

C37.114™

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

IEEE Power Engineering Society

Sponsored by the
Power System Relaying Committee



3 Park Avenue, New York, NY 10016-5997, USA

8 June 2005

Print: SH95314

PDF: S339314



Documents

Document Sharing Hub

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

Sponsor

Power System Relaying Committee
of the
IEEE Power Engineering Society

Approved 8 December 2004

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. This guide outlines the techniques and application considerations for determining the location of a fault on ac transmission and distribution lines. The document reviews traditional approaches and the primary measurement techniques used in modern devices: one-terminal 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, relays, system protection, traveling waves

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2005 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 8 June 2005. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by the Institute of Electrical and Electronics Engineers, Incorporated.

Print: ISBN 0-7381-4653-6 SH95314
PDF: ISBN 0-7381-4654-4 SS95314

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. The IEEE develops its standards through a consensus development process, approved by the American National Standards Institute, which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and serve without compensation. While the IEEE administers the process and establishes rules to promote fairness in the consensus development process, the IEEE does not independently evaluate, test, or verify the accuracy of any of the information contained in its standards.

Use of an IEEE Standard is wholly voluntary. The IEEE disclaims liability for any personal injury, property or other damage, of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of, or reliance upon this, or any other IEEE Standard document.

The IEEE does not warrant or represent the accuracy or content of the material contained herein, and expressly disclaims any express or implied warranty, including any implied warranty of merchantability or fitness for a specific purpose, or that the use of the material contained herein is free from patent infringement. IEEE Standards documents are supplied “**AS IS**.”

The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

In publishing and making this document available, the IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity. Nor is the IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing this, and any other IEEE Standards document, should rely upon the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position, explanation, or interpretation of the IEEE.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854
USA

NOTE—Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Authorization to photocopy portions of any individual standard for internal or personal use is granted by the Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Introduction

This introduction is not part of IEEE Std C37.114-2004, IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines.

This guide shall outline the techniques and application considerations for determining the location of a fault on AC transmission and distribution lines. We shall review traditional approaches and the primary measurement techniques used in modern devices: one-terminal 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.

Notice to users

Errata

Errata, if any, for this and all other standards can be accessed at the following URL: <http://standards.ieee.org/reading/ieee/updates/errata/index.html>. Users are encouraged to check this URL for errata periodically.

Interpretations

Current interpretations can be accessed at the following URL: <http://standards.ieee.org/reading/ieee/interp/index.html>.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents or patent applications for which a license may be required to implement an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Participants

The following is a list of participants in the Fault Location Working Group:

Karl Zimmerman, Chair

D. J. Novosel, Vice-Chair

G. E. Alexander
A. Apostolov
L. Budler
P. T. Carroll
J. Delaree
P. Gale

B. Jackson
H. Jacobi
M. Kezunovic
W. G. Lowe
R. Marttila
M. J. McDonald
M. S. Sachdev

T. Seegers
H. M. Shuh
T. S. Sidhu
D. Tziouvaras
J. E. Waldron
R. Young

The following members of the individual balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

William Ackerman
Steve Alexanderson
Gabriel Benmouyal
Kenneth Birt
Stuart Borlase
Stuart Bouchey
Daniel Brosnan
Gustavo Brunello
Carlos Castro
John W. Chadwick, Jr.
Stephen Conrad
Robert Copyak
James R Cornelison
Luis Coronado
Ronald Dauber
Douglas Dawson
Santpal Dhillon
Guru Dutt Dhingra
Randall Dotson
Paul Drum

Ahmed Elneweih
Gary Engmann
Kenneth Fodero
Anthony Giulianti
Manuel Gonzalez
Ajit Gwal
Roger Hedding
James D. Huddleston III
David Jackson
Joseph L. Koepfinger
David Krause
Gregory Luri
Keith Malmedal
Jesus Martinez
Thomas McCaffrey
Michael McDonald
Jeff McElray
Mark McGranaghan
Gary Michel
Dean Miller
Bill Moncrief

Anthony Napikoski
Charles Rogers
James Ruggieri
Mohindar Sachdev
Tony Seegers
Tom Short
H. Jin Sim
Mark Simon
Harinderpal Singh
Kevin Stephan
James Stoner
Glenn Swift
Rick Taylor
John Tengdin
Eric Udren
Gerald Vaughn
Charles Wagner
Philip Winston
Ray Young
Karl Zimmerman

When the IEEE-SA Standards Board approved this standard on 8 December 2004, it had the following membership:

Don Wright, Chair

Steve M. Mills, Vice Chair

Judith Gorman, Secretary

Chuck Adams
Stephen Berger
Mark D. Bowman
Joseph A. Bruder
Bob Davis
Roberto de Marca Boisson
Julian Forster*
Arnold M. Greenspan
Mark S. Halpin

Raymond Hapeman
Richard J. Holleman
Richard H. Hulett
Lowell G. Johnson
Joseph L. Koepfinger*
Hermann Koch
Thomas J. McGean

Daleep C. Mohla
Paul Nikolich
T. W. Olsen
Ronald C. Petersen
Gary S. Robinson
Frank Stone
Malcolm V. Thaden
Doug Topping
Joe D. Watson

*Member Emeritus

Also included are the following nonvoting IEEE-SA Standards Board liaisons:

Satish K. Aggarwal, *NRC Representative*
Richard DeBlasio, *DOE Representative*
Alan Cookson, *NIST Representative*

Jennie Steinhagen
IEEE Standards Project Editor

Contents

1. Overview	1
1.1 Scope	1
1.2 How to determine line parameters	2
2. References	3
3. Definitions, acronyms, and abbreviations	3
3.1 Definitions	3
3.2 Acronyms and abbreviations	4
4. One-ended impedance-based measurement techniques	4
4.1 Implementation: data and equipment required	5
4.2 System parameters and main sources of error: fault resistance and load	6
4.3 Algorithms	8
5. Two-terminal data methods	10
5.1 Implementation: data and equipment required	10
5.2 System parameters	11
5.3 Algorithms	11
6. Other fault location applications	12
6.1 Three-terminal lines	12
6.2 Series-compensated lines	12
6.3 Parallel lines	15
6.4 Distribution system faults	16
6.5 Locating faults on underground cables, paralleled cable circuits	18
6.6 Automatic reclosing effects on fault locating	20
6.7 Effect of tapped load	20
6.8 Phase selection, fault identification, sequential faults	21
6.9 Long lines and reactor and capacitor installations	21
6.10 Short duration faults	21
6.11 Effect of untransposed lines on accuracy of line parameters	22
6.12 Comparison of one-terminal and two-terminal impedance-based methods	23
7. Traveling wave techniques	26
7.1 Data and equipment required	27
7.2 Accuracy limitations	27
7.3 Traveling wave methods	28
8. Other techniques	29
8.1 Methods using synchronized phasors	29
8.2 Methods requiring time-tagging of the events	29
9. Conclusion	29
Annex A (informative) Bibliography	31
Annex B (informative) Additional information on series-compensated lines	34

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

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 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.

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

- a) Microprocessor devices
- b) Short-circuit analysis software
- c) Customer calls (distribution)
- d) Line inspection

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

- a) The speed to determine fault location is for human users (seconds or minutes), while relays usually need to detect fault within 10 ms to 50 ms. Consequently, additional information and more demanding and slower numerical techniques become available.
- b) A best fault data window can be selected to reduce errors.
- c) Communications enable transmitting data to a remote site using low-speed data communications or supervisory control and data acquisition (SCADA).
- d) 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.
- e) 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 ct 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
- Common algorithms
- Accuracy limitations of one-ended and two-ended impedance-based fault location methods
- Traveling wave methods and other methods
- Issues regarding distribution systems and underground cables

1.2 How to determine line parameters

1.2.1 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., and published in 1926 [B1]. 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, et al. [B2]).

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 require special equipment to set up the tests.

A third method involves the estimation of the line parameters through the solution of two-port equations based on synchronous phasor measurements 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.

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 synchronous 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 Annex A.

1.2.2 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, 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.

IEEE Std C37.2™, IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.^{1,2}

IEEE Std C37.90™, IEEE Standard for Relays and Relay Systems Associated with Electric Power Apparatus.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms*, [B3]³, should be referenced for terms not defined in this clause.

3.1.1 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.

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

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

3.1.4 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.

3.1.5 fault location error: Percentage error in fault location estimate based on the total line length: $e(\text{error}) = (\text{instrument reading} - \text{exact distance to the fault}) / \text{total line length}$.

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.

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

3.1.8 homogeneous system: A transmission system where the local and remote source impedances have the same system angle as the line impedance.

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

¹ The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

² IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

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

3.1.10 Peterson's coil: A tunable reactor used for impedance grounding a distribution or transmission system that is usually tuned to the resonance of the system.

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

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

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

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.

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

3.1.16 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.

3.2 Acronyms and abbreviations

CVT	capacitive voltage transformers
DMS	distribution management system
HMI	human-machine interface
MOV	metal oxide varistors
SCADA	supervisory control and data acquisition

4. One-ended impedance-based measurement techniques

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, we can estimate location for phase-to-ground faults).

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 4.2.

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:

- 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.
- Inaccurate fault type (faulted phases) identification.
- Influence of zero-sequence mutual effects on the components.
- 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_{0L} .)
- Insufficient accuracy of the line model (e.g., untransposed lines are represented as being transposed, and charging capacitance is not considered).
- Presence of shunt reactors and capacitors.
- Load flow unbalance.
- Measurement errors, current and voltage transformer errors, and bit resolution of A/D system.
- 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.

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.

4.1 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
- 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 [B15]).
- Correct fault type must be known (e.g., a-g, b-g, c-g, a-b).
- Some methods require pre-fault load data.

4.2 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.

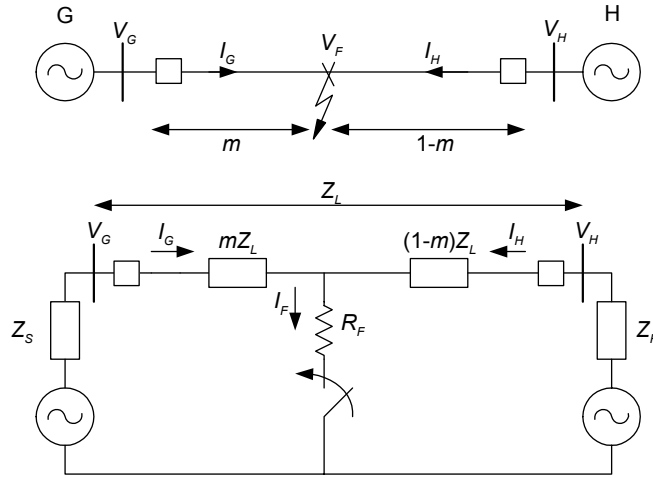


Figure 1— One-line and equivalent circuit for a three-phase fault on a transmission line with two sources, G and H

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_G and Z_H (source impedances). The voltage drop from terminal G can be written easily along with the per unit fault location, m :

$$V_G = mZ_L I_G + R_F I_F \quad (1)$$

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 (1) by the measured current, I_G .

$$Z_{FG} = \frac{V_G}{I_G} = mZ_L + R_F \frac{I_F}{I_G} \quad (2)$$

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