A New Multiterminal Fault Location Algorithm Embedded in Line Current Differential Relays

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A NEW MULTITERMINAL FAULT LOCATION ALGORITHM EMBEDDED IN LINE CURRENT DIFFERENTIAL RELAYS

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Abstract

Accurate fault location on transmission lines becomes increasingly beneficial by reducing outage times and allowing faster restoration of scarce power system assets back into service. Having natural access to synchronized remote current data, line current differential protection schemes can incorporate multiterminal fault location algorithms, allowing for more accurate fault location compared with single-ended methods. This paper describes a new algorithm for fault location for two-, three-, and four-terminal lines suitable for integration in a typical line current differential scheme. The paper presents the new algorithm in detail, includes examples of its operation, and presents test results based on simulations as well as some application considerations related to the loss of communications or data synchronization between the 87L scheme relays.

1 Introduction

The increasing availability of reliable digital communications in electric power utilities promotes applications of line current differential schemes (87L) as well as deployment of multiterminal fault locators.

Responding to all currents bounding the zone of protection, the current differential principle is sensitive, inherently selective, and secure. Also, differential protection is typically easy to apply because it does not require detailed short-circuit studies and settings calculations. In its application to power lines, the principle is little or not affected by weak terminals, series compensation, changing short-circuit levels, power swings, nonstandard short-circuit current sources, and many other issues relevant for protection techniques based on measurements from a single line end [1].

Accurate fault location becomes more important as margins in present power systems erode, calling for fast restoration of transmission lines after faults.

Embedding multiterminal fault location algorithms in line current differential relays is natural and cost-effective.

First, fault locators embedded in 87L protection schemes benefit from the synchronization method already in place for the 87L protection element and, as such, can often be applied without external time sources for synchronization, such as Global Positioning System (GPS) clocks.

Second, the embedded fault locators utilize the existing 87L communications channels, avoiding extra investment and complexity compared with standalone multiterminal fault locators.

This paper presents a new fault location algorithm optimized specifically for implementation in a typical line current differential scheme, addressing the following design criteria and requirements:

- Minimize the channel bandwidth requirements of the fault locator without increasing the amount of data sent in real time over the existing 87L channel.
- Identify the faulted line section in three- and four-terminal applications without the need to exchange voltage signals between the 87L relays.
- Report consistent fault location in all relays of the 87L scheme.
- Reduce the impact of the variability of fault resistance on the accuracy of fault location.
- Detect the loss of the high quality of data synchronization and fall back accordingly so that the accuracy of fault location is not adversely impacted by phase errors between the local and remote currents.
- Support the master-slave mode of 87L operation with only some relays (masters) in the scheme having access to all remote currents and the other relays (slaves) only providing current data to the masters and executing direct trips of their local breakers.
- Perform fault location upon a total loss of data synchronization or communications based on a single-ended algorithm.

In Section 2, we present relevant fault location fundamentals for two-terminal lines, introduce the new algorithm, illustrate its operation with an example, and discuss its accuracy. In Section 3, we explain how the new algorithm is applied to perform fault location in three- and four-terminal lines. In Section 4, we discuss some application considerations related to the loss of data synchronization or loss of communications between relays in the 87L scheme. Section 5 summarizes the paper, gathering some key conclusions.

2 Fault location for two-terminal lines

This section introduces a two-ended fault location algorithm. This algorithm is directly applied to two-terminal lines and becomes a part of the overall fault location scheme in three- and four-terminal applications.

2.1 Fundamentals

Over the last several decades, various fault location methods have been introduced. These methods are based on traveling waves or impedance measurements. The latter group includes single-ended and two-ended methods. The two-ended methods may use only remote currents or both remote currents and voltages. Furthermore, the remote signals can either be time-aligned with the local signals or not.

This variety of approaches stems from the fact that when looking at the faulted line from a single line terminal, we deal with one more unknown than the number of equations available.

Two-ended methods solve this problem by getting at least one measurement from the other end of the line. Single-ended methods solve this problem by making a reasonable assumption. Different assumptions yield different fault location methods.

The fault location algorithm described in this paper is based on the modified Takagi method [1].

Consider the two-terminal (L and R) transmission line shown in Fig. 1 with a fault at *m* per unit (pu) from the left terminal.

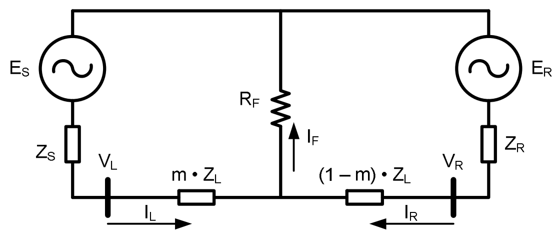

Fig. 1. Equivalent diagram of a two-terminal line with a fault at *m* pu from the left terminal.

The distance to the fault can be calculated using the following fundamental equation:

$$m = \frac{\mathrm{Im}\left(V_L \bullet I_F^*\right)}{\mathrm{Im}\left(I_L \bullet Z_L \bullet I_F^*\right)} \tag{1}$$

where: * is a complex conjugate operator.

Neglecting measurement errors in the current (I_L) and voltage (V_L) phasors, any errors in the line impedance (Z_L) data, system nonhomogeneity, and impact of charging current, (1) yields accurate results regardless of the fault resistance (R_F).

The obvious challenge in implementing (1) is that the fault current (I_F) is unknown to any single-ended method. By the nature of (1), however, only the angle of the fault current is required.

This angle can be reasonably approximated with the angle of the local negative-sequence current (if the negative-sequence network is homogeneous) or zero-sequence current (if the zero-sequence network is more homogeneous), leading to a practical and, in most operating conditions, accurate single-ended algorithm [3].

Fig. 2 illustrates this particular approach for a single-line-to-ground fault (in this paper, 1 = positive sequence, 2 = negative sequence, and 0 = zero sequence). From the figure, it is clear that:

$$\angle I_F \approx \angle I_{2L} \approx \angle I_{2R} \text{ and } \angle I_F \approx \angle I_{0L} \approx I_{0R} \tag{2}$$

as long as the negative- and zero-sequence networks are nearly homogeneous (i.e., the angles of the total impedance left and right of the fault point in Fig. 2 are similar).

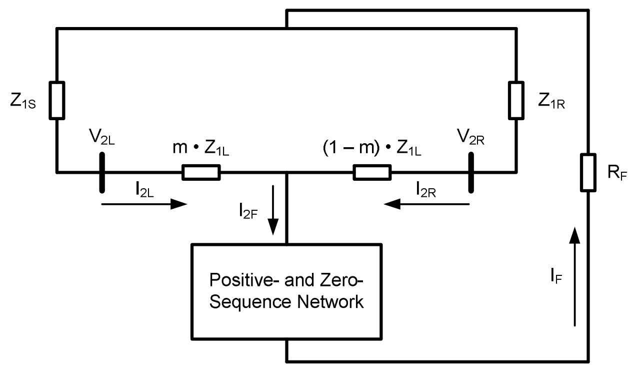

Fig. 2. Negative-sequence quantities in the sequence network for a single-line-to-ground fault.

Practical implementations of this method require fault type identification and work on the proper loop quantities in order to reflect the true positive-sequence impedance between the line terminal and the fault point. For example, for AG faults, we apply:

$$m = \frac{\mathrm{Im}\left(V_A \bullet I_2^*\right)}{\mathrm{Im}\left(\left(I_A + k_0 \bullet I_0\right) \bullet Z_{1L} \bullet I_2^*\right)} \tag{3}$$

where: k_0 is a zero-sequence compensating factor.

The usage of local negative-sequence current in (3) is referred to as polarization. The method of (3) is widely used and performs well as long as the negative-sequence network is homogeneous (which is typically the case) [1][3].

This method is further enhanced as described in the next subsection and becomes a fallback method in our implementation should the loss of communications or loss of data alignment prevent usage of the new method of Subsection 2.2.

2.2 Polarization with the differential signal

From Fig. 1, it is clear that the fault current (normally not available to any single-ended protection method) is the differential signal naturally available to the line current differential scheme:

$$I_F = I_L + I_R = I_{DIF} \quad (4)$$

As a result, (1) is not theoretical anymore but can be practically implemented substituting the fault current with the 87L differential current. For example, for AG faults, we apply:

$$m = \frac{\mathrm{Im}\left(V_A \bullet I_{2DIF}^*\right)}{\mathrm{Im}\left(\left(I_A + k_0 \bullet I_0\right) \bullet Z_{1L} \bullet I_{2DIF}^*\right)} \quad (5)$$

2.3 Sample test results

The sample two-machine system shown in Fig. 3 has been used to illustrate performance of the fault location algorithm. The fault location, *m*, has been varied in subsequent simulations plotting a number of points along the line length. Considerable fault resistance and infeed effect have been modeled (shown by the apparent impedance moved considerably to the right from the line impedance).

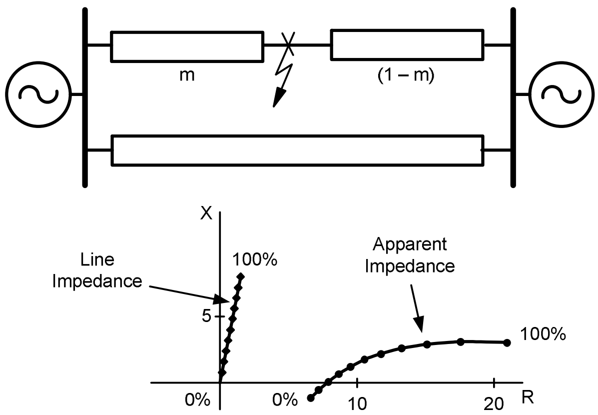

Fig. 3. Sample two-terminal system with mutually coupled parallel lines.

Fig. 4 plots fault location results when using the local negative-sequence, local zero-sequence, and differential currents for polarization.

Polarizing with the differential current (new method) gives the best results. The accuracy is only slightly degraded for faults away from the terminal due to the impact of the zero-sequence mutual coupling from the parallel line (which is not compensated in this example).

Usage of the local negative-sequence current gives good results for close-in faults. However, when the fault is farther away from the terminal, the results are less accurate. This is caused by network nonhomogeneity. The remote system in this example has a different angle of the equivalent negative-sequence impedance compared with the line and the local system. As the fault moves away from the local terminal, the networks from the fault point toward the local terminal and toward the remote terminal become less homogeneous.

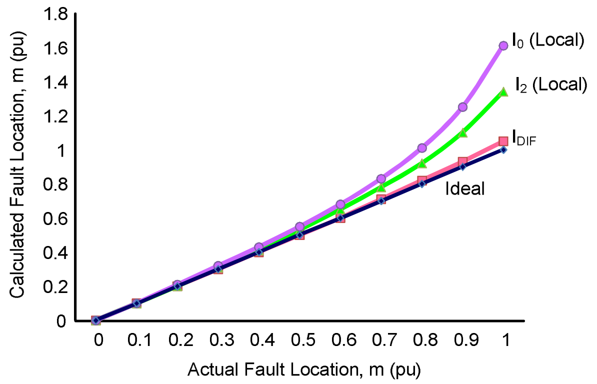

Fig. 4. Comparison of fault location results using local and differential polarizing currents.

The usage of the local zero-sequence current gives even worse results because we intentionally modeled higher nonhomogeneity in the zero-sequence network.

Of course, for lower values of the fault resistance or with no heavy load on the line, all three alternatives would yield good accuracy of the fault location [3]. In nonideal situations, however, the new method using the differential current for polarization gives considerably better results.

2.4 Accuracy discussion

The accuracy of the described fault location method can be analyzed based on the nature of (5). In particular:

- The algorithm uses line impedances (both positive and zero sequence) and is affected by errors in their values, especially the zero-sequence impedance (buried in the k_0 factor). Zero-sequence impedance is generally known to have lower accuracy and may change seasonally because of changes in soil resistivity (due to humidity changes) and conductor sag (due to heat and ice).
- The algorithm is impedance-based and therefore affected by line asymmetry. Even fully transposed lines are symmetrical only between their terminals. The two line segments created by a randomly located fault are not symmetrical in general.
- Errors in measuring the currents and voltages affect the accuracy as in any impedance-based algorithm.
- Last, but not least, phase errors in the polarizing signal (the differential current) impact the accuracy of fault location. This unique source of error is explained next.

Line current differential relays need to align the remote current data to coincide with the local currents before forming the differential signal. Two methods are practically used for current data alignment. When using symmetrical channels (equal latencies in the transmitting and receiving directions), 87L schemes typically align the data using the industry standard method known as the ping-pong algorithm [2]. When the channel is not symmetrical, the ping-pong algorithm introduces a time alignment error proportional to the amount of asymmetry, which yields a current phase error, which, in turn, creates a fictitious phase shift in the differential current during internal faults. When using asymmetrical channels, the 87L relays require a common (external) time reference to drive the current sampling [2]. Historically, GPS clocks either embedded in the 87L relays (rarely) or standing alone and connected via an IRIG-B input (more commonly) have been used as the time reference.

In any case, a small phase angle error in the differential current (perfectly tolerable to the 87L protection elements) would cause a considerable error in the fault location using method (5). To illustrate this, consider the system of Fig. 3 and assume a phase error in the range of ±10 degrees in the polarizing signal. Fig. 5 plots the fault location using the differential signal for polarization.

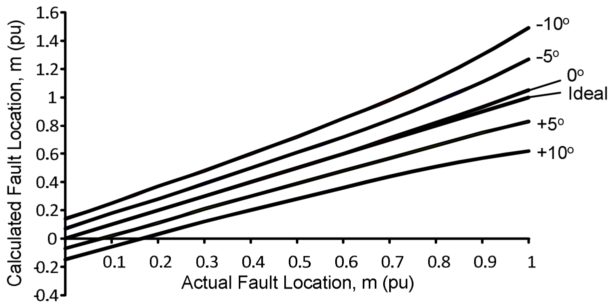

Fig. 5. Impact of phase errors in the differential signal on the accuracy of fault location using method (5) in the sample system of Fig. 3.

Consider, for example, an error of 5 degrees. Assuming a perfectly homogeneous network, the local and remote negative-sequence currents are perfectly in phase for an internal fault. If their magnitudes are equal, it would take a shift in the remote current of 10 degrees in order to shift the differential signal by 5 degrees. A 10-degree shift in a 60 Hz system can be caused by channel asymmetry equal to 2 • (10 degrees/360 degrees)/60 Hz = 0.93 milliseconds. This level of asymmetry is well within the tolerance of a typical 87L protection scheme, but in the system of Fig. 3, it would cause a significant fault location error (Fig. 5).

Therefore, the quality of data alignment must be monitored by the fault locator embedded in the 87L scheme. The basic principle of monitoring for quality of data alignment works as follows:

- When in the time-based mode (GPS), each relay of the 87L scheme must be locked to a valid time source. If the lock is lost or the source reports a time error, the quality of data alignment is declared low.
- When in the channel-based mode (ping-pong), if the angle difference between the local negative-sequence current and the differential negative-sequence current is greater than a threshold (a few degrees), the quality of data alignment is declared low.

Upon detected or suspected poor quality of alignment, the algorithm falls back from the two-ended method given by (5) to the single-ended method given by (3).

3 Fault location in multiterminal lines

In multiterminal lines, the process of locating a fault is typically performed in two steps. First, the faulted line section is identified. Second, equivalent voltages and currents are calculated for the faulted section, assuming all other sections are fault free, and a two-ended algorithm is executed for the faulted section.

3.1 Principle

Consider the three-terminal line shown in Fig. 6. Three 87L relays comprise the 87L scheme. Each relay has access to the local voltages and currents as well as the remote currents (but not voltages in our method).

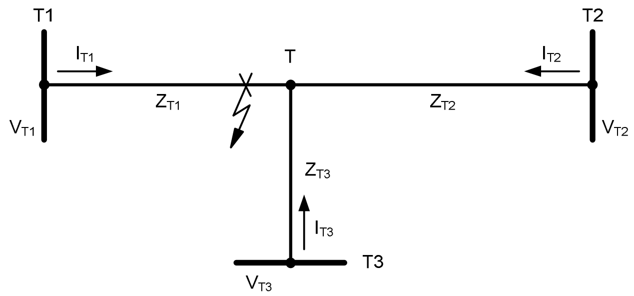

Fig. 6. Three-terminal line.

In our method, each relay assumes the fault is in the local section of the line and uses (5) to calculate the pu fault location.

Terminal 1 calculates:

$$m_1 = \frac{\mathrm{Im}\left(V_{T1} \bullet I_{DIF}^*\right)}{\mathrm{Im}\left(I_{T1} \bullet Z_{T1} \bullet I_{DIF}^*\right)} \tag{6a}$$

Terminal 2 calculates:

$$m = \frac{\mathrm{Im}\left(V_{T2} \bullet I_{DIF}^*\right)}{\mathrm{Im}\left(I_{T2} \bullet Z_{T2} \bullet I_{DIF}^*\right)} \tag{6b}$$

Terminal 3 calculates:

$$m = \frac{\mathrm{Im}\left(V_{T3} \bullet I_{DIF}^*\right)}{\mathrm{Im}\left(I_{T3} \bullet Z_{T3} \bullet I_{DIF}^*\right)} \tag{6c}$$

If the fault is actually on the local line segment, the pu fault location is below 1 pu. If the fault is beyond the tap point, the pu location is above 1 pu and the method is very unlikely to overreach (i.e., indicate $m < 1$ pu for a fault beyond the tap).

For a fault beyond the tap point, extra current flows toward the fault, elevating the voltage at the relay location, but is not measured by the relay. Consider the 87L relay at the T2 terminal in Fig. 6. The I_{T3} current produces a voltage drop between the tap point and the fault, but this current is not measured by the Terminal 2 relay. As a result, the fault location calculations at this terminal are very likely to yield a value greater than 1 pu regardless of the power flow on the line.

For example, under one load flow pattern in the system of Fig. 6 (load transfer from Terminal 2 to Terminals 1 and 3), the following results are obtained for a fault at 0.9 pu from Terminal 1: m_1 = 0.91 pu, m_2 = 1.30 pu, and m_3 = 1.55 pu. Under a different load pattern (load transfer from Terminals 1 and 3 to Terminal 2), the following results are obtained: m_1 = 0.89 pu, m_2 = 1.57 pu, and m_3 = 1.34 pu.

As can be seen in both cases, Terminal 1 correctly calculates the location as about 0.90 pu and Terminals 2 and 3 calculate values considerably higher than 1 pu.

The faulted line section identification is based on exchanging the locally calculated values of *m* and comparing them with 1 pu. The line section that reports m < (1 + margin) pu is declared faulty, and the corresponding value of *m* is reported. The value of margin is in the order of a few hundredths of pu and accounts for small measuring errors in the fault location, as discussed in Subsection 2.4.

In the presented numerical example, all three relays would indicate the T1-T section as the faulted section and report the fault location as 90 percent from the first terminal T1.

Additional considerations on this faulted line section identification method are:

- The values of *m* are communicated over the 87L channel using very limited bandwidth. This does not need to be performed in real time.
- For faults very close to the tap point, the three *m* values may be very similar, with more than one satisfying the m < (1 + margin) condition. This is acceptable because all the *m* values would be close to 1 pu, indicating even more that the fault is near the tap point.
- If a given relay cannot use the enhanced algorithm (5) and falls back into the single-ended method (3), the overall scheme still works (see more discussion in Section 4). The only difference is the method of calculating the *m* value.

3.2 Four-terminal lines

Consider the four-terminal line shown in Fig. 7.

In this case, the fault location algorithm is executed in two or three steps, depending on the actual fault location.

First, all the relays assume the fault is in their local sections. If the assumption is true, one of the relays would calculate the value of *m* below 1 pu, and the process would stop as explained in the previous subsection. For example, for the F1 fault in Fig. 7, the 87L relay at Terminal 4 would calculate m < 1 pu, and all four relays would report Section T4-P as faulty.

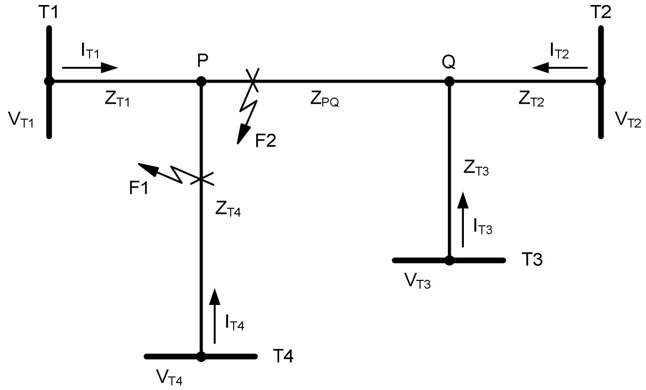

Fig. 7. Four-terminal line.

If none of the relays calculate m < 1 pu, the fault must be in the middle section between the two taps (Fault F2 in Fig. 7). Knowing that the local line sections are fault free, each relay calculates the equivalent currents and voltages for the P-Q section of the line using the voltage drop equation for the unfaulted section.

Terminal 1 calculates:

$$I_P = I_{T1} + I_{T4} \text{ and } V_P = V_{T1} - Z_{T1} \bullet I_{T1} \tag{7a}$$

Terminal 4 calculates:

$$I_P = I_{T4} + I_{T1} \text{ and } V_P = V_{T4} - Z_{T4} \bullet I_{T4} \tag{7b}$$

Terminal 2 calculates:

$$I_Q = I_{T2} + I_{T3} \text{ and } V_Q = V_{T2} - Z_{T2} \bullet I_{T2} \tag{7c}$$

Terminal 3 calculates:

$$I_Q = I_{T3} + I_{T2} \text{ and } V_Q = V_{T3} - Z_{T3} \bullet I_{T3} \tag{7d}$$

In order to calculate the currents in these equations, each relay is provided with a setting indicating the specific remote relay that is installed on the line section connected to the same tap (Relays 4 and 1 monitor line sections that connect to Tap P and Relays 2 and 3 monitor line sections that connect to Tap Q).

Having the P (or Q) currents and voltages calculated and having the Z_{PQ} impedance as a setting, each relay executes (5) and obtains a coherent fault location result. Relays 1 and 4 report *m* pu of the P-Q distance from Tap P, and Relays 2 and 3 report (1 – m) pu of the P-Q distance from Tap Q.

4 Understanding fault location results in master-slave applications

Improvement in the fault location accuracy of (5) over (3) is possible if the differential current is available to the relay. This is normally the case, but not necessarily in three-terminal applications when assuming channel failures.

Consider a three-terminal application and a channel failure between Relays 1 and 2, as shown in Fig. 8. This 87L scheme will switch to the master-slave mode, whereby the two relays that lose the mutual channel (Relays 1 and 2) serve the current data to the master (Relay 3). The master relay receives all required currents, provides the 87L function, and, upon a line fault, orders the slave relays to trip the remote breakers directly using in-band direct transfer trip (DTT) bits.

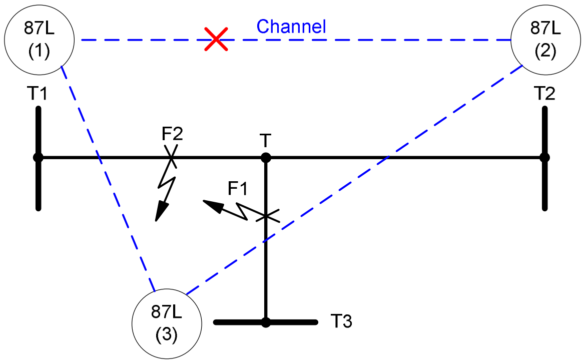

Fig. 8. Explanation of fault location reporting in master-slave configuration for three-terminal lines.

Of course, only Relay 3 can use the improved fault location method (5). Relays 1 and 2, having no access to the differential current, fall back and use the single-ended method (3). However, the overall scheme works correctly as explained below.

Assume the fault location F1 is on the line segment adjacent to the master Relay 3. In this case, the scheme calculates $m_1 > 1$ pu [using (3)], $m_2 > 1$ pu [using (3)], and $m_3 < 1$ pu [using (5)]. Relay 3 reports m_3 because it has all three *m* values and can perform the faulted section identification. This is the most accurate result because m_3 has been calculated using the enhanced method (5). Relays 1 and 2 (slaves) report their local *m* values because they are unable to collect *m* values from all remote peers. However, these values are greater than 1 pu, indicating the fault is in the Terminal 3 section of the line.

Assume next the fault is located at F2 on the line segment adjacent to the slave Relay 1. In this case, the scheme calculates $m_1 < 1$ pu [using (3)], $m_2 > 1$ pu [using (3)], and $m_3 > 1$ pu [using (5)]. The following values are reported.

Relay 3 (master) has access to all three *m* values and correctly reports m_1. This value may have some inaccuracy because m_1 has been calculated in the slave relay using the single-ended method (3). In theory, Relay 3 could calculate the tap voltage and current and execute method (5) for the remote line segment. However, we opted against this complication in the actual implementation of this method. Relay 1 (slave adjacent to the faulted line segment) reports the local m_1, which happens to be correct. Relay 2 (slave away from the faulted line segment) reports the local m_2, which happens to be incorrect. Again, this value is greater than 1 pu, indicating the fault is not in the Terminal 2 section of the line.

It is therefore advisable to interrogate all relays of the 87L scheme for fault reports generated while in the master-slave mode.

5 Conclusion

Embedding multi-ended fault location in line current differential relays brings many advantages. A single system serves both protection and fault location functions, allowing savings in communications, time synchronization, material costs, and engineering.

This paper presents a novel multi-ended fault location method designed specifically for ease of integration in line current differential schemes. The method improves the numerical accuracy of fault location compared with single-ended methods as well as indicates the faulted line section in three- and four-terminal line applications. Practical implementation aspects are considered to cover cases of loss of communications or degraded quality of data alignment.

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