39th Western Protective Relay Conference, 2012

Distance Relay Performance during Complex Fault Conditions

Zhiying Zhang, Ilia Voloh – GE Digital Energy – Multilin, Markham, Canada
Eli Pajuelo, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

1 Introduction

Distance protection relays are the most commonly used relays on transmission line protection applications for its simplicity, economy and effectiveness, which provide selective and high-speed clearance of transmission line faults. Compared to other relays, such as phase overcurrent relays, distance relays offer considerable economic and technical advantages, including,

- Simple principle, well known and widely accepted by users
- Built-in backup with multi zones, in which staged remote backup protections for adjacent lines are achieved
- Greater instantaneous trip coverage (typically 80-90% of the entire line section)
- Greater sensitivity
- Relatively independent of system changes
- Easier setting calculations and coordination
- Less dependence of load

In addition, compared to line differential relays which require high bandwidth communication channels, distance relays make decision based on the measurement of local voltage and current signals, but it's also easy to realize the instantaneous trip coverage of the full line length via pilot schemes with the aids of relatively low bandwidth communication links.

Transmission lines may experience many types of faults, but in general they can be divided into 3 categories: short circuit (shunt) faults, open circuit (series) faults and simultaneous (complex) faults [6][7].

- Shunt faults consist of single phase to earth faults (SLG), 2 phase faults (with or without earth connection, i.e. LLG or LL) and 3 phase faults (with or without earth connection).
- Series faults include one phase open circuit (1LO) and two phase open circuit (2LO).
- Simultaneous or complex faults are a combination of two or more faults that occur at the same time. They may be of the same or different types and may occur at the same or different locations.

Shunt faults are the most common type of faults on overhead transmission lines. They are often caused by nature events such as lightning strikes, heavy rain, strong winds, accumulation of snow and ice, fires, flooding, and physical contact such as trees and animals. Insulation failures due to insulator aging, degrading or contamination are also common reasons for the shunt faults. In addition, vandalism and human errors may also cause shunt faults.

Series open circuit faults may be caused by broken conductors or circuit breaker malfunction in one or two phases, for example, two phases of a circuit-breaker may close correctly but not the third phase or two phases may properly open but not the third phase which may get stuck in the closed position. Series faults do not occur frequently, it might be seen more happening in single pole tripping/reclosing applications on EHV or UHV lines. Open pole condition alone in single pole tripping/reclosing applications has been extensively studied in the literature, which will not be discussed in detail in this paper. However, simultaneous faults during open pole condition (open circuit plus earth fault) will be investigated.

Simultaneous faults do not happen often, and typically result from a common cause such as lightning strikes, or from different but consequential causes. The most common simultaneous faults are probably the faults on the double circuit parallel lines with a common cause, such as lightning strikes or tree contact, which could cause a simultaneous fault on each of the two circuits. Another common situation might be that an overvoltage condition caused by the first fault in the system lead sequentially to the 2nd fault in the system. Systems with high soil resistivity may experience simultaneous fault rates significantly higher than typical, it should be noted.

In this paper, the focus is on the investigation of distance relay performance under simultaneous or complex fault conditions, including cross-country faults, flashover faults, and faults during open pole conditions. Numerical distance relay comparators and their responses under these complex fault conditions are investigated. Limit conditions and restriction factors during these faults will be discussed. Solutions to overcome the limit conditions and measures to avoid mal-operations are explored as well. For the convenience of the analysis conducted in later sections, as a foundation, distance protection principle, characteristics and corresponding comparators are briefly reviewed.

2 Distance Protection Principle, Characteristic and Comparators

As the impedance of a transmission line is in general uniformly distributed along the line (the impedance per kilometers is fairly constant), the actual distance to a fault from the relay location can be estimated by measuring the apparent positive sequence impedance of the line. Such a relay is known as a distance relay.

A distance relay measures the apparent impedance derived from locally measured voltage and current signals. It is designed to operate only for faults occurring between the relay location and the selected reach point. Selectivity and backup protections are achieved by using several impedance elements with different impedance reaches in conjunction with different time delays, which are known as distance protection zones.

There are a few types of distance relay characteristics. The most commonly used types are mho and quadrilateral. The basic mho is a circle through the origin with the reach impedance as the diameter, which is simple, reliable and inherently directional; the quadrilateral typically consists of four straight lines (reactance, left and right blinders, and directional), which provides greater resistive coverage for resistive ground faults. The mho and quadrilateral characteristics are shown in Figure 1 below, where the various parameters displayed in this figure will be explained in the later comparator definition part.

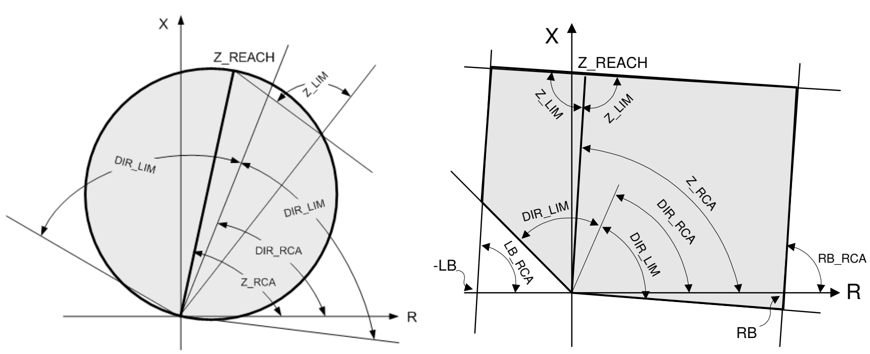


Figure 1. Distance Relay Characteristics- (a) mho, (b) Quadrilateral

Traditional distance relays have been successfully used worldwide for many years, which are based on the comparison of two quantities with either magnitude comparator (operating and restraint) or phase comparator (operating and polarizing). Such techniques are mature and are well understood by users in transmission line protection applications. Numerical distance relays emulate these techniques, with using the same or similar comparators that traditional distance relays have used, and may also include more comparators for additional security, selectivity and flexibility.

For the convenience of analyzing distance relay performance, sample comparators for mho and quadrilateral characteristics within a digital relay are shown in Table 1 and

Table 2 [5]. Note that comparators may be different depending on the relay make and design.

Table 1. Ground Distance Elements

Characteristic	MHO	QUAD	Limit Angle
Directional Supervision 1	I_0 • 1 ∠ DIR_RCA vs. V_1M		DIR_LIM
Directional Supervision 2	I_2 • 1 ∠ DIR_RCA vs. V_1M		DIR_LIM
Reactance	I • Z – V vs. I_0 • 1 ∠ Z_RCA		Z_LIM
Phase Selector	I_0 vs. I_2		50 degrees
Variable MHO	I • Z – V vs. V_1M		Z_LIM
Right Blinder		I • ZR – V vs. I • 1 ∠ (RB_RCA – 90°)	90 degrees
Left Blinder		I • ZL – V vs. I • 1 ∠ (LB_RCA + 90°)	90 degrees

Table 2. Phase Distance Elements

Characteristic	MHO	QUAD	Limit Angle
Directional Supervision	I • 1 ∠ DIR_RCA vs. V_1M		DIR_LIM
Reactance	I • Z – V vs. I • 1 ∠ Z_RCA		Z_LIM
Variable MHO	I • Z – V vs. V_1M		Z_LIM
Right Blinder		I • ZR – V vs. I • 1 ∠ (RB_RCA – 90°)	90 degrees
Left Blinder		I • ZL – V vs. I • 1 ∠ (LB_RCA + 90°)	90 degrees

Where

- Z_REACH is the reach impedance magnitude
- Z_RCA is the characteristic angle of the distance element (i.e. the reach impedance angle)
- Z_LIM is the limit angle of the distance element, for mho or quadrilateral with a straight top line, it's 90 degrees
- DIR_RCA is the characteristic angle of the directional element
- DIR_LIM is the limit angle of the directional element
- RB is the right blinder reach
- RB_RCA is the right blinder characteristic angle
- LB is the left blinder reach
- LB_RCA is the left blinder characteristic angle

All the above parameters are user settings. In addition, Z, ZR and ZL are derived parameters as defined below:

- Z = Z_REACH ∠ Z_RCA (reach impedance)
- ZR = RB • sin(RB_RCA) • 1 ∠ (RB_RCA– 90°) (right blinder impedance)
- ZL = LB • sin(LB_RCA) • 1 ∠ (LB_RCA+ 90°) (left blinder impedance)

V, I, I_0, I_2 and V_1M are measured voltage and current phasors as defined below:

- I_0 and I_2 are the zero sequence and negative sequence current phasors
- V_1M is positive sequence memory voltage phasor
- V and I are the measured voltage and current phasor for each fault loop, where k0=(Z0-Z1)/(3*Z1)

Table 3. V and I Signal for Each Fault Loop

Distance Elements	V	I
AG Loop in Ground Distance Element	VA	IA+k0*3I0
BG Loop in Ground Distance Element	VB	IB+k0*3I0
CG Loop in Ground Distance Element	VC	IC+k0*3I0
AB Loop in Phase Distance Element	VA-VB	IA-IB
BC Loop in Phase Distance Element	VB-VC	IB-IC
CA Loop in Phase Distance Element	VC-VA	IC-IA

3 Two-Port Network Analysis of Complex Fault Conditions

The analysis of various complex faults in power networks is a complex and challenging work. The commonly used method is based on the multi-port network theory, in which each of the fault points is treated as a port (a pair of terminals). With the use of sequence networks and the fault-port matrix, multi-port sequence networks can be interconnected based on the boundary conditions of the faults. Unknowns can be solved accordingly. The size of the fault-port matrix depends on the number of the simultaneous faults. Usually only 2 simultaneous faults are considered in real power system complex fault analysis, so two-port network theory combining with sequence networks and ideal transformers is typically used in power system simultaneous fault analysis, where ideal transformers are used to perform proper phase shift when the faulted phase is not the reference phase [4].

3.1 Two-Port Network

A two-port network is a network with two pairs of terminals as shown below:

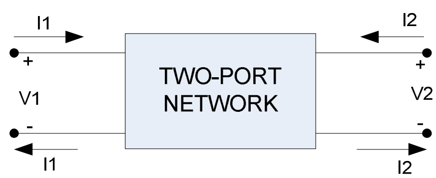


Figure 2. A Two-Port Network

The parameters of the two-port network with internal sources can be described below [4]:

$$\begin{bmatrix} V1 \\ V2 \end{bmatrix} = \begin{bmatrix} Z11 & Z12 \\ Z21 & Z22 \end{bmatrix} \begin{bmatrix} I1 \\ I2 \end{bmatrix} + \begin{bmatrix} VZ1 \\ VZ2 \end{bmatrix} \qquad \textbf{Eq 1}$$

Where VZ1 and VZ2 are the port voltages when the two ports are open circuit (i.e. I1=I2=0), which are the results due to internal sources. Z matrix can be obtained by injecting a unit current at one port and leave the other port open, and also with properly removing the internal sources, i.e. replace any voltage sources with short circuit and replace any current sources with open circuit.

(a) When I1=1 and I2=0, from Eq1, we can get Z11=V1, Z21=V2;

(b) When I1=0 and I2=1, from Eq1, we can get Z12=V1, Z22=V2.

Note that in (a) and (b), internal sources have been removed, i.e. VZ1=VZ2=0.

Eq 1 is the impedance form of parameters of the two-port network, which is suitable for solving the simultaneous faults with combinations of SLG shunt faults and two phase open (2LO) series faults. For these types of faults, sequence networks are connected in series.

As shown in the following equations, there are also admittance form (Y) and hybrid form (H) of parameters of the two-port network. The former (Y form) is suitable for solving the simultaneous faults with combinations of LLG shunt faults and single phase open (1LO) series faults, in which the sequence networks are both connected in parallel. The latter (H form) is suitable for solving the simultaneous faults with mixed types of faults, in which the sequence network connections are connected in series at one port and connected in parallel at the other port.

Admittance (Y) parameters:

$$\begin{bmatrix} I1 \\ I2 \end{bmatrix} = \begin{bmatrix} Y11 & Y12 \\ Y21 & Y22 \end{bmatrix} \begin{bmatrix} V1 \\ V2 \end{bmatrix} + \begin{bmatrix} IY1 \\ IY2 \end{bmatrix} \quad \textbf{Eq 2}$$

Hybrid (H) Parameters:

$$\begin{bmatrix} V1 \\ I2 \end{bmatrix} = \begin{bmatrix} H11 & H12 \\ H21 & H22 \end{bmatrix} \begin{bmatrix} I1 \\ V2 \end{bmatrix} + \begin{bmatrix} VH1 \\ IH2 \end{bmatrix} \quad \textbf{Eq 3}$$

3.2 Interconnections of Two Port Networks

Reference [4] has demonstrated typical network connections for different combinations of simultaneous faults. One of them is that two simultaneous SLG faults occur at two different locations K and K', which is the typical cross-country faults we are going to investigate in the next section of this paper.

The sequence network connection for the two simultaneous SLG faults is shown below:

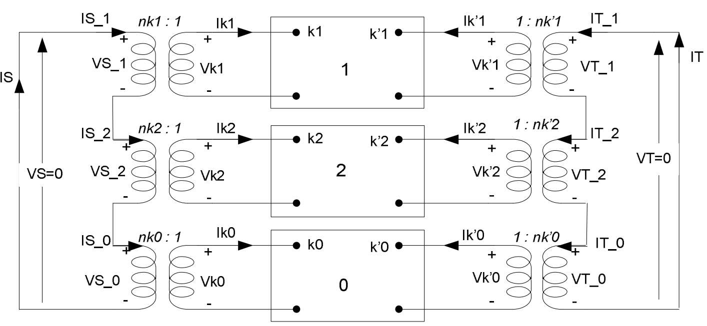


Figure 3. Sequence Network Connection for Two Simultaneous SLG Faults

In Figure 3, the reference phase is phase A. As mentioned earlier, the 6 ideal transformers are used for proper handling of phase shift when faults occur on the phases other than the reference phase. The transformer ratios are defined in the following table.

Table 4. Ideal Transformer Ratios

Fault Type at K (or K')	nk_0 (nk'_0)	nk_1 (nk'_1)	nk_2 (nk'_2)
AG	1	1	1
BG	1	a^2	a
CG	1	a	a^2

Where a=1∠120^0, $nk0 = \frac{VS\_0}{VK0} = \frac{IS\_0}{Ik0}$, $nk1 = \frac{VS\_1}{VK1} = \frac{IS\_1}{Ik1}$, $nk2 = \frac{VS\_2}{VK2} = \frac{IS\_2}{Ik2}$, $nk'0 = \frac{VT\_0}{Vk'0} = \frac{IT\_1}{Ik'0}$, $nk'1 = \frac{VT\_1}{VK'1} = \frac{IT\_1}{Ik'1}$ and $nk'2 = \frac{VT\_2}{VK'2} = \frac{IT\_2}{Ik'2}$

For each sequence network, we have

$$\begin{bmatrix} VK1 \\ VK'1 \end{bmatrix} = \begin{bmatrix} Z11_{(1)} & Z12_{(1)} \\ Z21_{(1)} & Z22_{(1)} \end{bmatrix} \begin{bmatrix} IK1 \\ IK'1 \end{bmatrix} + \begin{bmatrix} VZ1 \\ VZ2 \end{bmatrix}$$

$$\begin{bmatrix} VK2 \\ VK'2 \end{bmatrix} = \begin{bmatrix} Z11_{(2)} & Z12_{(2)} \\ Z21_{(2)} & Z22_{(2)} \end{bmatrix} \begin{bmatrix} IK2 \\ IK'2 \end{bmatrix}$$

$$\begin{bmatrix} VK0 \\ VK'0 \end{bmatrix} = \begin{bmatrix} Z11_{(0)} & Z12_{(0)} \\ Z21_{(0)} & Z22_{(0)} \end{bmatrix} \begin{bmatrix} IK0 \\ IK'0 \end{bmatrix}$$

Also based on the above definitions of nki and nk'i (i=0,1,2), we can get the following:

$$\begin{bmatrix} VS\_1 \\ VT\_1 \end{bmatrix} = \begin{bmatrix} Z11_{(1)} & \frac{nk1}{nk'1} Z12_{(1)} \\ \frac{nk'1}{nk1} Z21_{(1)} & Z22_{(1)} \end{bmatrix} \begin{bmatrix} IS\_1 \\ IT\_1 \end{bmatrix} + \begin{bmatrix} nk1 * VZ1 \\ nk'1 * VZ2 \end{bmatrix} \quad \text{Eq 4}$$

$$\begin{bmatrix} VS\_2 \\ VT\_2 \end{bmatrix} = \begin{bmatrix} Z11_{(2)} & \frac{nk2}{nk'2} Z12_{(2)} \\ \frac{nk'2}{nk2} Z21_{(2)} & Z22_{(2)} \end{bmatrix} \begin{bmatrix} IS\_2 \\ IT\_2 \end{bmatrix} \quad \text{Eq 5}$$

$$\begin{bmatrix} VS\_0 \\ VT\_0 \end{bmatrix} = \begin{bmatrix} Z11_{(0)} & Z12_{(0)} \\ Z21_{(0)} & Z22_{(0)} \end{bmatrix} \begin{bmatrix} IS\_0 \\ IT\_0 \end{bmatrix} \quad \text{Eq 6}$$

Based on the sequence network connections in Figure 3, we have

$$\begin{bmatrix} VS \\ VT \end{bmatrix} = \begin{bmatrix} VS\_1 \\ VT\_1 \end{bmatrix} + \begin{bmatrix} VS\_2 \\ VT\_2 \end{bmatrix} + \begin{bmatrix} VS\_0 \\ VT\_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad \text{Eq 7}$$

$$\begin{bmatrix} IS \\ IT \end{bmatrix} = \begin{bmatrix} IS\_1 \\ IT\_1 \end{bmatrix} = \begin{bmatrix} IS\_2 \\ IT\_2 \end{bmatrix} = \begin{bmatrix} IS\_0 \\ IT\_0 \end{bmatrix} \quad \text{Eq 8}$$

$$\begin{bmatrix} VS \\ VT \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z11 & Z12 \\ Z21 & Z22 \end{bmatrix} \begin{bmatrix} IS \\ IT \end{bmatrix} + \begin{bmatrix} nk1 * VZ1 \\ nk'1 * VZ2 \end{bmatrix} \quad \text{Eq 9}$$

Where

$$Z11 = Z11_{(0)} + Z11_{(1)} + Z11_{(2)} \quad \text{Eq 10}$$

$$Z12 = Z12_{(0)} + \frac{nk1}{nk'1} Z12_{(1)} + \frac{nk2}{nk'2} Z12_{(2)} \quad \text{Eq 11}$$

$$Z21 = Z21_{(0)} + \frac{nk'1}{nk1} Z21_{(1)} + \frac{nk'2}{nk2} Z21_{(2)} \quad \text{Eq 12}$$

$$Z22 = Z22_{(0)} + Z22_{(1)} + Z22_{(2)} \quad \text{Eq 13}$$

From equation 9, IS and IT can be solved, and then IS_1, IS_2, IS_0 and IT_1, IT_2, IT_0 are known as per equation 8. Based on equation 4 to 6, VS_1, VS_2, VS_0 and VT_1, VT_2, VT_0 can be solved, and then Vk1, Vk2, Vk0 and Vk'1, Vk'2, Vk'0 are known based on the ideal transformer ratio. After knowing Vk1, Vk2, Vk0, Vk'1, Vk'2 and Vk'0, the individual sequence network currents and voltages can be found by applying Kirchhoff's law to the individual networks.

4 Complex Fault Conditions and Distance Relay Performance Analysis

4.1 *Cross Country Fault*

A cross country fault refers to a situation where there are two or more simultaneous SLG faults at different locations on the system and possibly on different phases [3][6][7]. Several cross-country cases will be investigated, including cross country faults on parallel lines with or without mutual coupling, and on series adjacent lines.

4.1.1 A Cross Country Fault on Parallel Lines without Mutual Coupling

The first cross-country fault case we are investigating is a condition where two simultaneous SLG faults occurred on the parallel lines without mutual coupling as shown below:

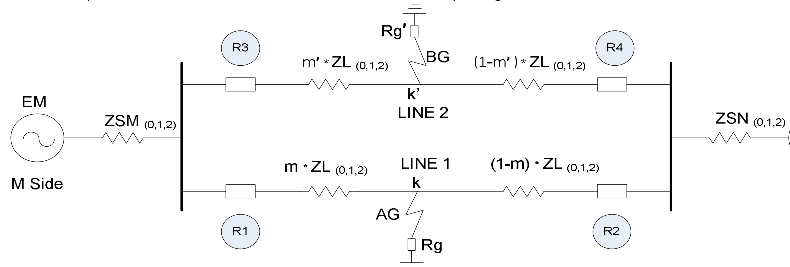


Figure 4. Single Line Diagram for Cross-Country Fault on Uncoupled Parallel Lines

An AG fault at location k in line 1 and a BG fault at location k' in line 2 occurred simultaneously. Note that (0, 1, 2) in the above figure are referred to zero, positive, and negative sequence parameters; m and m' are the distance to fault location k and k' from the left terminal in fraction of the total line length.

The simulated power system model contains the following parameters:

EM=230/√3kv∠0⁰
ZSM1=ZSM2=4Ω∠80⁰
ZSM0=10Ω∠70⁰
ZL1=ZL2=48.4Ω∠85.8⁰
ZL0=142.5Ω∠75.3⁰
EN=230/√3kv∠-30⁰
ZSN1=ZSN2=100Ω∠80⁰
ZSN0=200Ω∠75⁰
PT Ratio 2000:1
CT Ratio: 500:1 (2500/5)

Two-port network parameters derivation

Based on the two-port network theory described in section 3, the two-port network and sequence networks for this cross-country fault case are interconnected as shown in Figure 5.

From Figure 5, the corresponding two-port network parameters can be derived. For positive sequence networks, the impedance parameters and open circuit voltages at each of the fault ports are derived as shown in equation 14 to 19.

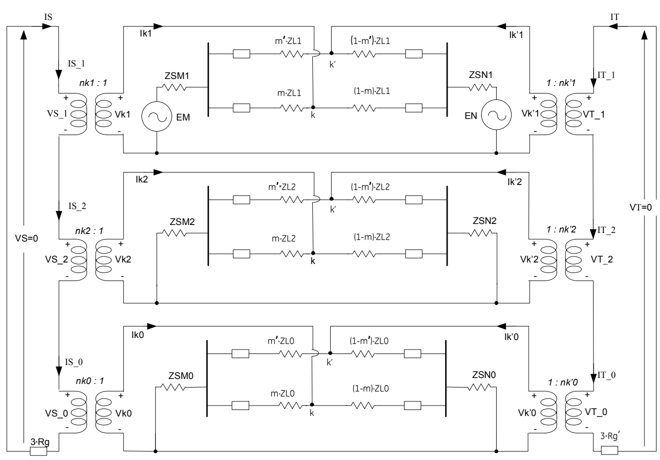


Figure 5. Sequence Network Connections for Cross-Country Fault on Parallel Lines

$$Z11_{(1)} = \frac{(2*ZSN1+(1-m)*ZL1)*\big((1+m)*ZSM1+m*(ZL1+ZSN1)\big)}{2*ZSM1+ZL1+2*ZSN1} - m*ZSN1 \qquad \textbf{Eq 14}$$

$$Z22_{(1)} = \frac{(2*ZSN1+(1-m')*ZL1)*\big((1+m')*ZSM1+m'*(ZL1+ZSN1)\big)}{2*ZSM1+ZL1+2*ZSN1} - m'*ZSN1 \qquad \textbf{Eq 15}$$

$$Z21_{(1)} = \frac{(2*ZSN1+(1-m)*ZL1)*\big((1-m')*ZSM1-m'*ZSN1\big)}{2*ZSM1+ZL1+2*ZSN1} + m'*ZSN1 \qquad \textbf{Eq 16}$$

$$Z12_{(1)} = \frac{(2*ZSN1+(1-m')*ZL1)*\big((1-m)*ZSM1-m*ZSN1\big)}{2*ZSM1+ZL1+2*ZSN1} + m*ZSN1 \qquad \textbf{Eq 17}$$

$$VZ1 = \frac{EM*(2*ZSN1+(1-m)*ZL1)+EN*(2*ZSM1+m*ZL1)}{2*ZSM1+ZL1+2*ZSN1} \qquad \textbf{Eq 18}$$

$$VZ2 = \frac{EM * (2 * ZSN1 + (1 - m') * ZL1) + EN * (2 * ZSM1 + m' * ZL1)}{2 * ZSM1 + ZL1 + 2 * ZSN1} \quad \textbf{Eq 19}$$

Because negative sequence and positive sequence impedances for both lines and sources are equal as per Figure 4, the negative sequence fault-port impedance matrix is exactly the same as the positive sequence one, i.e.

$$Z11_{(2)} = Z11_{(1)} \qquad Z22_{(2)} = Z22_{(1)} \qquad Z21_{(2)} = Z21_{(1)} \qquad Z12_{(2)} = Z12_{(1)}$$

The zero sequence impedance parameters of the two-port network are the same as defined in equation 14 to 17 except that all the positive sequence impedances need to be replaced with zero sequence impedances.

Cross-country Fault Analysis using Two Port Network Method

One example of the simultaneous faults we have applied is at 30% on line 1 and 80% on line 2 from the left terminal (i.e. m=0.3, m'=0.8), and fault resistances are not applied at both locations (Rg=Rg'=0 Ohms). Based on equation 14 to 19, we can get

$$\begin{bmatrix} Z11_{(1)} & Z12_{(1)} \\ Z21_{(1)} & Z22_{(1)} \end{bmatrix} = \begin{bmatrix} Z11_{(2)} & Z12_{(2)} \\ Z21_{(2)} & Z22_{(2)} \end{bmatrix} = \begin{bmatrix} 1.5363 + 15.2626i & 1.0289 + 7.6842i \\ 1.0289 + 7.6842i & 2.2863 + 22.8566i \end{bmatrix} \quad (\Omega\ primary)$$

$$\begin{bmatrix} VZ1 \\ VZ2 \end{bmatrix} = \begin{bmatrix} 131.63\ @\ 2.57^0 \\ 130.92\ @ -5.38^0 \end{bmatrix} \quad (kv)$$

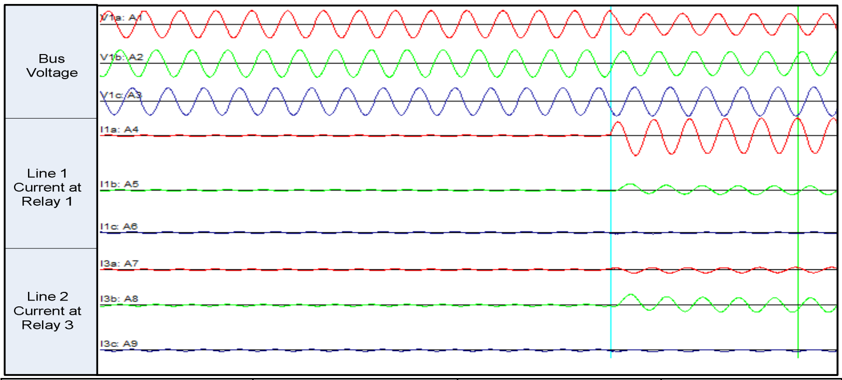
$$\begin{bmatrix} Z11_{(0)} & Z12_{(0)} \\ Z21_{(0)} & Z22_{(0)} \end{bmatrix} = \begin{bmatrix} 11.5802 + 41.2159i & 5.6049 + 18.7907i \\ 5.6049 + 18.7907i & 16.4143 + 60.2208i \end{bmatrix} \quad (\Omega\ primary)$$

According to the sequence network connections in Figure 5 and also the method described in 3.2, voltage and current at the two ports for each sequence network can be solved, and the corresponding voltage and current at the relay locations can also be calculated accordingly. For this cross-country fault, the voltages, currents and loop impedances at the 4 relay locations are calculated and shown in the table below, where all the values are in secondary quantities.

Table 5. Calculation Results of the Cross Country Fault under Investigation

	Phase	Voltage		Current		Ground Loop Impedance (ZAG, ZBG, ZCG)		Phase Loop Impedance (ZAB, ZBC, ZCA)	
		Mag (V)	Angle (0)	Mag (A)	Angle (0)	Mag (Ω)	Angle (0)	Mag (Ω)	Angle (0)
Relay 1	A	52.72	1.32	9.76	-74.05	3.63	85.80	8.62	95.01
	B	58.81	-123.03	2.48	158.03	10.73	7.79	50.35	103.13
	C	69.75	119.88	0.51	108.53	14.49	-132.62	10.29	39.79
Relay 2	A	41.77	5.39	2.17	-91.49	8.47	85.80	21.43	166.95
	B	17.25	-141.91	2.48	-21.97	3.58	-93.17	38.96	-71.57
	C	77.41	107.68	0.51	-71.47	23.16	179.55	56.14	50.37
Relay 3	A	52.72	1.32	1.55	-56.91	61.39	171.15	18.16	65.33
	B	58.81	-123.03	4.05	153.81	9.68	85.80	29.63	111.98
	C	69.75	119.88	0.51	108.53	28.30	-18.81	51.69	26.38
Relay 4	A	41.77	5.39	1.55	123.09	8.66	-117.27	22.73	43.74
	B	17.25	-141.91	3.94	140.46	2.42	85.80	19.39	139.78
	C	77.41	107.68	0.51	-71.47	27.83	-17.30	46.71	-166.51

The two-port network analysis results are also validated via EMTP simulations. The following figure shows the voltage and current signals measured at relay 1 and relay 3 from the simulation. Fundamental phasors have been extracted from the captured waveforms via Fourier analysis and the results are compared with the results in Table 5. It can be seen that the results in the following figure and the results in Table 5 agree to each other very well.



Extracted Phasors	Bus Voltage	Line 1 Current	Line 2 Current
Phase A	52.72∠2.5°	9.74∠-72.5°	1.51∠-54.4°
Phase B	58.86∠-122.0°	2.44∠159.7°	4.01∠155.1°
Phase C	69.92∠120.8°	0.51∠119.2°	0.51∠119.0°

Figure 6. Cross Country Fault (m=0.3 and m'=0.8) with EMTP Simulation

Ground Distance Elements Analysis

Based on Table 5, the ground distance loop impedances ZAG, ZBG and ZCG at each relay location are plotted in Figure 7, in which zone 1 reach is set to 80% of line length for all 4 relays. It can be seen that the ground distance elements are not affected by the simultaneous fault on the parallel line. AG loop impedances of relay 1 and relay 2, and BG loop impedances of relay 3 and relay 4 are all measured correctly at 30%, 70%, 80% and 20% of the line respectively.

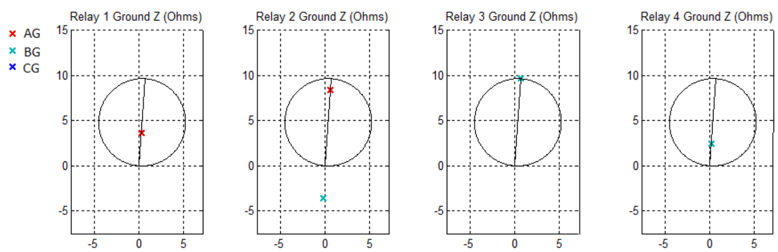
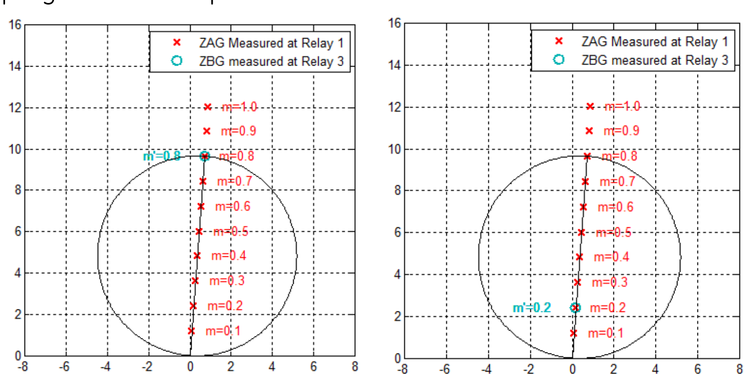


Figure 7. Ground distance loop impedances (ZAG, ZBG, ZCG) at 4 relays with 0 ohm AG fault at m=0.3 in line 1 and 0 ohm BG fault at m'=0.8 in line 2

The following two diagrams show ZAG measured at relay 1 and ZBG measured at relay 3 when m' is fixed at 80% and 20% of the line respectively and m is varied from 0.1-1.0, It can be seen the ground distance faulty loop impedances are not affected by the simultaneous fault on the parallel line if there is no mutual coupling between the parallel lines.

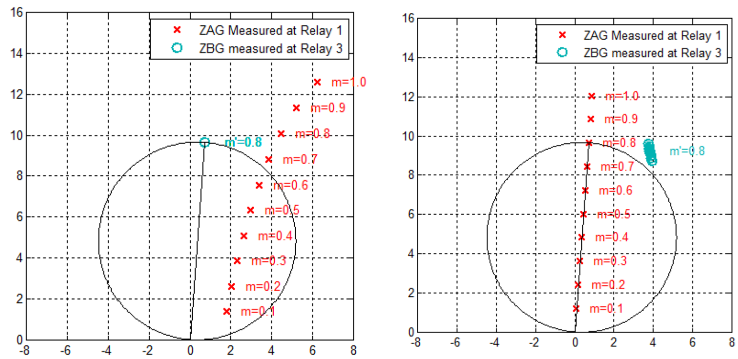


(a) (b)

Figure 8. Ground Distance Loop Impedances for 0 ohm AG fault at m and 0 ohm BG fault at m', (a) m' is fixed at 0.8, m varies from 0.1 to 1.0, (b) m' is fixed at 0.2, m varies from 0.1 to 1.0

Furthermore, the fault resistance effect is also evaluated. The following figure shows m' is fixed at 0.8 and m is varied from 0.1 to 1.0, but also with 10 ohms of fault resistance (Rg) being applied to line 1 AG fault. It can be seen from Figure 9 (a) that the fault resistance on line 1 only affects the ZAG measurement at relay 1. It does not affect the ZBG measurement at relay 3 at all.

Now the exact situation as above is applied, but 10 ohms of fault resistance (Rg') is applied on the BG fault of line 2. It can be seen from Figure 9 (b) that the fault resistance on line 2 only affects the ZBG measurement at relay 3. It does not affect the ZAG measurement at relay 1 at all.



(a) (b)

Figure 9. Fault Resistance Impact: (a) Fault Resistance on Line1 (Rg=10 Ohms) Only, (b) Fault Resistance on Line2 (Rg'=10 Ohms) Only

4.1.2 A Cross Country Fault on Parallel Lines with Mutual Coupling

The 2nd cross-country fault case we are investigating is exactly same as 4.1.1 except that the parallel lines are mutually coupled with zero sequence mutual impedance of ZLM0=95.3Ω∠70⁰ (primary Ω).

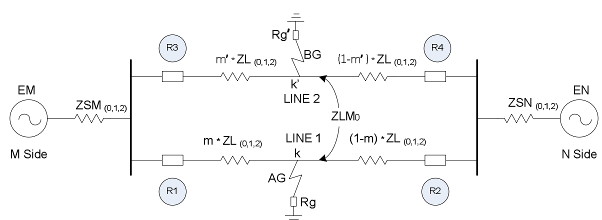


Figure 10. Single Line Diagram for Cross-Country Fault on Parallel Lines with Mutual Coupling

Two-port network parameters derivation for mutually coupled parallel lines

The fault-port matrix for positive sequence and negative sequence are same as 4.1.1, however, mutual impedance needs to be included into zero sequence fault-port impedance matrix, which makes the derivation of the zero sequence impedance parameters of the two-port network more complicated, because we not only need to consider the cases with m=m', but also need to consider the cases where m ≠ m'. As shown in the following diagram, with a unit current injected to port 1, voltage at port-1 and at port-2 are calculated, and Z11 and Z21 values are found accordingly.

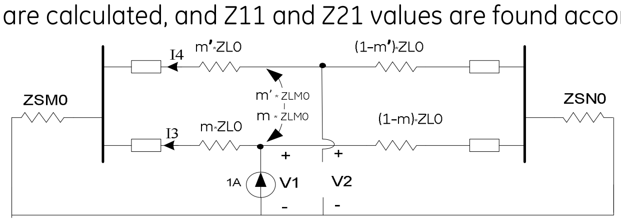


Figure 11. Zero Sequence Two-port Network Parameter Derivation

$$I3 = \frac{(2-m)*ZSN0 + (1-m)*(ZL0 + ZLM0 + ZSM0)}{ZL0 + 2*ZSM0 + 2*ZSN0 + ZLM0}$$ **Eq 20**

$$I4 = \frac{m*ZSN0 - (1-m)*ZSM0}{ZL0 + 2*ZSM0 + 2*ZSN0 + ZLM0}$$ **Eq 21**

$$Z11_{(0)} = I3*(m*ZL0 + ZSM0) + I4*(m*ZLM0 + ZSM0)$$ **Eq 22**

$$Z21_{(0)} = I3*(m'*ZLM0 + ZSM0) + I4*(m'*ZL0 + ZSM0) - (m'-m)*ZLM0(if\ m < m')$$ **Eq 23**

Similarly, with a unit current injected to port 2, Z22 and Z12 are derived as below.

$$I3 = \frac{m'*ZSN0 - (1-m')*ZSM0}{ZL0 + 2*ZSM0 + 2*ZSN0 + ZLM0}$$ **Eq 24**

$$I4 = \frac{(2-m')*ZSN0 + (1-m')*(ZL0 + ZLM0 + ZSM0)}{ZL0 + 2*ZSM0 + 2*ZSN0 + ZLM0}$$ **Eq 25**

$$Z22_{(0)} = I3*(m'*ZLM0 + ZSM0) + I4*(m'*ZL0 + ZSM0)$$ **Eq 26**

$$Z12_{(0)} = I3*(m*ZL0 + ZSM0) + I4*(m*ZLM0 + ZSM0) - (m-m')*ZLM0(if\ m' < m)$$ **Eq 27**

Two port network analysis

With the same fault condition as 4.1.1 described, i.e. m=0.3, m'=0.8, the zero sequence impedance parameters of the two-port network can be calculated as per above equations.

$$\begin{bmatrix} Z11_{(0)} & Z12_{(0)} \\ Z21_{(0)} & Z22_{(0)} \end{bmatrix} = \begin{bmatrix} 12.0226 + 42.5964i & 8.9214 + 28.2632i \\ 8.9214 + 28.2632i & 20.5961 + 72.3922i \end{bmatrix} \quad (\Omega\ primary)$$

With the same two-port network analysis method as described in 4.1.1, the voltages, currents and loop impedances at 4 relay locations are calculated.

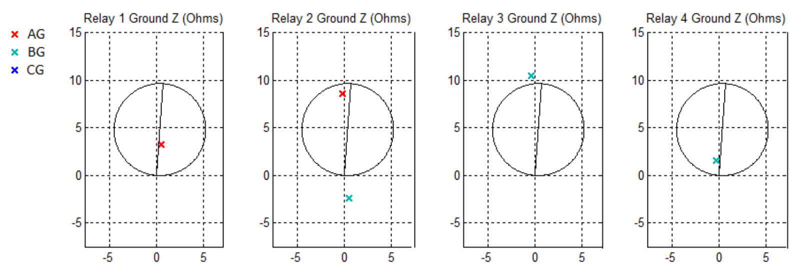


Figure 12. Ground Distance Loop Impedances (ZAG, ZBG, ZCG) with m=0.3 and m'=0.8

It can be seen that the mutual coupling has caused errors on ground distance loop impedance measurement. These errors could result in overreach or under-reach operation on ground distance elements.

To further analyze the impact, the following scenarios have been investigated:

(a) Cross-country faults at same locations (m=m')

The following figure shows ZAG measured at relay 1 and ZBG measured at relay3 when m in line 1 and m' in line 2 are varied together from 0.1 to 1.0 in step of 0.1. It can be seen that both ZAG and ZBG are moving away from its line RCA angle, and actually both are measured smaller than their true values, so as a result, overreach will likely happen.

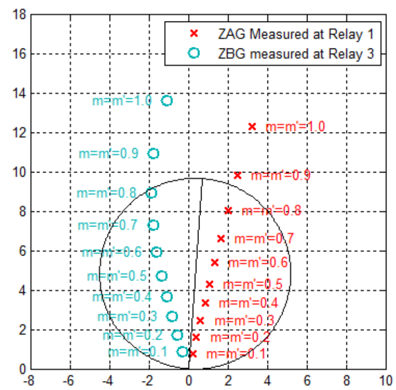


Figure 13. Ground Distance Loop Impedances without Mutual Coupling Compensation

The traditional method to correct the ground distance measurement errors caused by mutual coupling effect is to use the mutual coupling compensation feature, i.e. to compensate the current signal used in the ground distance elements from the parallel line ground current measurement as show below,

AG Loop Current in Ground Distance Element	IA+k0*3I0+K0M*IG
BG Loop Current in Ground Distance Element	IB+k0*3I0+K0M*IG
CG Loop Current in Ground Distance Element	IC+k0*3I0+K0M*IG

*Where K0M=ZLM0/(3*ZL1), IG is the ground current from the parallel line.*

When the mutual coupling compensation feature is applied to the ground distance fault loop impedance calculations, ZAG and ZBG measurement at relay 1 and 3 are re-plotted in the following figure. It can be seen that the measurement errors caused by the mutual coupling have been corrected. Both ZAG at relay 1 and ZBG at relay 3 are measured correctly now.

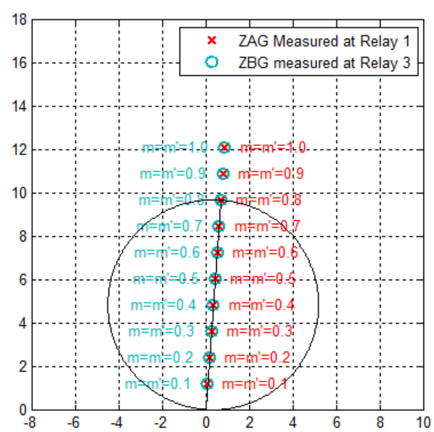


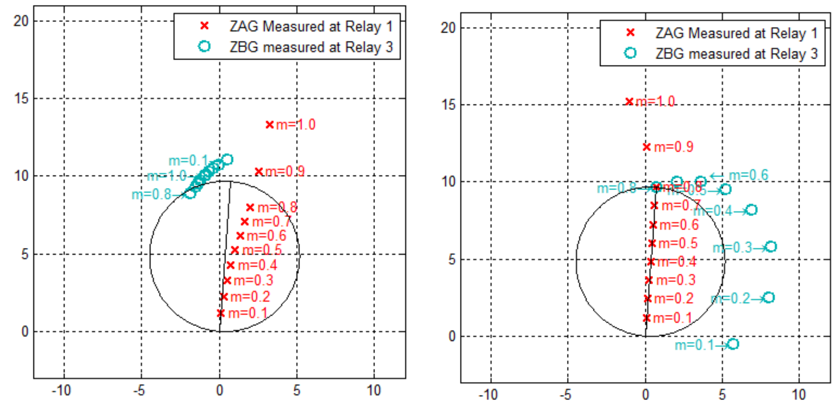
Figure 14. Ground Distance Loop Impedances with Mutual Coupling Compensation

It can be concluded that the mutual coupling compensation feature is very effective to overcome the ground distance measurement errors for simultaneous faults on mutually coupled lines occurred at the same location (m=m'), e.g. flashover faults due to lightning strikes.

In a practical application, zero sequence mutual coupling compensation using the zero sequence current from the parallel line may or may not be possible depending on the relative location of CTs with respect to the line grounding switches, as well as maintenance and operating practices [9]. Either case, with or without compensation can be studied according to the methods and criteria described here.

(b) ***Cross-country faults at different locations (m≠m')***

The following figure shows the first scenario with m≠m' we are investigating, in which m' is fixed at 0.8, and m is varied from 0.1 to 1.0 with step of 0.1. Figure 15 (a) is without mutual coupling compensation and Figure 15 (b) is with mutual coupling compensation.

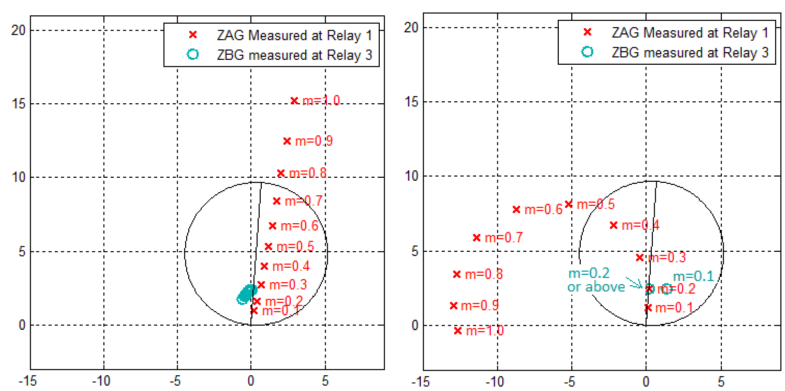


(a) (b)

Figure 15. (a) Without mutual coupling compensation, (b) with mutual coupling compensation

It can be seen from Figure 15 (b) that the ground distance elements at relay 1 (ZAG) will measure the impedances correctly with mutual coupling compensation as long as m≤m'. However, the ground distance at relay3 will contain significant errors when applying the mutual coupling compensation when m is changing in the range of 0.1 to 0.7 due to the fact of m' is bigger than m. Relay3 only measures impedance correctly when m is at 0.8 and above, in which the fixed m' in this test is equal to or less than m. This impact will be analyzed in detail in the following section.

A similar case is plotted below, in which m' in line 2 is fixed at 0.2, and m in line 1 is varied from 0.1 to 1.0 with step of 0.1.



(a) (b)

Figure 16. (a) Without mutual coupling compensation, (b) with mutual coupling compensation

Again, it can be seen that with the mutual coupling compensation, when m is at 0.1 or 0.2, relay1 measures the AG loop apparent impedance correctly without any errors. However, when m is at 0.3 or above, ZAG measurement is gradually departing away from the true value and will cause severe under-reach in relay 1. On the other hand, ZBG measurement at relay 3 will be correct when m is 0.2 or above with mutual coupling compensation.

It can be concluded that the mutual coupling compensation feature only works correctly for the relay with a shorter fault location than the one on the parallel line. The relay with a longer fault location may experience severer underreach or overreach than the relay without using the compensation feature.

The difficulties observed here for cross country faults at different locations were confirmed in a prior literature [8]. A more detailed analysis using the dynamic performance of the mho characteristic would be needed to establish the exact amount of overreach or underreach in a particular application.

Why Mutual Coupling Compensation doesn't Work for Cases with m≠m'

Let's analyze the mutual coupling compensation effect on relay 1 and relay 3 and investigate why the traditional mutual coupling compensation method only works for relay 1 but not for relay 3 for the cases with m<m'.

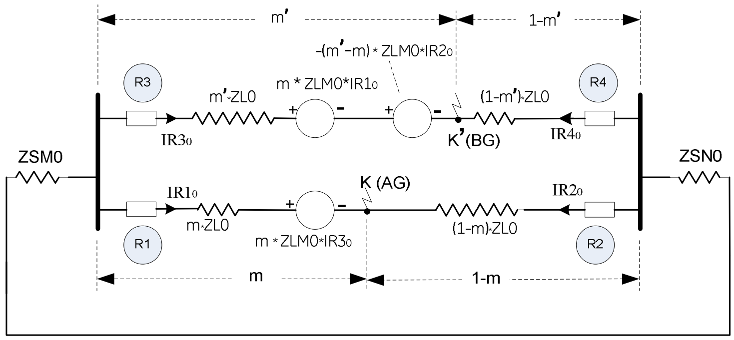


Figure 17. Zero Sequence Network with Mutual Coupling Effect Consideration for m<m'

The above figure shows zero sequence network with the consideration of the mutual coupling effects for m<m'. Let's assume no fault resistance and because m<m', for relay 1 to measure the apparent impedance from the relay location to the fault point, the mutual coupling effect is only coming from current $IR3_0$ on the parallel line, but for relay 3, the mutual coupling effect is coming from both $IR1_0$ for the portion of m and from $IR2_0$ for the portion of (m'-m). The fault loop impedance at the two relays (relay 1 and 3) can be derived as shown below:

At relay-1 location (use Phase A as the reference phase):

$$V1 = IR1_1 * m * ZL1$$
$$V2 = IR1_2 * m * ZL1$$
$$V0 = IR1_0 * mZL0 + IR3_0 * m * ZLM0$$
$$VA = V1 + V2 + V0 = IR1_1 * m * ZL1 + IR1_2 * m * ZL1 + IR1_0 * m * ZL0 + IR3_0 * m * ZLM0$$
$$= (IR1_1 + IR1_2 + IR1_0) * m * ZL1 + IR1_0 * \left(\frac{ZL0 - ZL1}{ZL1}\right) * m * ZL1 + IR3_0 * \frac{ZLM0}{ZL1} * m * ZL1$$

$$\boldsymbol{ZAG = m * ZL1 = \frac{VA}{\left(IA + \frac{ZL0-ZL1}{ZL1} * IR1_0 + \frac{ZLM0}{ZL1} * IR3_0\right)}} \qquad \textbf{Eq 28}$$

At relay-3 location (Use Phase B As the reference phase):

$$V1 = IR3_1 * m' * ZL1$$
$$V2 = IR3_2 * m' * ZL1$$
$$V0 = IR3_0 * m' * ZL0 + IR1_0 * m * ZLM0 - IR2_0 * (m' - m) * ZLM0$$
$$VB = V1 + V2 + V0 = IR3_1 * m' * ZL1 + IR3_2 * m' * ZL1 + IR3_0 * m' * ZL0 + IR1_0 * m * ZLM0 - IR2_0 * (m' - m) * ZLM0$$
$$= (IR3_1 + IR3_2 + IR3_0) * m' * ZL1 + IR3_0 * \left(\frac{ZL0 - ZL1}{ZL1}\right) * m' * ZL1 + IR1_0 * \frac{ZLM0}{ZL1} * m' * ZL1$$
$$- (IR1_0 + IR2_0) * \left(1 - \frac{m}{m'}\right) * \frac{ZLM0}{ZL1} * m' * ZL1 \ (if\ m < m')$$

$$\boldsymbol{ZBG = m' * ZL1 = \frac{VB}{\left(IB + \frac{ZL0-ZL1}{ZL1} * IR3_0 + \frac{ZLM0}{ZL1} * IR1_0 - (IR1_0 + IR2_0) * \left(1 - \frac{m}{m'}\right) * \frac{ZLM0}{ZL1}\ (if\ m<m')\right)}} \qquad \textbf{Eq 29}$$

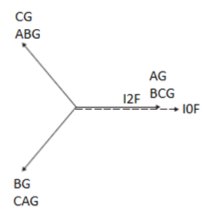
It can be seen from equation 28 and 29, with the traditional mutual coupling compensation applied, there will be no errors for relay 1, but there will be an error for relay 3. To correct this error, instead of applying $\frac{ZLM0}{ZL1} * IR1_0$ as the mutual coupling compensation in relay 3, the following should be applied when m<m':

$$\frac{ZLM0}{ZL1} * IR1_0 - (IR1_0 + IR2_0) * \left(1 - \frac{m}{m'}\right) * \frac{ZLM0}{ZL1}$$

However, this is not practical because $IR2_0$ is measured at the remote terminal which is not available to the local relay. Even if it is available, the fault distances to the two simultaneous faults (m and m') are also not known. So accurate mutual coupling compensation at all relay locations are impossible when m≠m', but fortunately simultaneous faults on parallel lines (especially double circuit lines) for typical low soil resistivity mostly occur at the same location and there will be no issues when m=m' as shown before. In case of high soil resistivity, the risk of cross country faults at different locations should be given more consideration.

Phase Selector Analysis

In ground distance elements, zero sequence and negative sequence current angles are used to determine the fault type. The angle relationship between I2F and I0F for different fault types should maintain the following relationship [5].



The following figure shows the angle difference between I2 and I0 of relay 1 as a function of fault location m (with AG fault in line 1) and m' (with BG fault in line 2). It can be seen, as m and m' both approach to 1.0, the angle difference is approaching 120 degrees because when m=m'=1, both faults are located at the remote bus, and at this point, two simultaneous SLG faults (AG at m and BG at m') change to one single LLG (ABG) fault. As per the above diagram, the expected angle difference between I0 and I2 for ABG fault is 120 degrees. In addition, it can also be seen that there is no obvious difference for lines with or without mutual coupling.

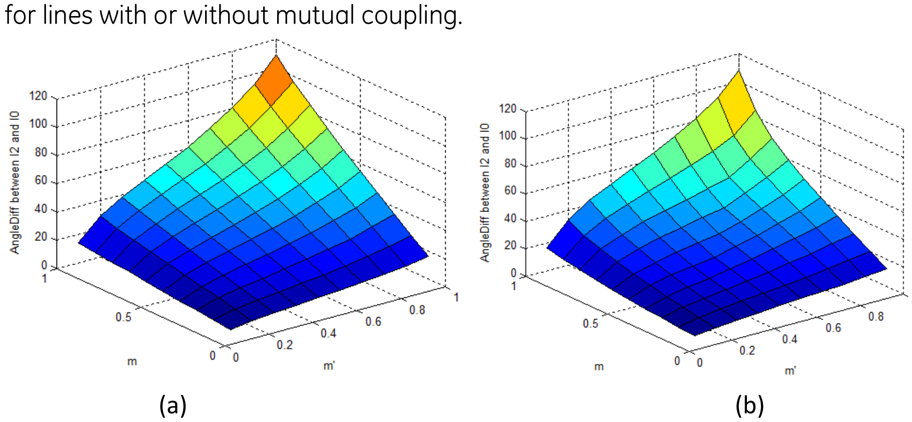


Figure 18. Relay 1 Angle Difference between I2 and I0 with AG Fault at m in Line 1 and BG Fault in line 2 at m' on parallel lines , (a) without mutual coupling, (b) with mutual coupling

It can be seen that as m and m' are both getting bigger (greater than 0.5), relay 1 and 3 may fail to recognize the fault as an AG and a BG fault type respectively, instead an ABG fault type will be claimed. Also phase distance element ZAB loop will start to pick up, and result in an undesired 3 pole tripping. On the other hand, at the remote terminal, relay 2 and relay 4 will be able to recognize the fault type as AG and BG fault respectively because (1-m) and (1-m') are smaller (less than 0.5), and can still trip single phase.

To prevent the undesired 3-pole tripping, a communication aided pilot scheme with more communication bits (e.g. 4 bits) can be used [5], in which not only the permissive or the blocking information is transmitted, but also the fault type information is transmitted as well. In this way, relay 1 and 2 will also be able to trip the faulty single phase based on the fault type information received from the remote terminal.

4.1.3 Cross-country Fault on Series Adjacent Line

Two simultaneous SLG faults occur on adjacent lines as shown below are investigated in this section.

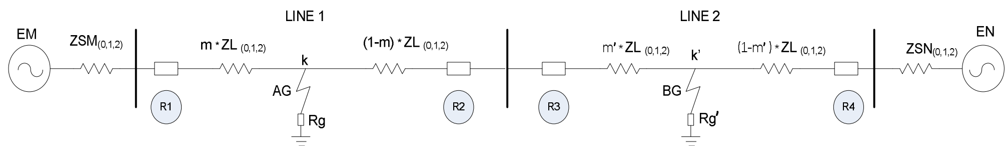


Figure 19. Cross Country Fault on Adjacent Lines

Two-port network impedance parameters are derived in the similar way as described in 4.1.1. The following figures show the ground distance loop impedances measured at relay 1 and 3 under two situations: (a) m' in line 2 is fixed at 0.8 and m in line 1 is varied from 0.1 to 1.0 in step of 0.1; (b) m' in line 2 is fixed at 0.2 and m in line 1 is varied from 0.1 to 1.0 in step of 0.1.

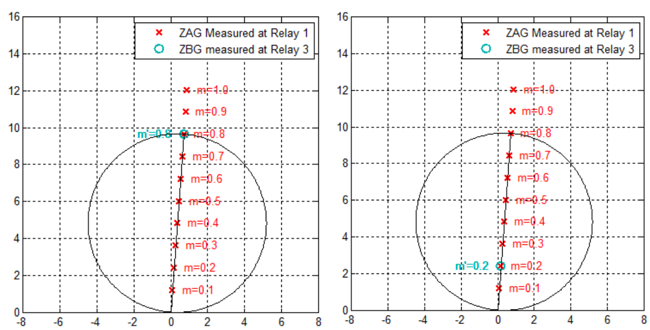
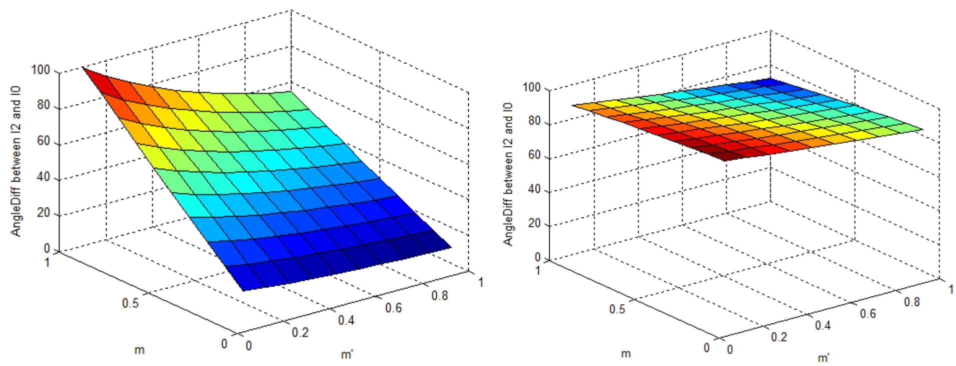


Figure 20. (a) m' is fixed at 0.8 and m is varied, (b) m' is fixed at 0.2 and m is varied

It can be seen that both relay 1 and relay 3 are able to measure the ground fault loop impedances correctly in both scenarios. They are not affected by the other simultaneous fault.

The angle difference between I2 and I0 measured at relay 1 and relay 2 are plotted in Figure 21. At relay 1, as shown in Figure 21 (a), when m'=0.1 and m=1.0, the angle difference approaches to the maximum (about 100 degrees). This makes sense because when m=1 and m'=0, the two SLG faults (AG at m and BG at m') really become a single LLG fault (ABG), the expected angle difference is supposed to be at 120 degrees for an ABG fault.

However, at relay 2, the phase selector is significantly affected by the reverse BG fault on line 2. It can be seen from Figure 21 (b) that the angle difference between I2 and I0 has never been satisfied (supposed to be at around 0 degree for AG type fault) regardless of the fault location variations. As a result, the phase selector will block the ground distance element from tripping. If there is no other main protection on the line, such as line differential protection, a compromised trip may be expected either by a phase distance element (might be backup zones) or a sequential tripping.



(a) (b)

Figure 21. I2 and I0 Angle Difference, (a) at relay 1, (b) at relay 2

4.2 Flashover Fault Analysis

Flashover faults refer to a situation where the inter-circuit faults occurred on double circuit lines, which are usually caused by a lightning stroke to the ground wire or to the tower although in some cases it can also happen following a direct strike to the phase conductor.

A flashover fault caused by a lightning stroke to the tower is studied, in which a fault AG on line1 and a fault BG on line 2 occur simultaneously, as shown in Figure 22. This is actually a special case of the cross country faults we have investigated in 4.1.2 with m=m'.

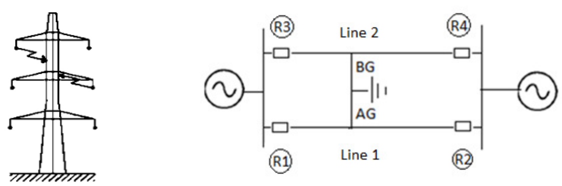


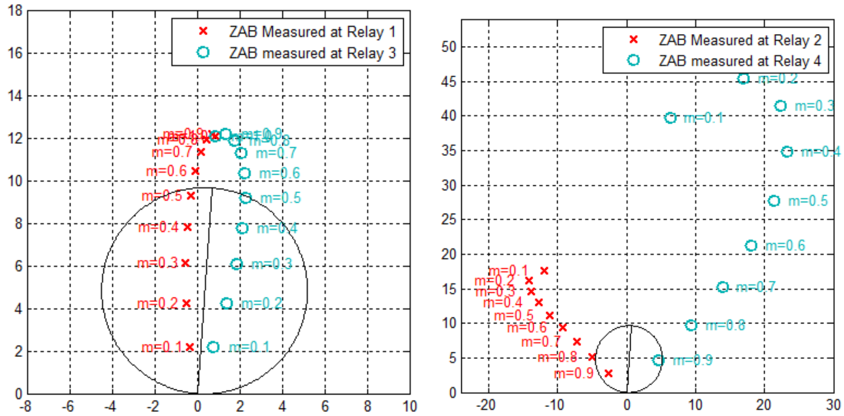
Figure 22. Lightning to tower

The ground distance element for relays with a strong source (i.e. relay 1 and 3) have been analyzed in 4.1.2 and the results were shown in Figure 13 and Figure 14. In this section, it will be studied further investigating the phase distance element and also the ground distance element performance for relays with weak sources (i.e. relay 2 and 4).

4.2.1 Phase Distance Element Analysis

It can be observed that the flashover fault at the same location in different lines has an impact on phase distance element that depends on the strength of the source impedance. The strong end does not represent any risk of overreach. In fact there is underreach in the order of 25% as we observed in Figure 23 (a) that ZAB distance element does not detect a fault at 60% of the line (m=0.6). The weak end, however, is not capable of detecting with the ZAB distance element this fault even for a fault location in the order of 20% from the weak end, i.e. m=0.8 in Figure 23 (b).

As said, the simultaneous faults shown in Figure 22 are actually two SLG faults in line 1 (AG) and line 2 (BG) respectively. Ground distance elements in line 1 and line 2 are expected to pick up the faults. However, when both faults are moving farther away from the relay, the ground distacne elements may be blocked by the phase selector, but on the other hand, phase distance elements, including backup zones, can help clear the faults.

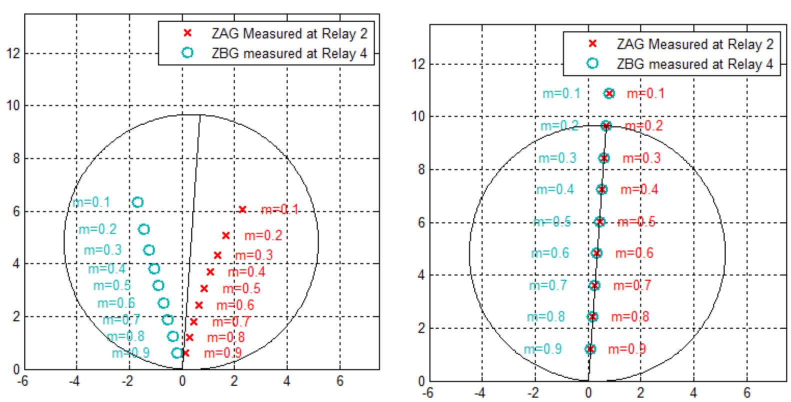


(a) (b)

Figure 23. Phase Distance Loop impedance ZAB in both lines for a zero ohm ABG simultaneous fault varying the fault location: (a) Strong end M side, (b) Weak end N side.

4.2.2 Ground Distance Element Analysis for Relays at Weak Source Side

As mentioned earlier, the ground distance element for the relays with the strong source has been analyzed before. In Figure 24, we study the performance of the ground distance elements in the weak N side for the same A-G to B-G fault is shown. As shown in Figure 24 (a), the weak end presents significant risks of overrech for the total length of the line if the mutual coupling compensation features is disabled. In Figure 24 (b), it is shown that the use of parallel line mutual compensation feature has effectively corrected the errors caused by mutual coupling.



(a) (b)

Figure 24. Ground Distance Loop impedances ZAG and ZBG for each line in the weak end N side for a zero ohm ABG simultaneous fault varying the fault location: (a) No mutual compensation, (b) Mutual compensation enabled.

So it can be concluded that the mutual coupling compensation is very effective to overcome the ground distance measurement error as long as the simultaneous SLG faults are at the same location regardless of the source impedance.

4.3 Open conductor plus earth fault

An open phase condition is probably most seen on UHV and EHV lines with single pole tripping and reclosing applications. In this section, we investigate an open-pole plus earth fault condition, which is shown in the following diagram, where B-phase is open and an AG fault occurs at the same time. To be generic, we have defined the line could be open anywhere in line 2 (at m').

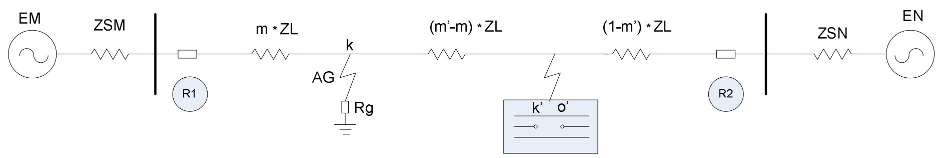


Figure 25. Open pole plus earth fault diagram

4.3.1 Two Port Network Parameter Derivation

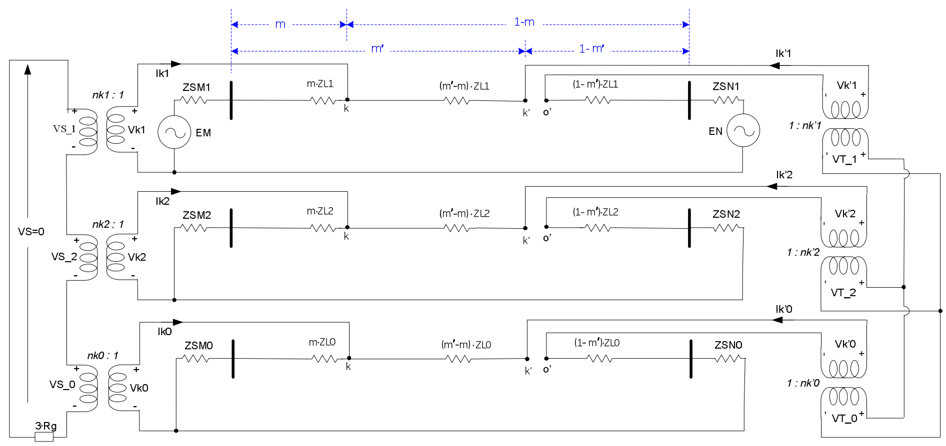


Figure 26. Sequence Network Connections for Open-pole Plus SLG fault

It is known that the sequence network connections for one phase open are the same as LLG fault connections, in which positive, negative and zero sequence networks are connected in parallel. As described in 3.1, the hybrid (H form) parameters are suitable for solving the simultaneous faults with mixed types of faults, in which the sequence network connections are connected in series at one port and in parallel at the other port.

$$\begin{bmatrix} V1 \\ I2 \end{bmatrix} = \begin{bmatrix} H11 & H12 \\ H21 & H22 \end{bmatrix} \begin{bmatrix} I1 \\ V2 \end{bmatrix} + \begin{bmatrix} VH1 \\ IH2 \end{bmatrix}$$

VH1 and IH2 are calculated with an open circuit at k (I1=0) and a short circuit at k' (V2=0). H11 and H21 are calculated with injecting I1=1 amps at k and V2=0 (short circuit) at k'; H22 and H12 are calculated with applying V2=1 volt at k' and I1=0 (open circuit) at k. The H form parameters are derived and shown in the following equations.

$$H11_{(1)} = \frac{(ZSN1 + (1-m)*ZL1)*(ZSM1 + m*ZL1)}{ZSM1 + ZL1 + ZSN1} \qquad \text{Eq 30}$$

$$H21_{(1)} = -\frac{ZSM1 + m*ZL1}{ZSM1 + ZL1 + ZSN1} \qquad \text{Eq 31}$$

$$H12_{(1)} = \frac{ZSM1 + m*ZL1}{ZSM1 + ZL1 + ZSN1} \qquad \text{Eq 32}$$

$$H22_{(1)} = \frac{1}{ZSM1 + ZL1 + ZSN1} \qquad \text{Eq 33}$$

$$VH1 = \frac{EM*[ZSN1 + (1-m)*ZL1] + EN*(ZSM1 + m*ZL1)}{ZSM1 + ZL1 + ZSN1} \qquad \text{Eq 34}$$

$$IH2 = \frac{EN - EM}{ZSM1 + ZL1 + ZSN1} \qquad \text{Eq 35}$$

4.3.2 Fault Analysis Using Two Port Networks

In this analysis, all the source and line impedance and source voltage parameters are exactly the same as defined in 4.1.1. Now open B-Phase of breaker 2 (terminal N) and then an AG fault occurs at 30% of the line, as shown in Figure 25.

According to the sequence network connections in Figure 26 and also the method described in 3.2, voltage and current at the two ports for each sequence network can be solved, and the corresponding voltage and current at the relay locations are also calculated accordingly.

Table 6. Calculation Results of the Open pole Plus Earth Fault

	Ph	Voltage		Current		Ground Loop Impedance (ZAG, ZBG, ZCG)		Phase Loop Impedance (ZAB, ZBC, ZCA)	
		Mag (V)	Angle (⁰)	Mag (A)	Angle (⁰)	Mag (Ω)	Angle (⁰)	Mag (Ω)	Angle (⁰)
Relay 1	A	53.05	1.00	9.27	-78.13	3.63	85.80	11.53	110.48
	B	67.50	-123.53	0.00	86.07	12.24	-27.48	123.84	-31.66
	C	69.39	121.65	0.93	121.23	14.44	-135.56	10.51	43.37
Relay 2	A	20.67	-26.37	1.21	-116.71	8.47	85.80	76.22	128.02
	B	77.16	-159.27	0.00	75.48	62.47	-51.55	105.15	127.33
	C	73.48	119.66	0.93	-58.77	37.19	-153.44	85.57	111.31

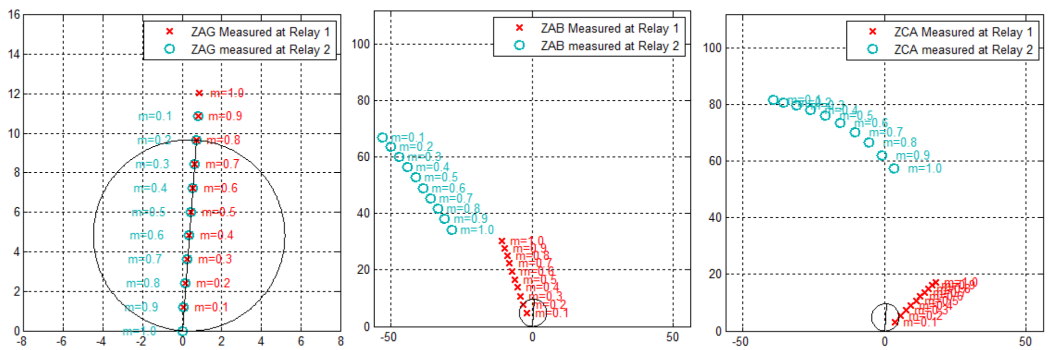
Since the open pole plus earth fault is a new case, in which the faults are mixed type, and the sequence network connections are different from previous cases (now with both series and parallel connection), EMTP simulations validations are also carried out. The EMTP simulation results are shown below in Table 7. It can be seen that both results are very close to each other, and the only exception is that in EMTP simulations, the phase B current at relay 1 is not zero and phase C current at relay 1 is not 180 degrees apart from phase C current at relay 2. Both discrepancies are actually caused by the shunt capacitance in the transmission line model, which is included in the EMTP simulations, but excluded in the two-port network analysis.

Table 7. EMTP Simulation Results

	Relay 1				Relay 2			
	Voltage		Current		Voltage		Current	
	Mag (V)	Angle (⁰)	Mag (A)	Angle (⁰)	Mag (Ω)	Angle (⁰)	Mag (Ω)	Angle (⁰)
A	53.02	1.7	9.23	-77.1	20.66	-26.1	1.21	-115.9
B	67.61	-123	0.09	-38.7	77.19	-158.9	0	-129.8
C	69.46	122.2	0.94	126.9	73.95	120.2	0.94	-59

4.3.3 Distance Element Performance Analysis

With the variation of the AG fault location (from m=0.1 to 1.0) during breaker2 B-phase open, it can be seen from Figure 27 (a) that the ground distance element for both relay 1 and relay 2 can measure the fault distance correctly.



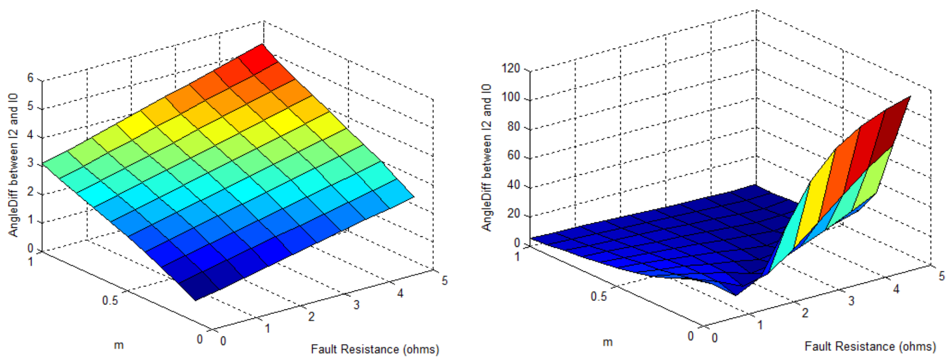
(a) (b) (c)

Figure 27. (a) Ground Distance ZAG, (b) Phase Distance ZAB, (c) Phase Distance ZCA

For the phase distance element, the relay at the strong source side (i.e. relay 1) could also pick up the close-in AG fault, where AB element could pick AG fault at 20% or below and CA element could pick AG fault at 15% or below, but the phase distance element at relay 2 with weak sources won't pick at all.

Phase Selector Comparator Analysis

The angle difference between I0 and I2 as a function of the fault location (m) and the fault resistance at relay 1 and relay 2 are plotted in the figure below. It can be seen that for the relay at the strong source side (relay 1), there are no issues at all. I0 and I2 are pretty much in phase and it won't change much as the fault resistance increases. However, for the relay at the weak source side (relay 2), the angle difference between I0 and I2 significantly increases as the fault resistance increases and the fault location (m) decreases (i.e. moving further away from relay 2). Though this appears that the ground distance element at the weak source side might be blocked by the phase selector, this actually won't occur, because a 3-pole tripping is required if one–pole is already open. The relay at the strong source will trip 3-pole first (with open pole detected), and then the relay at the weak source will trip 3-pole afterwards.



(a) (b)

Figure 28. Angle Difference between I0 and I2 at Relay 1 (a), and relay 2 (b)

5 Summary

In this paper, distance relay performance under various simultaneous fault conditions has been analyzed, including cross country faults, flashover faults and open conductor plus earth faults. Some analysis results and findings are summarized below.

- Two port network analyses is a very effective tool for analyzing simultaneous faults and complex operating conditions in power networks. The analysis results using two-port network theory agree well with EMTP simulation results.
- Mutual coupling compensation feature in ground distance protection on parallel line applications only works correctly for the simultaneous faults at the same location (e.g. flashover faults in which m=m'), or the relay with a shorter fault location than the one on the parallel line (if m≠m'). The relay with the longer fault location may experience severer under-reach or overreach than the relay without using the compensation feature.
- Phase selector based on the phase relationship between I0 and I2 could fail in the cross country faults on parallel lines and lead to an undesired 3-pole tripping, while pilot scheme with more communication bits can help overcome such limit condition.

Due to the time restrictions, some complex fault conditions are not included in this paper, including open-pole plus earth faults on parallel lines and flashover faults due to a direct strike to the phase conductors. It was not included also the impact of different loading and high resistance faults. The studies on these faults are planned to be conducted in our future work.

Biography

Zhiying Zhang received his B.Sc. and M.Sc. degrees from the North China Institute of Electric Power (now North China Electric Power University-NCEPU) and a Ph.D. degree from the University of Manitoba, Canada, all in Electrical Engineering. He has 24 years of experience in power system engineering, including 6 years with electric utilities and 18 years with relay manufactures in various technical positions. In 2007, he joined GE as an application engineer, and currently he is a principal applications engineer with the same company. Zhiying is a registered professional engineer in the province of Ontario and a senior member of IEEE.

Ilia Voloh received his Electrical Engineering degree from Ivanovo State Power University, Russia. After graduation he worked for Moldova Power Company for many years in various progressive roles in Protection and Control field. He is currently an applications engineering manager with GE Multilin in Markham Ontario, and he has been heavily involved in the development of UR-series of relays. His areas of interest are current differential relaying, phase comparison, distance relaying and advanced communications for protective relaying. Ilia authored and co-authored more than 20 papers presented at major North America Protective Relaying conferences. He is an active member of the PSRC, and a senior member of the IEEE.

Eli Pajuelo graduated from the National University of Engineering of Peru in 1990, and obtained M.Sc. degree in electrical & computer engineering from the University of Saskatchewan in 2006, where he is presently following graduate studies. From 1990 to 1992, he was with the National University of Engineering of Peru, and a part time software programmer in banking operations. From 1992 to 2003, he has been with General Electric, initially in Lima, Peru with their representative DITEC and later in their offices in Malvern, PA, USA and Markham, ON, Canada. In 2004, he joined the University of Saskatchewan, Saskatoon, SK, Canada to pursue M.Sc. and PhD studies. He also provides consulting services in advance protective relaying applications. He has worked mainly in protective relaying for transmission, distribution and currently in generating systems.

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