Simulation-Based Investigations of the Distance Relay Protection for Extended Double-Circuit Lines

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***Abstract*— As transmission lines are an extremely vulnerable part of the aging infrastructure, they are still a vital part of our society. As they are exposed to the harsh environment, they are incredible prone to faults and therefore it is vital to have protection relays for protecting the transmission lines, equipment and increase the flexibility and resilience of our power system. One of the most reliable protections is the distance protection and often used for transmission lines. With digital relays, real-time monitoring of the impedance is possible and operate at high speeds. This paper implements a model for extended double-circuit line circuit using Matlab/Simulink software to investigate the performance of the three-zones distance protection for extended double-circuit transmission lines, under different fault types and different fault distances.**

Keywords—Distance protection, Matlab/Simulink simulation, Mho relay, Symmetrical and unsymmetrical faults, Double-circuit line protection

I. Introduction

Power systems are an incredible complex system and vital for modern societies. Power systems are composed of complex parts like generators, transformers, and distribution lines [1] and a key component for stable operations is of course the protection systems. Since the infrastructure of power systems as a whole is so vast there is incredible capital investment in power systems and therefore the protection of the system as a whole is incredibly important. Transmission lines are one of the most vulnerable parts of a power system and especially overhead transmission lines as they are exposed to the harsh environment, extreme weather events and other external factors, therefore transmission lines are the part of the power system that is most prone to faults [2]. As a result, power systems often experience short circuit and symmetrical and unsymmetrical high-level fault current flow that can have damaging effects on equipment. Protection schemes for power systems consists of breakers, current transformers, voltage transformers, relays to isolate parts of a power system to isolate faults. As the protection relay sends a signal to a circuit breaker that opens the circuit. Protection relays can be categorized as electromechanical, static and numerical. Numerical relays are based on digital devices and composed of microprocessors or microcontrollers and they analyze current and voltage signals by monitoring and sampling it at desired times which can be used for calculating if a trip decision is to be made and thereby sending a signal to open a circuit breaker. Not so surprisingly numerical distance relays have been taking over static distance relays and electromechanical relays [3]. There are several approaches and schemes for power system protection. Combined protection schemes such as distance and differential protection method, overcurrent protection, especially for connections of renewable energy, are presented in [4].

For protection systems selectivity, time of trip and sensitivity are critical aspects of every protection scheme [5]. In high-voltage transmission systems, distance protection schemes provide an excellent protection and have been used reliable for decades [1], [6]. Distance relays estimate the resistance and reactance of the line impedance and estimate the proportion of the line length between the fault location and the location of the relay. The distance relay is a non-unit protection of a system and can work both as a primary and a backup protection [4]. There are several types of distance relay characteristics with different function and theories like mho, quadrilateral, reactance, admittance, polarized mho, offset mho and even more [7]. The downside of analog method for mho distance relay does not calculate the impedance, but digital relays could calculate the impedance in real time [6]. The distance relays operate by using voltage and current phasors for impedance calculations and can determine if a fault occurs within a set zone. Usually the zone settings are set at 80%, 120% and 200-225% of the lines [8].

The impedance calculations can be implemented for faults like single line to ground (L-G), double line to ground (L-L-G), line to line (L-L) and a three phase faults (L-L-L) [3]. To simulate the fault and distance relays, Matlab/Simulink has been used and proven to be a reliable tool for simulations of faults and protection system relays and is a powerful analysis software package since it offers a wide selection of libraries that allow for detailed simulations [7], [8]. In this paper, a model of 100 km double-circuit transmission line with extension of 100 km single-circuit line is simulated, and then different types of faults applied along the line to investigate the performance of a distance relay, with mho characteristic, for fault detection and location.

II. Model Description

The benefits of a double-circuit line are obvious, and of course allows for more stable connections in a system. The considered model consists of 220 kV, 100 km double-circuit transmission line with extension of 100 km single-circuit line, with required models for different fault types, at different locations. The model was set up in Matlab as a double single-circuit lines, for both simplification and further design possibilities. The mutual effect is expected to be little. Furthermore, the model could be used for future fault investigations for both double-circuit line and double single-circuit lines.

A. Extended Double Circuit Transmission Line

Double-circuit overhead transmission lines have been studied, as in [9]-[10]. The aim here is to create an extended double-circuit line with two utility grids connected at each side and a step-up transformer from 13.8 kV to 220 kV.

Then apply various types of faults to investigate and develop the distance protection scheme. To find suitable parameters for the system, data from various sources, [11], [12], and [13], are used to creating a realistic system. The distance relay is located on the lower line L1 of the double-circuit. The three lines are modelled using symmetrical Pi model, as a one Pi section for L2 and five Pi sections for L1 and L3, to simulate different faults at different locations, as shown in Figs. 1-4. The accuracy of Pi model is accepted for the modelled length and no need for using uniform line model. Circuit breakers (CB) are placed at buses, at each end of both lines, which receive signals to be closed. The simulated system is shown in Fig. 1. As the system model was so large in scale, a subblock is created for the L1 and L3 (extended line). The subsystem blocks for the transmission lines can be seen in Fig. 2 for the double-circuit line (L1), and in Fig. 3 for the extended line (L3). It can be seen that each part of the transmission line is attached to a fault block. The fault block can be controlled through Matlab. The fault block is simple in design and uses the Simulink library to create faults and a Boolean logic block is added to control what system and at what time the fault occurs. The subsystem block in Simulink for the faults can be seen in Fig. 4.

B. Model Parameters

The power systems consist of 13.8 kV three phase generator and a step-up transformer of 4000 MVA that increases the voltage to 220 kV and the circuit becomes a double circuit where each line is 100 km and with the same parameters, on the other end of the line there is a 100 km extension of the line before it reaches a three-phase voltage source of 220 kV and 20.000 MVA. The parameters for the transmission line are given in Table I.

TABLE I. TRANSMISSION LINE DESIGN PARAMETERS

Sl. No	Transmission Line Parameters	Values
1.	Length of Transmission Line	200 km
2.	Nominal Frequency	50 Hz
3.	Voltage	220 kV
4.	Line Resistance ($R_1 = R_2$)	0.01273 Ω/km
5.	Line Inductance ($L_1 = L_2$)	0.9337×10^{-3} H/Km
6.	Line Capacitance ($C_1 = C_2$)	$12.74 \times 10^{-9}\ F/km$
7.	Zero Sequence Resistance, R_0	0.3864 Ω/Km
8.	Zero Sequence Inductance, L_0	4.1264×10^{-3} H/Km
9.	Zero Sequence Capacitance, C_0	$7.751 \times 10^{-9}\ F/$Km

C. Fault Impedance Calculations

To measure the fault impedances as seen by the distance relay the impedance formulas can be seen in Table II. To implement a distance protection scheme it is vital to have a clear understanding of the calculations for the fault impedances. For the system is a three-phase system, we have:

- V_a, V_b and V_c: Voltages of phases *a, b* and *c.*
- I_a, I_b and I_c : Currents of phase *a, b* and *c.*
- The zero-sequence current is given in (1).

$$I_0 = (I_a + I_b + I_c) / 3 \tag{1}$$

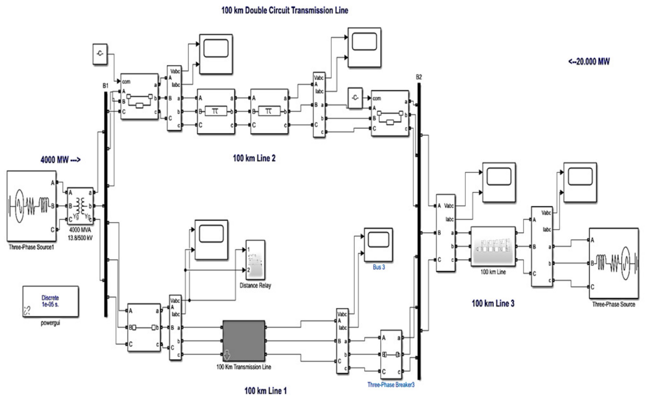

Fig. 1. Matlab/Simulink model for 100 km double-circuit (L1 and L2) extended by a 100 km single-circuit (L3) overhead 220 kV transmission line

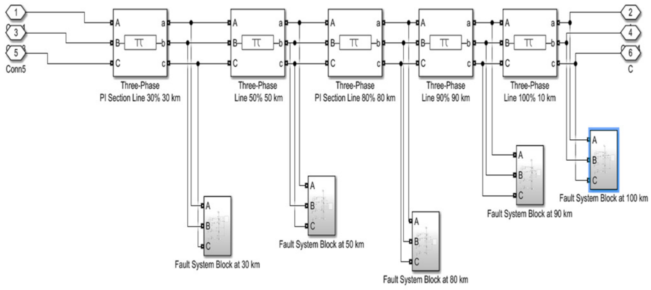

Fig. 2. Matlab/Simulink model for one of the double-circuit overhead 100 km, 220 kV transmission line (L1)

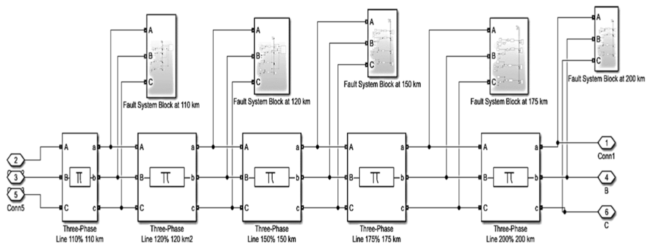

Fig. 3. Matlab/Simulink model for 100 km extended overhead 220 kV transmission line (L3)

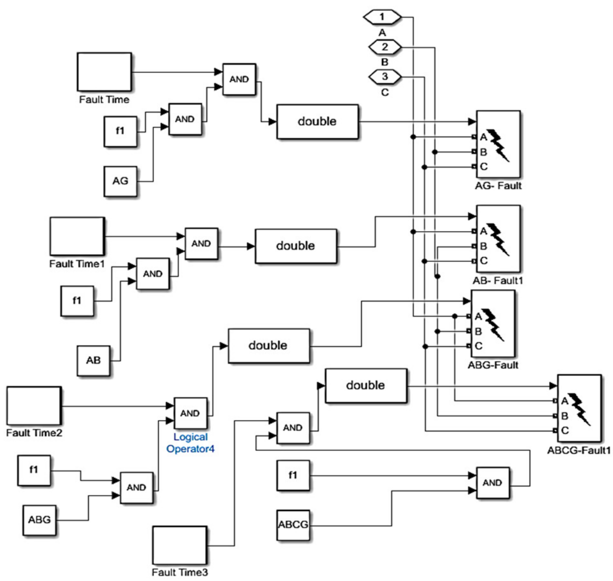

Fig. 4. Fault control block in Matlab/Simulink

TABLE II. FAULT IMPEDANCE ALGORITHM

Fault Types	Calculations/Algorithm
Phase A-Ground (A-G)	$Z_a = \frac{V_a}{I_A + 3K_0 I_0}$
Phase B-Ground (B-G)	$Z_b = \frac{V_b}{I_b + 3K_0 I_0}$
Phase C-Ground (C-G)	$Z_c = \frac{V_c}{I_c + 3K_0 I_0}$
Phase A-B, A-B-Ground (AB, AB-G)	$Z_{AB} = \frac{V_a - V_b}{I_a - I_b}$
Phase A-C, A-C-Ground (AC, AC-G)	$Z_{AC} = \frac{V_a - V_c}{I_a - I_c}$
Phase B-C, B-C-Ground (BC, BC-G)	$Z_{BC} = \frac{V_b - V_c}{I_b - I_c}$
Phase A-B-C	$Z_{ABC} = \frac{V_A}{I_A}, \frac{V_C}{I_c}\ or\ \frac{V_B}{I_B}$

The residual compensation factor (K_0) is often used in distance relay to compensate for the difference between the phase impedance and the ground impedance [4]. The compensation factor is given in (2), where k is generally a value of 1 or 3 depending on the design [14].

$$K_0 = (Z_0 - Z_1) / k Z_1 \tag{2}$$

Where Z_0 represents the zero sequence impedance and Z_1 the positive sequence impedance.

The model parameters in Table I are used, and there is still some modifications needed especially on the reactance side as we need to get the impedance values in the form of $Z=R+jX$. Using a frequency (f) of 50 Hz, the positive and zero sequence impedances could be calculated as in (3) and (4).

$$Z_1 = R_1 + j2(50)\, L_1 = 0.01273 + j0.2933 \quad \Omega/Km$$

$$Z_0 = R_0 + j2(50)\, L_0 = 0.3864 + j1.2963 \quad \Omega/Km$$

D. Mho Characteristic for Distance Relay

The standard approach for zones setting is to take the impedance of the line at 80%, 120% and 200-225%. The line in question is $L1$ as has a length of 100 km and is the lower part of the double-circuit line as seen in Fig. 1. The faults are located at 30, 50, 80, 90, 100 km in Line L1 and on 110, 120, 150, 175 and 200 km on the extended line L3, which occur outside of the double-circuit zone. Since the parameters for all lines are the same ($Z_{L1}= Z_{L2}= Z_{L3}$), the zone setting for zone 2 and 3 needs to account for the split of the fault current.

Then, we could use current division as follows.

$$I_{Fault\text{-}L1} = I_{Fault\text{-}L3} \times Z_{L2} / (Z_{L1} + Z_{L2}) = 0.5\, I_{Fault\text{-}L3}$$

The seen impedance by the relay is the ratio between the voltage to the current ($Z = V / I$). Due to unequal fault currents, for faults in the extended line, the impedance of the L3 part must be doubled.

Therefore, the zones' setting impedance values are as follows.

$$Z_{Zone1} = 80\,(0.01273+j0.2933)$$

$$\mathbf{Z_{Zone1}} = 1.0184+j23.464 = 23.4861\angle 87.52\,°\,\Omega$$

$$Z_{Zone2} = 100\,(0.01273+j0.2933) + 2\times 20\,(0.01273+j0.2933)$$

$$\mathbf{Z_{Zone2}} = 1.7822+j41.066 = 41.1047\angle 87.52\,°\,\Omega$$

$$Z_{Zone3} = 100\,(0.01273+j0.2933) + 2\times 100\,(0.01273+j0.2933)$$

$$\mathbf{Z_{Zone3}} = 3.8190+j87.999 = 88.0818\angle 87.52\,°\,\Omega$$

III. FAULT IMPEDANCE MODEL IN SIMULINK

The three-phase current and voltage waveforms are measured using a measurement block, before the values are used for calculations of the impedance values, the signals are filtered through a discrete Fourier filter. For impedance calculations of the different faults, three different blocks are designed based on [7], [3] and [15]. Within the distance relay block, the signals needed are sent to each calculation block based on the fault impedance algorithm, as seen in Fig. 5. For the top block for calculating the impedance of L-L fault between phase A-B or A-B-G, the Simulink model can be seen in Fig. 6. For three phase faults and three phase faults to ground the impedance block was simply VA/IA as seen in Fig. 7. For, the single line to ground block, the sequence compensator factor are calculated in Matlab m-file that run the Simulink model. The impedance calculation block in Simulink can be seen in Fig. 8.

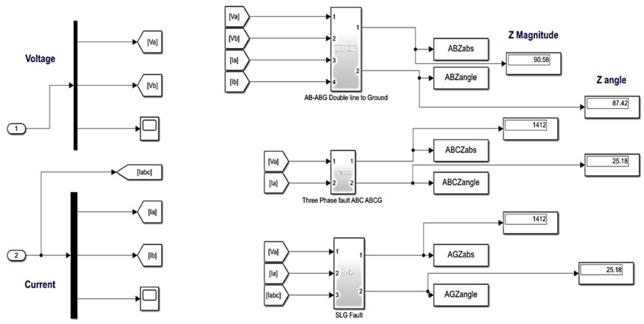

Fig. 5. Distance relay model

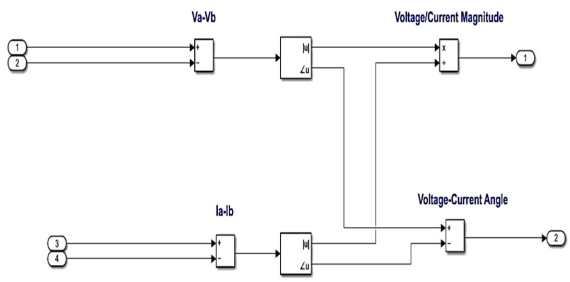

Fig. 6. L-L fault model, between phases A-B and A-B-G

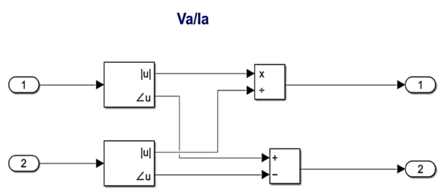

Fig. 7. Three phase fault model

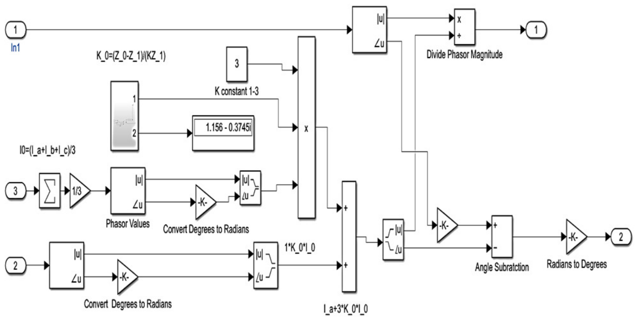

Fig. 8. Single line to ground model (A-G)

IV. Simulation Results

The model is ran in Matlab environment and designed to implement desired faults at specific locations and display the impedance diagram (R-X diagram). To confirm the correct operation, the system is ran without any faults, and the voltage and current waveforms can be seen in Fig. 9. The current and voltage during a fault, at a distance of 30 km, can be seen in Figs. 10-13.

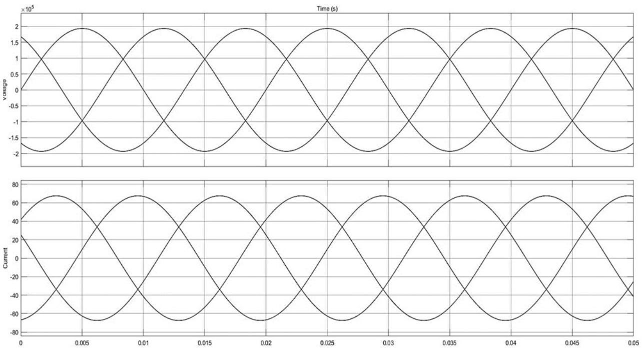

Fig. 9. Voltage and current waveforms

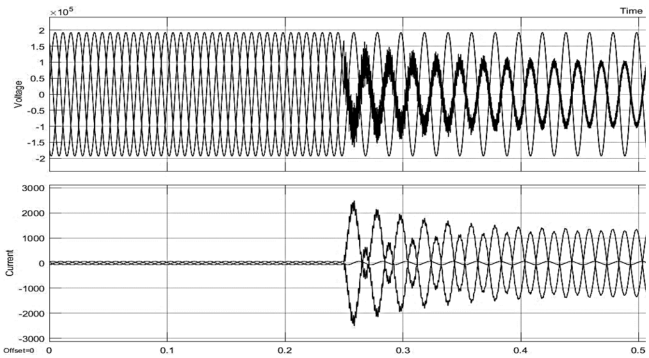

Fig. 10. Voltage and current waveforms during A-B fault at 30 km.

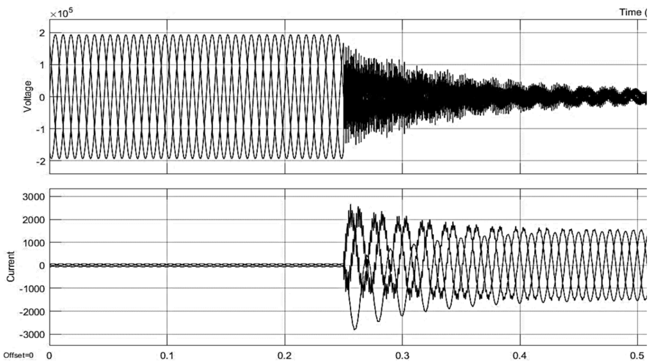

Fig. 11. Voltages and currents during a three-phase fault (A-B-C) at 30 km.

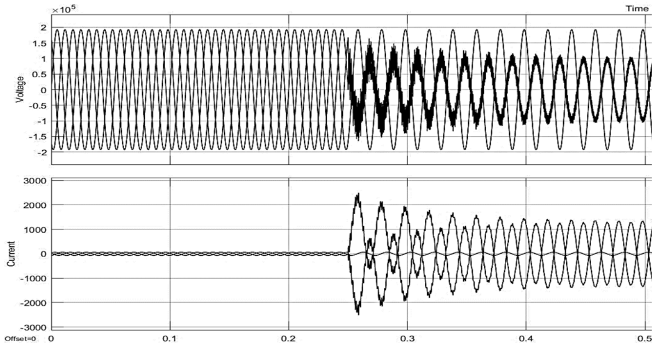

Fig. 12. Voltages and currents during L-L-G fault (A-B-G) at 30 km.

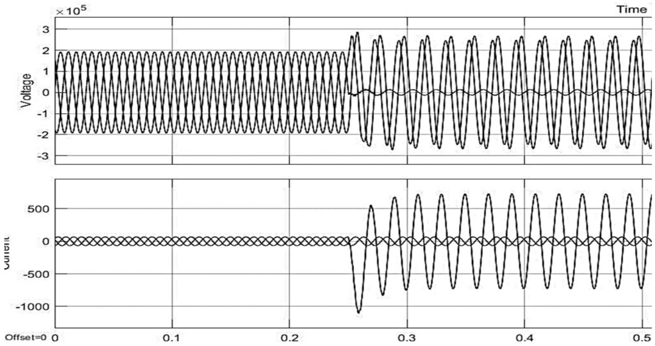

Fig. 13. Voltages and currents during a fault A-G at 30 km.

During faults, the three-phase distance relay blocks, which are connected to the transmission line, calculate the impedance from the differences of phase voltages and phase currents, thereby tracking the impedance and based on the impedance values, a signal could be sent to a circuit breaker to open. Since the model is a high-voltage of 220 kV and of a total length of 200 km, as the fault gets closer to the second bus where the two transmission lines meet, there will be an increase in fluctuations. Therefore, the faults are going to be broken up into zones. For reference, Zone 0 is added for the full line impedance (100 km, distance 100%).

A. *Faults within Zone 1*

The Zone 1 setting is 23.4861∠87.52° Ω. Different faults were created at different distances of 30, 50 and 80 km, and the results are shown in Table III. The trajectory of the measured impedance with time, for different fault types at different impedances, are shown in Figs. 14-19. The greatest difference between the Zone 1 at 80 km and the measured value is for a line to ground fault (A-G) that had a measured impedance of 22.22∠88.09° Ω. while A-B, A-B-G and A-B-C were at 23.55∠87.5° Ω..

TABLE III. Fault Impedance

Fault Location	Fault Impedance Zones (Ω)			
	A-G	**A-B**	**A-B-G**	**A-B-C-G**
30 km	8.74∠87.79°	8.81∠87.52°	8.81∠87.52°	8.81∠87.51°
50 km	14.44∠86.48°	14.69∠87.51°	14.69∠87.51°	14.69∠87.51°
80 km	22.22∠88.09°	23.55∠87.50°	23.55∠87.50°	23.55∠87.50°
90 km	23.67∠90.45°	26.50∠87.46°	26.50∠87.49°	26.51∠87.50°
100 km	17.05∠132.4°	29.49∠87.56°	29.49∠87.56°	29.48∠87.52°
110 km	20.25∠144.8°	35.44∠87.52°	35.44∠87.52°	35.43∠87.50°
120 km	24.27∠154.4°	41.45∠87.54°	41.45∠87.54°	41.42∠87.47°
150 km	39.91∠172.1°	59.58∠87.49°	59.58∠87.49°	59.57∠87.47°
175 km	54.93∠178.7°	74.94∠87.43°	74.94∠87.43°	74.94∠87.42°
200 km	50.17∠130.7°	90.58∠87.42°	90.58∠87.42°	90.57∠87.41°

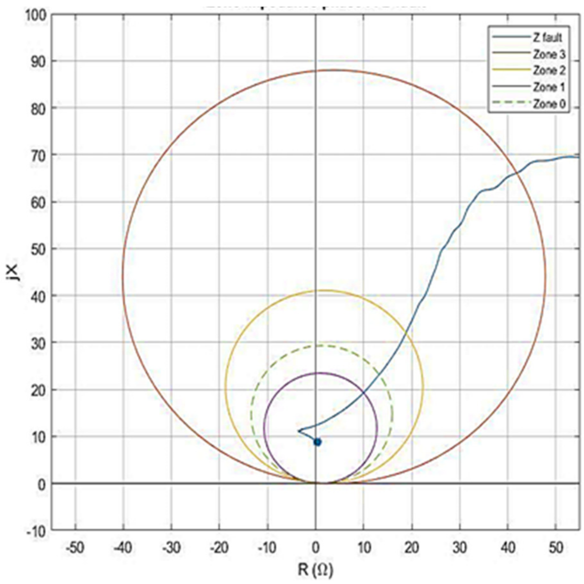

Fig. 14. Impedance trajectory at 30 km A-B fault

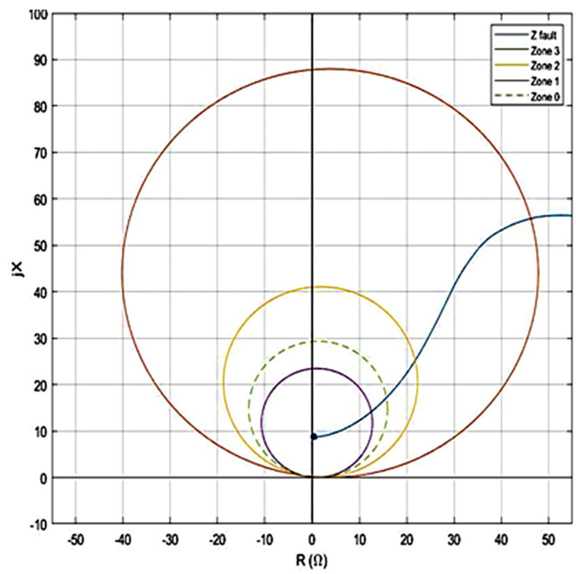

Fig. 15. Impedance trajectory at 30 km A-B-C fault

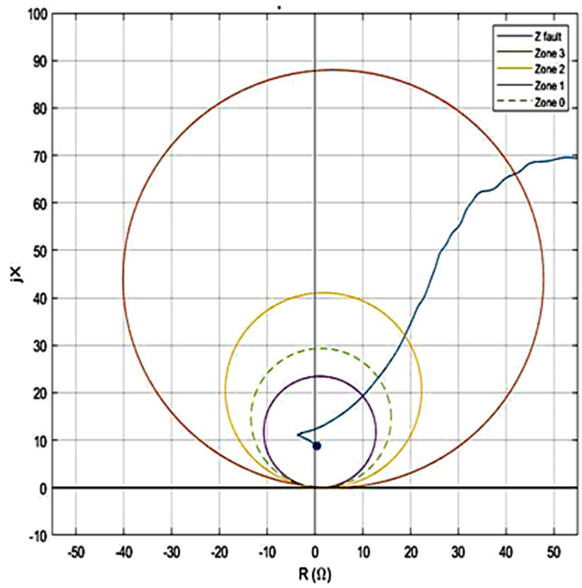

Fig. 16. Impedance trajectory at 30 km A-B -G fault

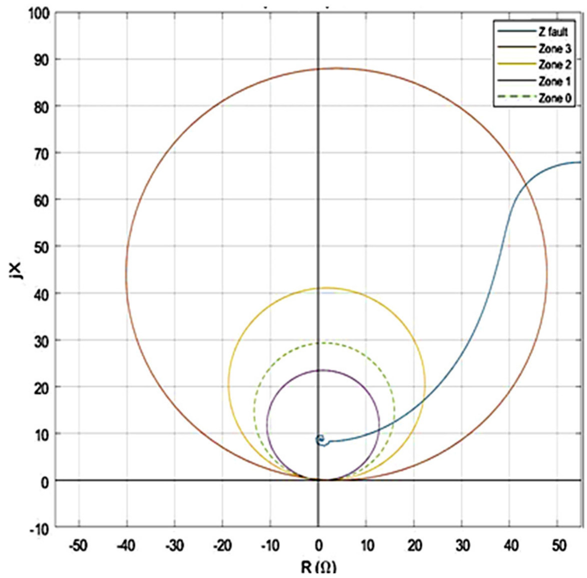

Fig. 17. Impedance trajectory at 30 km A-G fault

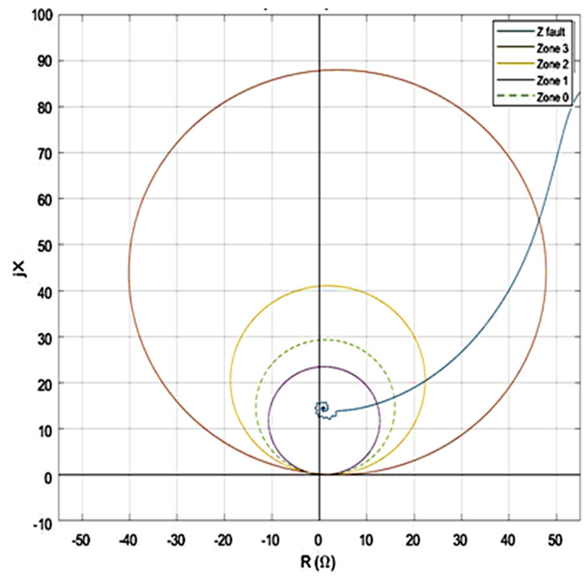

Fig. 18. Impedance trajectory at 50 km A-G fault

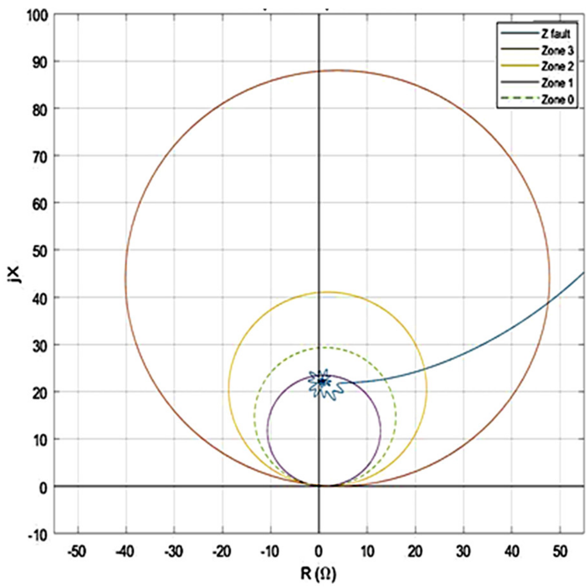

Fig. 19. Impedance trajectory at 80 km A-G fault

B. Faults within Zone 2

The Zone 2 setting is 41.1047∠87.52° Ω. For faults A-B, A-B-G and A-B-C the measured impedance value seemed to match fairly closely as seen in Table III. However, the A-G fault impedance value drops drastically and the phasor angle reached over 90° at the 90 km. The trajectory of the measured impedance with time, for A-G fault at 90 km, is shown in Fig. 20.

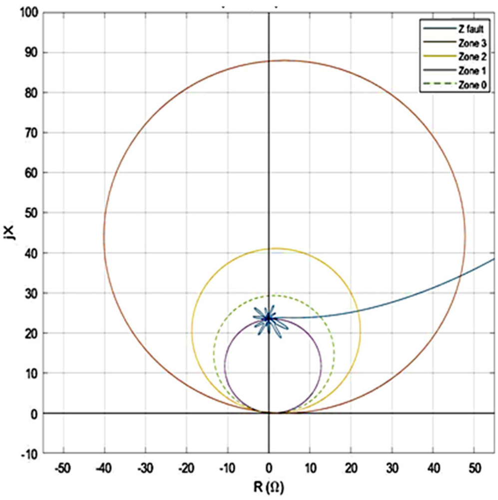

Fig. 20. Impedance trajectory at 90 km A-G fault

C. Faults within Zone 3

The Zone 3 setting is 88.0818∠87.52° Ω. For faults A-B, A-B-G and A-B-C the measured impedance value seemed to match fairly close, as seen in Table III. However, the calculated impedance value is greater than 88.08 and therefore the Zone 3 setting should modified. However, the A-G fault impedance value drops drastically and the phasor angle reaches 178° at 175 km before dropping again at the 200 km fault location. The trajectory of the measured impedance with time, for A-B-C-G fault at 150 km, is shown in Fig. 21.

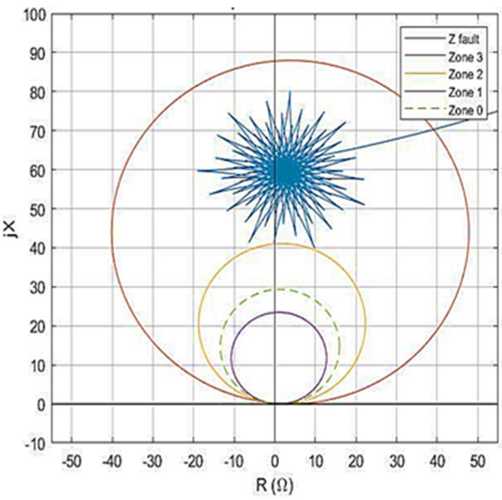

Fig. 21. Impedance trajectory at 150 km A-B-C-G fault

V. CONCLUSIONS

An extended double-circuit transmission line has been simulated in Matlab/Simulink, for investigation and development of distance protection, under different fault types and locations.

The Mho relay impedance characteristics have been used with a three zones settings. Based on the results, it clear that the distance relay could be applied for extended double-circuit transmission lines, although some minor setting modifications are needed for more accurate results of a phase to ground (A-G) fault. The line is modelled, in Matlab, as a double single-circuit lines for simplification and further investigation possibilities, and the mutual effect is expected to be little. Then, the model could be used for future fault investigations for both double-circuit line and double single-circuit lines. The accuracy of Pi model is accepted for the modelled length (maximum of 100 km) and hence no need for using uniform line model. Future work might propose a new setting with a recommended characteristic of distance relays, and consider different types of protective relays applicable to the considered system and investigate the effect of line length in the proposed modelling here.

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