NEW MULTI-ENDED FAULT LOCATION DESIGN FOR TWO- OR THREE-TERMINAL LINES

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INTRODUCTION

This paper presents a new fault location system for multi-terminal transmission lines. The algorithm used by this system is suitable for inclusion in a numerical protection relay, which communicates with remote relay(s) over a protective relaying channel. The data volume communicated between relays is sufficiently small to be easily transmitted using a digital protection channel. The new algorithm does not require data alignment, pre-fault load flow information, phase selection information, and does not perform iterations to calculate the distance to the fault. Pre-fault load flow, zero-sequence mutual coupling, fault resistance, power system nonhomogeneity, and current infeeds from other line terminals or tapped loads do not affect the fault location accuracy.

Transmission line fault location has been the subject of interest to utilities and researchers since the early 1950s (1). Accurate fault location information helps operators and utility personnel to expedite service restoration, reduce outage time, operating costs, and customer complaints.

Impedance-based fault location techniques make use of fundamental frequency voltages and currents, and can be classified in single-ended and multi-ended methods.

Single-ended, impedance-based fault location has become a standard feature in most microprocessor-based protective relays (2-5). This methodology is attractive because it is simple, fast, and does not require communications. Applications with strong zero-sequence mutual coupling, higher fault resistance, tapped loads, and nonhomogeneous power systems challenge the accuracy of single-ended fault location methods (2). To date, the simple reactance and the Takagi-based (3) are the two major single-ended fault location algorithms.

The simple reactance method works reasonably well for homogeneous systems when the fault does not involve significant fault resistance and load current. Large errors are introduced to the fault location estimate by remote-end current feed, load impedance, power transmission angle, and differing angles of line and power system source impedances.

Takagi et al (3) improved the simple reactance method by introducing a new single-ended method that calculates the reactance of a faulted line, and provides some correction to errors caused by various factors such as load flow, and fault resistance. Schweitzer (2) recognized the limitations of both the reactance and Takagi methods, and introduced the modified Takagi algorithm. This new method improves the performance of the Takagi algorithm when some system data are available.

Takagi et al (3), and Erikson et al (5) proposed single-ended fault location techniques that utilized both pre-fault and post-fault currents, and post-fault voltages at one line terminal. Their technique required current distribution factors and impedances of equivalent sources behind the relay terminals. Source impedance variations due to line switching or generation variations influence the current distribution factors and introduce errors in the fault location estimate.

Two-ended impedance-based fault locating methods can improve upon the accuracy of single-ended methods. Schweitzer (2) introduced a two-ended method, which did not require source impedance data, or synchronized sampling at the two ends of the line. However, the method in (2) required knowledge of pre-fault load flow information for phase alignment.

Existing two-ended methods (2, 7-9) require the phase alignment of data sets captured at both ends of a monitored line using pre-fault load flow information, iterative methods, and communication of a significant amount of data between relay terminals. In addition, a number of multi-terminal methods (7,9-10) are not applicable to overhead lines with zero-sequence mutual coupling.

NEW APPROACH TO MULTI-ENDED FAULT LOCATION

Two-Terminal Lines

The new method uses negative-sequence quantities from all line terminals for the location of unbalanced faults. By using negative-sequence fault quantities, we overcome the difficulties associated with pre-fault load flow, overhead line zero-sequence mutual coupling effects, and zero-sequence current infeeds from tapped loads along the transmission line. The algorithm employed at each line end uses uses the following quantities from the remote terminal:

- Magnitude of negative sequence current, $|I_2|$.
- Calculated negative sequence source impedance, $Z_2\angle\theta_2°$

Consider the sequence connection diagram shown in Figure 1 for a single line-to-ground fault. The negative-sequence voltage (V_{2F}) at the fault is the same when viewed from either end of the protected line.

At Relay S: $V_{2F} = -I_{2S} \cdot \left(Z_{2S} + m \cdot Z_{2L}\right)$ (1)

At Relay R: $V_{2F} = -I_{2R} \cdot \left(Z_{2R} + (1-m) \cdot Z_{2L}\right)$ (2)

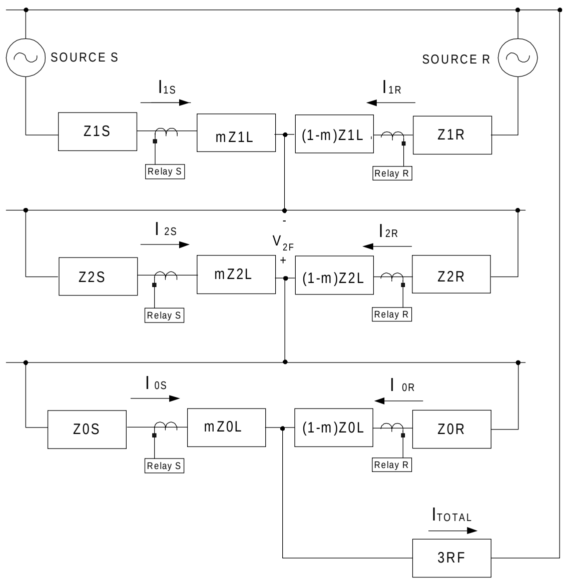

Figure 1: Connection of Sequence Networks for a Single Line-to-Ground Fault at m

By eliminating V_{2F} from Equations 1 and 2 and rearranging the following expression results:

$$I_{2R} = I_{2S} \cdot \frac{\left(Z_{2S} + m \cdot Z_{2L}\right)}{\left(Z_{2R} + (1-m) \cdot Z_{2L}\right)} \tag{3}$$

Taking the magnitude from both sides of Equation 3 and rearranging we get Equation 4.

$$\left|I_{2R}\right| = \frac{\left|\left(I_{2S} \cdot Z_{2S}\right) + m \cdot \left(I_{2S} \cdot Z_{2L}\right)\right|}{\left|\left(Z_{2R} + Z_{2L}\right) - m \cdot \left(Z_{2L}\right)\right|} \tag{4}$$

Taking the square of both terms of Equation 4, expanding and rearanging terms yields a quadratic equation of the form:

$$a \cdot m^2 + b \cdot m + c = 0 \tag{5}$$

Equation 5 can be solved for m using a quadratic solution.

The above mathematical derivation, indicates that the relay at each line terminal of the two-terminal line must transmit a minimal amount of information. The information sent by Relay S for a two-terminal application is:

1. The magnitude of the negative sequence current, $| I_{2S} |$
2. The magnitude of the negative sequence source impedance, $| Z_{2S} |$
3. The angle of negative sequence source impedance, $\theta_{2S}°$

Using the above information combined with the negative sequence quantities measured by each relay, we can solve for the fault location at each terminal without iterations.

Three-Terminal Lines

Many times utilities connect another line with a positive-sequence source to an existing two-terminal line. Such lines are much more complex to protect using conventional distance and directional protection schemes. These same lines present great difficulty in the task of fault location. Figure 2 shows a double-circuit three-terminal transmission line arrangement.

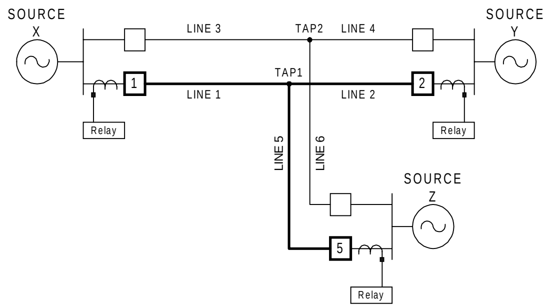

Figure 2: Typical Double-Circuit Three-Terminal Application

Let us assume that we have fault locating devices at each end of a transmission line. For a single-line-ground fault on Line 1 in Figure 2, the relays at terminals 1, 2, and 5 operate to clear the fault and at the same time exchange a minimal amount of information over a protection channel for the purpose of accurate fault location.

The sequence connection diagram in Figure 3 assumes a single-line-ground fault located m per-unit distance from Bus X, which is connected to Source X. Note that the parallel three-terminal line was omitted to simplify the diagram and the explanation of the algorithm without loss of accuracy. With the fault on Line 1, we observe that the negative-sequence voltage at the tap can be calculated by Relays 2 and 5 and the calculated tap voltage, $V_{2TAP,}$ is the same, if we assume for the moment that the relays sample synchronously.

Fault location knowledge on Line 1 is not required to accurately calculate V_{2TAP} at Relays 2 and 5. Instead, the required parameters are the negative-sequence line impedances from Relay 2 and Relay 5 to the tap point, and the negative-sequence voltage and current phasors measured by the relays.

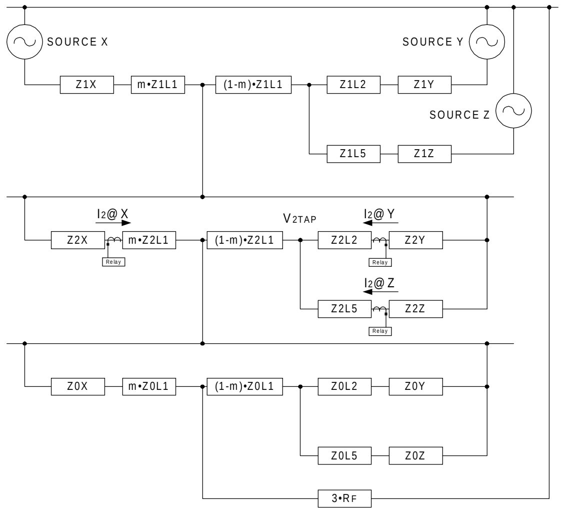

Figure 3: Sequence Network Connection for Three-Terminal System

Each relay calculates V_{2TAP} as follows:

At Relay 1: $V_{2TAP@1} = V_{2@1} - Z_{2L1} \cdot I_{2@X}$
At Relay 2: $V_{2TAP@2} = V_{2@2} - Z_{2L2} \cdot I_{2@Y}$

At Relay 5: $V_{2TAP@5} = V_{2@5} - Z_{2L5} \cdot I_{2@Z}$

For faults on Line 1, $|V_{2TAP@2}| = |V_{2TAP@5}|$. Each relay calculates V_{2TAP} and transmits this information to the remote terminals. Once each relay receives the calculated tap voltage from the other two terminals it proceeds with the identification of the faulted section by comparing the magnitudes of $|V_{2TAP@1}|$, $|V_{2TAP@2}|$, and $|V_{2TAP@5}|$, along with the calculated single-ended fault location values. The faulted line section is the one whose V_{2TAP} voltage magnitude does not equal the V_{2TAP} calculated by the other two relays. In the example shown in Figure 3, $|V_{2TAP@2}|$ and $|V_{2TAP@5}|$ have the closest magnitude match.

Once the fault location system identifies the faulted line section, Relay 2 and Relay 5 calculate an apparent negative-sequence source impedance by the parallel combination of $(Z_{2L2} + Z_{2Y})$ and $(Z_{2L5} + Z_{2Z})$. This conversion is simply $V_{2TAP}/(I_{2@Y} + I_{2@Z})$. $I_{2@Y}$ and $I_{2@Z}$ from Relays 2 and 5 cannot be added directly without phase alignment because the relays sample the power system analog quantities asynchronously. The alignment angle between Relays 2 and 5 is simply calculated as the $\angle(V_{2TAP@2}/V_{2TAP@5})$. After determining this angle, Relay 2 phase shifts the negative-sequence current from Relay 5 and adds the result to its own negative-sequence current. Relay 5 performs a similar calculation, and both relays then calculate an apparent negative-sequence source impedance from the tap looking into the power system.

The minimal information sent by each relay to each of the other relays in the three-terminal application is:

1. Magnitude of the negative sequence current $|I_{2RELAY}|$
2. Angle of the negative sequence current $\angle I_{2RELAY}$
3. Magnitude of the negative sequence voltage $|V_{2TAP}|$
4. Angle of the negative sequence voltage $\angle V_{2TAP}$

From the above information, each relay determines the faulted line section, reduces the three-terminal line arrangement into a two-terminal equivalent and applies the two-terminal methodology described earlier to calculate the location of the fault. After each relay calculates its multi-ended fault location, it calculates the total fault current and fault resistance R_F. The power system operator can then interrogate any relay to determine the correct fault location

ALGORITHM TESTING AND RESULTS

The algorithm presented above has been tested extensively using steady-state and transient methods. The next two sections of the paper describe the results of this algorithm and its comparison it to single-ended algorithms.

Steady-State Testing

Figure 2 shows the example three-terminal system we modeled to test the algorithm. Table 1 shows the results of the new method as compared to single-ended methods.

Legend:

I_{2P}	Single-Ended Negative-Sequence Current Polarized Fault Locator
X,Y,Z	Terminals X, Y, and Z

From the data in Table 1, we see that the new method of fault location described in this document out-performs the single-ended method.

Table 1: Fault Location Results for a Three-Terminal Line

Fault on Line 1 m p.u. from Terminal X	New Algorithm at R-1	Relay-1 with I2p at X	Relay-3 with I2p at Y	Relay-5 with I2p at Z
0.0	0.0	0.00	14.74	13.63
0.1	0.1	0.09	12.24	11.50
0.2	0.2	0.18	10.41	9.86
0.3	0.3	0.27	8.89	8.47
0.4	0.4	0.36	7.56	7.23
0.5	0.5	0.45	6.34	6.09
0.6	0.6	0.54	5.20	5.00
0.7	0.7	0.62	4.10	3.96
0.8	0.8	0.70	3.05	2.96
0.9	0.9	0.77	2.03	1.97
1.0	1.0	0.75	1.02	1.01

The new method was also compared with a single-ended method using zero-sequence current polarization and the results are similar to the ones shown in Table 1. The performance of both single-ended methods is influenced by zero-sequence mutual coupling and system nonhomogeneity. To see the effect of nonhomogeneity, notice that the error in both methods increases as the fault location is moved away from the relay location.

Electromagnetic Transient Program Testing

Figure 4 shows one power system modeled with the Electromagnetic Transient Program (EMTP) to test the new algorithm. The system consists of two sources and two parallel, 100 mile mutually coupled 500 kV lines. Various types of faults were simulated, by varying the load flow magnitude and direction, fault resistance, and fault incidence angle.

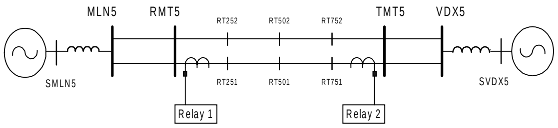

Figure 4: EMTP Model of a Two-Source System

The transient data generated by EMTP were processed with a software program which models the fault location algorithm, associated logic, and ability to introduce varying amounts of phase shift to the data from one relay terminal to simulate the effects of asynchronous sampling. Figures 5 and 6 show results of the new algorithm for a line-to-ground fault at 75% from Bus RMT5, and comparison with a single-ended fault location algorithm.

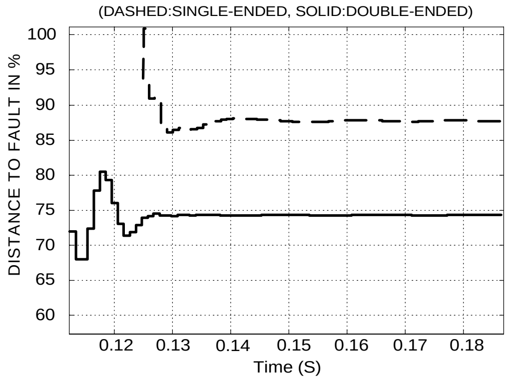

Figure 5: Fault Location from Relay 1 (Ideal=75)

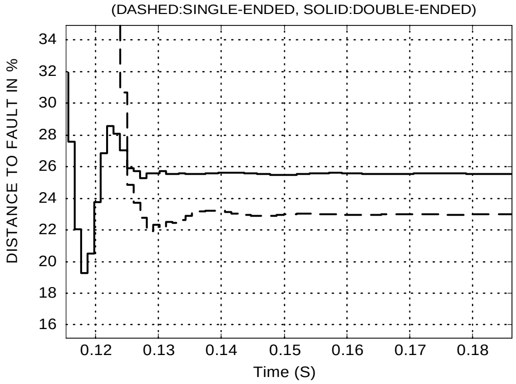

Figure 6: Fault Location from Relay 2 (Ideal=25)

Figure 7 shows the calculation of fault resistance by Relays 1 and 2. The fault resistance is displayed in secondary ohms. The ct and ccvt ratios are 400/1 and 4330/1 respectively. The primary fault resistance used in this example was 30 ohms (2.77 Ω secondary).

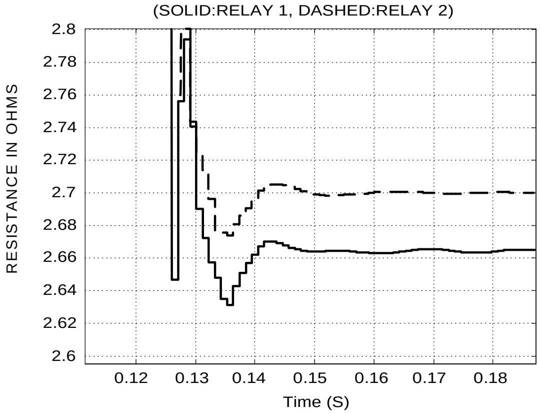

Figure 7: Secondary Fault Resistance Calculation

CONCLUSIONS

Single-ended fault location methods can be accurate if the power system is fairly homogeneous, and the mutual coupling between parallel transmission lines in the zero-sequence network is weak.

Multi-ended fault location algorithms can greatly improve the fault location accuracy. Many of the existing algorithms require the transfer of large amounts of data, alignment of the data sets, and iterative solutions to calculate the distance to the fault point. This makes their application limited to processing the data offline and adds considerable amount of time in the fault location process. In addition, some of the existing two-terminal methods cannot adequately handle mutual coupling and tapped loads with zero-sequence current infeeds, and are not applicable to more than two- terminal lines.

The new algorithm presented in this paper has many advantages over existing methods in that it can calculate the location of the fault in nearly real time, it is immune to mutual coupling and tapped loads, and does not require data alignment or pre-fault load information. It is also applicable to three-terminal lines with great accuracy (error rate of less than one percent). In addition, the new algorithm calculates the fault resistance and the total current in the fault path. The ability of the relays to calculate the actual fault location and present the data to operations personnel make it very attractive, since operators do not have to use off-line computer programs to process and analyze event reports after the occurrence of a fault.

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