

IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines

IEEE Power and Energy Society

Sponsored by the
Power System Relaying Committee



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IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines

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Power System Relaying Committee
of the
IEEE Power and Energy Society

Approved 10 December 2014

IEEE-SA Standards Board

Abstract: Electrical faults on transmission and distribution lines are detected and isolated by system protective devices. Once the fault has been cleared, outage times can be reduced if the location of the fault can be determined more quickly. The techniques and application considerations for determining the location of a fault on ac transmission and distribution lines are outlined in this guide. Traditional approaches and the primary measurement techniques used in modern devices are reviewed: one- and two-terminal impedance-based methods and traveling-wave methods. Application considerations include: two- and three-terminal lines, series-compensated lines, parallel lines, untransposed lines, underground cables, fault resistance effects, and other power system conditions, including those unique to distribution systems.

Keywords: fault location, IEEE C37.114™, relays, synchrophasor, system protection, travelling waves

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Introduction

This introduction is not part of IEEE Std C37.114-2014, IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines.

This guide outlines the techniques and application considerations for determining the location of a fault on ac transmission and distribution lines. The guide reviews traditional approaches and the primary measurement techniques used in modern devices: one- and two-terminal impedance-based methods and traveling-wave methods. Application considerations include: two- and three-terminal lines, series-compensated lines, parallel lines, untransposed lines, underground cables, fault resistance effects, and other power system conditions, including those unique to distribution systems.

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1. Overview

1.1 Scope

This guide outlines the techniques and application considerations for determining the location of a fault on ac transmission and distribution lines. This document reviews traditional approaches and the primary measurement techniques used in modern devices: one-terminal and two-terminal impedance-based methods, [synchronized sampling methods](#) and traveling-wave methods. Application considerations include: two- and three-terminal lines, series-compensated lines, parallel lines, untransposed [lines, tapped](#) lines, underground cables, fault resistance effects, and other power system conditions, including those unique to distribution systems.

1.2 Purpose

The guide assists power system engineers and operators in applying fault-locating techniques on their systems. Users learn the strengths and limitations of fault location data and when further analysis is required using additional methods and when more data must be gathered. This guide assists in fault location and therefore faster restoration of power systems through improved understanding of fault-locating techniques.

1.3 Techniques and requirements for fault-locating devices

This guide discusses various approaches to determine fault location, with emphasis on automatic methods performed by microprocessor devices. The following are some [tools](#) [techniques](#) used to determine fault location:

- Microprocessor devices
- Short-circuit analysis software
- Customer calls (distribution)
- Line inspection

A device capable of determining the physical fault location has different requirements than a fault detection device:

- The speed to determine fault location is for human users (seconds or minutes), while relays usually need to detect faults within 10 ms to 50 ms. Consequently, additional information and more demanding and slower numerical techniques become available.

- A best fault data window can be selected to reduce errors.
- Communications enable transmitting data to a remote site using [dedicated](#) ~~low-speed~~ data communications or supervisory control and data acquisition (SCADA).
- More accurate phasor calculations can be achieved by using digital filtering of the voltage and current samples that would introduce an unacceptable delay for the relaying applications.
- High accuracy is needed for efficient dispatch of repair crews. Unlike protective relays, which need to detect whether faults are in the zones established by current transformer locations, pilot channels, and reach coordination, fault location data must be very accurate to save the time and reduce the expenses of the crews searching in bad weather and/or over rough terrain.

In this guide, the following are examined:

- Data and equipment required
- Commonly [used](#) algorithms
- Accuracy limitations of one-ended and two-ended impedance-based fault location methods
- [Synchronized sampling method](#)
- Traveling-wave methods and other methods
- Issues regarding distribution systems and underground cables

1.4 How to determine line parameters

1.4.1 Line parameters for impedance estimation

Accurate fault location based upon impedance estimation will depend on the accuracy of calculated transmission impedances. The common method of calculation is based on equations developed by J. R. Carson, ~~et al.~~¹, and published in 1926 [B3]. There are many good textbooks devoted to the topic of power system analysis that will show the development of Carson's equations used for determining the line impedances. It is not necessary to show the development of these equations here. Relay engineers have used the equations for many years to model power systems for performing short-circuit studies. A typical short-circuit computer program would utilize short or medium length line impedances derived from calculations based upon the assumption of fully transposed lines over a homogeneous right-of-way. The only significant details added to the model are the effects of zero-sequence mutual coupling between parallel sections of lines. The results obtained from these impedance models for determining relay coordination and performing postmortem analysis are very good. The question that remains is whether these calculated impedances are sufficient to obtain the desired level of accuracy in the location of faults. Accuracy to within 1% of error has been claimed for the calculated impedances (Eriksson, [Saha, and Rockfeller](#) ~~et al.~~ [B5]).

Another method of determining the line impedance parameters involves the direct measurement of the open circuit, and short-circuit voltages and currents. The accuracy is about the same as calculations based on Carson's equations. This method ~~would~~ requires special equipment [and network conditions \(i.e., the line must be taken out of service\)](#) to set up the tests.

A third method involves the estimation of the line parameters through the solution of two-port equations based on synchronized phasor measurement obtained from direct measurements from a digital relay or a fault recorder. The use of controlled tests to obtain the data and using the higher sampling rate of a digital recorder can result in impedance parameters with a high accuracy. It should be noted that all three techniques rely on an accurate value for the length of the line.

¹ [The numbers in brackets correspond to those of the bibliography in Annex A.](#)

It is suggested that the calculations for most lines can still be made using Carson's equations. These parameters can then be verified using ~~the~~ synchronized phasors of method three or by experience from the calculation of the locations from faults with verifiable locations. In spite of the accuracy of the line impedance parameters, the accuracy of fault location will be dependent upon the location technique employed, the sampling rate of the data collected, and the presence of unknown variables, most notably the amount of fault resistance.

Line parameter errors introduced on lines without transpositions are described in 5.12.

1.4.2 Parameters required for ~~the~~ traveling-wave fault locating

When a current-based traveling-wave fault locator is commissioned, the remote units are programmed with the substation and line name, sensitivity, and default sampling settings. No specific line parameters (impedances, etc.) are required for the remote units. The host personal computer ([PC](#)), on command, can receive the data from each of the remote units. Once the PC has the data files, the information is analyzed and the line length can be determined. The only inputs required to analyze fault data with the traveling-wave fault locator are line length and wave velocity. The individual line length can be determined by energizing the line. The procedure is to energize the line in a radial fashion and then measure the time the reflected wave takes to return to the source. The known line length is compared with the length determined by the timing of the reflected wave. This method may not always give accurate results due to the effects of pre-insertion resistors and the closing point on the voltage sine wave. It is not always necessary to rely solely on this method because the line length calibration can also be determined from evaluation of any faults occurring on adjacent line sections.

2. References

~~The following referenced documents are indispensable for the application of this standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.~~

2. Definitions, acronyms, and abbreviations

2.1 Definitions

For the purposes of this [document guide](#), the following terms and definitions apply. The ~~Authoritative~~ IEEE Standards Dictionary [Online Terms](#), [B3]³, should be [consulted](#) ~~referenced~~ for terms not defined in this clause.²

dc thumping: A procedure of applying dc voltage pulses to an underground cable with the intent of locating a cable irregularity with a listening device.

digital recorder: A device that can perform analog-to-digital conversions and store the information in digital form for later retrieval.

distributed intelligence: Gathering data from many different devices for analysis and decision making in a central device.

evolving fault: A fault where the phases involved change over time. For example, a phase-to-ground fault becomes a phase-to-phase-to-ground fault.

² [IEEE Standards Dictionary Online subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.](http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html)

³ ~~The numbers in brackets correspond to those of the bibliography in Annex A.~~

fault location error: Percentage error in fault location estimate based on the total line length: e (error) = (instrument reading – exact distance to the fault) / total line length.

~~**3.1.6 GPS time synchronization:** A method of using a time signal from the global positioning system (GPS) satellite system for time synchronizing equipment.~~

homogeneous line: A transmission line where impedance is distributed uniformly on the whole length.

homogeneous system: A transmission system where the local and remote source [sequence](#) impedances have the same system angle as the line [sequence](#) impedance.

[**intelligent electronic device \(IED\):** Any device incorporating one or more processors with the capability to receive or send data/control from or to an external source \(e.g., electronic multifunction meters, digital relays, controllers\).](#)

nomograph: A graph that plots measured fault location versus actual fault location by compensating for known system errors.

Peterson's coil: A tunable reactor used for impedance grounding a distribution or transmission system that is usually tuned to [be in the](#) resonance [with the capacitance to ground](#) of [all the](#) system [components](#).

pre-insertion resistor: A resistor that is inserted in parallel with each set of breaker contacts during the closing stroke of the breaker.

series-compensated line: A transmission line with series capacitors.

superposition current: The summation current at any point in a linear network that results from the voltages applied at various points in the network.

synchronized phasor or synchrophasor: A phasor calculated from data samples using a standard time signal as the reference for the measurement.

~~3.1.14 synchronous phasor~~: ~~Phasor measurements taken at some point in time that can be referenced to measurements from other locations taken at the same point in time.~~

time code stamping: Associating an accurate time with a particular event.

time synchronization: A method of using a time signal from an accurate time source for time-synchronizing equipment.

traveling wave: The resulting wave when the electric variation in a circuit takes the form of translation of energy along a conductor, such energy being always equally divided between current and potential forms.

2.2 Acronyms and abbreviations

~~CVT~~	~~capacitive voltage transformers~~
~~DMS~~	~~distribution management system~~
~~HMI~~	~~human machine interface~~
MOV	metal oxide varistors
<u>PMU</u>	<u>phasor measurement units</u>
SCADA	supervisory control and data acquisition
<u>SLG</u>	<u>single-line to ground</u>

3. One-ended impedance-based measurement techniques

3.1 Background

One-ended impedance-based fault locators calculate the fault location from the apparent impedance seen looking into the line from one end. 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, and additionally, if the zero-sequence source impedance, Z_0 , is known, [the](#) location for phase-to-ground faults can also be estimated).

If the fault resistance is assumed to be zero, ~~we can~~ use one of the impedance calculations in Table 1 to estimate fault location. The exact mathematical equations for fault location taking into account fault resistance and load are found in 3.3.

Table 1 — Simple impedance equations

Fault type	Positive-sequence impedance equation ($mZ_{1L} =$)
a-ground	$V_a / (I_a + kI_R)$
b-ground	$V_b / (I_b + kI_R)$
c-ground	$V_c / (I_c + kI_R)$
a-b or a-b-g	V_{ab} / I_{ab}
b-c or b-c-g	V_{bc} / I_{bc}
c-a or c-a-g	V_{ca} / I_{ca}
a-b-c	Any of the following: V_{ab} / I_{ab} , V_{bc} / I_{bc} , V_{ca} / I_{ca}
where k is $(Z_{0L} - Z_{1L}) / 3Z_{1L}$ Z_{0L} is the zero-sequence line impedance m is the per unit distance to fault (e.g., distance to fault in kilometers divided by the total line length in kilometers) I_R is the residual current	

Voltage and current data are used to determine the impedance to the fault location, as shown in Table 1. By knowing the line impedance per unit, the distance to the fault per unit can be determined. A correct fault location estimate, unfortunately, is affected by many factors not represented by these equations:

- a) The combined effect of the load current and fault resistance (reactance effect). The value of the fault resistance may be particularly high for ground faults, which represent the majority of the faults on overhead lines.
- b) Inaccurate fault type (faulted phases) identification.
- c) Influence of zero-sequence mutual effects ~~on the components~~.
- d) Uncertainty about the line parameters, particularly zero-sequence impedance. It is often difficult to obtain an accurate zero-sequence impedance (Z_{0L}) for the line. The value of Z_{0L} is affected by soil resistivity, which can be difficult to measure and may be changeable. A 20% error in Z_{0L} can introduce a 15% error in the calculated fault location. In addition, this impedance is not uniformly distributed along the line length. (100 to 1 variation in earth resistivity produces about a 2 to 1 change in Z_0 .)
- e) Insufficient accuracy of the line model (e.g., untransposed lines are represented as being transposed, and charging capacitance is not considered).
- f) Presence of shunt reactors and capacitors.
- g) Load flow unbalance.
- h) [Series-compensated and multi-terminal lines.](#)
- i) Measurement errors, current and voltage transformer errors, and bit resolution of [analog to digital conversion \(A/D\)](#) system.
- j) The filtering system necessary to extract the phase voltages and current phasors. For example, if the fault voltages and currents do not reach steady-state value (as in a fault with time varying resistance) or if the fault is cleared with a delay smaller than the filter nominal response time, then the estimated fault location could have substantial errors.

k) [Clock sampling rate of the device.](#)

To improve the fault location estimate, it is important to eliminate or reduce errors caused by inadequate assumptions or inaccurate data applied to fault location algorithms. The algorithms will be more accurate if more information about the system is available.

3.2 Implementation: data and equipment required

One-ended fault location methods require the following equipment for implementation:

- A microprocessor-based relay or other device that measures three-phase voltages and currents and calculates a fault location estimate
- [A Dial-up](#) communications ~~or SCADA~~ interface to remotely obtain the fault location estimate

The following data or information is required from the equipment:

- Phase-to-ground voltages and phase currents. Some algorithms can accommodate delta-connected voltages, but only if zero-sequence source impedance is known at the time of fault (Schweitzer [B55]).
- Correct fault type must be known (e.g., a-g, b-g, c-g, a-b).
- Some methods require pre-fault load data.

3.3 Determination of measurement error

3.3.1 Background

There are different methods for determining the measured fault location error. Following are three methods for determining the measurement error that will be described further, including their advantages and the intended use for each method:

- a) Absolute error
- b) Relative error based on line length
- c) Traditional relative error

While absolute error gives a value regardless of the line length, relative errors are more useful to compare various fault location methodologies independently of the power system. For example, for a 10-mile short line, a calculation error of 5 miles is large. For a 200-mile-long line, a calculation error of 5 miles is relatively small.

3.3.2 Absolute error

Absolute error is defined as:

$$e_a = |m_m - m_t| \quad (1)$$

(New)

where

e_a is the absolute error – per unit (p.u.), percentage (%), or distance (miles or kilometers)

m_m is the measured fault location – per unit (p.u.), percentage (%), or distance (miles or kilometers)

m_t is the true fault location – per unit (p.u.), percentage (%), or distance (miles or kilometers)

Understanding a range of error values, for a particular fault location methodology used in a particular power system, could provide useful guidance to the crew that needs to travel to an actual location of the fault to fix a problem.

3.3.3 Relative error based on line length

The fault location error based on line length is calculated as follows:

$$e_l = \frac{|m_m - m_t|}{L} \quad (2)$$

(New)

where

e_l is the relative error based on line length – per unit (p.u.), percentage (%), or distance (miles or kilometers)

L is the line length – per unit (p.u.), percentage (%), or distance (miles or kilometers)

3.3.4 Traditional relative error

The traditional fault location error is calculated as follows:

$$e_t = \frac{|m_m - m_t|}{m_t} \quad (3)$$

(New)

where

e_t is the traditional relative error – per unit (p.u.) or percentage (%)

Unless this relative error is used within the context of pure statistical analysis, it is less intuitive to practical application in locating faults.

3.3.5 Comparison of measurement error methods

The advantage of the definition based on line length is that the absolute fault location error is independent of the location of the fault. For example, for a 100-mile-long line with an error of 5 miles, the error e_l is 0.05 p.u. or 5% regardless if the fault is at the beginning of the line or at the end of the line.

For the traditional method, the same absolute error of 5 miles for the same line 100-mile line would be different depending on the fault location. For example if a fault is at 10 miles from the substation at the beginning of the line, the error e_t is 0.5 p.u. or 50%. If fault is at 90 miles from the substation at beginning of the line (or 10 miles from the substation at the other end of the line), the error e_t is 0.056 p.u. or 5.56%.

For single-ended algorithms, both methods could be used. However, for double-ended methods, it could be confusing to use the traditional method, as the fault location could be calculated from both ends of the line, so the true value needs a common reference to be compared with.

Furthermore, as for a particular power network, the combination of system source impedance ratios and location of the fault have a major effect on accuracy of single-ended algorithms. When evaluating and comparing errors of various algorithms, it is very important to take this into account. It may be easier to compare various algorithms having a common reference (such as the line length). Staging faults at the end of the line with favorable source impedance ratios could result in a misleading high accuracy.

From a statistical standpoint, the interest is in the deviation of the predicted location from the true location based on the total (i.e., total line length). Each line is treated as the total distribution of all possible faults and each fault would be treated as a single sample of this distribution. The absolute error stated here is actually a sample error. For the purposes of fault location, it is preferred then to state the relative error based on the line length. Using this preferred method, the errors for several faults on a given line would appear uniform regardless of their location along the line.

The reverse of this would be to apply a predicted error (based on experience) to a measured location to assist in a line patrol. For example, a fault is predicted to be of 23 miles on a 100-mile line. From experience, it could be predicted that the true location will be discovered within 5% of the line length. Therefore, a patrol would be instructed to expect the location to be somewhere between 18 and 28 miles from the substation.

3.4 Error due to reactance effect ~~System parameters and main sources of error: fault resistance and load~~

Issues in estimating the fault location using local data can be described by considering the simplified, single-line diagram of the system shown in Figure 1.

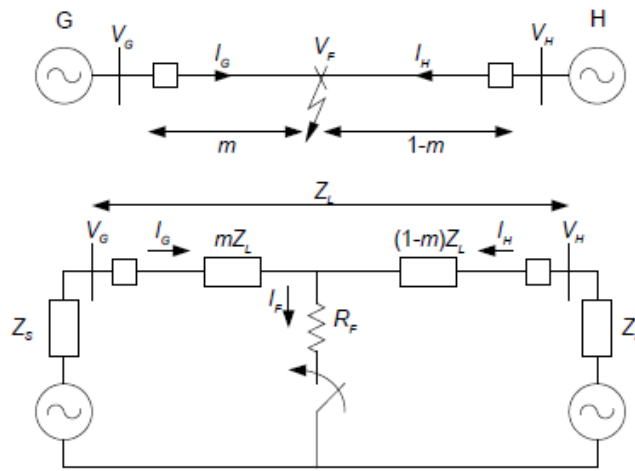


Figure 1 — One line and equivalent circuit for a three-phase fault on a transmission line with two sources, G and H

A fault with resistance R_F is on the homogeneous line with an impedance Z_L between terminals G and H. The terminal voltages are V_G and V_H . The currents from both ends of the line, I_G and I_H , contribute to the total current in the fault, I_F . The parts of the system behind the local and remote terminals are replaced with the Thevenin equivalents having the impedances Z_S and Z_R (source impedances). The voltage drop from terminal G can be written easily along with the per unit fault location, m :

$$V_G = mZ_L I_G + R_F I_F \quad (4)$$

where

V_G is the voltage at terminal G

m is the distance to the fault in per unit

Z_L is the line impedance between terminals G and H

I_G is the line current from terminal G

R_F is the fault resistance

I_F is the total fault current

The value of the impedance measured at terminal G may be found by dividing Equation (4) by the measured current, I_G .

$$Z_{FG} = \frac{V_G}{I_G} = mZ_L + R_F \frac{I_F}{I_G} \quad (5)$$

where

Z_{FG} is the apparent impedance to the fault measured at terminal G

If the ratio of the fault current, I_F , and the current at the fault locator location, I_G , is a complex number, the fault resistance will be represented as an impedance with a reactive component. The reactive component can be inductive or capacitive, depending on the angle of the ratio of the two currents. The reactive component will be zero only if the angle is zero. This is the case if the infeed current from the remote terminal, I_H , is zero or is in phase with the local current, I_G . The reactive component can produce an error in the fault location estimate as shown in Figure 2.

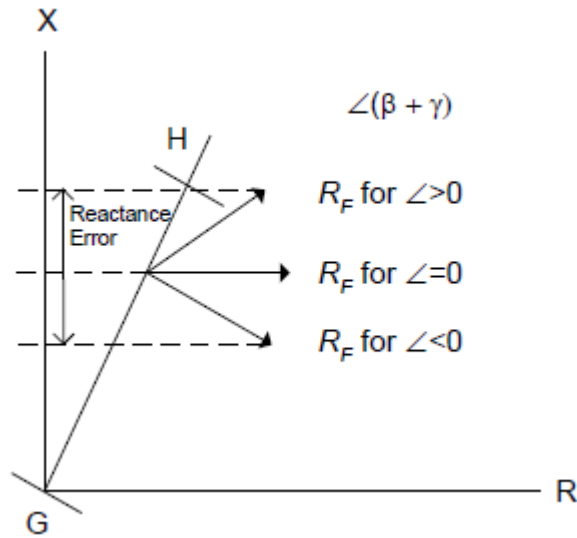


Figure 2 — Graphical interpretation of the fault resistance and pre-fault load errors

In order to analyze which parameters affect the angle of I_F/I_G , superposition may be used to separate the pre-fault and fault systems. Let the pre-fault load current be represented by I_L , and the difference (superimposed) current by $\Delta I_G = I_G - I_L$. Equation (5) may be rewritten as:

$$Z_{FG} = \frac{V_G}{I_G} = mZ_L + R_F \frac{1}{d_s n_s} \quad (6)$$

where

d_s is the current distribution factor as shown in Equation (7)

n_s is the circuit loading factor as shown in Equation (8)

$$d_s = \frac{\Delta I_G}{I_F} = \frac{Z_H + (1-m)Z_L}{Z_H + Z_L + Z_G} = |d_s| \angle \beta \quad (7)$$

$$n_s = \frac{I_G}{I_G - I_L} = \frac{I_G}{\Delta I_G} = |n_s| \angle \gamma \quad (8)$$

Thus the angle of the current ratio I_F/I_G , and therefore the reactive component caused by the fault resistance, is determined by two factors. The current distribution factor, d_s is determined by the system impedances. If the system is homogeneous, then the angle of d_s , β , is zero. If there is load flow on the system, the angle of n_s , γ , will not be zero. However, if the magnitude of the fault current, I_G , is much greater than the magnitude of the load current, I_L , the angle γ will approach zero. The sum of the angles, $(\beta + \gamma)$, will determine the reactive component caused by fault resistance, R_F .

Various techniques can be used to reduce the effect of the fault resistance, R_F , most of which need to make certain simplifying assumptions to achieve implementation. The performance of the fault location algorithm, with respect to R_F , is dependent on the assumptions that have been made. Some typical algorithms are described in 3.5.

3.5 Algorithms

3.5.1 Background

Depending on the circuit data available, different fault location algorithms may be implemented. This section provides an overview of different fault location algorithms that attempt to limit the error due to fault resistance and load current.

3.5.1 Simple reactance method

With the simple reactance method, the device measures the apparent impedance, then determines the ratio of the measured reactance to the reactance of the entire line. This ratio is proportional to the distance to the fault. The method assumes that the current through the fault resistance is in phase with the current at the measurement point, and there is no load prior to the fault.

The reactance algorithm is one of the earliest algorithms that compensates for the fault resistance by measuring only the imaginary part of the apparent line impedance Z_G . Per unit distance to the fault is shown in Equation (9):

$$m = \frac{\text{Im}(V_G/I_G)}{\text{Im}(Z_L)} \quad (9)$$

For the line-to-ground fault (a-g), the calculation would be as shown in Equation (10):

$$m = \text{Im} \left[\frac{V_{Ga}}{I_{Ga} + k_0 I_R} \right] / \text{Im}(Z_{1L}) \quad (10)$$

where

k_0 is $(Z_{0L} - Z_{1L})/3Z_{1L}$ and residual current $I_R = 3I_0$.

The error is zero if the fault resistance is zero or if I_G and I_F are in phase. For a fault with a high resistance, the algorithm may introduce considerable reactance error, as shown in Figure 2. The reactance effect increases or reduces the apparent line reactance to the fault, leading to an error in apparent fault location. Some one-terminal data algorithms, described in 3.5.2, have been developed to compensate for the reactance effect.

3.5.2 Fault location method without using source impedances

The above can be improved upon with elimination of load current by determining the change in current on occurrence of a fault. This method, which uses superposition current ΔI_G , has been discussed in the literature by various researchers, most notably by Takagi, et al [B58]. In addition, Eriksson, [Saha, and Rockfeller et al.](#) [B5] use the distribution factor, d_s , to represent the voltage drop across the fault resistance, R_F . Equation (4) can be written as:

$$V_G = mZ_{1L}I_G + R_F \frac{\Delta I_G}{d_s} \quad (11)$$

Equation (12) shows the result that is obtained if both sides of Equation (11) are multiplied by the complex conjugate, ΔI_G^* , using only the imaginary part:

$$\text{Im}(V_G \Delta I_G^*) = m \text{Im}(Z_L I_G \Delta I_G^*) + R_F \text{Im}\left(\frac{1}{d_s}\right) \quad (12)$$

If the system is homogenous, the angle of the current distribution factor is nearly zero ($\text{Im}(1/d_s) = 0$) and the fault location is:

$$m = \frac{\text{Im}(V_G \Delta I_G^*)}{\text{Im}(Z_L I_G \Delta I_G^*)} \quad (13)$$

The current distribution factors for the parts of the network, located on either side of the fault point, are assumed to have the same arguments (consequently, $\beta = 0$). Put another way, this method is accurate if the fault current at the fault locator is in phase with the fault current at the fault. The error of the method is proportional to the fault resistance and $\sin \beta$ (see Figure 2). The value of β generally varies with the distance to fault and cannot be calculated unless the source impedances are accurately known. In general, the stronger the local source, the closer the value of β tends toward 0. This method compensates for the error caused by the circuit loading (complex number nS , angle γ).

A method in Novosel, et al. [B39] uses an assumption that the current distribution factor in the negative-sequence network is a real number. For the unbalanced ground faults, this method does not require pre-fault currents, and the zero-sequence distribution factor does not affect [the](#) fault location estimate. Although adequate accuracy is expected for the variety of fault cases, the assumptions above may lead to approximate solutions. The methods in this category compensate for load and fault resistance but are sensitive to [an](#) argument of the current distribution factor that is not equal to zero in nonhomogenous systems. One implementation of this multiplies both the numerator and denominator of Equation (13) by a phasor of unity magnitude and angle β .

Another method (modified Takagi) uses the zero-sequence current (I_R) instead of the superposition current (ΔI_G), and angle correction (β) derived from the source impedance data to account for a nonhomogeneous system:

$$m = \frac{\text{Im}(V_G I_R^* e^{-j\beta})}{\text{Im}(Z_{1L} I_G I_R^* e^{-j\beta})} \quad (14)$$

This method can improve the fault location estimate by reducing the reactance effect error. However, angle correction, β , makes the fault location accurate at only one point on the line. The result is that ground faults at other points on the line do not have a precise β setting to achieve accurate fault location.

3.5.3 Fault location methods using source impedance

The significance of the distribution factor is discounted in the method described in Eriksson, [Saha, and Rockefeller, et al.](#) [B5], which uses a positive-sequence model of the transmission line and source impedances at the two ends of the line. In this case, knowledge of the source impedances is required, which is not necessarily always known to the desired accuracy.

If the source impedances are known, the fault location can be accurately estimated without assumptions. One method discussed in Eriksson, [Saha, and Rockefeller et al.](#) [B5] substitutes Equation (7) in Equation (11). Since the current distribution factor dS is a function of the source impedances, the line impedance, and the unknown fault location m , a quadratic equation follows:

$$m^2 - mk_1 + k_2 - k_3 R_F = 0 \quad (15)$$

where

- k_1 complex function of local voltage
- k_2 complex function of current, ~~and~~
- k_3 complex function of source impedances

By separating Equation (15) into a real and an imaginary part, one has two equations with two unknowns, m and R_F . The per unit distance to the fault m can be calculated by eliminating R_F and solving for m .

Methods using source impedances are not sensitive to the reactance effect (compensation for load and fault resistance, and argument of current distribution factor) but require the input of the source impedances as the setting parameters. They [provide](#) ~~ensure~~ very accurate results for every network [if providing](#) the source impedances are equal to the set value. Errors can occur when the source impedances are not equal to the set values used by the fault locator.

4. Two-terminal data methods

4.1 Background

Present communications technology allows for use of data from both ends of the transmission line. The calculation of fault location using data from two ends is fundamentally similar to the single-ended methods except now a means exists to determine and [reduce](#) ~~minimize~~ or eliminate the effect of fault resistance and other similar factors that tend to throw off the accuracy of the estimate. These factors, such as nontranspositions, strong or weak sources, loading, and others, have been discussed earlier. There have been many articles on variations of the fundamental techniques aimed at improving the accuracy in locating faults. Details of many of these variations can be found in the articles referenced in this guide (i.e., [Girgis, Hart, and Peterson et al.](#) [B10], ~~Aldy, et al. [B11]~~, Hart, [Novosel, and Udren et al.](#) [B15], Kezunovic [B24], Lawrence, [Cabeza, and Hochberg \[B31\]](#), Novosel, et al. [B38], and Tziouvaras, [Roberts, and Benmouya et al.](#) [B61]).

Positive, negative, or zero sequence components may be used and the choice depends on the type of fault and on the extent of system imbalances such as mutual coupling (Makki, et al. [B35]). Positive-sequence components are present in all fault types which simplifies automation because the fault type does not need to be calculated. Negative-sequence components are useful for mitigating the effects of mutual coupling and are present in most fault types except for balanced three-phase faults (Turner [B60]). Zero-sequence components are also useful especially when system imbalances are properly mitigated but are only present in unbalanced fault types. ~~The two-terminal location methods are more accurate than one-terminal methods and are able to minimize or eliminate the effects of fault resistance, loading, and charging current. Fault type does not need to be calculated. Therefore, positive-sequence components are used rather than zero-sequence, thus eliminating adverse effects of zero-sequence components.~~ The main drawback is the fact that data from both ends must be gathered at one location to be analyzed, whereas the one-terminal location can be done at the line terminal by the relay or other device collecting the data. Effective two-terminal fault location requires an efficient means of collecting oscillographic or phasor data from electronic devices at each end of a line following a fault and processing that data automatically. To simplify the procedure of providing the utility personnel with the proper information at the proper location (such as dispatching center) when needed, the system-wide solution is desirable (~~see~~ Girgis, [Hart, and Peterson et al.](#) [B10]).

This location technique, therefore, takes more time, but speed is not critical for human users. A response in seconds or minutes is adequate. The collected data must also be at least roughly synchronized from each end before analysis is performed. This can be accomplished analytically or through time code stamping. Factors incorporated in the calculations to handle specific error-causing problems may further complicate analysis. Software or other analysis tools are required to properly identify parameters for the fault and implement a two-terminal algorithm. The two-terminal technique has been tested in the field with accurate results (Novosel, et al. [B38], Peterson, et al. [B44]).