Parametric sensitivity analysis of SEL-421 distance relay algorithms used in compensated line

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Abstract. This paper presents the use of Global Sensitivity Analysis (GSA) methods to analyze the sensitivity level of the performance of the impedance measurement algorithm of SEL-421 distance relay protection when used to perform transmission line protection with compensation circuit. This GSA technique was developed to see the dominance effect of system uncertainty (or factors). Two techniques that might be used for sensitivity analysis using GSA are Quasi-Monte Carlo (QMC) and data sampling with Sobol technique. Experimental is done with DlgSILENT software to do modeling of the power system, simulation, and calculation of impedance and algorithm error. The testing is carried out automatically with the help of the developed algorithm using DPL (DlgSILENT Programming Language). SIMLAB software, in this case, (with Sobol technique) is applied to generate some non-linear factor data and analyze the output of variations in impedance measurement errors.

1. Introduction
Distance relay protection is the safety used on the transmission line and must work properly in the event of a fault to the protected line. When this relay works based on the measurement of the line impedance from where the relay is placed to the fault point, it must be considered the factors that can affect the accuracy of the relay’s work especially if the compensation circuit is used to compensate for the line that is electrically shorter of line impedance [1].

Figure 1 is a model of single line diagram for faults simulation where a series capacitor $SC$, and non-linear $MOV$ are placed in the middle of a protected transmission line. The impedance measurement function of SEL-421 that is placed on one side of the protected line is a very protective relay at the time of the fault. This algorithm uses a closed loop of the positive sequence to calculate fault impedance $Z_m$.

This relay is simple in how it works, but some uncertainty parameters strongly influence the accuracy of the measured fault impedance / (e.g., fault resistance $R_f$, power flow angle $\delta_f$, and correction factor from relay $k_0$, etc.) [2,3]. In this case, the $\Delta Z$ (eq. 6) of fault impedance measurement error will appear in the $Z_m$ calculation.

Due to the value of factors cannot be predicted and greatly influence the IEDs performance, the testing of IEDs need to be done. Performance of testing for IEDs against only the influence of one uncertainty factor on the protection performance of the line with compensation circuit line has been carried out by researchers [3,4-6], but testing to analyze the effect of some factors simultaneously to the performances of the algorithm has not been carried out.
Figure 1. Model of power fault simulation

\[ F_1 \text{ - fault before } SC_S + MOV_S \]
\[ F_2 \text{ - fault after } SC_S + MOV_S \]

To test the accuracy of the algorithm, simulation of fault in phase-A to the ground is carried out at points \( F_1 \) and \( F_2 \) where some factors that affect the performance of the relay algorithm are as shown in Figure 1 with red color. In previous studies, a statistical approach was used in system performance analysis [7], namely Global Sensitivity Analysis (GSA)[8]. In this paper, this technique will be used to analyze the performance of the SEL-421 distance relay algorithm for fault impedance measurement. Figure 5 shows an automatic method for the testing algorithm of the compensated transmission line, where the combination of DiGSEILNT PowerFactory software [9], SIMLAB software [8] has been used. From the Figure, the program’s DPL was developed to carry out the testing process automatically.

2. Effect of uncertainty on impedance measurement

To analyze the parameter uncertainty of the impedance measurement algorithm with the compensation circuit, as shown in Figure 1. For this purpose, Figure 2 shows a symmetrical component of two-sources where phase A to ground fault is necessarily simulated after compensation circuit that is at fault location point of \( F_2 \), with sequence component of voltage and current. The fault impedance calculation by the SEL-421 algorithm is based on the value of current and voltage, which is identified locally by the located relay. Summing the sequence of voltage components in phase-A fault to the ground in \( F_2 \) is explained as follow [1]:

\[ V_1 + V_2 + V_0 = 3R_F I_F \]  

(1)

The sequence of voltage in (1) is determined by the sequence components of the voltage and current on the S side of the line, to produce
Where

- \( p \) = distance from the relaying point to the fault point \( F_2 \)
- \( V_C \) = voltage dropt in \( SC_S + MOV_S \)

and the measured impedance for the fault at point \( F_2 \) behind series capacitor is stated as:

\[
Z_m^R = \frac{V_{SA}}{I_{SA}} = Z_{1LSR} + 3R_F \frac{I_F}{I_{SA}} + \frac{V_C}{I_{SA}} = Z_{1LSR} + \Delta Z_{1LSR}
\]

where \( V_{SA} \) is a phase-A voltage measurement to the ground and the \( I_{SA} \) current measured from phase-A is compensated by the current sequence of \( I_{SA} \) which is also measured by the relay

\[
I_{SA}^C = I_{SA} + k_0 I_{0SA}
\]

the zero order compensation factor \( k_0 \) is defined by

\[
k_0 = \frac{Z_{0LSR} - Z_{1LSR}}{Z_{1LSR}}
\]

From the description above it can be concluded that the impedance error measurement for disturbances after/as a factor function is

\[
\Delta Z = f(R_F, \delta_F, k_0)
\]

The effect of factors on errors in the process of measuring the impedance of the fault is simulated through Figure. 1 with system parameters as shown in Table-1. Zone-1 of positive-sequence (see Figure 3, 4) is set to 80% and 120% for zone-2 settings. Figure 3 shows that the impedance measurement is influenced by the \( R_F \) and by power flow angle \( \delta_F \). As in Figure 4, the compensation circuit of \( SC_S + MOV_S \) also contributes to impedance measurement error.
Figure 2. Symmetrical components of two sources for phase-A to ground simulated at $F_2$.

Figure 3. Faults impedance simulated in front of the series capacitor.
Figure 4. Faults impedance simulated behind of series capacitor

The following are the used system parameters

Table 1. Characteristic system.

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

Table 2. Uncertain value of factors

| Line            | [Ω]   | [Hz]   | [Ω]   | [Ω]   | [Ω]   |
|----------------|-------|--------|-------|-------|-------|
| fault resistance | [R_f] | 0 – 50 Ω | 1.32+j15 | 2.33+j26.6 | 60 |
| load flow angle | [δ_f] | 10° ± 10% |         |         |       |
| k_0            | [-]   | 0.794 ± 5% |         |         |       |
The effect of the uncertainty factor (in Table-2) will cause uncertainty in measuring impedance $Z_m$. Figure 3 and Figure 4 show the result of fault impedance as a function of factors and simulated in front and behind $SC_c + MOV_s$. It is shown that fault impedance measurement for the faults simulated before and after the capacitor will change the impedance measurement propagation.

3. Sensitivity analysis of impedance measurement algorithm

GSA with the QMC technique requires a large computation time, so this technique is very suitable for small parameter vectors. Figure 5 is the methodology for testing the sensitivity of parameter where the uncertainty of the performance indexes $f(x)$ is measured using the variance value of fault impedance error. Part of the performance index that is determined by the uncertainty factor can be used to assess the dominance of factor $x_i$. This calculation is carried out by calculating the average values of all sample parameters, except $x_i$ (kept constant for a single calculation). Furthermore, the calculation of variance of error for different $x_i$ can be expressed as:

$$V_i = V\left\{ E \{ f(x) \mid x_i \} \right\}$$  \hspace{1cm} (7)

The expected computation $E(*)$ is calculated with multidimensional integrals using the QMC approach and Sobol’s sample technique. The effect of parameter $x_i$ on the performance index $f(x)$ can be expressed by

$$S_i = \frac{V\left\{ E \{ f(x) \mid x_i \} \right\}}{V\left( f(x) \right)}$$  \hspace{1cm} (8)

$V\left( f(x) \right)$ is the total performance index and stated with

$$V\left( f(x) \right) = V\left\{ E \{ f(x) \mid x_i \} \right\} + E \{ f(x) \mid x_i \}$$  \hspace{1cm} (9)

then the interaction effect between factor $x_i$ and $x_j$ is stated with

$$V_{ij} = V\left\{ E \{ f(x) \mid x_i, x_j \} \right\} + V\left\{ E \{ f(x) \mid x_j \} \right\} - V\left\{ E \{ f(x) \mid x_i \} \right\}$$  \hspace{1cm} (10)

Where $V\left\{ E \{ f(x) \mid x_i, x_j \} \right\}$ is the interaction of the effects of $x_i$ and the model output. Finally, for $n$ parameters, the total index performance can be composed as $(x)$, otherwise known as Analysis of Variance decomposition (ANOVA)

$$V\left( f(x) \right) = \sum_{i=1}^{n} V_i + \sum_{i=1}^{n} \sum_{j=i+1}^{n} V_{ij} + V_{1,2,...,n}$$  \hspace{1cm} (11)

4. Result and analysis

Figure 1 is a model of testing techniques for simulating phase-A disturbances to the ground along a protected line by DigSILENT PowerFactory software [9]. The uncertainty factor values are uniformly distributed with intervals as in Table-2. Figure 5 is a developed test method, where the algorithm
performance testing is done by SIMLAB software [10] based on the Sobol’s quasirandom sequence technique and also used for statistical calculations to measure the sensitivity of algorithms based on the GSA method.

![Figure 5. Methodology for parameter sensitivity testing.](image)

Computational sensitivity indices that are computed by SIMLAB are shown in Figure 6,7. The results shown are the results of statistical calculations, which are calculated based on 1024 samples of uncertainty parameters value and simulated for the three fault locations in front and behind $SC_i + MOV_i$. The conclusion of these graphs can be analyzed as follows:

1. Effect of fault resistance $R_f(x_1)$, power flow $\delta_f(x_2)$ and zero-sequence compensation $k_0(x_3)$ are high to the performance of the algorithm for the fault simulated at 0.3 p.u. in front and behind $SC_i + MOV_i$, but the effect of fault resistance still more dominant.

2. For a fault at 0.6 p.u.,0.9 p.u. in front and behind/uncertainty parameters does not affect the measurement impedance, but for a fault at 0.6 p.u after capacitor, the effect of zero-sequence compensation $k_0(x_3)$ is higher. However, for distribution of impedance measurements that is as shown in Figure 3 and Figure 4, impedance measurement errors may be caused by the influence of compensation circuit of $SC_i + MOV_i$. 
5. Conclusion
This paper presents a sensitivity analysis for the impedance calculation algorithm of the IED that is used to protect the transmission line with capacitor compensation. It can be seen that the effect of the accuracy of the algorithm is influenced by not only the influence of the system uncertainty but also effect of the influence of $SC_s + MOV_s$. The influence of these factors on the performance of IED has been tested by changing the value of factors simultaneously for each test. For the testing, multidimensional requirements of the factors are sampled using the Sobol’s quasi-random sequence. From the result, it is shown that the effect of factors to the performance of IED is high for the fault simulated 0.3 p.u before and after compensation circuit but the effect of fault resistance is still dominant. At 0.6 p.u after compensation circuit effect of zero-sequence of compensation is high. The procedure is done
automatically using algorithms developed with DPL (DIGSILENT Programming Language) and integrated with SIMLAB to analyze variations of output and calculate the sensitivity of impedance measurement algorithms.

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