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EFFECTS OF VARYING FAULT IMPEDANCE ON DISTANCE PROTECTION SCHEMES OF 11 KV DISTRIBUTION SYSTEMS

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ABSTRACT

Distance protection schemes are used in the protection of transmission and distribution lines and they use distance relay in their operations. The protection scheme is always partitioned into two or more zones and each zone is a certain percentage of the entire length of the line (which may also include the next line). With all things being equal, the tripping of the relays is solely a function of the zones where the fault occurred, that is, the location of the occurrence of the fault. However, it has been shown in this paper through simulations in Power System Computer-Aided Design (PSCAD) that for a LLG fault on the line (in Zone 1), the distance relay/protection system tripped inaccurately in Zone 2 for a fault impedance of 0.1Ω, 0.5Ω and 5Ω and trips accurately in Zone 1 for fault impedance of 1Ω, and 10Ω for the same type of fault and same location. Also, for a fault impedance of 0.1Ω, the system tripped at Zone 1 for LL and 3 phase faults and tripped in Zone 2 for LG and LLG faults for the same fault impedance and at the same location. This indicates that tripping zone in distance protection schemes are not solely dependent on fault locations but also slightly dependent on the fault impedance and type of fault.

Keywords: Effects; variations; fault type; fault impedance; distance protection.

1. INTRODUCTION

Faults in power systems are short circuit that occur when the insulation of the systems fails thereby causing a low impedance path either between phases or phase(s) to ground (Rao, 2007; Obi *et al*., 2015; Obi *et al*., 2016; Obi *et al*., 2022). The consequences of these faults if not cleared ranges from damages to equipment, injury or even death of personnel and instability in the network (Gupta, 2005; Chen *et al*., 2021; Jeevan, 2022; Oputa *et al*., 2023). Hence, a lot of efforts has been made to isolate any faulty part of the circuit when a fault occurred in such area. The protection with fuses and manual circuit breakers were the first to emerge at the end of the eighteenth century. The use of relays to protect power systems began with the overcurrent protection scheme with the overcurrent relay. Under-voltage and over-voltage relays (working on the same principles as the overcurrent relays) (Nwachi *et al*., 2022) are now in use. In this overcurrent protection system, the time dial setting (TDS) determines the actual operating time of the relay while plug setting multiplier (PSM) determines the required amount of current values with which the relay is to pick up. However, finding optimum values of TMS and PSM of this relay must be well coordinated, else the relay may malfunction. Different algorithm/optimization techniques have been put forward to obtain optimal TDS and PSM of the relays. These include a new metaheuristic algorithm, the JAYA algorithm and the simplex method firefly algorithm (Noghabi *et al*., 2009; Bedekar *et al*., 2010; Pragati and Amol, 2017; Sergio *et al*., 2021; Michele *et al.,* 2022). However, the fact that the operating time and pick up values of the overcurrent relays depend on the fault current which varies with the fault type and circuit characteristics, the overcurrent relay and protection scheme was less attractive in protecting high voltage systems (grids) where different power plants and load centers are interconnected. This is because any malfunction of this relay may cause instability in the concerned grid (Keil and Jager, 2008; Mahat *et al*., 2011; Funlayo *et al*., 2012; Venkatanagaraju and Biswal, 2022; Gupta *et al*., 2023).

This led to the emergence of the distance relays and protection scheme (Obi *et al*., 2014) which operates when the impedance seen by the relay is less than the predetermine/set impedance of the relay. The relay calculates the seen impedance by extracting the voltage and current from the complex post – fault waveforms (Murthy, 2007; Mohammed and Ciohotaru, 2022). Different algorithm has been put up by different researchers in extracting the voltage and current from the complex post – fault waveform. The least squares matrix pencil algorithm of extracting the complex fault current and voltage waveform parameters makes use of the function model that makes square fitting (Suonan *et al*., 2010; Khaled *et al*., 2023). However, under this condition the function model of the input signal is given in advance which stands as a strong problem of this algorithm. Another algorithm developed was the fast Fourier transform algorithm with full cycle window to remove the DC offset value (contained in power line fault current) and to obtain the fundamental component of the current and voltage signals by using a microcontroller (Verma and Sinha, 2016). However, this algorithm presents a compensation matrix in the frequency domain which reduces the accuracy current and voltage signal extraction which is a major setback in the algorithm. Fast phasor calculation algorithm was also pulsated (Arpanahi *et al*., 2022; Chen *et al*., 2022). This algorithm uses the matrix pencil method in extracting the fault current and voltage waveform (Wang *et al*., 2014).

In the past, different composition of the distance protection has been put forward. For example, a directional comparison distance protection scheme using average superimposed components of voltage and currents has been proposed (Hashemi *et al*., 2013). The current and voltage values are approximately zero under the normal operating condition and none zero value during a fault. The algorithm provides fast fault detection in less than half cycle time and almost 100% coverage of the line. However, this approach suffers from inherent inaccuracy due to the application of the resistance – inductance (R – L) type line model and complexity in protection criterion. An impedance differential protection scheme for pilot protection of transmission lines using the voltage and currents of both local and remote ends to calculate the differential impedance (Tohid *et al*., 2015). The proposed scheme is capable of fast discrimination between internal and external faults and eliminates the problem of line capacitive charging current and source impedance strength which are the challenges of the conventional scheme. However, the scheme requires a reliable communication channel for data transmission. A pilot distance protection scheme based on the fault component integrated power was used as a criterion for discrimination between internal and external faults was developed by (Tohid *et al*., 2014). As the integrated power is a sum of active powers which are injected into the transmission line from both ends, the integrated power is divided into pre-fault and post fault powers and the difference between the two values is called the faulty component. When there is a fault, the pre-fault power is equal to the active losses of lines while fault component integrated power is equal to zero. But when a fault occurs, it changes from its zero value to a non – zero value. The method is able to quickly discriminate the normal condition, internal fault and external fault. A technique for transmission line protection scheme based on alienation coefficients for current signals was also developed (Masoud and Mahfouz, 2010; Shaik *et al*., 2014; Rathore *et al*., 2021). The fault selection algorithm is based on alienation technique of two half successive cycles with the same polarity and used only three lines current measurement available at the relay location. This algorithm was purely for transmission system containing just one transmission line linking two buses alone. A high speed power line protection scheme was proposed using High – Speed Directional and fault Type Selection (HSD-FTS) algorithm (Benmouyal *et al*., 2004; Yadav and Thoke, 2011; Piesciorovsky *et al*., 2022). This used a high-speed distance element which is a logical system for its operation. This algorithm prevents zone 1 element overreach especially in series compensated transmission lines.

Despite all these research works carried out on the distance relay and DPS, the accuracy at which these relay trip in their protective zones have not been examined. Hence, this paper investigates the accuracy of the DPS in terms of tripping zones for the occurrence of different faults types and impedance on an 11kV distribution power system.

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2. METHODOLOGY

2.1 Modelling of the Distance Relay/Protection Scheme

Consider the 3-phase line shown in Figure 1 with voltage $E_a, E_b, and\ E_c$ for the 3 phases and $I_a, I_b, and\ I_c$ are the current flowing in the phases respectively with line impedance Z.

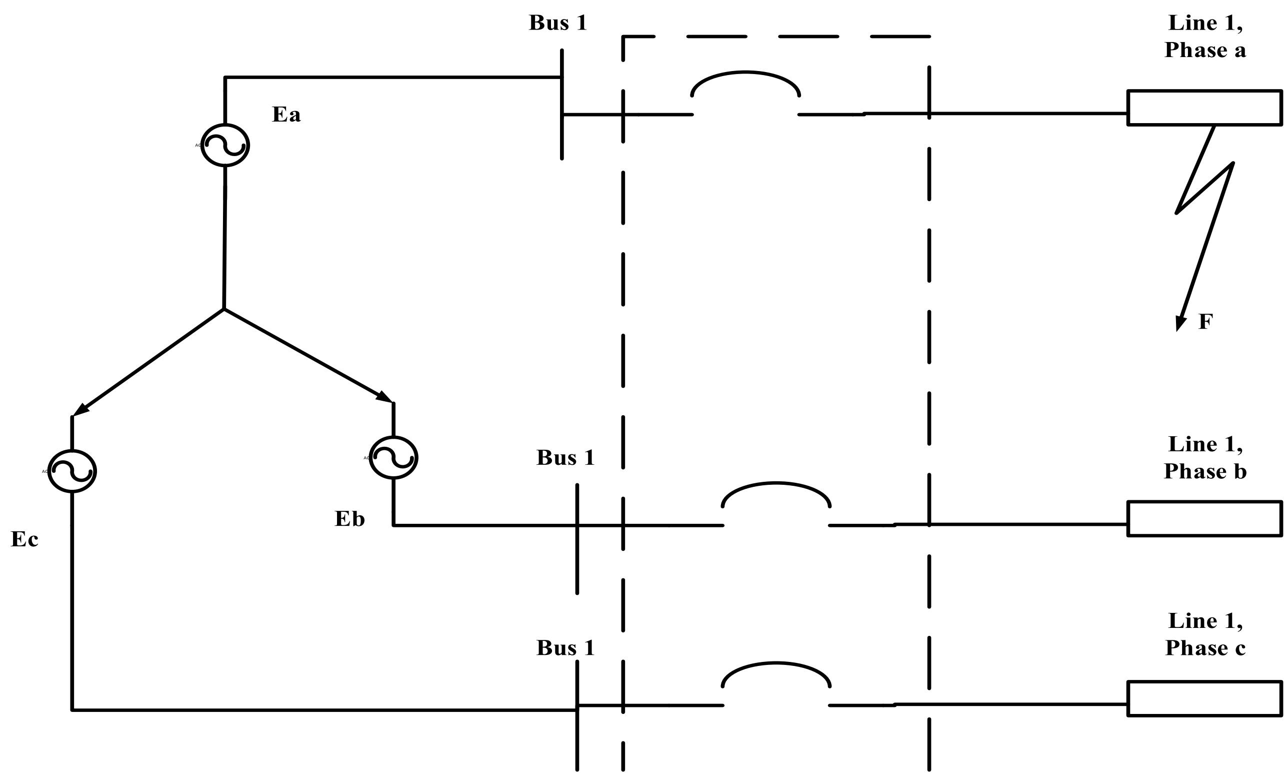

Figure. 1: Three Phase line with fault

Applying the sequence component network for a LG fault,

If the bus voltage is $V_a, V_b, and\ V_c$ for the 3 phases of the bus

$$V_a = V_a^0 + V_a^1 + V_a^2 \tag{1}$$

$$V_a = I_a^1 Z_1 + I_a^2 Z_2 + I_a^0 Z_0 \tag{2}$$

Equation (2) can be rewritten as

$$V_a = I_a^1 Z_1 + I_a^2 Z_1 + I_a^0 Z_1 + I_a^0 Z_0 - I_a^0 Z_1 \tag{3}$$

or

$$V_a = \left(I_a + \frac{Z_0 - Z_1}{Z_1} I_a^0\right) Z_1 \tag{4}$$

Hence,

$$Z_{seen} = \frac{V_a}{I_a + \frac{Z_0 - Z_1}{Z_1} I_a^0} \tag{5}$$

Equation (5) can be written as

$$Z_{seen} = \frac{V_a}{I_a + K_0 I_a^0} = \frac{V_a^0 + V_a^1 + V_a^2}{I_c + K_0 I_c^0} \tag{6}$$

Where

$$K_0 = \frac{Z_0 - Z_1}{Z_1} \tag{7}$$

Similar to Equation (7), for faults involving line ‘b’ and ‘c’ to ground are respectively,

$$Z_{seen} = \frac{V_b}{I_b+K_0 I_b^0} = \frac{V_b^0+V_b^1+V_c^2}{I_c+K_0 I_c^0} \quad (8)$$

$$Z_{seen} = \frac{V_c}{I_c+K_0 I_c^0} = \frac{V_c^0+V_c^1+V_c^2}{I_c+K_0 I_c^0} \quad (9)$$

Again, applying the sequence components for a LL fault between ‘a’ and ‘b’, the potential between lines ‘a’ and ‘b’ is $V_a - V_b$ and the resultant current between the lines is $I_a - I_b$.

Then the impedance seen is

$$Z_{seen} = \frac{V_a - V_b}{I_a - I_b} \quad (10)$$

Taking Kirchoff’s voltage law (KVL) from bus 1 to bus 2 as shown in Figure 1,

$$V_a^1 - I_a^1 Z_1 - I_a^2 Z_2 - V_a^2 = 0 \quad (11)$$

or

$$V_a^1 - V_a^2 = (I_a^1 - I_a^2) Z_1 \text{ , as } Z_1 = Z_2 \quad (12)$$

Impedance seen by the distance relay is therefore

$$Z_{seen} = \frac{V_a^1 - V_a^2}{I_a^1 - I_a^2} \quad (13)$$

Similarly, for LL fault between ‘b’ and ‘c’

$$Z_{seen} = \frac{V_b - V_c}{I_b - I_c} = \frac{V_a^1 - V_a^2}{I_a^1 - I_a^2} \quad (14)$$

And for fault between phases ‘a’ and ‘c’

$$Z_{seen} = \frac{V_a - V_c}{I_a - I_c} = \frac{V_a^1 - V_a^2}{I_a^1 - I_a^2} \quad (15)$$

For a LLG fault between lines ‘b’ and ‘c’ to ground and applying the sequence components on Figure 1,

$$V_b = V_a^0 + a^2 V_a^1 + a V_a^2 = V_c = V_a^0 + a V_a^1 + a^2 V_a^2 \quad (16)$$

And the fault current that flows in the lines ‘b’ and ‘c’ (combined) to ground is

$$I_b + I_c = I_a^0 + a^2 I_a^1 + a I_a^2 + I_a^0 + a I_a^1 + a^2 I_a^2 \quad (17)$$

since $1 + a + a^2 = 0$, rewrite Equation (17) as

$$I_b + I_c = 2I_a^0 - (I_a^1 + I_a^2) \quad (18)$$

Hence, the impedance seen by the relay is given as

$$Z_{seen} = \frac{V_b (or\ V_c)}{I_b + I_c} \quad (19)$$

Using the sequence components, Equation (19) is written as

$$Z_{seen} = \frac{V_a^0 + a V_a^1 + a^2 V_a^2}{2I_a^0 - (I_a^1 + I_a^2)} \quad (20)$$

In same way, for lines ‘a’ and ‘c’ to ground,

$$Z_{seen} = \frac{V_a (or\ V_c)}{I_a + I_c} \quad (21)$$

Lines ‘a’ and ‘b’ to ground, impedance seen is

$$Z_{seen} = \frac{V_a (or\ V_b)}{I_a + I_b} \quad (22)$$

For faults involving all 3 phases, the impedance seen by the relay is simply

$$Z_{seen} = \frac{V_a^1}{I_a^1} \quad (23)$$

By combining Equations 6, 8, 9, 13, 14, 15, 20, 21, 22 and 23, one can represent the command control/model diagram of the protective system model as shown in Figure 2. The truth table of the operation of Figure 2 is presented on Table 1.

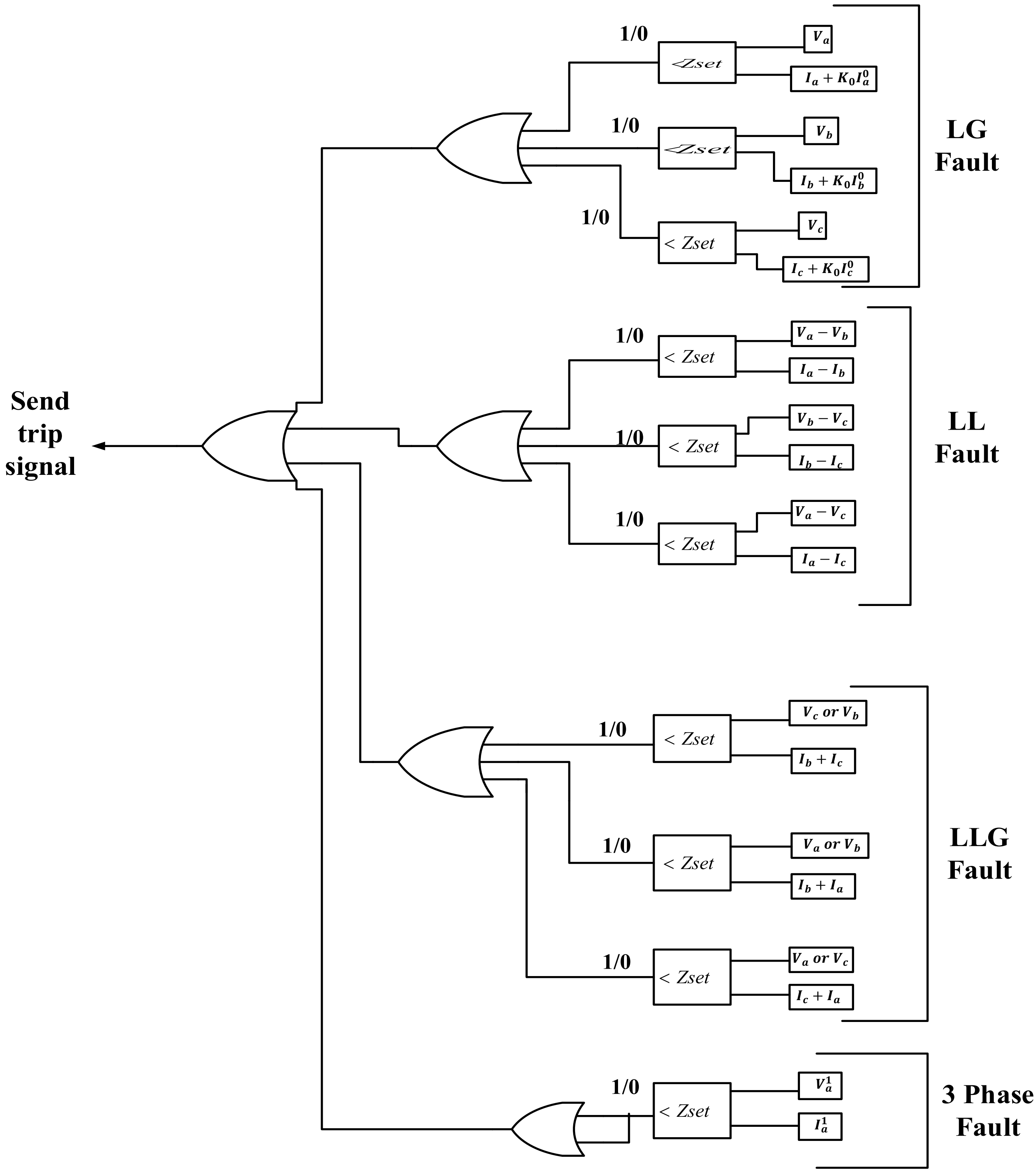

Figure. 2: Command control/model diagram of the conventional protective system

Table 1: Truth table for the logic operation of the distance relay

A_{LG}	B_{LG}	C_{LG}	Y_{LG}	AB	AC	BC	Y_{LL}	ABG	ACG	CBG	Y_{LLG}	3Φ	$Y_{3\emptyset}$	0/P
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	1	0	0	1	1	0	0	1	1	1	1	1
0	1	0	1	0	1	0	1	0	1	0	1			1
0	1	0	1	0	1	0	1	0	1	0	1			1
1	0	0	1	1	0	0	1	1	0	0	1			1
1	0	1	1	1	0	1	1	1	0	1	1			1
1	1	0	1	1	1	0	1	1	1	0	1			1
0	1	1	1	0	1	1	1	0	1	1	1			1
1	1	1	1	1	1	1	1	1	1	1	1			1

Using Boolean algebra, the logic equations for the operation of the distance relay as presented in Figure 1 are:

$$A_{LG} + B_{LG} + C_{LG} = Y_{LG} \quad (24)$$

$$AB + AC + CB = Y_{LL} \quad (25)$$

$$ABG + ACG + BCG = Y_{LLG} \quad (26)$$

$$3\emptyset + 3\emptyset = Y_{3\emptyset} \quad (27)$$

$$O/P = Y_{LG} + Y_{LL} + Y_{LLG} + Y_{3\emptyset} \quad (28)$$

Where A_{LG} is line A to ground fault, B_{LG} is line B to ground fault, C_{LG} is line C to ground fault.

AB is line A to line B fault, AC is line A to line C fault, BC is line B to line C fault.

ABG is line A to line B to ground fault, ACG is line A to line C to ground fault, BCG is line B to line C to ground fault.

Y_{LG} is occurrence of a line to ground fault, Y_{LL} is occurrence of a line-to-line fault, Y_{LLG} is occurrence of a double line to ground fault, $Y_{3\emptyset}$ is the occurrence of a 3-phase fault and O/P is the occurrence of any type of fault.

3. RESULTS AND DISCUSSION

3.1 Simulation of the model in PSCAD

To test the model developed and see how change in fault resistance value affect the trip location in the protection of a distribution line using the distance relay, we consider a short 11kV distribution line (shown in Figure 3) of length 43km having just two protection zones – 1 and 2.

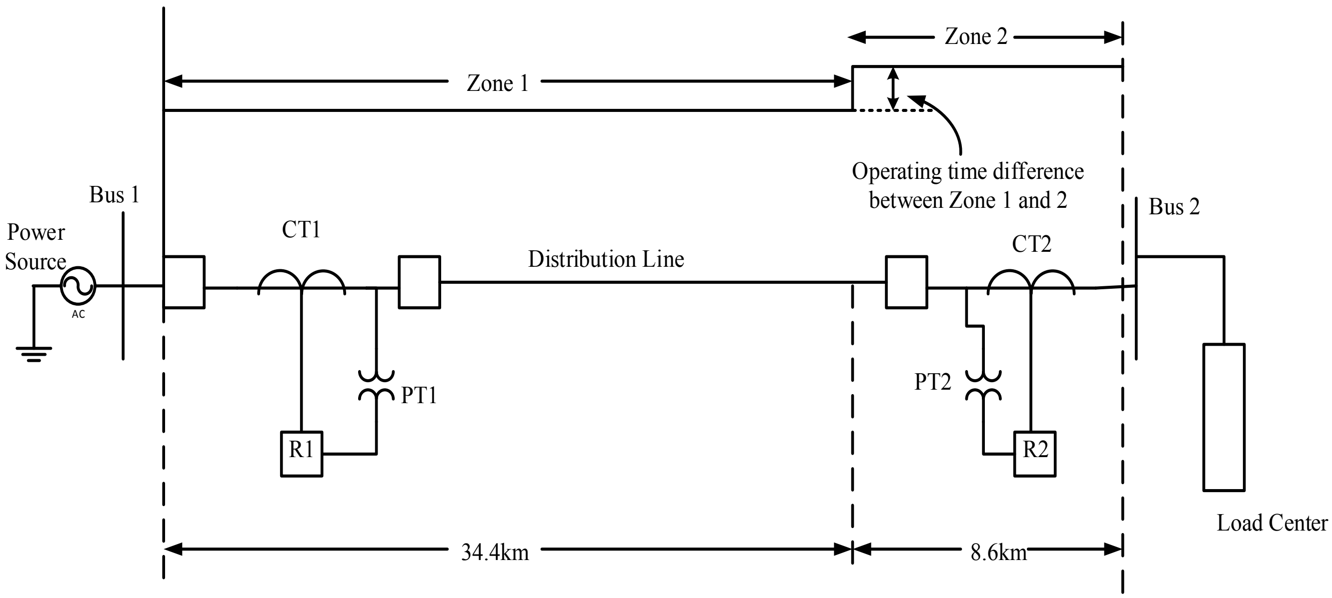

Figure 3: Two – zone distance protection of a line

Zone 1 gives instantaneous protection to 80% of the 43km line (up to 34.4km) while Zone 2 acts as a backup to Zone 1 for the first 80% of the line and also protect the remaining 20% of the line (34.41km to 43km) and may include some time delay and the line parameters are presented in Table 2

Table 2: Line parameters

Length of Line	43km	
Line Positive sequence resistance (same as negative sequence)	$0.02582 \times 10^{-3}(\Omega/m)$	
Line Positive sequence reactance (same as negative sequence)	$0.1291 \times 10^{-3}(\Omega/m)$	
Line Positive sequence capacitance (same as negative sequence)	$210.10(\Omega/\Omega^{-1})$	
Line Zero sequence resistance	$0.1365 \times 10^{-3}(\Omega/m)$	
Line Zero sequence reactance	$1.021 \times 10^{-3}(\Omega/m)$	
Line Zero sequence capacitance	$423.251710(\Omega/\Omega^{-1})$	
Fault impedance used	Fault ON resistance	10Ω
	Fault OFF resistance	1.0E6 Ω
K	$6.826\angle 4.23°$	
Zone 1 (One)	0.0km to 34.4km	
Zone 2 (Two)	34.41km to 43km	

To design the impedance circle diagram in PSCAD, we take the total impedance Z_t for the length of the line,

$$Z_t = 43(0.02582 + j0.1291)\Omega = (1.11026 + j5.5513)\Omega = 5.66\angle 78.7°\Omega \quad (29)$$

The protection system uses a CT and PT with turn ratio of 300/1 and 500/1 respectively. Thus, transferring this total impedance in the primary sides of the instrument transformers to their secondary sides,

$$Z_{tsec} = \frac{300/1}{500/1} \times 5.66\angle 78.7° = 3.396\angle 78.7°\Omega \quad (30)$$

Hence, Zone 1 covers impedance up to $0.8 \times 3.396\angle 78.7°\Omega = 2.7168\angle 78.7°\Omega$ while Zone 2 covers the entire length of $3.396\angle 78.7°\Omega$.

We shall investigate the effect of using fault resistance values of 0.1Ω, 0.5Ω, 1Ω 5Ω and 10Ω for the same fault location for the same type of fault and see the effects for LL, LLG and LLL faults between the same phase sequences at each point in time, and see how variations in fault impedance affect the tripping zones. We consider faults occurring at Zone 1, precisely at 30 km on the line.

On simulating the system in PSCAD after the introduction of the faults, the impedance circle diagrams below show the region where the tripping occurred. Figure 3a to 3e shows the zone where the tripping takes place for a LG (AG) fault for different impedance values.

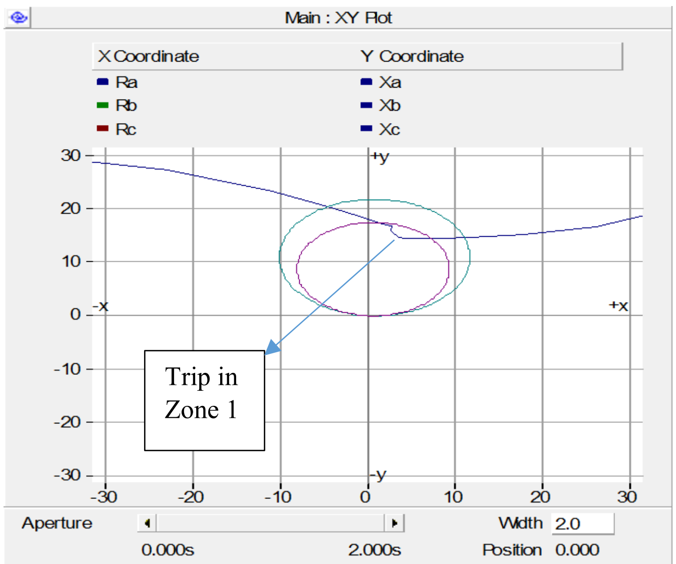

Figure 3a: LG fault of 10Ω

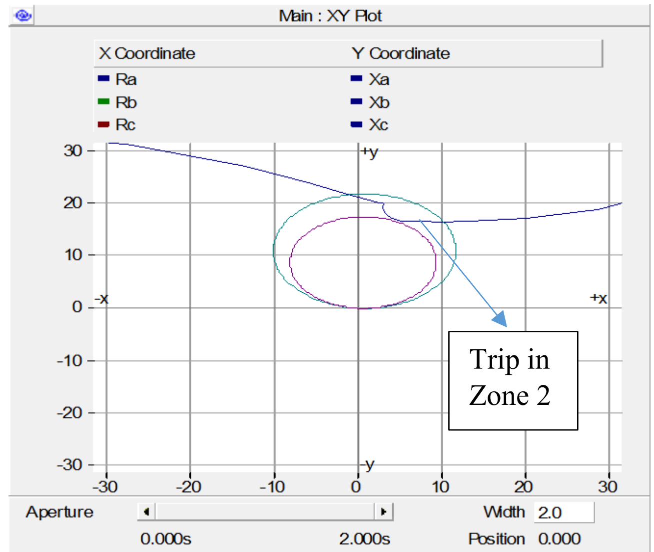

Figure 3b: LG fault of 0.1Ω

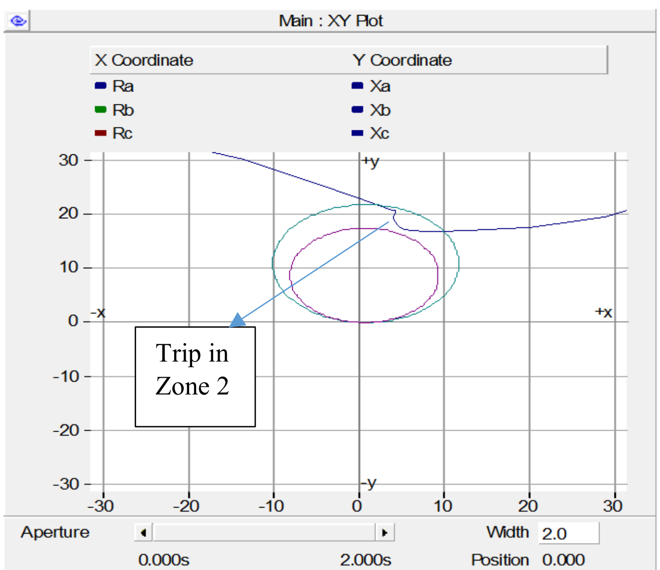

Figure 3c: LG of 1Ω

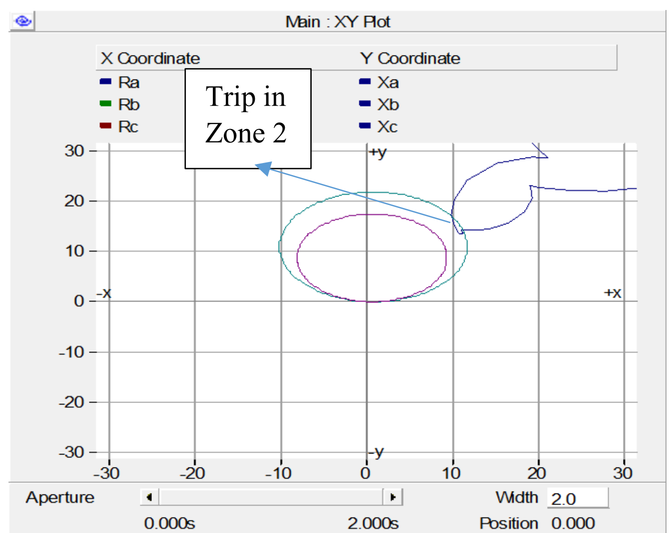

Figure 3d: LG fault of 5Ω

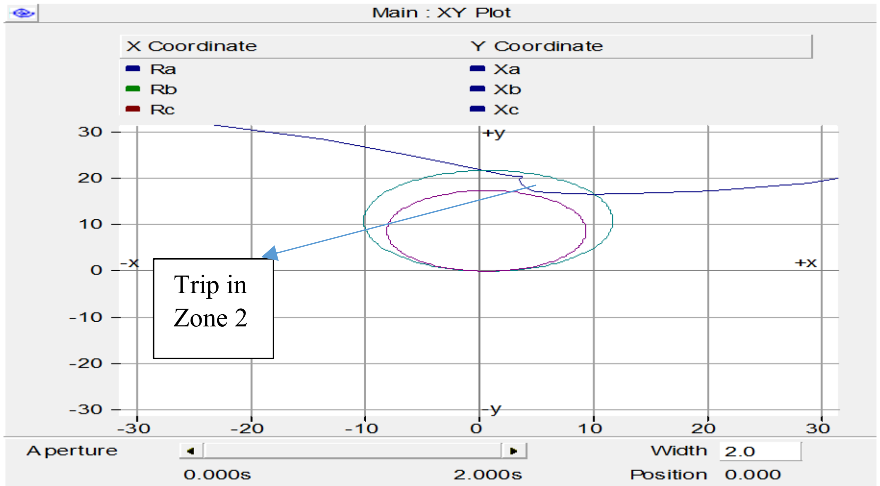

Figure 3e: LG fault of 0.5Ω

For a LL (AB) fault, the impedance circle diagrams are presented in Fig 4a to 4e below

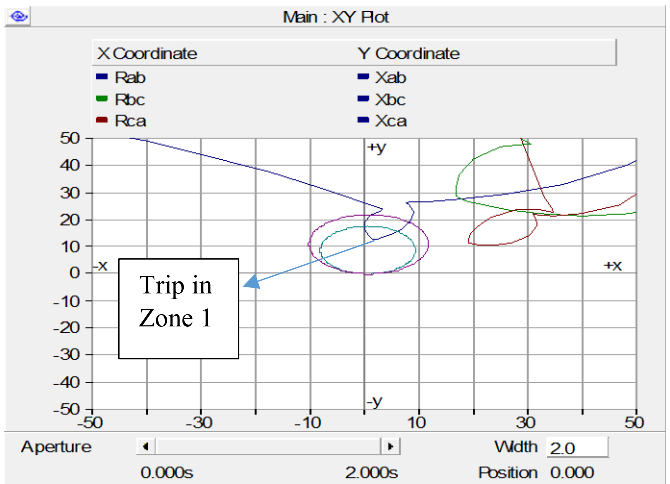

Figure 4a: LL fault of 1Ω

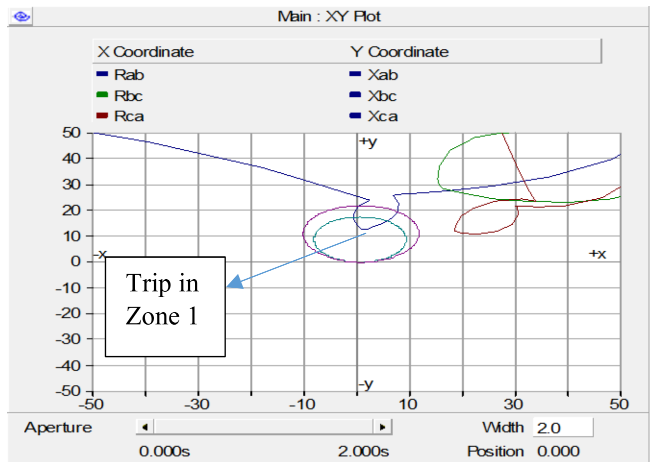

Figure 4b: LL fault of 5Ω

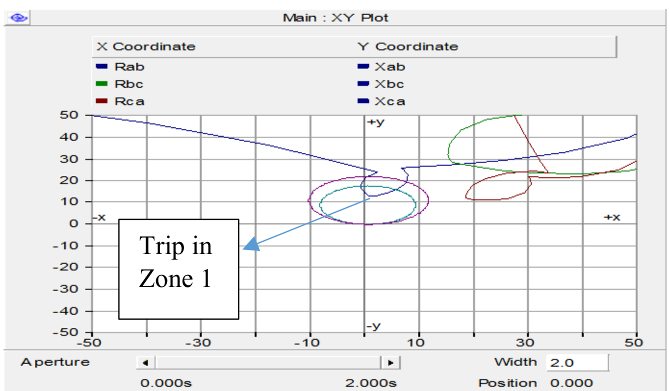

Figure 4c: LL fault of 0.1Ω

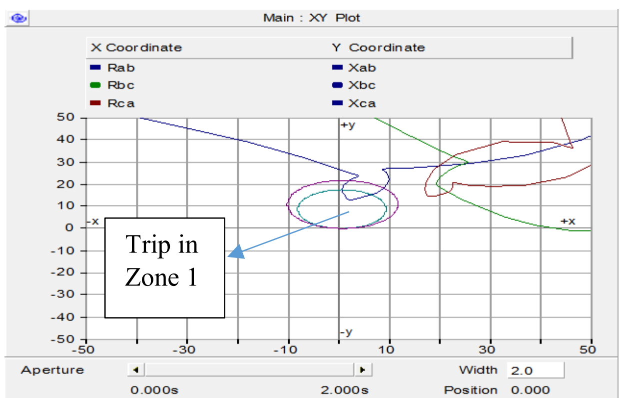

Figure 4d: LL fault of 0.5Ω

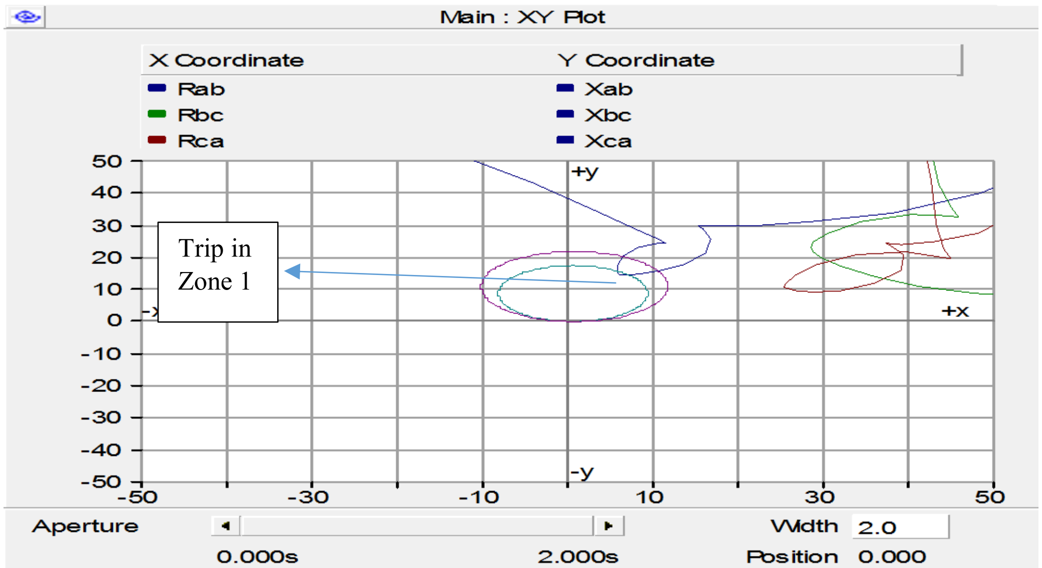

Figure 4e: LL fault of 10Ω

Table 3: Tripping zones for different faults with different faults impedance on the line.

S/N	Fault impedance (Ω)	Fault Type	Trip Zone	Fault Location (km)
1	0.1Ω	LG	Zone 2	30.0
		LL	Zone 1	
		LLG	Zone 2	
		3 Phase	Zone 1	
2	0.5Ω	LG	Zone 2	30.0
		LL	Zone 1	
		LLG	Zone 2	
		3 Phase	Zone 1	
3	1Ω	LG	Zone 2	30.0
		LL	Zone 1	
		LLG	Zone 1	
		3 Phase	Zone 2	
4	5Ω	LG	Zone 2	30.0
		LL	Zone 1	
		LLG	Zone 2	
		3 Phase	Zone 1	
5	10Ω	LG	Zone 1	30.0
		LL	Zone 1	
		LLG	Zone 1	
		3 Phase	Zone 1	

Table 3 shows the summary of different faults with different faults impedance occuring at 30km of the line under analysis which is supposed to be zone 1 as the line is 43m long.

3.2 Discussion of results

It was observed that for a LLG fault (between ABG), occurring at 30km on the line (Zone 1), the distance relay/protection system tripped inaccurately in Zone 2 for a fault impedance of 0.1Ω, 0.5Ω and 5Ω and trips accurately in Zone 1 for fault impedance of 1Ω, and 10Ω. Similarly, for a LG fault (between AG), the distance relay/protection system tripped in Zone 1 for a fault impedance of 10Ω alone and tripped inaccurately in Zone 2 for fault impedance of 0.1Ω, 0.5Ω, 1Ω and 5Ω. Also, it was observed that for a fault impedance of 0.1Ω at same location, the system tripped at Zone 1 for LL and 3 phase faults and tripped in Zone 2 for LG and LLG faults. As stated previously, on the secondary side of the CT and PT, Zone 1 covers impedance up 2.7168∠78.7°Ω while Zone 2 covers impedance above 2.7168∠78.7°Ω to impedance up to 3.396∠78.7°Ω. Beyond this value is not included in the protection as it is not within the line of interest. Hence, when fault of any type and fault impedance occurred at any location, the tripping location depend on the Thevenin impedance at the fault location calculated or seen by the relay. If the value is up to 2.7168∠78.7°Ω, the tripping will occur in Zone 1. If the value is above 2.7168∠78.7°Ω but up to 3.396∠78.7°Ω, then it will trip in Zone 2.

4. CONCLUSION

From the study carried out on distance protection schemes of power distribution systems using PSCAD, the impedance seen by the distance relay/protection scheme is the effective or Thevenin impedance at that point of fault. Hence, the following remarks on distance protection schemes can be made.

(i) The distance protection schemes are characterized by indiscrimate tripping in the protection zones. For example, a fault can occur in Zone 1 and may trip in Zone 2 and vise visa. This can be regarded as inaccurate tripping in the zones.

(ii) Fault impedance value inflence the tripping zone or location of such protection schemes. For example, a 0.1Ω LL fault occuring in a location in Zone 1 may trip in that Zone 1 while the same type of fault (LL), occuring at that same location in Zone 1 but a different fault impedance may trip in Zone 2.

(iii) The type of fault also affect the tripping location. For example, for a fault impedance of 0.1Ω, the system tripped at Zone 1 for LL and 3 phase faults and tripped in Zone 2 for LG and LLG faults at same location and impedance.

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