Phasor Based Numerical Mho Distance Relay: Model Development

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Abstract – The advancement in science and engineering led to the development of relays, started by electromechanical, and followed by solid-state, and lately digital and numerical relays. Numerical relays are the result of the application of microprocessor technology in the relay industry. This paper describes an approach for detailed modeling of a numerical distance relay using MATLAB/SIMULINK. The distance relaying is for use in a modeled EHV transmission system. A section of 400 kV, 350 km length transmission lines is chosen for the case study. The numerical relay is modeled having Mho characteristics suitable for three-zone distance relaying. A set of tests were performed to investigate the applicability and consistency of the developed relay model. The results showed that the numerical relay model respond satisfactorily to fault incidents and in accordance with the expected results of the performed tests.

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Keywords: – Distance protection; Mho characteristic; Impedance relays; Numerical relays.

1. Introduction

Protective relays are the most important piece of equipment used in the protection of power systems. Distance relay is one of the effective protective relays that are used for the protection of extra high voltage transmission lines. Distance relays are considered of the high speed class and can provide both primary and back-up protections [1].

Distance relay response is based on the measured impedance between the relay location and the fault point. As the impedance per km of a transmission line remains relatively constant, the relay essentially responds to the "Distance" to a fault [2]. This protection philosophy has found favor as the set-points are based on the line impedance which is relatively constant and easy to determine.

Software models of relays in the form of equations representing the operating characteristics of relays have long been used by academics and manufacturers for designing relays and checking their performance. These models describe characteristics which are defined in a variety of ways such as reactance versus resistance [3].

The power system block set toolbox, available in the MATLAB environment provides a tool for relay modeling [4]. The information on which such models are based is either available from manufacturer leaflets, patents, or from technical papers describing the relay performance. Numerical relay models can be divided into two categories. First, the "Phasor-based models", in which only the fundamental frequency component of voltages and currents are used and were the first to be widely used by industry and academics to design relays and check their performance. The second category models, "Transient relay model", take into consideration the high frequency and decaying DC component of voltages and currents, in addition to the fundamental frequency components; this type is rarely used as it needs sophisticated filters in order to remove the DC and high frequency components [5].

This work presents a phasor based model approach for the mho characteristic distance relay. The model then built in MATLAB/SIMULINK is to be tested for satisfactory operation under various fault incidents. Other distance relay characteristics can be built in a similar way.

2. Fundamentals of Distance Protection

Distance protection principles involve the division of the voltage at the relaying point by the measured current. The apparent impedance so calculated is compared with the relay reach point impedance (i.e. zone setting). If the apparent impedance is less than the reach point impedance, i.e. relay to fault point distance is less than the zone setting, the distance relay must initiate the removal of the fault [6]. Distance relay zone settings are based upon the line positive sequence impedance, therefore, appropriate voltage and current inputs and a processing algorithm are required to calculate the line positive sequence impedance seen at the relaying point for all fault types.

Tables (1) and (2) provide the algorithms that are needed to calculate the positive sequence impedance measured between distance relay location and the fault point for different fault types. Symbol (m) in Table (2) is the compensation factor [7], and given by, ($\mathrm{m} = (Z_0 - Z_1)/Z_1$). Z_1 and Z_0 are the line positive and zero sequence impedances respectively. The $I_{a,\ b,\ c}$ are the phase currents, the $V_{a,\ b,\ c}$ are the line to neutral phase voltages, and the a, b, c are the phase designation in a 3-phase system.

Table 1 Apparent impedance for multiphase faults

Apparent Impedance	Suitable for Faults:
$\frac{V_a - V_b}{I_a - I_b} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_ab}$	'a'-'b' Ungrounded 'a'-'b' Grounded 3-Phase Ungrounded 3-Phase Grounded
$\frac{V_b - V_c}{I_b - I_c} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_bc}$	'b'-'c' Ungrounded 'b'-'c' Grounded 3-Phase Ungrounded 3-Phase Grounded
$\frac{V_c - V_a}{I_c - I_a} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1\_ca}$	'c'-'a' Ungrounded 'c'-'a' Grounded 3-Phase Ungrounded 3-Phase Grounded

Table 2 Apparent impedance for phase -to-ground faults

Apparent Impedance	Suitable for Faults:
$\frac{V_a}{I_a + mI_0} = Z_{1\_a}$	'a' to Ground
$\frac{V_b}{I_b + mI_0} = Z_{1\_b}$	'b' to Ground
$\frac{V_c}{I_c + mI_0} = Z_{1\_c}$	'c' to Ground

The operating characteristics of distance relays can be obtained by either amplitude comparison or phase comparison of the sets of vectors derived from the current and voltage signals of the protected line. Phase comparison is more widely implemented in modern relays [8], and hence, it is considered in this work.

A general distance relay characteristic is derived by a two-input comparator of vectors S_1 and S_2 given by (1 and 2) [9]:

$$S_1 = I_r Z_R - K_1 V_r \quad (1)$$

$$S_2 = K_2 V_r + K_3 I_r Z_R + K_4 V_{pol} \quad (2)$$

Where, S_1, and $S_2$are the relay comparator input signals; $Z_R$is the relay reach impedance, and the $K_{1,2,3,4}$ are complex constants define the relay characteristics.

The parameters V_r and I_r are the appropriate loop voltages and currents resemble those given in Table (1) and Table (2). Examples are listed below:

$V_r = V_a - V_b$For the A-B element;
$I_r = I_a - I_b$For the A-B element;

and/or,

$V_r = V_a$For the A-Ground element;
$I_r = I_a + m\, I_0$ For the A-Ground element;

The angular displacement of vectors S_1 and S_2 is considered positive if S_1 leads S_2. The phase comparator operates if the following condition is satisfied [10]:

$$-90^0 \le \angle S_1 - \angle S_2 \le 90^0 \quad (3)$$

or,

$$|\ \angle S_1 - \angle S_2\ | \le 90^0 \quad (4)$$

The use of this approach in the development of the distance relay mho characteristics will be presented in the following section. However, in numerical relays it is possible to design operating characteristics of almost any shape by changing the values of the 'K' parameters in the comparator inputs.

3. Mho Self-Polarized Characteristics

The mho relay characteristics are defined as circles in the impedance plane which passes through the origin. This characteristic is obtained by setting: $K_1 = K_2 = 1$, and $K_3 = K_4 = 0$. Hence (1) and (2) become:

$$S_1 = I_r Z_R - V_r \quad (5)$$

$$S_2 = V_r \quad (6)$$

To represent the mho relay characteristics, it is necessary to implement the voltage phasors S_1 and S_2 in the impedance plane.

This is accomplished by dividing (5) and (6) by the current I_r, yielding:

$$S'_1 = Z_R - Z_r \quad (7)$$

$$S'_2 = Z_r \quad (8)$$

Figure 1a demonstrates an example of the mho relay with the operating conditions met. It can be seen that with Z_r measured inside of the characteristic circle, the angular difference between S'_1 and S'_2 will be less than 90 degrees, which fulfils the operating condition. Figure1b demonstrates an example of the mho relay with the operating conditions not met [11].

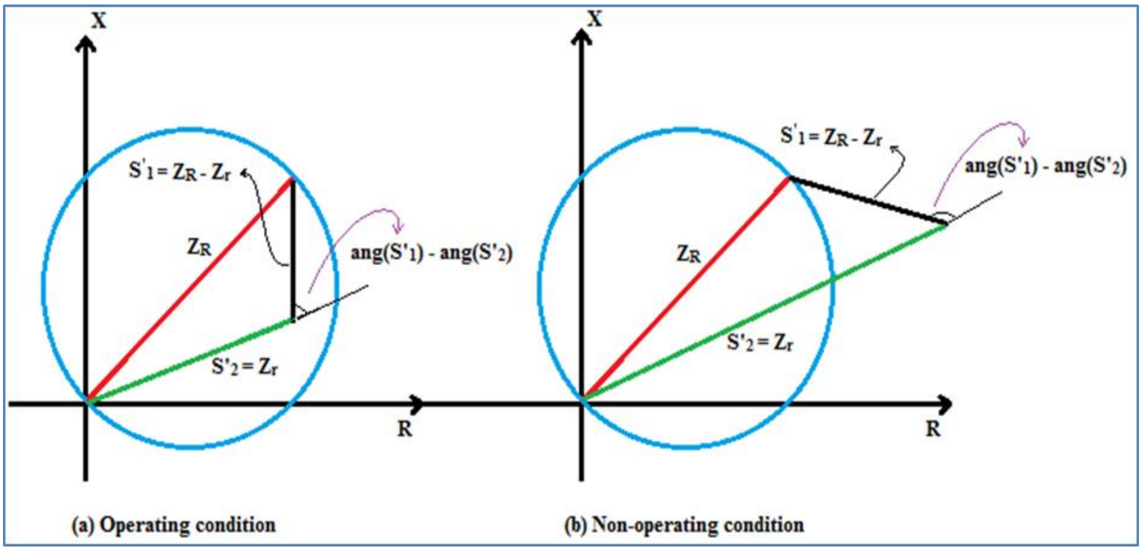

Figure 1 Relay Mho characteristics

4. Numerical Distance Relay Model

The MATLAB/SIMULINK phasor model of the mho characteristic distance relay is built based on the apparent impedance equations presented in Tables 1 and 2 with phase comparator inputs of (5) and (6) for mho characteristics. The distance relay model contains 6 elements, 3 for multi-phase faults and the other 3 elements for phase to ground faults. The inputs for the phasor relay model are the fundamental frequency component of voltages and currents. The structure and contents of the phase and the ground element models of a 3-zone distance relay are presented as follow:

a) Phase element model

Figure 2 shows the developed relay phase elements model, the input signal (voltages and currents) differences are fed to the appropriate relay elements along with the settings for the three zones in vector form. The contents of element 1 (i.e. element A-B) block are shown in figure 3. Element 2 and 3 (i.e. element B-C and C-A) are identical and similar to that of element 1. The element model contains two parts, one for the apparent positive sequence impedance calculation which is depicted in figure 3a. The second part shown in figure 3b is for the generation of trip signals, if the angular criterion of the mho characteristic is met, an 'on-delay' timer will activate and trip the breaker after an appropriate time delay.

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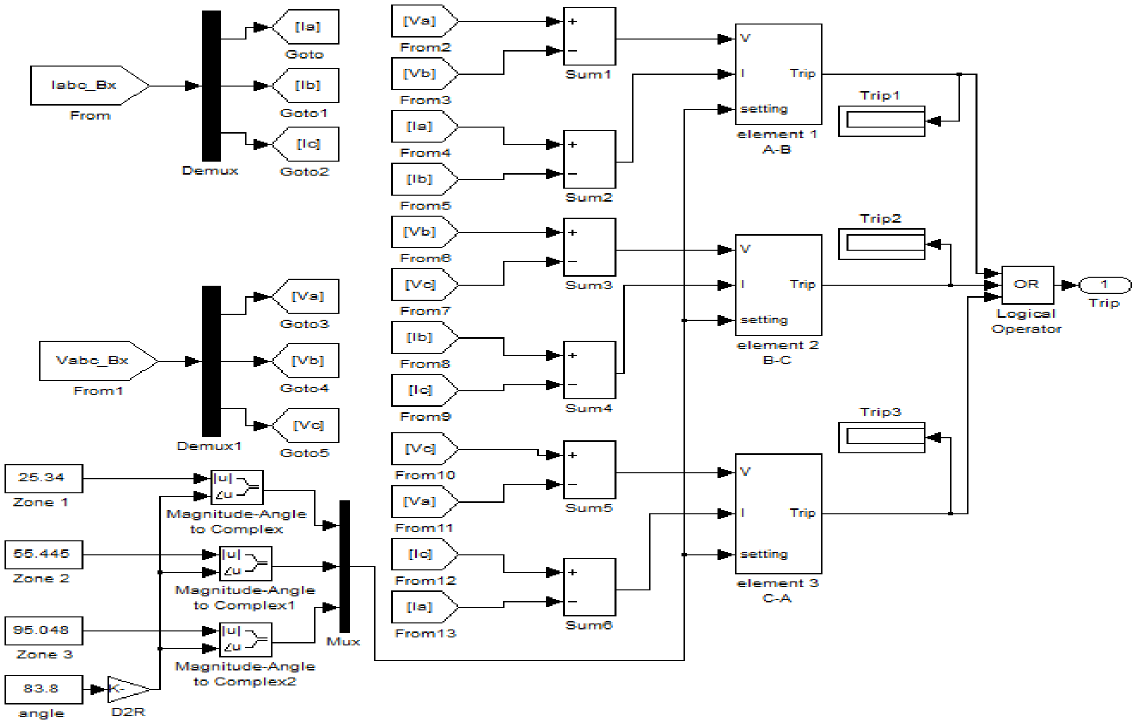

Figure 2Phase mho relay model

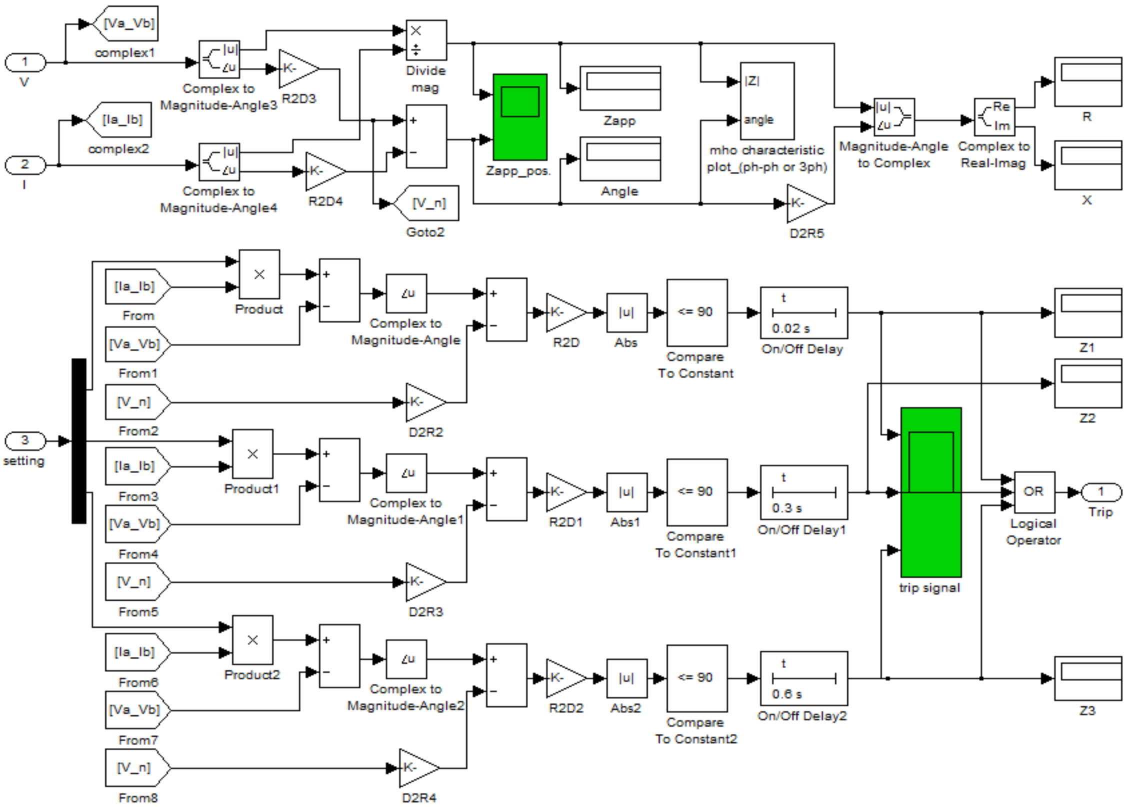

Figure 3 Element (1) of the phase mho relay of figure 2

b) Ground element model

Figure 4 shows the developed ground elements model implementing the ground relay algorithms of Table 2. This model is very similar to the phase mho relay one with two alterations. The first alteration, compensated zero-sequence current (mI_0) has been calculated and added to each phase current. The second alteration, phase voltages and compensated phase currents are now the new operating quantities instead of the line values used in the phase relays. For the rest of the ground mho relay model regarding functionality, settings and elements construction, they are identical to that in the phase mho relay.

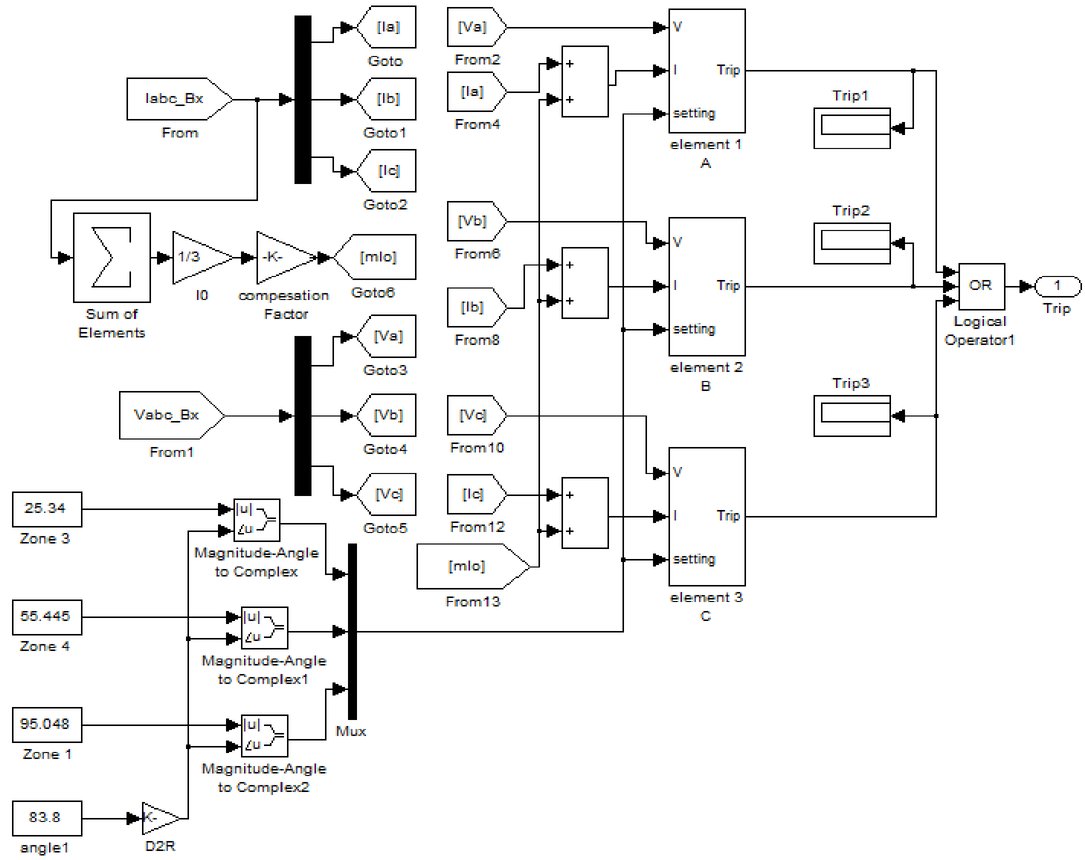

Figure 4 Ground mho relay model

5. Test System Parameters and Calculations

A four bus EHV transmission system is considered for testing the developed distance relay model. The system shown in figure 5 resembles part of a 400kV, 50Hz, 350km length transmission system. The line parameters are;

Z_1=Z_2=0.034+j0.315 Ω/km

Z_0=0.299+j0.975 Ω/km

The source end characteristics considered here are;

S_A, short circuit level = 7892 MVA, $|V_A|$ = 1.0 p.u

S_D, short circuit level = 7892 MVA, $|V_D|$ = 0.97 p.u

The loading state considered is that to produce 20° load angle lead for $\overline{V}_A$ over $\overline{V}_D$.

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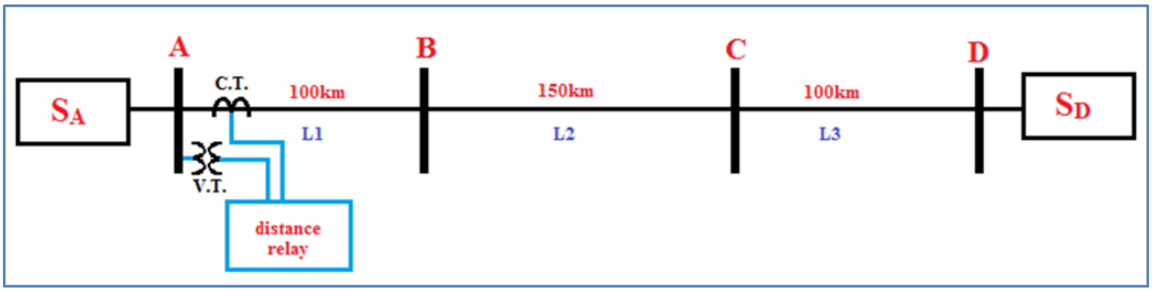

Figure 5 Test system single line diagram

The mho characteristic distance relay located at bus A has the following zone settings:

- Zone1 reach =80% of line L1

Zone1 reach = 0.8 * 100 * (0.034+j0.315) = 25.34∠83.83° Ω

This zone has no intentional time delay. Practically it needs very short time for the equipment's to respond; therefore its operation is set to 2ms.

- Zone2 reach =line L1+ 50% line L2

Zone2 reach = (0.034+j0.315) (175) = 55.445∠83.83° Ω

This zone time delay is set to 0.3s.

- Zone3 reach = (line1 + line2) * 120%

Zone3 reach = (0.034+j0.315) (250) * 1.2= 95.048∠83.83° Ω

This zone time delay is set to 0.6s.

- Compensation factor = m = $\frac{Z_0 - Z_1}{Z_1}$ = 2.24∠-15.622°

The number and direction of zones and the setting for the zone reach and time delay can be changed as desired.

6. Simulation Results

The test system described in section (5) is modeled using MATLAB/SIMULINK, version (7.6.0, R2008a). With the distance relay located at bus A, several fault scenarios can be staged to get and quantify the relay model response. That is to show the model ability to detect the fault and respond according to the fault location and for the different fault types.

Figures 6 to 9 show samples of the apparent impedance trajectory output of the distance relay model with the three zone boundaries of mho characteristics for 3Ph(Three phase fault), LL(Line to line fault), LLG(Line to line to ground fault) and SLG(Single line to ground fault) respectively.

Figure 10 shows a sample of the 3 zones trip signals associated with a LL fault at 100km from the relay location.

7. Conclusions

This work presents a detailed phasor model for a distance relay of mho characteristics. Mho relays are inherently directional so there is no need for directional elements in the relay model. Simulation results of different faults regarding type and position show clearly the accurate performance of the developed distance relay model. The simulations also show the impedance trajectory settling at its corresponding zone of protection depending on fault position. The model versatility, adaptability and applicability promote it for use in power system simulators. Also, it can be used as a training tool to help users understand how a distance relay works and how settings are performed.

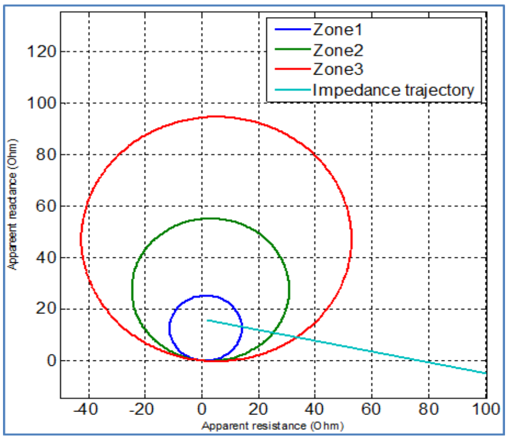

Figure 6 Trajectory of 3Ph. fault at 50 km from bus A

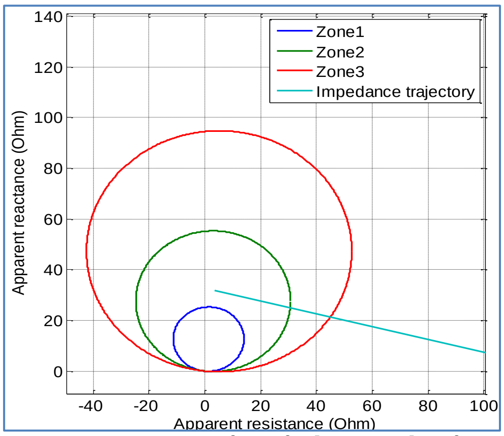

Figure 7 Trajectory of LL fault at 100 km from bus A

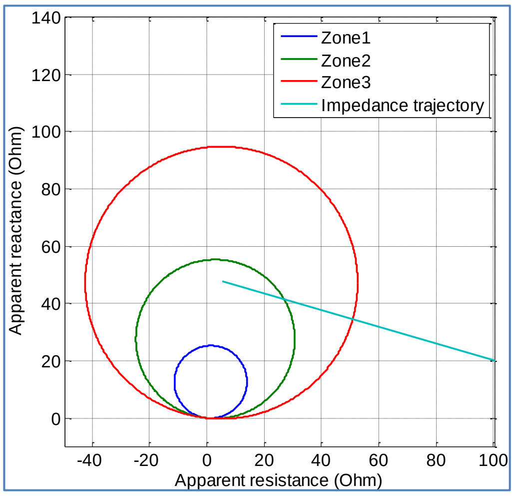

Figure 8 Trajectory of LLG fault at 150 km from bus A

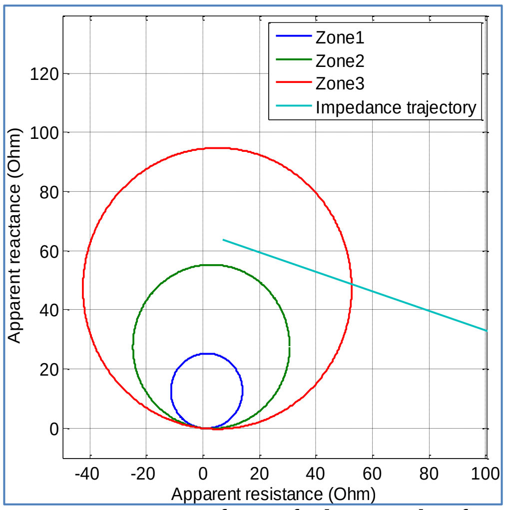

Figure 9 Trajectory of SLG fault at 200 km from bus A

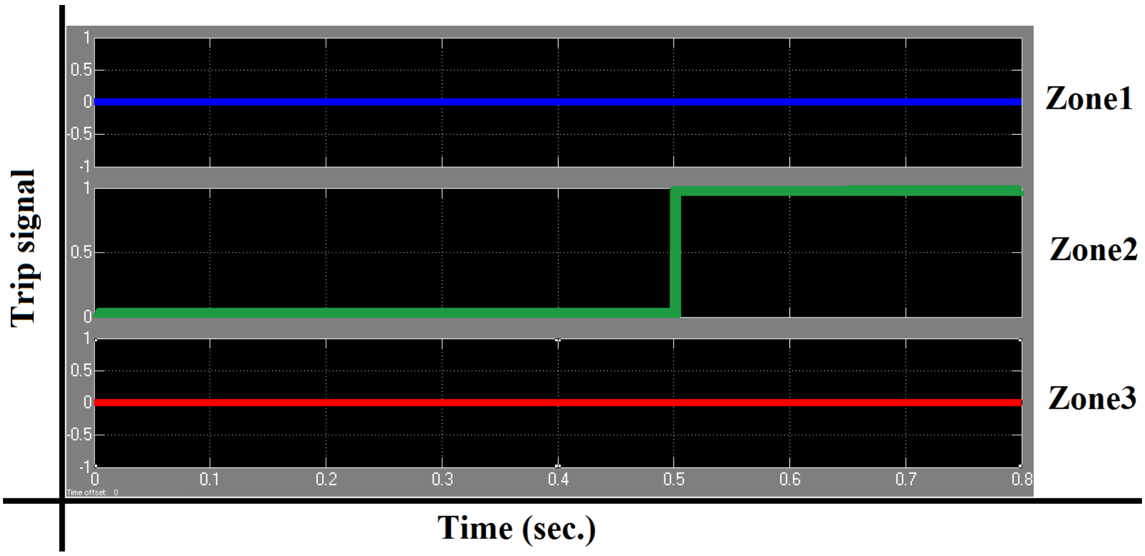

Figure 10 Trip output of distance relay for LL fault at 100km from bus A

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