p-ISSN 2301–4156 | e-ISSN 2460–5719

Performance Investigation of Transmission Line Protective Relays Using Series Compensators

Nanang Rohadi[1], Nendi Suhendi[2]

[1] Electrical Engineering Study Program, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Sumedang 45364 INDONESIA (tel.: 081290820565; email: [1]nanang.rohadi@unpad.ac.id, [2]n.suhendi@unpad.ac.id)

[Received: 27 April 2023, Revised: 3 July 2023]
Corresponding Author: Nanang Rohadi

ABSTRACT — This paper aims to investigate the measurement results of closed loop fault impedance using conventional distance relay algorithms (SEL-421 distance relay) when used as protective tools on transmission lines with series compensators and several uncertainty parameters (factors). Several system's factors can emerge concurrently, and the series compensators may affect the relay algorithm's performance, particularly on the phase fault to ground. However, the existing testing method of the relay performance only alters one factor while simultaneously keeping others constant. This technique is no longer relevant when several factors are not considered simultaneously, affecting the relay performance during faults. For algorithm investigations as in actual conditions, several fault scenarios were performed at the fault point before and after series compensators while simultaneously changing the values of several factors in the system model through fault simulations. This research employed the DIgSILENT PowerFactory for power system modeling and fault simulation. In fault testing simulations, Thevenin equivalent circuit with two sources and 42% series compensator were placed in the center of a 300 km of a 400 kV transmission line. Several fault scenarios and the fault impedance measurement as a function of changes in several factor values were performed automatically. An automated testing simulation was developed using the DIgSILENT Programming Language (DPL) to read data samples generated through the SIMLAB software for several factors. A series compensator affected the performance of the relay algorithm for calculating the fault impedance when faults occurred after the compensator. For faults after the compensator, changing several factors simultaneously affects the relay's accuracy and aggravates the relay's performance, specifically relay operation failure in the form of underreaching and overreaching. The developed testing technique is expected to be utilized as a cutting-edge testing tool for the development and implementation of relays in a timely manner and as in actual conditions.

KEYWORDS — Relay Performance, Distance Relay, Uncertainty Parameter, Series Compensator, Relay Algorithm, DPL.

I. INTRODUCTION

The distance relay serves as a protective relay, which is an essential part of the transmission line system. In its implementation, the distance relay protection serves to protect the transmission line during the event of faults. It must operate accurately at the time faults occur by identifying the emerging faults and then isolating parts experiencing faults [1]. The conventional distance relay is designed to correctly detect the fault impedance values based on local measurements of the fault current and voltage magnitude signals [2]. The distance relay operates based on the current phasor, while the voltage for the impedance measurements by the relay algorithm is affected by multiple factors [3], [4].

More attention must be paid to the accuracy of the distance relay through the relay algorithm performance when employing the distance relay on transmission lines with series compensators using overvoltage protection devices in the form of metal oxide varistors (MOV). A series compensator to compensate for the series inductive reactance of the transmission line can enhance the electric power transfer through the line, increase the stability of the power system, reduce losses in the power system, and improve the voltage regulation at the receiving end [2], [5], [6]. Despite its advantages, series capacitors can disrupt the protection performance of conventional distance relays (SEL-421 distance relays), which operate based on phasor quantities (nonpilot relays) [7]. This condition gets worse when the value of the installed series capacitor exceeds that of the compensated line impedance. It poses a problem for the relay algorithm to measure the fault impedance, particularly when faults occur after the compensator [2]. In this condition, the noise impedance measurement done by the algorithm is no longer directly proportional to the physical distance of the transmission line. The line distance measured by the relay algorithm from the point of fault occurrences to the location of the installed relay is the line impedance at fault in the zone-1 which electrically can be seen as shorter [2], [5]. Furthermore, several prior studies have elucidated the problems arising in the performance of protective relays as the results of the series capacitor installation and a number of factors [7]–[10].

Thevenin equivalent circuit (see Figure 1) for the fault simulation is in the form of a single-line diagram of the transmission line on the high-voltage system. The performance of distance relay algorithms was evaluated using a transmission line spanning 300 km. This transmission line was equipped with a conventional distance relay installed on the side of the line, with a series compensator circuit $SC_S + MOV_S$ of 42% installed on the center of the transmission line, between voltage sources E_M and E_N. As exhibited in Figure 1, red indicates parameters that may disrupt the relay performance, including the presence of the series capacitor installed on the transmission line.

This paper aims to investigate the relay algorithm's performance by conducting several simulations during phase A fault condition to ground as a function of changing the values of several factors (indicated by red in Figure 1). The relay performance investigation serves as a function of changes in factor values carried out simultaneously. The application of the automatic testing technique [1] is indispensable to investigating the relay algorithm's performance when fault occur before and after the series compensator $SC_S + MOV_S$.

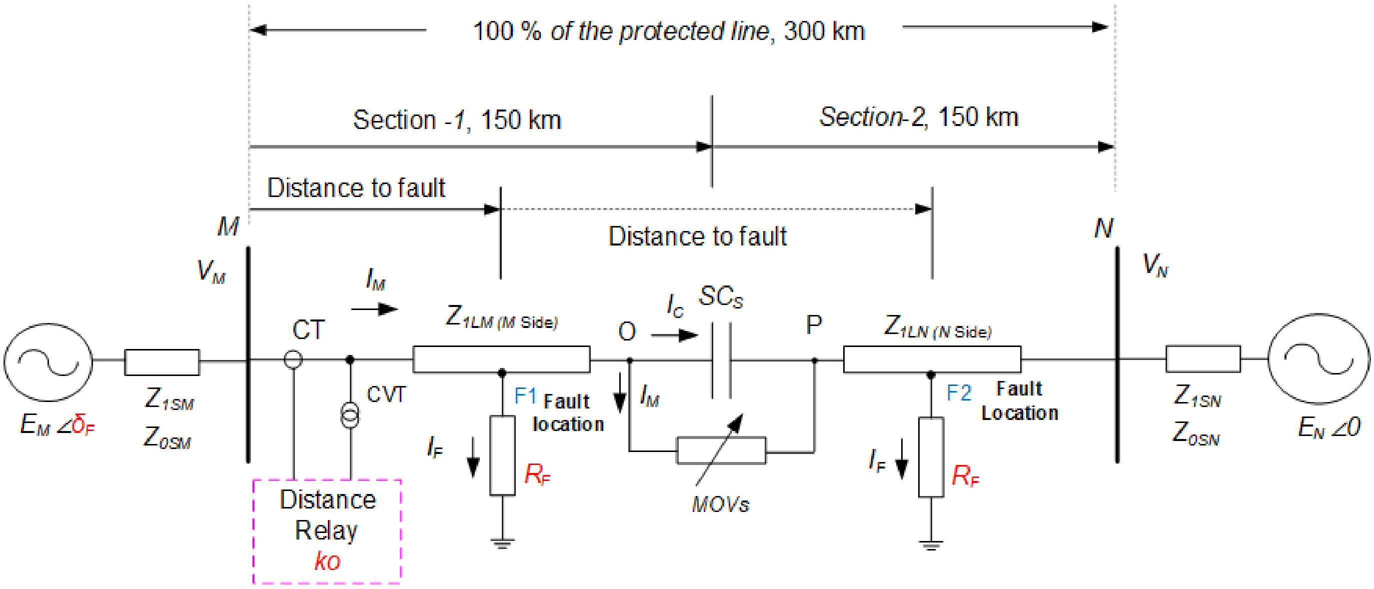


Figure 1. Single transmission line with series compensators: F_1- fault before $SC_S + MOV_S$ and F_1- fault after $SC_S + MOV_S$.

Prior research has examined the effects of series compensator and several factors as well as proposed solutions on the measurement of the distance relay performance [11], [12]. Nevertheless, the developed method only observed the relay performance on a single factor, while keeping other factors constant at the same time. This technique does not reflect the actual condition, considering that several factors can occurs simultaneously, as demonstrated in the testing method developed in this research.

II. ISSUES OF USING SERIES COMPENSATORS

As previously explained, installing the series compensator on a transmission line is one of the alternative methods to increase the delivery of electric power on a transmission line and improve the power system stability. The utilization of series capacitors can also enhance relative stability. The generator necessitates this stability in order to maintain synchronization during faults. Conversely, unfavorable conditions will arise in the protective relay operation when faults occur as a result of the series compensator' influences.

As illustrated in Figure 1 and in accordance with the testing results that will be explained in the forthcoming section, the series compensator had no effect on the accuracy of the fault impedance measured by the algorithm for the fault occurring before compensator F_1. The transmission line in this condition was as though it were not compensated, so the fault impedance would be directly proportional to the fault distance (fault location), as shown in (1).

$$(R_{1m} + jX_{1m}) * p \qquad (1)$$

where

p = the fault point F_1 distance to the relay location (km)
R_{1m} = the line resistance (Ω/km)
X_{1m} = the line reactance (Ω/km).

In this condition, the transmission line exhibited inductive characteristics, so the fault current lagged behind the fault voltage and produced a proportional fault impedance measurement as a function of the fault distance.

The influence of the compensator on fault at point F_2 could result in a voltage inversion, wherein the voltage angle at M underwent a change of 180° [13]. As shown in Figure 1, in a condition where the MOV overvoltage protection is presumed not working in the event of faults, the voltage inversion can be expressed as in (2).

$$X_{1SM} < X_C < (X_{1SM} + X_{1LM} + X_{1LN\ (F_2)}). \qquad (2)$$

The voltage inversion on the M busbar, which was read by the relay through the secondary side of the capacitive voltage transformer (CVT), was as a reverse impedance phenomenon because the line was capacitive when it was assumed $X_C > X_{1LM}$, that was, the voltage lagged behind the current by 90°. The line's characteristics change as a result of compensating for the inductive reactance value of the channel in the N segment. Fault impedance measurement errors in the form of maloperation of the relay can arise, particularly in faults after the series capacitor, because it can affect the basic relationship between the relay operation and line impedance [14]. Electrically, it appeared that the line was shorter under these conditions, and the distance relay operation in the zone-1 area would overreach. Therefore, it is necessary to adjust the range limit in zone-1 (0.8 p.u.) in order to prevent relay maloperation during a fault event. In contrast, for a fault before the compensator, the forward fault impedance measurement was carried out by the relay because the line was inductive, i.e., the voltage angle precedes the fault current. In this circumstance, the measurement error according to (6) and (7) is solely influenced by several system's factors.

The reduction in line impedance for faults at F_2 due to the compensation for the channel reactance pX_L to X_C can be expressed in $pX_L = X_L - X_C$. The simulation with a number of n at the fault point before the capacitor (point F_1) and after the capacitor F_2 with several factors can affect the performance of the relay. Series compensators ($SC_S + MOV_S$) with 42% compensation were placed in the center of the capacitor's line. The results of previous investigations showed that the relay did not experience errors when faults occurred before the compensator [10]. The results of simulation without the influence of several factors and simulations for faults at F_1 can be explained through simulation result pictures.

The typical transmission line for faults prior to the compensator (fault at point F_1) can be characterized as a transmission line without compensator. Therefore, the fault impedance measurement estimated by the algorithm has a linear and proportional relationship to the line's length as a function of the fault location before the compensator. In this condition, measurement errors appear when several factors influence it [2], [10]. The fault impedance measurement for faults on a transmission line without a series compensator is a function of the fault location at F_1. The transmission line impedance for the fault before the compensator was inductive, so the fault current in the said loop system lagged behind the voltage at the M bus.

When faults occurred after the capacitor (fault at point F2), the series compensator circuit of the SC_S changed the output impedance measurement's characteristics. Under these conditions, the relay range of the zone-1 at the distance relay setting was 80% (0.8 p.u.). When a fault occurred at point F_2, with an assumption that the overvoltage protection of the MOV_S series compensator did not work, the relay would overreach because of a reduction in electrical impedance due to the compensators [10]. In this case, it is necessary to implement several techniques to decrease the zone-1 setting. Doing so can make the protection operates more accurately, as has been shown in previous studies [15], [16]. For faults at F_2, the fault impedance estimation was as if it were still in zone-1 (coverage area of 0.8 p.u.) due to the influence of the series capacitors; in addition, a number of factors would decrease the operating accuracy of the relay [2].

III. MEASUREMENT OF THE FAULT IMPEDANCE USING SERIES COMPENSATORS AND SEVERAL FACTORS

The estimation of the fault impedance containing capacitance and inductance values is based on the calculation of positive sequence closed loop impedance [2]. The relay's response in the event of faults is based on local measurements of the fault voltage and current signals by the relay through the secondary side of the instrument transformer (current transformer/CT and CVT). In this case, conventional distance relays are easily operated, but the performance of the Z_{1m} positive sequence impedance calculation algorithm of the relay can be affected by the system's external and internal factors, whose actual values are unknown [1], [10], [12]. These factors include fault resistance R_F, load flow angle δ_F, and zero sequence impedance Z_{0L}; all of which influence the zero-sequence compensation value, namely k_0, which will be used in the measurement algorithm.

The fault impedance measurement, as a function of the ratio of the fault voltage to the fault current compensated by the series compensator, will result in an impedance measurement error of ΔZ_{1m}. The measurement error leading to the failure of the relay's operation is a function of the presence of the compensator (fault at F_2) and several factors. Both affect the accuracy of the positive sequence impedance measurement by the relay algorithm.

The investigation of relay performance based on fault impedance measurement is described so as to analyze the impact of series capacitor circuits ($SC_S + MOV_S$) and a number of uncertainty parameters (factors) that can affect the accuracy of the distance relay algorithm when faults occur at points F_1 and F_2. For the purposes of measuring the fault impedance, the schematic diagram and the power system were modeled using a Thevenin equivalent circuit (see Figure 1) with two voltage sources E_M and E_N, and positive sequence source impedances Z_{1SM} and Z_{1SN}. The proposed model was configured with the DIgSILENT software in red (Figure 1) since several factors were also observed. Based on measurements of the voltage signal and fault current captured by the relay through the secondary side of the CT and CVT instrument transformers, the relay's impedance measurement performance was determined.

The fault impedance measurement in the relay algorithm was based on the zero-sequence current k_0 compensation. The compensation factor was affected by the impedance of the zero-sequence line Z_{0L} and the impedance of the positive sequence line Z_{1L}, whose values were not known. Consequently, k_0 as a measurement calibration constant contained value uncertainty, so it was presumed that it could ultimately impact the accuracy of impedance measurements.

For faults at point F_1, the measurement of the impedance Z_{1m} by the relay was not affected by the series compensator, unlike when the fault occurred at point F_2. Hence, the impedance measurement analysis must be differentiated and several factors in red were taken into account (see Figure 1). In this condition, the fault impedance seen by the relay to point F_2 differed from the line impedance without a compensator. It occurs due to the influence of a number of factors and series compensators.

Figure 2 presents symmetrical components of the phase A fault to the ground with the fault resistance R_F (factor). The sequence of the symmetrical component of the voltage can be expressed using (3) [12].

$$\underline{V}_1 + \underline{V}_2 + \underline{V}_0 = 3R_F\underline{I}_F. \tag{3}$$

Next, (3) can be explicated below.

$$V_1 = V_{1SA} - Z_{1LS}I_{1SA} - V_{1C} - mZ_{1LR}I_{1SA} \tag{4a}$$

$$V_2 = V_{2SA} - Z_{2LS}I_{2SA} - V_{2C} - mZ_{2LR}I_{2SA} \tag{4b}$$

$$V_0 = V_{0SA} - Z_{0LS}I_{0SA} - V_{0C} - mZ_{0LR}I_{0SA} \tag{4c}$$

with m denotes the distance from the capacitor to the fault point F_2; V_C is the voltage drop of $SC_S + MOV_S$; 0,1,2 represents sequence symbols of zero, positive, and negative; and L, S, A represent source line and phase A, respectively.
By stating that the positive sequence line impedance is the same with the negative sequence impedance, namely $Z_{1L} = Z_{2L}$, the voltage measurement can be expressed as follows.

$$\begin{aligned} V_{MA} &= V_C + Z_{1LM}\left[I_{MA} + \frac{Z_{0L}-Z_{1L}}{Z_{1L}} I_{0MA}\right] + 3R_F I_F \\ V_{MA} &= V_C + Z_{1LM}[I_{MA} + k_0 I_{0MA}] + 3R_F I_F \\ V_{MA} &= V_C + Z_{1LM} I_{MA}^C + 3R_F I_F. \end{aligned} \tag{5}$$

Then, it can be stated that

$$V_{MA} = V_{1MA} + V_{2MA} + V_{0MA}$$
$$V_C = V_{1C} + V_{2C} + V_{0C}$$
$$I_{MA} = I_{1MA} + I_{2MA} + I_{0MA}$$
$$Z_{1LMN} = Z_{1LM} + mZ_{1LN}$$
$$Z_{2LMN} = Z_{2LM} + mZ_{2LN}$$
$$Z_{0LMN} = Z_{0LM} + mZ_{0LN}$$

so that the impedance measurement at fault at point F_2 can be expressed by (6).

$$\begin{aligned} Z_{1m} &= \frac{V_{MA}}{I_{MA}^C} = Z_{1LMN} + 3R_F\frac{I_F}{I_{MA}^C} + \frac{V_C}{I_{MA}^C} \\ &= Z_{1LMN} + \Delta Z_{1LMN} \end{aligned} \tag{6}$$

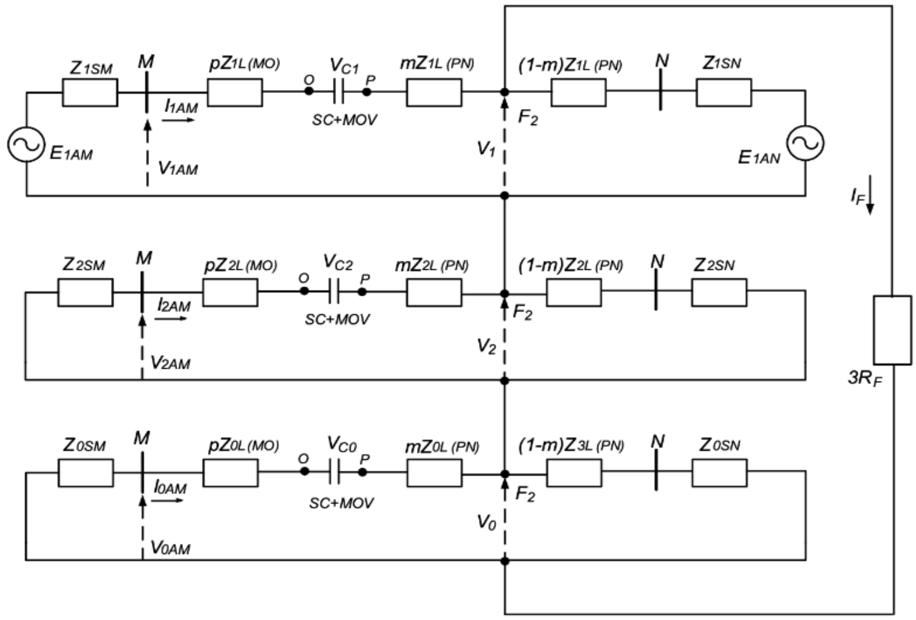


Figure 2. Symmetrical components for phase A fault to ground at the point F_2.

where V_{MA} is the phase A voltage to the ground measured on the M side and I_{MA}^C is the current I_{MA} compensated with zero-sequence k_0 and measured by the relay. I_{MA}^C is stated in (7).

$$I_{MA}^C = I_{MA} + k_0 I_{0MA}. \quad (7)$$

The compensation for the zero-sequence k_0 in (5) is defined as (8).

$$k_0 = \frac{Z_{0L} - Z_{1L}}{Z_{1L}}. \quad (8)$$

It can be seen in (6) and (7) that the error in measuring the impedance Z_{1m} by the relay algorithm, especially the fault at point F_2, can be expressed at least as a function of several factors and the occurrence of voltage drop across the series capacitor V_C, as defined in (9).

$$\Delta Z_{1m} = f(R_F, ko, \delta_F, V_C). \quad (9)$$

It can be seen from (6) that several factors and the voltage across the series capacitor can affect the accuracy of the impedance measurement. Next, the analysis of the performance of the algorithm focused on the effect of the error in (9), i.e., by several factors a number of factors on the impedance Z_{1m} measurement.

IV. SIMULATION OF FAULT AND EVALUATION

In previous research, testing of the effect of a number of factors was examined by alternately observing one factor while keeping the other factors constant [16]. The testing technique does not represent the actual conditions when observing the relay operation when faults occur. In actual conditions, the influence of a number of factors on relay performance can occur simultaneously in the event of faults. In this study, a newly developed method for investigating the relay performance was the same as in actual conditions; namely, a random value of several system's factors was generated at a specific value limit (see Table I). Parameter uncertainty values were generated randomly, then sampled (read) automatically [1] through the developed testing algorithm. A number of parameter uncertainty values (factors) of the system model were simultaneously adapted according to random values prior

TABLE I
INTERVAL OF FACTOR VALUE AFFECTING THE FAULT IMPEDANCE MEASUREMENT (SEE FIGURE 1)

Uncertainty Parameter	Symbol	Value Interval
x_1	R_F	[0 : 50] Ω
x_2	δ_F	[-30 : 30] deg.
x_3	k_o	[0,797 : 0,881]

to simulation at the fault points before and after the series compensator, as a function of a number of factors automatically and also as a function of the presence of series capacitors.

The influence of the series compensator on the impedance measurement was also observed, especially the noise after the compensator. The relay algorithm testing simulation for a number of fault scenarios involved two computational scopes, namely SIMLAB software [17] and DIgSILENT PowerFactory [18]. DIgSILENT was used for modeling protection systems and power system simulation models, while SIMLAB was used to generate random values from factors within a certain range of values (see Table I). In this experiment, testing and computing the fault impedance values were performed automatically through a program developed using the DPL compiler tool provided by DIgSILENT. The working step of this automated testing system [1] involved the utilization of an algorithm (developed through DPL) to concurrently read random parameter values from a number of samples with a uniform distribution that were randomly generated. Then, a number of experimental scenarios were run to simulate faults at points F_1 and F_2 (see Figure 3). Measurement of the fault impedance by the algorithm of the distance relay model was based on the measured value of the compensated current I_{MA}^C and the fault voltage V_{MA} obtained from readings on the CT and CVT secondary side outputs as input from the algorithm [19]. Several fault simulation scenarios were run automatically for a number of fault points along the protected line, i.e., in the area before and after the series compensator, with a number of samples of the factors to be tested. It was done to determine the accuracy of the fault impedance measurement by the algorithm. Relay test investigations were more focused on the fault area in

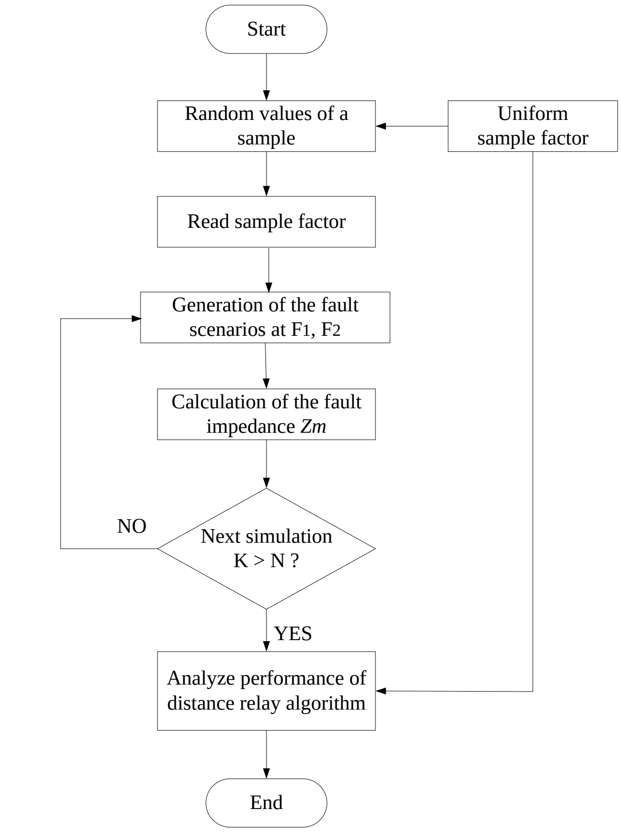


Figure 3. Diagram of the relay algorithm testing procedure.

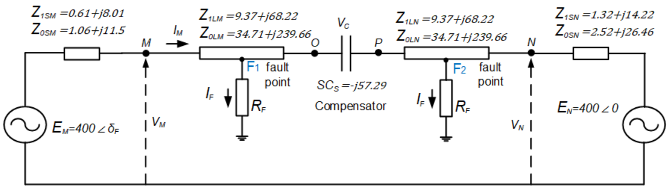


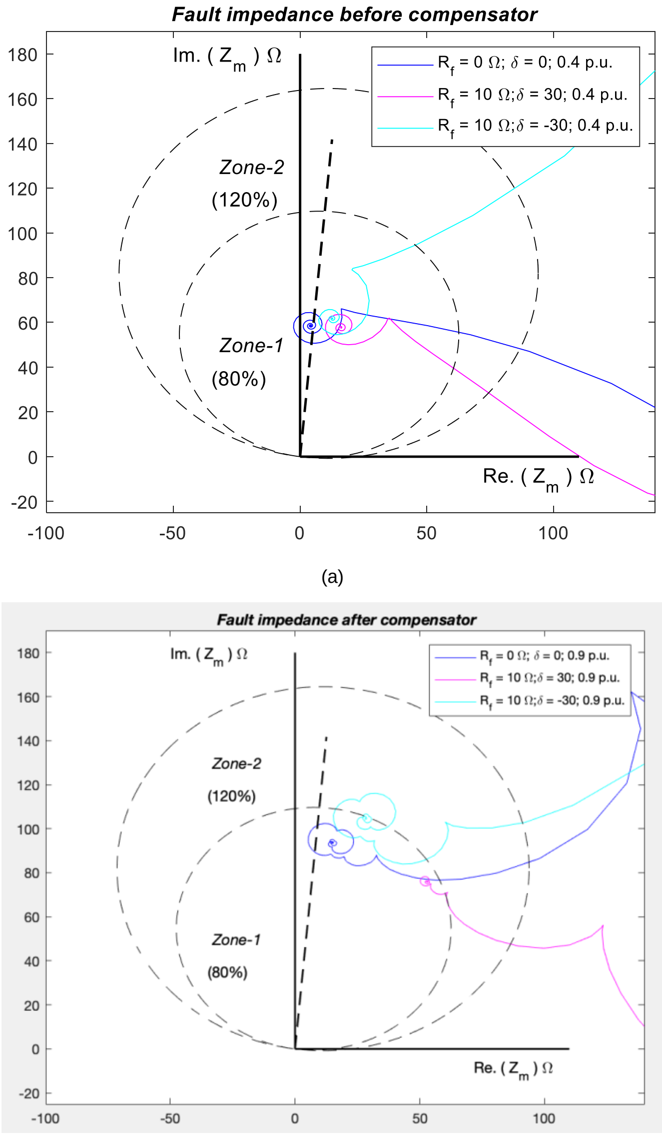
Figure 4. System parameter for the fault simulations.

zone-1 to the boundary line, which was a critical area in which the protective relay must work immediately.

In the experimental scenario, as shown in Figure 1 and Figure 3, the type of phase A to ground fault (or it could be another type of fault) was simulated at fault points F_1 and F_2 for the purpose of testing the performance of the relay algorithm. The relay algorithm carried out the measurement of positive sequence fault impedance Z_{1M} as in (6), namely as a function of random values of several factors as well as the influence of the series compensator SC_S for faults at F_1 and F_2.

To demonstrate the effect of factor changes on the impedance measurement error, as in (9), several fault simulations at points F_1 and F_2 were conducted using the system parameters, as shown in Figure 4. Zone-1 of the distance relay was set at 80% of the total length of the protected line, and zone-2 was set at 120% so that it could reach the next line. It was presumed that the line characteristics before and after 42% of the SC_S were identical. This study focuses on investigating relay performance based on predetermined test scenarios, with system parameters for modeling and testing derived from reliable sources.

Figure 5(a) shows the tracing of the impedance measurement of the phase A fault impedance to the ground for the fault simulations of 0.4 p.u (40%) of the total protected lines at point F_1, which is affected by several factors R_F=10 Ω and $\delta_F = 0°, \pm 30°$. It can be seen that the closed loop fault



(b)

Figure 5. Tracking of the fault impedance measurement, (a) for fault at F_1, (b) for fault at F_2.

impedance measurement, specifically $pZ_{1m} + \Delta Z_{1m}$, deviated from the actual measurement pZ_{1LM} (blue color). The measurement error ΔZ_{1m} as a function of the R_F and δ_F factors affected the measurement accuracy [20] and is illustrated in Figure 5(a). It can be seen that the change in the fault impedance value shifted to the right due to the addition of the R_F value, which could also cause the fault impedance value to shift up or down due to changes in the load flow angle δ_F (magenta and cyan).

Figure 5(b) shows trace impedance measurements in the fault simulation after the series compensator, namely at F_2, 0.9 p.u. (90%), with $R_F = 0°, 10\ \Omega$ and $\delta_F = 0°, \pm 30°$. It can be seen that the impedance measurement error ΔZ_m was significantly affected by a number of factors and the voltage drop across the series capacitor V_C. Consequently, the effect of the uncertainty on the impedance measurement at that location, namely dZ_m, is considered uncertain and a maloperation event because two possible failures can occur, namely in the form of overreaching and underreaching. Figure 6 provides a more in-depth description of the characteristic change of the fault impedance as a function of the number of samples of the factors (δ_f, R_f, k_o) and the series compensator (SC_S).

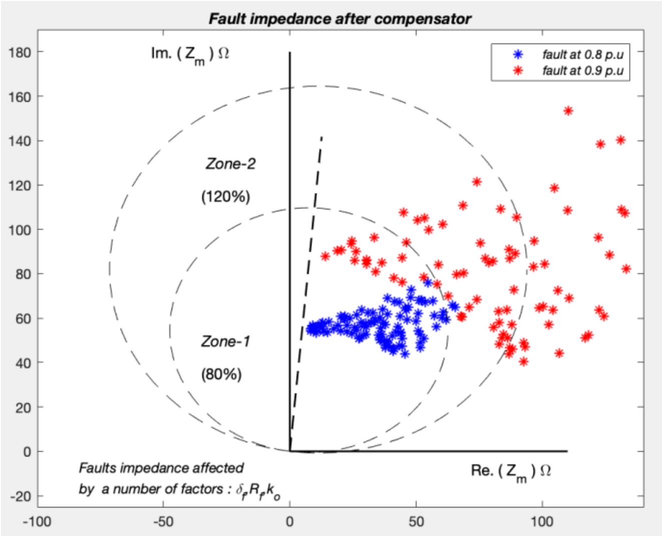


Figure 6. Measurement of fault impedance at a number of fault after the compensator with random changes in parameter values (Table I).

In order to better demonstrate the effect of the system uncertainty parameter (factor) on the measurement of the fault impedance Z_{1m}, simulations were carried out for a number of fault locations and the presence of compensators was also taken into consideration. The impedance measurement is a function of several random sample values of the factors (Figure 3) generated (uniform distribution) with the specifications as in Table I and the implemented value intervals of the factors R_F, δ_F , and k_o . Impedance simulation and calculations are performed automatically by an algorithm with a program developed using the DPL tool from DIgSILENT, for data collection, simulation, and impedance computation [1].

Figure 6 reveals that the impedance calculation by the algorithm, denoted by an asterisk, is the fault in the boundary area (0.8 p.u.) of zone-1 and the area zone-2 (0.9 p.u.). Simulations and impedance measurements were performed as a function of a number of factors and showed that there had been maloperation of the relay, namely in the form of overreaching and underreaching, both for faults at 0.8 p.u and 0.9 p.u. Fault locations in zone-2 (0.9 p.u) exhibited extreme condition, where impedance measurement indicate that the fault is as if it were in zone-1 or zone-3. It is owing to the collaborative influence of a number of factors and the existence of a series compensator. This condition must be avoided because it can impact system security due to the failure of protection work as expected. In this case, it can be assumed that the conventional distance relay (SEL-421 distance relay) is not good for use as a protection for transmission lines with series compensators.

V. CONCLUSION

This study presents the results of an investigation of the fault impedance measurement function in the relay algorithm implemented in the conventional distance relay model (SEL 421 distance relay type) on a transmission line with two voltage sources, a series compensator, and several factors. The results of the tests showed that the performance of the relay algorithm in the event of faults before and after the compensator was influenced by several factors. In addition, the series compensator can also be observed. For the fault before the compensator (at point F_1), a number of factors significantly contributed to the accuracy of the impedance calculation in zone-1. Fault impedance measurement error was still dominated by the fault resistance R_F, but the relay worked well for fault experiments at 0.4 p.u., for instance. The series compensator contribution affected the accuracy of the algorithm against fault after the series compensator was exacerbated by the presence of several factors. The Failure of the relay operation could occur for fault simulation in zone-1 (0.8 p.u) or zone-2 (0.9 p.u.). In this condition, the fault measurement could be read by the relay as if it were in zone-2 and zone-3, or even overreaching occurred for the fault point at 0.9 p.u. (zone-2) and underreaching due to the influence of several factors. The relay performance testing technique developed for investigation could be implemented through several fault simulation scenarios which were performed automatically using algorithms developed with DPL software.

CONFLICT OF INTEREST

The authors declare no conflict of interest with anyone during the writing of this publication.

ACKNOWLEDGMENT

We wish to thank Universitas Padjadjaran and Faculty of Mathematics and Natural Sciences of Universitas Padjadjaran for funding this research and providing assistance during this research conducted.

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