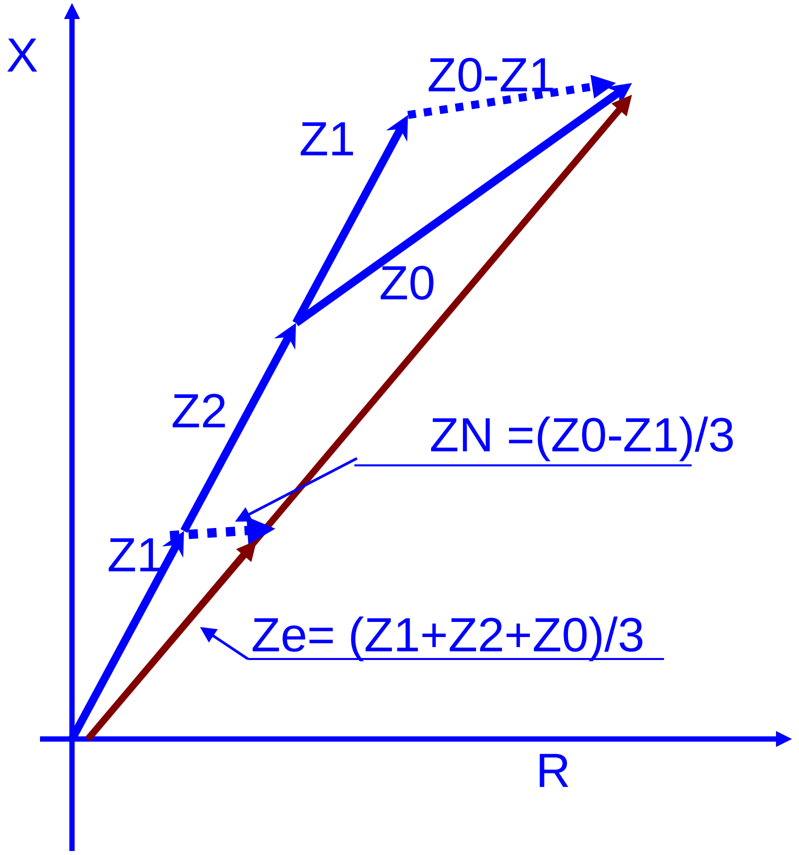
$$= I_A/3\ (jX_1 + jX_2 + jX_0)$$

$$= I_A\ jX_1 + I_A\ j\ (X_0 - X_1)/3$$

**Including resistance**

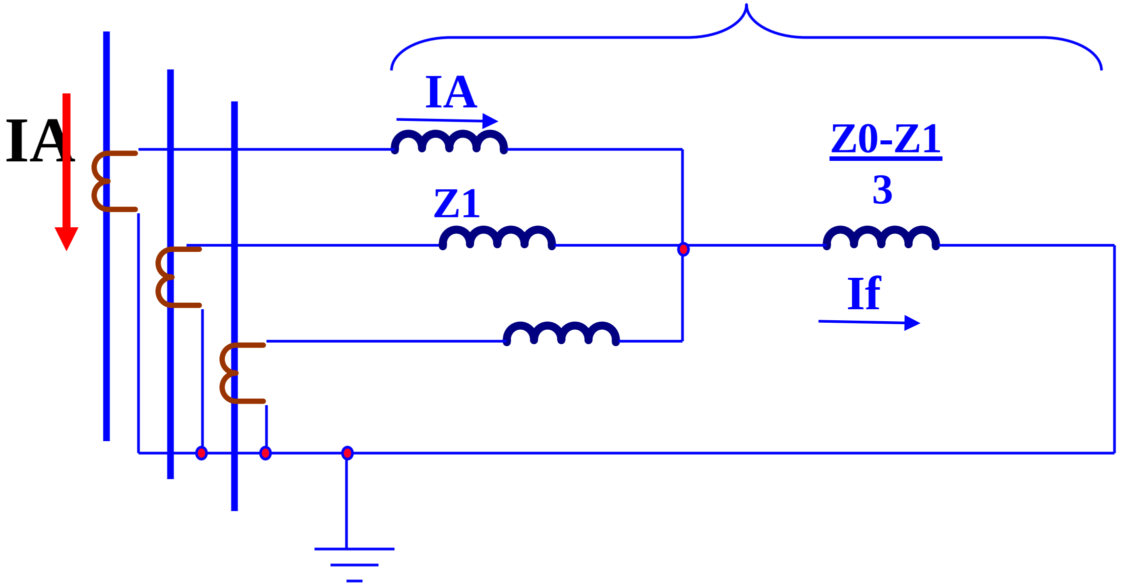
$$V_A = I_A\ Z_1 + I_A\ (Z_0 - Z_1)/3$$

# *Loop Impedance: Zn Line Ground Faults*



# *Static Relay Design with Replica Impedance*

VA = IA {(Z1)+ (Z0-Z1)/3} = IA /3* { 2Z1+Z0}
=IA1*Z1 + IA2*Z2+IA0*Z0



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# Source Impedance Modeling

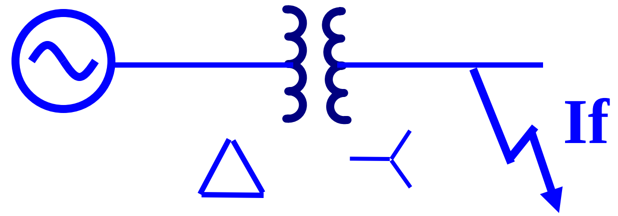
- ***In EHV systems GSU is connected Wye with a neutral solidly grounded***
- ***When several generators are involved a Thevenin's equivalent network of the sources yield a lower impedance to the flow of ground fault current compared to mutliphase short circuits.***

# Source Impedance Modeling

- ***When the line of interest is fed from long lines, the source impedance behind the bus is dominated by the line parameters which have a much higher zero sequence impedance than positive sequence sequence impedance.***
- ***The magnitude of the current during SLG is lower than 3P or P-P faults***

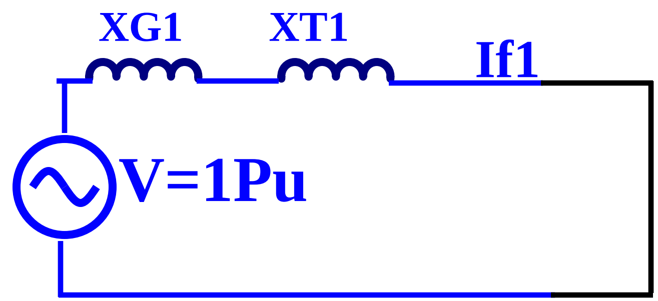
# *Case when 1ph fault current > 3 ph fault current*

**Single Line Diagram**

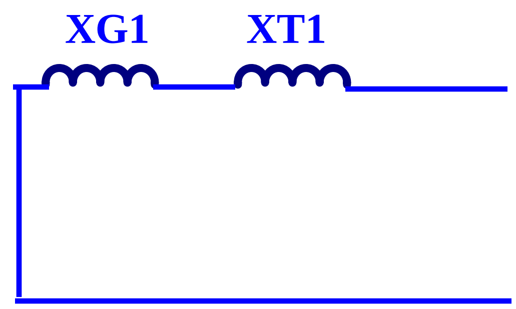



## Eqvt. Circuit
## 3ph Fault

**Single Line Diagram**
**Positive Sequence**

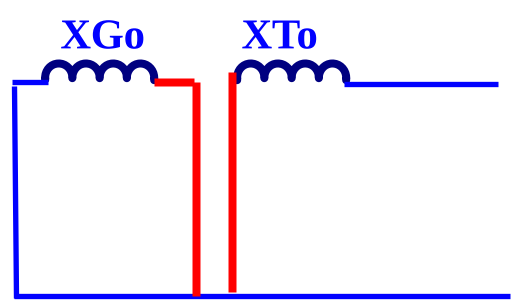



**Negative Sequence**




**Rf=0**
**If1= If**
**= 1/(XG1+XT1)**

**Zero Sequence**



# *Case when 1ph fault current > 3 ph fault current*

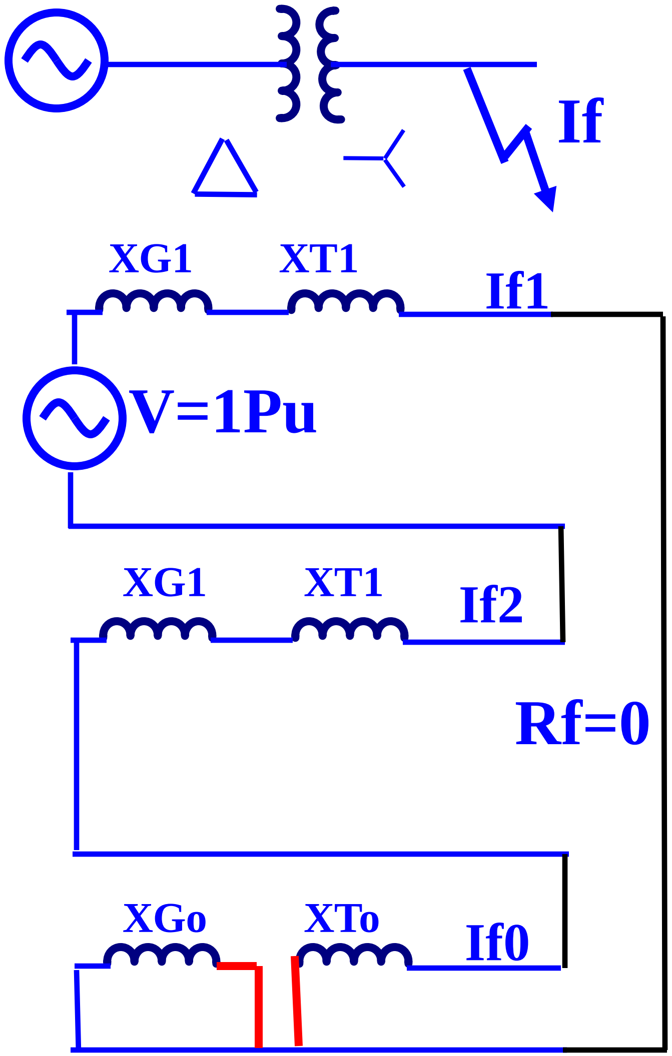
Single Line Diagram

## Eqvt. Circuit
## 1Ph-G Fault

Single Line Diagram
Positive Sequence

Single Line Diagram
Negative Sequence

Single Line Diagram
Zero Sequence




**Rf=0**
**XG1=XG2**
**XT1=XT2=XT0**
**If1= If2=If0=If/3**
**If/3= 1/(2XG1+3XT1)**
**So,**
**If = 3/(2XG1+3XT1)**
**= 1/(67%XG1+XT1)**

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# *Fault Resistance*

- ***Depends on tower footing resistance***
- ***Ground Resistance***
- ***Arc Resistance***

***First two assessed locally***

***Emperical formula exist to decide fault resistance***

# *Distance Relays and Fault Resistance*

- ***Distance relays have a limited reach along the resistive direction***

- ***For a 115v secondary Vt, and 5 amp secondary CT theoretical limit is***

  ***115/5 = 13 ohms on the secondary side***

***Ground fault resistances above this limit will have to use ground overcurrent protection, or directional comparison***

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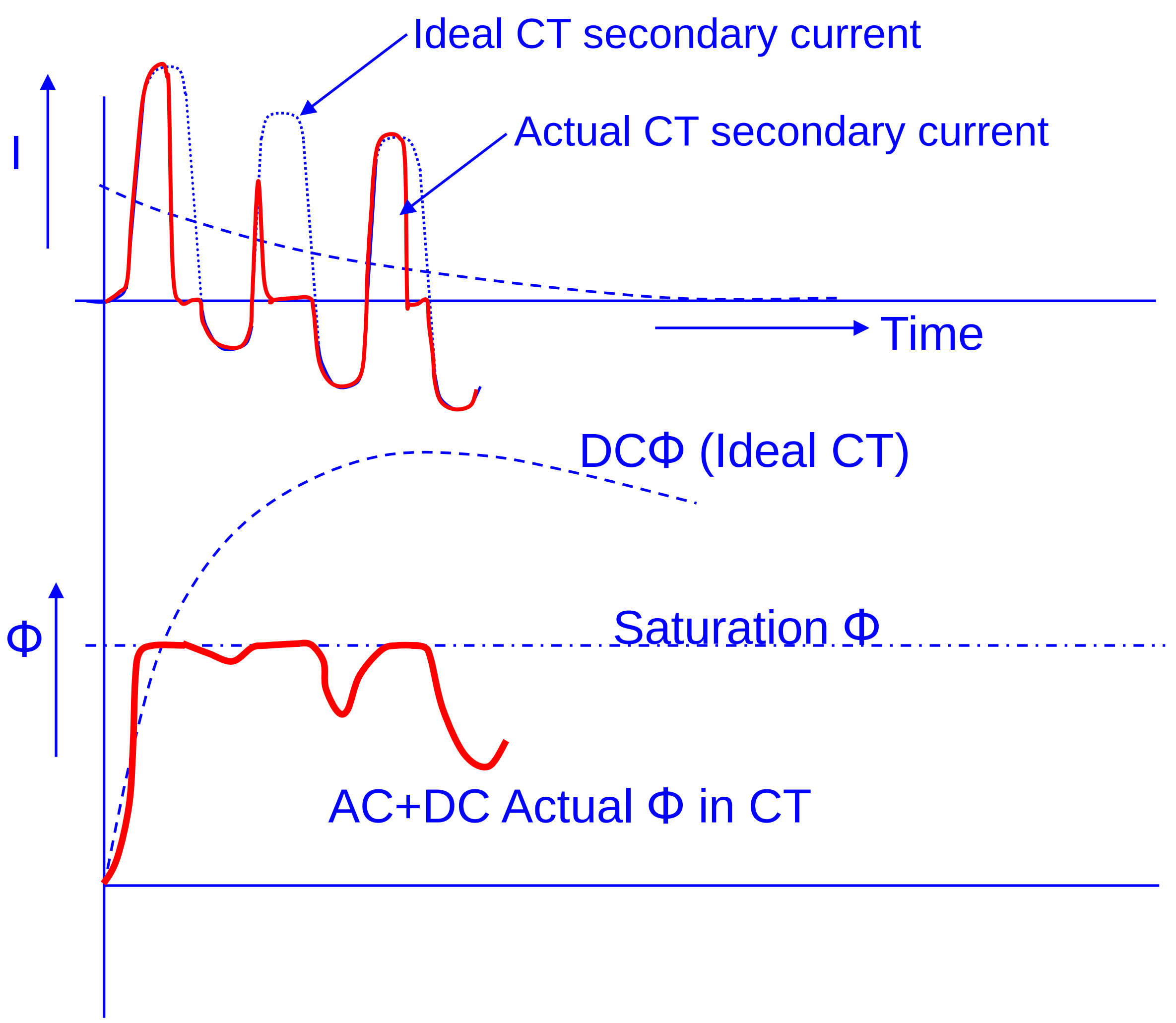
# *Current transformer*

- ***Outcome of modeling depends on the fidelity of the CT waveform that is fed into the model***
- ***During system faults with high X/R in the system, there could be large DC offsets with time constants running into 10's of milliseconds close to a generating station.***

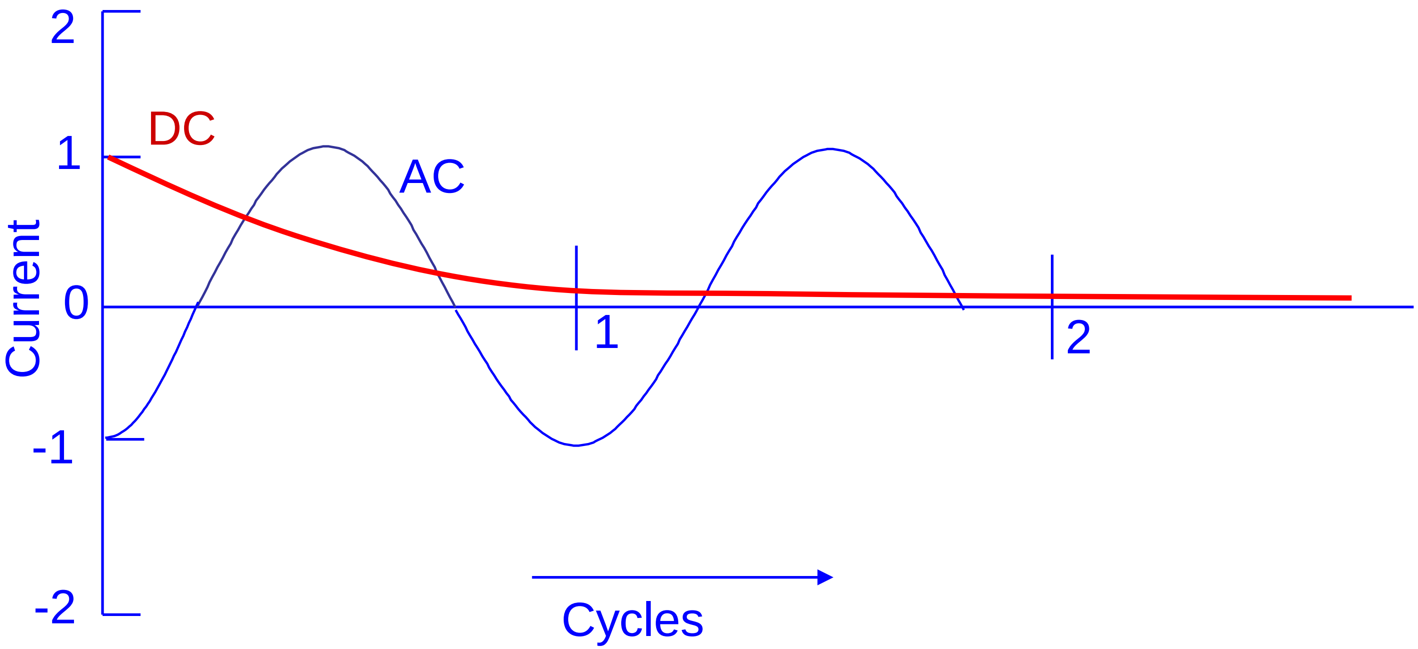
# *Current Transformers*

- ***CT's are designed to translate AC waveforms.***
- ***Can cope with low magnitude, short duration DC transients***
- ***A large magnitude, DC offset with a long time constant would be asking the CT to translate a DC waveform***
- ***A CT tries for the first cycle but..***

# *CT Saturation, its effects on CT secondary Waveforms*



# *DC Transients in Current Waveform*



# *Voltage Transformers*

- ***With electromagnetic VT's reproduction is fairly accurate but VT's a too expensive to EHV systems***
- ***When the line impedance is small compared to the source impedance, the voltage at the line terminal cannot be certain due to measuring errors. Can't be confident fault is inside or outside zone.***

# *CCVT's*

- ***Transients associated with capacitive discharge of the VT secondary pose special problems.***
- ***A slightly delayed tripping is often the result.***
- ***Ferroresonance of the CCVT secondary may also cause distorted signals.***
- ***Suppression networks cause additional delays in response***

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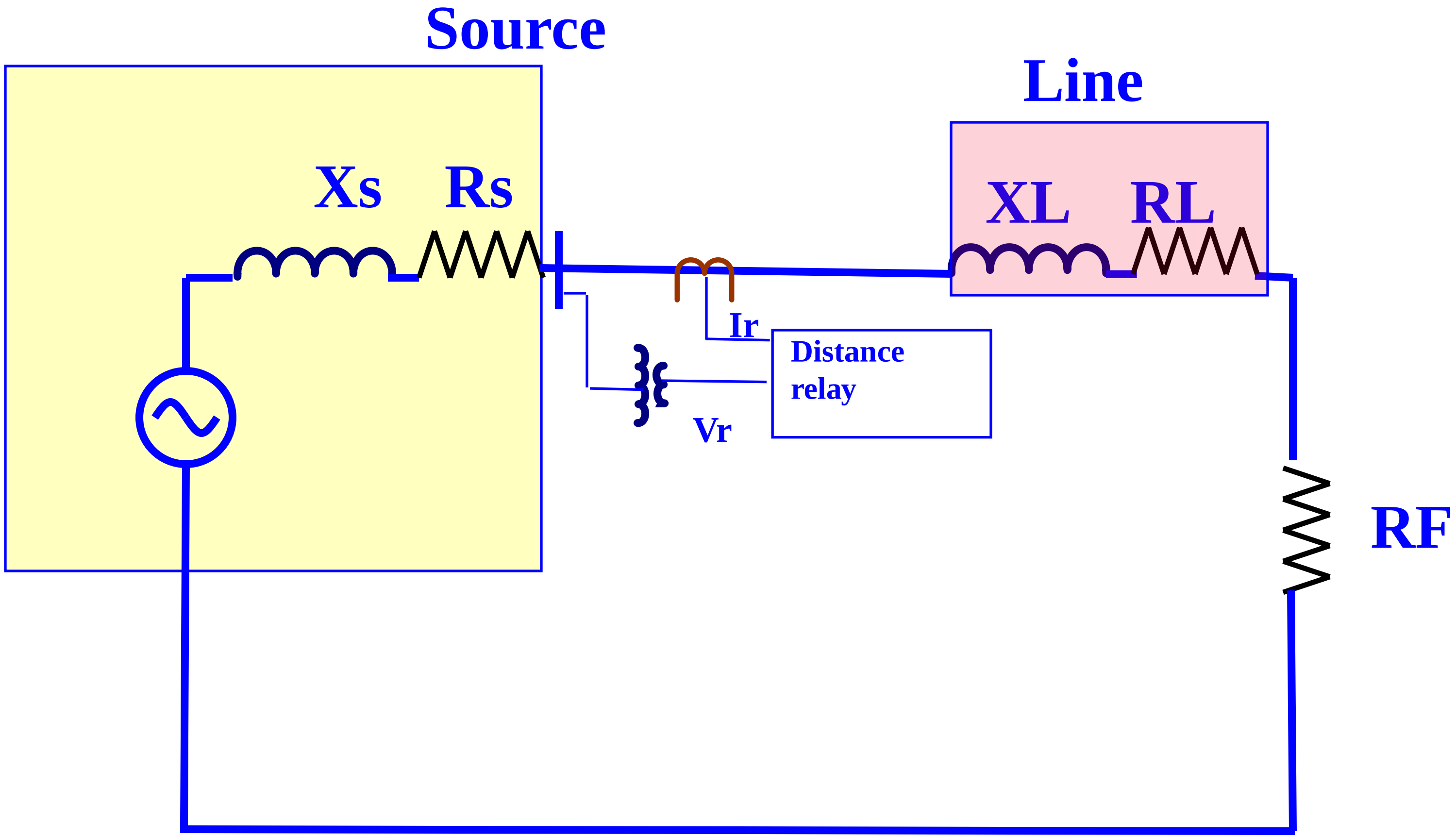
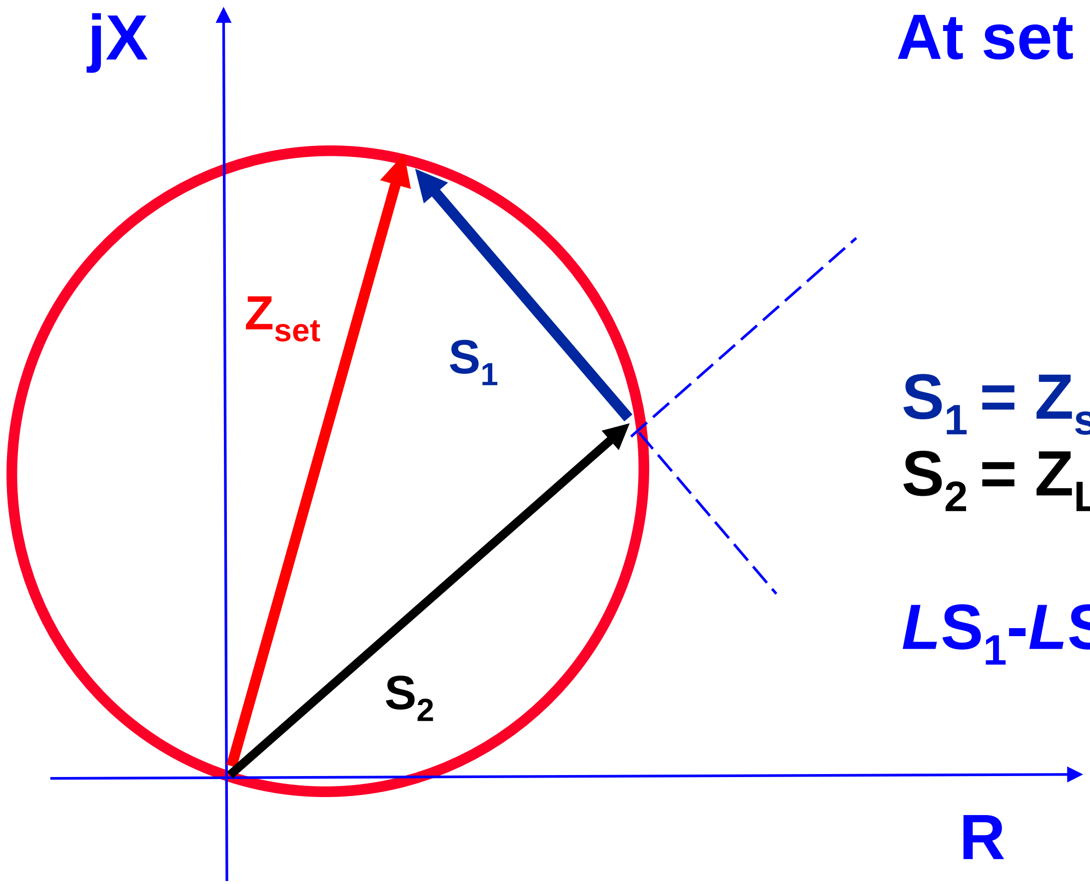
# *Line model*



# *Distance Relay*

- ***A current proportional to the line current $I_R$ at the relaying point is passed through a replica $Z_{set}$***
- ***A voltage is developed across the replica $V_{set}$***
- ***A comparison is done against the actual system voltage measured $V_R$***

# *Mho Comparator*




**At set reach**

$S_1 = Z_{set} - Z_L$

$S_2 = Z_L$

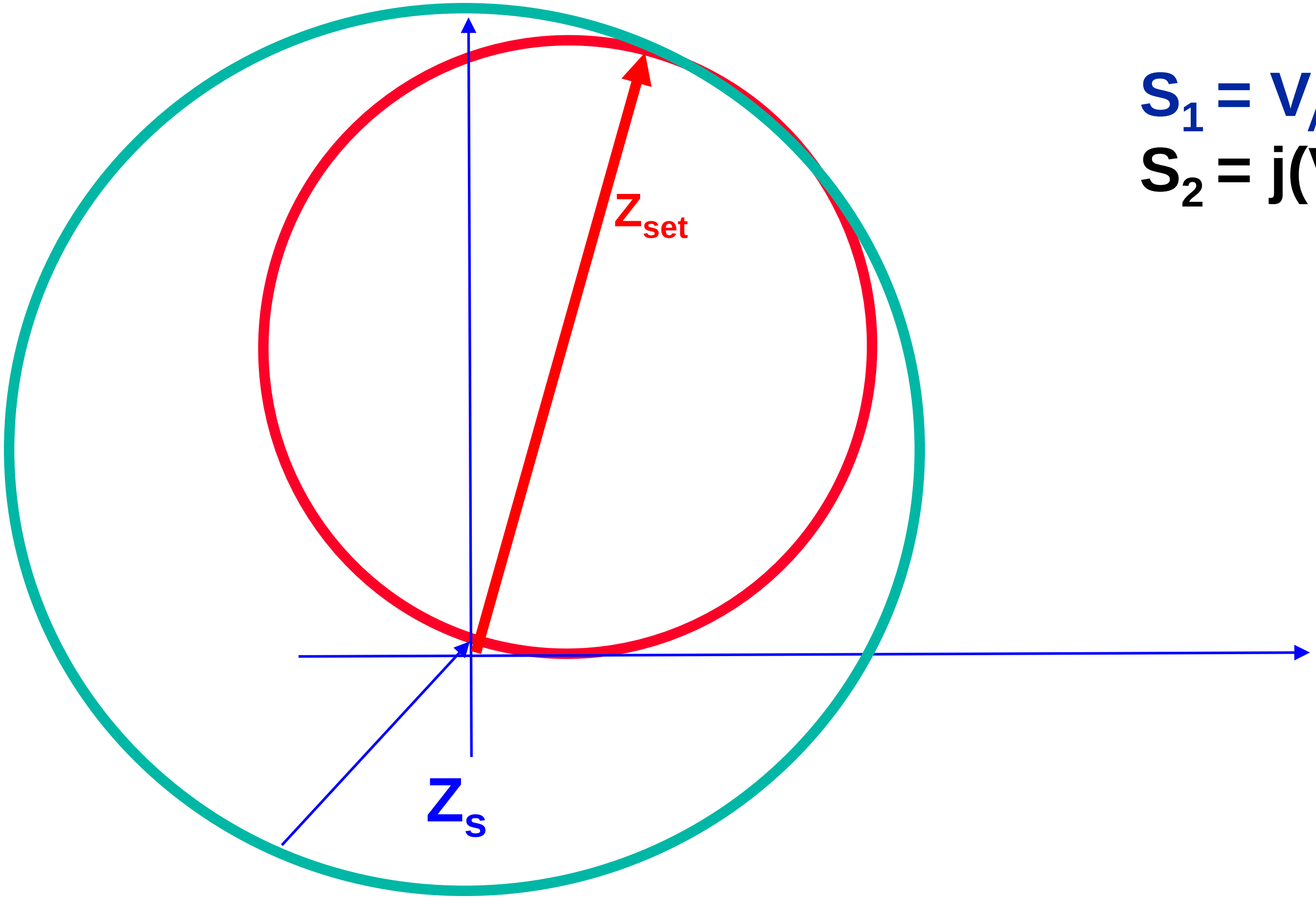
$\angle S_1 - \angle S_2 = 90°$

# Reference Voltage VR

- Faulted phase voltage
- Voltage from the other phases
- Voltage from the pre fault(using memory) circuits

- Result cross polarized mho, inherently expanding characteristic with the source impedance behind the bus contributing to the expansion

# *Cross Polarized Mho*




$S_1 = V_A - (I_A + k_0 I_0)Z_{set}$

$S_2 = j(V_C - V_B)$

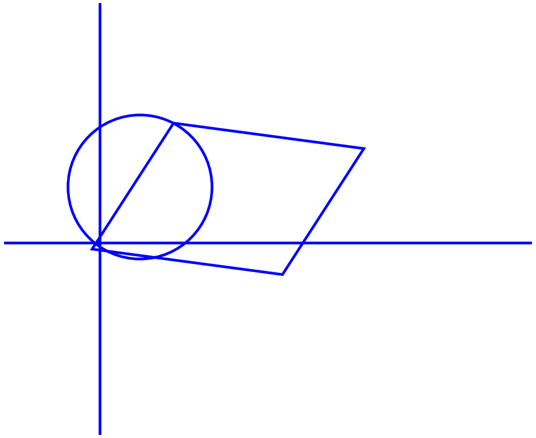
# *Cross polarized Mho*

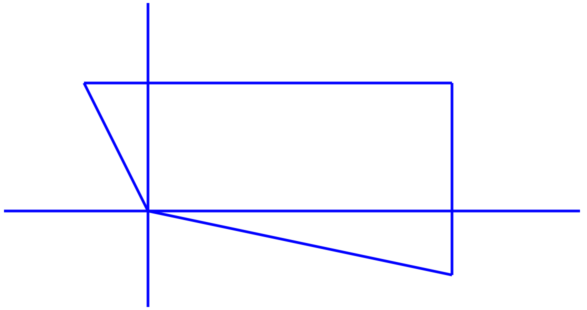
- ***When the source impedance is high, the fault current is lower, resulting in higher arc resistance.***
- ***The expansion of the characteristic is thus inherently in step with higher fault arc resistances to ensure good resistance coverage.***

# Quadrilateral Characteristic

- ***In cases line lengths are medium and with very strong sources, the resistive reach of the Mho without expansion may not be sufficient to capture desired fault arc resistance.***
- ***In such cases Quad or Reactance shaped characteristics can be used.***

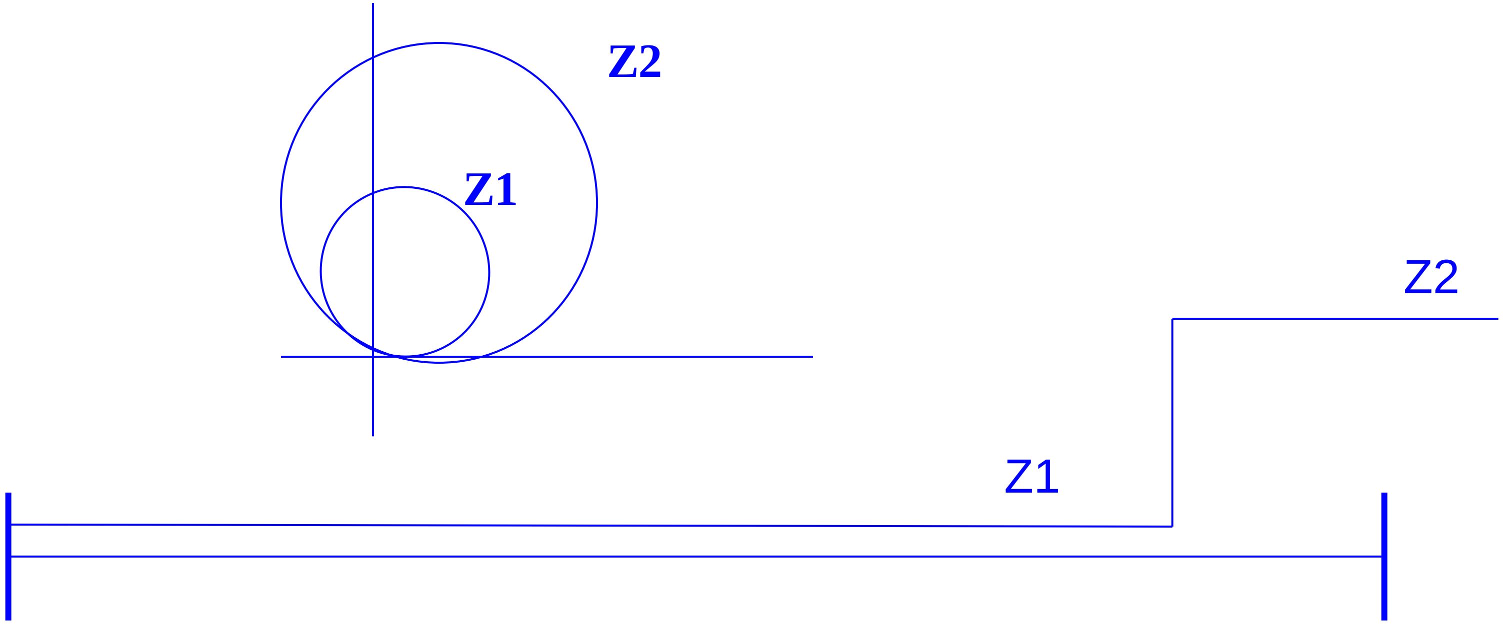
# *Quad And Composite Characteristics*





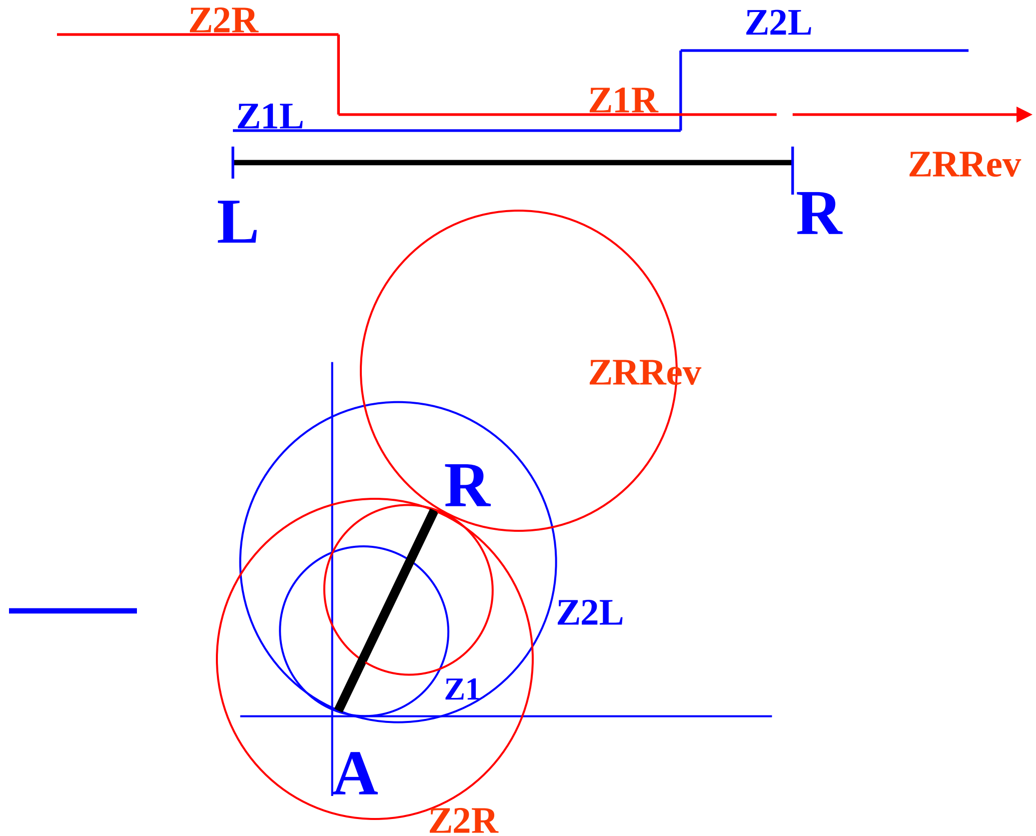
## *Stepped Distance*

- ***Each line end relay operates independently***
- ***No communication between the terminals***

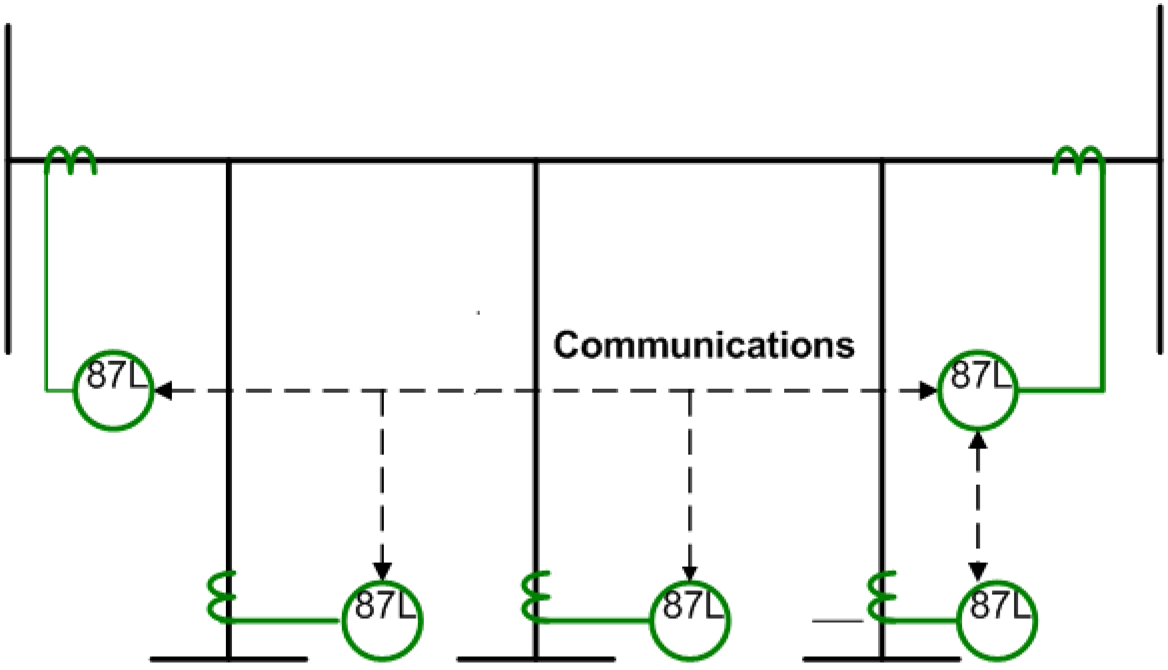


# *Pilot Systems*

- ***PUTT***
  ***L End: Z1L + (Z2L&Z1R)***
- ***POTT***
  ***L End: Z1L+(Z2L&Z2R)***
- ***Block***
  ***L End: Z1L+(Z2L*t*ZRRev)***



# *Multi Terminal Line Differential protection*



# Outline

- *Introduction*
- *Transmission Line Model*
- *Sequence Impedances*
- *Mutual Impedance*
- *Source Impedance Modeling*
- *Fault Resistance*
- *CT and VT Performance*
- *Distance Relay Characteristics*
- *Conclusions*

# *Conclusions*

- ***A good understanding ground faults is essential before applying a protection scheme to meet overall system clearance parameters.***
- ***A good understanding of the behavior and dynamics of CT's, PT's or CCVT's before applying in protection schemes***
- ***When in Doubt use Line Differential !***