A Study of Single Ended Fault Locator on SEL Relay

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ABSTRACT

Locating transmission line faults quickly and accurately is very important for economy, safety and reliability of power system; therefore fault location become an important supplementary function in numerical relays. These fault location algorithm typically rely on the calculation of impedance from the fundamental frequency voltage and current phases measured in the substation. Because of the same signals as the other protection and measurement functions in the numerical relays, impedance based methods have become a popular means of transmission line fault locating.

This paper presents fault location algorithms based on the single terminal method of SEL using impedance measurement. A 220 kV, 69.9 km transmission line and SEL-421 type numerical relay selected as examples for fault simulation and relay testing. Matlab simulation results show the method is a good and powerful tool to help identify the correct fault location for fault resistance and load current inaccuracies on the transmission line when fault occurs.
Keywords: *Fault classification, fault location, transmission line, matlab/simulink.*

INTRODUCTION

Application fault location on overhead lines where require high reliability is important. Accurate, consistent results for all types of faults quickly displayed in a control room or engineering center where the information need to direct maintenance teams in the fast restoration of power, particularly on transmission lines with distributed loads. Power system operators can identify and isolate faulted sections on tap-loaded lines and remove them by opening circuit breakers or switches remotely along the line, restoring power to the tap loads serviced by the un-faulted transmission sections (Saha and Izykowski, 2009).

Fault location data that is readily available from the numerical relays. The data includes voltages, currents, relay elements, and relay inputs and outputs in both relays on each terminal with sequence of event recording, historical event logging, and oscillographic of event data. In addition to fault location, reports also shows the calculated fault location, time and date of event, and relay settings.

As a result, the location error of Toshiba is a maximum of ±2.5 km for faults at a distance of up to 100 km, and a maximum of ±2.5% for faults at a distance between 100 km and 250 km (Toshiba, 2006) or accurate fault location of Siemens is ≤ 2.5% of line length (without intermediate infeed) (Siemens, 1995) and Areva is ≤ 5% (Areva, 2010).

In this paper, a fault location algorithm of SEL using only one terminal data is a popular means of transmission line fault locating. It implements to the SEL-421 relay and a simulated power system. In addition, results show that algorithm consistently and significantly yielded accurate location of the actual fault, the content needed to meet challenge for training of protection engineers which describe in detail below.

IMPEDANCE BASED FAULT LOCATION METHOD

Various fault location methods, with acceptable accuracy for most of the practical applications, have been developed using one end techniques. These techniques utilise measurements of three-phase current and three-phase voltage from one line end. Fault locators calculate the fault location from the apparent impedance. An example system is shown in Figure 1. To locate all fault types, the phase to ground voltages and currents in each phase must be measured. (If only line to line voltages are available, it is possible to locate phase to phase faults; if the zero sequence source impedance, Z_0, is known, we can estimate the location for phase to ground faults).

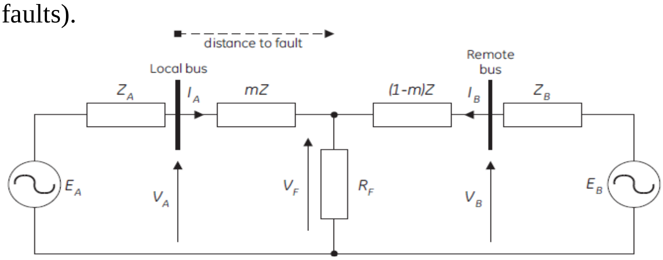

Figure 1: Equivalent system for fault location

Simple Reactance Method

From Figure 1, the voltage drop from the A end of the line is:

$$V_A = m.Z.I_A + R_F.(I_A + I_B) \quad (1)$$

If the fault resistance (R_F) is assumed to be zero, we can use one of the impedance calculations in Table 1 to estimate the fault location. Save the imaginary part, and solve for *m* [1]: $\mathrm{Im}(V_A/I_A)=Im(m.Z_{1L})$ = m. X_{1L}

$$m = \frac{\mathrm{Im}(V_A/I_A)}{X_{1L})} \quad (2)$$

Table 1: Simple Impedance Equations

Fault type	Positive-Sequence Impedance Equation (mZ1L =)
AG	$V_A^A/(I_A^A + K_0 I_{0A})$
BG	$V_A^B/(I_A^B + K_0 I_{0A})$
CG	$V_A^C/(I_A^C + K_0 I_{0A})$
AB or ABG	$(V_A^A - V_A^B)/(I_A^A - I_A^B)$
BC or BCG	$(V_A^B - V_A^C)/(I_A^B - I_A^C)$
CA or CAG	$(V_A^A - V_A^C)/(I_A^A - I_A^C)$
ABC	All three AB, BC, and CA loops are analyzed and the final result is selected based upon consistency of the results.

Where:

K_0 is $(Z_{0L} - Z_{1L})/3Z_{1L}$

Z_{0L} is the zero-sequence line impedance.

Z_{1L} is the positive-sequence line impedance.

m is the per unit distance to fault (for example: distance to fault in kilometers divided by the total line length in kilometers).

I_{0A} is the zero-sequence current.

Reviews: For an ideal homogeneous system, these angles are identical. As the angle between I_A and I_F Increases, or $R_F \neq 0$, the error in the fault location estimate increases.

Takagi Method

The method requires prefault and fault data. It improves upon the simple reactance method by reducing the effect of load flow and minimizing the effect of fault resistance. The key to the success of the Takagi method is that the angle of I_A is the same as the angle of I_F.

From equation (1), the currents from the local and remote systems can be parted between their fault (F) and pre-fault load (pre) components:

$$I_A = I_{AF} + I_{Apre} \tag{3}$$

and neglecting shunt parameters of the line:

$$I_B = I_{BF} - I_{Apre} \tag{4}$$

Inserting the I_A and I_B equations into the V_A equation and solving for the fault resistance yields:

$$R_F = \frac{V_A - m.Z.I_A}{I_{AF}(1 + I_{BF}/I_{AF})} \tag{5}$$

Assuming the fault components of the currents, I_{AF} and I_{BF} are in phase, and observing that the fault resistance, as impedance, does not have any imaginary part gives:

$$\mathrm{Im}\left(\frac{V_A - m.Z.I_A}{I_{AF}(1 + I_{BF}/I_{AF})}\right) = 0 \tag{6}$$

Where: Im() represents the imaginary part of a complex number.

Solving the above equation for the unknown m creates the following fault location algorithm:

$$m = \frac{\mathrm{Im}(V_A.I_{AF}^*)}{\mathrm{Im}(m.Z.I_{AF}^*)} \quad (7)$$

Where: * denotes the complex conjugate and $I_{AF} = I_A - I_{Apre}$.

Modified Takagi

Another method (modified Takagi) uses zero-sequence current (I_{0A}) for ground faults instead of the superposition current. Therefore, this method requires no prefault data. Modified Takagi also allows for angle correction. If the user knows the system source impedances, the zero sequence current can be adjusted by angle T to improve the fault location estimate for a given line (Zimmerman and Costello).

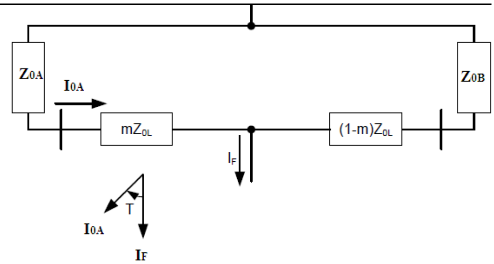

Figure 2: Zero-Sequence Current Angle Correction

$$m = \frac{\mathrm{Im}(V_A.I_{0A}^*.e^{-jT})}{\mathrm{Im}(Z.I_A.I_{0A}^*.e^{-jT})} \quad (8)$$

The angle T selected will be valid for one fault location along the line. Figure 2 shows how to calculate T.

TESTING FAULT LOCATOR IN SEL-421 RELAY

SEL developed the SEL421distance relay with fault locator. It can provide high speed and time-delayed protection for transmission and distribution lines. Analog inputs from current and voltage transformers delivered to the protective relaying element to locate a fault. The relay uses fault location methods: the simple reactance method, or the Takagi method, or modified Takagi (Schweitzer Engineering Laboratories, 2011).

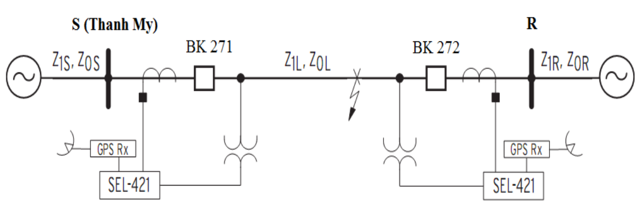

Figure 3: Schematic diagram of one-end fault location

This application example is for a double-ended 230 kV overhead transmission line with SEL-421 protection at each end, which shows in Figure 1. To verify the feasibility of the SEL's fault location function that was implemented on the relay SEL 421 (S/N: 2007134228) at overhead line 271 of 500kV substation Thanh My in Viet Nam. Testing of the fault locator function in the relay is comprised of the following steps:

The first, perform to build a tool calculate distance fault that writes by Matlab GUI based on the above-mentioned methods are represented in figure 4. Impedance based methods require voltage and current phasors recorded by the relay during the fault. They also require positive and zero-sequence line impedance per unit length (Z_{1L} and Z_{0L} in Ω/km) and pre-fault load current. The relay fault locator uses the values you enter for calculate the distance to fault in kilometres.

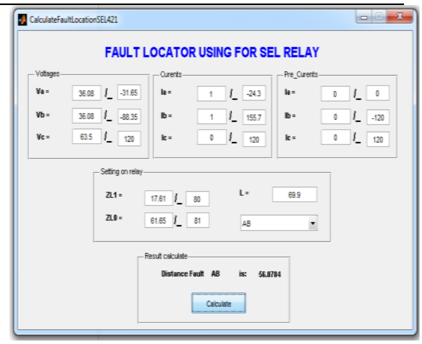

Figure 4: Tool calculate distance to fault

The next, we use the PC-based Acselerator QuickSet or Command Prompt in Window 7 to configure the SEL-421 and analyze fault records with relay element response. The SEL-421 has Mho characteristic options for five zones. We have set four zones of phase and ground distance protection and applied faults by using constant current methods. The setting parameters applied with the Line Configuration, Phase Distance Elements and Ground Distance Elements in the relay is:

Line Configuration:	**Phase Distance Elements:**	**Ground Distance Elements:**
Z1MAG = 17.61	Z1P = 14.09Ω	Z1MG = 14.09Ω
Z1ANG = 80^0	Z1PD = 0 cycles	Z1GD = 0 cycles
Z0MAG = 61.65	Z2P = 21.13Ω	Z2MG = 21.13Ω
Z0ANG = 81^0	Z2PD = 15 cycles	Z2GD = 15 cycles
LL = 69.9km	Z3P = 1.41Ω	Z3MG = 1.41Ω
	Z3PD = 75 cycles	Z3GD = 75 cycles
	Z4P = 42.26Ω	Z4MG = 42.26Ω
	Z4PD = 75 cycles	Z4GD = 75 cycles

Further, test faults performed by Omicron's CMC 256 that is the ideal equipment for testing of all relay generations (electromechanical, static, numerical, IEC 61850 IEDs) requiring very high accuracy. The CMC 256 used to generate the 3 phase fault currents and voltages (show on fig 5) which exactly simulates the fault types (Omicron, 2012).

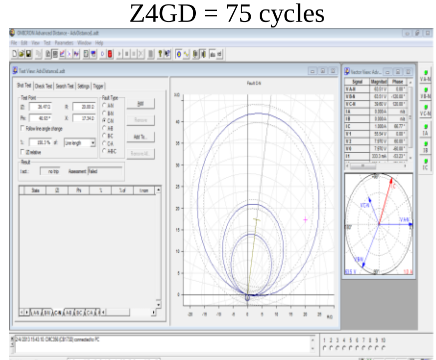

Figure 5: Advanced distance test view

The relay will record a fault report when the relay issues a trip. This report is an ASCII text file providing information regarding the fault as seen by the relay. Typical information included in this type of report is trip time, targets, distance to fault, pre-fault current and voltage quantities, and post-fault current and voltage quantities… as shown in figure 6 (Schweitzer Engineering Laboratories, 2011).

Finally, we read the disturbance report and compare with values which are calculated by a tool calculate distance to fault. The results for the checking can be seen in table 2.

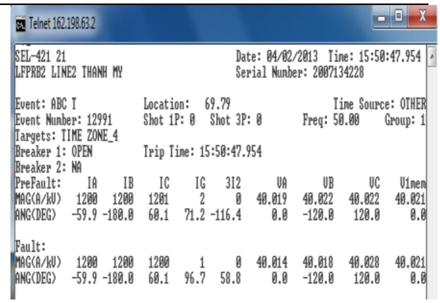

Figure 6: Event recorded

Table 2: Results checked on relay

Parameter injection	Calculated fault location [km]	Measured fault location [km]	%Error
$V_a = 1\angle 80^0$; $I_a = 1\angle 0^0$	2.16	2.15	0.015
$V_b = 16\angle -39^0$ $I_b = 1\angle -120^0$	34.67	34.62	0.072
$V_c = 32.43\angle 120^0$; $I_c = 1\angle 42.04^0$	69.58	69.36	0.315
$V_a = 1\angle 80^0$; $I_a = 1\angle 0^0$ $V_b = 1\angle 260^0$; $I_b = 1\angle -120^0$	3.56	3.26	0.43
$V_b = 12\angle -40^0$; $I_b = 1\angle -120^0$ $V_c = 12\angle 140^0$; $I_c = 1\angle 60^0$	47.63	47.77	0.201
$V_a = 24.36\angle 0^0$; $V_b = 24.36\angle -120^0$; $V_c = 24.36\angle 120^0$; $I_a = 1\angle -34.83^0$ $I_b = 1\angle -154.83^0$; $I_c = 1\angle 85.17^0$	56.07	55.91	0.229

Reviews: when we generate fault type (AG, BG, CG AB, BC and ABC), the measuring tolerances is smaller than 1 %.

SIMULATION STUDIES

This section presents the simulation results to evaluate the developed fault location algorithm of SEL relays. The Simulink model used to simulate the algorithm used is shown in the Figure 7. The studied power system is a 220 kV, 125 MVA, 50 Hz, 69.9 km transmission line system.

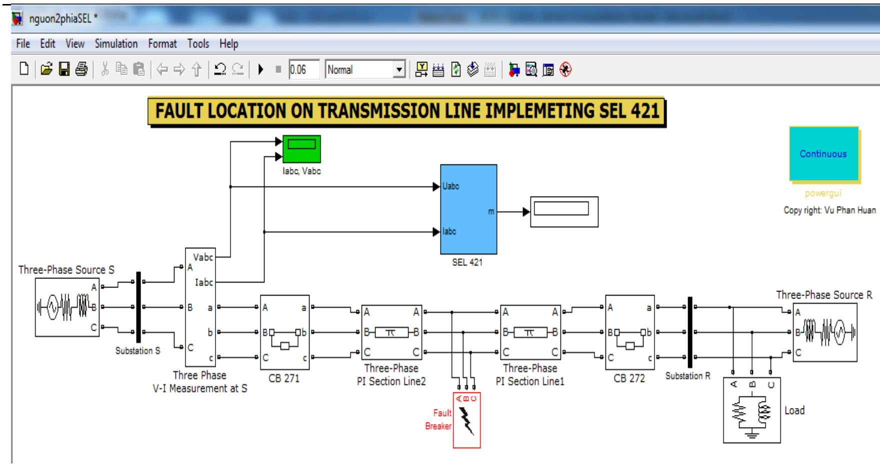

Figure 7: The simulink model used to simulate the developed algorithm

This model consists of (TEQSIM International Inc., 2000):

1. The transmission line: three phase section line is used to represent the transmission line. Line sequence impedance:
   - R_{L1}=0.0437 (Ω), R_{L0}=0.138(Ω).
   - L_{L1}=0.78973 (mH), L_{L0}=2.8(mH).
   - C_{L1}=0.038 (μF), C_{L0}=0.038 (μF).
2. Three-phase measuring blocks to measure the three phase line and load current and voltage values.
3. A numeric display block to indicate the calculated random per unit length of the fault location.
4. Three phase fault block to deduce fault types and specify the parameters.
5. Mathematical block to calculate the per unit length of the fault location, using the methods in section II.

The simulation of the algorithm is focused on all fault types that occupies about (1 to 100) % of the transmission line faults at 0.06s. The results of the simulations are the voltage and current waveforms of the three phases at the header of the line, the same information that can be obtained from real faults. The voltage and current phasors are found taking the fundamental frequency by using the fast Fourier transform. With the phasors and the model of the network, now the algorithms can be computed where fault locate on results shown on table 3.

Table 3: The fault location results under various fault locations on the line.

Type fault	Resistance Fault [Ω]	Actual fault Location [km]	Measured fault Location [km]	%Error
AG	1	1	1.002	0.003
	10	15	15.08	0.115
	20	30	30.19	0.272
	30	45	45.43	0.616
	40	60	61.64	2.347
BG	1	1	1.002	0.003
	10	15	15.08	0.115
	20	30	30.19	0.272
	30	45	45.44	0.63
	40	60	61.72	**2.461**
CG	1	1	1.007	0.011
	10	15	15.08	0.115
	20	30	30.19	0.272
	30	45	45.43	0.616
	40	60	61.63	2.332
AB	1	1	0.9912	0.013
	10	15	14.9	0.144
	20	30	30.0	0
	30	45	44.77	0.33
	40	60	58.6	2.003
BC	1	1	1.011	0.016
	10	15	14.9	0.144
	20	30	30.05	0.072
	30	45	44.94	0.086
	40	60	59.23	1.102
AC	1	1	1.009	0.013
	10	15	15.03	0.043
	20	30	29.22	1.116
	30	45	44.84	0.229
	40	60	58.85	1.646
ABG	1	1	0.9908	0.014
	10	15	14.9	0.144
	20	30	30.0	0
	30	45	44.77	0.33
	40	60	58.6	2.003
BCG	1	1	1.011	0.016
	10	15	14.9	0.144
	20	30	30.05	0.072
	30	45	44.94	0.086
	40	60	59.24	1.088
ACG	1	1	1.009	0.013
	10	15	15.03	0.043

	20	30	29.22	1.116
	30	45	44.85	0.215
	40	60	58.85	1.646
ABC	1	1	1.013	0.019
	10	15	15.04	0.058
	20	30	30.06	0.086
	30	45	44.95	0.072
	40	60	59.22	1.116

Reviews: the measuring tolerances are smaller than 2.5 % of the line length.

The estimation accuracy is evaluated by the percentage error calculated as:

$$\%Error = \frac{\left|\text{Actual Location - Estimated Location }\right|}{\text{line the of Length Total}} \times 100$$

Where the location of the fault is defined as the distance between the bus at which the measuring equipment are installed, and the fault point. As can be seen, the fault location estimates are satisfactory.

CONCLUSION

Conclusions of the discussions presented in the paper can be summarized as follows:

- The paper considers aspects of using substation relay data; primarily event triggered data collected from substation SEL421, for fault location calculation.
- This method was simulated using MATLAB and is tested for fault resistance for various types of faults and various fault location.
- SEL use algorithms that correct for fault resistance and load current inaccuracies. Line length accuracies of ± 2.5% are typical for single-ended locators systems. Simulation studies have shown that the algorithm will help reduce outage time, save money, and improve system reliability.

REFERENCES

Areva, *Feeder Management and Bay Control P132*, 2010.

GE Multilin (2009), *L90 Line Current Differential System, UR Series Instruction Manual*.

Karl Zimmerman and David Costello, *Impedance-Based Fault Location Experience*, Schweitzer Engineering Laboratories.

MM Saha, J Izykowski (2009), *Fault location on power networks*, Springer.

Omicron (2012), *CMC-356 user manual*.

Schweitzer Engineering Laboratories (2011), *SEL-421 Relay Protection and Automation System*.

Siemens, *Introduction manual numerical distance protection relay Siprotec 7SA511*, 1995.

TEQSIM International Inc, a sublicense of Hydro-Quebec, and The Mathworks Inc (2000), *Power System Blockset User's Guide*.

Toshiba, *Introduction manual distance relay GRZ100*, 2006.