Fault Locator Based on Line Current Differential Relay Sychronized Measurements

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1. Introduction.

The ability to accurately determine the location of faults on power systems lines are important as they facilitate faster inspection and shorter repair times, leading to faster restoration of the faulted lines. This greatly increases system reliability. At the same time, accurate fault location is a technical challenge because the fault location estimation is done based on the limited amount of information gathered at the line terminals. Problems which must be overcome include finite transmission line parameters accuracy, instrument measurement errors, coupling to adjacent transmission lines, unknown and often non-linear fault resistance, finite duration of faults resulting in short time window opportunity to capture necessary data.

The most common approach is to use voltage and current measurements from a single line terminal to estimate the fault location using various assumptions and approximations. Such approaches are referred as impedance-based single-ended methods and are nowadays a standard built-in function in the transmission line relays. All these methods are based on a certain assumptions due to lack of accurate information to solve equations. When assumptions are satisfied for a given fault situation, the fault result is accurate. When the assumptions are not satisfied, significant error may occur. Impedance based methods are challenged by too many factors, including but not limited to;

- Parallel lines mutual coupling,
- Uncertainty in K0 factor
- Fault resistance and power flow,
- System homogeneity,
- Weak-infeed applications etc.

Fault location systems that utilize information from more than one line terminals are referred to as multi-ended fault locators. A multi-ended fault locator eliminates the key weaknesses of a single-ended approach, but requires communication channels to rely data from geographically dispersed line terminals to a single location where the actual fault location calculations are performed. Some multi-ended methods don't require synchronization of the data between line terminals. Accuracy of such non-synchronized measurements methods is affected by following factors:

- Variable in time arc resistance produces variations in phasors values
- Transients in voltages and currents due system response to the fault and instrument transformers transients.
- Transients in phasors measurement due to filtering and phasor estimation. Time window to capture phasors for accurate result transient "pre-fault to fault" is shortly followed by

the switch-off transient. With a modern 1.5- or 2-cycles breakers operating time capturing fault steady state phasors becomes short, therefore challenging to capture correct values.

- Fast-evolving faults may produce set of phasors and fault types at line terminals, which do not match each other, if phasors are not captured at the same instance.

Some methods are using positive-sequence or negative-sequence voltages and currents. Three-phase balanced faults do not produce any negative-sequence signals Therefore such method has to add the positive-sequence based equations to eliminate this weakness. As a result, two sets of calculations must be run in parallel, or coarse fault type identification must be performed. Purely negative-sequence method produces nearly zero result for currents and voltages for three-phase balanced faults.

A typical single- or multi-ended fault locator requires knowledge of the fault type, i.e. which and how many conductors are involved in the fault, knowledge of the mutual coupling to adjacent lines located on the same towers or in close proximity, and some other auxiliary information. The remote portion of the multi-ended locator mentioned above needs to send both negative- and positive-sequence based signals, or the two portions of the locator must work flawlessly in terms of fault type identification. These extra factors are found through separate procedures, and if delivered to the main fault location procedure with errors, they will impact the overall fault location accuracy.

This paper presents a new patent pending multi-ended systems working in real time, such as locators integrated within line current differential relays protection relays, taking advantage of data transmitted already between terminals and adding minimum transmitted data to not exceed bandwidth requirements for 87L communications.

2. New Method.

2.1. Goals of a new method

Goals of a new method were as following:

- Take advantage of the transmitted synchronized per-phase phasors for the line current different protection. Line current differential operates nearly at the same time, thus capturing fault phasors at practically same instance.
- Two- or three-terminal applications should be covered. In three-terminal applications the algorithm reports the affected section of the line (T1-T, T2-T, T3-T), and the fault location from the terminal closest to the fault (fault is between this terminal and the tap).
- It is preferred to minimize the amount of extra information added to the line current differential packet.
- Eliminate fault location error due to mutual coupling, fault resistance, load, non-homogeneity, non-synchronized measurements
- Eliminate reliance of the algorithm on the phase selection information for fault location. A single set of fault location equations applies to all fault types and phase involvement. However, phase selection information can be used for determination of fault resistance.
- Take advantage of compensation of the line charging current: the positive impact of the compensation shall be passed on the fault location algorithm by using compensated currents versus measured currents.

- It is preferred to include compensation for mutual coupling with a parallel line. The mutual coupling is characterized by the neutral current of the parallel line (3I0) wired to the ground current input of the relay, and measured by this relay as a phasor.
- It is desirable that algorithm reports fault resistances when possible. If relevant for accuracy, the algorithm shall assume multiple fault resistances for multi-phase faults and match such fault models to the measured currents and voltages. For example, single-line-to-ground and line-to-line faults are modeled with 1 unknown resistance, double-line-to-ground faults could be modeled with 2 or 3 unknown resistances, etc.
- Make fault location results available at all terminals immediately after fault.
- During line current differential channel failures provide single-ended fault location result at each terminal as a backup.

The new fault detection system is based on the idea that synchronized voltage and current measurements at all ends of the transmission line make it possible to use network equations directly to compute the fault location without assumptions or approximations, using the composite signals and associated network only. The composite signal is created in such a way that regardless of the fault type, there is a disturbance in the composite signals. The composite voltage at the fault can be computed from each end of the line by subtracting the line drop to the fault from the voltage at that end using the composite voltages at the terminals, composite currents and appropriate impedance. There are more equations in this composite signal model than unknowns, so that it possible to solve for the fault location that will match the fault voltage estimates made from all ends of the line. This simplifies the system and makes it highly accurate by removing both assumptions and model parameters that may have inherent accuracy limitations such the zero-sequence impedance of the line. The systems and calculations for two-ended and three-ended systems are similar and will be described further.

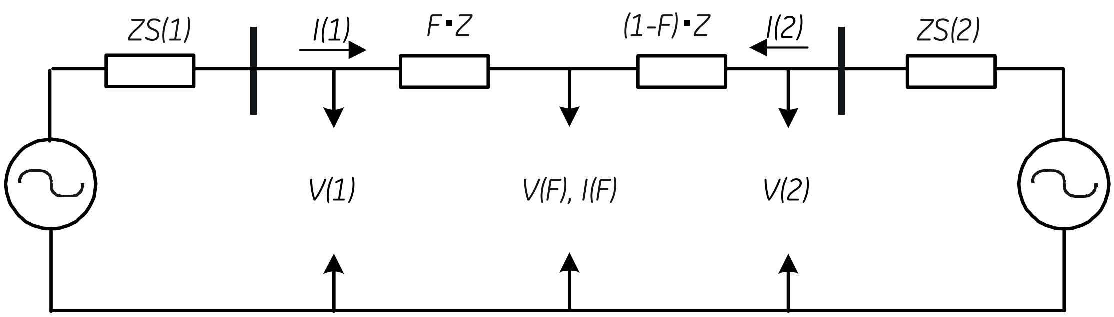


Figure 1. Two-terminal line model

2.2. Two-terminal line

The two-ended system executes an algorithm on measurements separately on each terminal. Either result is sufficient to locate the fault. Both terminals will compute exactly the same fault location, since they use exactly the same equations applied to the same data. This could be summarized that the calculations are symmetrical in terms of identical equations executed at both ends of the line, and redundant in terms of the results remaining in the a prior known relationship. Thus, the two-ended system can compare the results of the calculations to ensure accuracy. In a further embodiment of the two-ended system, the system can be configured to subsequently calculate fault resistance at each terminal from the fault location plus local measurements, so that each terminal may compute a slightly different estimate. The two estimate values can be averaged to increase accuracy.

The system algorithm is based upon the following fault measurements and settings with reference to Figure 1:

I(1)=composite current phasor flowing into the line at first terminal
I(2)=composite current phasor flowing into the line at second terminal
V(1)=composite voltage phasor at first terminal
V(2)=composite voltage phasor at second terminal
Z=complex line impedance
L=line length between first and second terminals,
F=fraction fault location from first terminal
D=F·L=distance from first terminal to fault location

The new algorithm uses generalized Clarke transform to represent voltages and currents for the purpose of fault locating. The traditional Clarke transform works for both instantaneous and phasor values, and uses the following equation for one of its components:

$$V = \frac{2 \cdot VA - VB - VC}{3} \qquad \text{(Eq. 1)}$$

The above has a weakness of zeroing out currents for BC faults, and as such does not meet the requirement of delivering a signal representing the fault under all circumstances. Therefore equation (1) is generalized by this invention as follows:

$$V = \frac{2 \cdot VA - b \cdot VB - b^{*} \cdot VC}{3} \qquad \text{(Eq. 2)}$$

Where b is a complex number given by:

$$b = 1 + j \cdot \tan(\alpha) \qquad \text{(Eq. 3a)}$$

and b* is a conjugate of b, or mathematically:

$$b^{*} = 1 - j \cdot \tan(\alpha) \qquad \text{(Eq. 3b)}$$

where alpha is an arbitrary angle. Note that with alpha=0, the generalized Clarke transform of this invention becomes the traditional Clarke transform. This particular implementation uses $\alpha = pi/4$, or 45 degrees. It shall be noted, however, that many angles meet the requirements of representing any type of fault and being not sensitive to the ground current coupling. Also, it shall be noted that many other combinations of the phase signals (A,B,C) make the requirements of representing any type of fault and being not sensitive to the ground current coupling. This algorithm ensures that a single signal is created to represent the three measured signals (A,B,C) for the fault location purposes, in such a way that the ground currents do not affect the said signal, and the said signal is non-zero for all fault types

Both phase currents (IA,IB,IC) and voltages (VA,VB,VC) at all the points of interest are converted into the composite signal such as the generalized Clarke transform using the same transformation method throughout the network of interest. This conversion takes place in the line current differential relays that locate the faults, and is performed mathematically on all signals when deriving the fault location method and equations.

In the case of phase current measurements that are compensated for charging current of the transmission line, the compensated phase current phasors are used when deriving the composite current signals, and will provide a fault location estimate that takes full advantage of the compensation. Effects of charging current are described further below.

The fractional fault location is given by:

$$F = \mathrm{Real}\left[\frac{\frac{V(1)-V(2)}{Z}+I(2)}{I(1)+I(2)}\right] \qquad \text{(Eq. 4)}$$

Equation (4) takes advantage of redundancy in the data. There are more equations than unknowns, so a least mean squares fit is used. The equation is independent of faulted phase, fault type, fault resistance, and zero-sequence (ground current) coupling to an adjacent transmission line, if any.

It is important to understand the value of the total line impedance of the transmission line, Z, used in equation (4). This value is a complex ratio of the composite voltage and composite current measured at one end of the line with the other end under fault. Note that the fault type is not relevant, and the said ratio, will be the same regardless of the fault type. Practically this impedance is equal to the negative or positive sequence impedance of the line and is readily available.

Equation (4) can be computed at either or both first and second line terminals, producing exactly the same fault location estimate, except measured from opposite ends of the line. As one will recognize, the roles of the two terminals are exchanged when changing the terminal at which equation (4) is computed. The two F values should sum identically to 1.

2.3. Three-terminal line

The two-terminal algorithm described above is readily extended to a three-terminal system, such as shown in Figure 2. The situation for a three-terminal system is illustrated for the case in which the fault is on the line from the first terminal to the tap. The situations for a fault located on one of the other two line segments are not shown, but can be obtained by a cyclic permutation of line indices.

The three-terminal system executes an algorithm at each terminal that has information from all three terminals. In the case where one communication channel is down, this may be only one of the three terminals. The system algorithm has two parts—one part that determines which line segment is faulted, and a second part that locates the fault on the faulted segment. As with the two-terminal system, the algorithm will calculate exactly the same fault location from each terminal.

The following measurements and parameters are assumed to be available:

I(1), I(2), I(3)=composite current phasors flowing into first, second and third line segments
V(1), V(2), V(3)=composite voltage phasors at first terminal, second terminal, and third terminal
Z(1), Z(2), Z(3)=complex composite impedance of first, second and third line segments
L(1), L(2), L(3)=line lengths of first, second and third line segments

It is, of course, the goal to determine which line segment has fault, and the distance of the fault from the corresponding line terminal. The following parameters are used to determine the line with fault and distance from a given terminal to the fault:

N=terminal index of the faulted line segment (N=1, 2, or 3)
F=fractional fault location from Nth terminal
D=F·L(N)=distance from Nth terminal to fault location

Initially, three separate estimates of the voltage at the tap are made, assuming unfaulted condition between the tap point and a given terminal, starting at each of the first, second and third terminals. The fault location algorithm thus uses the following estimates of the tap voltage:

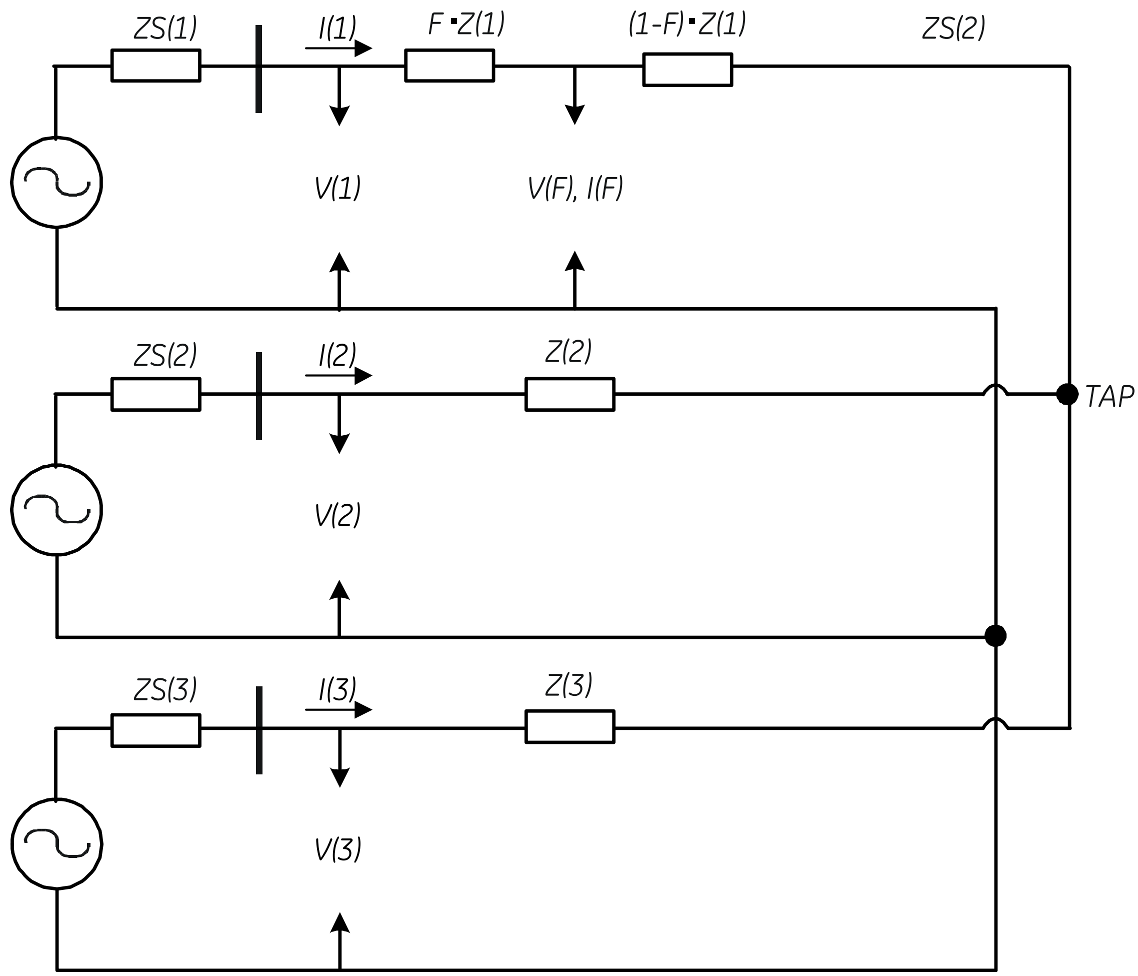


Figure 2. Three-terminal line fault location model

$$VT(1) = V(1) - I(1) \cdot Z(1)$$
$$VT(2) = V(2) - I(2) \cdot Z(2) \qquad \text{(Eq. 5)}$$
$$VT(3) = V(3) - I(3) \cdot Z(3)$$

where VT(1), VT(2) and VT(3) are the tap voltages calculated from each of the first, second and third terminals, respectively.

Next, the line segment containing the fault is determined. Recognizing that the voltage drops around a loop through the unfaulted line segments will sum to zero can do the determination of the line. Residual voltage phasors are computed for each loop. The loop with the lowest residual voltage contains the two unfaulted line segments. In other words, only one line segment is faulted and the two unfaulted segments allow the two terminals to estimate the real tap voltage. As a result if a given pair of terminals determines the same tap voltage, the fault must be between the tap and the third terminal. The following equations are used to calculate the squared magnitudes of the residual voltage phasors in each loop as indicators:

$$R^2(1) = |VT(2) - VT(3)|^2$$
$$R^2(2) = |VT(3) - VT(1)|^2 \qquad \text{(Eq. 6)}$$
$$R^2(3) = |VT(1) - VT(2)|^2$$

where $R^2(1)$, R^2 (2), and R^2 (3) are the squared magnitudes. The index, N=1, 2 or 3, of the line containing fault is the same as the smallest residual voltage phasor indicator. In the case where all of the indicators R^2 (1), R^2 (2), and R^2 (3) are approximately equal to each other, then the fault is close to the tap.

Once the index N of the line, containing fault is determined, the fault is located using a formula derived for the two-terminal lines fed with data appropriate for that line segment. Each formula is obtained from any of the other formulae by a cyclic permutation of the indices N. The formulae for each index or line are given below. First, a best estimate of the voltage phasor at the tap point and the fault current contribution from the tap are computed using current phasors and the tap voltage estimates computed in equation (5), above:

$$\text{if } N = 1: VT = \frac{VT(2) + VT(3)}{2};\ IT = I(2) + I(3);\ Z = Z(1)$$
$$\text{if } N = 2: VT = \frac{VT(1) + VT(3)}{2};\ IT = I(1) + I(3);\ Z = Z(2) \qquad \text{(Eq. 7)}$$
$$\text{if } N = 3: VT = \frac{VT(1) + VT(2)}{2};\ IT = I(1) + I(2);\ Z = Z(3)$$

The fractional fault location from the terminal end of the line segment, containing fault is then computed from the terminal and tap current and voltage phasors. The tap point acts exactly as the other terminal in the two-terminal algorithm.

$$\text{if } N = 1: F = \text{Real}\left[\frac{\frac{V(1) - VT}{Z} + IT}{I(1) + I(2) + I(3)}\right]$$
$$\text{if } N = 2: F = \text{Real}\left[\frac{\frac{V(2) - VT}{Z} + IT}{I(1) + I(2) + I(3)}\right] \qquad \text{(Eq. 8)}$$
$$\text{if } N = 3: F = \text{Real}\left[\frac{\frac{V(3) - VT}{Z} + IT}{I(1) + I(2) + I(3)}\right]$$

The actual distance down the particular line is subsequently computed by multiplying the fractional distance by the length of the affected line segment $D = F \cdot L(N)$.

Equation (8) can be implemented at any or all of the three terminals that have the necessary information available. All three results will be identical. It should be noted that some care must be taken with the fact that the three terminals have different indices within each terminal in a peer-to-peer architecture such as described in the embodiment of Figure 2. As will be appreciated, if all three communications channels are in operation, then all three terminals can compute the fault location, whereas, if only two are in operation, then only one terminal can perform the computation—the terminal, which is connected to both operational channels. If only one channel is operational, then faults cannot be detected or located using the system. As will be understood, all of the required measurements can be obtained and calculations can be made using conventional single-ended method.

2.4. Fault resistance

Fault resistance can be computed as well. Once the fault is located, it is a simple matter to estimate the fault resistance. The details depend on the fault type and the number of terminals. The following explanation considers the two-terminal equations. The three terminal equations are similar, and are easy to understand how to obtain those equations from the two-terminal explanation below.

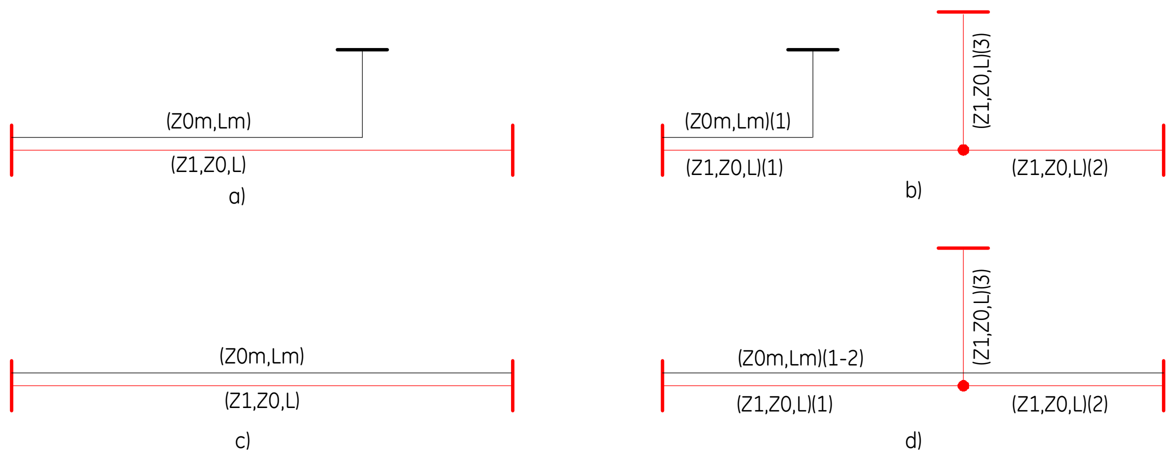


Figure 3. Typical configurations of mutually coupled lines

For a single line to ground fault, the fault resistance is estimated by taking the real part of the ratio of the fault voltage and current phasors for the faulted phase. The voltage phasor is estimated by starting at the terminal end, where phase voltage phasors are known and subtracting the voltage drop at the fault. The possible effects of the mutual coupling from an adjacent line are considered. Figure 3 demonstrates some typical configurations of mutually coupled lines: a) partially coupled lines originated at one bus but terminated at different buses; b) partially coupled 3-terminal lines; c) double circuit line originated and terminated at the same buses; d) 3-terminal line with mutually coupled 2 legs to the tap only. It should be noted that (c) configuration only is preferred to apply mutual coupling compensation for the fault location purposes (same as for distance relaying as well). Other three configurations are not feasible for implementation using new method, as 3I0 current from parallel line is not measured at all terminals. It means that 3I0 current from parallel line should be transmitted in the packet to all terminals, which increases packet of 87L data very much, especially in the case of 3-terminal line.

With reference to Figure 1 and Figure 4, the case of a phase A to ground fault is considered. The equations for B to ground faults or C to ground faults are similar, except the quantities from the appropriate phase are used.

First and most important is that fault location result is not impacted by the mutual coupling and gives correct fault location result as shown in previous calculations above. Next we calculate the portion of mutual coupling:

$$\text{if}(D < L_m)\ F_m = D / L_m \ \text{else}\ F_m = 1 \qquad \text{(Eq. 9)}$$

which means that if fault on the line, then mutual coupling impedance of the portion F_m of line involved in the fault, is considered to calculate zero-sequence voltage drop due to mutual coupling.

Estimate the phase to ground phase A voltage at the fault from local relay:

$$V_A(F) = V_A(1) - F \cdot \left(\left(I_A(1) - I0(1) \right) \cdot Z1 + I0(1) \cdot Z0 \right) - F_m \cdot I0_m \cdot Z0_m \qquad \text{(Eq. 10)}$$

where $I0m$ is zero-sequence current measured from the parallel line ($I0m = 3I0_m / 3$) and $Z0_m$ is a mutual impedance of the line

and compute phase A current at the fault location:

$$I_A(F) = I_A(1) + I_A(2) \qquad \text{(Eq. 11)}$$

where index 1 refers to current measurement from local terminal and index 2 refers to current measurements from the remote terminal.

Finally, compute the fault resistance:

$$R_A(F) = \text{Real}\left(\frac{V_A(F)}{I_A(F)} \right) \qquad \text{(Eq. 12)}$$

Analysis of the phase-to-phase fault is simpler, because we do not have to worry about zero sequence coupling. The following is the result for a phase A to B fault.

First, estimate the phase-to-phase voltage at the fault:

$$V_{AB}(F) = \left(V_A(1) - V_B(1) \right) - F \cdot \left(I_A(1) - I_B(1) \right) \cdot Z1 \qquad \text{(Eq. 13)}$$

Estimate the phase to phase fault current:

$$I_{AB}(F) = \frac{1}{2}\left(I_A(1) + I_A(2) - I_B(1) - I_B(2) \right) \qquad \text{(Eq. 14)}$$

Finally, compute the phase-to-phase fault resistance, using result of equations above:

$$R_{AB}(F) = \text{Real}\left(\frac{V_{AB}(F)}{I_{AB}(F)} \right) \qquad \text{(Eq. 15)}$$

The B to C and C to A cases are similar, with a cyclic permutation of the phase indices

For the three-phase fault situation, an equivalent fault resistance is reported as the real part of the ratio of the positive sequence voltage to current at the fault. In the case of a three-phase fault, a somewhat better estimate of the voltage at the fault can be constructed by averaging the estimates using positive sequence voltages and currents from both ends:

$$V(F) = \frac{1}{2}\left(V(1) - F \cdot I(1) \cdot Z1 + V(2) - (1 - F) \cdot I(2) \cdot Z1 \right) \qquad \text{(Eq. 16)}$$

The fault resistance is:

$$R(F) = \text{Real}\left(\frac{V(F)}{I(1) + I(2)} \right) \qquad \text{(Eq. 17)}$$

Finally, the case of an A phase to B phase to ground fault is considered, using the following fault resistance model in Figure 4:

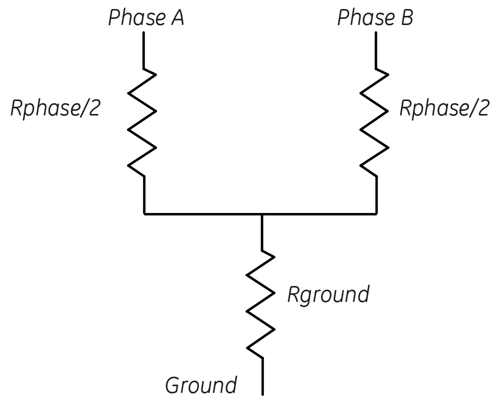


Figure 4. Fault resistance model

Because of the involvement of the zero sequence network, the equations for fault voltage for the single line to ground fault are applied to both phases:

Compute the distance to the fault and mutual coupling impedance of the portion F_m of line involved in the fault as for single-line-to-ground fault above:

Estimate the A phase to ground voltage at the fault:

$$V_A(F) = V_A(1) - F \cdot ((I_A(1) - I0(1)) \cdot Z1 + I0(1) \cdot Z0) - F_m \cdot I0_m \cdot Z0_m \quad \text{(Eq. 18)}$$

Estimate the B phase to ground voltage at the fault:

$$V_B(F) = V_B(1) - F \cdot ((I_B(1) - I0(1)) \cdot Z1 + I0(1) \cdot Z0) - F_m \cdot I0_m \cdot Z0_m \quad \text{(Eq. 19)}$$

Compute the A phase fault current:

$$I_A(F) = I_A(1) + I_A(2) \quad \text{(Eq. 20)}$$

Compute the B phase fault current:

$$I_B(F) = I_B(1) + I_B(2) \quad \text{(Eq. 21)}$$

Compute the phase-to-phase resistance:

$$R_{ph}(F) = 2 \cdot \mathrm{Real}\left(\frac{V_A(F) - V_B(F)}{I_A(F) - I_B(F)}\right) \quad \text{(Eq. 22)}$$

Finally, compute the ground resistance:

$$R_{gr}(F) = \frac{1}{2} \cdot \mathrm{Real}\left(\frac{V_A(F) + V_B(F)}{I_A(F) + I_B(F)}\right) - \frac{R_{ph}(F)}{4} \quad \text{(Eq. 23)}$$

Thus, the resistance of the fault can be computed in different ways as described above to account for fault type and mutual coupling. The fault resistance information combined with the fault location enables operators of power transmission lines to more effectively manage their systems. As discussed above, the information can be obtained from any terminal connected to the minimum number of other terminals to receive the necessary data for determining the fault location and/or fault resistance.

For fault resistance calculations, fault type should be determined first. Phase-segregated line current differential principle is the best phase selector. First of all, line differential protection triggers fault location algorithm for the line internal faults only. Secondly, weak-infeed, load, fault resistance and other factors, which challenge impedance based or sequence components based methods, do not affect line differential faulted phase determination. Thirdly, it provides symmetrical fault type identification at all line terminals and same fault location result. If, however, sequence components differential element operates, such as neutral or negative-sequence differential, then determination of the faulted phase for SLG fault is still needed using outside of line differential means.

2.5. Charge current compensation

If line current differential relay is capable to perform charging current compensation, it is possible to extend the benefits of charging current compensation into fault location.

Charging current compensation usually in the relay is based on a simple lumped approximate model of charging capacitance for both zero-sequence and for non-zero-sequence. For the algorithms considered in this paper, only the positive sequence model is relevant.

Since the fault location system utilizes the composite signal network, the model circuit shown in FIG. 4 approximates the network reasonably well. The normal (unfaulted) system state model is equivalent to presuming that the total charging current depends on the total line capacitance and the average of the voltages V(1), V(2) at both ends of the lines. The implicit assumption in this current compensation model is that the voltage on the line varies linearly along the line from one end to the other. This is true during normal (unfaulted) conditions, but is not true during faulted conditions. Accordingly, the result is that these assumptions are violated by a fault condition. This works well for fault detection, but requires a further investigation of the effect of charging current on fault location.

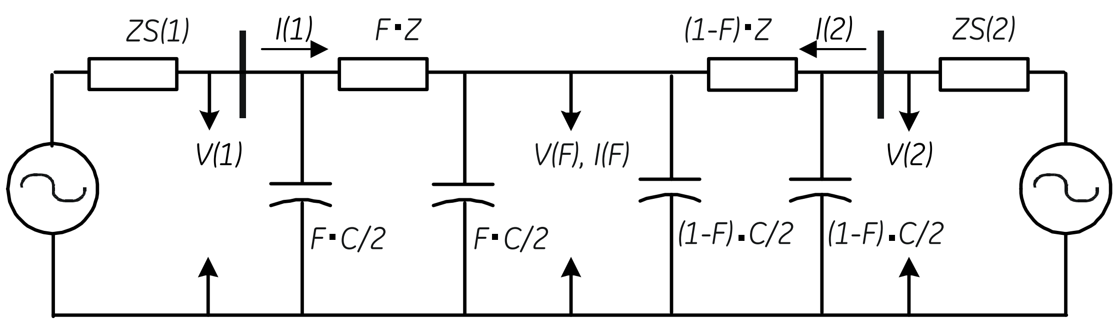


Figure 5. Faulted line model with charging current

During a fault, the voltage profile on the line is approximately two straight lines from the terminals to the fault, which results in the model shown in Figure 5. If a device is operating on the system in a charging current compensation mode, the composite current phasors on each line become:

$$\hat{I}(1) = I(1) - j\omega\frac{C}{2}V(1) \;\; ; \;\; \hat{I}(2) = I(2) - j\omega\frac{C}{2}V(2) \qquad \text{(Eq. 23)}$$

where C is the capacitance understood as the representing the composite charging current of the line under a composite excitation voltage. In practical situations this capacitance is equivalent to so called positive or negative sequence capacitances of the line.

The equation for the composite voltage drop from the first terminal to the fault, as shown in Figure 5, is:

$$F \cdot I(1) \cdot Z = V(1) \cdot \left(1 + F^2 \cdot j\omega \frac{C}{2} \cdot Z\right) - V(F) \qquad \text{(Eq. 24)}$$

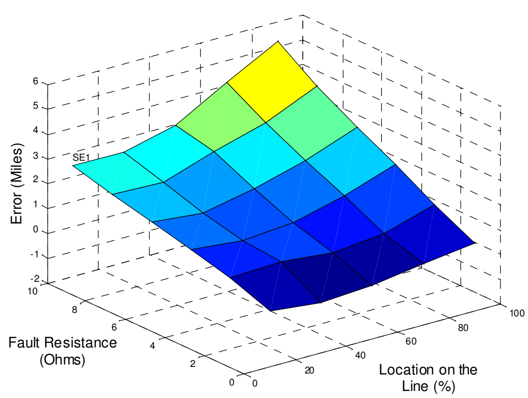
and the voltage drop from the second terminal to the fault is:

$$(1-F) \cdot I(2) \cdot Z = V(2) \cdot \left(1 + (1-F)^2 \cdot j\omega \frac{C}{2} \cdot Z\right) - V(F) \qquad \text{(Eq. 25)}$$

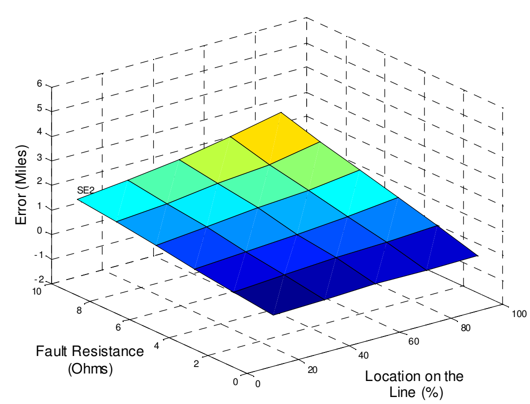
It can be noticed from equations 23 to 25 that both current and voltages are affected line shunt capacitance, thus introducing an error in fault location result if not compensated for $j\omega C$ factor. For 100 miles line the error in fault location is about 0.2%, but for 500 miles is as high as 5%.

3. Comparative testing with single-ended methods.

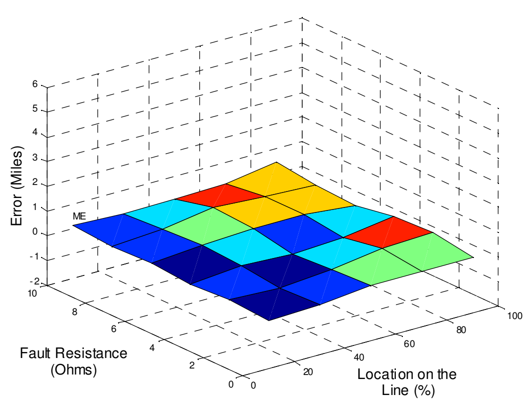
For the purpose of illustration of the new algorithm and a comparison with single-ended fault locators, RTDS testing with a sample line was carried out. Line under testing was 345kV double-circuit line 99.5 miles length, with $Z1=61.3\Omega\angle 84.7°$, $Z0=192.8\Omega\angle 73.1°$ and mutual-coupling $Z0M=110.6\Omega$ impedances. Sources: S1 (where single-ended fault locators were located) $S1Z1=23.07\Omega\angle 79°$, $S1Z0=23.7\Omega\angle 75.3°$ impedances and S2 were $S2Z1=40.9\Omega\angle 86°$, $S2Z0=81.35\Omega\angle 77°$



SEFL relay 1



SEFL relay 2



MEFL relay

Figure 6. Error for variable fault resistance for fault along the line, 0.66pu output power

Two different manufacturers single-ended impedance based fault location method relays were used for this testing denoted further as SEFL 1 and SEFL 2, side by side with a multi-ended method MEFL relay.

3.1. Error for variable fault resistance with an export 0.66pu power flow.

Figure 6 illustrates the error of 3 fault locators for this test. Parallel line was switched off to eliminate effect of mutual coupling. Error is reported in miles as this is what most important for operations personal dispatched to inspect the line. We can see that for 0 fault resistance all 3 methods give good results. However, the farther the fault and the higher is fault resistance, error is reaching 5 miles for SEFL relay 1, 2.5 miles for SEFL relay 2 and stays almost flat not exceeding 0.5 miles for multi-ended method relay.

3.2. Error for variable fault resistance with an import 0.66pu power flow.

Figure 7 illustrates the error of 3 fault locators for this test. Parallel line was switched off to eliminate effect of mutual coupling. Error is reported in miles as this is what most important for operations personal dispatched to inspect the line. We can see that for 0 fault resistance all 3 methods give good results. However, the farther the fault and the higher is fault resistance, error is reaching 6 miles for SEFL relay 1, 4.5 miles for SEFL relay 2 and stays almost flat not exceeding 0.25 miles for MEFL.

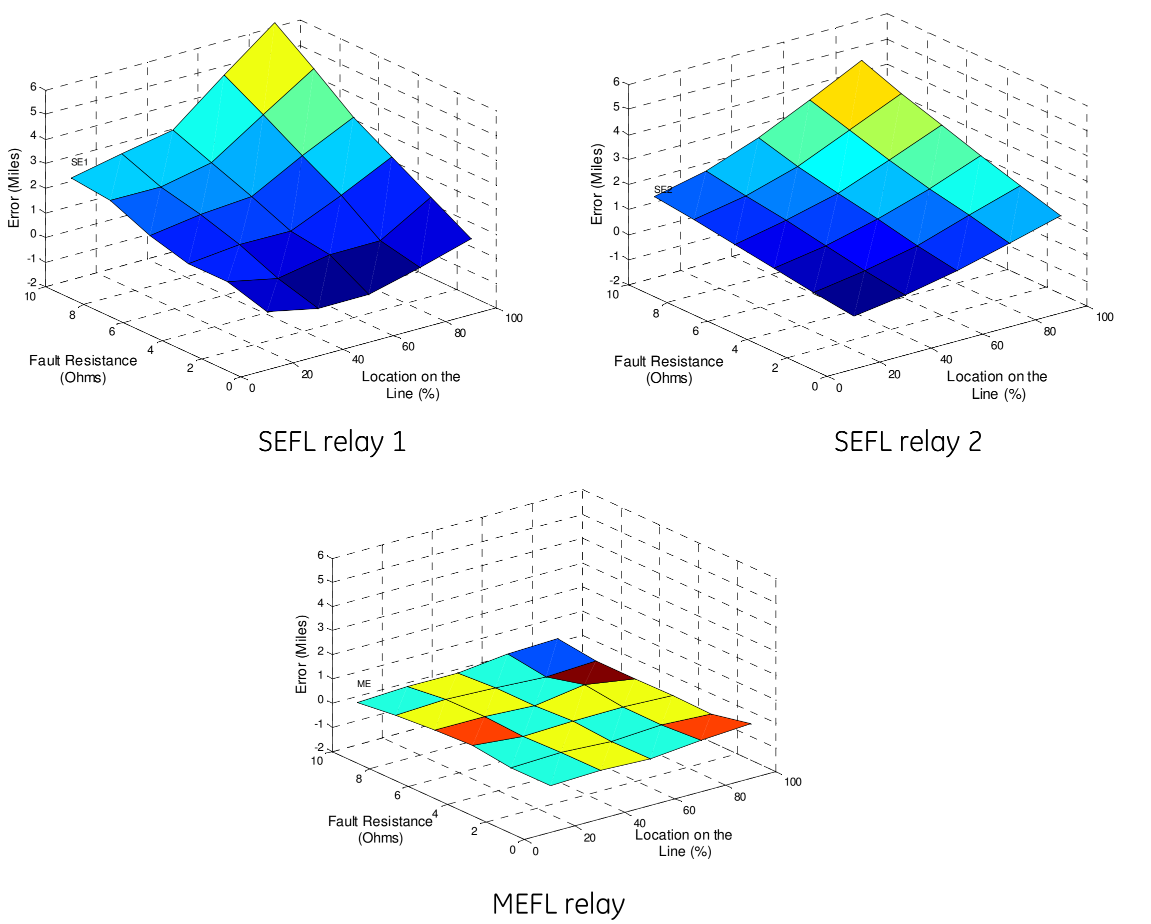
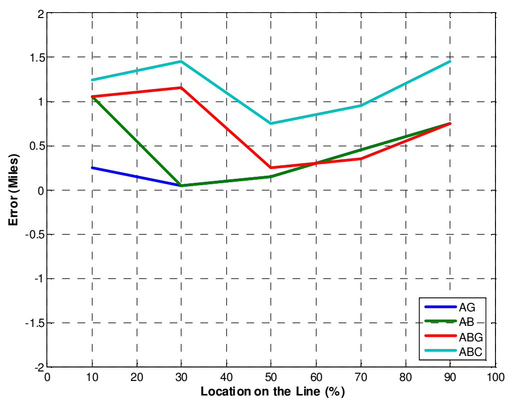


Figure 7. Error for variable fault resistance for fault along the line, 0.66pu import power

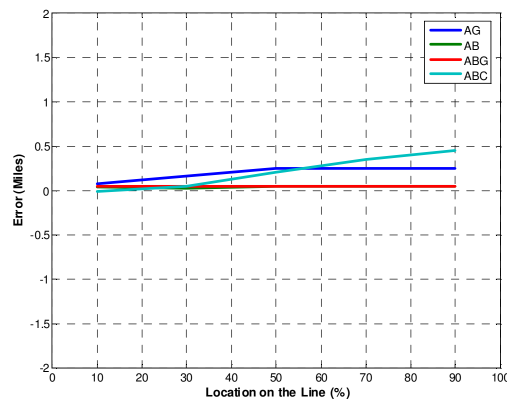
Power import flow is causing noticeable error increase for the single-ended methods, while multi-ended method is not affected.

3.3. Error for different fault types with an export 0.66pu power flow.

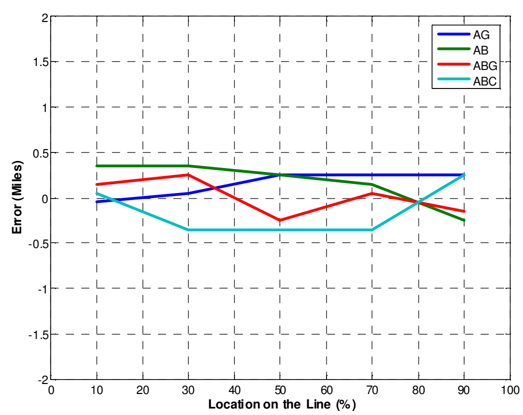
Figure 8 illustrates the error of 3 fault locators for this test. No mutual coupling and no fault resistance is applied for this fault. Four fault types AG, AB, ABG and ABC were applied. For export power SEFL1 method exhibits extra error of 1.5 miles maximum for multi-phase fault while 2 methods give good results.



SEFL relay 1



SEFL relay 2



MEFL relay

Figure 8. Error for fault type test for fault along the line, 0.66pu export power

3.4. Error for different fault types with an import 0.66pu power flow.

Figure 9 illustrates the error of 3 fault locators for this test. Same conditions, as in 3.3 above, but with importing 0.66pu power. We can see that SEFL1 error is slightly lower but SEFL2 is exhibiting now significant error of up to 2 miles. MEFL result is still within 0.5 miles error.

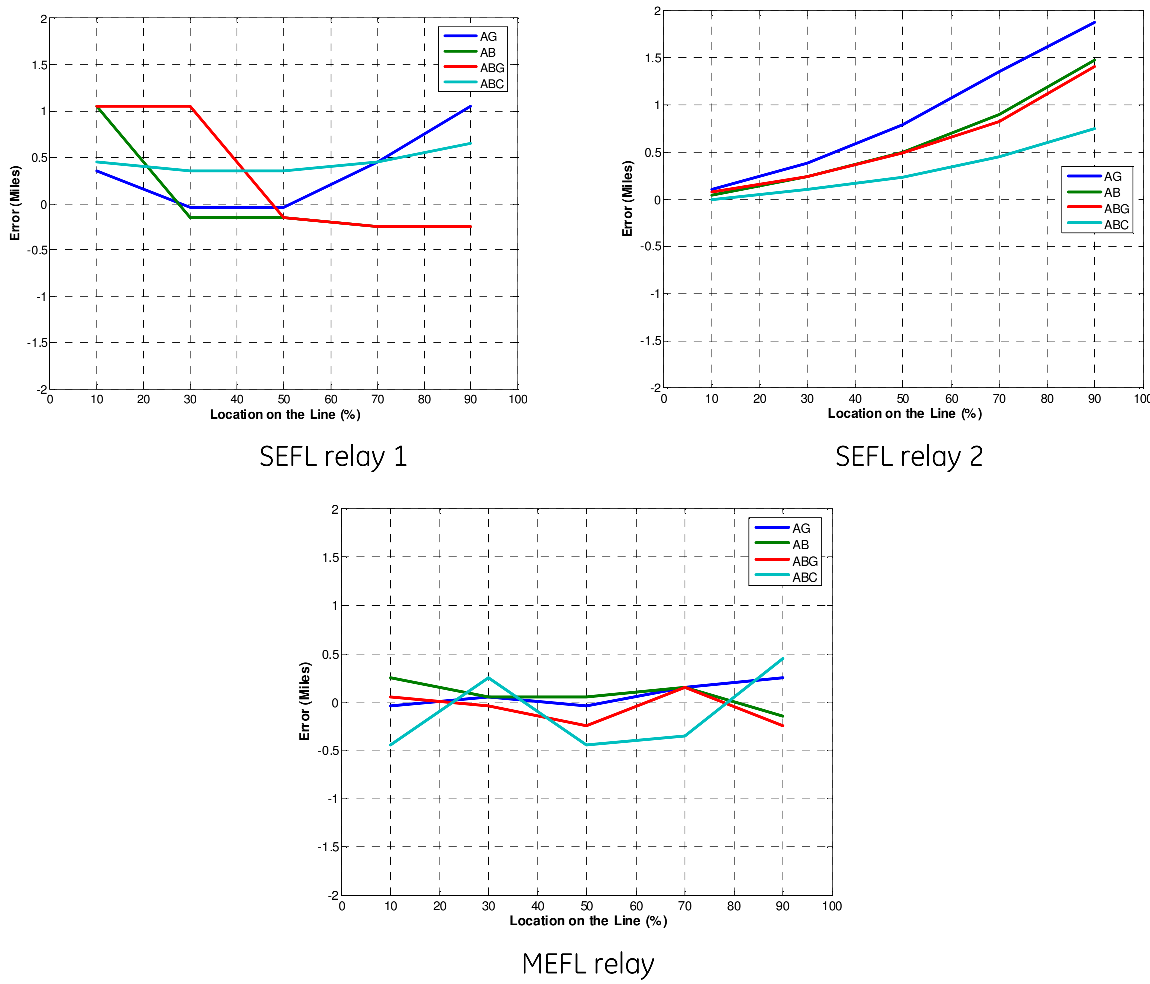


Figure 9. Error for fault type test for fault along the line, 0.66pu import power

3.5. Error for mutual coupling effect combined with fault resistance with an import 0.66pu power flow.

Figure 10 illustrates the error of 3 different fault locators for this test. SLG fault applied always at 50% of line length with a variable value of mutual coupling impedance and variable fault resistance while importing 0.66pu power. Mutual coupling impedance is expressed as a ratio of mutual zero-sequence impedance to line self zero-sequence impedance Z0M/Z0 from 0 to 0.8 ratio range. Also fault resistance was applied 0 to 8 ohms. We can see that SEFL relay 1 error is reaching 6 miles and SEFL relay 2 is reaching 3.7 miles error for the worst mutual coupling and fault resistance. MEFL relay result is not exceeding 0.5 miles error.

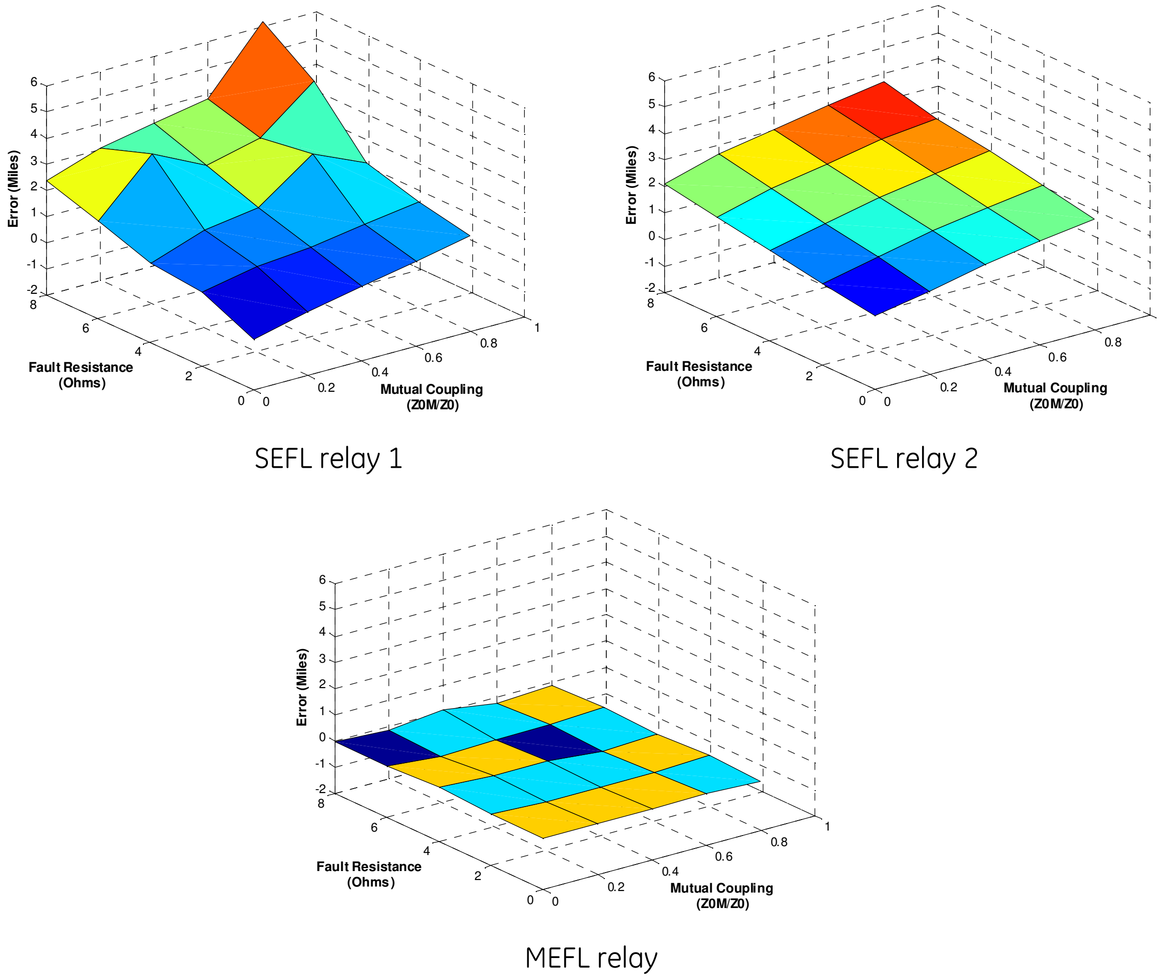


Figure 10. Error for mutual coupling effect combined with a fault resistance. Test for a fault 50% on the line, 0.66pu import power

3.6. Error for SIR, system non-homogeneity combined with fault resistance with an import 0.66pu power flow.

Figure 11 illustrates the error of 3 different fault locators for this test. SLG fault with a fixed 4Ω fault resistance applied always at 50% of line length with a variable value of SIR (source impedance ratio) and angle between local (behind terminal where SEFL relays are connected) and remote sources while importing 0.66pu power. We can see that SEFL relay 1 error is reaching 5 miles for SIR tests while SEFL relay 2 is not capable to calculate fault location for SIR greater than 6. MEFL relay result is not exceeding 0.35 miles error.

System non-homogeneity combined with 4Ω fault resistance is causing error of 2.15 miles for SEFL relay 1 and 1.84 miles for SEFL relay 2 while MEFL relay result is not exceeding 0.25 miles error.

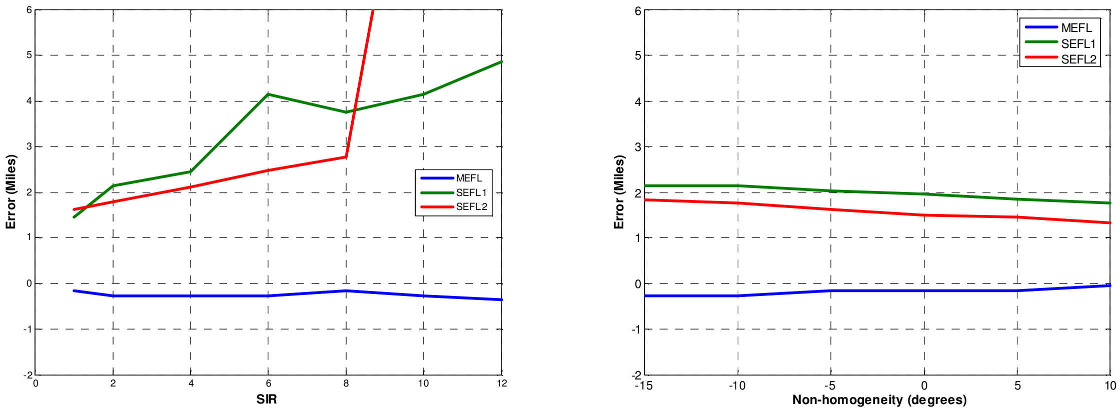


Figure 11. Error for SIR, system non-homegenuity combined with a fault resistance. Test for a fault 50% on the line, 0.66pu import power

4. Conclusions

This paper presents new multi-ended method for locating faults on the transmission lines and incorporated into line current differential relay. Advantages of this method are:

- Integrated into line current differential relay via 87L channel, thus no additional cost associated with additional communications channel or additional devices/wiring is involved for fault location purposes.
- Applicable to both two and three terminal applications with real-time fault location and fault resistance reporting at all terminals.
- Immunity to the zero-sequence coupling of adjacent system elements and uncertainty in K0 factor.
- Immunity to a fault type, fault resistance, power flow, system non-homogeneity and weak-strong source applications.
- Increased accuracy comparable with travelling wave fault locators due to synchronized measurements, charge current compensation.

Single-ended methods are impacted by too many factors, which makes then unreliable for operating personal.

It was demonstrated in this paper that new fault location method based on the synchronized line current differential measurements gives significant advantage over single-ended methods in accuracy and gives accuracy comparable with a travelling wave fault locators at no extra cost.

5. References

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5.2. A.A. Girgis, D.G. Hart, W.L. Peterson, "A new fault location technique for two- and three-terminal lines", IEEE Transactions on Power Delivery, Vol. 7, No.1, January 1992, pp. 98-107.

5.3. GE Publication GER-3963, "Evaluation of a Phasor-Based Fault Location Algorithm", GE Alexander, JM Kennedy.

6. Biography

Ilia Voloh received his Electrical Engineer degree from Ivanovo State Power University, Russia. He then was for many years with Moldova Power Company in various progressive roles in Protection and Control field. Since 1999 he is an application engineer with GE Multilin in Markham Ontario heavily involved in the development of UR-series relays. His areas of interest are current differential relaying, phase comparison, distance relaying and advanced communications for protective relaying. Ilia authored and co-authored more than 20 papers presented at major North America Protective Relaying conferences. He is a member of the PSRC, and a senior member of the IEEE

Zhiying Zhang has over 20 years of experience in electric power utilities and relay manufacturers. Currently he is an application engineer with GE Multilin. He holds a B.Sc degree and a M.Sc. degree from the North China Electric Power University (NCEPU) and a Ph.D. degree from the University of Manitoba, Canada. He is a registered professional engineer in the province of Ontario, and a senior member of IEEE.

William Premerlani received his Doctor of Engineering from Rensselaer Polytechnic Institute and joined GE's research laboratory in 1975, where he has been doing advanced development for many of GE's businesses. Lately he has been focusing on theoretical aspects of protective relaying. He is a Professional Engineer and a member of IEEE.