Performance of impedance measurement algorithm applied in line with a compensation circuit

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Abstract. This paper describes a performance of impedance measurement algorithms of SEL-421 distance relay protection when applied to protect series compensated line during fault conditions. The Performance is carried out by varying the value of uncertainty parameters to the accuracy of the impedance measurement algorithm of the relay for the simulated faults, which is measured from the located relay to the fault points. Experiments were carried out with a combination of DIgSILENT PowerFactory software to model and simulate electrical power protection systems with a system voltage of 400 kV and a line length of 300 km with compensation circuit placed in the middle of a protected transmission line. For a fault simulated 0.45 p.u. in front of compensation circuit, the relay still works correctly. However, there will be an operation failure of the relay for the fault simulated at 0.8 p.u. behind compensation circuit. Faults simulation and performances are performed automatically through the algorithm developed using the DIgSILENT Program Language (DPL). From the enclosed results, the developed method is applicable for testing the performance of the IEDs algorithm.

1. Introduction

Distance relay protection is a transmission line protection device in a high voltage system. Figure 1 shows a single line diagram of a power system model where a protected line located between two sources of voltage $E_S$ and $E_R$ is equipped with SEL-421 distance relay and series capacitor circuit as line compensation. The relay that is located at one of line terminal works based on the calculation of fault impedance $Z_m$ and its performance is greatly influenced by some factors that will affect the calculation of fault impedance. More attention also needs to be taken into account when the use of series capacitor compensation that can affect the characteristic of the line [1]. The protected line, in this case, is electrically shorter. This existence of a series capacitor will compensate the value of the inductive reactance.

An impedance measurement system in one-ended distance relay, the algorithm function for measuring impedance is very important for the protection monitoring process where the response of the relay to the faults is based on positive-sequence of loop impedance based on the measurement of voltage and current locally on one side of the transmission line terminal. This protection relay is simple in its operation, but the accuracy of the impedance calculation is greatly influenced by some factors or called uncertainty parameters, which will affect the measurement of fault impedance $Z_m$.
[2,3]. In this case, the calculation of the $Z_m$ will contain an error $\Delta Z_m$ which will affect the performance of the relay operation and consequently the relay does not work as expected.

Figure 1. Single-line diagram model for faults simulation (red color indicates uncertain parameters)

- $F_1$ - Location of fault before compensation circuit
- $F_2$ - Location of fault behind compensation circuit

Furthermore, the presence of series capacitor compensation SCs with Metal Oxide Varistors MOVs on protected line will also cause problems with impedance reduction for non-pilot distance relays algorithm [4]. In this case, the compensation circuit will produce uncertainty value from their response and finally will affect the performance of the algorithm [2,5].

Figure 1 is a simulation of faults at $F_1$ and $F_2$, where the voltage and current of the MOV as shown in Figure 2 can be expressed by the following equation [6].

$$i_{mov} = p \left( \frac{V_c}{V_{REF}} \right)^q$$

During fault, $V_c$ is immediately protected by $MOV_s$ after voltage capacitor $V_c$ exceeds $V_{REF}$ reference voltage. When a fault occurs at $F_1$, the capacitor does not affect the performance of the algorithm, however for the fault at/after the SCs, it will affect the performance of the algorithm [1].

Due to the influence of some uncertainty parameters, the presence of the compensation circuit and to view the performance of the distance relay, the application of testing with IEDs is needed. Practical problems and solutions to the performance of fault impedance algorithms with series capacitors, actually, have been carried out by the researcher [2,7-9], where performance studies are conducted to investigate relay performance based on the effect of just one factor.
Figure 1, 5 show the basic idea to explain some factors that can affect the accuracy of the impedance measurement algorithm during fault conditions. The fault points of $F_1$ and $F_2$ are simulated automatically for the fault of phase A to ground. The error of fault impedance calculation can occur and will impact the $Z_m$. There is a number of uncertainty parameter that can be investigated to see the effect on the accuracy of the impedance measurement algorithm, but we only focus on three factors, such as fault resistance $r$, zero-correction factors of impedance measurement algorithm $k_o$, and load flow angle $\delta_F$.

![Figure 2. MOV Characteristic.](image)

In this publication, the proposed method was demonstrated for testing a specific algorithm that was implemented for SEL-421 multifunctional fault protection [10] when a circuit compensation $SC_s + MOV_s$ was placed in the middle of a protected transmission line.

2. The Issue of using Circuit Compensation

The application of on the transmission line is one alternative to increase the distribution of electrical power to the load and to improve power system stability [11, 12]. The relative stability of the generator can be improved which is needed by the generator to remain in synchronous condition during the fault [11].

Other on the contrary, problems will arise in the use of capacitors such as voltage inversion and reach of measurement of distance relay protection relays with impedance methods [3]. This condition is affected by series capacitors $SC_s$ and nonlinear $MOV_s$ which can change the characteristics of the line impedance and ultimately produce errors in the calculation of fault impedance $Z_m$.

2.1. Reduction of fault resistance

The use of series compensation circuit can reduce the value of the impedance measured by the located relay, in this case, $X_{CO}$ will compensate the induction reactance $X_L$ and hence the impedance can be expressed as $pX_L = X_L - X_{CO}$.

Figure 3 showed the simulation of fault impedance reduction for fault transmission lines with series capacitors ($SC_s + MOV_s$) with 60% line compensation and placed in the middle of the protected line. For the fault simulated in front of the capacitor (0.45 p.u.) at the point $F_1$, the impedance measurement is correct that is still in zone-1. In this case, series capacitors do not affect the accuracy.
of fault impedance measurement algorithm. The simulation uses the parameters system as shown in table-1 with fault resistance $R_f = 50$ Ω.

When the capacitor is in an active condition that is when the fault at $F_2$ (fault at the border of zone-1, 0.8 p.u.), $SC_s + MOV_s$ will change the characteristics of the fault impedance calculation. As a result, the zone-1 setting becomes overreaching due to the series capacitor; even the measured fault impedance is in zone-3. To avoid operating failure due to errors in calculating fault impedance (overreaching) for a fault at $F_2$ point, the zone-1 can need to be set smaller than 80% of the protected line.

![Mho fault impedance tracking](Image)

**Figure 3.** Mho fault impedance tracking.

2.2. **Reverse Voltage**

The reverse voltage is another problem experienced by IEDs when protecting a line with compensation circuits where $V_{LS}$ and $V_{LR}$ differ by 180°. This occurs when the capacitive reactance negative $X_{CO}$ is greater than the positive reactivity of line $pX_L$ when a fault simulated at point $F_2$. In real conditions, the bus voltage $V_S$ is used by the IED, errors in the calculation of impedance will be generated in the fault of $F_2$. However, the opposite condition can occur if the total fault reactance loop is positive for fault in $F_2$, then the voltage read on the located relay is positive [13] just the same as when the fault occurred at $F_1$. In this condition, the relay will receive the correct voltage information, and the calculation of the impedance error will be accurate unless later affected by uncertainty parameters.

3. **Calculation of fault impedance for compensated line**

The application to analyze fault impedance algorithm as a function of the uncertainty parameters, the simulation of faults between two source terminals with compensation circuit located in the middle of
the line is applied (see Figure 1,4). The schematic of the power system is modeled with a Thevenin equivalent circuit with two sources of $E_S$ and source impedances of $Z_S$ and $Z_R$. All elements are modeled using the DlgSILENT PowerFactory software. In the figure, uncertainty parameters are expressed in red color. Phase A to the ground faults is simulated to see the effect of factors in different locations of $F_1$ and $F_2$ through fault resistance $r$.

For a fault, at $F_1$ (fault in front of $SC + MOV$) the impedance $Z_{ms}$ at the located relay is the same as the uncompensated line (line without series capacitor). The performance index of the impedance algorithm calculated by SEL-421 algorithm is based on measuring voltage and current signals depending on the simulation scenarios.

![Figure 4](image_url)

**Figure 4.** Symmetrical components of two sources for phase-A to ground simulated at $F_2$

The impedance calculation is based on a zero-sequence current compensation method. The factor of $k_0$ depends on the impedance of the zero sequence $Z_{OLS}$, which is not known exactly. For a fault in $F_2$, a different analysis must be applied when $SC + MOV$ and other factors (identified in red color) can affect the accuracy of the impedance calculation. In this case, the fault impedance $Z_{ms}$
measured by the located relay to fault point at $F_2$ (distance = $d + m$) is not always the same as $Z_{LS} + pZ_{LR}$.

One phase fault (phase-A) to ground between series capacitors to the end of the line (fault at/in Figure 1) is more complex. The number of components of the voltage sequence for a fault at $F_2$ when there is a phase fault to the ground can be stated [1] as follow:

$$V_1 + V_2 + V_0 = 3R_F I_F$$

Eq.2 is the positive sequence of voltage, and currently see from terminal S and can be stated as:

$$V_i = V_{iAS} - V_{iLS} I_{LS} - V_{iC} - pZ_{LR} I_{LS}$$
$$V_2 = V_{2AS} - V_{2LS} I_{2S} - V_{2C} - pZ_{2LR} I_{2S}$$
$$V_0 = V_{0AS} - V_{0LS} I_{0S} - V_{0C} - pZ_{0LR} I_{0S}$$

p is expressed as the distance from point O to F2, and the measurement of impedance is then stated with

$$Z_m^r = \frac{V_{SA}^r}{I_{SA}^r} = Z_{LS} + \frac{3R_F I_F + V_C}{I_S^c}$$
$$= Z_{LS} + \Delta Z_{LSR}$$

where $V_{SA}$ is the voltage of phase-A to the ground and $I_S^c$ is $I_{SA}$ of measured phase-A with compensated by the zero-sequence current $I_{0SA}$ which is also measured by the relay and it is stated in.

$$I_{SA}^c = I_{SA} + k_0 I_{0SA}$$

Zero sequence compensation factor $k_0$ is defined as

$$k_0 = \frac{Z_{0LSR} + Z_{1LSR}}{Z_{1LSR}}$$

impedance measurement error $\Delta Z$ (2) is defined as a function of the uncertainty factor $\delta F_{RF}$.

$$\Delta Z = f\left(R_F, \delta F_{RF}\right)$$

4. Fault impedance simulation and Evaluation

The method for testing the SEL-421 algorithm is shown as in Figure 5. The current values $i(t)$ and voltage $v(t)$ for faults simulated at points $F_1$ and $F_2$ are generated by the power system model developed with DIgSILENT PowerFactory. The current and voltage magnitude disturbance measured from secondary CT and VT during the fault at/with system parameters for testing is shown in Table1.

Mho fault impedance for fault simulated in front of the capacitor ($F_1$) and after capacitor ($F_2$) with the random value of fault resistance $R_F$ in the range 0-50 Ω is shown in Figure 6. The capacitor compensation value is determined as 70% of the protected transmission line and equipped with Metal...
Oxide Varistor (MOVₖ) and placed in the middle of the line. Figure 2 is the relationships between series capacitors and MOVₖ which is equated with Rᵥ resistance and Xᵥ reactance. From the figure, it is shown that the characteristics of the two values will depend on the current value of Iᵥ passing through the two components. Concerning this, two different analyses need to be done for at (F₁) and (F₂). Fault at the point F₂ will affect the performance of the algorithm function of the protection relay.

Figure 5. Block diagram of the automation testing.

4.1. Fault in front of the capacitor
Figure 3, 6 is the measurement of fault impedance simulated in front of the capacitor, which is 0.45 p.u with Rᵥ = 50 Ω and power angle δᵥ = 0°. The simulation results show how the measurement of Zₘ impedance is affected by /, which is the deviation from the actual impedance value of pZ₁LS. But when the fault current Iᵥ is supplied by two sources, the closed loop impedance is sensitive not only from Rᵥ but also from δᵥ [1,14].

4.2. Fault behind capacitor
In Figure 3,6 also shows the impedance measurement for the fault simulated after the capacitor, which is 0.8 p.u with Rᵥ = 50Ω and δᵥ = 0°. From the simulation, it is shown how Zₘ impedance measurement error is caused not only the effects of Rᵥ and but also the influence of the presence of the compensation circuit. The calculation of/ for a fault at F₂ is not constant when the values of Rᵥ and Xᵥ depend on current Iᵥ (Figure 2).
Figure 6. Fault impedance, $R_F = 0 - 50 \ \Omega$

Table 1. System parameters for testing.

| Line | [km] | [kV] | [%] | [Ω] | [Ω] | [nF/km] | [nF/km] |
|------|------|------|-----|-----|-----|---------|---------|
| length | 300 | 400 |
| voltage compensation sequence impedance | 60 |
| positive sequence impedance | 8.25+j94.5 |
| zero sequence impedance | 82.5+j308 |
| positive sequence capacitance | 13 |
| zero sequence capacitance | 8.5 |

MOVs

| reference current | [kA] | 1 |
| reference voltage | [kV] | 150 |
| exponent | [-] | 23 |

Sistem R,S

| positive sequence impedance | [Ω] | 1.32+j15 |
| zero sequence impedance | [Ω] | 2.33+j26.6 |
| system frequency | [Hz] | 60 |

5. Conclusion
The method for testing fault impedance algorithm of SEL-421 for protection of line with series compensation circuit has been presented. The developed technique can show that the performance of algorithms that are affected by uncertainty parameters and compensation circuit can be observed. The factor of fault resistance $R_F$ is very dominant in affecting the measurement results even though the relay can still work well for the fault simulated at 0.45 p.u (fault at the front of the SCs). However, the operation failure of the relay occurs for fault after compensation circuit (e.g., fault at 0.8 p.u).
where the effect of $SC_s + MOV_{s,1}$ and other factors will cause the relay to fail, i.e., there is a fault reading to zone-2 or zone-3 for faults simulated in zone-1. The fault simulation scenarios are implemented in DIgSILENT PowerFactory software, and testing automation is carried out through algorithms developed with DPL (DIgSILENT Programming Language).

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