IJCTA, 10(02), 2017, pp. 165-181

Mutual Impedance based Protection Scheme for Series Compensated Transmission Line

M. Karthikeyan* and R. Rengaraj**

Abstract : Mutual impedance based distance protection scheme is presented for series-compensated transmission lines in this paper. Positive sequence impedance is used by the conventional distance protection scheme to protect a transmission line against short circuit faults. The positive-sequence impedance of the fault path is affected due to the presence of series-compensation, thereby causing the distance relay to mal-operate. In order to overcome this drawback, the concept of mutual impedance based relaying is proposed as a new protection scheme. The mutual impedance between the relay and fault point is computed using the current and voltage at both the ends of the line. The protection scheme is tested against single- line-to-ground faults and double-line-to-ground faults and reliable results are obtained. The performance of the proposed scheme is evaluated and compared with conventional distance protection scheme with computer simulations using MATLAB.

Keywords : Mutual impedance, distance protection, series-compensated transmission line.

1. INTRODUCTION

The presence of series compensation increases the loadability of transmission line and it helps in improving the power system stability. It provides a better voltage profile along the transmission line [1]. The transmission line and interconnected distribution networks are protected by the distance relays [2]. The predefined positive-sequence impedance is set as threshold for the distance relays to operate. The presence of series compensator in the fault path affects reach and directionality of distance relays. The major problems associated with the reach of distance relays are: 1) the locus of fault impedance is affected because of the reduction in series inductance of line, decreasing the reliability of relay and 2) subsynchronous resonance introducing remarkable delays in the response of digital phasor estimation methods [3]. The presence of series compensation on the performance of directional relay is analyzed in [4].

In a series-compensated transmission line, the metal oxide varistor (MOV), which protects the capacitor from over voltages during fault condition acts nonlinearly resulting in mal-operation of distance relay. The voltage drop along the series capacitor is used in [5] with additional parameters to increase the accuracy and speed of the distance relays for zone one protection. In [6], pilot protection scheme for series-compensated lines to prevent malfunctions of the main line and its adjacent line relays are provided. A new directional relaying scheme using the phase difference between the prefault and postfault current is presented in [7]. Traveling wave-based methods [8]-[10] and superimposed-based methods [11] using the transient features of current and voltage during fault conditions shows high-speed performance. But these schemes suffer two drawbacks: (1) if, the current and voltage samples after fault inception are not properly achieved, the relay malfunctions. (2) for slowing evolving faults, the required traveling waves are not generated.

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A new distance protection scheme using mutual impedance between phases is proposed in this paper. The proposed scheme can protect the line against single line to ground and double line to ground faults. Since the mutual impedance is not affected by series compensation, the proposed scheme can provide a reliable protection for series-compensated transmission lines. The rest of the paper is organized as follows: Section II analyzes the effect of series compensation on distance relaying. Section III explains that computation of mutual impedance for the proposed scheme. Section IV presents the proposed protection scheme. Section V shows the simulation results. Finally, Section VI contains the conclusion of the paper.

2. EFFECTS OF SERIES COMPENSATION ON DISTANCE RELAYING

Fig. 1, shows an uncompensated transmission line. Z_a, Z_b and Z_c are the self impedances of the phases *a, b,* and *c,* respectively. The mutual impedances between each of these two phases is represented by Z_{ab}, Z_{bc}, and Z_{ac}. The suffixes *x* and *y* represents the sending end and receiving end parameter respectively. From Fig.1, the following equations can be written in a three-phase system:

$$\left.\begin{aligned} V_{ax} &= Z_a I_a + Z_{ab} I_b + Z_{ac} I_c + V_{ay} \\ V_{bx} &= Z_{ab} I_a + Z_b I_b + Z_{bc} I_c + V_{by} \\ V_{cx} &= Z_{ac} I_a + Z_{bc} I_b + Z_c I_c + V_{cy} \end{aligned}\right\} \quad (1)$$

Using the matrix representation, (1) can be represented as

$$V_x = Z_{abc} I + V_y,$$

where

$$Z_{abc} = \begin{bmatrix} Z_a & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_b & Z_{bc} \\ Z_{ac} & Z_{bc} & Z_c \end{bmatrix} \quad (2)$$

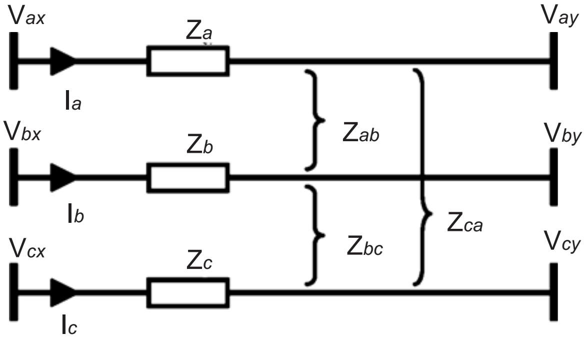


Figure 1: Simple transmission line

Assuming that all three-phase conductors are the same and the line is fully transposed, it can be stated that $Z_a = Z_b = Z_c = Z_s$ and $Z_{ab} = Z_{bc} = Z_{ac} = Z_m$.

$$Z_{abc} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \quad (3)$$

The sequence impedance matrix of Z_{abc} is denoted by Z_{012} and is given by

$$Z_{012} = [Z_0\ Z_1\ Z_2]^T = A^T Z_{abc} A$$

$$= \begin{bmatrix} Z_s + 2Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s - Z_m \end{bmatrix} \quad (4)$$

where Z_0, Z_1, and Z_2 are known as zero, positive, and negative-sequence impedances, and

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle 240^\circ & 1\angle 120^\circ \\ 1 & 1\angle 120^\circ & 1\angle 240^\circ \end{bmatrix} \tag{5}$$

From (4), the zero-sequence and positive-sequence impedances are given by $Z_0 = Z_s + 2Z_m$ and $Z_1 = Z_s - Z_m$. Now, the mutual impedance between phases is given by

$$Z_m = \frac{Z_0 - Z_1}{3} \tag{6}$$

Consider a series compensator with the impedance Z_{com} is located at the beginning of the transmission line as shown in Fig. 2. Using relations similar to (1)-(4) results

$$Z_{abc} = \begin{bmatrix} Z_{com} + Z_s & Z_m & Z_m \\ Z_m & Z_{com} + Z_s & Z_m \\ Z_m & Z_m & Z_{com} + Z_s \end{bmatrix} \tag{7}$$

$$Z_{012} = \begin{bmatrix} Z_{com} + Z_s + 2Z_m & 0 & 0 \\ 0 & Z_{com} + Z_s - Z_m & 0 \\ 0 & 0 & Z_{com} + Z_s - Z_m \end{bmatrix} \tag{8}$$

Therefore, the zero and positive-sequence impedances are given by

$$Z_0 = Z_{com} + Z_s + 2Z_m \tag{9}$$

$$Z_1 = Z_{com} + Z_s - Z_m \tag{10}$$

It is observed from (10) that the positive-sequence impedance value is changed because of the presence of the series compensation. Hence if the distance relay trip setting is based on the positive-sequence impedance, the relay malfunctions. Therefore, this impedance is not sufficient for relaying.

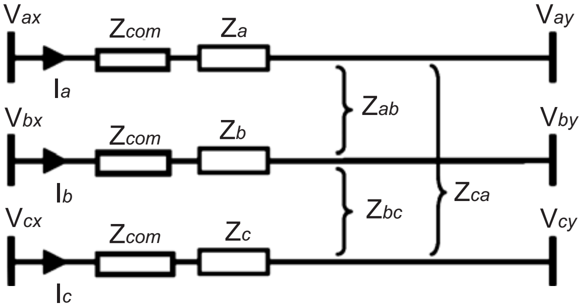


Figure 2: Series-compensated transmission line

3. COMPUTATION OF MUTUAL IMPEDANCE FOR DISTANCE RELAYING

The mutual impedance of the series-compensated line is calculated using (6). The zero-sequence and positive-sequence impedances should be computed to calculate mutual impedance as in [12]. For this purpose, a series-compensated transmission line is considered as shown in Fig. 3(*a*). The line to be protected is XY. The relay is located at the bus X. The measured voltage and current signals at the receiving end Y are available in the sending end X using synchronous measurements and high-speed communication between the two ends. For a single line to ground fault in the a – phase, the sequence circuits are shown in Fig. 3(*b*). In Fig. 3(*b*), the suffixes 0,1, 2 represents the zero, positive and negative-sequence components. Using Fig. 3(*b*), the following equations can be derived.

$$V_{0x} = I_{0x}(Z_{com} + Z_{0x}) = V_{0y} - I_{0y}Z_{0y} \tag{11}$$

$$V_{1x} - I_{1x}(Z_{com} + Z_{1x}) = V_{1y} - I_{1y}Z_{1y} \tag{12}$$

Z_{1y} is the positive-sequence impedance to fault which is measured by the relay R_y and is given by

$$Z_{1y} = \frac{V_{ay}}{I_{ay} + mI_{0y}} \tag{13}$$

where $m = (Z_{0y} - Z_{1y})/Z_{1y}$.

Hence $Z_{0y} = KZ_{1y}$,

where $K = m + 1$.

Hence (11), can be written as

$$V_{0x} - I_{0x}(Z_{com} + Z_{0x}) = V_{0y} - K_{0y}Z_{0y} \tag{14}$$

Now,

$$Z_{0x} + Z_{com} = \frac{V_{0x} - V_{0y} + KI_{0y}Z_{1y}}{I_{0x}} \tag{15}$$

From (12), we get

$$Z_{1x} + Z_{com} = \frac{V_{1x} - V_{1y} + I_{1y}Z_{1y}}{I_{1x}} \tag{16}$$

Subtracting (15) from (16) results

$$Z_{1x} - Z_{0x} = \frac{V_{1x} - V_{1y} + I_{1y}Z_{1y}}{I_{1x}} - \frac{V_{0x} - V_{0y} + KI_{0y}Z_{1y}}{I_{0x}} \tag{17}$$

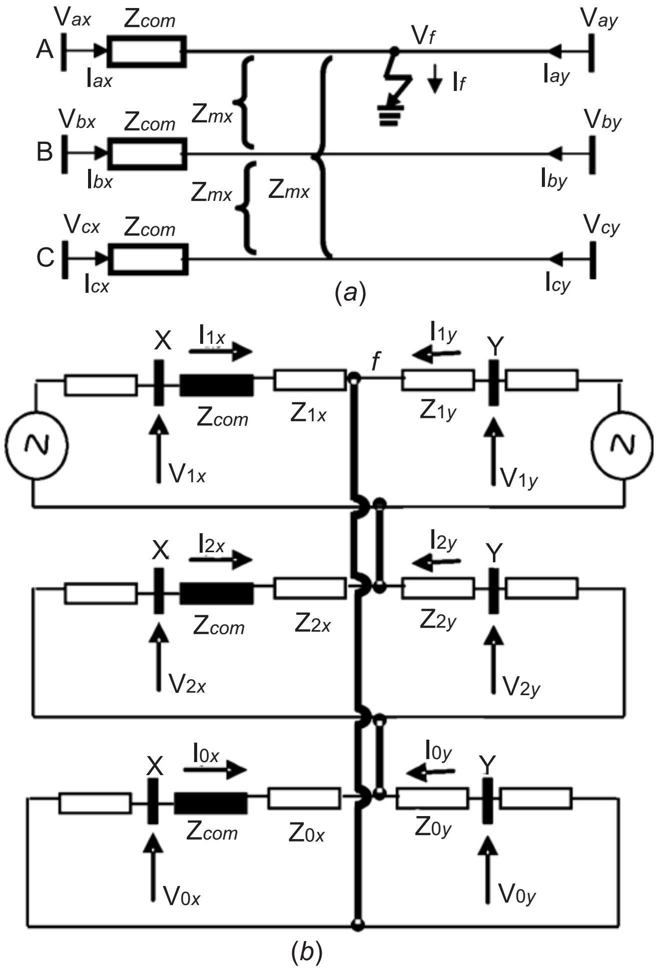


Figure 3: (*a*) Series-compensated transmission line (*b*) Sequence circuit for a single line-to-ground fault

Comparing (6) and (17) we get that the mutual impedance between phases of the series-compensated line XY is given by

$$Z_{mx} = \frac{V_{0x} - V_{0y} + I_{0y}Z_{1y}}{3I_{0x}} - \frac{V_{1x} - V_{1y} + KI_{1y}Z_{1y}}{3I_{1x}} \qquad (18)$$

4. PROPOSED SCHEME

The calculated mutual impedance is proportional to the distance between the relay and fault point. Hence, the concept of protective zone similar to the conventional distance protection can be used to the proposed protective scheme. Since the nature of mutual impedance is mainly inductive, the proposed relay characteristics are similar to the reactance relay. A typical relay characteristic is shown in Fig. 4. $X_{\text{pick-up}}$ is equal to 85% of mutual reactance of the main protected line giving first zone of protection. The second and third zones of protection can be achieved by setting the mutual reactance according to their reaches. The proposed scheme is able to protect the 85% of the line length instantaneously by setting the relay pick-up value $X_{\text{pick-up}}$ to 85% of mutual reactance of the line. The remaining 10 to 15% of the line length will be protected in zone 2 with a definite time delay.

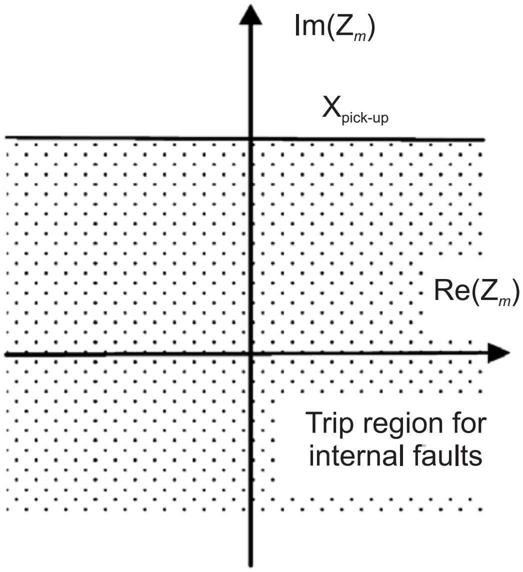


Figure 4: Characteristic of the proposed relay

Under normal operating conditions, the power system operates as a symmetrical three-phase system. The zero and negative-sequence networks are open circuited. Hence according to (17) and (18), the mutual impedance calculation is not possible during normal operating conditions. The mutual impedance is to be computed only during faults. For this purpose conventional fault detection methods can be applied. Similarly during three-phase faults and phase-to-phase faults, the zero-sequence network will not be available. Therefore the proposed scheme cannot be used under these conditions.

The proposed scheme is able to protect the transmission line against single line to ground faults and double line to ground faults. Since most of the faults are single line to ground fault, the proposed scheme can be used for practical cases. However, it is recommended to use the proposed scheme as a backup protection since it cannot be used against three phase and phase-to-phase faults. The proposed scheme is implemented for zone 1 protection and it can be easily designed for zones 2 and 3.

5. SIMULATION RESULTS

The simulated system is shown in Fig. 5. The test system data are given in Table 2. The test system consists of a voltage source at the sending and receiving end respectively. The proposed scheme is implemented in the relay R_x . The transmission line XY is assumed to have a length of 100 km. The degree of compensation is 40%. The series capacitor is protected by the MOV's against over voltages.

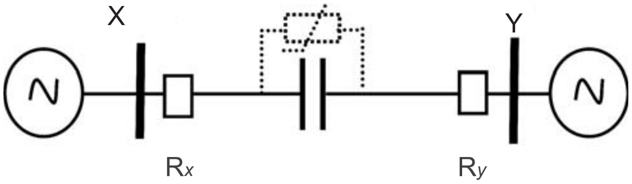


Figure 5: Simulated system

A. Conventional Distance Protection relay

To compare the performance of the protection scheme, the conventional distance protection relay is developed as per the method presented in [12]. The conventional distance relay model is shown in Fig.6. A numerical distance relay is developed that can process only the digital data. Hence, it is necessary to have an analog to digital conversion in the system. And also it is necessary to filter the harmonic components to allow only the fundamental components. This is carried out by the filtering block in each phase separately for current and voltage. In order to retain the information to perform the relaying function, the sampling rate must be at least four times the fundamental frequency (1256 rad/s). The quantizer is used to quantize a smooth signal into a stair-step output and a digital filter is used to filter out the decaying offset DC components. Then the magnitude and phase is plotted for each phase using discrete Fourier transform. The ratio of voltage to current *i.e.*, impedance is calculated based on the magnitude and phase of current and voltage of each phase which is obtained from the discrete Fourier transform.

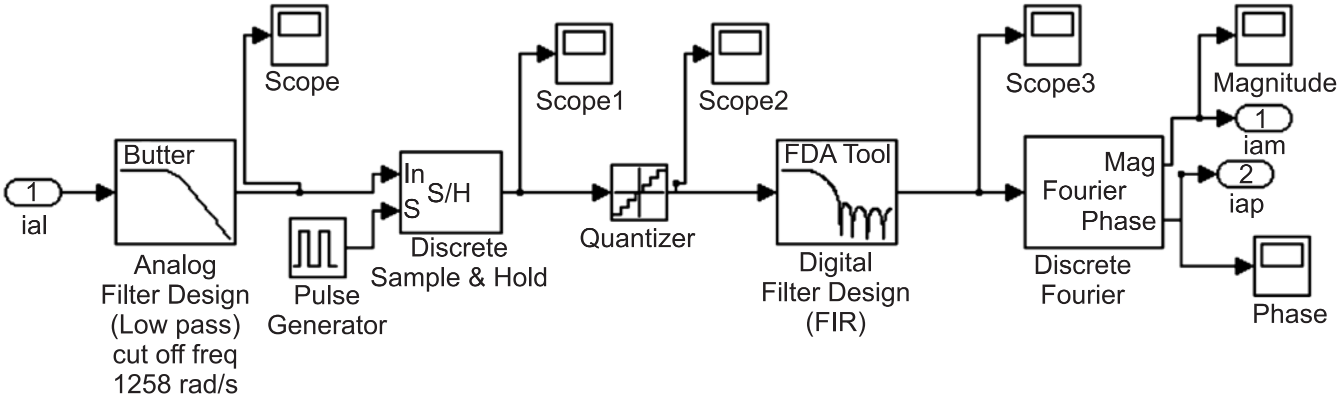


Figure 6: Distance relay model

B. Proposed Distance Protection Relay

Fig. 7 shows the SIMULINK model of the proposed distance protection relay for series-compensated transmission line. The voltage and current signals at both ends of the transmission line are measured. Then the mutual impedance is computed using (18). This computed mutual impedance is used as the parameter to trip the proposed distance protection relay. The proposed scheme with series compensation (SC) operates similarly to an uncompensated transmission line. This is because the mutual impedance computed is unaffected by series compensation.

A single-line-to-ground fault on phase *a* is applied at 10% (Internal fault) and 90% (External fault) of the line XY at $t = 0.4$ *s*, and $R_f = 1$ ohm. The three phase current waveforms are shown in Fig. 8 (*a*) & (*b*).

The performance of the conventional distance protection scheme and the proposed protection scheme is shown in Fig. 9 for a single-line-to-ground (SLG) fault on phase a at 10% of transmission line length with fault inception at t =0.4 s and R_f = 1ohm. The boundary for protection zone is a red circle in the conventional distance protection scheme and in proposed scheme it is the red line. When the transmission is uncompensated, both schemes operate correctly and detect the internal fault as shown in Fig. 9(a) and (b). In Fig. 9(c), for the series-compensated line, the distance relay may malfunction and fails to operate.

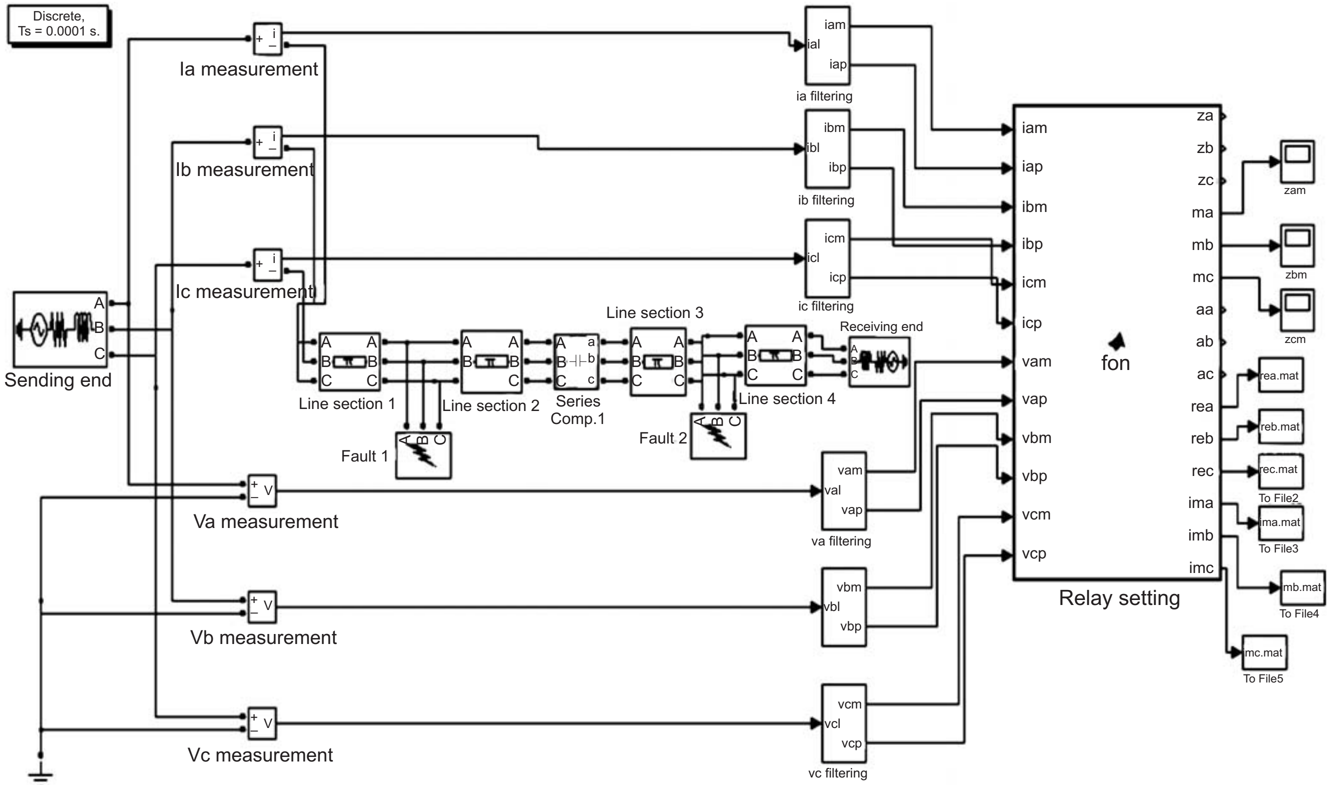
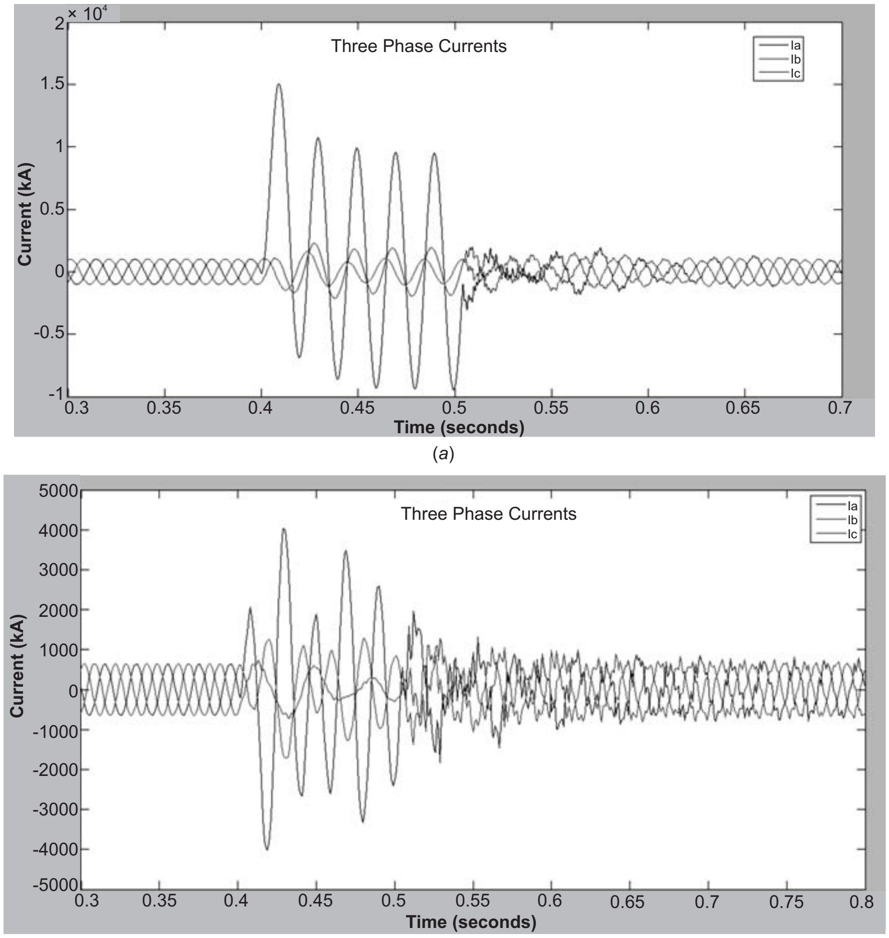


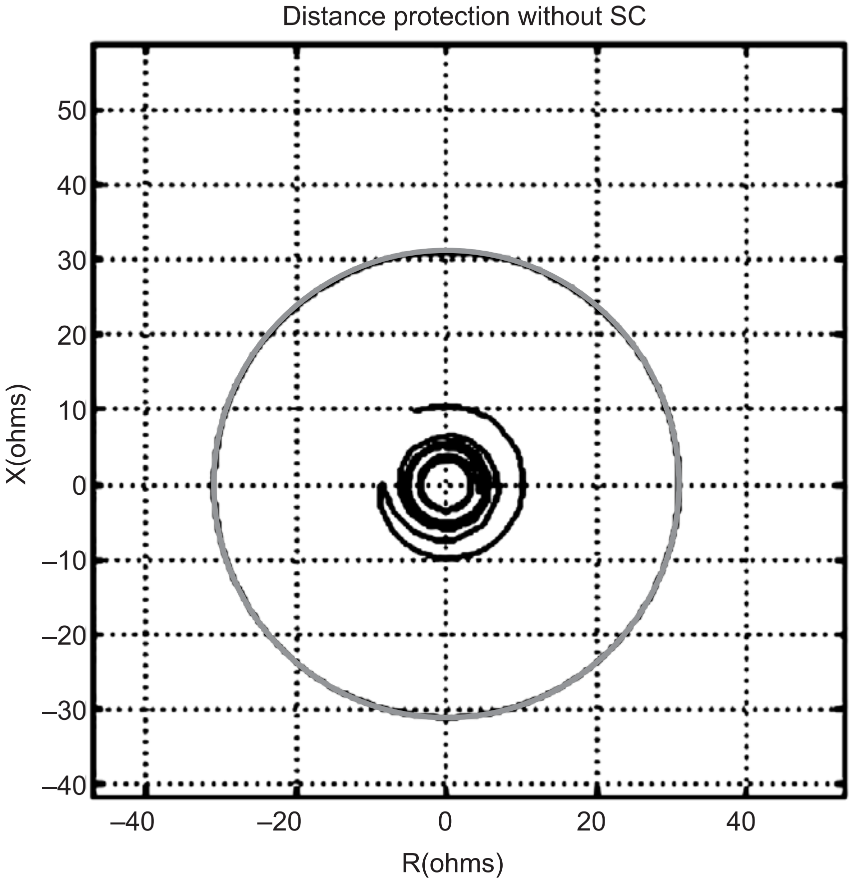
Fig. 7. SIMULINK model of the proposed distance relay for series-compensated transmission line



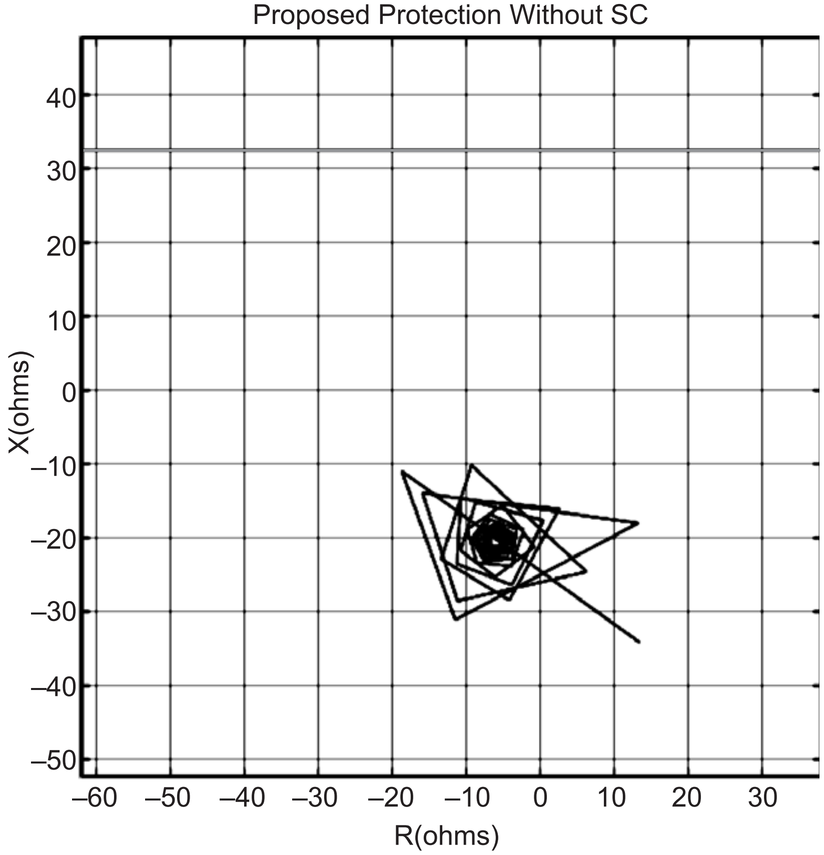
(*a*)

(*b*)

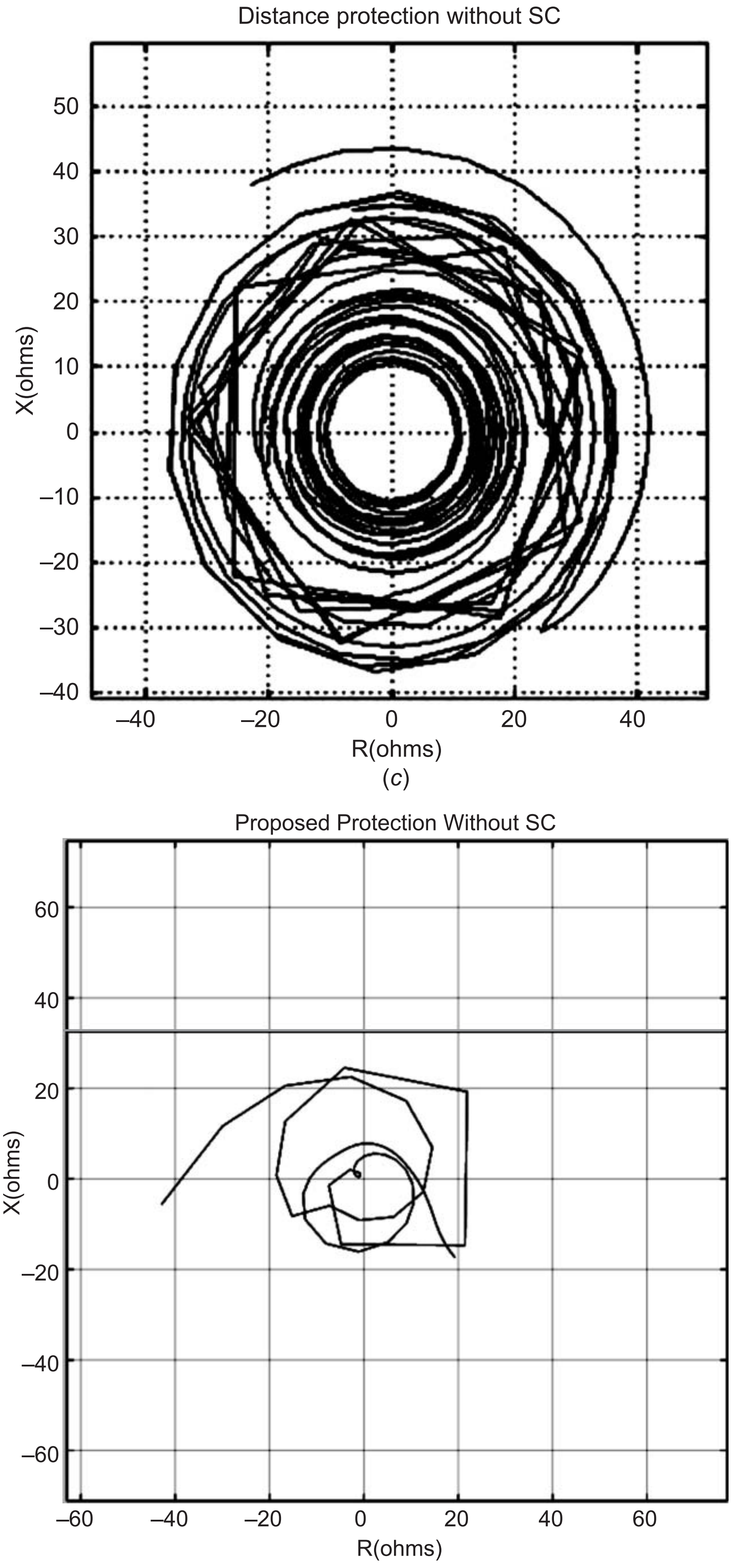
Figure 8: Three-phase current (*a*) Internal fault (*b*) External fault


Distance protection without SC
X(ohms)
50
40
30
20
10
0
–10
–20
–30
–40
–40
–20
0
20
40
R(ohms)

(*a*)


Proposed Protection Without SC
X(ohms)
40
30
20
10
0
–10
–20
–30
–40
–50
–60
–50
–40
–30
–20
–10
0
10
20
30
R(ohms)

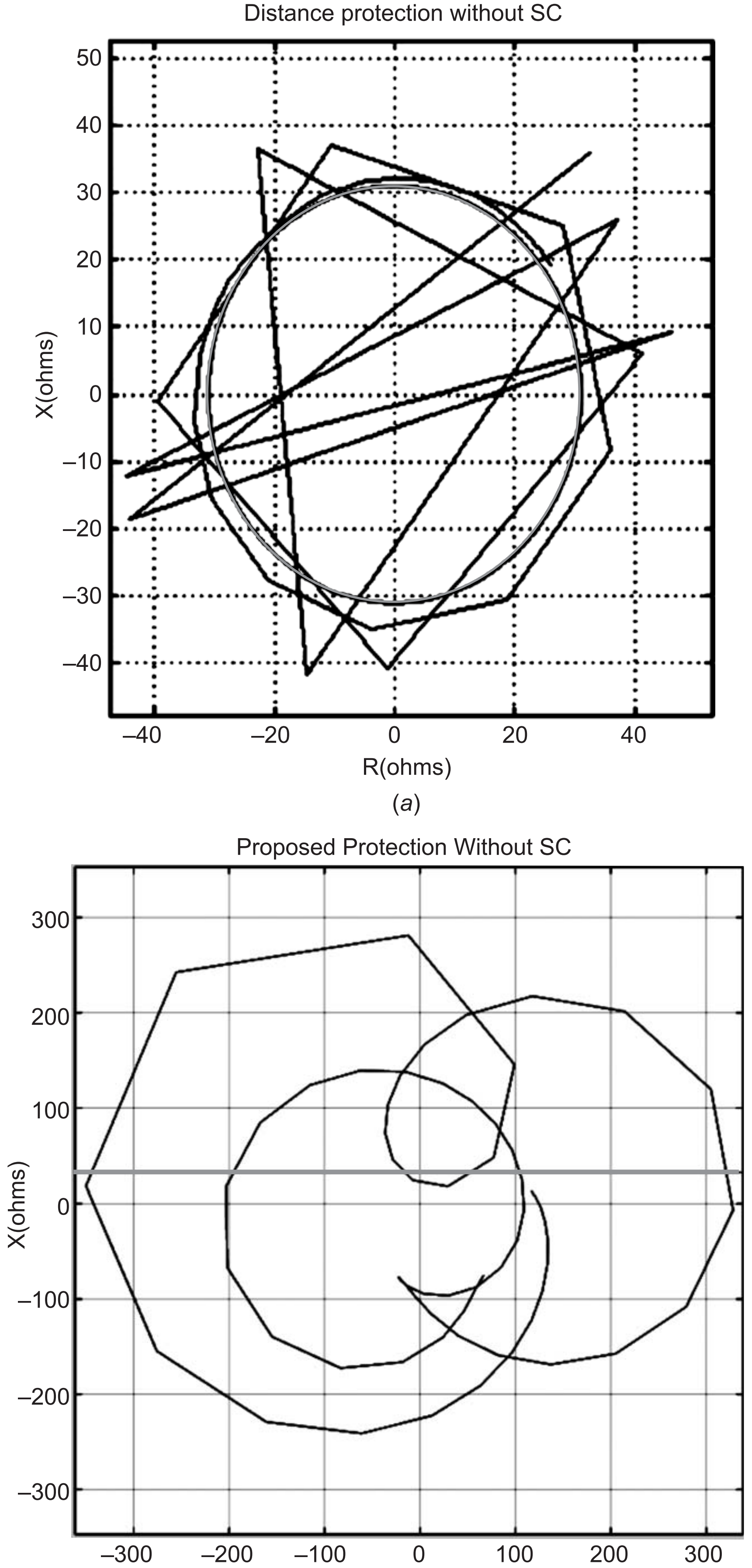
(*b*)



(*c*)

(*d*)

Figure 9: Simulation results for an internal SLG fault (*a*) Distance protection without SC (*b*) Proposed protection without SC (*c*) Distance protection with SC (*d*) Proposed protection with SC


Distance protection without SC
50
40
30
20
10
0
–10
–20
–30
–40
X(ohms)
–40
–20
0
20
40
R(ohms)
Proposed Protection Without SC
300
200
100
0
–100
–200
–300
X(ohms)
–300
–200
–100
0
100
200
300

(*a*)

(*b*)

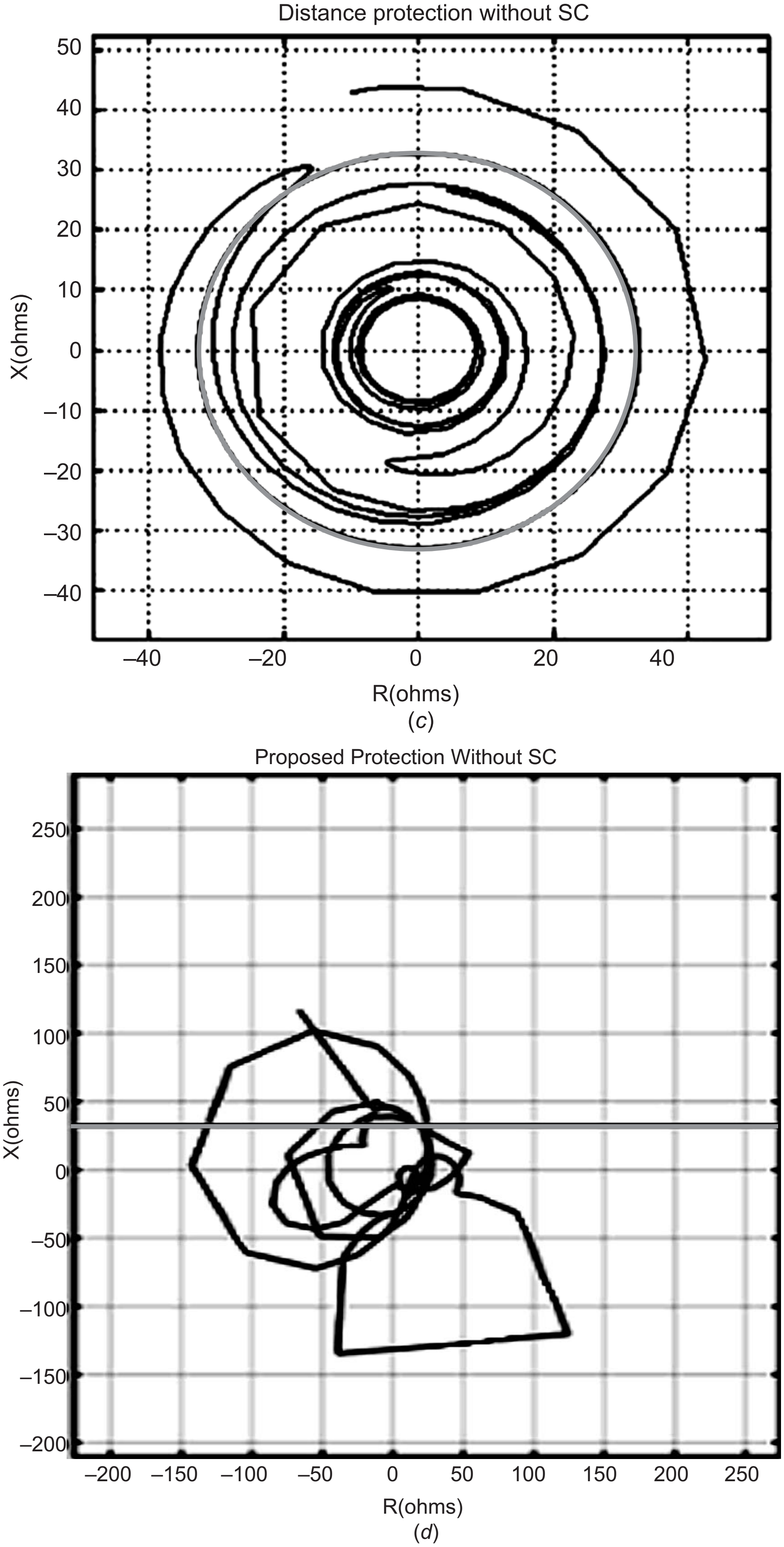
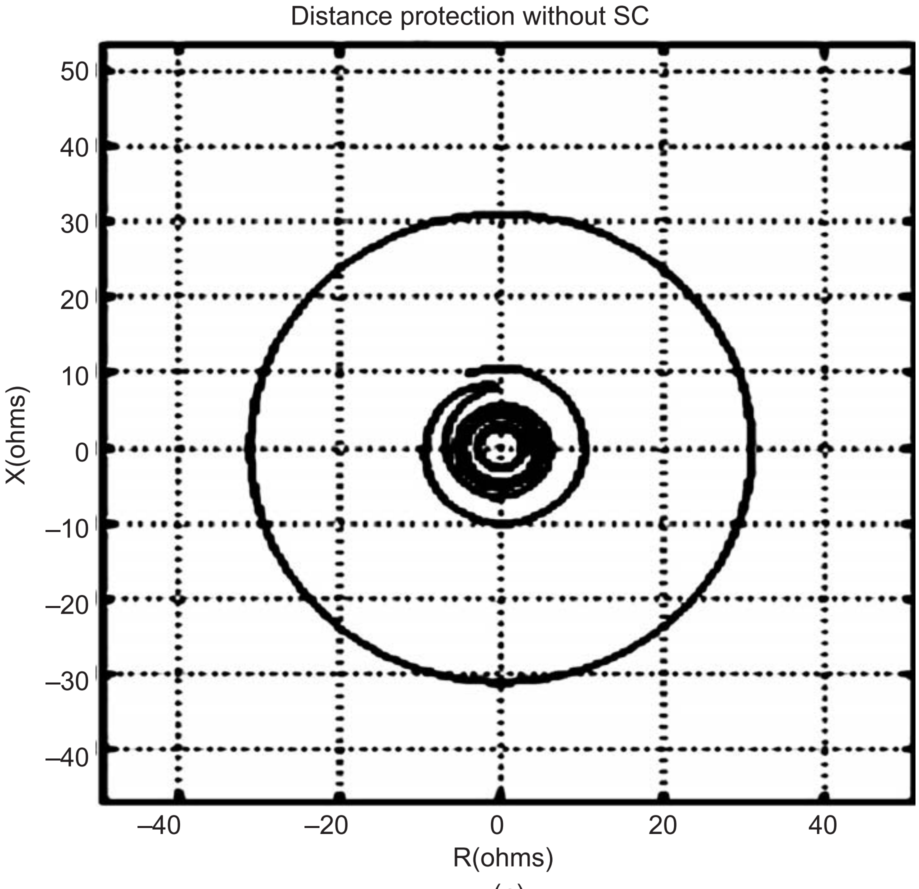
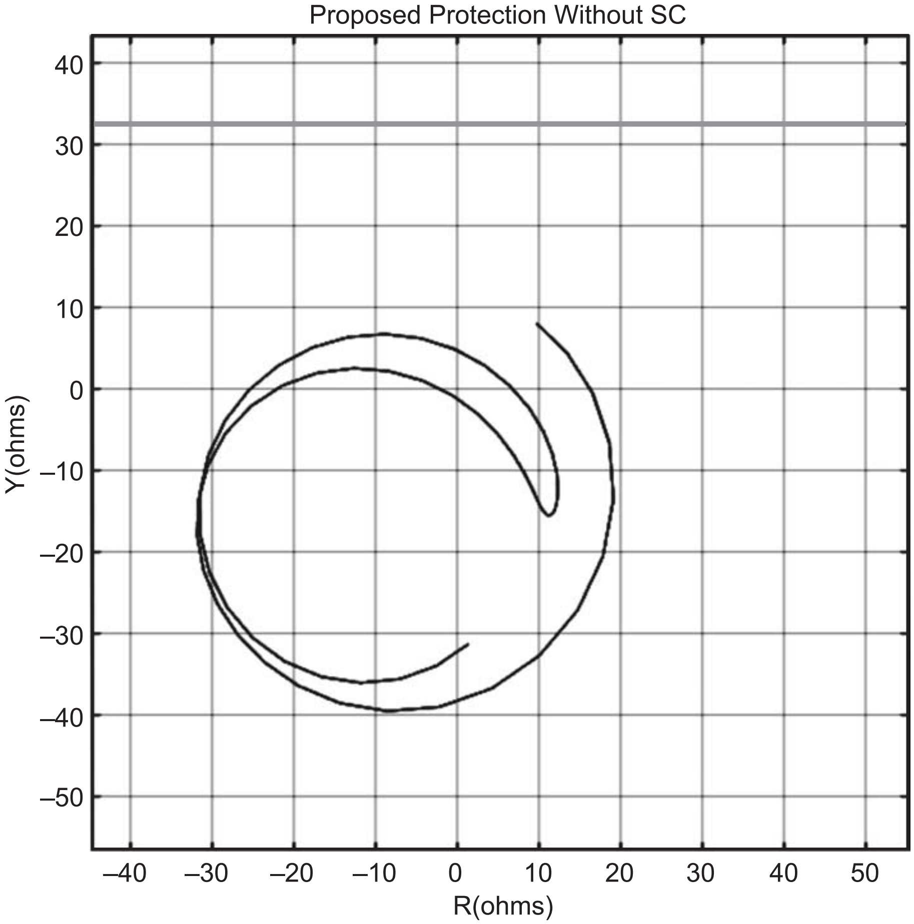


Figure 10: Simulation results for an external SLG fault (*a*) Distance protection without SC (*b*) Proposed protection without SC (c) Distance protection with SC (*d*) Proposed protection with SC


Distance protection without SC
50
40
30
20
10
0
–10
–20
–30
–40
X(ohms)
–40
–20
0
20
40
R(ohms)

(*a*)


Proposed Protection Without SC
40
30
20
10
0
–10
–20
–30
–40
–50
Y(ohms)
–40
–30
–20
–10
0
10
20
30
40
50
R(ohms)

(*b*)

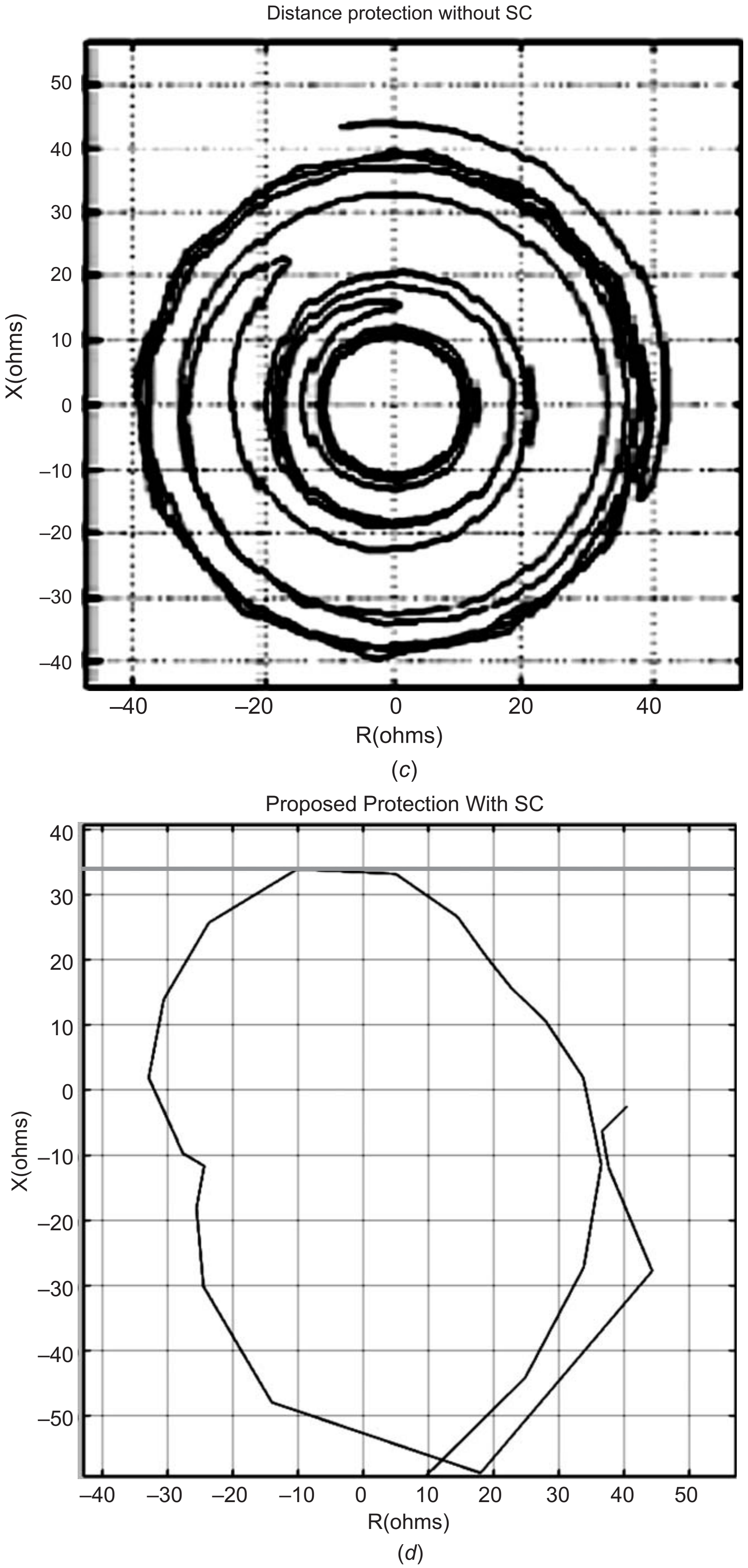
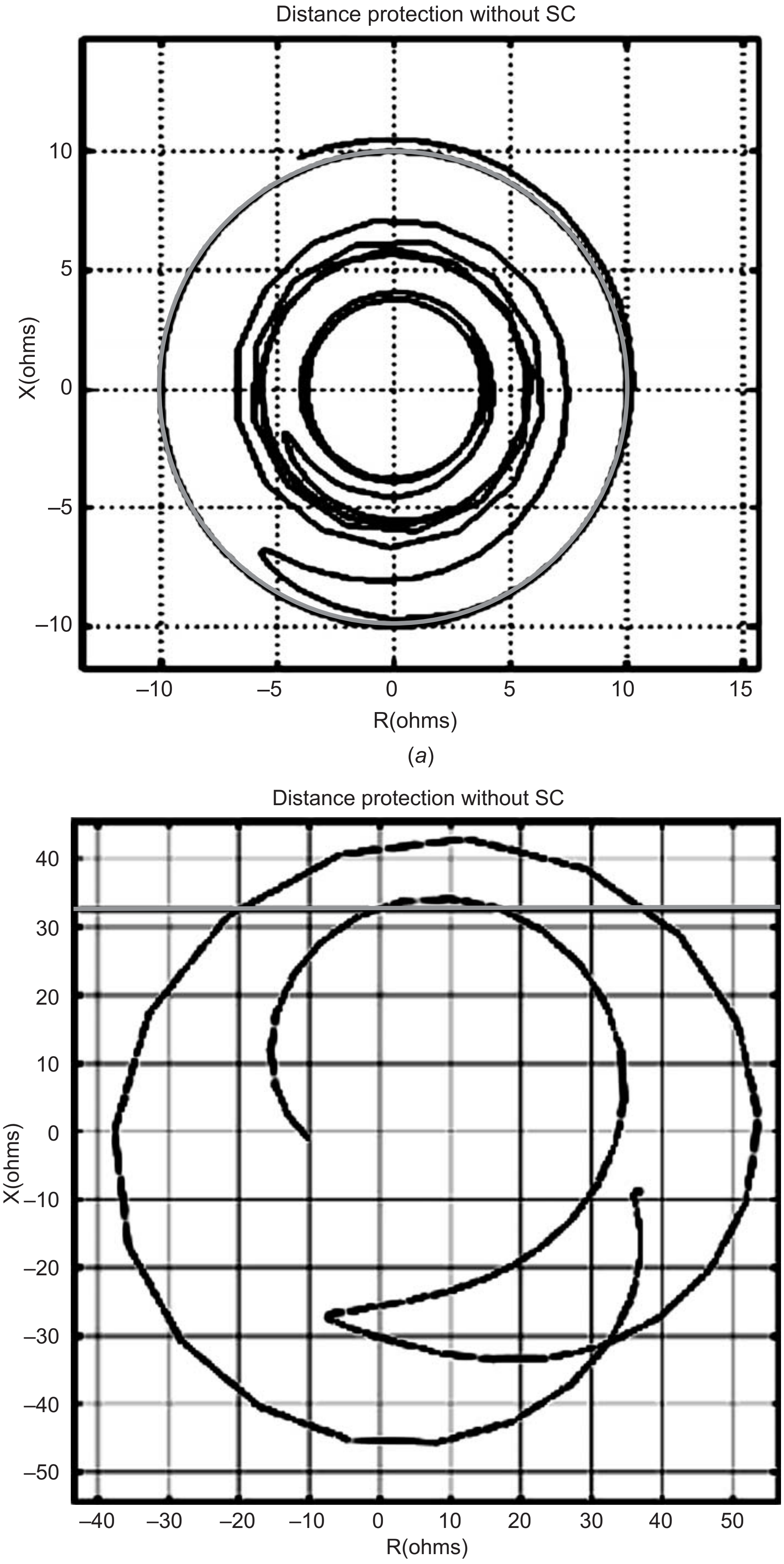
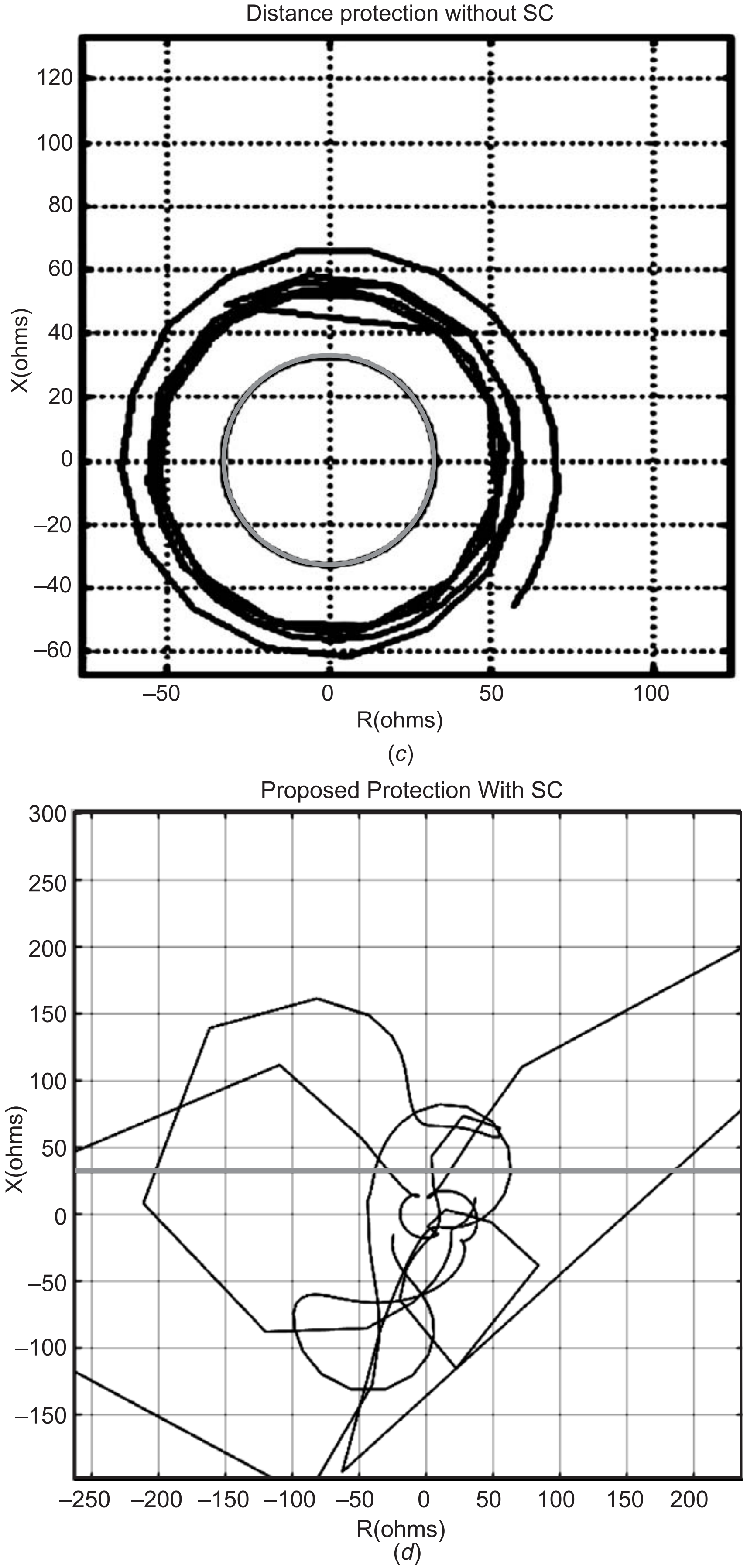


Figure 11: Simulation results for an internal DLG fault (*a*) Distance protection without SC (*b*) Proposed protection without SC (*c*) Distance protection with SC (d) Proposed protection with SC


Distance protection without SC
X(ohms)
R(ohms)
10
5
0
–5
–10
–10
–5
0
5
10
15
Distance protection without SC
X(ohms)
R(ohms)
40
30
20
10
0
–10
–20
–30
–40
–50
–40
–30
–20
–10
0
10
20
30
40
50

(*a*)

(*b*)



(*c*)

(*d*)

Figure 12: Simulation results for an external DLG fault (*a*) Distance protection without SC (*b*) Proposed protection without SC (*c*) Distance protection with SC (*d*) Proposed protection with SC

It is inferred from Fig. 9(*b*) and (*d*) that the proposed scheme does not fail to operate even during the presence of the series compensator. An external SLG fault at 90% of transmission line length with R_f = 10 ohms is applied on the *a* phase. From Fig. 10 (*a*) and (*b*) it is inferred that both protection schemes provide reliable performance for uncompensated line. Fig. 10(*b*) and (*d*) shows that the proposed scheme is not affected by series compensation.

Similarly a double-line-to-ground fault (DLG) is applied at $t = 0.4s$ with R_f = 10 ohms on phases *a*, *b* at 70km of transmission line. From Fig 11(*a*) and (*b*), it can be seen that the internal fault is detected by the both schemes. For series-compensated line, the proposed scheme performs well with the computed mutual impedance making the relay within the reach. An external DLG fault at 90% of transmission line length with R_f = 10 ohms is applied between *a* & *b* phases. From Fig. 12 (*a*) and (*b*) it is inferred both protection schemes provide reliable performance for uncompensated line. Fig. 12 (*b*) and (*d*) shows that the proposed scheme is not affected by series compensation.

The robustness of the proposed scheme is verified by various test cases by varying the system parameters like load angle (0-60°), fault resistance (0-50 ohms). Few of the test cases are shown in Table I. The obtained mutual impedance used for tripping the proposed distance protection relay is shown in the last column of Table 1. It is noted that by varying the system parameters like load angle and fault resistance, the performance of the proposed distance protection relay is unaffected. Similarly by changing the other parameters like degree of compensation, location of the series compensator at the beginning, middle, and both the ends of the line, the performance of the proposed scheme is unaffected. In all the cases, the proposed scheme performs well and satisfactory results are obtained.

Table 1

Performance of the Proposed Scheme in Different Conditions

Fault Type	*Fault Location*	R_f (Ω)	Δδ	Z_m (Ω)
ag	XY 10%	0	10	$-0.22 + j4.08$
ag	XY 10%	10	30	$0.3 + j5.23$
ag	XY 10%	50	10	$52.3 + j5.23$
ag	XY 70%	0	60	$5.61 + j20.32$
ag	XY 70%	10	30	$16.24 + j21.68$
abg	XY 10%	0	10	$-2.32 + j3.67$
abg	XY 10%	10	30	$0.4 + j6.55$
abg	XY 10%	50	10	$50.3 + j12.3$

It is inferred that the series compensation has no effect on the proposed scheme because the proposed scheme uses the mutual impedance between the fault point and the location of the relay. Mutual impedance doesn't get affected by the presence of metal oxide varistor. Since the proposed protection scheme can be used against the single-line-to-ground and double-line-to-ground faults alone, it can be used as a backup distance protection scheme.

6. CONCLUSION

In this paper, a distance protection scheme is proposed for series-compensated transmission lines. The main requirement for this scheme is that the conventional distance relay fails to operate for series-compensated transmission lines. The proposed protection scheme uses the mutual impedance between phases, instead of the positive-sequence impedance, for protection against the single-line-to-ground and double-line-to-ground faults. Therefore, it can be used as backup protection. The proposed protection scheme is verified for single-line-to-ground and double-line-to-ground fault with computer simulations using MATLAB/ SIMULINK. The obtained results indicate that the proposed distance protection scheme is accurate and reliable for the protection of series-compensated transmission line.

Table 2

Simulated System Data

Parameter	*Value*
System Voltage	500 kV
System Frequency	50 Hz
Lines Positive Seq. Series Impedance	$0.0185 + j0.3766\Omega$/km
Lines Positive Seq. Capacitive Reactance	0.2279 MΩ -km
Lines Zero Seq. Series Impedance	$0.3618 + j1.2277\Omega$/km
Lines Zero Seq. Capacitive Reactance	0.34513 MΩ-km
Sources Positive Seq. Impedance	$1.43 + j16.21\ \Omega$
Sources Zero Seq. Impedance	$3.068 + j28.746\ \Omega$
MOV Reference current	10 kA
MOV Reference Voltage	338 kV

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