A New Digital Distance Relaying Scheme for Series-Compensated Double-Circuit Line During Open Conductor and Ground Fault

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***Abstract*—This paper presents a new digital distance relaying scheme which takes care of a simultaneous open conductor and ground fault occurring coincidently on the same phase at the same point on a series-compensated double-circuit line. The effect of series compensation, mutual zero-sequence coupling, remote infeed/outfeed, and fault resistance on the relay reach has been considered by the proposed scheme. The conventional digital distance relay having facility of series compensation fails to provide adequate protection in the presence of such conditions. The proposed scheme is based on the derivation of the compensated values of impedance using symmetrical component theory. To validate the proposed scheme, numerous computer simulations have been carried out using MATLAB/SIMULINK software on an existing 400-kV, 300-km-long series-compensated double-circuit transmission line. At the end, a comparative evaluation between the proposed scheme and the conventional scheme having a facility of series compensation is carried out. Simulation results demonstrate the effectiveness of the proposed scheme since the percentage error is within $\pm 4.19\%$.**

***Index Terms*—Digital distance protection, mutual coupling, open conductor and ground fault, series-compensated double-circuit line.**

I. INTRODUCTION

INCREASED transmittable power, improved system stability, reduced transmission losses, enhanced voltage control, increased loading capacity, and more flexible power-flow control are the major technical reasons behind installing series capacitors (SCs) on long transmission lines. However, SCs and their protective devices (typically metal–oxide varistors (MOVs) and/or air gaps), create several problems for the conventional protection schemes [1].

Further, the occurrence of simultaneous faults on series-compensated double-circuit lines can initiate serious problems of power system instability. Simultaneous faults, such as flashover faults to ground, cross-country faults, and open conductor and ground faults are those faults which occur either at the same or different locations on a double-circuit transmission line [2]. Among such types of faults, simultaneous open conductor and ground fault creates serious power system disturbance that can lead to incorrect tripping of the conventional digital distance relay [2], [3]. This type of fault may occur on an overhead line due to a phase conductor breaking at a point near the tower. The broken conductor on one side of the tower is being held by the suspension insulators and that on the other side has fallen to ground. Performance of the conventional digital distance relay is also affected by the presence of zero-sequence mutual coupling impedance between double-circuit lines. The situation could become even worse when the impact of fault resistance is considered. In certain conditions, that may cause the protected line's middle section to lose the first zone coverage altogether [4].

Spoor and his colleagues [5] suggested the use of carrier-aided permissive over-reach transfer tripping scheme or a carrier blocking scheme to detect intercircuit faults. However, this scheme requires a communication channel which increases cost and reduces reliability in case of failure of link. Agrasar and his co-workers [6] discussed the effect of intercircuit faults on the conventional distance relay for double-circuit lines. However, they have not considered the effect of simultaneous open conductor and ground fault on series compensated double-circuit lines. Saha and his co-workers [7] proposed an algorithm to protect series-compensated transmission lines against various types of phase and ground faults. But they have not considered the impact of simultaneous faults. Further, they have not analyzed the effect of mutual zero-sequence impedance and fault resistance.

Several researchers have carried out ground fault analysis for single-circuit series-compensated transmission lines [8]–[10]. Few researchers have analyzed the intercircuit faults on double-circuit lines without considering the effect of series compensation [11], [12]. Some of the researchers have presented a solution to the problems of mutual coupling present between double-circuit lines along with the effect of fault resistance [13], [14]. But they have not considered the effect of series compensation.

Hence, none of the previously published papers have given the complete solution to protect series-compensated double-circuit lines during simultaneous open conductor and ground fault considering the effects of other abnormalities, such as mutual coupling, remote infeed/outfeed, and fault resistance. Therefore, there is a need to develop a new digital distance relaying scheme that provides accurate protection to series-compensated double-circuit lines during a simultaneous open conductor and ground fault without using remote-end data or communication link. This paper attempts to describe that facet of the problem.

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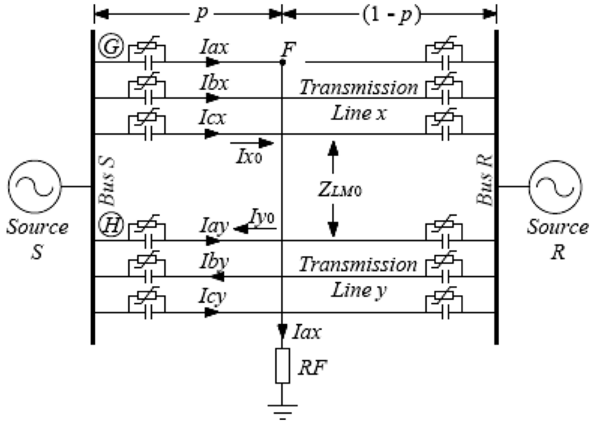


Fig. 1. Model of a simultaneous open conductor and ground fault.

Several aspects, such as the effect of mutual zero-sequence coupling, remote infeed/outfeed, and fault resistance during a simultaneous open conductor and ground fault have been considered by the proposed scheme.

II. PROTECTION ISSUES OF SERIES-COMPENSATED DOUBLE-CIRCUIT LINES DURING SIMULTANEOUS OPEN CONDUCTOR AND GROUND FAULT

A. Series-Compensated Double-Circuit Line Network

Fig. 1 shows a model of a series-compensated double-circuit line with half series compensation provided at each end of both transmission lines. X_G and X_H are the values of capacitive reactance of SC located at G and H, respectively. X_C is the value of capacitive reactance of SC with respect to full series compensation provided to each transmission line. Therefore, $X_G = X_H = X_C/2$. Further, $V_{G120}, I_{G120}, Z_{G120}$, and $V_{H120}, I_{H120}, Z_{H120}$ are the sequence (positive, negative, and zero) components of voltages, currents, and impedances of the SC/MOV combination located at G and H, respectively.

A simultaneous open conductor and ground fault has occurred on line x at fault location F, which is at p percentage from the relaying point G. During a simultaneous open conductor and ground fault, phase A of line x on Bus S side has broken and fallen to ground whereas phase A of line x on Bus R side has broken but is being held by the suspension insulators. In this situation, because of the presence of mutual zero-sequence impedance between double-circuit lines, the ground unit of the conventional digital distance relay having a facility of series compensation at G may underreach/overreach. Conversely, the conventional digital distance relay having a facility of series compensation at Bus R completely fails to detect an open-circuit fault [2].

B. Linearized Equivalent Model of SC/MOV

Fig. 2 shows a model of SC/MOV developed by Goldsworthy [15] to analyze a simultaneous open conductor and ground fault on a series-compensated double-circuit line. In Fig. 2, $i_{\rm pu}$ represents the per-unit value of the fault current (i) passing through SC/MOV with respect to the capacitor protective-level current $(i_{\rm ref})$. X_C represents the capacitive reactance of the capacitor bank.

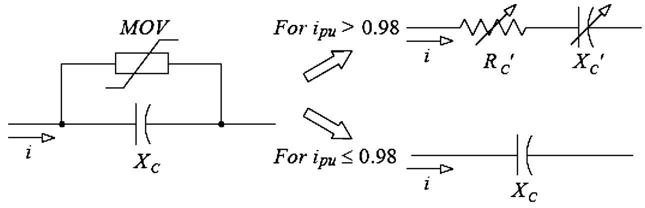


Fig. 2. Goldsworthy's model of the SC/MOV combination.

As shown in Fig. 2, for $i_{\rm pu} > 0.98$, the SC/MOV parallel combination is approximated by linear impedance consisting of resistance R'_C and reactance X'_C connected in series. Their values are expressed by (1) and (2) as follows [15]:

$$\begin{aligned} R'_C = {} & X_C(0.0745 + 0.49e^{-0.243 i_{\rm pu}} - 35e^{-5 i_{\rm pu}} \\ & - 0.6e^{-1.4 i_{\rm pu}}) \end{aligned} \tag{1}$$

$$X'_C = X_C(0.1010 - 0.005749 i_{\rm pu} + 2.088e^{-0.8566 i_{\rm pu}}). \tag{2}$$

During a simultaneous open conductor and ground fault, if the solid ground fault will occur, then a very high value of fault current $(i_{\rm pu} > 0.98)$ will pass through the capacitor bank connected to the grounded phase A of line x at G. Therefore, the MOV will start conducting a portion of fault current. Hence, Goldsworthy's equations can be applied during this condition to determine equivalent resistance R'_C and equivalent reactance X'_C of SC/MOV (refer to Fig. 2).

But if high-resistance ground fault will occur, then a low value of fault current $(i_{\rm pu} < 0.98)$ may pass through the capacitor bank connected to the faulted phase A at G. As a result, as shown in Fig. 2, the value of SC will not change.

Furthermore, for both of the aforementioned situations, the magnitude of currents passing through the remaining healthy phases (phases B and C) of line x will always be less than rated current of the capacitor bank (i.e., $i_{pu} < 0.98$) and hence, twhe value of SC connected in healthy phases will not change.

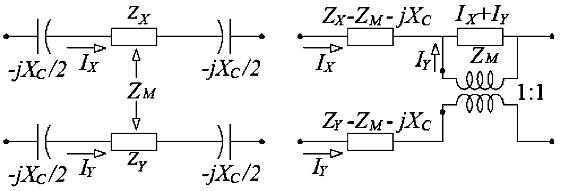
C. Mutual Coupling and Fault Resistance

In case of series compensated double-circuit lines, the series capacitor compensates the zero sequence self-impedance of the two lines. But the zero sequence mutual impedance between series compensated lines remains the same as that of uncompensated lines. Therefore, the relative effect of series compensation becomes more pronounced than that observed in the uncompensated line [1].

Fig. 3 shows the effect of zero sequence mutual coupling on series compensated double-circuit line. It is clear from Fig. 3 that the reactance of series capacitor affects only to the self-impedance of two lines whereas mutual impedance remains unchanged with reference to the uncompensated case [1].

D. A Simultaneous Open Conductor and Ground Fault

A simultaneous open conductor and ground fault creates voltage and current unbalance in the SC/MOV parallel combination. In this situation, symmetrical components of voltages and impedances of SC/MOV parallel combination are expressed by (3) and (4) as shown at the bottom of the next page [16], where Z_A, Z_B, and Z_C are Goldsworthy's equivalent



(a) (b)

Fig. 3. Equivalent circuit of zero-sequence mutual coupling. (a) Mutually coupled double-circuit lines; (b) equivalent using 1:1 transformer.

impedances of SC/MOV combination connected in phases A, B, and C, respectively and "a" is 120° phase-shift operator.

During a simultaneous open conductor and ground fault, the fault currents are not equally distributed among the three phases of transmission line. Therefore, Goldsworthy's equivalent impedances of SC/MOV connected in the three phases are not equal as they depend on the values of fault current [15].

III. Analysis of Simultaneous Open Conductor and Ground Fault

For all analysis, positive and negative sequence impedances (Z_{L1} and Z_{L2}) of double-circuit lines are assumed to be equal. Z_{LM0} is the zero-sequence mutual coupling impedance present between the two lines. E_{ax} and I_{ax} are the voltage and current of phase A of line x measured at the relaying point G, respectively. Further, E_{x120}, I_{x120} and E_{y120}, I_{y120} are the sequence (positive, negative, and zero) components of voltages and currents of line x and line y measured at the relaying points G and H, respectively. In the equations throughout the entire discussion, subscripts 1, 2, and 0 represent positive-, negative-, and zero-sequence components, respectively.

It is to be noted that during a simultaneous open conductor and ground fault, the Bus S side conductor has been assumed to be broken and fallen to the ground. Since a ground path is involved in this situation, the fault resistance (R_F) plays a key role in the measurement of apparent impedance. Hence, different values of R_F (25, 50, 100, and 150 Ω) have been considered in the fault analysis. The ground units of the conventional digital distance relay located at G, having facility of series compensation, measures incorrect value of impedance.

On the contrary, the other end of the conductor (Bus R side) has been assumed to be hanged on the tower without touching the ground. The conventional phase and ground distance relays located at Bus R completely fail to detect this open conductor fault. To solve this problem of conventional digital distance relays, a new scheme has been proposed in this paper. A detailed analysis of the conventional digital distance relaying scheme having a facility of series compensation and the proposed scheme are given in the following subsections.

A. Impedance Measured by the Conventional Scheme

As shown in Fig. 1, during simultaneous open conductor and ground fault, the ground unit of the conventional digital distance relay at G sees this fault as a single-line-to-ground fault and measures apparent impedance (Z_{app}) as follows:

$$Z_{app} = \frac{E_{\text{ax}} - V_{\text{SC}}}{I_{ax} + K_0 I_{x0} + K_M I_{y0}} \tag{5}$$

where

V_{SC} voltage drop across series-capacitor bank

$$K_0 = \frac{Z_{L0} - Z_{L1}}{Z_{L1}} \quad \text{and} \quad K_M = \frac{Z_{LM0}}{Z_{L1}}.$$

On the other hand, bus R side conventional (phase and ground) digital distance relays completely fail to detect this type of fault.

B. Impedance Measured by the Proposed Scheme

During a simultaneous open conductor and ground fault, the open conductor fault can be sensed by checking the following two conditions:

1) The positive-sequence current divides between the negative-sequence and zero-sequence currents, that is$I_1 = -(I_2 + I_0)$ [17].
2) The phase current of the opened phase is zero.

Hence, in this paper, the open conductor fault is not discussed further.

The main objective of this paper is to measure the correct value of impedance of the grounded section of transmission line. In this situation, the magnitude of fault current passing through the SC/MOV parallel combination connected in phase A at G depends on the value of fault resistance. Based on that value of fault current, an equivalent impedance of SC/MOV located at G and connected in phase A is given by

$$Z_{GA} = (R'_G - jX'_G) \quad \text{for} \quad i_{\text{pu}} > 0.98 \tag{6}$$

$$Z_{GA} = -jX_G \quad \text{for} \quad i_{\text{pu}} \leq 0.98. \tag{7}$$

Furthermore, during the same situation, the magnitude of fault current passing through other healthy phases on line x (phases B and C) is always less than the SC/MOV reference current setting $(i_{pu} < 0.98)$. Hence, the impedances of SC/MOV connected in phases B and C of line x are given by

$$Z_{GB} = Z_{GC} = -jX_G. \tag{8}$$

$$V_{012} = Z_{012} I_{012} \tag{3}$$

$$Z_{012} = \frac{1}{3}\begin{bmatrix} Z_A + Z_B + Z_C & Z_A + a^2 Z_B + a Z_C & Z_A + a Z_B + a^2 Z_C \\ Z_A + a Z_B + a^2 Z_C & Z_A + Z_B + Z_C & Z_A + a^2 Z_B + a Z_C \\ Z_A + a^2 Z_B + a Z_C & Z_A + a Z_B + a^2 Z_C & Z_A + Z_B + Z_C \end{bmatrix} \tag{4}$$

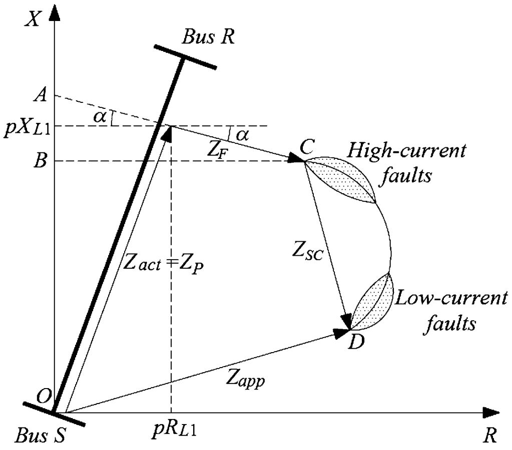


Fig. 4. Impedance seen at the relaying point G during a simultaneous open conductor and ground fault.

The positive-, negative—, and zero-sequence components of impedances of SC/MOV (Z_{G120}) at G are determined by substituting the values of Z_{GA}, Z_{GB}, and Z_{GC} in (4). Hence, the sequence (positive, negative, and zero) components of voltages of SC/MOV (V_{G120}) at G are determined by

$$V_{G120} = Z_{G120} I_{G120}. \tag{9}$$

Using (6)–(9), the voltage V_{GA} appeared across SC/MOV connected in phase A and is located at G and given by

$$V_{\mathrm{GA}} = V_{G1} + V_{G2} + V_{G0} = -jX_G I_{ax} \text{ for } i_{\mathrm{pu}} > 0.98 \tag{10}$$

$$V_{GA} = V_{G1} + V_{G2} + V_{G0} = (R'_G - jX'_G) I_{ax} \text{ for } i_{\mathrm{pu}} \leq 0.98. \tag{11}$$

Referring to Fig. 1, during a simultaneous open conductor and ground fault, symmetrical components of voltages (E_{x1}, E_{x2}, and E_{x0}) at relaying point G on line x are expressed by

$$E_{x1} = V_{G1} + pZ_{L1} I_{x1} + R_F I_{x1} \tag{12}$$

$$E_{x2} = V_{G2} + pZ_{L1} I_{x2} + R_F I_{x2} \tag{13}$$

$$E_{x0} = V_{G0} + pZ_{L0} I_{x0} + R_F I_{x0} + pZ_{LM0} I_{y0}. \tag{14}$$

Now, voltage E_{ax} at the relaying point G on line x can be determined by adding (12)–(14) as follows:

$$E_{\mathrm{ax}} = V_{GA} + pZ_{L1} I_{\mathrm{ax}} + p(Z_{L0} - Z_{L1}) I_{x0} + pZ_{LM0} I_{y0} + R_F I_{\mathrm{ax}}. \tag{15}$$

Therefore, the actual value of impedance (Z_{act}) that should be measured by the proposed scheme is given by

$$Z_{\mathrm{act}} = pZ_{L1} = Z_P = \frac{1}{I_K} [E_{\mathrm{ax}} - V_{GA} - R_F I_{\mathrm{ax}}] \tag{16}$$

where $I_K = I_{\mathrm{ax}} + K_0 I_{x0} + K_M I_{y0}$.

A simultaneous open conductor and ground fault is reflected as a single-line-to-ground fault at G. The apparent impedance (Z_{app}) measured by the conventional ground distance relay at G is shown in Fig. 4 [16]. Hence, the actual impedance (Z_{act}) that should be measured by the proposed scheme is given by

$$Z_{\mathrm{act}} = Z_P = Z_{\mathrm{app}} - Z_{\mathrm{SC}} - Z_F. \tag{17}$$

Comparing (16) and (17), the impedances Z_{app}, Z_{SC}, and Z_F can be defined as

$$Z_{\mathrm{app}} = \frac{E_{\mathrm{ax}}}{I_K}, \quad Z_{\mathrm{SC}} = \frac{V_{GA}}{I_K} \quad \text{and} \quad Z_F = R_F \times \frac{I_{ax}}{I_K}. \tag{18}$$

Now, in order to obtain Z_{act}, impedance Z_{SC} (determined in (18)) is subtracted from Z_{app}. Afterwards, vector Z_F is extended up to point A on the reactance axis (Fig. 4). Now OA is determined by

$$OA = OB + (BC \times \tan \alpha) \tag{19}$$

where the argument α is the angle between I_{ax} and I_K.

Hence, Z_{act} is determined at the intersection point of two straight lines $C - A$ and $O - Z$. Here, $O - Z$ represents the impedance vector of line x. Now, assuming R and X as resistance $(\Omega/)$km) and reactance (Ω/km) of line x, the impedance of the faulted portion of line x is given by [18]

$$pR_{L1} = \frac{OA}{\left(\frac{X}{R}\right) - \left(\frac{OB-OA}{BC}\right)} \tag{20}$$

$$pX_{L1} = \frac{\mathrm{X}}{\mathrm{R}} \times \frac{OA}{\left(\frac{X}{R}\right) - \left(\frac{OB-OA}{BC}\right)}. \tag{21}$$

IV. Results and Discussions

In this section, a simultaneous open conductor and ground fault on a 400-kV, 300-km-long series-compensated double-circuit line has been simulated considering wide variations in fault location (0% to 80% in steps of 10%), different levels of series compensation (30%, 50%, and 70%), different values of zero-sequence mutual coupling impedance (50%, 60%, and 70% of zero-sequence impedance of the line), different values of the power transfer angle (+15°, 0°, and −15°) and different values of fault resistance (25, 50, 100, and 150 Ω). The system and line parameters are given in Tables VII–IX. Throughout the entire discussion, Z_{app} and Z_P represent impedances measured by the conventional ground distance relay and the proposed scheme, respectively. R_{app} and X_{app} represent the resistive part and reactive part of fault impedance measured by the conventional scheme, respectively. R_P and X_P represent the resistive part and reactive part of fault impedance measured by the proposed scheme, respectively. R_{act} and X_{act} represent the actual values of resistive part and reactive part of the fault impedance of line x, respectively. δ and R_F represent the power transfer angle between two buses (S and R) and fault resistance present in the faulted path, respectively. K_C represents the level of series compensation (in percent) provided to each line. It is defined as the ratio of capacitive reactance of SC (X_C) connected to the line to the inductive reactance (X) of the complete section of the line. $\varepsilon_{\mathrm{Rapp}}$ and $\varepsilon_{\mathrm{Xapp}}$ indicate the percentage error in the measurement of resistive part and reactive part of the fault impedance given by the conventional scheme, respectively. ε_{RP} and ε_{XP} indicate the percentage error in the measurement of resistive part

TABLE I
EFFECT OF CHANGE IN p AND δ ON RESISTANCE AND REACTANCE MEASUREMENT

p (%)	R_{act} (Ω)	X_{act} (Ω)	$\delta = +15^0$				$\delta = -15^0$			
			R_P (Ω)	ε_{RP} (%)	X_P (Ω)	ε_{XP} (%)	R_P (Ω)	ε_{RP} (%)	X_P (Ω)	ε_{XP} (%)
0	0	0	0.1	-	1.06	-	0.11	-	1.18	-
10	0.994	10.27	1.04	4.16	10.7	4.19	1.02	2.65	10.51	2.34
20	1.987	20.54	2.05	3.15	21.16	3.02	1.99	0.13	20.52	-0.10
30	2.981	30.81	3.03	1.64	31.33	1.69	2.93	-1.71	30.26	-1.79
40	3.975	41.08	4.02	1.14	41.5	1.02	3.87	-2.64	40.05	-2.51
50	4.969	51.35	5.01	0.84	51.76	0.80	4.83	-2.79	49.93	-2.77
60	5.962	61.62	6.02	0.97	62.19	0.93	5.8	-2.72	59.95	-2.71
70	6.956	71.89	7.04	1.21	72.73	1.17	6.75	-2.96	69.73	-3.00
80	7.950	82.16	7.99	0.51	82.53	0.45	7.67	-3.52	79.31	-3.47

and reactive part of the fault impedance given by the proposed scheme, respectively. These errors are defined as

$$\varepsilon_{\text{Rapp}} = \frac{R_{\text{app}} - R_{\text{act}}}{R_{\text{act}}} \times 100\%$$

$$\varepsilon_{\text{Xapp}} = \frac{X_{app} - X_{\text{act}}}{X_{\text{act}}} \times 100\% \qquad (22)$$

$$\varepsilon_{RP} = \frac{R_P - R_{\text{act}}}{R_{\text{act}}} \times 100\%$$

$$\varepsilon_{XP} = \frac{X_P - X_{\text{act}}}{X_{\text{act}}} \times 100\%. \qquad (23)$$

The simulation results are discussed in the next subsections.

A. Change in Fault Location and Power Transfer Angle

Table I represents the performance of the proposed scheme in terms of error in the measurement of resistance and reactance of the grounded portion of line x for a simultaneous open conductor and ground fault at different fault locations (0% to 80% in steps of 10%) having different power transfer angles $(+15°, -15°)$, with $K_C = 70\%$, $K_M = 70\%$ and $R_F = 50\ \Omega$. It is to be noted from Table I that for $\delta = +15°$, the percentage error (for most of the cases) in the measurement of resistance and reactance by the proposed scheme decreases as the fault location moves away from the relaying point. Subsequently, for $\delta = -15°$, the percentage error is positive for local end faults whereas it becomes negative and increases for remote end faults. Still, the maximum percentage error is within $\pm 4.19\%$.

Fig. 5 shows the simulation results given by the conventional ground distance relay and the proposed scheme for a simultaneous open conductor and ground fault at different fault locations (0% to 80% in steps of 10%), different power transfer angles $(-15°, 0°, +15°)$, with $K_C = 70\%$, $K_M = 70\%$, and $R_F = 50\ \Omega$. It is to be noted from Fig. 5 that irrespective of the direction of power flow, the conventional ground distance relay located at G completely fails to detect the faults occurring after 30% of the line length from bus S. On the other hand, the proposed scheme provides very accurate results for all fault locations having different power transfer angles. The fault impedance given by the proposed scheme exactly coincides with the actual impedance of line.

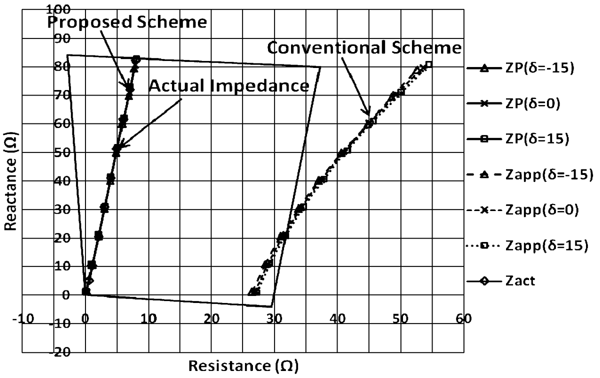


Fig. 5. Fault impedance measurement with varying p and δ.

TABLE II
EFFECT OF CHANGE IN K_M ON RESISTANCE MEASUREMENT

p (%)	R_{act} (Ω)	$K_M = 50\%$		$K_M = 60\%$		$K_M = 70\%$	
		R_P (Ω)	ε_{RP} (%)	R_P (Ω)	ε_{RP} (%)	R_P (Ω)	ε_{RP} (%)
0	0	0.05	-	0.05	-	0.05	-
10	0.994	1.02	2.65	1.02	2.65	1.01	1.64
20	1.987	2.02	1.64	2.02	1.64	2	0.63
30	2.981	3.03	1.64	3.02	1.30	3	0.63
40	3.975	4.02	1.14	4.02	1.14	3.99	0.38
50	4.969	5.01	0.84	5.01	0.84	4.98	0.23
60	5.962	6.02	0.97	6.02	0.97	5.98	0.30
70	6.956	7.05	1.35	7.04	1.21	6.99	0.49
80	7.950	8.1	1.89	8.09	1.77	8.03	1.01

TABLE III
EFFECT OF CHANGE IN K_M ON REACTANCE MEASUREMENT

p (%)	X_{act} (Ω)	$K_M = 50\%$		$K_M = 60\%$		$K_M = 70\%$	
		X_P (Ω)	ε_{XP} (%)	X_P (Ω)	ε_{XP} (%)	X_P (Ω)	ε_{XP} (%)
0	0	0.52	-	0.52	-	0.52	-
10	10.27	10.52	2.43	10.51	2.34	10.45	1.75
20	20.54	20.87	1.61	20.84	1.46	20.65	0.54
30	30.81	31.27	1.49	31.25	1.43	31	0.62
40	41.08	41.52	1.07	41.51	1.05	41.2	0.29
50	51.35	51.79	0.86	51.79	0.86	51.43	0.16
60	61.62	62.21	0.96	62.18	0.91	61.76	0.23
70	71.89	72.82	1.29	72.77	1.22	72.26	0.51
80	82.16	83.7	1.87	83.59	1.74	82.98	1.00

B. Variation in Zero-Sequence Mutual Coupling Impedance

Tables II and III show the performance of the proposed scheme in terms of error in the measurement of resistance and reactance of the faulted portion of line x for a simultaneous open conductor and ground fault at different fault locations (0% to 80% in steps of 10%) having different percentages of zero-sequence mutual coupling impedance (50%, 60%, and 70%) with $\delta = +15°$, $K_C = 70\%$ and $R_F = 25\ \Omega$. It has been observed from Tables II and III that the maximum percentage error given by the proposed scheme remains within $\pm 2.65\%$.

Fig. 6 shows the simulation results provided by the conventional ground distance relay and the proposed scheme for a simultaneous open conductor and ground fault at different fault locations (0% to 80% in steps of 10%) having a different percentage of zero-sequence mutual coupling impedance (50%, 60%, and 70%) with $\delta = +15°$, $K_C = 70\%$ and $R_F = 25\ \Omega$.

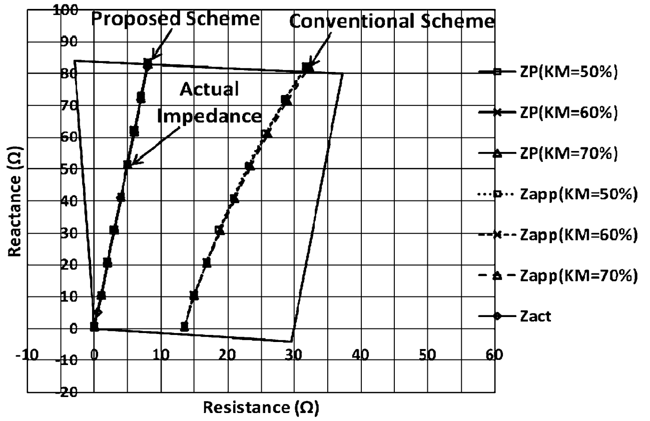


Fig. 6. Fault impedance measurement with varying p and K_M.

TABLE IV
EFFECT OF CHANGE IN K_C ON RESISTANCE MEASUREMENT

p	R_{act}	K_C = 30%		K_C = 50%		K_C = 70%	
(%)	(Ω)	R_P (Ω)	ε_{RP} (%)	R_P (Ω)	ε_{RP} (%)	R_P (Ω)	ε_{RP} (%)
0	0	0.06	-	0.08	-	0.1	-
10	0.994	1.03	3.65	1.035	4.16	1.035	4.16
20	1.987	2.01	1.14	2.03	2.14	2.05	3.15
30	2.981	2.99	0.30	3.01	0.97	3.03	1.64
40	3.975	3.97	-0.12	3.99	0.38	4.02	1.14
50	4.969	4.97	0.03	4.98	0.23	5.01	0.84
60	5.962	5.92	-0.71	5.99	0.47	6.02	0.97
70	6.956	6.91	-0.66	6.93	-0.37	7.04	1.21
80	7.950	7.92	-0.37	7.92	-0.37	7.99	0.51

TABLE V
EFFECT OF CHANGE IN K_C ON REACTANCE MEASUREMENT

p	X_{act}	K_C = 30%		K_C = 50%		K_C = 70%	
(%)	(Ω)	X_P (Ω)	ε_{XP} (%)	X_P (Ω)	ε_{XP} (%)	X_P (Ω)	ε_{XP} (%)
0	0	0.58	-	0.82	-	1.06	-
10	10.27	10.67	3.89	10.7	4.19	10.7	4.19
20	20.54	20.77	1.12	20.96	2.04	21.16	3.02
30	30.81	30.88	0.23	31.08	0.88	31.33	1.69
40	41.08	41.04	-0.10	41.23	0.37	41.5	1.02
50	51.35	51.32	-0.06	51.5	0.29	51.76	0.80
60	61.62	61.2	-0.68	61.9	0.45	62.19	0.93
70	71.89	71.4	-0.68	71.64	-0.35	72.73	1.17
80	82.16	81.83	-0.40	81.82	-0.41	82.53	0.45

It is to be noted from Fig. 6 that the loci of fault impedance provided by the conventional ground distance relay located at G are far away from the actual impedance locus. On the other hand, the loci of fault impedance of the proposed scheme get superimposed on the actual impedance locus.

C. Change in Level of Compensation

Tables IV and V show the simulation results in terms of percentage error in the measurement of resistance and reactance given by the proposed scheme, respectively, for a simultaneous open conductor and ground fault at different fault locations (0% to 80% in steps of 10%) having different levels of series compensation (30%, 50%, and 70%) with $\delta = +15°$, $K_M = 70\%$ and $R_F = 50$ Ω. It is to be noted from Tables IV and V that for low levels of series compensation (K_C = 30% and 50%), the percentage error given by the proposed scheme is initially positive and decreases as the fault location moves away from the relaying point up to a certain portion of line length (say $p = 30\%$ for $K_C = 30\%$ and $p = 60\%$ for $K_C = 50\%$). Afterward, it becomes negative for remote end faults. Further, for a high level of series compensation ($K_C = 70\%$), as the fault location moves away from the relaying point, the percentage error in the measurement of resistance and reactance given by the proposed scheme decreases. However, the percentage error for all cases stays within ±4.19%.

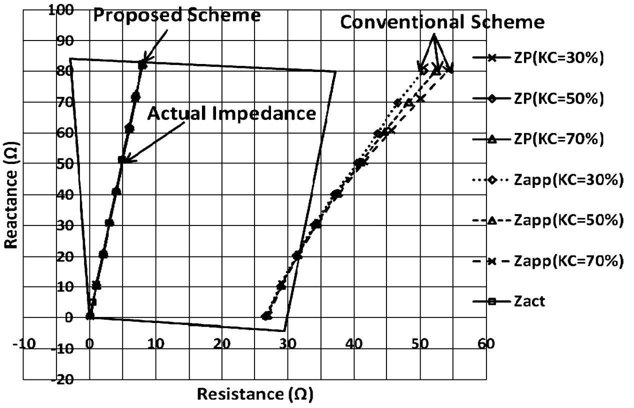


Fig. 7. Fault impedance measurement with varying p and K_C.

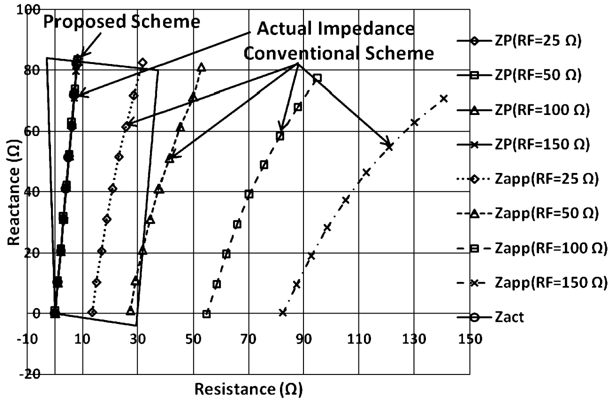


Fig. 8. Fault impedance measurement with varying p and R_F.

Fig. 7 shows simulation results given by the conventional ground distance relay and the proposed scheme for a simultaneous open conductor and ground fault at different fault locations (0% to 80% in steps of 10%) having different levels of series compensation (30%, 50%. and 70%) with $\delta = 15°$, $K_M = 70\%$ and $R_F = 50\,\Omega$. It has been observed from Fig. 7 that as the level of compensation increases, the locus of fault impedance provided by the conventional ground distance relay located at G moves away from the first zone boundary. Further, for faults after 20% of the line length, the loci of fault impedance move outside the first zone boundary. On the other hand, the proposed scheme measures the correct value of fault impedance for all fault locations and for different levels of series compensation.

D. Change in Fault Resistance

Fig. 8 shows simulation results provided by the conventional ground distance relay and the proposed scheme for a simultaneous open conductor and ground fault at different fault loca-

TABLE VI
EFFECT OF CHANGE IN R_F ON REACTANCE MEASUREMENT

p (%)	X_{act} (Ω)	$R_F = 100\ \Omega$				$R_F = 150\ \Omega$			
		X_{app} (Ω)	ε_{Xapp} (%)	X_P (Ω)	ε_{XP} (%)	X_{app} (Ω)	ε_{Xapp} (%)	X_P (Ω)	ε_{XP} (%)
0	0	-0.16	-	0.05	-	0.12	-	0	-
10	10.27	9.74	-5.16	10.14	-1.27	9.45	-7.98	10.41	1.36
20	20.54	19.53	-4.92	20.56	0.10	18.9	-7.98	20.99	2.19
30	30.81	29.29	-4.93	31	0.62	28.2	-8.47	31.46	2.11
40	41.08	39.05	-4.94	41.47	0.95	37.32	-9.15	41.78	1.70
50	51.35	48.77	-5.02	51.94	1.15	46.21	-10.01	51.89	1.05
60	61.62	58.23	-5.50	62.37	1.22	54.8	-11.07	61.67	0.08
70	71.89	68.01	-5.40	72.73	1.17	62.98	-12.39	70.95	-1.31
80	82.16	77.47	-5.71	82.94	0.95	70.63	-14.03	79.51	-3.23

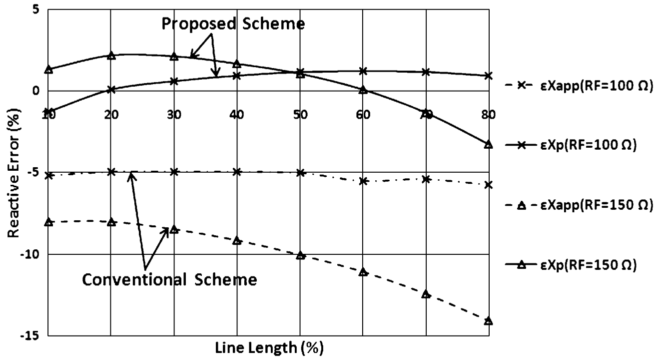


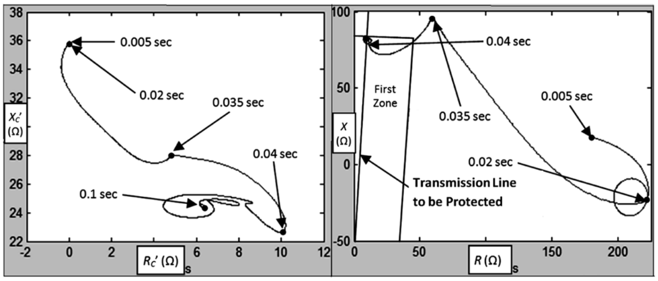
Fig. 9. Error in reactance measurement with varying p and R_F.

tions (0% to 80% in steps of 10%) having different values of fault resistance (25, 50, 100, and 150 Ω) with $\delta = +15°$, $K_M = 50\%$ and $K_C = 70\%$. It has been observed from Fig. 8 that for a low value of R_F (up to 25 Ω), even though the locus of fault impedance provided by the conventional ground distance relay lies within the first zone boundary, it is far away from the actual impedance locus. In addition, the same relay partially or completely loses its first zone coverage for a simultaneous open conductor and ground fault with other higher values of R_F. On the other hand, the proposed scheme measures the correct value of impedance for all fault locations having different values of fault resistance.

Table VI and Fig. 9 show the simulation results in terms of reactances X_P and X_{app} measured by the proposed scheme and the conventional scheme, respectively, for a simultaneous open conductor and ground fault at different fault locations (0% to 80% in steps of 10%) having different values of fault resistance (100 Ω and 150 Ω) with $\delta = +15°$, $K_M = 50\%$ and $K_C = 70\%$. It is to be noted from Table VI and Fig. 9 that the percentage error in the measurement of reactance given by the conventional scheme increases as the value of fault resistance increases. It has been observed from Table VI that the value of percentage error is -5.71% in case of $R_F = 100\ \Omega$ whereas it amplifies up to -14.03% during $R_F = 150\ \Omega$. Conversely, the maximum percentage error given by the proposed scheme remains within ±3.23% even in case of higher values of fault resistances ($R_F = 100\ \Omega$ and $150\ \Omega$).

E. Close-In and Remote-End Faults

It is to be noted from Figs. 5–8 that the conventional ground distance relay located at G sees a simultaneous open conductor and ground fault occurring just after the relaying point with a great percentage of error. Furthermore, for most of the cases, the same relay sees the remote-end fault outside the first zone boundary. On the other hand, the proposed scheme always measures the correct value of fault impedance of the line during close-in and remote-end faults.



(a) (b)

Fig. 10. SC/MOV and proposed scheme performance before and after the fault.

TABLE VII
TRANSMISSION-LINE PARAMETERS

Positive-sequence resistance R_{L1} (Ω/km)	0.030944
Zero-sequence resistance R_{L0} (Ω/km)	0.16816
Zero-sequence mutual resistance R_{LM0} (Ω/km)	0.11771
Positive-sequence inductance L_{L1} (H/km)	1.0517×10^{-3}
Zero-sequence inductance L_{L0} (H/km)	3.9368×10^{-3}
Zero-sequence mutual inductance L_{LM0} (H/km)	2.7557×10^{-3}
Positive-sequence capacitance C_{L1} (F/km)	11.28×10^{-9}
Zero-sequence capacitance C_{L0} (F/km)	7.2813×10^{-9}
Zero-sequence mutual capacitance C_{LM0} (F/km)	-5.097×10^{-9}
Line voltage (kV)	400
Line length (km)	300

TABLE VIII
SOURCE PARAMETERS

Source voltage (kV)	400
Short circuit level (MVA)	20000

TABLE IX
SC/MOV SPECIFICATIONS

K_C (%)	i_{ref} (kA)	X_G (Ω)	$v_{ref} = \sqrt{2}\, i_{ref} X_G$ (kV)
70	1	35.945	127.085
50	1	25.675	90.775
30	1	15.405	54.465

F. SC/MOV and Proposed Scheme Performance During Fault

The performance of SC/MOV and the proposed scheme are shown in Fig. 10 considering a simultaneous open conductor and ground fault at 80% of the line length, having $\delta = +15°$, $K_M = 70\%$, and $K_C = 70\%$. Further, the fault is assumed to occur at 0.02 s. Fig. 10(a) shows equivalent resistance (R_C') and equivalent reactance (X_C') of the SC/MOV determined by Goldsworthy's equations before (0.005 to 0.02 s) and after (0.02 to 0.04 s) the fault. Furthermore, Fig. 10(b) shows the fault impedance locus given by the proposed scheme on the $R - X$ plane considering the same situation.

It is to be noted from Fig. 10(a) that during the prefault condition; only SC will conduct the current whereas MOV will not conduct the current. In this situation, the magnitude of X_C' is the maximum whereas the magnitude of R_C' is zero. Therefore, as shown in Fig. 10(b), the impedance locus given by the proposed scheme will settle down very far from the first zone boundary of a digital distance relay. Conversely, after the occurrence of a fault, SC and MOV both will conduct the fault current. Therefore, the magnitude of R'_{C} increases whereas the magnitude of X'_{C} decreases. Hence, the locus of fault impedance begins to move toward the first zone boundary and settles down within the first zone boundary.

V. ADVANTAGES OF THE PROPOSED SCHEME

1) The proposed scheme is not affected by a change in level of series compensation given to the double-circuit lines.
2) The reach of the proposed scheme is not influenced by the zero-sequence mutual coupling impedance present between two lines.
3) The proposed scheme avoids the problem of incorrect operation of ground units of the conventional digital distance relay having a facility of series compensation during open conductor and ground fault and measures the correct value of fault impedance.
4) The proposed scheme is immune to the loading effect of the series-compensated double-circuit line and measures the correct value of fault impedance for different values of the power transfer angle.
5) The proposed scheme is accurate and robust against wide variations in system and fault parameters as the value of percentage error is found to be within ±4.19%.

VI. CONCLUSION

A new digital distance relaying scheme presented in this paper provides adequate protection to series-compensated double-circuit lines during a simultaneous open conductor and ground fault. The proposed scheme is based on the derivation of the compensated values of impedance using the symmetrical components theory. It measures the correct value of fault impedance for different fault locations, different values of fault resistance, various zero-sequence mutual coupling impedance, different levels of series compensation, and various system loading conditions. Further, it does not require remote-end data. A comparative evaluation of the proposed scheme and the conventional scheme indicates that the proposed scheme is highly accurate and robust against wide variations in system and fault parameters as its percentage error is within ±4.19%.

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