

Distribution Fault Location and Waveform Characterization

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PRODUCT DESCRIPTION

Automated fault location algorithms for distribution systems require monitoring equipment to record voltage and current waveforms during an event. In addition, most of these algorithms require circuit-impedance parameters to evaluate the fault location. Locating incipient faults and fault waveform characterization is the main aim of this project. This project builds on work done in 2008 towards sub-cycle blip identification using an algorithm based on arc voltage.

Results and Findings

This project can be divided into two main parts:

1. Incipient fault location: Sub-cycle incipient faults can be used to detect probable fault location candidates in the distribution system, well before the actual fault occurs at that location. A fault-location algorithm based on arc voltage was developed, implemented, and validated with known fault-location results. This algorithm uses the arc voltage during the fault to accurately determine the location without any knowledge of the circuit impedance data. Moreover, arc voltage-based algorithms located the faults much more accurately in comparison with other impedance-based algorithms. The same algorithm was applied to sub-cycle self-clearing faults that act as precursors to the full-blown faults. The algorithm was found to be very accurate in identifying and locating these sub-cycle events.
2. Fault characterization: Faulted voltage and current waveforms were analyzed to determine their root causes. Common and unique signatures were identified and were used to classify a large data set based on the nature and cause of the fault. These classes include cable faults (cable, joint or splice, and termination failures), animal and tree contact faults, lightning-induced faults, and faults cleared by current-limiting fuses.

Challenges and Objectives

The ultimate goal of distribution fault-location project is to develop a commercial-grade fault-location system that utilities can integrate into their systems. EPRI's PQView system is used as the platform for the fault-location system. A large set of actual field data was validated to make sure that approaches were developed that would work with real monitoring data and real faults. Taking into account a number of factors, such as numerical issues, result interpretation, and fault characteristics, best possible approaches were identified and used.

The main challenges in achieving the ultimate objective are integrating the monitoring data from a wide variety of data sources like relays and meters, integrating circuit information from Cyme or GIS, and incorporating a user interface into a control center.

Application Value and Use

Providing operators with relatively accurate and reliable knowledge of incipient location will prevent catastrophic events. Moreover, having knowledge about the root cause behind a fault will result in tremendous improvement in utility restoration efforts. Automated fault-location systems provide a distance to the fault (or impedance estimate). This system can be used to avoid manual

patrolling of the entire feeder in case of a main feeder lockout. It can also be used for circuits with repeated momentary interruptions to pinpoint the section of the circuit causing such problems.

Self-clearing fault identification can be used to avoid distribution system faults. The fault location provided by the application of an arc voltage-based algorithm on these sub-cycle events can be used as an alarm to send patrolling parties in the vicinity of the identified location to check for any future problems. Thus, reliability of the distribution system can be improved significantly. A logic can be developed that will identify the frequency of these self-clearing faults and provide an alarm signal at the right moment. Fault characterization can be used to expedite service restoration. Knowledge of the actual cause of the fault can be used by the patrolling party to carry the most appropriate equipment required during restoration. It can also be used to identify future occurrences of the faults having similar characteristics. Analysis on different classes may provide a means to prevent such faults on the distribution line.

EPRI Perspective

The research results on locating incipient faults look promising. With more development, the approach could help improve system reliability, especially on urban cable systems. The algorithms and methods used to locate incipient faults may also improve approaches for locating other types of faults, especially those with messy waveforms and high harmonics. Though not as promising, the fault event classification has identified several fault signatures that are worth exploring more.

Approach

Existing fault-locating methods for underground cables and overhead lines were reviewed. The arc voltage-based method identified in the 2008 project formed the basis of the analysis. This algorithm was derived, implemented, and validated with monitoring data, fault information, and circuit data collected from the actual distribution field. Time-domain simulation models were also validated. Advanced signal-processing techniques were explored to identify the best possible numerical techniques that will lead to the most accurate fault-location results. Pre-processing of waveforms and post-processing of impedance-to-faults estimates were employed for this purpose. Both of these methods led to significant improvement in the fault-location results. This algorithm was applied to a large number of pre-cursor incipient fault events selected from the voluminous distribution system waveform database. The results were seen to be quite useful in predicting the actual fault location based on the pre-cursor events. The importance of sample window length along with analysis of multi-phase-shifting faults is presented in the report. A modified version of the arc voltage-based algorithm is proposed that takes into account a more realistic model for the distribution line. It is expected to improve the fault-location results. Finally, signal-processing tools were used to uncover common and unique characteristics of each fault type. The signal-processing tools were used on a large number of voltage and current waveform data sets, measured at monitoring stations on the distribution system, for each fault type. The characteristics extracted from the waveforms were tabulated and were used to classify the fault events based on the root cause and the nature of the fault. An individual characteristic alone is insufficient to provide an estimate of the fault type. However, by combining common and unique characteristics extracted from a fault event, in future work it may be possible to estimate the fault type accurately.

Keywords

Fault location	Distribution reliability
Short circuits	Faults
Arcs	Power quality

EXECUTIVE SUMMARY

The work documented herein is a subset of the EPRI Distribution Fault Location Study project. It is a multi-year project with an ultimate goal of developing a commercial-grade fault-locating tool implemented in EPRI's PQView platform. The work focuses on two particular areas:

- Location of incipient fault events: Incipient faults self-clear with a duration of $\frac{1}{4}$ to $\frac{1}{2}$ cycle. They commonly occur in failing cable splices. Initially, these incipient faults appear infrequently. As the failure develops, they occur more and more often and eventually result in a complete cable fault. Therefore, by detecting and estimating the location of these incipient fault events, a complete splice fault may be prevented. The goal in this area is to develop, validate, and implement a robust algorithm to locate fault precursors, particularly half-cycle blips eventually leading to a complete fault. Existing impedance-based fault-locating algorithms are not applicable because they work only with faults having a duration of one or more cycles.
- Estimation of fault types: As a part of an effort to expedite service restoration, fault waveforms are analyzed to determine their root causes. Characteristics of a fault waveform provide clues about the nature of the fault. Cable faults have different characteristics compared with animal-contact faults. Therefore, the goal in this effort is to determine common and unique (differentiating) waveform characteristics that can be used to estimate different fault types. These fault types include cable faults (cable, joint or splice, and termination failures), animal- and tree-contact faults, lightning-induced faults, and other faults cleared by current-limiting fuses.

Arc Voltage-Based Algorithm for Locating Incipient Faults

The development of an incipient-fault-locating algorithm started with the evaluation of existing algorithms that make use of voltage and current waveforms as their input data. An arc-voltage-based fault-locating algorithm implemented in the time-domain model is best suited for estimating the location of short-duration incipient faults. This is consistent with findings reported in first- and second-year work of the Fault Location Study project. The arc-voltage-based algorithm was further developed and validated using data generated by a simulation model as well as field measurement data. Estimates of resistance and reactance (or impedance) to fault were validated with known fault events provided by participating utilities. A few procedures were developed to improve the impedance-to-fault estimates, including choosing the proper window length and identifying the reactance to the fault.

The algorithm is applied and tested with fault data containing known incipient and full fault events. The reactance-to-fault estimates are compared to known values, and estimation errors are generally less than 15%. This is reasonable considering that the algorithm requires only voltage and current waveforms collected from a power quality monitoring system. Figure ES-1 shows a current waveform containing three incipient and one full fault events. The estimated reactance to an incipient fault location is approximately 1.1 Ω .

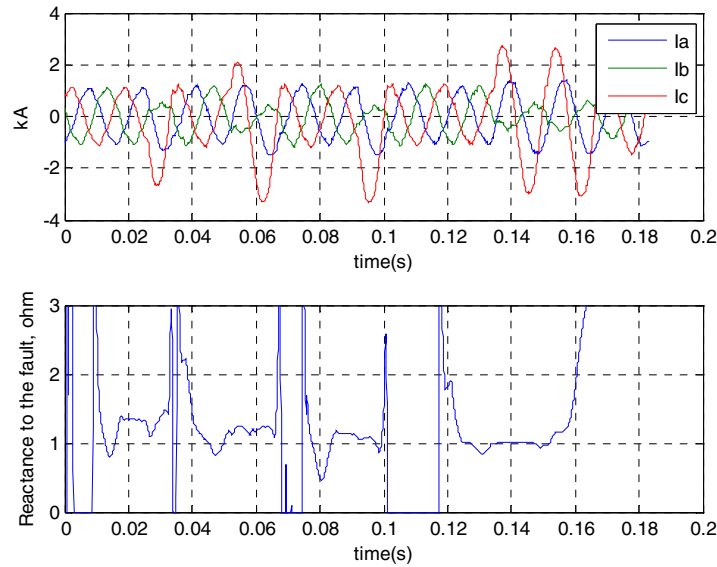


Figure ES-1
Current Waveform Having Incipient Faults and Their Reactance-to-Fault Estimate

Considering the nature of the fault duration, data requirement, algorithm implementation, and accuracy of reactance to fault estimates, the arc-voltage-based fault-locating method is considered suitable and ready for practical demonstration and application in an operational setting. It has been shown to work reliably on a number of cable incipient-fault cases.

Waveform Characterization for Estimating Fault Types

Determining the fault type based on characteristics extracted from event waveforms is a challenging task. Signal-processing tools are used to uncover common and unique characteristics of each fault type. These characteristics were quantified and then tabulated based on multiple events. These characteristics include but are not limited to the presence of impulse-like oscillations, the number of phases involved, duration of a fault event, phase angle, time of day, spectral content (time-frequency and time-scale), rate of rise of voltage or current, and the arc voltage.

Based on the analysis of characteristics, it was found that they are better characterized as common characteristics than unique characteristics in cable faults due to insulation, splice, and termination failures. Their common characteristics include the number of phases involved, duration, and spectral contents. Similar findings were also observed with animal- and tree-contact events and lightning-induced events. Unique or differentiating characteristics are arc voltages, time of day and season, and also time-scale (wavelet) spectral content. Figure ES-2 shows the voltage waveforms from two events caused by cable splice failure. The event in the top figure has pronounced characteristics of a splice failure, while the event in the bottom figure is rather difficult to identify.

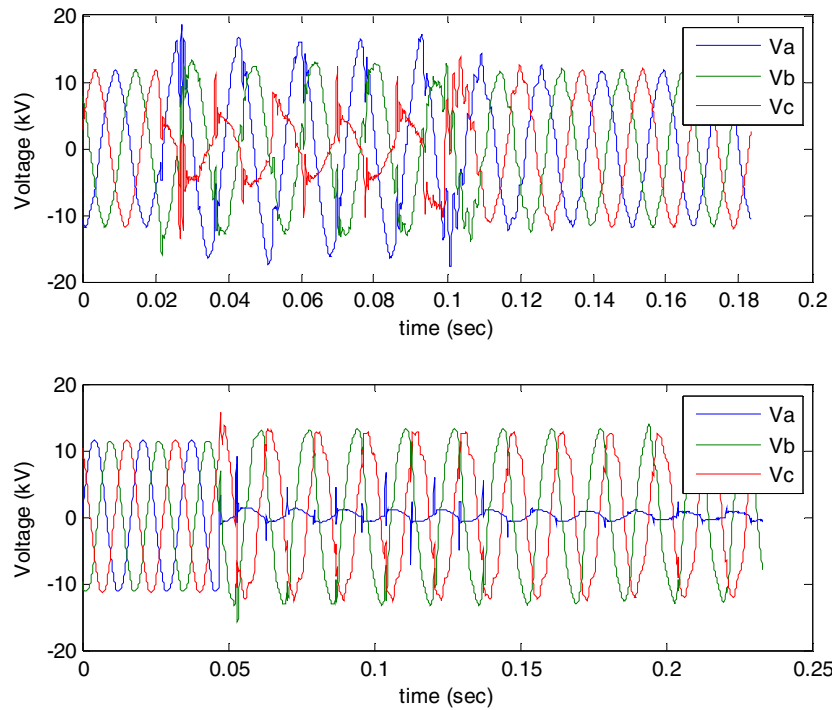


Figure ES-2
Voltage Waveforms of Cable-Splice Failure

An individual characteristic alone is insufficient to provide an estimate of the fault type. However, by combining common and unique characteristics extracted from a fault event, in future work it may be possible to estimate the fault type accurately. In summary, it is relatively simple to determine and extract characteristics from event waveforms of a known fault type but doing the reverse (analysis of characteristics to determine the fault type) remains a challenge. For this reason, practical technology for estimating fault types is not yet ready to try in an operational setting. It requires more work in aggregating and correlating information from individual signatures.

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1

INTRODUCTION

Background and Motivation

Electrical short-circuit or fault events can take place on overhead lines, underground cables, and any power equipment. While the fault is on the system, end users served off the faulted and parallel feeders may experience voltage sags. Depending on the layout of the distribution circuit, the cause of the fault, and the utility fault-clearing practice, the duration of voltage sags can be as little as a quarter of a cycle to as much as six cycles or longer. End-users downstream from a protective device (e.g., a recloser attempting to clear the fault) may experience multiple momentary interruptions.

Fault events of very short duration that do not necessitate the operation of any protective device are called *temporary faults*. Generally, they are self-clearing because the phenomenon giving rise to the fault mitigates itself without any external intervention. On the other hand, fault events lasting for several cycles require the operation of an overcurrent protective device.

This report documents efforts to improve and advance fault-locating methods for distribution-system applications. The efforts were part of a larger initiative known as the Distribution Fault Location Study project. Its ultimate goal is to develop a commercial-grade fault-locating tool implemented in EPRI's PQView platform. Earlier work on this project has been documented in the following two EPRI reports:

- Distribution Fault Location: Field Data and Analysis, Report Number 1012438 (2006) [1]. This report evaluates a number of impedance-based fault-locating algorithms using distribution fault data. These algorithms are based on impedance to the fault, reactance to the fault, current estimation, Takagi method, and nonlinear arc methods. Seven utilities provided over 1,500 fault events for analysis. Each event has monitoring data, a system circuit model, and a known outage location from an outage-management database. Based on the evaluation, the nonlinear arc and fault-current methods have been shown to be the most accurate. This report made a very important finding. It shows and demonstrates that it is possible to use monitoring waveforms to predict the arc voltage during a fault. The finding is validated using field measurement data collected during the EPRI's Distribution Power Quality project. The implication of this finding is that it can be used to improve fault-locating algorithms, differentiate or determine types of faults, and estimate arc power and energy for possible applications in evaluating safety hazards, arc flash boundaries or clothing requirements, and failure forensics.
- Distribution Fault Location: Prototypes, Algorithms, and New Technologies, Report Number 1013825 (2008) [2]. The report proposes a framework for implementing fault-locating algorithms in EPRI's PQView. The fault-location system includes fault-location algorithms

integrated with a monitoring event database and system circuit information. These two components are integrated and presented to the operator. The main challenge in the implementation is in integrating the monitoring data from a wide variety of data sources like relays and meters, integrating circuit information, and developing a user interface into a control center. The report develops an inrush-identification algorithm to make sure that inrush events are not incorrectly located. Furthermore, the report demonstrates that location of events causing half-cycle blips that are pre-cursors to full failures can be estimated using the arc-voltage method with reasonably accuracy. This finding can be used to locate incipient failures and thus avoiding complete cable faults.

Objective

The work presented in this report is built on efforts described in the above two reports. It has a common objective; that is to use waveform data collected from existing monitoring equipment to locate faults quickly so as to reduce restoration times. To meet this objective, this work focuses on two areas:

- Location of incipient fault events: Incipient faults self-clear with a duration of $\frac{1}{4}$ to $\frac{1}{2}$ cycles. They occur in failing cable splices. Initially, these incipient faults appear infrequently. As the failure develops, they occur more and more often and eventually result in a complete cable fault. A fault-locating algorithm based on nonlinear arc-voltage method proposed in the earlier effort [1] was further developed and utilized. The goal in this work is to develop, validate, and implement a robust algorithm to locate fault precursors, particularly half-cycle blips that eventually lead to a complete fault.
- Estimation of fault types: As a part of an effort to expedite service restoration, fault waveforms are analyzed to determine their root causes. Characteristics of a fault waveform provide clues about the nature of the fault. Cable faults have different characteristics compared with animal-contact faults. Therefore, the goal in this effort is to determine common and unique (differentiating) waveform characteristics that can be used to estimate different fault types. These fault types include cable faults (cable, joint or splice, and termination failures), animal- and tree-contact faults, lightning-induced faults, and other faults cleared by current-limiting fuses.

Approach and Results for Incipient Fault Location

For the purpose of developing a robust fault-locating estimation algorithm, the following efforts were taken:

- Review of existing fault-locating methods – Impedance-based and the nonlinear arc-voltage-based methods are reviewed for their effectiveness in locating half-cycle self-clearing faults. The impedance-based algorithms generally work in the phasor domain and thus require duration of one or more cycles to provide reasonable location estimates. A few algorithms require a line's zero-sequence impedance in addition to the positive-sequence impedance data. Given these requirements and the short duration of incipient faults, the applicability of impedance-based algorithms is limited. However, a fault-locating method based on the

nonlinear arc voltage appears to be very promising. This is consistent with the analysis reported in [1] and [2].

- Algorithm development and validation – The arc-voltage-based method is derived, implemented, and validated using fault events generated using time-domain simulation models as well as known fault events. The arc voltage is assumed to have an ideal square-wave-shape and is in phase with the arc current. The inputs to the algorithm are the voltage of the faulted phase and the neutral current. The outputs are the estimates of arc voltage, resistance, and reactance to the fault location. Three validation procedures are performed:
 - Validation of arc voltage using fault-event waveforms collected during the EPRI Distribution Power Quality (DPQ) project. A few arcing fault events captured near a power quality monitoring device were identified and used to validate the estimates of arc voltage.
 - Validation of resistance and reactance estimates using fault waveforms generated using time-domain simulation models. The arc voltage is set to zero, while resistance and reactance to the fault are varied.
 - Validation of resistance and reactance estimates using actual field data, which involves known and sustained fault events. These events have duration of three or more cycles with known resistance and reactance to the fault. Longer-duration events typically yield relatively constant resistance and reactance estimates. Such estimates are indicative of useful results. The accuracy of these estimates is also compared to those of impedance-based methods.

The implemented algorithm is validated as described above, and it is shown that arc voltage and estimates of resistance and reactance to the fault match with reference values reasonably well.

- Procedures to improve the fault-location algorithm – To improve the performance of the arc-voltage method, additional procedures were developed. They include modification to the numerical techniques used in the algorithm, as well as processing input waveforms and output estimates:
 - The accuracy with which the numerical terms used in the algorithm are calculated determines the accuracy of the predicted fault location. Instead of using a finite difference in performing a derivative operation, smoothing splines and non-negative least square approaches have been utilized. These advanced methods improve numerical stabilities.
 - Improvement in the estimates by properly selecting the analysis window width, pre-processing waveforms, and post-processing of impedance estimates is demonstrated. The pre-processing involves filtering high-frequency oscillation in voltage and current waveforms. The post-processing determines the best resistance and reactance estimates during the fault period. Different approaches such as simple averaging, back-substitution, median estimate, and linear fit are evaluated. The width of the analyzing window is crucial in producing useable estimates. Various window widths are evaluated. It is generally found that the window width should be set to relatively match the duration of the fault. As a general rule, for a quarter- to half-cycle fault event, the window width should be a quarter- to a half-cycle long. For a half- to one-cycle fault event, the width

should be a half to one cycle. For a multi-cycle event, the window width should be one cycle. Because the window width is used for the time-domain analysis (not for the frequency-domain analysis), the number of samples in the window width does not necessarily correspond to the power of two (64, 128, or 256). Instead, any integer number can be used; thus 96 and 192 would be valid as well.

- Application to pre-cursor events – The implemented algorithm is applied and tested with precursor (or incipient) and full fault events. Actual cases from the field data pertaining to self-clearing faults were selected, and the arc-voltage-based algorithm is used to identify these $\frac{1}{4}$ - to $\frac{1}{2}$ -cycle events. The estimates are seen to be helpful in locating incipient faults well ahead in time. Thus, simply detecting the self-clearing faults and running the arc-voltage algorithm for location estimates may prevent sustained faults on the distribution system.
- Practicality of the algorithm – The algorithm is applied and tested with fault data containing known incipient and full fault events. The reactance to fault estimates are compared to known values, and estimation errors are generally less than 15%. This is reasonable considering that the algorithm requires only voltage and current waveforms collected from a power quality monitoring system. Considering the nature of the fault duration, data requirement, algorithm implementation, and accuracy of reactance to fault estimates, the arc-voltage-based fault-locating method is considered suitable and ready for practical demonstration and application in an operational setting. It has been shown to work reliably on a number of cable incipient-fault cases.
- Further improvements – Important topics relevant for future work are identified. They include modifying the arc-voltage algorithm for an underground distribution system model and analysis of evolving faults. The following preliminary analyses on these issues are presented in this report:
 - A modified version of the arc-voltage-based algorithm is proposed to take into account a more realistic model for the distribution line. The capacitance of the distribution line or the cable along with the resistance and reactance parameters is used to formulate the fault equations. Incorporating capacitance in the analysis could improve the accuracy of the fault location especially in the case of underground cables, where the line capacitance is significant and cannot be neglected. More analysis is required to conclude the benefits of this study.
 - Analysis of single-line-to-ground (SLG) faults evolving into multi-phase faults is also presented. An assumption is made to simplify the analysis of multi-phase faults by treating double-line-to-ground faults as an SLG fault on one of the involved phases. The fault-location estimates from this assumption are found to be very close to the actual fault location obtained by using the initial SLG event. More waveforms need to be tested to determine the accuracy of this method.

Approach and Results for Fault Waveform Characterization

Estimating fault types based on waveform characteristics is a challenging task. We started the effort by visually inspecting hundreds of fault waveform data sets and correlating them to fault event logs to determine known and verifiable fault events. Signal-processing tools were then

used to uncover common and unique characteristics of each fault type. These characteristics include but are not limited to the presence of an impulse-like oscillation, the number of phases involved, duration of a fault event, phase angle, time of day, spectral content (time-frequency and time-scale), rate of rise of voltage or current, and the arc voltage. Fault events considered are those of cable failures (cable, splice, termination), lightning-induced, and animal and tree contacts.

Based on the analysis of characteristics, it was found that they are better characterized as common characteristics than unique characteristics in cable faults due to insulation, splice, and termination failures. Their common characteristics include the number of phases involved, duration, and spectral contents. Similar findings were also observed with animal- and tree-contact events and lightning-induced events. Unique or differentiating characteristics are arc voltages, time of day and season, and time-scale (wavelet) spectral content. An individual characteristic alone is insufficient to provide an estimate of the fault type. However, by combining common and unique characteristics extracted from a fault event, it is possible to estimate the fault type accurately.

In summary, it is relatively simple to determine and extract characteristics from event waveforms of a known fault type, but doing the reverse (i.e., analysis of characteristics to determine the fault type) remains a challenge. For this reason, practical technology for estimating fault types is not yet ready to try in an operational setting. It requires more work in aggregating and correlating information from individual signatures.

2

METHODS FOR LOCATING DISTRIBUTION FAULTS

A short-circuit condition or a fault in a utility distribution system results in voltage sags and interruptions. End users on a faulted feeder will experience voltage sags during the fault. This may possibly be followed by sustained, momentary, or instantaneous interruptions depending on the type of the fault and the overcurrent protective device clearing the fault. End users on parallel feeders may experience a series of voltage sags as the fault is being cleared. Common overcurrent protective devices on distribution feeders are circuit breakers, line reclosers, sectionalizers, and fuses.

Faults occur on both underground and overhead distribution lines. Because the overhead lines are more susceptible to weather conditions than buried underground cables, the number of faults taking place on overhead distribution lines is higher than on underground cables. Fortunately, the majority of overhead line faults are temporary. On the other hand, cable faults have a higher likelihood to result in sustained interruptions. These faults may occur due to accidental contacts, aging of the cable over a period of time (wear and tear), faulty installation, and natural causes such as lightning, flooding, and subsidence, to mention just a few.

An overview of fault-location algorithms for distribution lines is presented in this chapter. The unique characteristics of self-clearing faults are presented. This is followed by a discussion on prevalent methods for locating faults in underground cables and overhead lines.

Self-Clearing Faults

Most cable failures are gradual and take place over a period of time in contrast to other instantaneous faults on distribution lines. These faults are initially incipient in nature and generally self-clear without the operation of an overcurrent protective device. Such a phenomenon is very common in a cable splice following moisture penetration into the splice, which results in the insulation breakdown. When this happens, an arc is produced, and it evaporates water, creating high pressure vapors, which in turn extinguish the arc, making such faults self-clearing. The unique characteristics of self-clearing faults are as follows:

1. Fault duration is less than one cycle, generally $\frac{1}{4}$ to $\frac{1}{2}$ cycles. Self-clearing Events #1 and #3 shown in Figure 2-1 represent half-cycle blips. Event #2 is slightly longer in duration.
2. A fault generally starts near the peak of the voltage waveform [3]. This can be observed from the voltage waveform during self-clearing Event #1 shown in Figure 2-1, where the fault occurs at the peak of the negative voltage cycle.
3. No overcurrent protective device operates. This is generally indicated by a smooth faulted current waveform, which makes such faults harder to notice.

4. Self-clearing faults are generally precursors to permanent faults on the same phase. In Figure 2-1, self-clearing Events #1, 2, and 3 are precursor events. They are also known as *incipient events*.
5. These incipient faults may turn permanent after self-clearing many times over a period of a couple of months. Once permanent, they will cause the operation of the overcurrent protective device.
6. The frequency of incipient fault occurrence increases over time. There might be just one or two such events initially, but their frequency will increase rapidly before they are about to turn permanent.

Figure 2-1 shows a cable-failure event involving a couple of self-clearing faults preceding a permanent fault.

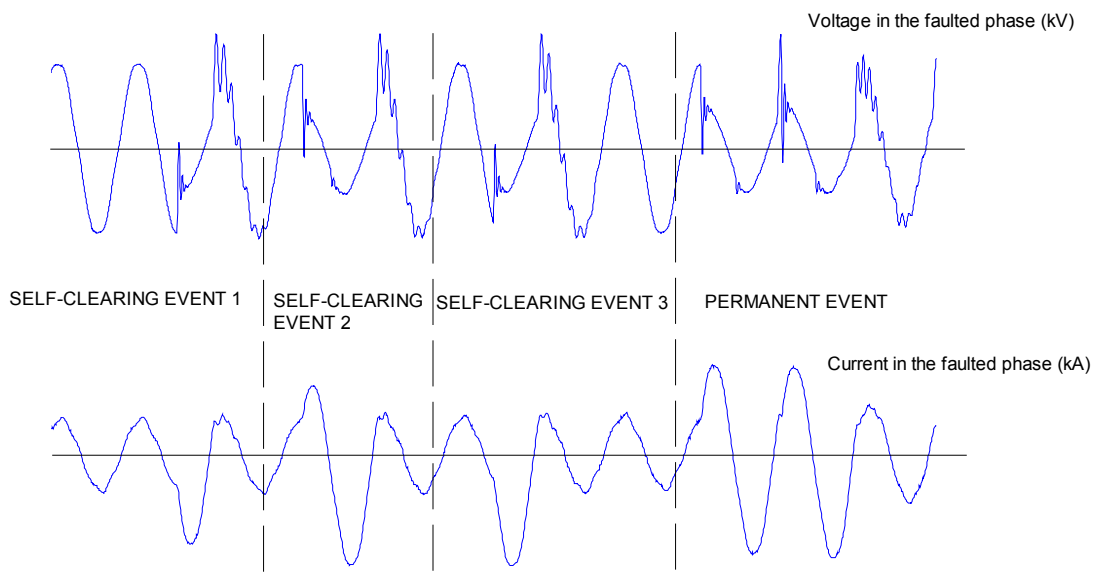


Figure 2-1
Self-Clearing Faults Preceding a Permanent Fault

It is very important to identify these self-clearing faults well ahead of time before they turn permanent and affect the continuity of supply. Many existing fault-locating algorithms are unable to determine half-cycle incipient fault locations. They do estimate distance to the fault location once a full fault has occurred and cleared by a protective device. An attempt is made in Chapter 3 and 4 to determine the location of self-clearing faults so that crews may be dispatched to repair the faulted section well ahead of time.

Underground Cable Fault Location

Underground cables have distributed capacitance throughout their length. The simplified representation of an underground cable is shown in Figure 2-2.

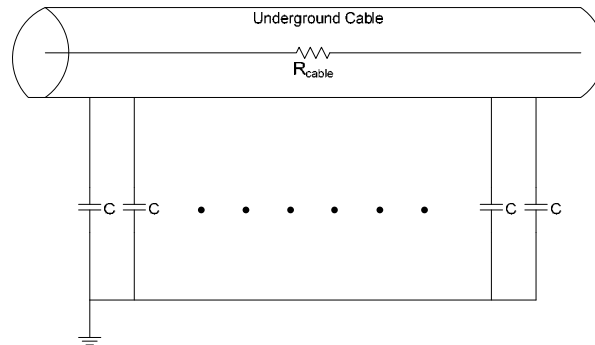


Figure 2-2
Underground Cable with Distributed Capacitance

The value of the capacitance, C , varies depending on the system voltage, zero-sequence return paths, stored charges, and other factors. In addition, ohmic resistance of the cable, R_{cable} , is usually very small. Such errors in the line impedance may lead to inaccurate fault-distance estimates.

The following steps are involved while locating an underground distribution cable fault [2] [4] [5]:

1. *Diagnosis*: When a permanent fault occurs, a protective device operates. Thus, the first indication of a possible fault is provided by the operation of a protective device. Because protective devices are also prone to malfunction because of incorrect settings, a high-voltage test must be conducted on the cable to determine whether it is faulted or not. If faulted, the fault resistance should be measured using a low-voltage resistance test instrument. An AVO or pulse-echo instrument may also be used to diagnose cable discontinuity and moisture ingress. The diagnosis is generally required to determine whether preconditioning is required or not.
2. *Preconditioning*: Altering the characteristics of the diagnosed fault is known as preconditioning. It usually depends on the instrument used during fault location. These characteristics can be changed either by passing a high current through the fault to carbonize the insulation, by allowing moisture ingress into the faulted cable, or by re-energizing a dead faulted cable. A fault burner may be used to transform a high-resistance fault into a low-resistance fault. A fault burner applies a high voltage to break high resistance followed by high current to lower the fault resistance. Another commonly employed preconditioning method is to alter a fault from an unstable flashing condition to a stable resistive fault.
3. *Pinpoint*: In this stage, tests are performed in the locality indicated by the previous stage to confirm the precise fault location. These are called tracer algorithms. They usually require

patrolling and walking along the faulted cable route in the field. Acoustic (application of surge generator and sound detection) and earth gradient (applying a source and measuring return current) techniques have been identified to pinpoint a fault on the cable [6]. A brief description is provided below:

- a. *Thumper*: This process involves application of pulsed DC voltage to the cable. A thumping noise is discharged as the gap at the failure point repeatedly sparks over. The process involves charging of a capacitor that is eventually discharged into the cable using a triggered gap. The thumping sound can be used as a criterion for precise fault location by the patrolling party.
- b. *Application of transient voltage and current waves*: The time period between the transient peaks is used to pinpoint the fault.
- c. *Core-to-core conductive mode*: This procedure is helpful in pinpointing core-to-core faults and employs the use of a conductive connection onto two cores of the cable, as shown in Figure 2-3. An audio frequency generator is connected between the two faulty cores, and the signal radiated from cable is traced along its route. There exists a shorting link between the same two cores at the opposite end of the cable. If such a connection is not possible, the signal may be applied by connecting the generator conductively between the cable sheath and a remote earth or by using an inductive mode in which the signal is applied by feeding a generator into an aerial adjacent to the cable.

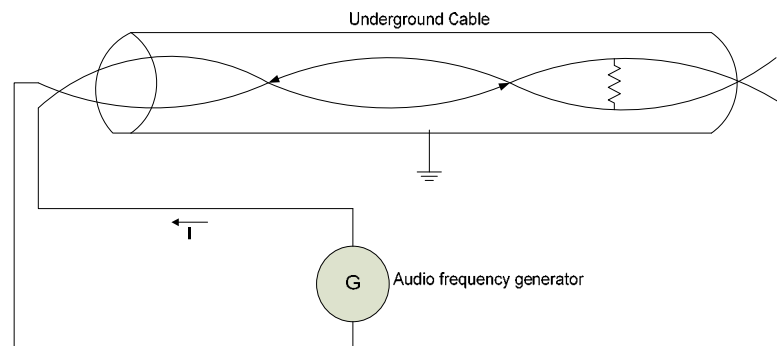


Figure 2-3
Pinpointing Core-to-Core Faults

The above fault-location approaches, including the terminal and tracer methods, are suitable only when the fault has become permanent (after a complete fault has occurred and has been cleared by protective relaying). Thus these methods have limited application in locating incipient faults.

Fault-Location Methods for Overhead Distribution Lines

A number of overhead fault-location methods have been developed and evaluated in the recent past [7][8][9]. They are summarized below:

1. *Nomograph*: This method is a graphical tool used to estimate fault location. Measured fault location versus actual fault location is plotted by compensating for known system errors [10]. It is a translation graph that maps the estimate from the relay to a more realistic estimate using circuit characteristics. It can also be used for varying conductor configurations.

2. *Traveling wave*: A traveling wave may be one-ended or two-ended [11]. Traveling-wave methods are generally applicable for longer lines. The one-ended traveling-wave fault locator has been developed for HVDC lines, and efforts are being made to apply it to AC lines. On the other hand, the two-ended traveling-wave fault locator scheme is applicable to AC lines. This scheme measures the relative time of arrival of the traveling-wave front produced by the fault, at the two ends of the line. A wide bandwidth (high-speed) communication channel is required for accurate time measurement. Fault location can be calculated from this measurement.
3. *Artificial neural networks*: These networks are generally based on the information about the status of the protective devices, such as circuit breakers and relays. A learning set is used to train the neural network [12][13][14].
4. *Prony analysis*: Application of Prony analysis on the fault signals results in a linear relationship between the fault location and the inverse of damping coefficient of the fundamental-frequency component in the Prony model [15]. This linear relationship naturally implies a simple algorithm to detect the fault location when a fault occurs on a transmission line.
5. *Global positioning system technology (GPS)*: When a line fault occurs, travelling waves propagate in both directions away from the fault point. Satellite-synchronized clocks (GPS) are used in each end of the monitored line for absolute time marking of the arrival of the first incoming wave front. Synchronized phasors along with GPS technology have also been used for fault-distance estimation [16].
6. *Offline tools– Event reports-based*: This method is based on the reports prepared from the previous system events. It is generally evaluated offline.
7. *Impedance-based method*: Voltage and current data from the waveforms obtained at the monitoring stations are used to calculate impedance based on the ohm's law ($Z = V/I$). Impedance during the fault interval when compared with the cumulative impedance in the circuit model will provide the approximate fault-distance estimate [1][17]. Impedance-based methods may be categorized as:
 - a) *Single-ended*: Data from just one monitoring station is used in this method. In other words, it implies looking into the line from one end. Such methods assume that the electrical system is homogenous [11][18].
 - b) *Double-ended*: Data from multiple monitoring stations located on opposite side of the fault is used for fault location [18][19].

Impedance-Based Fault-Location Algorithms

Impedance-based methods are suitable for waveform-based fault-locating applications. They utilize voltage and current waveforms captured by power quality monitors. Figure 2-4 represents the faulted electrical distribution system. Either the single- or double-ended approach can be used for fault location depending on the availability of power quality monitors.

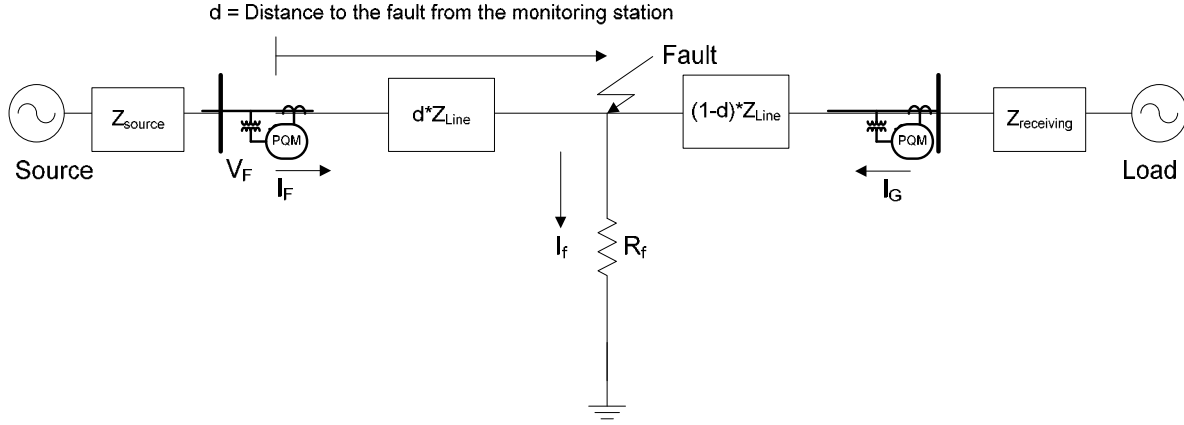


Figure 2-4
One-Line Equivalent for a Faulted Electrical System

The impedance to the fault depends on many factors such as no or imperfect transposition between the fault and measurement bus, load flow, fault resistance, and mutual coupling to neighboring circuits. The drawback of the impedance-based method is that it is difficult to include the above-mentioned factors in the analysis. Some of the single-ended methods are discussed as follows:

- *Simple Ohm's Law-based method:* According to this method, fault location can be obtained by simply finding the impedance during the fault period using Ohm's Law. This is given in Eq. (2.1). Complex voltage and current values in Eq. 2-1 will result in a complex distance estimate. The real part of d ($Re(d)$) will give the distance estimate, whereas the imaginary part of d ($Im(d)$) should turn out to be negligibly small.

$$d = \frac{V_F}{I_F \cdot Z_{Line}} \quad \text{Eq. 2-1}$$

where, V_F = voltage during the fault monitored by the left power quality (PQ) monitor, V

I_F = current during the fault monitored by the left PQ monitor, A

Z_{Line} = line impedance, ohms per length unit

- *Absolute impedance to the fault method:* The absolute values of voltage, current, and impedance can be used to determine the fault location as given by Eq. 2-2.

$$d = \frac{abs(V_F)}{abs(I_F) \cdot abs(Z_{Line})} \quad \text{Eq. 2-2}$$

- *Reactance to the fault method:* In this method, only the imaginary part is considered, so that fault location is given by Eq. 2-3.

$$d = \frac{\text{Im}\left(\frac{V_F}{I_F}\right)}{\text{Im}(Z_{Line})} \quad \text{Eq. 2-3}$$

All the above-mentioned methods are highly affected by R_f (fault resistance) and the phase difference between current at the left (I_F) and right (I_G) of the PQ monitor.

For faults involving ground, loop impedance should be used instead of line impedance because of the ground return path. Conductor sizing also affects the fault-distance estimate, which is considered constant in all the above methods.

- *Takagi method:* This method is based on the assumption that accurate pre-fault data is available for fault-distance calculation purposes [20]. It also accounts for system load and arc resistance. A superposition current is used to determine a term that is in phase with fault current, I_f . The superposition current is given by Eq. 2-4.

$$I_{sup} = I_F - I_{PRE} \quad \text{Eq. 2-4}$$

Using superposition current, fault location can be estimated as given by Eq. 2-5.

$$d = \frac{\text{Im}(V_F \cdot I_{sup}^*)}{\text{Im}(Z_{Line} \cdot I_F \cdot I_{sup}^*)} \quad \text{Eq. 2-5}$$

This method reduces the error due to R_f and phase difference between I_F and I_G .

Some of the drawbacks of the Takagi method are as follows:

- It makes use of a linear arc-resistance model for distribution faults, which in general is highly nonlinear.
- It makes use of a constant-current load model for distribution circuits. However, for multiphase faults, a constant-impedance load model should be used to factor the load impedance.
- It makes use of the actual line current rather than the residual current ($I_A + I_B + I_C$) for line-to-ground faults. The residual current allows for more accurate load-current reduction because during an SLG fault residual current works out best for comparing bus-level currents to feeder-level currents.
- Difficulty in application to lines with changing conductors or conductor sizes. For such applications, the Z_L needs to be calculated at each node.

If zero-sequence current ($3I_{0s}$) is used for ground faults instead of superposition current, this method is known as *modified Takagi method*, and the fault-location estimate is given by Eq. 2-6.

$$d = \frac{\text{Im}(V_F \cdot (3I_0)^* \cdot e^{-jT})}{\text{Im}(Z_{\text{Line}} \cdot I_F \cdot (3I_0)^* \cdot e^{-jT})} \quad \text{Eq. 2-6}$$

It has the advantage of correcting angle differences in the source impedance.

- *Santoso et al algorithm* [21]: This method assumes that the positive- and zero-sequence line-impedance parameters (z_l, z_0) are available. According to this method, the fault-location estimate lies in a range given by Eq. 2-7.

$$\frac{u_l X_{mF} - v_l R_{mF}}{u_l x_l - r_l v_l} \leq d \leq \frac{u_l X_{mF} - v_l R_{mF}}{|z_l| |p|} \quad \text{Eq. 2-7}$$

$$\text{where, } p = \frac{3I_A^0}{(I_A + k \cdot I_A^0)} = u_1 + jv_1$$

I_A^0 is the zero-sequence component of the faulted current

I_A is the fault current (in phasor terms)

z_l is the positive-sequence line impedance given by

$$z_l = r_l + jx_l$$

$$R_{mF} = \text{re} \left(\frac{V_A}{I_A + k \cdot I_A^0} \right)$$

$$X_{mF} = \text{imz} \left(\frac{V_A}{I_A + k \cdot I_A^0} \right) \text{ and}$$

$$k = \frac{Z_0 - Z_1}{Z_1}$$

This method is based on analysis in the spectral domain. The faulted voltage and current phasors are obtained by applying a running window and performing an FFT operation. A range of approximate fault location is provided by this algorithm.

- *Current estimation method*: Measured fault current is compared with available fault current at different points to determine the fault-location candidates [22].
- *Voltage-sag estimation method*: This is a voltage-only method and has the advantage that no current measurement is required. The voltage during the fault is compared with its pre-fault value to determine the voltage sag. A voltage-divider model along the circuit is used to determine the fault location [23].

Most of the above-mentioned algorithms have a common assumption that the fault is a bolted fault (zero fault arc resistance), which is not always the case. Some temporary faults have

significant arc voltage resulting in significant arc resistance. The drawbacks of the one-ended impedance methods also include the following:

- a. They do not take into account the effect of load and fault resistance.
- b. They have problems associated with zero-sequence mutual coupling caused by parallel lines.
- c. They have problems with accuracy limits of system parameters, especially z_0 . System non-homogeneity is also neglected in single-ended methods.
- d. They may lead to incorrect fault identification because of inaccurate relay measurement. System in-feeds may also affect the fault-distance estimate.
- e. They have problems associated with short-duration faults and faults on lines that are not fully transposed.

These drawbacks can be overcome by using an arc voltage-based fault-location algorithm discussed in Chapter 3. The arc voltage-based fault-locating method is single-ended and thus requires only voltage and current waveform data collected from one monitoring station. This method, implemented in the time domain, is suitable for locating incipient fault events as well as complete fault events. Chapters 3, 4, and 5 present the derivation, implementation, validation, and applications of this method.

3

APPLICATION OF ARC VOLTAGE IN DISTANCE ESTIMATION

Power quality monitors present in the distribution network record the voltage and current waveforms during a fault. Fault-location algorithms utilize this data to estimate the location of the fault in terms of the distance or reactance and resistance from the monitoring station. As pointed out in Chapter 2, existing fault-locating algorithms are suitable for estimating the location of sustained faults, i.e., only when the fault duration is one cycle or longer. This is because they generally work in frequency or phasor domains. Unfortunately, they have limited value in locating sub-cycle incipient faults.

Based on work completed in the early part of the EPRI Fault Location Study project, it is demonstrated that the arc voltage-based method is a potential tool for locating incipient fault events. Preliminary results have been reported in [1], [2], and [24]. The arc voltage-based method was first developed in [25][26][27] for the purpose of differentiating temporary and sustained faults.

In this Chapter, an in-depth discussion of the arc voltage-based fault-distance estimation method is presented. The work in this chapter builds on the work reported in [24]. The basics of the arc-voltage theory are briefly reviewed. This is followed by the formulation, derivation, and implementation of the distance-estimation algorithm. The subsequent section explores the improvements that can be achieved in distance estimates by pre-processing of the inputs as well as the post-processing of the results.

Arc Voltage Theory

An electric discharge results when the air or any other medium between two electrodes is ionized and there is a flow of charges. An arc is a self-sustained electrical discharge, which can be caused by short circuits on the power system exhibiting low voltage drop and capable of sustaining large currents. The arc can be formed in air, vacuum, oil, or in any other medium. For air to break down, the voltage gradient must be equal to or greater than $3 \times 10^6 \text{ V/m}$. An electric arc is dangerous as the arc power is dissipated in the environment and involves high temperatures (typically thousands of Kelvins). It can initiate a fire, lead to thermal degradation, pressure rise, conductor melting or evaporation, jets, and sometimes high noise production [28]. An electric arc can be classified into two categories. A high-pressure arc is the one that exists at or above the atmospheric pressure, while the low-pressure arc generally occurs in vacuum.

The arc voltage is an important quantity while studying arcs. The Ayrton equation [29] given by Eq. 3-1 is one of the many equations that give the relationship between the arc voltage, arc length, and the current. This equation is applicable over only a limited range of current and voltage values.

$$e_0 = A + B.d + \frac{c + D.d}{i}$$

Eq. 3-1

where, e_0 = arc voltage
 d = arc length
 i = arc current
 A, B, C and D are constants

The arc voltage remains constant over a wide range of currents and arc lengths. Hence, the arc resistance is a nonlinear function of the voltage. Generally, it is preferred to measure the arc in terms of the voltage rather than the resistance. Arc voltage is strongly dependent on the inherent physical properties of the faulted equipment. High heat conductivity causes the arc to restrict and create a higher-density current flow (and more resistance), which results in a higher voltage gradient. The arc voltage gradient is also a function of pressure (generally proportional to P^k , where k varies with the ionizing gas).

The current in the power system is a 60-Hz sinusoidal wave, which crosses zero twice in one cycle. This phenomenon is very useful in interrupting the arc. When the current flowing through the arc decreases, the resistance of the arc increases, and simultaneously the ionization level also drops. The arc disappears just before the actual current zero. However, it can reignite when the current starts flowing in the next half cycle because of the stored energy in the system inductance, leading to a quick buildup of the recovery voltage. This is shown in Figure 3-1 [30], where I_a and E_a are the respective current and voltage waveforms during the arc-extinction process, E_{extn} is the peak of extinction voltage, and E_{rein} is the peak of re-ignition voltage. In addition, the voltage required to sustain the arc is less than that required for reigniting the arc.

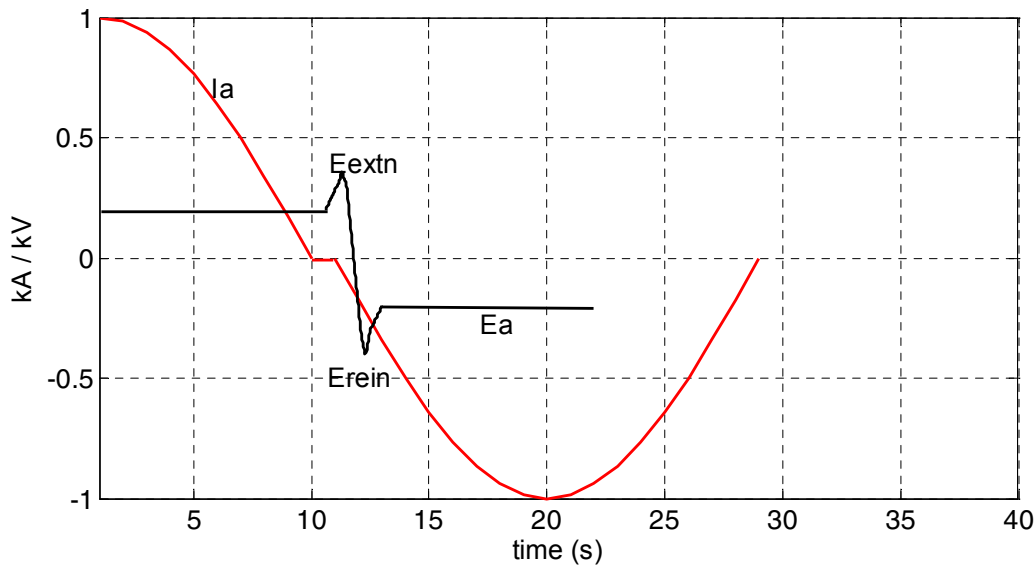


Figure 3-1
Voltage and Current Variations during Arc-Extinction Process

Importance of Arc Voltage in Fault Location

Having the knowledge of the arc voltage during a fault has many advantages. Some of these are summarized below:

1. Arc voltage can help deduce the characteristics of a fault. This can potentially help determine the cause of the fault by analyzing the waveforms at the power quality monitoring site. Once a specific range for arc voltage has been identified, it can be used to classify the fault causes such as splice failure, lightning, animal contact, or other causes. Such characterization is discussed in Chapter 6 onwards.
2. Generally, a relatively low arc voltage (V_{arc}) corresponds to a fault that is more likely to be permanent in nature, whereas a high arc voltage value indicates that the fault is temporary. The value of V_{arc} can be used to decide the operation of the automatic reclosers [31][32]. It must be noted that several permanent faults are also observed to have high arc voltage. Thus, all permanent faults do not possess low arc voltage.
3. Arc voltage can be used to estimate the arc power and energy. Both of these quantities can be used for investigating manhole explosions, equipment failure forensics, and estimation of arc flash during a fault [33].
4. Incorporating the arc voltage in the distance-estimation algorithms generally improves their accuracy. This is because fault-arc resistance cannot be assumed as zero (bolted fault) in all the cases, especially the ones with significant arc voltage. The indicators of high arc voltage are that the voltage bulges to the left and the current looks tipped to the right. This is shown in Figure 3-2 (courtesy [34]).

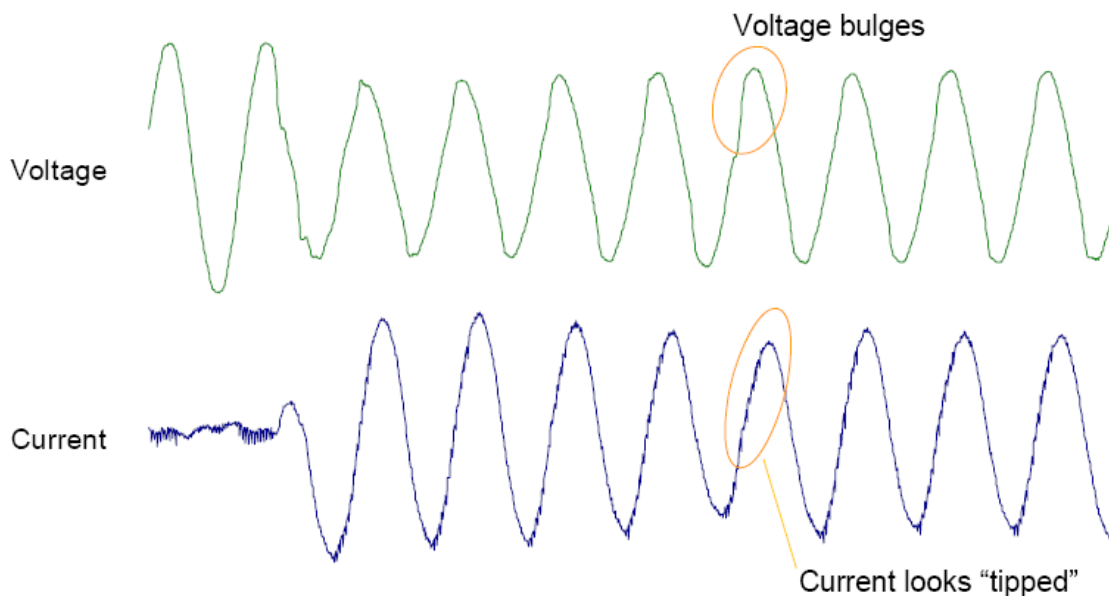


Figure 3-2
High Arc Voltage Characteristics – Voltage Bulges and Tipped Current

As stated earlier, a long electric arc during a fault event is partially ionized gas (plasma) discharge in free air. An arc current waveform is predictable and can be expressed analytically once the circuit parameters are known. However, it is very difficult to obtain an analytical expression for the arc-voltage curve because of the nonlinear arc resistance. The arc resistance, being strongly dependent on the physical properties of the faulted equipment, results in a distorted arc-voltage curve, as shown in Figure 3-3. In general, there is a blip at the start of the waveform (it is not an ideal square wave) because the arc cools off at the current zero, decreasing the ionization rate and increasing the arc resistance. Once the temperature increases, the voltage flattens out. Presence of high odd harmonics makes the arc voltage waveform resemble a distorted square wave.

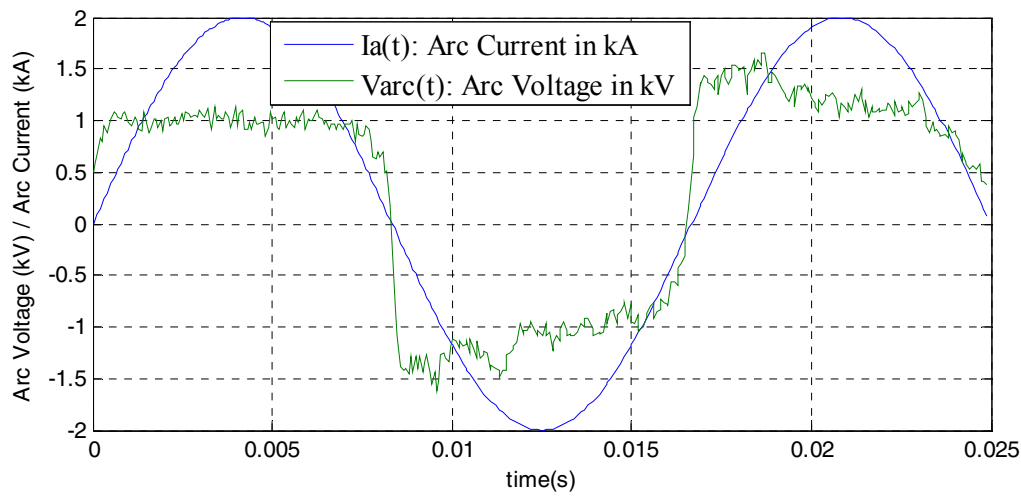


Figure 3-3
Actual Arc Voltage $V_{arc}(t)$ and Arc Current $I_a(t)$

The following assumptions have been made to simplify the analysis of arc voltages:

1. Arc voltage has an ideal square-wave shape as shown in Figure 3-4. This implies that the arc voltage is constant irrespective of the arc current.
2. Arc current and voltage are in phase as shown in Figure 3-4.
3. A normalized arc-voltage model is used with $|V_{arc}| = 1$ per unit.

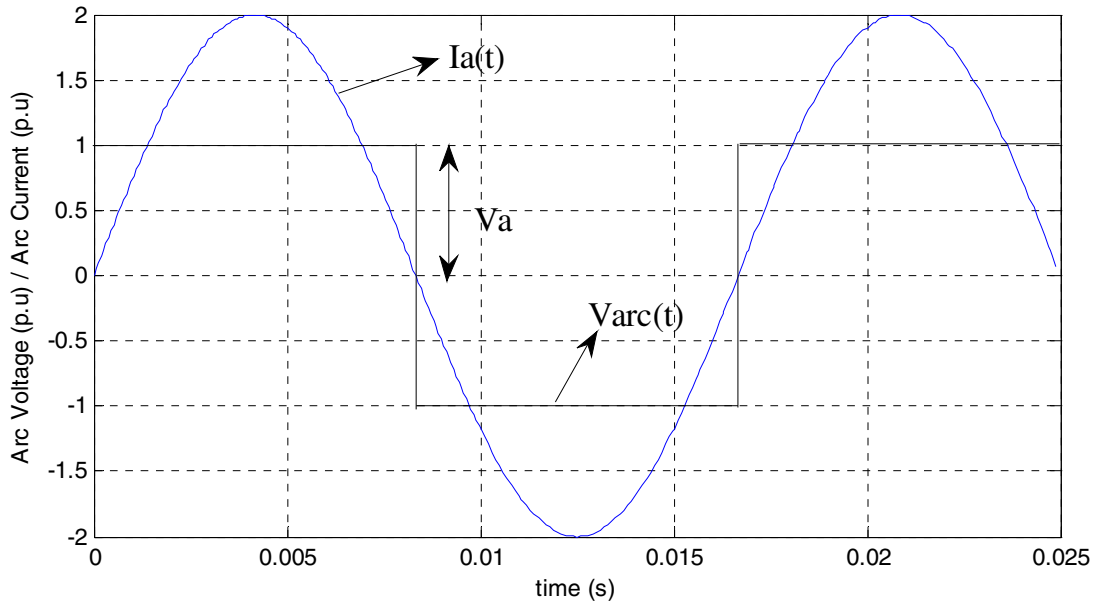


Figure 3-4
Assumed Arc Voltage $V_{arc}(t)$ and Arc Current $I_a(t)$

Using a Fourier transform, the model in Figure 3-4 can be represented by a Fourier series containing odd sine components only, as given in Eq. 3-2. [27]

$$V_{arc}(t) = \sum_{r=1}^{\infty} a_r V_a \sin(r\omega t) \quad \text{Eq. 3-2}$$

where, $V_{arc}(t)$ = the instantaneous arc voltage

a_r = the coefficient of the r^{th} harmonic. $r = 1, 3, 5, \dots$

ω = the fundamental frequency in radians

Coefficients a_r can be calculated using a Fourier transform in the discrete domain (DFT). Hence, the above model can be used to obtain the fundamental component of an arc voltage along with other harmonics. In general, the arc voltage during the fault is a combination of a square wave and a random white-noise input, which can be expressed as given by Eq. 3-3.

$$V_{arc}(t) = V_a \times \text{sgn}[I_a(t)] + \mathcal{L}(t) \quad \text{Eq. 3-3}$$

where, $V_{arc}(t)$ and $I_a(t)$ = the arc voltage and current, respectively

$\mathcal{L}$ = the random zero mean white Gaussian noise

V_a = the amplitude of the square wave

$\text{sgn}[I_a(t)] = 1$, if $I_a(t) > 0$ and -1 if $I_a(t) \leq 0$

Arc Voltage-Based Fault-Distance Estimation

This method is based on the application of time-domain approach to voltage and current waveforms captured from PQ monitors. It is a single-end terminal data-based approach and generally uses the line impedance parameters for estimating the distance to the fault. However, implementing modified numerical methods in the algorithm can lead to fault-location estimates without the knowledge of the circuit data. The algorithm is based on the approach described in [27].

Derivation

Consider a single-phase-to-ground arcing fault on a three-phase transmission line, as shown in Figure 3-5. Phase voltages V_A , V_B , and V_C and line currents I_A , I_B , and I_C are captured by a PQ monitor. V_{arc} is the arc voltage at the fault location, R_a is the fault resistance, and V_{Fault} is the faulted phase voltage at the fault location.

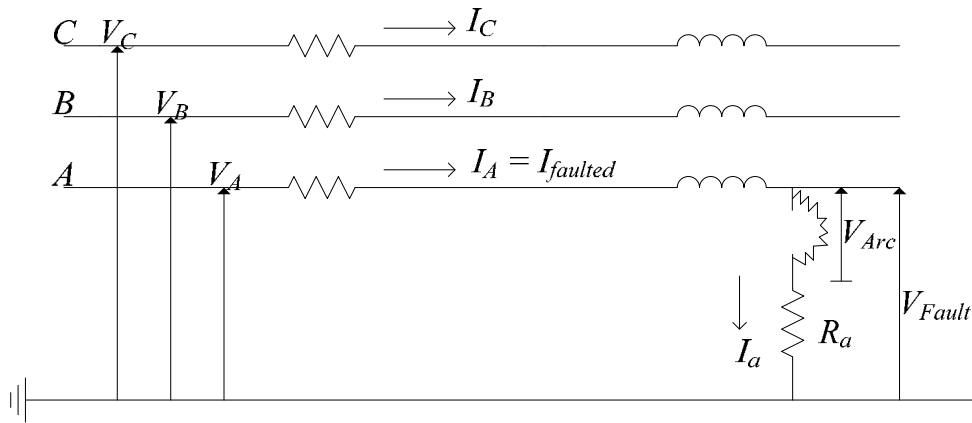


Figure 3-5
Circuit Used for Arc Voltage-Based Fault-Location Algorithm Derivation

Figure 3-6 and Figure 3-7 are obtained by transforming the three-phase circuit in Figure 3-5 into three single-phase circuits represented by the positive-, negative-, and zero-sequence components. Positive- and negative-sequence equivalent circuits are identical as shown in Figure 3-6. R and L are the positive-sequence line resistance and inductance, respectively. The zero-sequence equivalent circuit is shown in Figure 3-7. R_0 and L_0 are the zero-sequence line resistance and inductance, respectively.

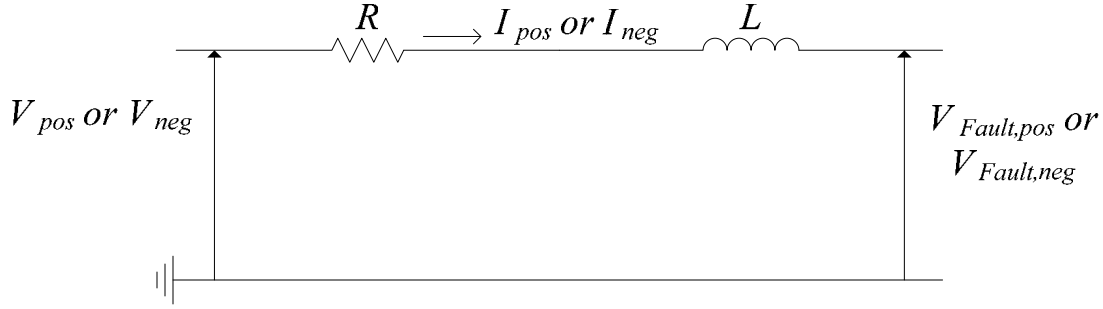


Figure 3-6
Equivalent Positive/Negative-Sequence Network Circuit

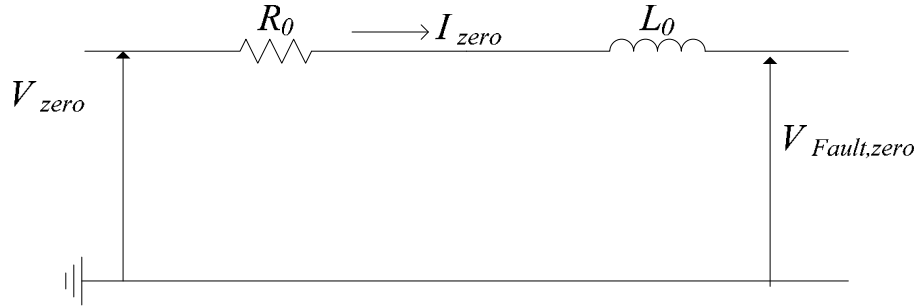


Figure 3-7
Equivalent Zero-Sequence Network Circuit

From the equivalent circuits of Figure 3-6 and Figure 3-7, Eq. 3-4, Eq. 3-5, and Eq. 3-6 can be written in the time domain:

$$V_{pos} = R \cdot I_{pos} + L \cdot \frac{dI_{pos}}{dt} + V_{Fault,pos} \quad \text{Eq. 3-4}$$

$$V_{neg} = R \cdot I_{neg} + L \cdot \frac{dI_{neg}}{dt} + V_{Fault,neg} \quad \text{Eq. 3-5}$$

$$V_{zero} = R \cdot I_{zero} + L \cdot \frac{dI_{zero}}{dt} + V_{Fault,zero} \quad \text{Eq. 3-6}$$

It must be noted that the positive- and negative-sequence line parameters R and L are not frequency-dependent, so Eq. 3-4 and Eq. 3-5 are valid. That is not the case with Eq. 3-6, where R_0 and L_0 are frequency-dependent. This variation will depend on a number of factors, such as tower configuration and soil resistivity. For the application and the frequency range under consideration, an approximation is made to treat all line parameters as frequency-independent. This simplifies the time-domain approach, and the resulting equations can be solved very easily by a computer program [35][36].

Adding Eq. 3-4, Eq. 3-5, and Eq. 3-6, Eq. 3-7 is obtained.

$$V = V_{pos} + V_{neg} + V_{zero} = R.I + (R_0 - R).i_0 + L.\left(\frac{dI}{dt} + K_L.\frac{di_0}{dt}\right) + V_{Fault} \quad \text{Eq. 3-7}$$

where, V = the sum of all sequence voltage components

I = the sum of all sequence current components

i_0 = the zero sequence current given by Eq. 3-8

$$i_0 = \frac{1}{3}.(I_A + I_B + I_C) \quad \text{Eq. 3-8}$$

K_L is the coefficient that can be calculated from the line-impedance parameters in advance and is given by Eq. 3-9.

$$K_L = \frac{(L_0 - L)}{L} \quad \text{Eq. 3-9}$$

The voltage at the fault location can be written as:

$$V_{Fault} = V_{Fault,pos} + V_{Fault,neg} + V_{Fault,zero}$$

Moreover, from Figure 3-5, the faulted phase voltage can be written as:

$$V_{Fault} = V_{arc} + R_a.I_a \quad \text{Eq. 3-10}$$

where, V_{Fault} = the voltage of the faulted phase at the fault location

V_{arc} = the arc voltage arising due to the fault

R_a = the fault resistance

I_a = the fault current at the fault location

Using Eq. 3-3 in Eq. 3-10, Eq. 3-11 is obtained:

$$V_{Fault} = V_a.\text{sgn}[I_a(t)] + R_a.I_a + \mathcal{L}(t) \quad \text{Eq. 3-11}$$

The fault current can be assumed as given in Eq. 3-12:

$$I_a = k_a \cdot i_0 \quad \text{Eq. 3-12}$$

where, k_a = a proportional coefficient

i_0 = the zero-sequence current

In general, the amplitude of the square wave is the product of the arc voltage gradient and the length of the path. The arc voltage over the range of currents from 100 A to 20 kA lies between 12 and 15 kV/cm. The length of the path is the flashover length between the conductors or flashover length of a suspension insulator string.

Combining Eq. 3-7, Eq. 3-11, and Eq. 3-12, Eq. 3-13 is obtained:

$$V = R \cdot I + L \left(\frac{dI}{dt} + K_L \cdot \frac{di_0}{dt} \right) + V_a \cdot \text{sgn}(i_0) + R_e \cdot i_0 + \Xi \quad \text{Eq. 3-13}$$

Where, R_e is given by $R_e = (R_0 - R + k_a \cdot R_a)$.

Ξ is the error taking into account all measuring and modeling errors.

Uniform sampling of the voltage and current waveforms captured by the PQ monitors provides the instantaneous point-by-point data values for the three-phase voltages and currents. The use of Eq. 3-13 requires the pre-knowledge of line impedance parameters (z_l and z_0) along with the numerical calculation of the derivative of current ($\frac{di}{dt}$).

Unlike other frequency-domain fault-location methods, such a time domain-based algorithm is not influenced by the decaying DC component. Neglecting a few terms in Eq. 3-13, it can be written as a simple equation for the faulted phase without the loss of generality. This approach is explained in the next section.

Implementation of Arc Voltage-Based Fault-Location Algorithm

For a general analysis, it is assumed that the line impedance parameters are unknown. The single-line diagram for a faulted circuit can be represented as shown in Figure 3-8.

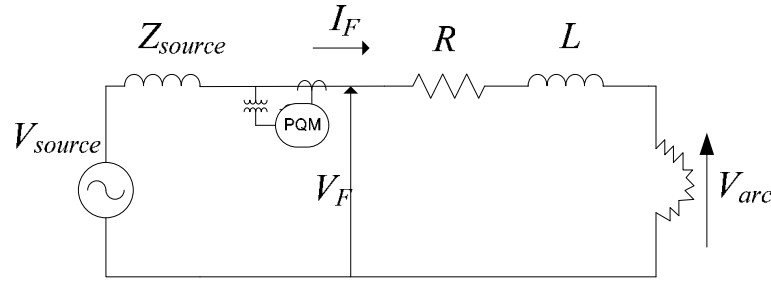


Figure 3-8
Circuit for Arc-Voltage Estimation

Based on the monitoring location and following Eq. 3-13, the voltage at the monitoring site V_F for the faulted phase can be written as shown in Eq. 3-14:

$$V_F = R \cdot I_F + L \cdot \frac{dI_F}{dt} + V_{arc} \cdot \text{sgn}(I_F) \quad \text{Eq. 3-14}$$

where, V_F = the fault phase voltage measured at the monitoring site

I_F = the fault current

L = the line inductance

R = the line resistance

V_{arc} = the arc voltage at the fault location

$\text{sgn}(I_F) = 1$, if $I_F > 0$ and -1 if $I_F \leq 0$

Using neutral current ($I_n = I_A + I_B + I_C$) instead of faulted phase current I_F in Eq. 3-14, Eq. 3-15 is obtained:

$$V = R \times I_n + L \left(\frac{dI_n}{dt} \right) + V_{arc} \times \text{sgn}(I_n) \quad \text{Eq. 3-15}$$

Unlike faulted phase current, the neutral current has the benefit of accounting for load current. Once all the currents are summed up, load current is balanced and thus gets eliminated. Hence, better results are obtained when the neutral current is considered in the algorithm instead of the faulted phase current.

A number of methods can be used to find the derivative of I_n with respect to time. One of the methods is the simple trapezoidal method, from which:

$$\frac{di}{dt} \approx \frac{i(n+1) - i(n-1)}{2T}$$

However, in this report, a method based on smoothing splines is used to differentiate I_n with respect to time. It is observed to be the most appropriate method for determining the derivative, $\frac{di_n}{dt}$, in Eq. 3-15. The smoothing-spline method uses the curve-fitting procedure and fits a smoothing spline to the current waveform and calculates the derivative at each point of the waveform. It is a method of smoothing (fitting a smooth curve to a set of random observations) using a spline function. Let (x_i, Y_i) be a sequence of observations, modeled by the relationship $E(Y_i) = \mu(x_i)$ [37]. The smoothing spline estimate ν of the function μ is defined to be the minimizer (over the class of twice differentiable functions) of Eq. 3-16:

$$\sum_{i=1}^n (Y_i - \nu(x_i))^2 + \lambda \int \nu''(x)^2 dx \quad \text{Eq. 3-16}$$

where, λ is a smoothing parameter, controlling the trade-off between fidelity to the data and roughness of the function estimate. It is observed that the smoothing-spline method results in the reduction of noise when compared with the trapezoidal method.

For solving Eq. 3-15, let d_i represent the differentiation of I_n with respect to time. d_i is calculated by fitting a smoothing spline to the neutral current (I_n) waveform and differentiating the resulting waveform point-by-point with respect to time.

Thus, Eq. 3-15 can be written in a matrix form as given in Eq. 3-17:

$$[V] = [I_n \quad d_i \quad \text{sgn}(I_n)] \begin{bmatrix} \mathbf{R} \\ \mathbf{L} \\ \mathbf{V}_{\text{arc}} \end{bmatrix} \text{ or } V = [a_1 \quad a_2 \quad a_3] \mathbf{X} \quad \text{Eq. 3-17}$$

where, $a_1 = I_n$

$$a_2 = d_i$$

$$a_3 = \text{sgn}(I_n)$$

$$[\mathbf{X}]^T = [\mathbf{R}, \mathbf{L}, \mathbf{V}_{\text{arc}}]$$

Equation 3-17 is valid at every point in the voltage and current waveform. A running data window is used to solve this equation. With 128 or 256 samples per window (corresponding to a half or one cycle of a waveform), Eq. 3-17 is clearly an over-determined system of equations with just three unknowns given by $[\mathbf{X}]$. Such an over-determined system of equations can be

solved using non-negative least-square method. This ensures that only positive values of R , L , and V_{arc} are considered.

The non-negative least-squared algorithm (NNLS) minimizes the sum of squares of the errors (or white noise). Eq. 3-17 can be written in the matrix form as:

$$[A] \cdot [X] = [x]$$

The least-error-squares estimate of $[X]$ is given by the following equation:

$$[X] = [[A]^T \cdot [A]]^{-1} [A]^T \cdot [x]$$

Hence, all the unknown parameters can be estimated using the NNLS approach. It must be noted that the arc voltage during the fault may vary considerably due to arc's tendency to grow (elongate) or shrink over a period of time. However, resistance and reactance to the fault should be constant during a fault. Once constant values for R and L are known, impedance from the monitoring point to the fault location (Z_{fault}) can be obtained, and hence the fault location can be estimated.

The impedance to the fault obtained using I_n in the arc voltage-based algorithm is the loop impedance (Z_{loop}) instead of positive-sequence impedance (Z_1), which is the case if only phase current is used,

$$\text{where, } Z_{loop} = \left(\frac{(2Z_1 + Z_0)}{3} \right)$$

The number of samples (data window length) employed plays a major role in the quality of results achieved. The effect of window length is discussed in Chapter 5.

Considerable improvement is achieved by processing the input and output of the arc voltage-based algorithm. Generally, voltage and current waveforms are sampled at different sampling rates. Thus, the sampling rate needs to be adjusted before using it in the algorithm. Moreover, smoothing of the voltage and current waveforms can help improve the accuracy of the results. Estimates of resistance and reactance to the fault act as outputs of the algorithm and can be processed further to estimate the best possible numerical value. Pre-processing of input waveforms and post-processing of impedance estimates are explained in the following sections.

Pre-Processing to Improve Estimates

Pre-processing involves adjusting the sampling rate and smoothing voltage and current waveforms. These are discussed below.

Sample-Rate Adjustment

Generally, most voltage waveforms are sampled at 256 samples per cycle in contrast to current waveforms, which are sampled at 128 samples per cycle. For consistency of the sampling rate in the algorithm, it is advantageous to have identical sampling rate for both the waveforms. Thus, either current needs to be up-sampled or voltage needs to be down-sampled by a factor of two. Current up-sampling is observed to provide better estimates when compared to voltage down-sampling. This is mainly because some valuable information might be lost during the voltage

down-sampling process. Current up-sampling, on the other hand, interpolates the in-between data points, providing a waveform smoothing effect. The up-sampling process increases the sampling rate of the original sequence by an integer factor (in our case, 2). The low-pass data-interpolation algorithm [36] is used, which makes use of the following steps:

1. It expands the input vector to the correct length by inserting zeros between the original data values.
2. It designs a special symmetric FIR (finite impulse response) filter that allows the original data to pass through unchanged and interpolates between data so that the mean-square errors between the interpolated points and their ideal values are minimized.
3. It applies the filter to the input vector to produce the interpolated output vector.

Smoothing Voltage and Current Waveforms

Smoothing the voltage and current waveforms before using them in the fault-distance-estimation algorithm yields better results. Arc voltage, resistance, and reactance estimates thus obtained have less noise and variations during the fault period. This can be achieved by the application of moving average filter to the voltage and current samples obtained after sampling the respective waveforms. The number of sample points to be smoothed is given by the span. Generally, a span is taken equal to 16 or 32 data samples, depending on the noise in the signal.

Different methods can be used for smoothing. Some of these are as follows [36]:

1. Moving average: This is the simplest method employed for smoothing. A low-pass filter with filter coefficients equal to the reciprocal of the span is used.

For example, taking the span equal to 5, the first few elements of the smoothed data are given by:

$$y_s(1) = y(1)$$

$$y_s(2) = \left(\frac{y(1) + y(2) + y(3)}{3} \right)$$

$$y_s(3) = \left(\frac{y(1) + y(2) + y(3) + y(4) + y(5)}{5} \right)$$

$$y_s(4) = \left(\frac{y(2) + y(3) + y(4) + y(5) + y(6)}{5} \right)$$

where, y_s is the smoothed data, and y is the original data set. Similarly smoothed data elements can be obtained for different span lengths.

2. A method involving local regression using weighted linear least squares and a first degree polynomial model can also be used for smoothing.
3. The same linear regression method as discussed above with a second degree polynomial model can also be used for smoothing.

4. Savitzky-Golay filter: A generalized moving average with filter coefficients determined by an unweighted linear least-square regression and a polynomial model of specified degree (generally second) is used. The method can also accept non-uniform predictor data.
5. Smoothing splines: Smoothed data can also be generated by fitting smoothing splines to the respective waveforms.

The simplest moving-average filter was used to test the improvement achieved. The results before and after smoothing are now discussed.

The three-phase voltage and current waveforms during an event are shown in Figure 3-9. Actual reactance to the fault from the circuit database was found to be 4.0907Ω .

The neutral current is calculated and smoothed using a span equal to 32 samples. Original and smoothed waveforms for the neutral current are shown in Figure 3-10. The level of improvement achieved in the impedance to the fault is shown in Figure 3-11 and Figure 3-12. They show the results before and after the smoothing operation, respectively. It can be clearly seen that the reactance estimate prior to smoothing is close to 0.3Ω . The estimate improves to 3.85Ω after the neutral current waveform is smoothed and used in the arc voltage-based fault-location estimate. Because it is very close to the actual reactance to the fault, it can be concluded that in most cases smoothing leads to improved results.

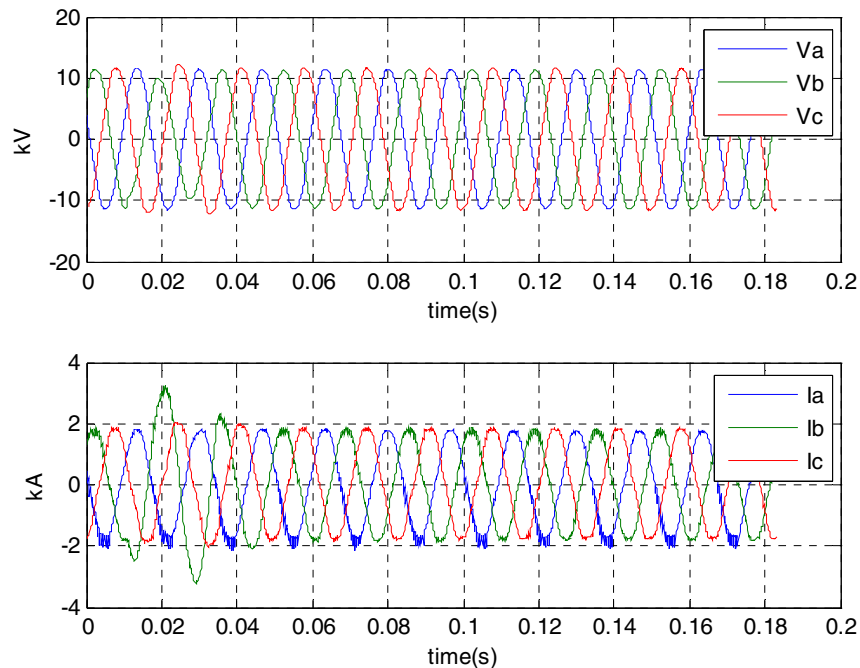


Figure 3-9
Voltage (Top) and Current (Bottom) during an SLG Event

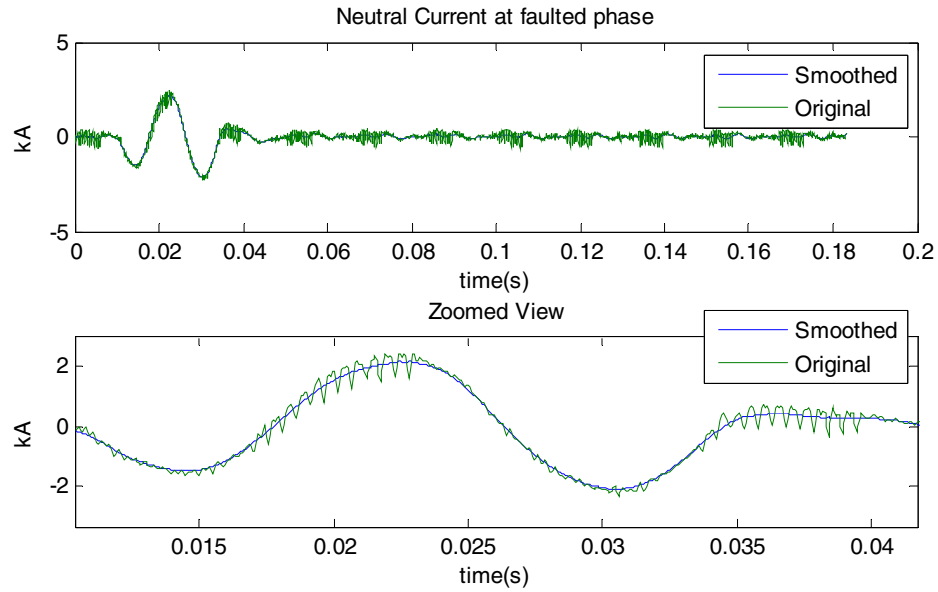


Figure 3-10
Smoothed versus Original Neutral Current (Bottom Is the Zoomed View)

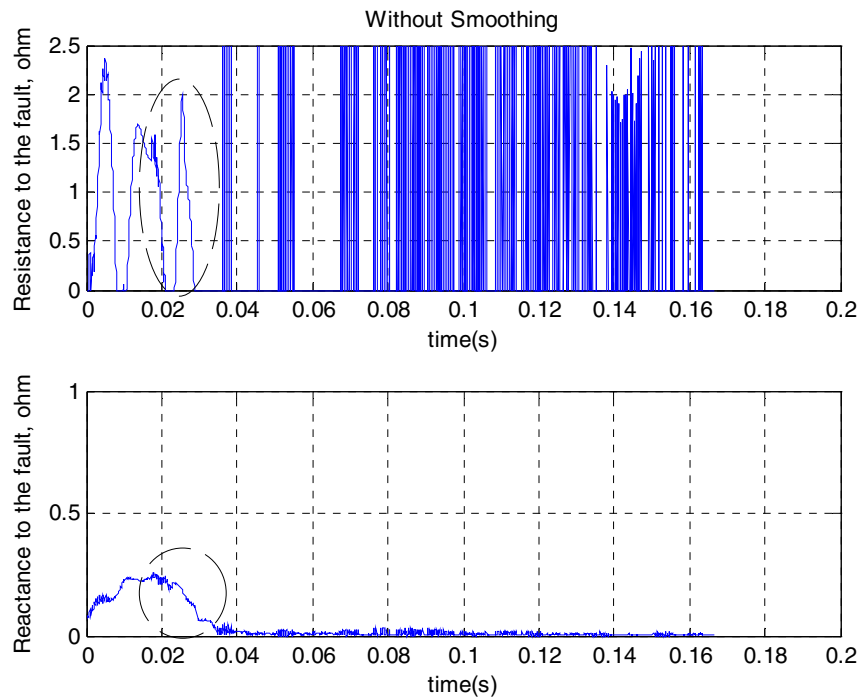


Figure 3-11
Resistance and Reactance Estimate Without Smoothing

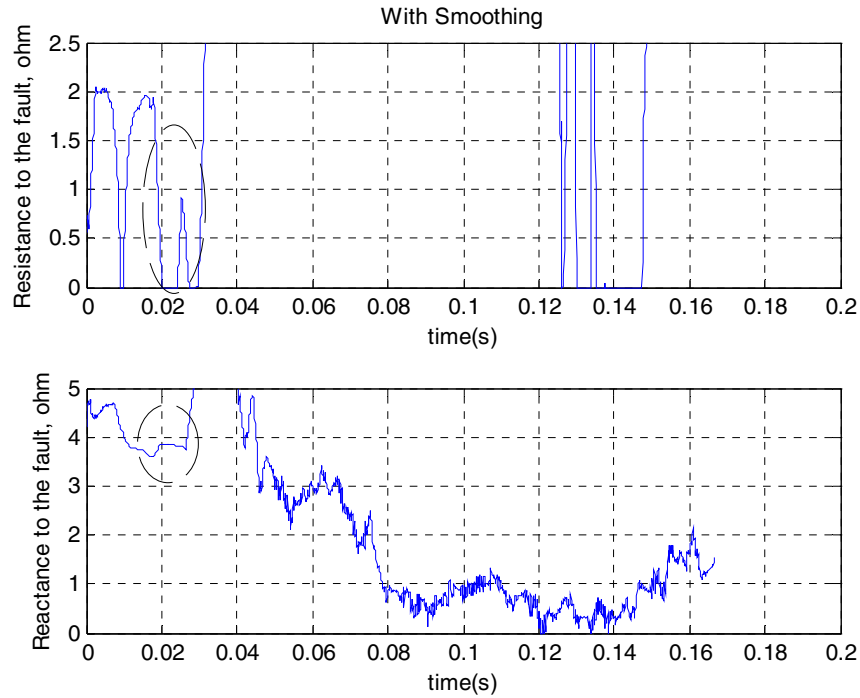


Figure 3-12
Resistance and Reactance Estimate With Smoothing

Post-Processing to Improve Estimates

Post-processing involves the selection of the best possible numerical value for the output estimates so as to accurately determine the location of the incipient faults.

Selecting Best-Match Fault Resistance (R) and Reactance (X_L) Estimates

Post- processing of the results obtained is helpful in pinpointing the impedance to the fault and determining the best-match estimates automatically without visual inspection. An arc voltage-based fault-location algorithm uses a window-based time domain approach, resulting in a range of values for fault resistance and reactance over the entire faulted portion of the waveform. It is very important to choose the best-match value of R and X_L out of this range that will result in the least error when compared with the actual impedance to the fault. Most of the time, the results obtained are stable during the fault or vary within a very small range. The following methods were used to pinpoint the R and X_L estimate during the fault. Both of these methods require that the fault duration be known in advance. The algorithm to determine accurate fault duration is discussed later in the appendix.

1. *Simple averaging*: All of the estimates obtained during the fault interval are averaged, providing the best possible estimate for R and X_L :

$$R_{best} = R_{avg} = \frac{R_{f1} + R_{f2} + \dots + R_{fn}}{n}$$

$$X_{best} = X_{avg} = \frac{X_{f1} + X_{f2} + ... + X_{fn}}{n}$$

where, $R_{f1}, R_{f2}, \dots, R_{fn}$, and $X_{f1}, X_{f2}, \dots, X_{fn}$ are the respective resistance and reactance estimates during the fault period. f_1 and f_n indicate the start and end of the fault period, respectively.

Reasonable results can also be obtained by simply taking the average of the highest and lowest value of the result during the fault period. For example, if R_{max}, R_{min} and X_{max}, X_{min} are the respective maximum and minimum values of fault resistance and reactance obtained during the faulted portion of the waveform, the best estimate for fault resistance (R_{best}) and fault reactance (X_{best}) can be obtained by using Eq. 3-18 and Eq. 3-19, respectively.

$$R_{best} = \frac{R_{max} + R_{min}}{2} \quad \text{Eq. 3-18}$$

$$X_{best} = \frac{X_{max} + X_{min}}{2} \quad \text{Eq. 3-19}$$

Figure 3-13 shows the voltage and current waveforms captured by the PQ monitor during a sustained event. The resistance and reactance estimates obtained using the arc voltage-based fault-location algorithm are shown in Figure 3-14. The maximum and minimum resistance and reactance to the fault values during the fault period were identified.

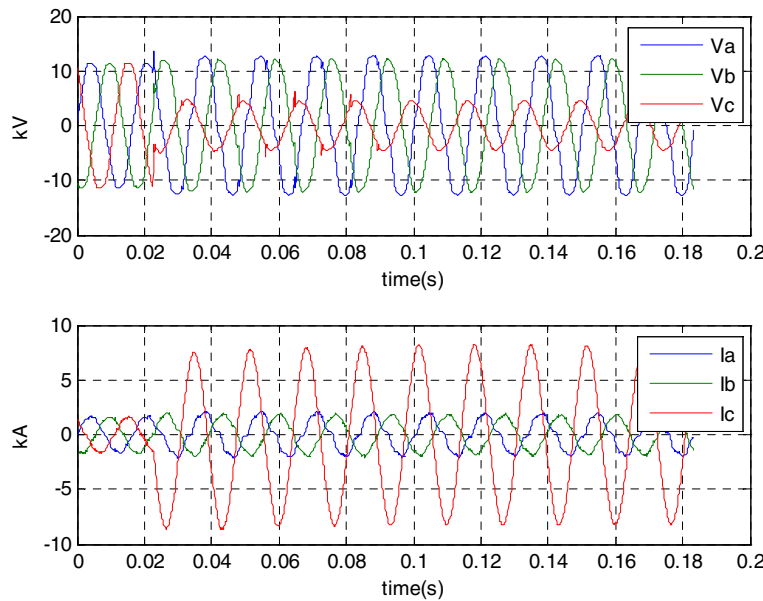


Figure 3-13
Voltage and Current during a Sustained Event

Average resistance and reactance estimates during the fault period are:

$$R_{best} = R_{avg} = 0.36775 \, \Omega$$

$$X_{best} = X_{avg} = 0.48357 \, \Omega$$

Best estimates can also be obtained using Eq. 3-18 and Eq. 3-19 as given below:

$$R_{best} = \frac{0.3729 + 0.3314}{2} = 0.35215 \, \Omega$$

$$X_{best} = \frac{0.4998 + 0.4083}{2} = 0.45405 \, \Omega$$

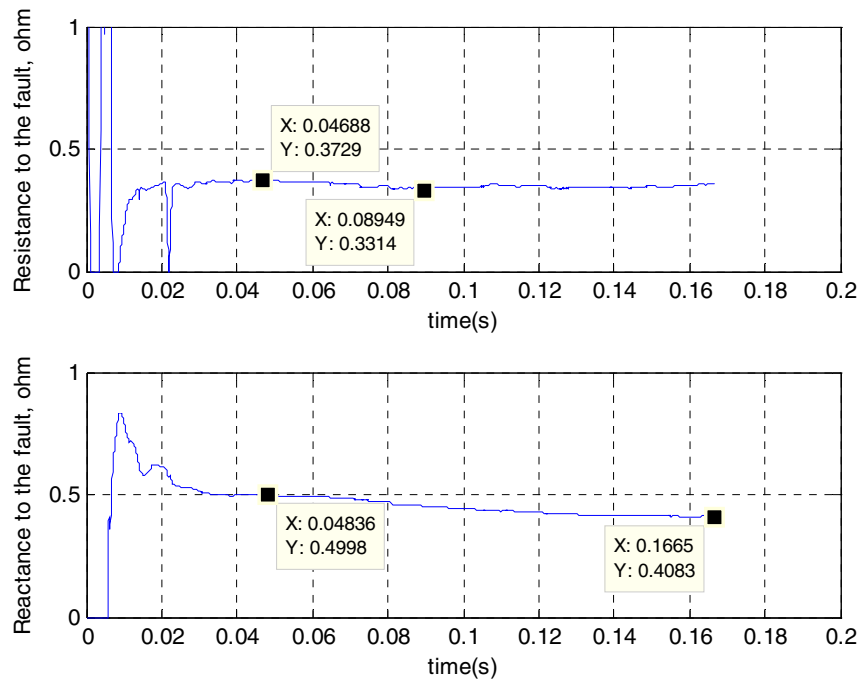


Figure 3-14
Resistance and Reactance Estimate with Maximum/Minimum Values

The actual reactance to the fault from the circuit database is 0.523Ω.

Percentage error (averaging all the estimates during the fault period) =

$$\frac{0.523 - 0.48357}{0.523} = 7.54\%$$

Percentage error (averaging minimum and maximum estimates during the fault period) =

$$\frac{0.523 - 0.45405}{0.523} = 13.18\%$$

1. *Back substitution*: In this method, the estimated parameters are substituted back to Eq. 3-20. The best estimate for arc voltage, resistance, and reactance to the fault will result in the least-square error when the estimated voltage in the faulted phase is compared with that measured by the PQ monitor.

$$V_{F,estimated} = R \cdot I_F + L \cdot \frac{dI_F}{dt} + V_{arc} \cdot \text{sgn}(I_F) \quad \text{Eq. 3-20}$$

The problem can now be identified as given in Eq. (3.21).

$$\min(e^2) = \min(\sum (V_{F,estimated} - V_{F,measured})^2) \quad \text{Eq. 3-21}$$

where, $V_{F,estimated}$ is the faulted voltage estimated by substituting the parameters back into Eq. 3-20, and $V_{F,measured}$ is the faulted voltage measured at the PQ monitoring station.

The time instant along the waveform where the least-squared error exists is found out. The parameters at that time instant are considered to be the best-estimated parameters. This method is expressed in Eq. 3-22.

$$R_{best} = R(t_{LSE}), X_{best} = X(t_{LSE}) \text{ and } V_{arc, best} = V_{arc}(t_{LSE}) \quad \text{Eq. 3-22}$$

These estimates, when substituted back in Eq. 3-20, will give the $V_{F,estimated}$ that is the best possible match for $V_{F,measured}$ in the least-squared error sense.

The same event (single-line-to-ground fault on phase C) explained in a simple averaging method is tested with back substitution to obtain the best estimates for resistance and reactance to the fault.

$$t_{LSE} = 0.08151 \text{ secs}$$

$$R_{best} = 0.3379 \Omega$$

$$X_{best} = 0.4644 \Omega$$

$$\text{Percentage error (using back substitution)} = \frac{0.523 - 0.4644}{0.523} = 11.20\%$$

The $V_{F,estimated}$ using the best resistance and reactance estimates is compared with the $V_{F,measured}$ at the PQ monitor, as shown in Figure 3-15.

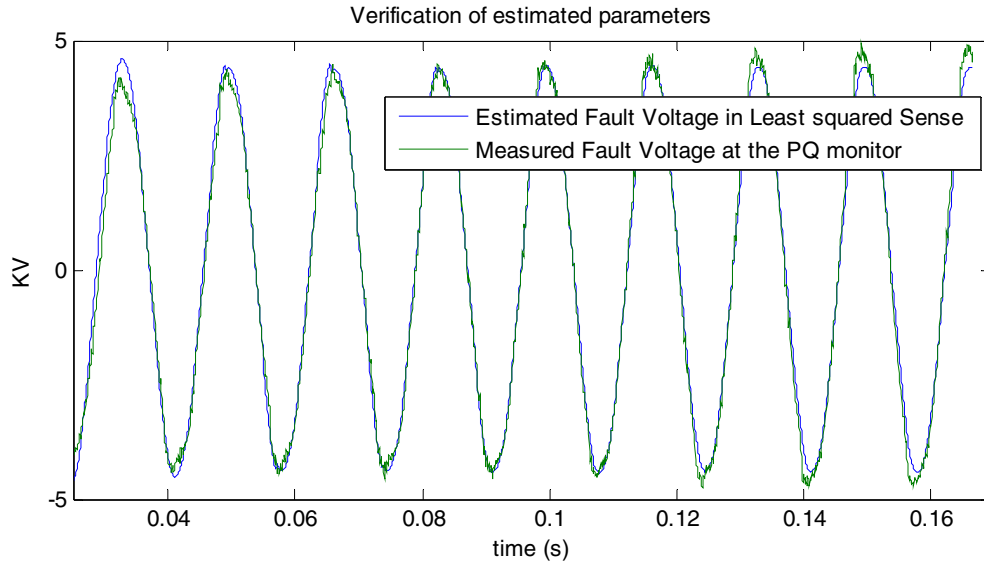


Figure 3-15
Comparison between Estimated and Measured Fault Voltage

1. *Median estimate*: The best estimate can also be obtained by taking the median of all the estimates during the fault. A median is described as the number separating the higher half of a sample, a population, or a probability distribution, from the lower half. It can easily be found by arranging all the observations from lowest value to highest value and picking the middle one. If there is an even number of observations, the median is not unique; thus the mean of the two middle values provides the median value.

For the example discussed above, the median was found to be 0.468Ω .

$$\text{Percentage error (using median)} = \frac{0.523 - 0.468}{0.523} = 10.50\%$$

2. *Linear fit of estimates*: In this method, a straight line ($ax+b$) is fitted to the estimates during the fault period. By finding a , the slope of the linear fit to the estimates can be determined, and hence the stability of the results during the fault period can be determined. This method has the advantage of assessing the usability of the estimates. If gradient a is steep, the estimate may not be reliable. On the other hand, if the gradient a is gentle, it is indicative of a useful estimate. A midpoint in between the line can be considered as the best estimate. The length of the straight line can be determined based the start and end of the fault duration.

For the example discussed above, slope (a) was found to be around -0.9 , indicating comparatively stable estimates. The midpoint of the linear fit is found to be around 0.4577Ω .

$$\text{Percentage error (using linear fit)} = \frac{0.523 - 0.4577}{0.523} = 12.49\%$$

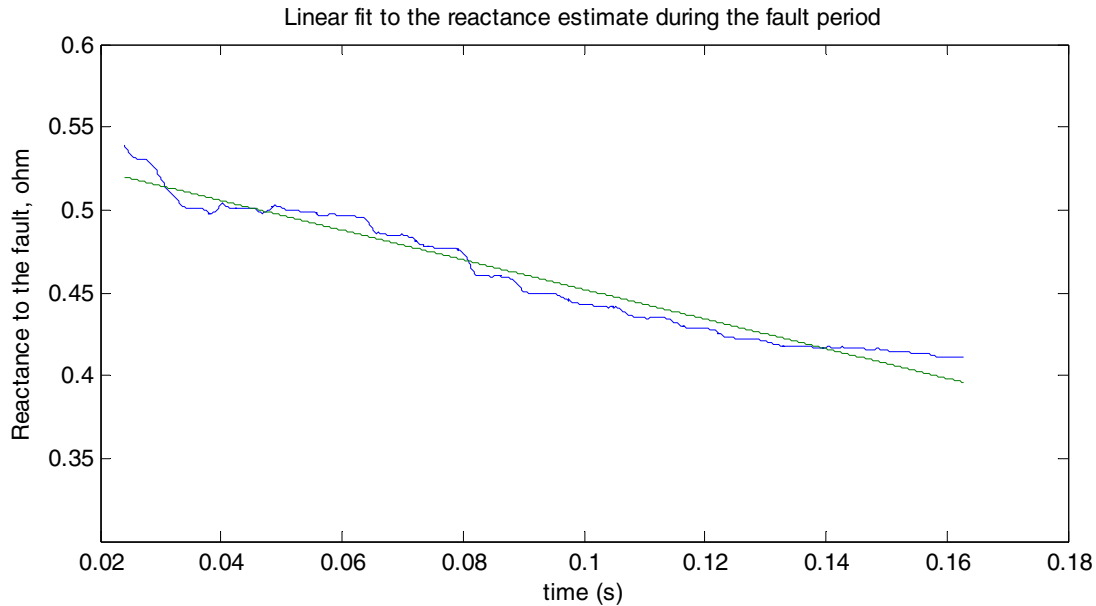


Figure 3-16
Linear Fit to the Reactance Estimates during the Fault

It must be noted that either of these methods can be used for selecting the best resistance and reactance estimates to the fault. However, estimate averaging, back substitution, and median approaches are found to be the most robust. The linear-fit estimate method requires further analysis to evaluate its robustness.

Summary

The importance of arc voltage during the fault period is explained in this Chapter. This is followed by derivation of the arc voltage-based fault-location algorithm for an SLG fault. The approach for implementing this algorithm along with waveform pre-processing and selecting best possible estimates during the fault period is discussed in detail. It is also shown that more accurate results (when compared with actual fault location from the database) are obtained when data processing is employed. Future work includes the development of arc-voltage algorithm for multi-phase faults. The impact of arc power and energy is an important issue for future analysis. Other signal-processing techniques will also be tested to improve the accuracy of the existing algorithm. Analyzing more data corresponding to one particular event can also lead to identification of accuracy range and predicting a fault-location range for that set. Different models can also be fitted to the data to estimate constant multipliers for each fault-location algorithm. All of these measures might prove helpful in increasing the accuracy of the algorithm.

4

VALIDATION OF THE DEVELOPED ALGORITHM

In this Chapter, the arc voltage-based algorithm developed and implemented in Chapter 3 is validated using data generated by simulation models as well as those collected from known arcing and sustained fault events. The arc-voltage estimate is first validated using known arcing-fault events collected during the EPRI Distribution Power Quality (DPQ) project. The impedance (resistance and reactance) to the fault is then validated using simulated and known fault events.

Validation of Arc-Voltage Estimates – Arcing-Fault Waveforms

A few waveforms from EPRI's DPQ study [38][39] were identified and used for validating the arc-voltage estimation described in Chapter 3. These waveforms were captured by power quality monitors installed on a 12.47-kV distribution feeder.

In this study, three monitors were installed for each selected feeder, one at the substation and two along the feeder. The waveform obtained from the substation monitor was used to estimate the arc voltage by applying the arc-voltage algorithm. This estimate was then compared with that of a downstream monitor that measured the voltage across the arc directly.

Figure 4-1 shows the faulted distribution feeder along with the monitoring stations (A and B). The arc-voltage algorithm was applied to waveforms obtained from monitoring station A (far upstream from the fault) and was compared with actual faulted phase voltage waveforms obtained from monitoring station B (downstream from A, but near and upstream from the fault).

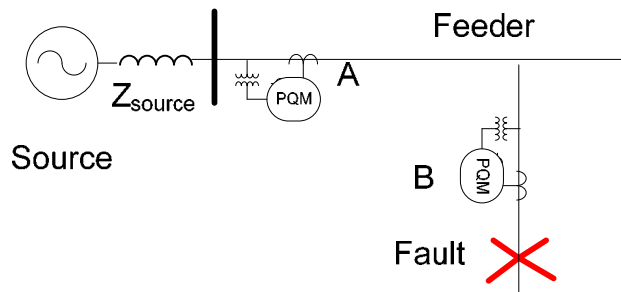


Figure 4-1
A Faulted Distribution Feeder

The voltage and current waveforms at monitors A and B are shown in Figure 4-2 and Figure 4-3, respectively. The fault can be classified as an SLG fault on phase B of the distribution feeder. An arc-voltage algorithm was applied to the waveforms shown in Figure 4-2 to estimate the voltage across the arc.

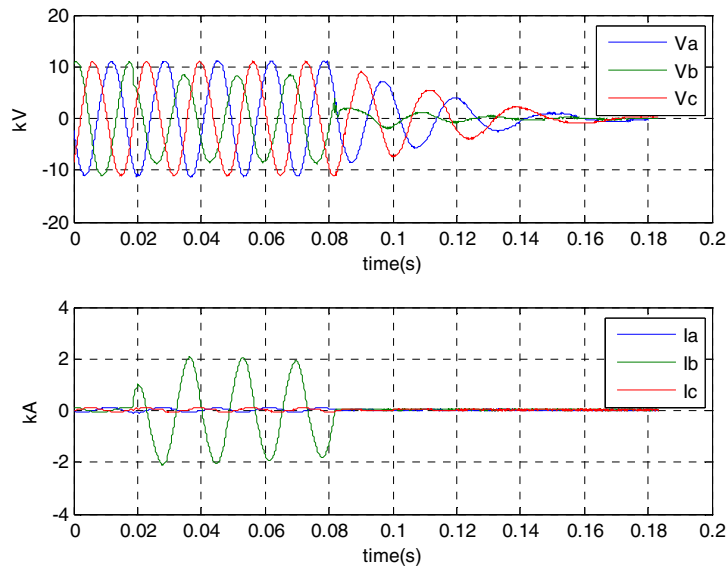


Figure 4-2
Voltage and Current at Monitoring Station A (Substation Monitor)

The arc voltage in Figure 4-3 has the classic square-wave shape. This can be approximated as measured arc voltage at the fault location because the monitor B is barely upstream from the fault location.

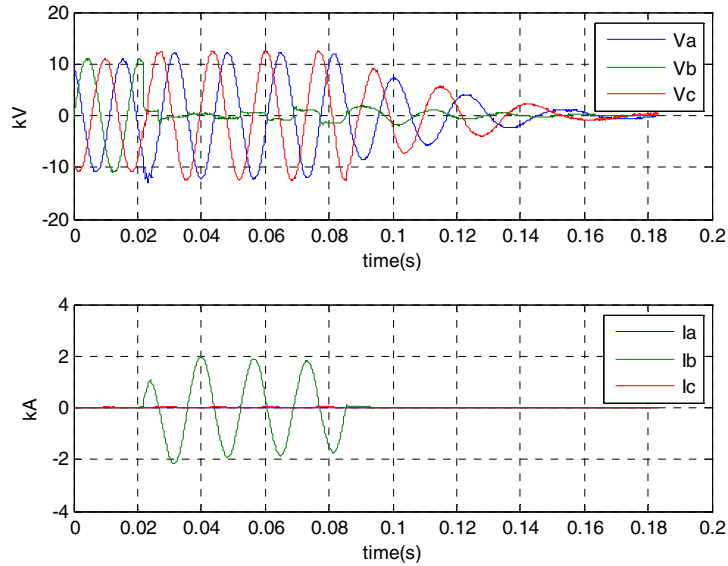


Figure 4-3
Voltage and Current Measured at Monitoring Station B (Downstream from A, Barely Upstream from Fault Location)

Moreover, being very near to the fault location, the impedance to the fault is very small (refer to Figure 3-8); hence, Eq. 3-14 can be written as given by Eq. 4-1.

$$V_F = V_{arc} \cdot \text{sgn}(I_F)$$

Eq. 4-1

Thus, assuming that R and L are very small, the voltage at PQ monitor B is equal to arc voltage across the fault. Figure 4-4 compares the estimates of arc voltage based on the substation monitor (monitor A) with the actual measurement of the arc voltage from the downstream feeder site (monitor B). Arc voltage magnitude was observed to increase during the event. This can be attributed to arc-elongation phenomenon.

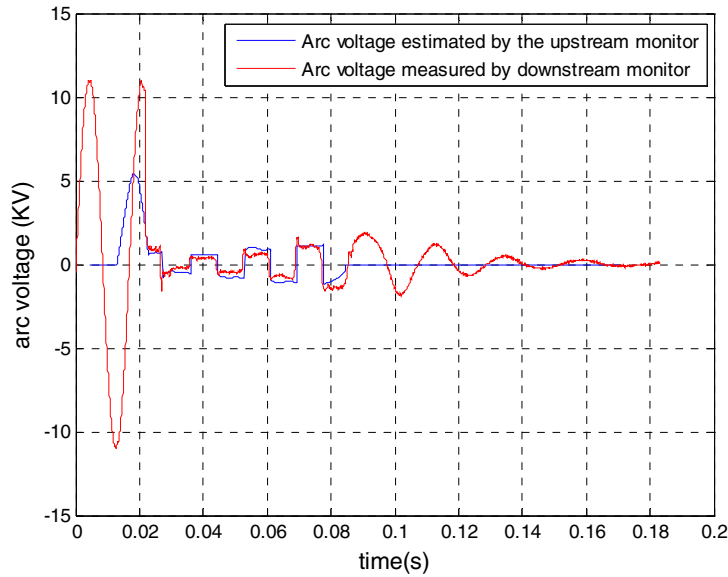


Figure 4-4
Comparison between Estimated and Measured Arc Voltage

One more DPQ event is discussed as follows. Voltage and current waveforms at upstream and downstream monitors are analyzed as before. This event involves an evolving fault with only one phase (phase B) faulted initially, but eventually the fault involves all the three phases. The comparison between estimated and measured arc voltage for this event is shown in Figure 4-5. Good estimation was observed between the estimated and measured voltage even in this case. The results from the DPQ waveforms clearly validate the accuracy of the arc voltage-based fault-location algorithm.

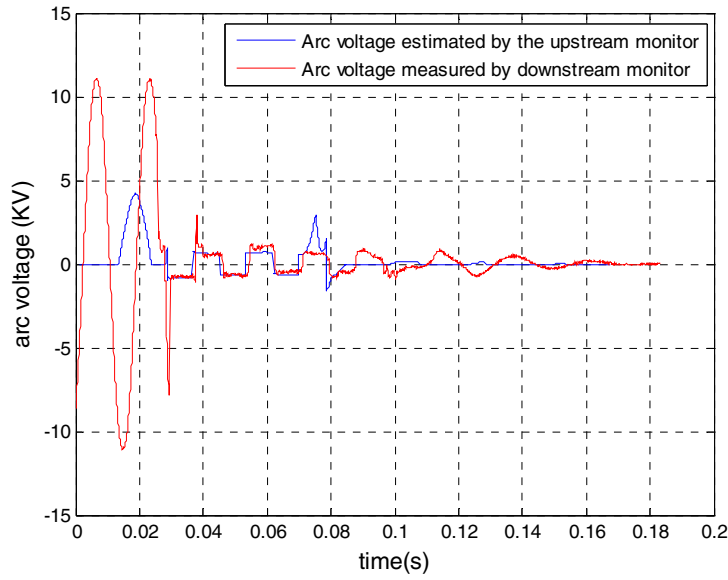


Figure 4-5
Comparison between Estimated and Measured Arc Voltage

Validation of Impedance-to-Fault Estimates – Simulated Fault Events

An SLG fault was simulated on a 12.47-kV distribution feeder as shown in Figure 4-6. A three-phase 34.5-kV voltage source was used along with a 10-MVA step down transformer that feeds a 12.47-kV distribution feeder. SLG faults with different fault duration were simulated on phase A. It was assumed for all the cases that no arc voltage was present at the fault location. Voltage and current were measured at a point along the distribution feeder, which can be assumed to be the PQ monitoring station. The impedance from the point where V_F and I_F were measured to the fault was assumed to be Z_{fault} .

where, $Z_{fault} = 0.35 + j2\pi f \cdot (0.00116714)$ or

$$R_{fault} = 0.35 \, \Omega \text{ and } X_{fault} = 0.00116714 \cdot (2\pi \cdot 60) = 0.4401 \, \Omega$$

Waveforms for V_F and I_F during an SLG fault of duration equal to 10 cycles are shown in Figure 4-7. These waveforms act as input to the arc voltage-based fault-location algorithm from which the impedance to the fault is estimated. The resistance and reactance estimates to the fault along with the arc voltage estimate across the fault are shown in Figure 4-8.

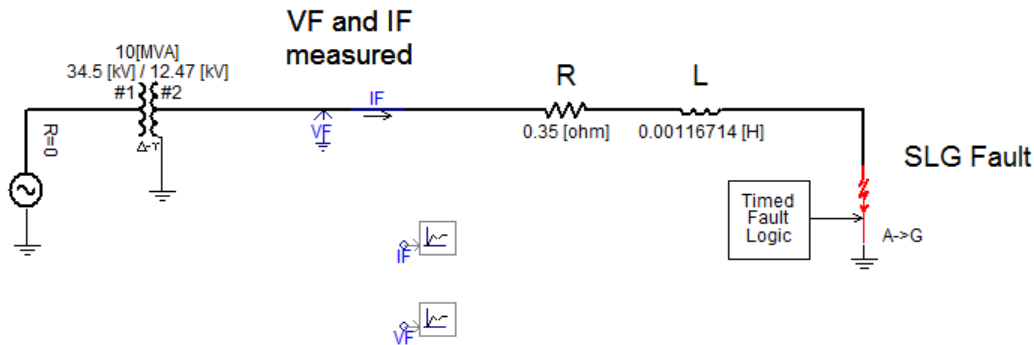


Figure 4-6
Single-Line-to-Ground Fault Simulated on Distribution Feeder

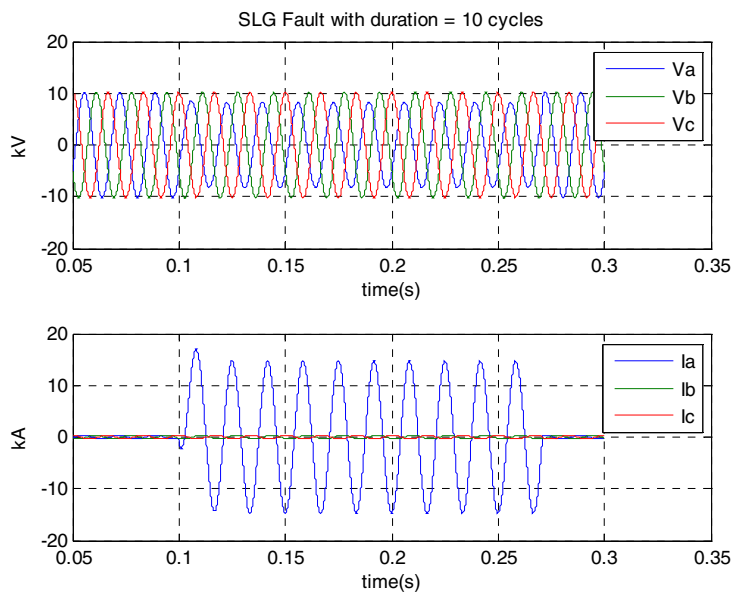


Figure 4-7
Faulted Phase Voltage and Current Waveforms at the Monitoring Point (Fault Duration = 10 Cycles)

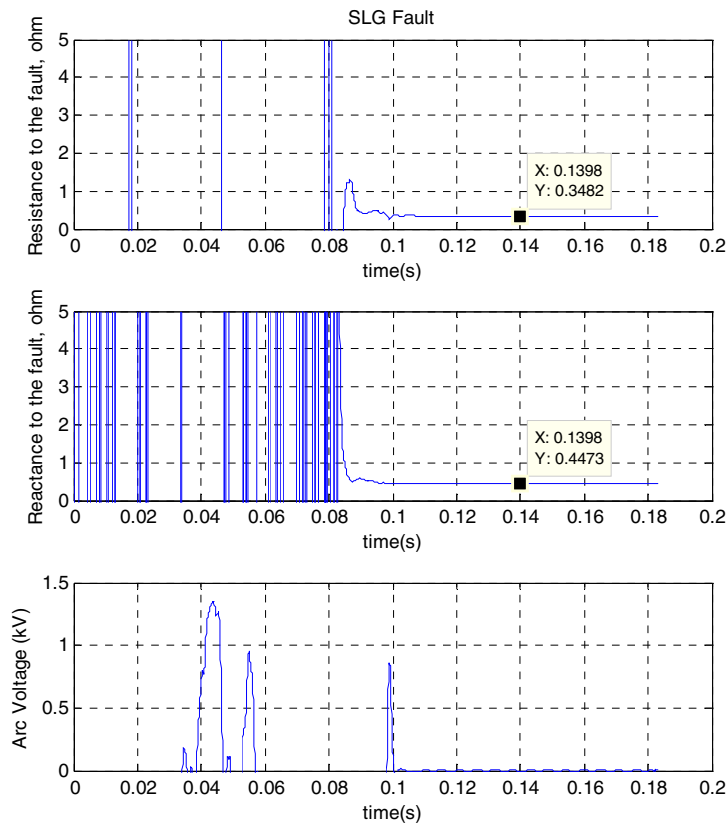


Figure 4-8
Resistance (Top) and Reactance (Middle) Estimates to the Fault, Arc Voltage (Bottom)
Estimate at the Fault Location (Fault Duration = 10 Cycles)

It can be clearly seen from Figure 4-8 that the resistance and reactance estimates to the fault are stable during the fault period and match with the parameters from the simulation model. Cases of SLG faults with duration of five, one, and one-half cycles are also simulated to observe the effect of fault duration on the arc voltage-based algorithm. Waveforms for V_F and I_F during an SLG fault of duration equal to $\frac{1}{2}$ cycle are shown in Figure 4-9. The results from the algorithm are zoomed during the fault period and shown in Figure 4-10.

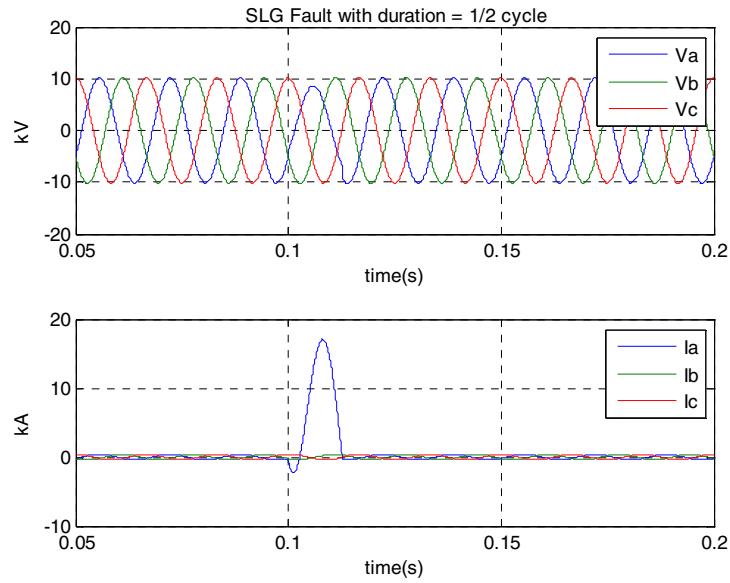


Figure 4-9
Faulted Phase Voltage and Current Waveforms at the Monitoring Point (Fault Duration = $\frac{1}{2}$ Cycle)

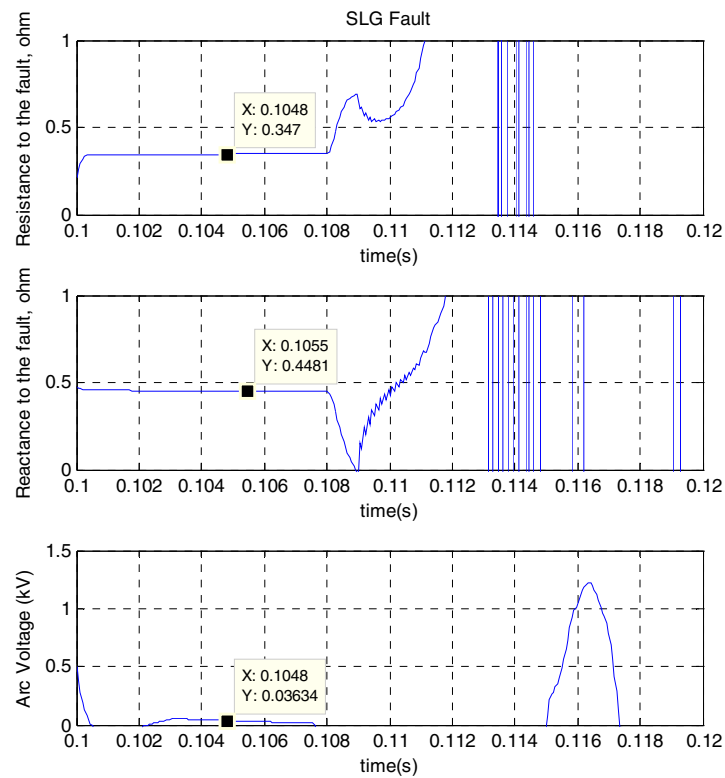


Figure 4-10
Zoomed View of Resistance (Top) and Reactance (Middle) Estimates to the Fault, Arc Voltage (Bottom) Estimate at the Fault Location (Fault Duration = $\frac{1}{2}$ Cycle)

Again, the results are very close to the simulation parameters. However, the percentage error has slightly increased. Table 4-1 shows the impact of fault duration on the obtained results.

Table 4-1
Impact of Fault Duration on V_{arc} , R , and X_L

Fault Duration (No. of Cycles)	Window length (No. of Samples)	V_{arc} (kV)	Percentage Error in V_{arc} (%)	R (Ω)	Percentage Error in R (%)	X_L (Ω)	Percentage Error in X_L (%)
10 cycles	256	0	0	0.3482	0.514	0.4473	1.63
5 cycles	256	0	0	0.3482	0.514	0.4473	1.63
1 cycle	128	0.029	0*	0.3475	0.7143	0.4479	1.77
½ cycle	64	0.036	0*	0.3470	0.857	0.4481	1.817

* Very small error because rated voltage is in kV. The maximum arc voltage observed during the fault period is reported

It can be concluded that the longer the duration, the smaller the error in the results. Moreover, reasonable and relatively accurate results are obtained from the arc voltage-based fault-location algorithm, even for short-duration faults. The effect of window width is discussed in more detail in Chapter 5.

Validation of Impedance-to-Fault Estimates – Sustained and Known Fault Events

A database of waveforms from a number of monitoring stations collected as part of the EPRI Fault Location Study project was utilized to validate the accuracy of the arc voltage-based fault-location algorithm. Sustained faults are mainly discussed in this section. These permanent faults continue over a period of time, typically having duration more than three or four cycles. They are generally unable to self-clear and require a protective device to operate and isolate the faulted line. Some cases were analyzed to validate the impedance-to-fault estimates from the algorithm.

As shown in Figure 4-11, a sustained fault exists on phase A for around 8½ cycles. The resistance and reactance estimate from the arc voltage-based algorithm is shown in Figure 4-12.

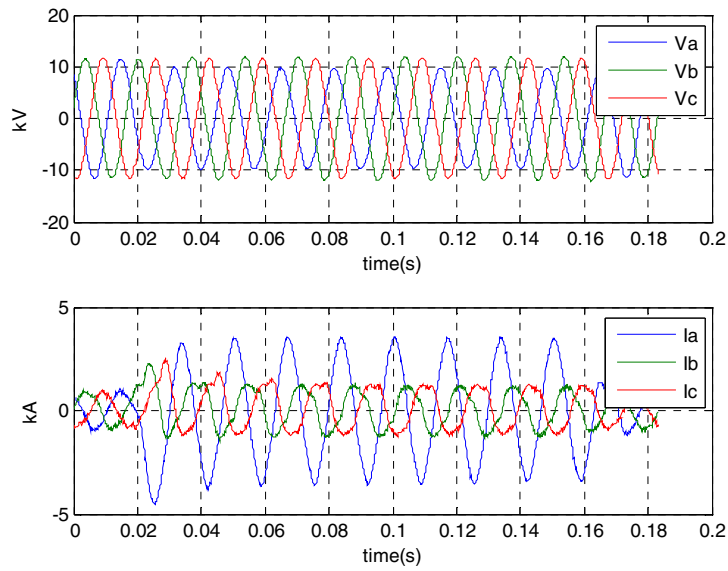


Figure 4-11
Voltage and Current during an SLG Event

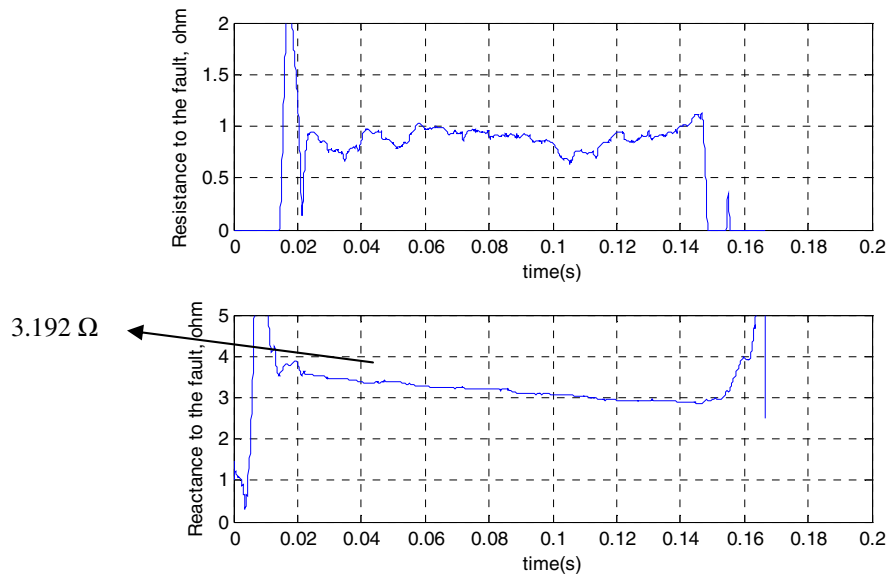


Figure 4-12
Resistance and Reactance to the Fault Estimate

In this case, the actual fault distance from the monitoring station was found to be 3.2708 Ω. Relatively stable resistance and reactance estimates are indicative of useful fault-location results. The reactance estimate to the fault was found to be equal to 3.192 Ω.

$$\text{Percentage error} = \frac{3.2708 - 3.192}{3.2708} = 2.41\%$$

It was observed that if the arc voltage obtained from the arc-voltage algorithm is very small or close to zero, then the fault can be classified as *sustained* with respect to time. However, the converse is not all true. Some permanent faults with significant arc voltage magnitude have also been observed.

One more sustained fault on the distribution feeder is analyzed below. The voltage and current waveforms in all the three phases captured at the monitoring station during a sustained event are shown in Figure 4-13.

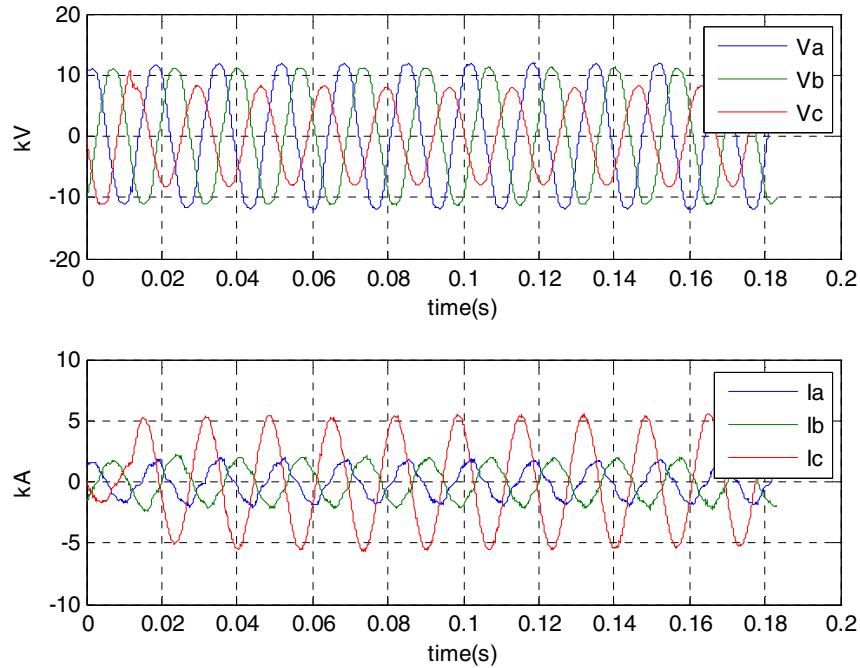


Figure 4-13
Voltage and Current during a Sustained Fault

By selecting a window length of 256 samples and running the arc voltage-based fault-location algorithm on the faulted data set, the following results were obtained over the entire time range. Only the parameter values obtained during the fault are to be considered. More details about the proper window-selection procedure are presented in Chapter 5.

Figure 4-14 shows the resistance (R) and reactance (X_L) to the fault along with the arc-voltage estimate for the above sustained fault.

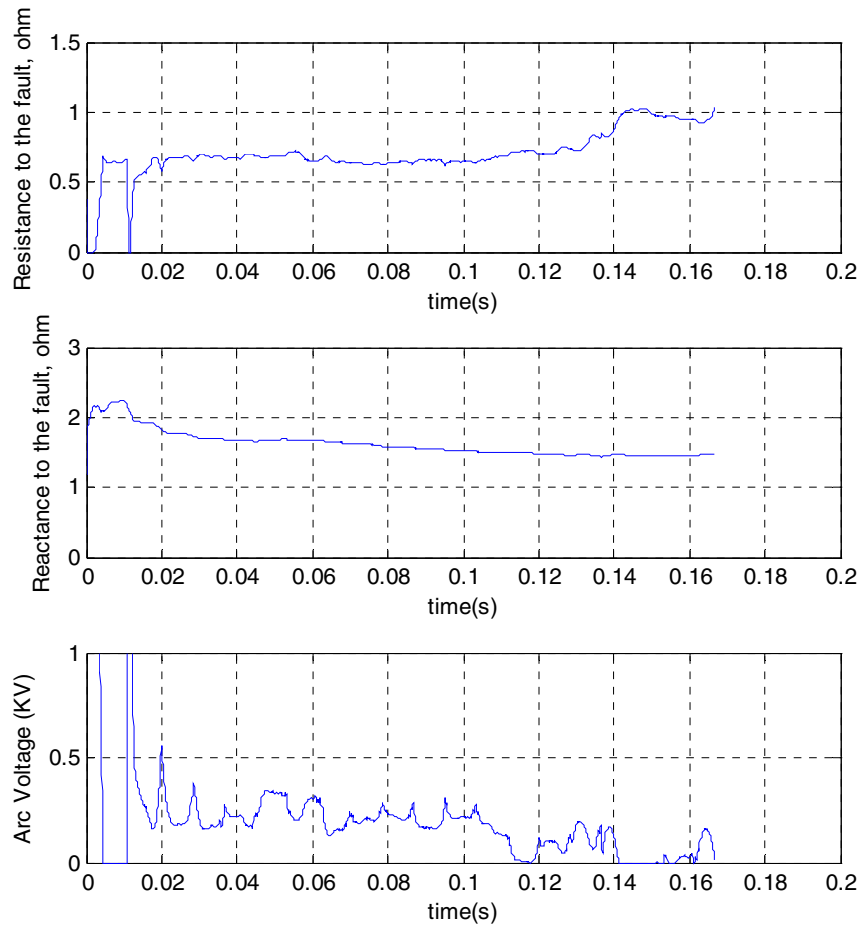


Figure 4-14
Resistance (Top), Reactance (Middle), and Arc Voltage (Bottom) Estimate

These R and X_L estimates, being the resistance and inductance to the fault, can be used to determine the distance to the fault.

Observe that during the fault, the reactance estimate is decaying but is close to 1.57Ω (using back substitution). This decaying characteristic may be attributed to the slight unbalance in the three-phase system. A sustained SLG fault simulated in this chapter, being independent of any unbalance, is observed to generate constant results over the entire fault period.

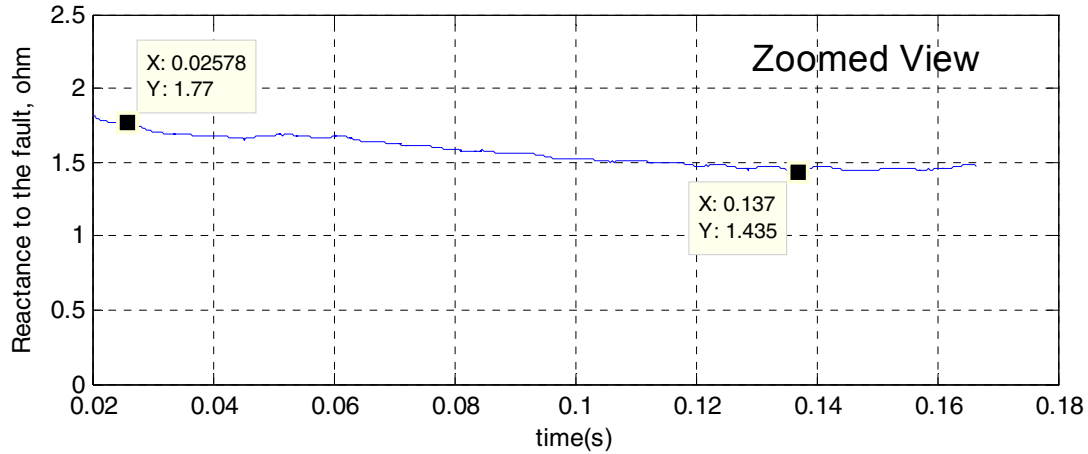


Figure 4-15
Simple Averaging to Find Best Reactance Estimate

In the above case, the actual impedance to the fault from the utility database was found to be $0.79+j1.54 \Omega$.

$$\text{Percentage error} = \frac{1.57 - 1.54}{1.54} = 1.948\%$$

By simple averaging of the maximum and minimum reactance estimates, the best reactance estimate to the fault is given by:

$$X_{best} = \frac{1.77 + 1.435}{2} = 1.6025 \Omega$$

$$\text{Percentage error} = \frac{1.6025 - 1.54}{1.54} = 4.06\%$$

Instead, if all the estimates are averaged, the best reactance estimate to the fault is found to be 1.5525Ω .

$$\text{Percentage error} = \frac{1.5525 - 1.54}{1.54} = 0.81\%$$

The median reactance estimate during the fault is found to be 1.5272Ω .

$$\text{Percentage error} = \frac{1.54 - 1.5272}{1.54} = 0.83\%$$

Thus taking the arc voltage into account generally yields reasonably accurate fault-location estimates. Moreover, back substitution, averaging, and median techniques are observed to yield good results.

Comparison of Accuracy Relative to Impedance-Based Methods

In the following discussion, the accuracy of the arc voltage-based fault-locating method is compared to other impedance-based methods. Two sustained fault events, about 10 cycles in duration, were selected so that impedance-based methods can be applied. Their relative distance or reactance estimates are tabulated.

Event 1–Voltage Sag on Phase B Resulting in a Sustained Fault

The line-impedance data for this event is provided below:

$$z_l = 0.426 + 0.573i$$

$$z_0 = 1.082 + 1.815i$$

Figure 4-16 shows the voltage and current waveforms during the event. Figure 4-17 shows the estimated resistance and reactance to the fault.

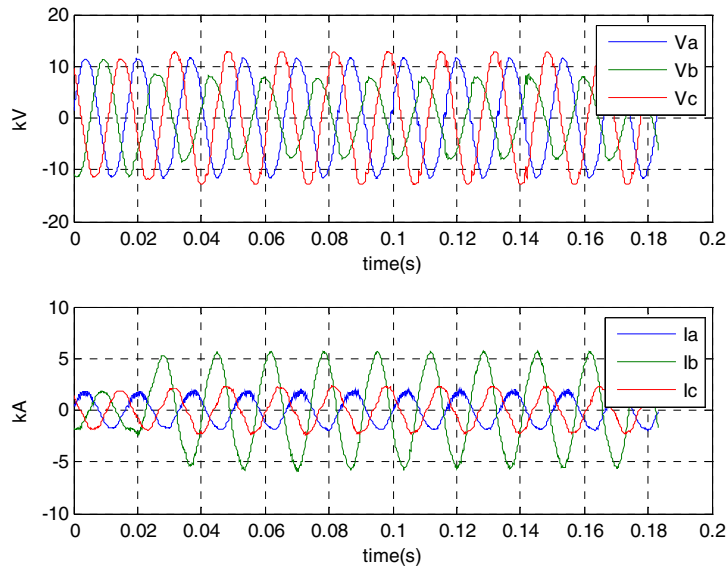


Figure 4-16
Voltage and Current during an SLG Event

Stable estimates during the fault period indicate the accuracy of the arc voltage-based algorithm. Simple averaging was employed to determine the best possible reactance to the fault estimate.

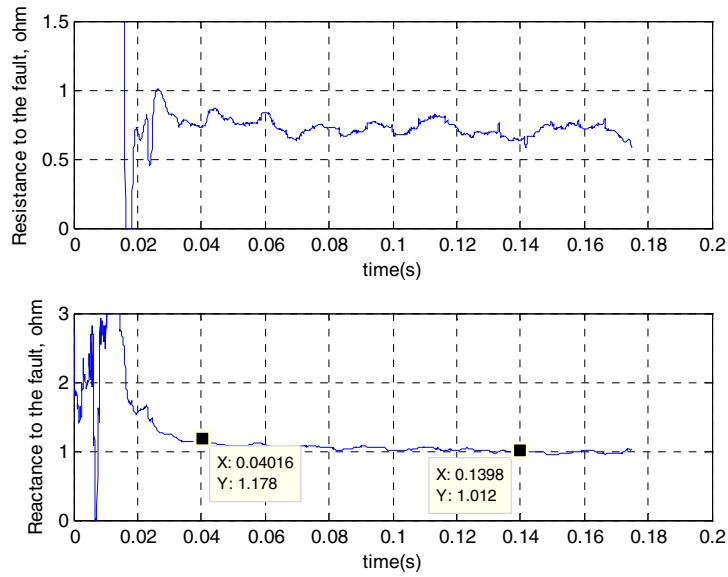


Figure 4-17
Resistance and Reactance Estimates

During the fault duration:

$$X_{\text{fault}} = \frac{(X_{\text{max}} + X_{\text{min}})}{2} = \frac{1.178 + 1.012}{2} = 1.095 \, \Omega$$

For this event, the comparison of results from all other overhead fault-location algorithms is provided in Table 4-2 (column 2). Comparisons with other fault-location methods are performed for one more case discussed below.

Event 2 – Sustained SLG Fault on Phase B

The line-impedance data for this event is provided below:

$$z_l = 0.1952 + 0.418i$$

$$z_0 = 0.8957 + 1.435i$$

Figure 4-18 shows the voltage and current waveforms during this event. Application of arc voltage-based algorithms gives resistance and reactance estimates as shown in Figure 4-19.

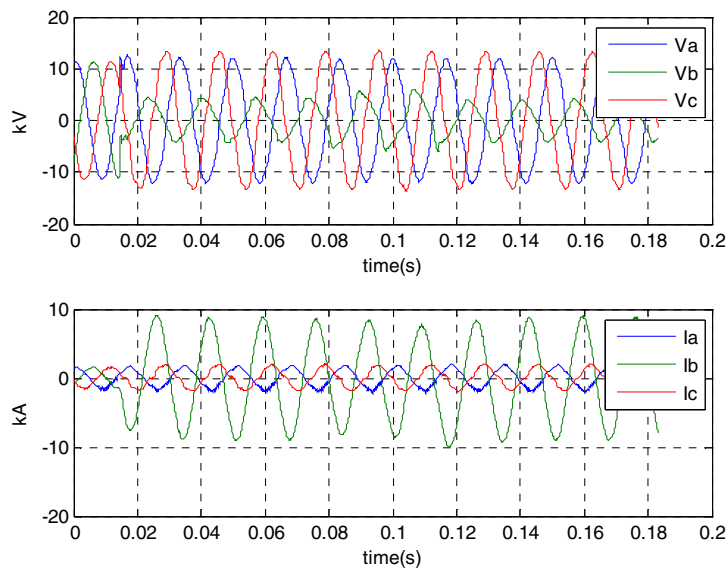


Figure 4-18
Voltage and Current during an SLG Fault

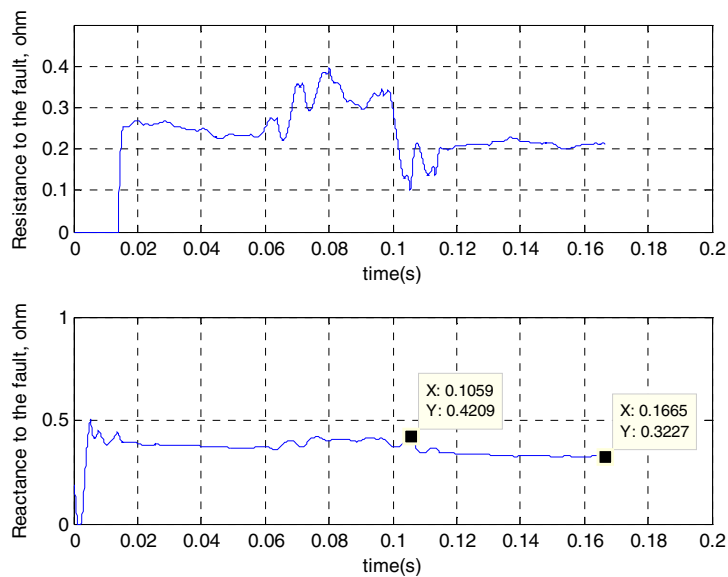


Figure 4-19
Resistance and Reactance Estimates

Back substitution was used to determine the best reactance estimate. The reactance was found to be 0.4467Ω . The results from all other overhead fault-location algorithms are provided in Table 4-2 (column 4).

Table 4-2
Comparison of Fault Distance

Method	Fault Location: Case 1 (Ω)	Percentage Error (%)	Fault Location: Case 2 (Ω)	Percentage Error (%)
Actual Fault Distance from Circuit Database	1.118	0	0.435	0
Arc Voltage-Based Method	1.095	2.05	0.446	2.52
Simple Ohm's Law-Based Method	1.121	0.268	0.563	29.4
Absolute Value of Impedance	1.244	11.27	0.483	11.03
Reactance to the Fault	1.276	14.13	0.582	33.8
Takagi Method	1.053	5.81	0.512	17.7
Santoso Et Al Method	0.978 to 1.591	0 to 42*	0.512 to 0.559	17.7 to 28.5

*0% since actual result lies in the range and 42% is the maximum error in this range

Additional 27 SLG fault events were analyzed. Comparison results are summarized in Figure 4-20 and Table 4-3. The plots between the actual impedance to the fault from the circuit database (ohms) versus impedance estimated from the algorithm (ohms) for different fault-location methods are shown in Figure 4-20. The absolute error for all of these cases was calculated, and the average was performed. The average percentage errors for all the fault-location algorithms are presented in Table 4-3.

Table 4-3
Average Absolute Error Obtained from Actual Field Data Cases (27 Cases)

Method	Average Percentage Error
Arc Voltage-Based Method	12.58
Simple Ohm's Law-Based Method	16.22
Absolute Value of Impedance	16.17
Reactance to the Fault	21.98
Takagi Method	17.45
Santoso Et Al Method	14.39 to 17.48

From Figure 4-20, it can be seen that the results from all the methods are quite close to the actual fault location. However, in general, least percentage error is observed when the arc voltage-based algorithm is used. This method also overcomes some of the drawbacks of the frequency (spectrum)-based fault-location methods discussed in Chapter 2. Furthermore, it works quite accurately for short-duration fault events as well.

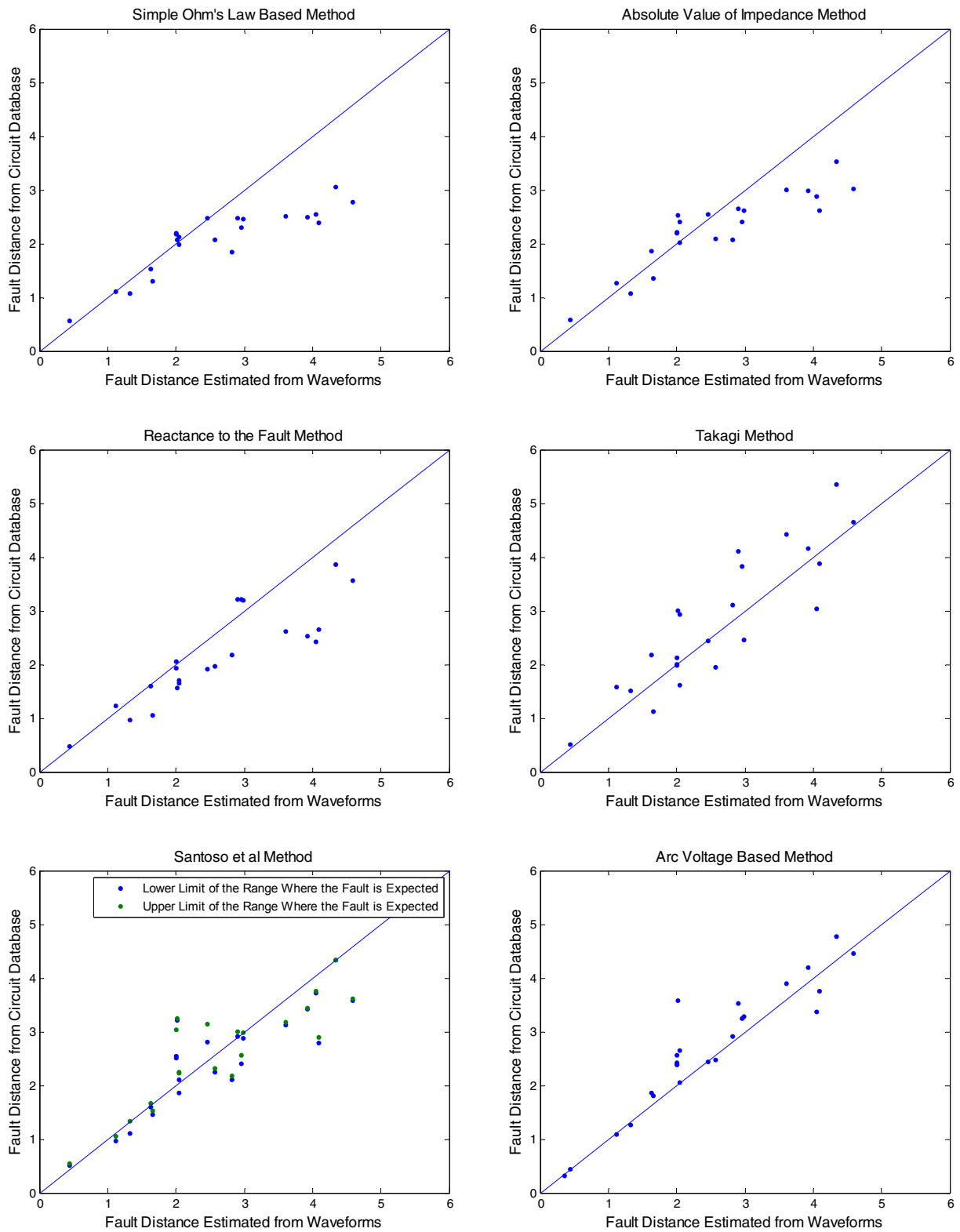


Figure 4-20
Comparison of Actual and Estimated Fault Location (Ohms) Using Different Algorithms

Summary

An arc voltage-based algorithm was validated using field measurement and simulation data. A few DPQ fault event data sets were identified and used for arc-voltage validation by comparing arc voltages estimated (from an algorithm) at an upstream monitor with that measured at a downstream monitor. Results prove that the arc voltage-based algorithm estimates the arc voltage at the fault location quite accurately. The accuracy of the algorithm for varying fault duration was evaluated by simulating such faults on a distribution system. It is observed that even short-duration faults ($\frac{1}{4}$ to $\frac{1}{2}$ cycle) are accurately identified. Moreover, resistance and reactance estimates to the fault match almost exactly with the circuit data used in the simulation. This is followed by analysis of the actual distribution network data sets obtained from power quality monitors. Fault-location estimates were obtained using different algorithms, and a comparison was done to check for accuracy of these algorithms. In most cases, the arc voltage-based algorithm is observed to provide estimates that are quite close to the actual fault location. Moreover, the average error for all the analyzed cases comes out to be the least for the arc voltage-based method (around 10 to 15%) when compared with other impedance-based fault-location methods.

5

APPLICATION TO SELF-CLEARING AND EVOLVING FAULT LOCATION

In this Chapter, the algorithm developed and validated in Chapters 3 and 4 is applied to temporary faults, with primary focus on sub-cycle faults ($\frac{1}{4}$ to $\frac{1}{2}$ cycle). An attempt to identify and locate the precursor self-clearing faults in distribution networks is demonstrated. This chapter also provides recommendations on the length of the analysis window in the estimation algorithm based on the duration of the fault. Finally, preliminary analysis on phase-shifting (evolving) faults is presented.

Using Arc Voltage for Incipient-Fault Location

Short-duration faults are very common on distribution lines. In general, the duration of the fault determines whether the protective device will operate or not. For example, if the duration of the fault is less than half a cycle, it is possible that the protective device will not operate as the fault self-clears a number of times before turning permanent. There is a very high possibility that these temporary faults go unnoticed until they eventually turn permanent and trip the protective device. This is generally the case if the cable splice is about to fail due to water or moisture entering inside the cable. On the other hand, if the fault duration is more than half a cycle but less than two cycles, it might lead an overcurrent protective device to operate. In such a case, the fault will usually be interrupted, a recloser will close the faulted line, and normal operation will continue.

The arc voltage-based algorithm was applied to temporary faults, and the following results were obtained. The voltage and current waveforms in all the three phases captured at the monitoring station along with the neutral current are shown in Figure 5-1. The location of the incipient fault is 2.04375 Ω from the power quality monitor. The incipient-fault location was determined by way of circuit databases and information from fault event logs.

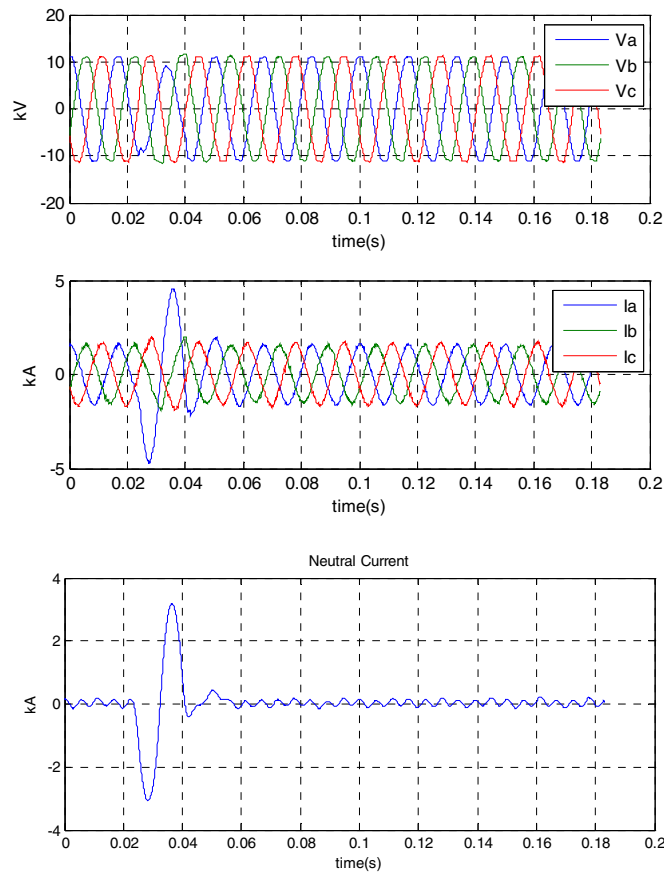


Figure 5-1
Voltage and Current during a Temporary Fault (Top and Middle), Neutral Current (Bottom)

The resistance and reactance estimates from the arc-voltage algorithm are shown in Figure 5-2. The zoomed view for reactance during the fault period is shown in Figure 5-3.

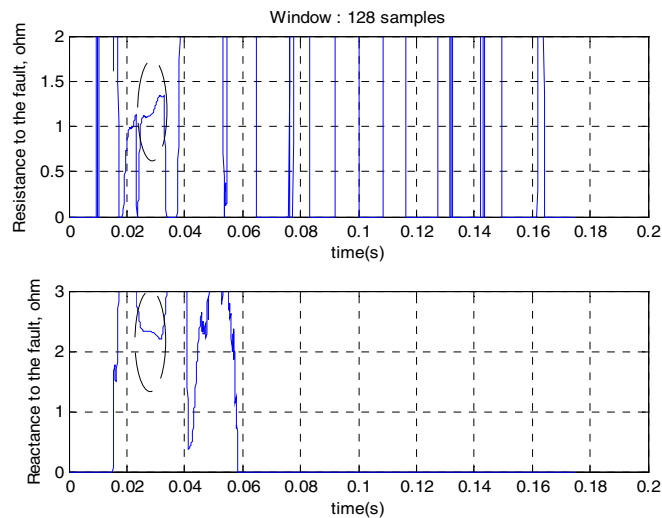


Figure 5-2
Resistance and Reactance Estimate with 128 Samples/Window

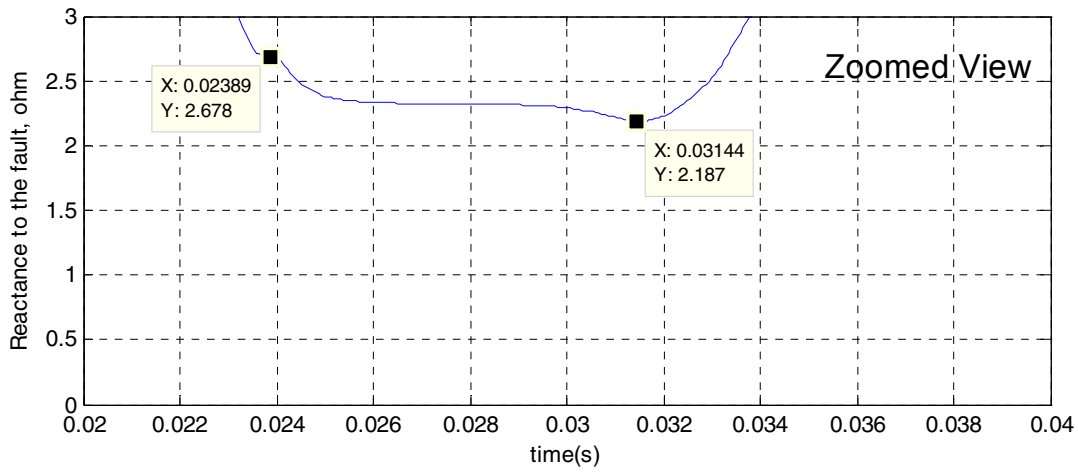


Figure 5-3
Simple Averaging to Find Best Reactance Estimate

Simple averaging is used to find the best reactance estimate to the fault:

$$X_{best} = \frac{2.678 + 2.187}{2} = 2.4325 \, \Omega$$

$$\text{Percentage error} = \frac{2.4325 - 2.04375}{2.04375} = 19.02\%$$

By averaging all the estimates, the best reactance estimate is found to be 2.2962 Ω .

$$\text{Percentage error} = \frac{2.2962 - 2.04375}{2.04375} = 12.35\%$$

Using back substitution, reactance to the fault is found to be 2.187 Ω .

$$\text{Percentage error} = \frac{2.187 - 2.04375}{2.04375} = 7\%$$

The median reactance estimate is found to be 2.3196 Ω .

$$\text{Percentage error} = \frac{2.3196 - 2.04375}{2.04375} = 13.5\%$$

Thus, results close to actual fault location were obtained with back substitution method. It must be noted that varying the number of samples per window will vary the nature of the results during the fault period. In fact, for short-duration faults, determining accurate window length is the key to accurate fault location. Incorrect window length may lead to under- or over-estimation. The effect of window length is presented in the next section.

Effect of Number of Samples in the Window

Voltage waveforms are generally sampled at 256 samples per cycle, whereas current waveforms are sampled at 128 samples per cycle. Hence, for consistency in the algorithm, current is up-sampled so that one cycle (for both voltage and current) corresponds to 256 samples. The current up-sampling is also observed to result in fewer oscillations in the current waveform, leading to better fault-location estimates.

The number of samples in the running data window (window length) has a major impact on the accuracy and quality of the results obtained. Faults differ in their duration, and hence it is very important to identify such faults by using the most appropriate sliding window. The window length, at the same time, should result in noise levels that do not hinder the accurate interpretation of the estimates during the fault period. The temporary fault shown in Figure 5-1 is analyzed in more detail by varying the window length. Figure 5-4 shows a sliding window with 256 samples (i.e., window width is one cycle long) applied to the voltage and current waveforms. The corresponding reactance-to-fault estimate is also shown.

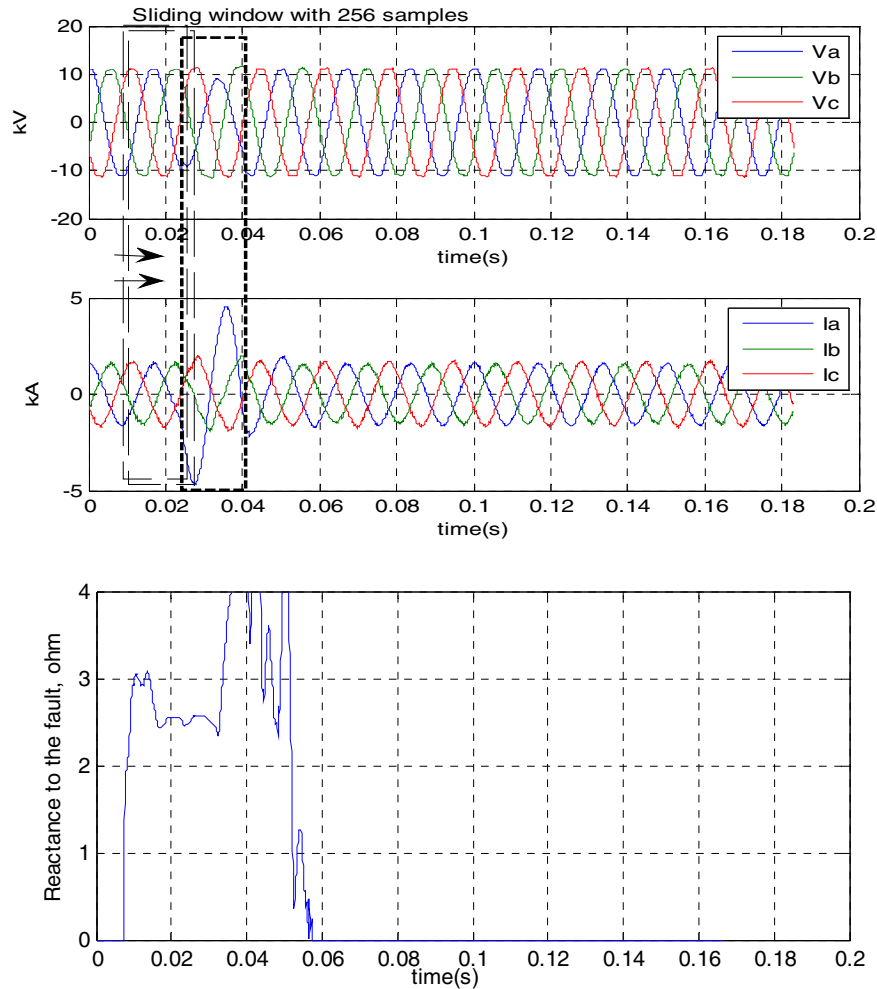


Figure 5-4
Sliding Window with 256 Samples Applied to Voltage and Current Waveforms (Top),
Corresponding Reactance to Fault Estimate (Bottom)

It can be observed from the reactance estimate that the algorithm with 256 samples per window (one cycle long) finds the correct reactance estimate to the fault even before the fault current starts. This is because the sliding window finds the reactance estimate by looking forward one cycle or 256 samples in advance. Hence, the first dotted window in Figure 5-4 is the point where the algorithm starts to identify the fault and tracks the correct value well before the complete faulted current cycle has arrived. This cycle is shown in Figure 5-4 surrounded by a highlighted window. The results corresponding to this highlighted window are expected to be the most accurate. It must be noted that the data points corresponding to the fault inactive period just add random noise to the optimization problem without affecting the results significantly. A similar analysis with a half-cycle window width (128 samples) is presented in Figure 5-5.

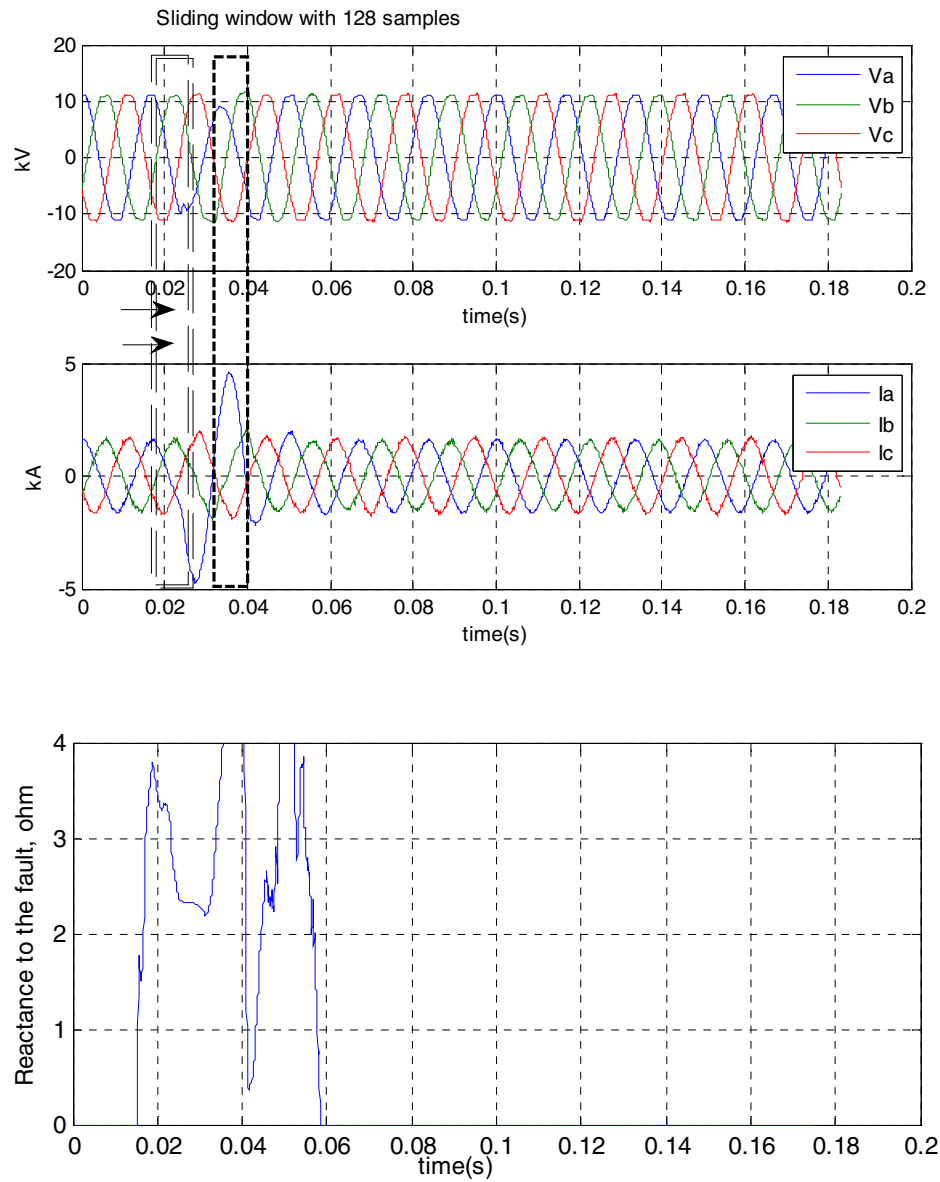


Figure 5-5
Sliding Window with 128 Samples Applied to Voltage and Current Waveforms (Top),
Corresponding Reactance to Fault Estimate (Bottom)

It can be noticed from Figure 5-5 that the algorithm still estimates the results well in advance of the actual fault cycle, but not as early as in the previous case with 256 samples per window. This is because a shorter (half-cycle) window is used, and thus the window looks just 128 sample points ahead. Again, the first dotted window shown in Figure 5-5 corresponds to the first cycle when the algorithm starts giving correct estimates during the fault. The highlighted window is the most appropriate window to calculate the estimates. Figure 5-6 shows the results obtained when a quarter-cycle window (64 samples per window) is chosen.

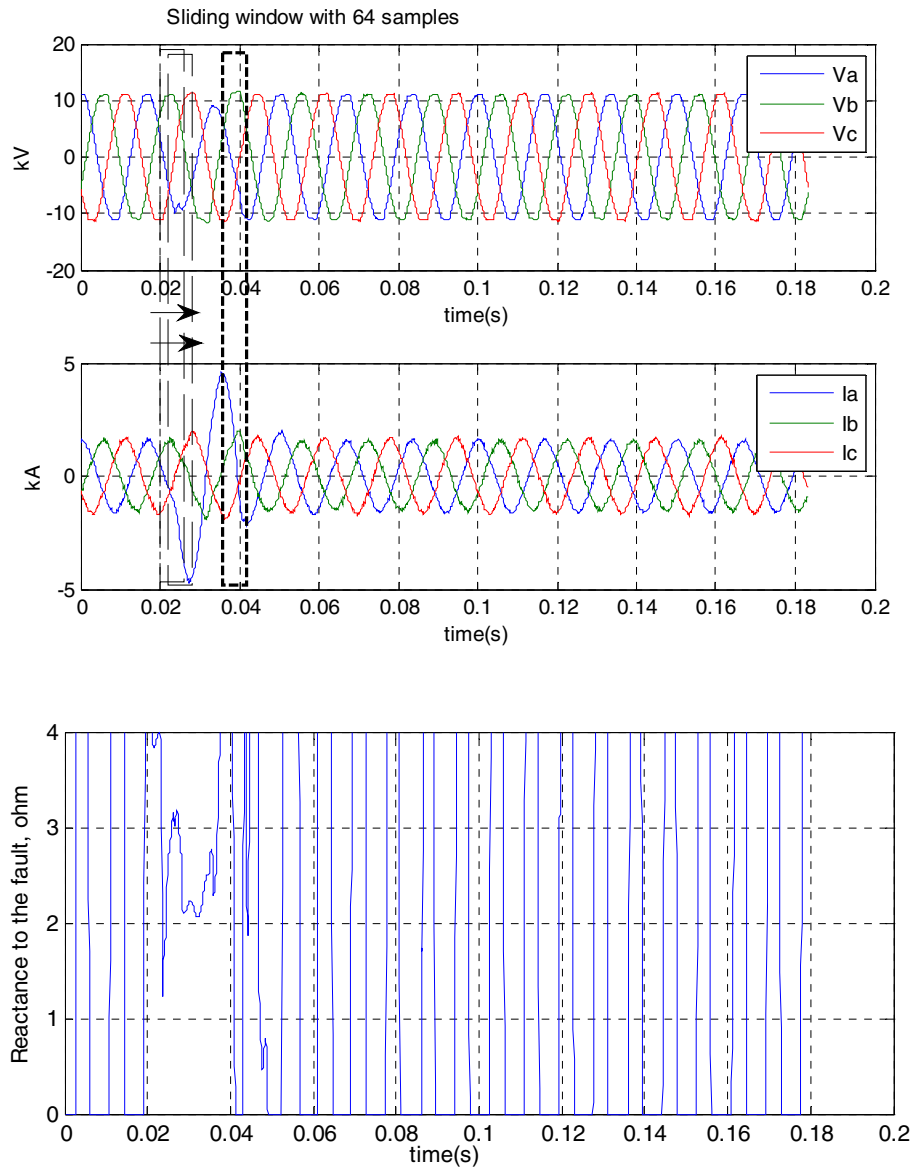


Figure 5-6
Sliding Window with 64 Samples Applied to Voltage and Current Waveforms (Top),
Corresponding Reactance to Fault Estimate (Bottom)

From the above analysis, we conclude that fault duration is the most important factor that determines the width of the analyzing window. Sustained faults having a duration of more than three or four cycles can be easily identified if the window length is less than the duration of the

fault. However, using a very small window introduces a lot of noise in the results, which makes the interpretation of the estimates more difficult. On the other hand, a longer window filters out most of the noise, providing almost constant resistance and reactance estimates during the fault period. Thus, in the case of a sustained fault, better results are obtained if a one-cycle window (256 samples) is chosen.

Similarly, a one-cycle window is observed to provide accurate results for even temporary faults of a duration more than one complete cycle. However, in some cases, sustained faults and temporary faults of a duration more than one cycle are accompanied by frequent glitches every one-half to one-quarter of a cycle. This is shown in Figure 5-7. In such a case, the estimates are not exactly constant and may vary within a wide range of values, making the interpretation difficult. Thus the samples per window need to be adjusted to take into account these short-duration glitches. These glitches can be treated as temporary faults of duration less than one cycle (generally $\frac{1}{2}$ to $\frac{1}{4}$ cycles). A comparatively fewer number of samples per window (128 or 64) are required to identify such short-duration faults. The selection rule used for sustained faults is also applicable to the temporary faults. The rule states that the window length should be selected such that it is always less than or equal to the fault duration.

Saturation may also significantly affect some of the events. Ways to identify and account for saturation are explained in [1]. In general, a longer window length decreases the impact of saturation on the longer event. The tradeoff is that shorter-duration events might get unnoticed.

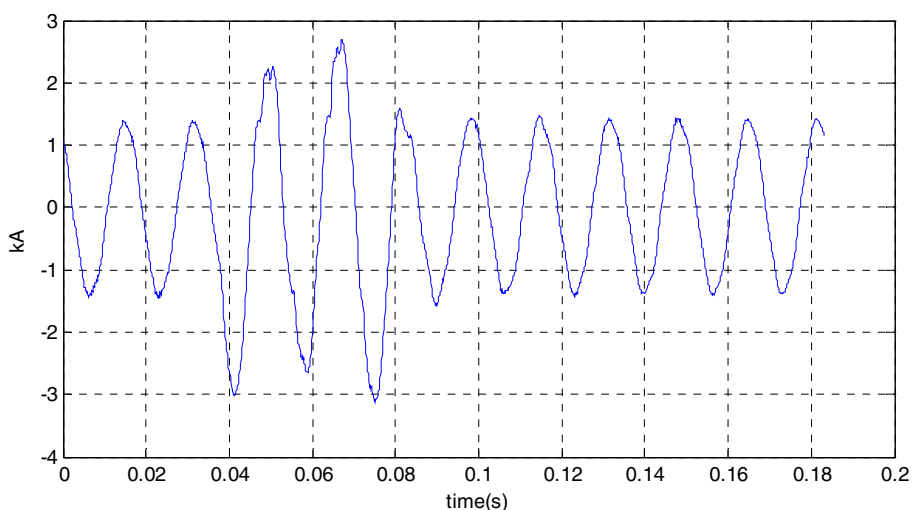
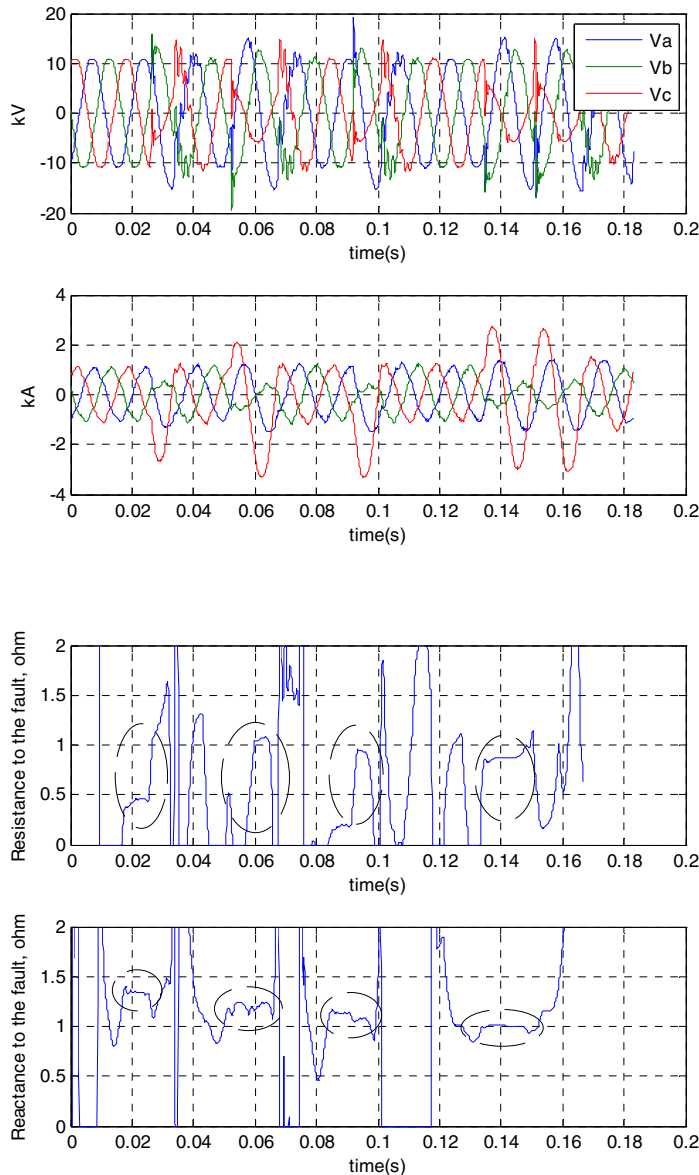


Figure 5-7
Glitches during an Event

More analysis was performed to determine the accurate window length in the case of self-clearing faults. A series of self-clearing events on Phase C are shown in Figure 5-8 (top). This is a characteristic waveform during a cable failure. The frequency of self-clearing events increases over time, and eventually the cable fails permanently.

The application of arc voltage-based algorithm (with 256 samples per window) on these self-clearing events gives the results shown in Figure 5-8 (bottom). It can be seen that the results are consistent for all of the fault events and can be used for pre-location purposes. However, the first

three self-clearing events in Figure 5-8 (top) are not exactly faults of duration of more than one cycle. Thus, using a 256 sample window for these events will overestimate the fault location, leading to erroneous results. Hence, a better analysis is required in this situation.



Series of Self-Clearing Faults

Resistance and Reactance Estimates for Self-Clearing Faults Shown Above

Figure 5-8
Series of Self-Clearing Faults (Top), Resistance and Reactance Estimates (Bottom) with 256 Samples per Cycle Window Length

These varying durations of self-clearing events are evaluated with different window lengths for the arc voltage-based algorithm. The results for each of these self-clearing events obtained by using different window lengths are compared and tabulated in Table 5-1. Event 1 and 3 being $\frac{1}{4}$ to $\frac{1}{2}$ cycle events are expected to be best identified by choosing a window between 64 and 128

samples per window (corresponding to $\frac{1}{4}$ and $\frac{1}{2}$ cycle). This can be achieved in the following two ways.

1. Run the arc voltage-based algorithm with a 64 and a 128 sample window. The best reactance-to-fault estimate obtained from both the cases is averaged to obtain the accurate fault-location estimate for these $\frac{1}{4}$ to $\frac{1}{2}$ cycle events. From Table 5-1, for Self-Clearing Event 1, the average reactance estimate is found to be around 1.067 Ω (using the median estimates). Similarly, for Self-Clearing Event 3, the average reactance estimate is found to be around 1.11 Ω (using the median estimates).
2. Choose a non-conventional window containing 100 data samples. It must be noted that the arc voltage-based analysis is in the time domain, and hence usage of window lengths—which are an exact multiple of two (i.e. 2^k)—is not necessary. Using a 100 or 96 sample window length in the arc-voltage algorithm can provide accurate fault location for events with a duration between $\frac{1}{4}$ to $\frac{1}{2}$ cycle. From Table 5-1, for Self-Clearing Event 1, a reactance estimate using 100 samples per window is found to be around 0.996 Ω . Similarly, for Self-Clearing Event 3, a reactance estimate using 100 samples per window is found to be around 0.985 Ω .

Table 5-1
Comparison of Estimated Reactance to the Fault

Event Detail	Reactance to the fault (Ω)							
	256 Samples (One Cycle)		128 Samples ($\frac{1}{2}$ Cycle)		100 Samples ($\frac{3}{8}$ Cycle)		64 Samples ($\frac{1}{4}$ Cycle)	
	Median	Mean	Median	Mean	Median	Mean	Median	Mean
Self Clearing Event 1 ($\frac{1}{4}$ to $\frac{1}{2}$ Cycle Event)	1.34	1.342	1.257	1.43	0.996	1.08	0.877	0.8047
Self Clearing Event 2 ($\frac{1}{2}$ to 1 Cycle Event)	1.21	1.203	0.9654	0.973	0.9502	0.9659	0.941	0.9415
Self Clearing Event 3 ($\frac{1}{4}$ to $\frac{1}{2}$ Cycle Event)	1.12	1.107	1.275	1.438	0.985	1.1095	0.948	1.454
Self Clearing Event 4 (2 Cycle Event)	1.005	1.01	0.92	0.987	0.9167	0.9922	0.848	0.81

For Self-Clearing Event 2, the fault duration is between $\frac{1}{2}$ to one cycle (but more close to $\frac{1}{2}$ cycle). Thus, either the average of estimates obtained from 128 and 256 samples per window is

taken or an appropriate non-conventional window is selected. Using the average of the 128 and 256 sample windows, the reactance estimate is found to be around 1.087Ω . Using a 150 sample window, the reactance estimate obtained is close to 1Ω .

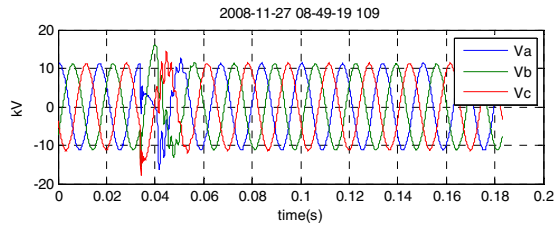
The final self-clearing event has a duration of more than one cycle. Thus, a 256 sample window is expected to work well for this case. Notice from Table 5-1 that the reactance estimate from Table 5-1, where the reactance estimate of 1.005Ω is obtained using a one-cycle long window in the algorithm.

In conclusion, it is better to select a window length on a case-by-case basis. The window width is used for time-domain analysis and not for frequency-domain analysis. Hence, the number of samples in the window width does not necessarily require being a power of two (64, 128, or 256). Instead, an appropriate integer number based on the fault duration can be used as the length of the window. This is where the advantage of accurate fault duration comes into play. Once accurate fault duration is known appropriate, non-conventional window length can be used to accurately locate these short-duration faults. Moreover, for short-duration faults, data points during the fault inactive period add to noise. Thus, using a window greater than the actual fault duration will generally overestimate the results. On the other hand, a very small window length tends to underestimate the results. More cases of non-conventional window length are discussed in the following section.

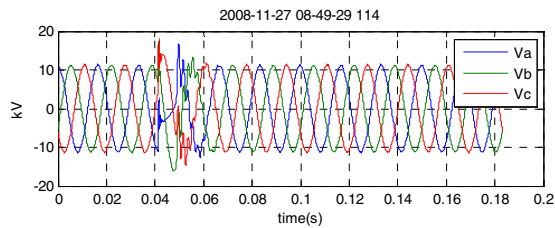
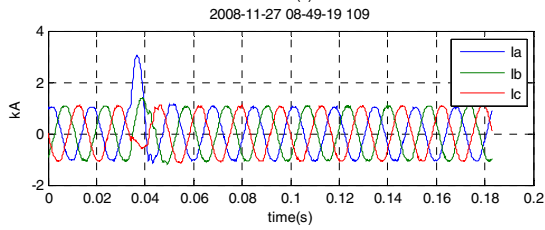
Application to Self-Clearing Faults Leading to a Complete Fault

The most important application of the arc voltage-based fault-location algorithm is locating self-clearing faults before they turn permanent and affect the service continuity. A large waveform database was analyzed to determine such cases. One such case is discussed below.

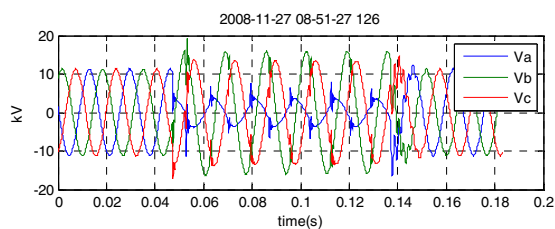
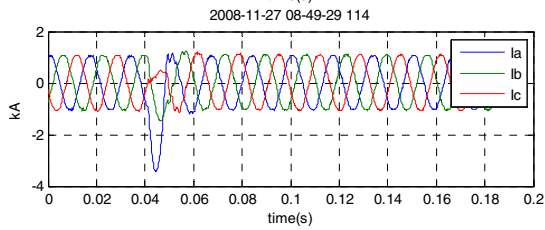
A series of faulted voltage and current waveforms captured by a particular PQ monitor are shown in Figure 5-9. The arc voltage-based algorithm with varying samples per window (generally 64, 100, and 128 samples per window for $\frac{1}{2}$ to $\frac{1}{4}$ cycle blips and 256 samples per window for sustained fault) was applied to all the cases, and the resistance and reactance estimates for each waveform were obtained. Event 1 (top) in Figure 5-9 represents the first precursor self-clearing event that takes place on phase A. It was captured by the PQ monitor on 27th November, 2008 at 08:49:19AM.



Precursor Self-Clearing
Event 1



Precursor Self-Clearing
Event 2



Permanent Fault

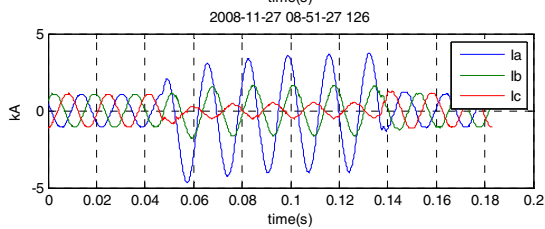
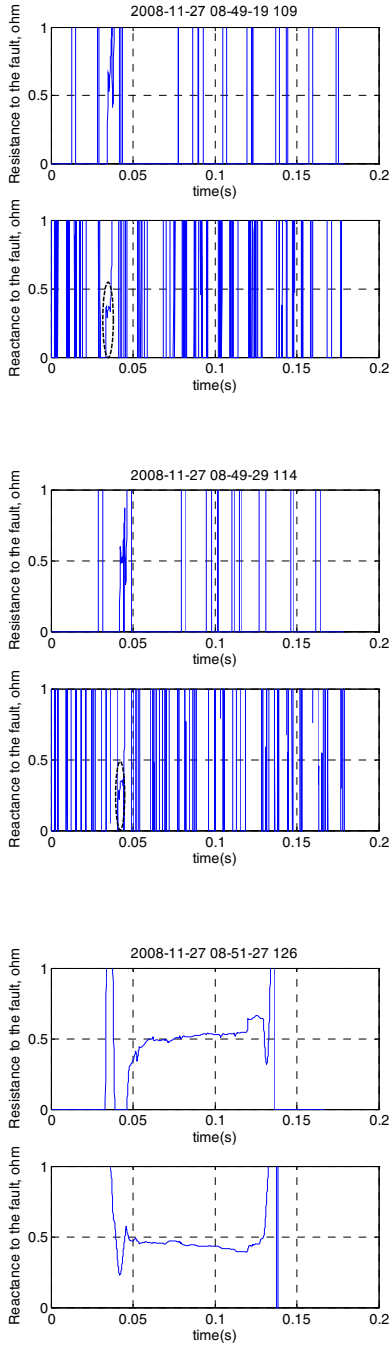


Figure 5-9
Voltage and Current during a Series of Self-Clearing Events Turning into Permanent Fault

The second plot in Figure 5-9 represents one more self-clearing event (Event 2) taking place on the same phase. This event was captured on 27th November, 2008 at 08:49:29AM. It was observed that on the same day (27th November, 2008) a permanent fault was captured by the PQ monitor on phase A at 08:51:27AM. This permanent event is also shown in the third plot in Figure 5-9. The first two self-clearing events can be referred to as *precursor events* leading to this permanent fault. Such an approximation is tested by running the algorithm and observing the reactance to the fault

For all of these events, the corresponding resistance and reactance estimates along with the zoomed view are shown in Figure 5-10. For the first self-clearing event, the lower estimate for the reactance to the fault was found to be around 0.38Ω using 64 samples per window, whereas the upper estimate is around 0.7159Ω using 128 samples per window. Thus the reactance to the fault can be estimated to be around 0.548Ω by simply averaging the lower and upper estimates. As explained earlier, a nonconventional window length can also be used instead of the averaging approach. For the Self-Clearing Event 2, the reactance estimates are between 0.3566Ω and 0.6833Ω , whereas for the permanent fault, the lower and upper limits of the reactance estimate during the fault period are 0.5711Ω and 0.3921Ω , respectively. Using simple averaging, the reactance to the fault comes around 0.482Ω . The final results are shown in Table 5-2.

Resistance and Reactance Estimates for Self-Clearing Events Shown Above



Zoomed View of Corresponding Reactance-to-Fault Estimate

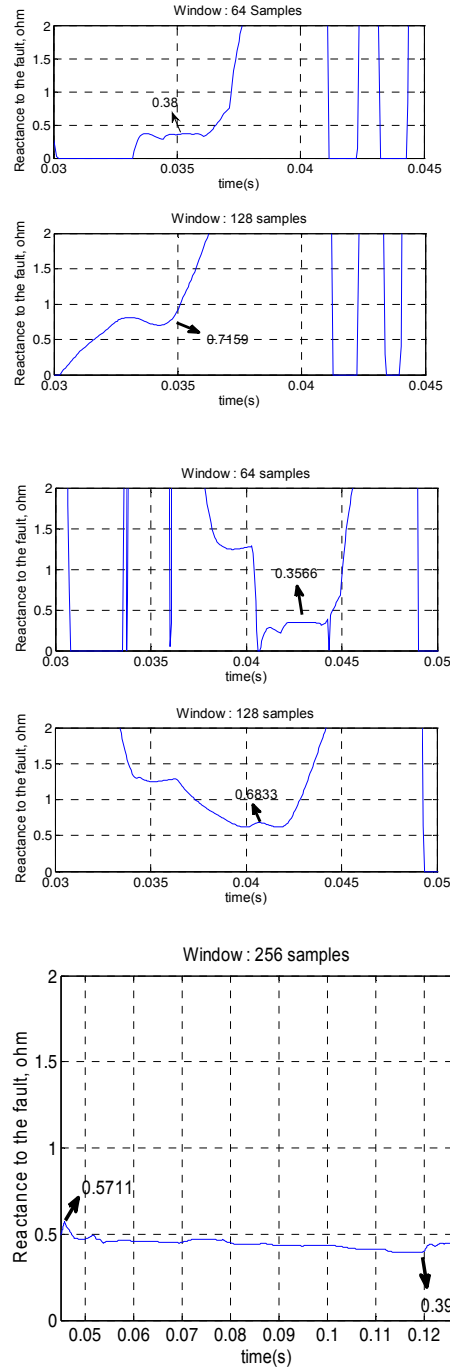


Figure 5-10
Resistance and Reactance Estimate Along with Zoomed Reactance Estimate during the Fault Period for Self-Clearing Event 1 (Top), Self-Clearing Event 2 (Middle), and Final Permanent Fault (Bottom)

For this case, the actual fault distance is unknown. However, assuming the estimated reactance during the permanent fault as the actual location, the percentage errors for the results obtained by the precursor events are given in Table 5-2.

Table 5-2
Results for Locating Self-Clearing Faults

Event Name	Event Date/Time	Reactance-to-Fault Estimate (Ω)	% Error
Self Clearing Event 1	27 th November, 2008, 08:49:19AM	0.548	13.69
Self Clearing Event 2	27 th November, 2008, 08:49:29AM	0.519	7.67
Permanent Fault	27 th November, 2008, 08:51:27AM	0.482	N/A

Thus, the application of an arc voltage-based algorithm on all three waveforms captured at different time instants results in almost the same reactance to the fault (close to 0.5 Ω). It can be concluded that the first two self-clearing events were precursors to the final full fault event. If reactance was calculated only using the first self-clearing event and a lineman was dispatched to patrol the identified location, the eventual permanent fault could have been avoided.

Three more self-clearing event cases are discussed below. Case 1 and Case 2 each consist of two self-clearing faults followed by a permanent failure. Case 3 consists of a single precursor event followed by a sustained fault. The arc-voltage algorithm is applied to all of these cases.

Case 1: Self-Clearing Fault Location – Two Precursors Prior to a Full Fault

At 19:40:16 PM on 12th November, 2008, an SLG precursor event took place on phase B of a distribution feeder as shown in Figure 5-11. The fault duration for this event is around $\frac{1}{4}$ to $\frac{1}{2}$ cycle. Thus, based on the window-length analysis presented earlier, three different window lengths are tried in the arc-voltage algorithm. The corresponding results are shown on the right-hand side. Taking 64 samples per window, reactance to the fault was found to be around 0.156 Ω . With 128 samples in the window, this estimate changed to 0.515 Ω . Trying the nonconventional 100-sample window length, the reactance was found to be 0.3455 Ω (very close to the average of 0.156 Ω and 0.515 Ω).

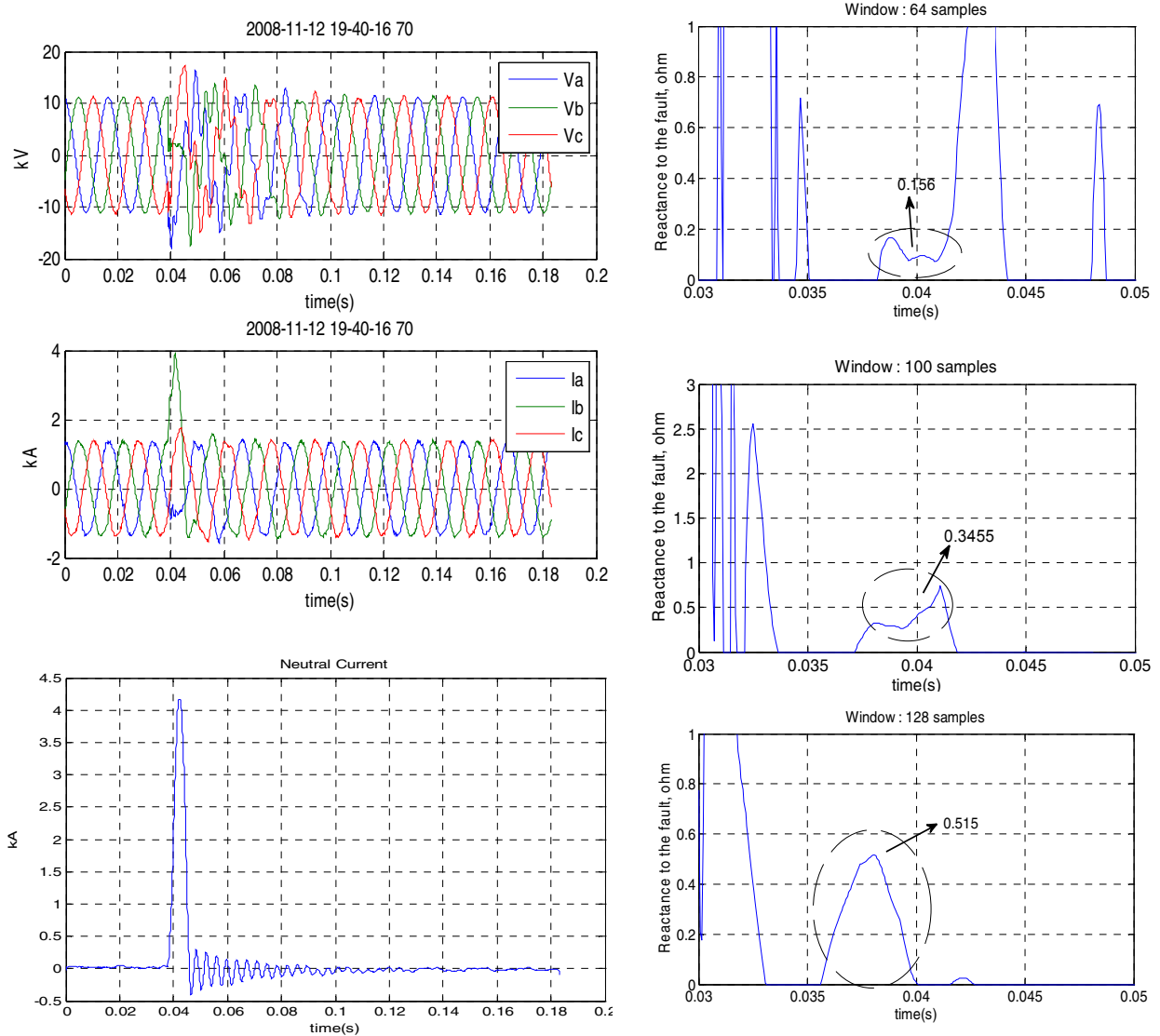


Figure 5-11
Precursor Self-Clearing – Case 1, Event 1

Similar analysis was performed on the second precursor event taking place on phase B on 12th November, 2008 at 21:04:48 PM (around 1.5 hours after the first self-clearing event). The event is shown in Figure 5-12. The reactance estimates corresponding to 64, 100, and 256 samples per window were found to be around 0.163, 0.443, and 0.632 Ω , respectively. Again, the use of 100 sample window results in a reactance estimate very close to the average of the results obtained from 64 and 128 sample window.

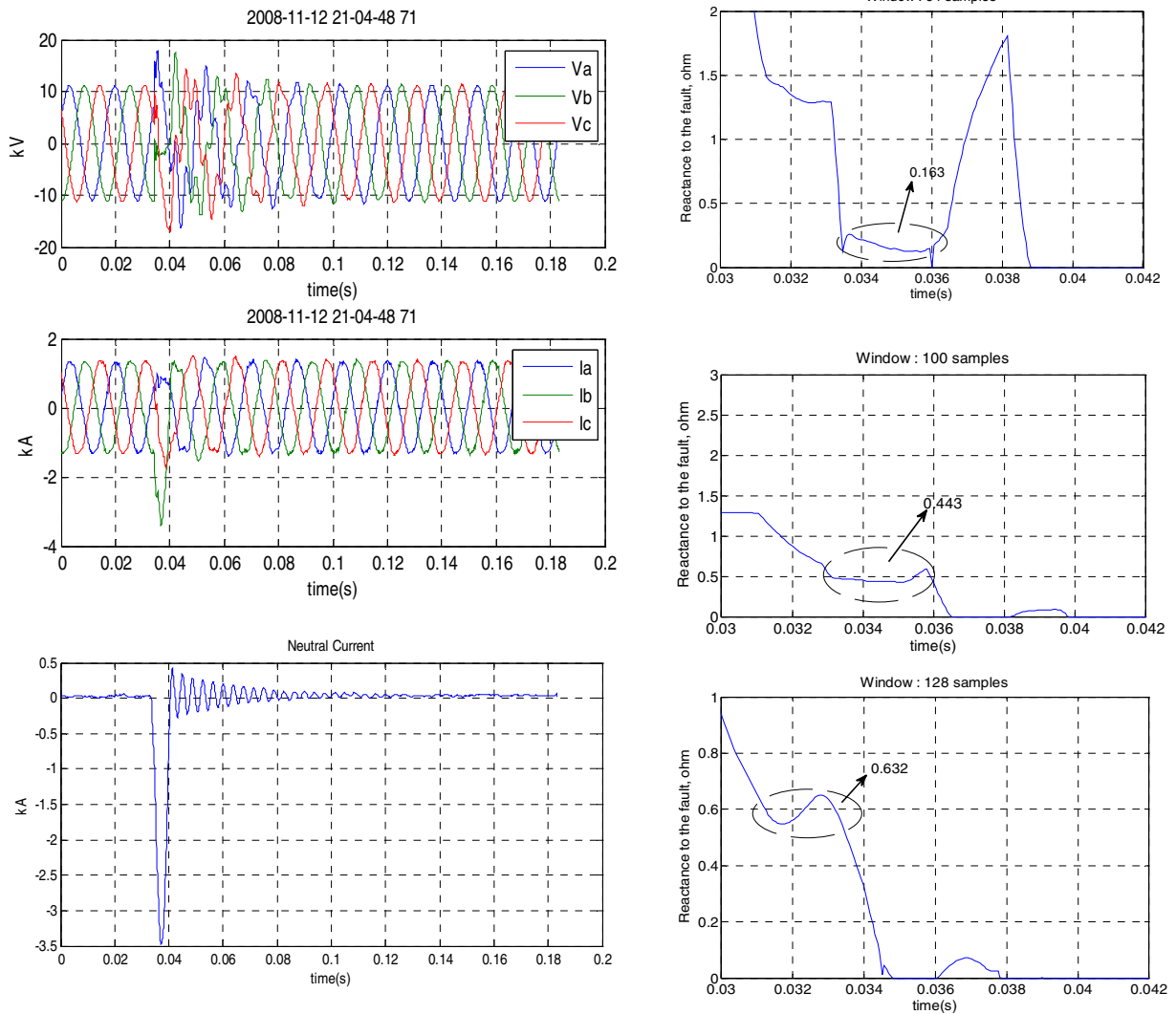


Figure 5-12
Precursor Self-Clearing – Case 1, Event 2

The final permanent fault on phase B took place on 14th November, 2008 at 15:51:00 PM (almost two days after the second precursor event) and is shown in Figure 5-13. This sustained fault was cleared by the operation of an overcurrent protective device. The fault duration was observed to be around 3 to 4 cycles, indicating the use of a 256 sample window. The corresponding reactance estimate is shown on the right side. The reactance estimate is not very stable and varies in a wide range. This can be attributed to the glitches found in the fault current.

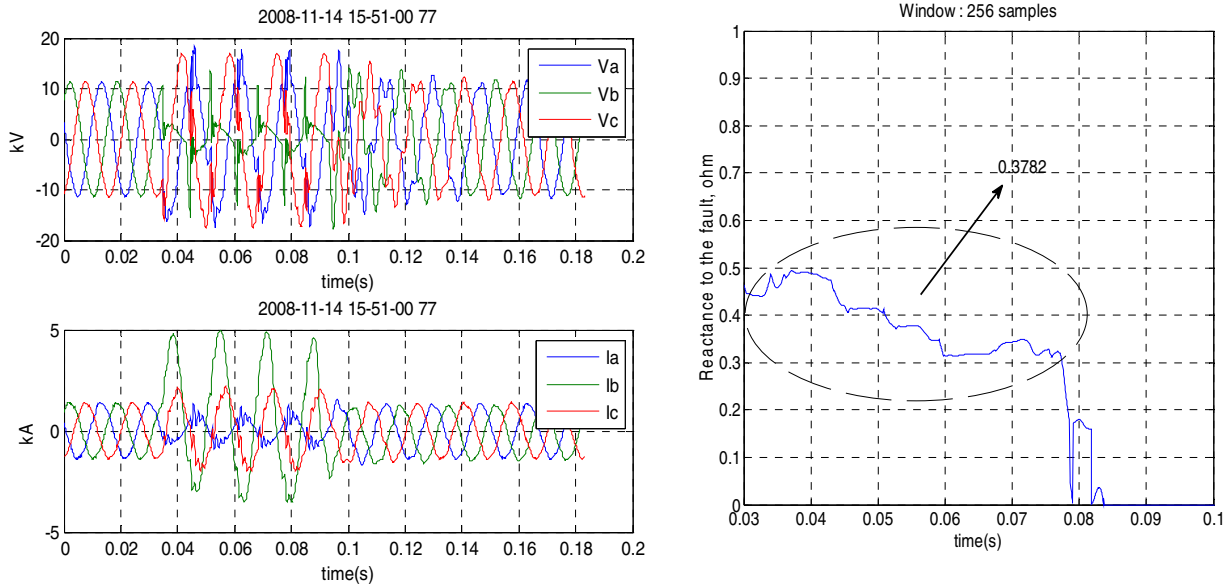


Figure 5-13
Permanent Fault – Case 1

Hence, for the permanent fault, the reactance estimate is observed to be around 0.3782Ω , which is very close to the estimates observed earlier in the case of the two precursor events, 0.345 and 0.443Ω , respectively. Thus, accurate fault pre-location can be achieved using the arc voltage-based fault-distance-estimation algorithm. The results for this case are compared and tabulated in Table 5-3.

Case 2: Another Self-Clearing Fault Location – Two Precursors Prior to a Full Fault

A self-clearing SLG fault taking place on phase B on 11th December, 2008 at 20:44:33 PM is shown in Figure 5-14. The event duration was found to be between $\frac{1}{4}$ to $\frac{1}{2}$ cycles. Thus, three window lengths were tested in the algorithm. Using a 64 sample window yields a reactance estimate close to 2.4032Ω . For 100 and 128 sample window, the reactance estimate increases to 2.566Ω and 3.0411Ω , respectively. From observation, 100 samples per window seems to be the best window length for this event.

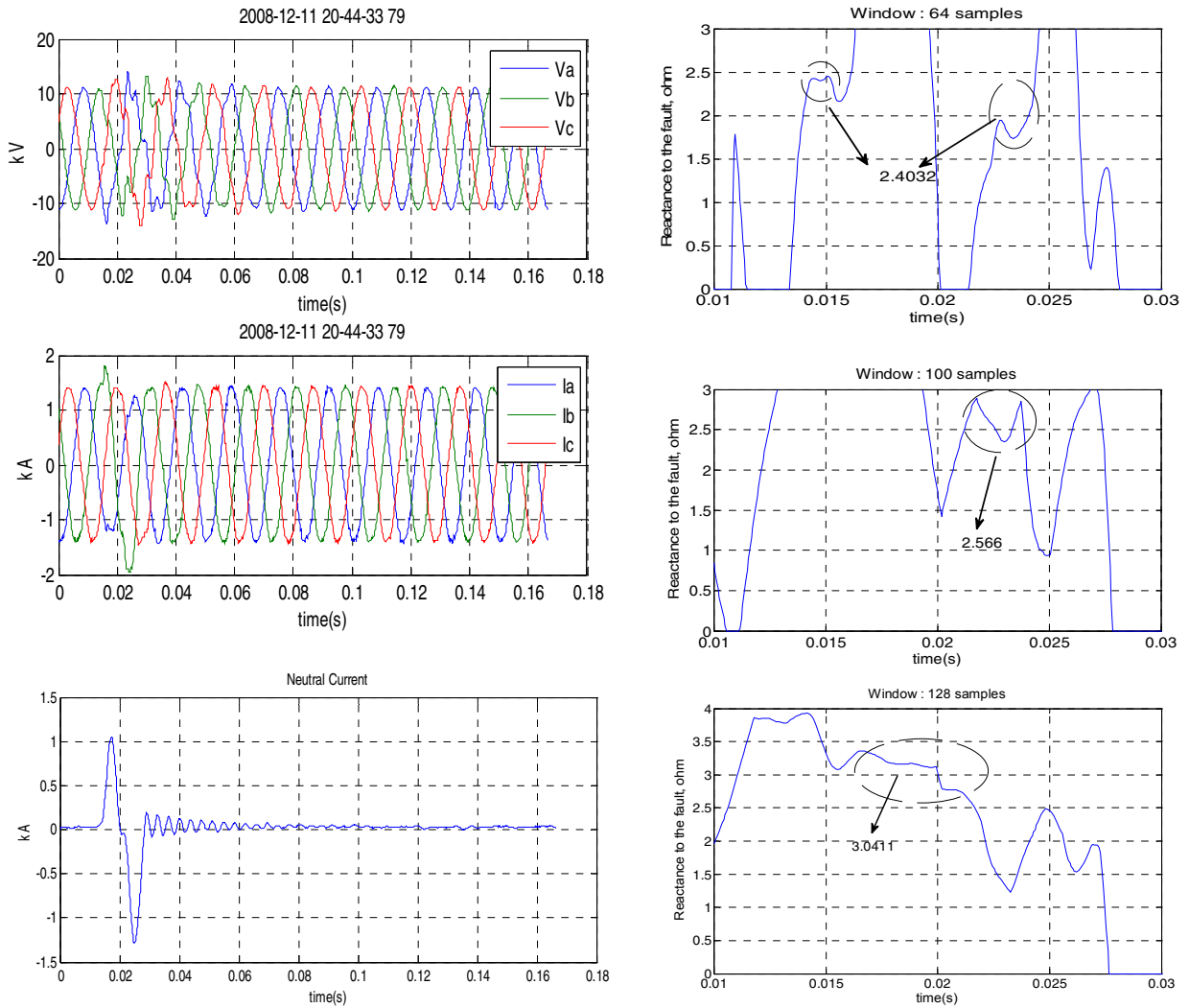


Figure 5-14
Precursor Self-Clearing – Case 2, Event 1

One more precursor event takes place on the same day (that is, on 11th December, 2008) at 20:46:14 PM (3 minutes after the first self-clearing event) and is shown in Figure 5-15. This event is also observed to be present on the same phase (phase B) and has a duration between $\frac{1}{4}$ and $\frac{1}{2}$ cycle. The reactance estimates corresponding to 64, 100, and 256 sample windows are found to be around 2.0367, 2.486, and 2.854 Ω , respectively.

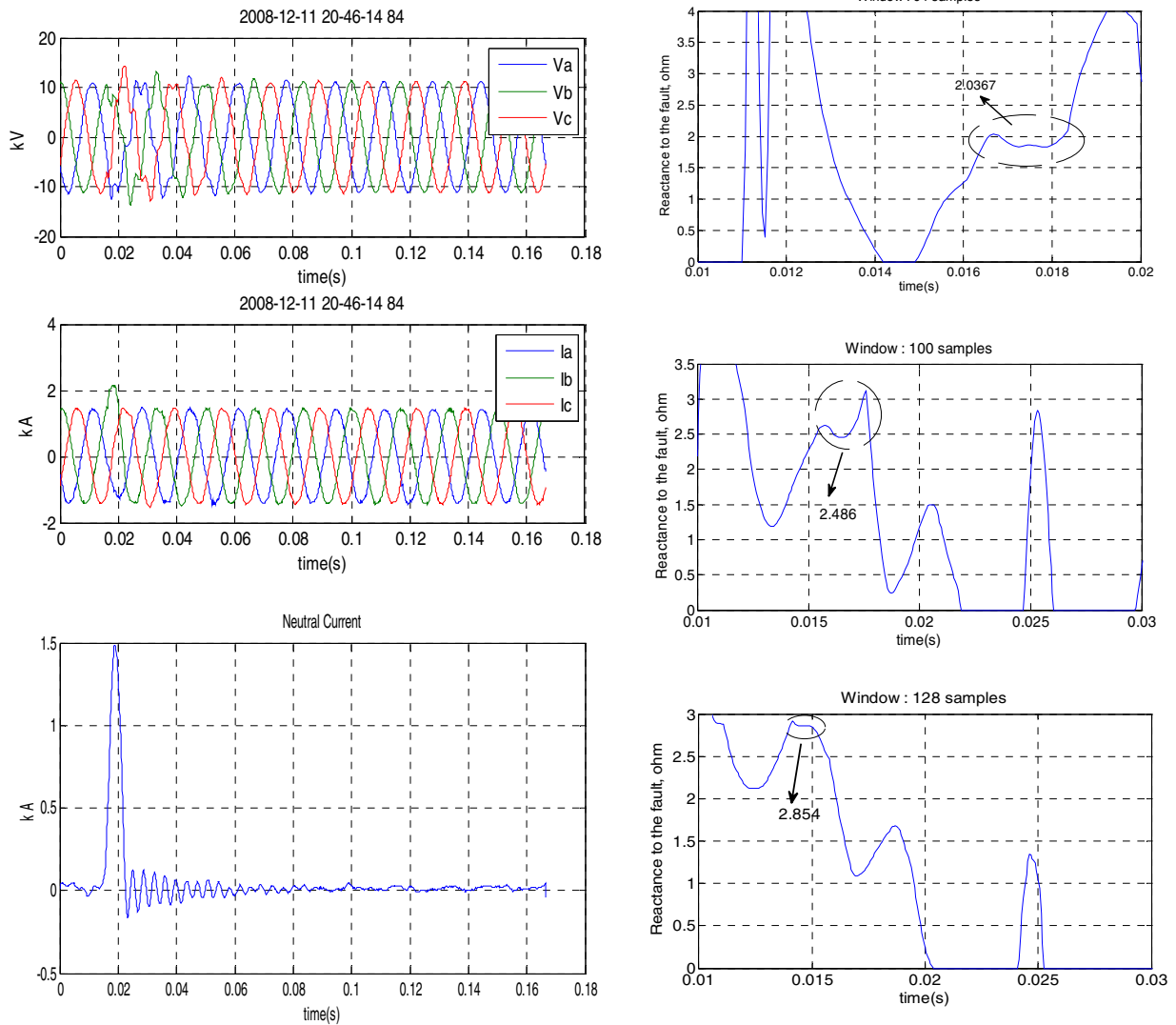


Figure 5-15
Precursor Self-Clearing – Case 2, Event 2

Finally a permanent fault took place on phase B a few seconds after the second self-clearing event (11th December, 2008 at 20:46:21 PM). It is shown in Figure 5-16. Being a longer-duration fault, a 256 sample window was used, and the reactance estimate to the fault was observed to be around 2.7939Ω (quite close to 2.566 and 2.486Ω , respective estimates obtained for the first two self-clearing events). The results for this case are also compared and tabulated in Table 5-3.

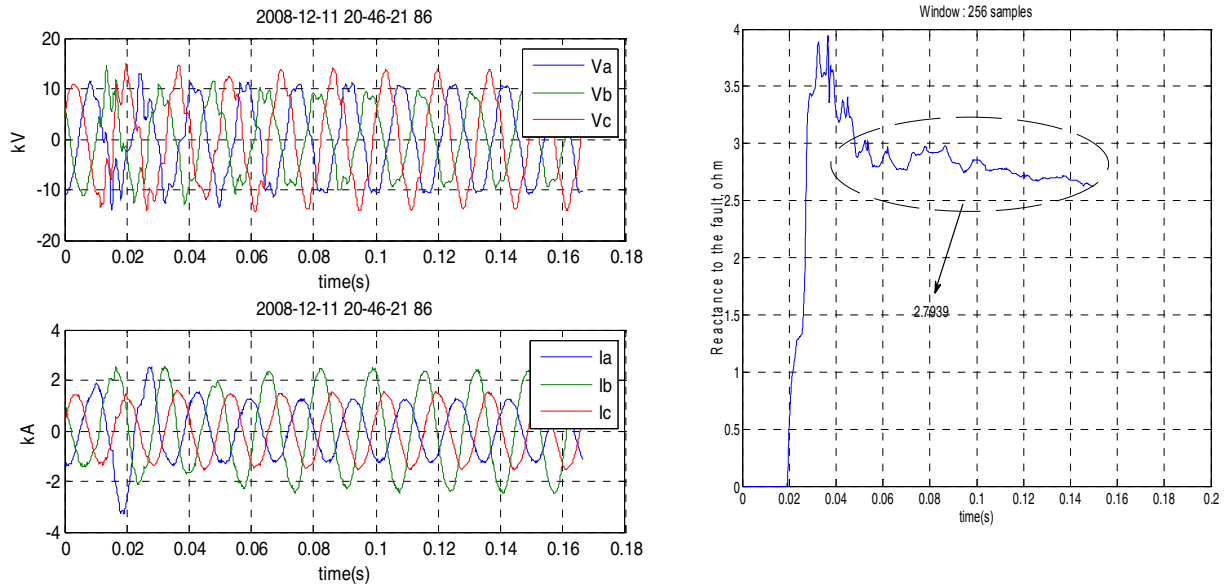


Figure 5-16
Permanent Event – Case 2

Case 3: Self-Clearing Fault Location – One Precursor Event Prior to a Full Fault

A self-clearing SLG fault took place on phase A on 25th December, 2008 at 02:58:21 AM. It is shown in Figure 5-17. The duration of this event is again observed to be between $\frac{1}{4}$ and $\frac{1}{2}$ cycle. Thus applying the same approach, the reactance to the fault is estimated to be around 0.608, 0.694, and 0.8775 Ω , respectively, for 64, 100, and 128 sample window.

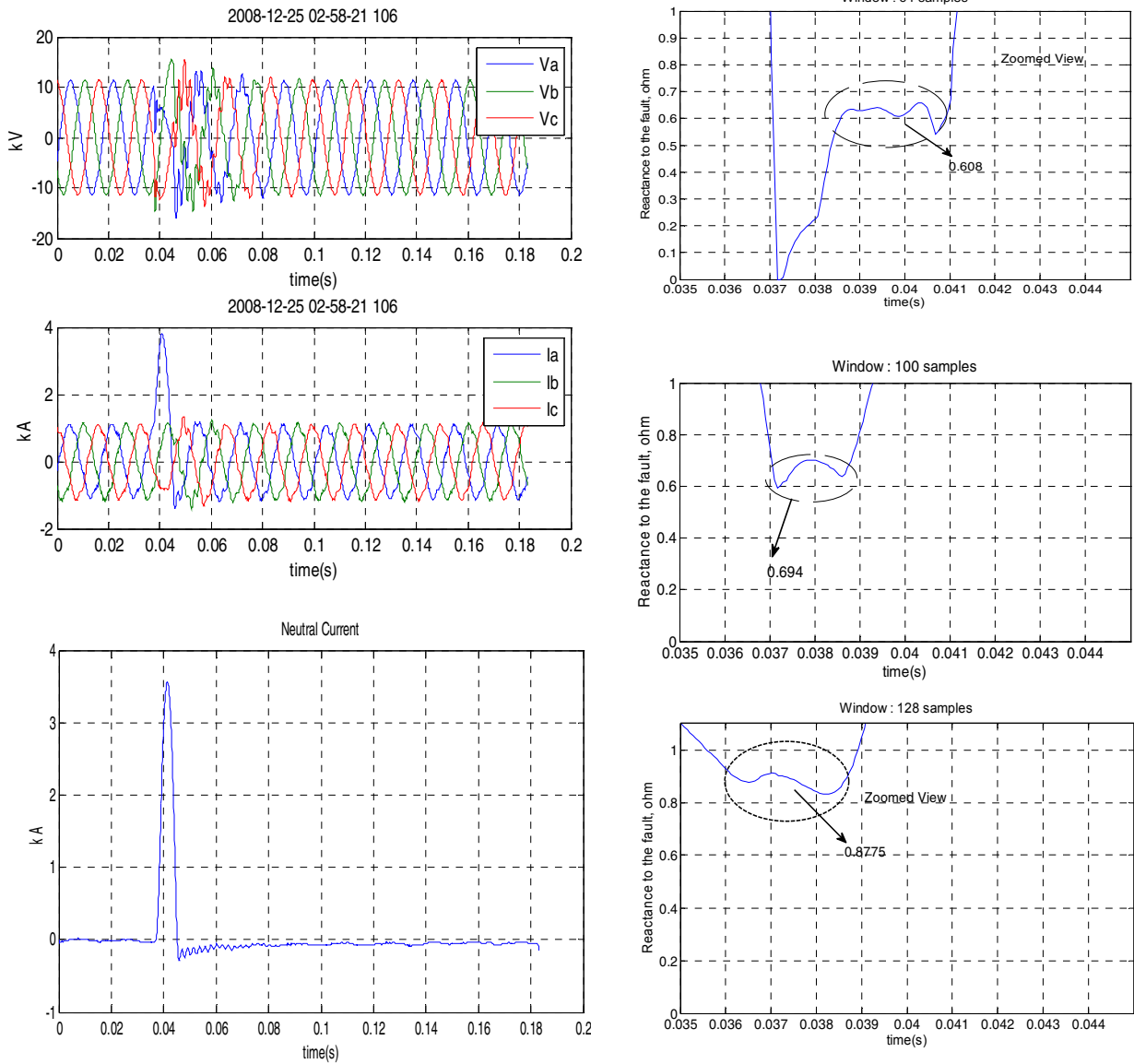


Figure 5-17
Precursor Self-Clearing Event 1

A few seconds after the above self-clearing fault on Phase A, a permanent fault on the same phase followed. It is shown in Figure 5-18. This sustained event occurred on 25th December, 2008 at 02:58:21 AM. Applying a 256 sample window, the reactance estimate is found to be 0.658Ω (very close to 0.694Ω obtained during the precursor event.)

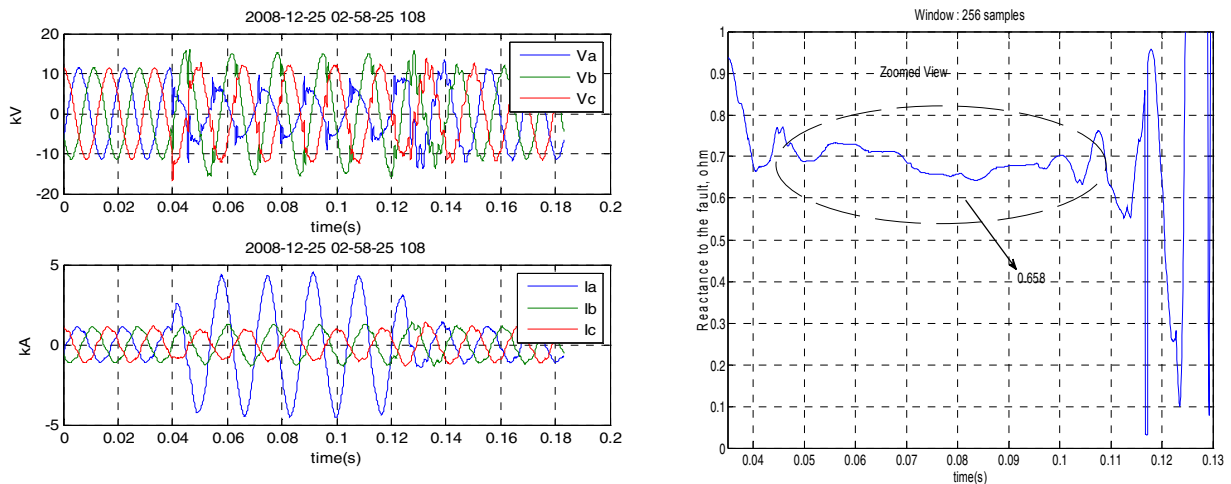


Figure 5-18
Permanent Event

Table 5-3 shows the comparison of incipient fault locations obtained from the three cases discussed above. Average percentage error for all the cases (treating the estimate obtained from the sustained fault as the actual fault location) can be found out very easily. One method is to average all the estimates from the precursor self-clearing faults to find the most probable location of the incipient fault. Weighted average could also be employed by assigning more weight to the most recent self-clearing fault. Another method to find the error is by considering the most recent self-clearing fault as the most probable fault location. The first method was used to find the average percentage error in Table 5-3.

Table 5-3
Comparison of Self-Clearing Fault Results for the Cases Discussed Above

Case No.	Reactance to the Incipient-Fault Location (Ω)			Average Percentage Error (%)
	Self - Clearing Event 1	Self - Clearing Event 2	Permanent Fault	
Case 1	0.3455	0.443	0.3782	4.23
Case 2	2.566	2.486	2.7939	9.59
Case 3	0.694	N/A	0.658	5.47

The proximity of the results clearly validates the application of the arc-voltage algorithm for incipient-fault location. In fact, in all the three cases discussed above, the average percentage error is found to be less than 10%, indicating the accuracy with which self-clearing faults can identify a probable permanent fault location on the distribution system.

Analysis of Evolving Faults

The three phases in a distribution system are in very close proximity, increasing the risk of a single-line-to-ground fault transferring into multiple phases. Such a shifting between faulted phases can be attributed to the presence of the arc. This is explained below in Figure 5-19.

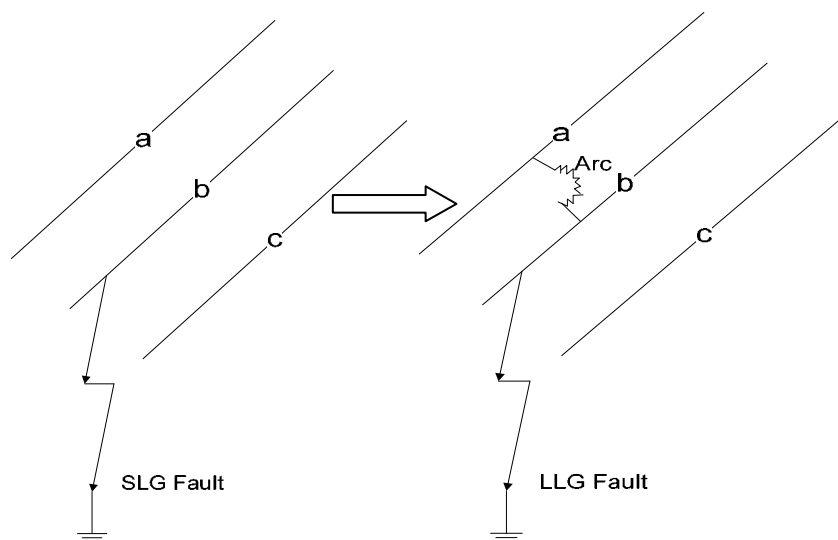


Figure 5-19
SLG Fault Evolving to an Line-to-Line-to-Ground (LLG) Fault

The fault started on a single phase (B), and the arc generated during the event evolves it to a double-line-to-ground fault involving one additional phase (phase A). Voltage and current waveforms along with the neutral current during such an event are shown in Figure 5-20. The neutral current clearly indicates the involvement of the ground during the fault.

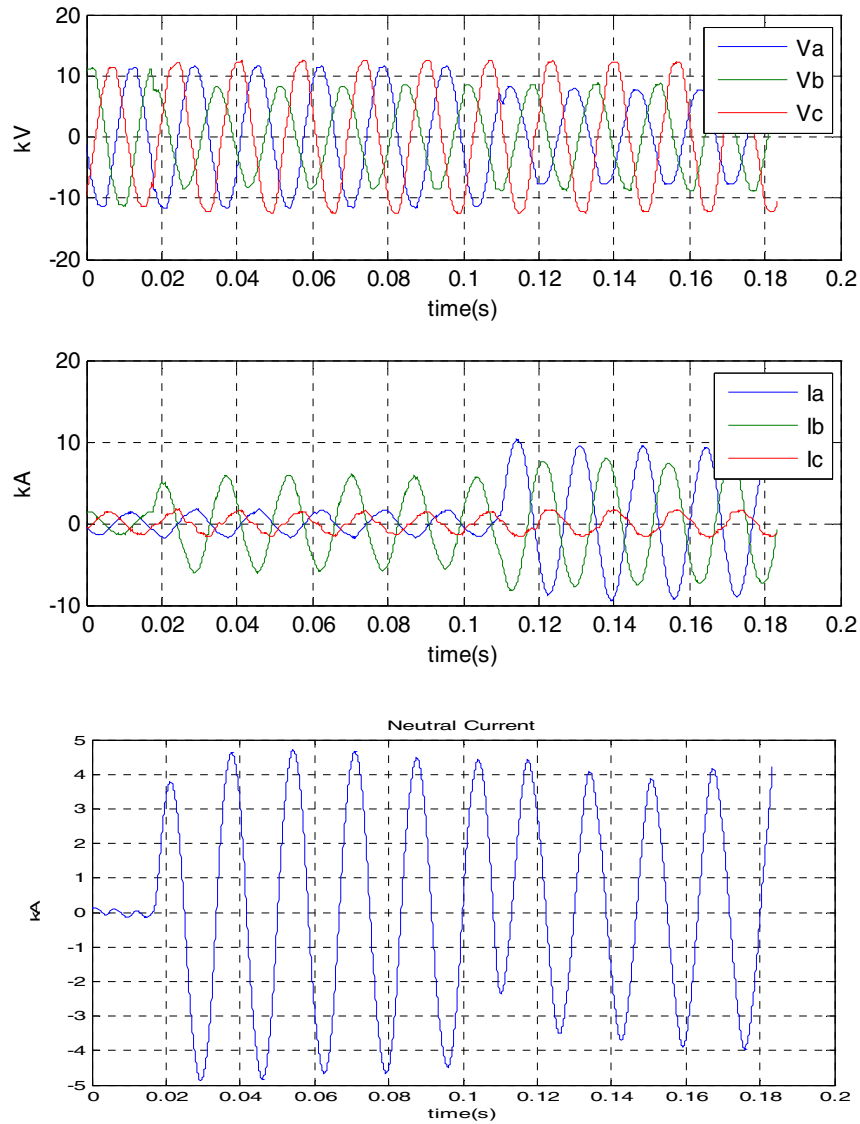
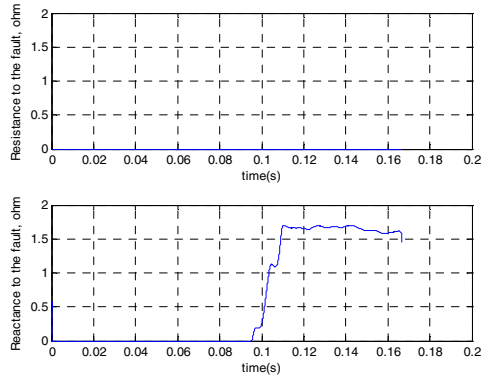


Figure 5-20
Fault That Started as a Single-Line-to-Ground Fault on Phase B and Evolved into a Double-Line-to-Ground Fault (A-B-G)

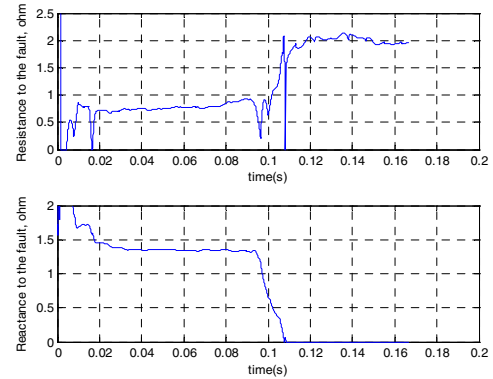
In the following analysis, the arc voltage algorithm is applied to both the phases, A and B, treating the fault as a single-line-to-ground event on the respective phase. Thus, during the LLG fault period, we assume that an LLG fault can be treated as an SLG fault on one of the two involved phases (in our case, the phase that was not initially faulted but gets involved in the fault by the faulted phase). The results from the arc-voltage algorithm are shown in Figure 5-21.

Treating the Fault as an SLG on Phase A



Reactance Estimate :1.66

Treating the Fault as an SLG on Phase B



Reactance Estimate :1.35

Figure 5-21

Comparison of Resistance and Reactance Estimates by Treating an Evolving Fault as an SLG Fault on Individual Phases

It can be seen that the reactance to the fault obtained by treating the A-B-G fault as an A-G fault is quite close to the actual fault location estimated by considering the initial B-G fault period. Another evolving fault case is presented in Figure 5-22.

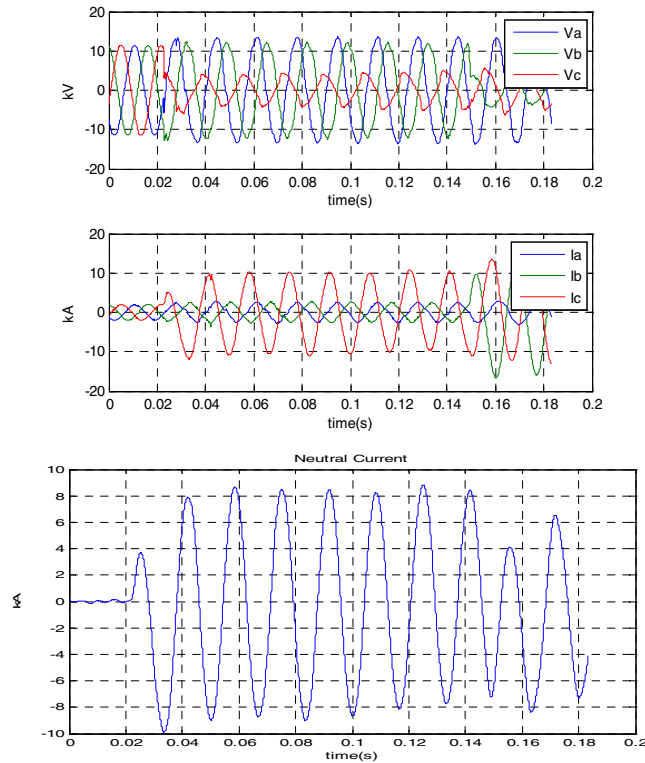


Figure 5-22

SLG Fault on Phase C (C-G) Evolving to an LLG Fault (C-B-G)

The estimates obtained by running the arc voltage algorithm on each of the phases involved during the fault are given in Figure 5-23.

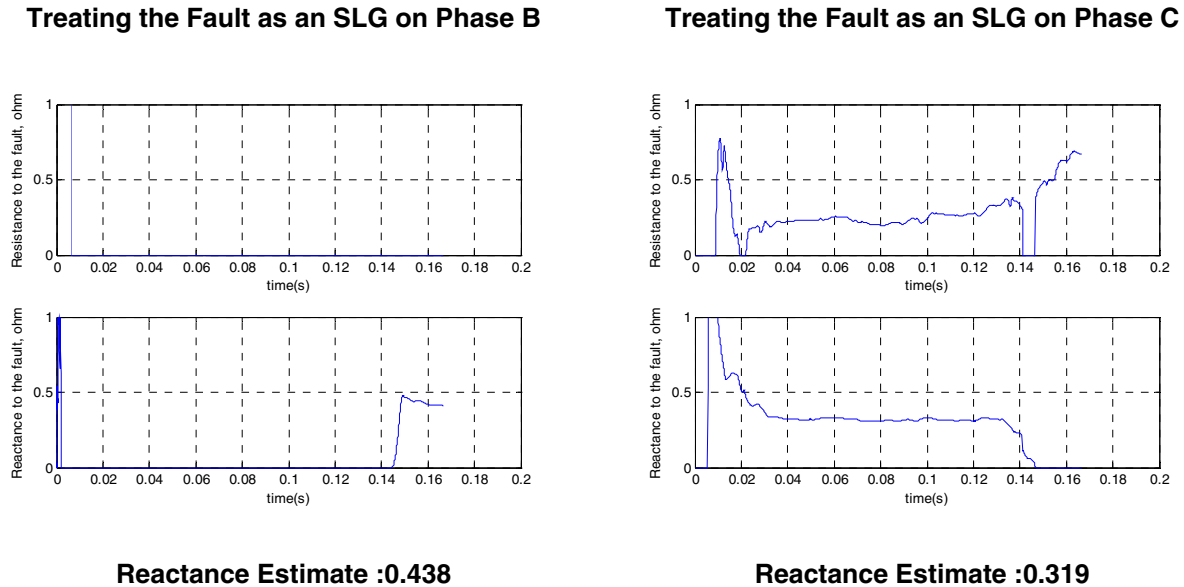


Figure 5-23
Comparison of Resistance and Reactance Estimates by Treating an Evolving Fault as an SLG Fault on Individual Phases

In this case also, the reactance estimate obtained by treating C-B-G as a B-G fault is quite close to the actual estimate obtained by running the algorithm in the C-G period. It must also be noted that treating an LLG fault as an SLG fault always overestimates the reactance to the fault.

Although this approach looks promising, more future work and analysis need to be done before arriving at a final conclusion.

Summary

One of the most important applications of an arc voltage-based algorithm is discussed in this chapter. Most phasor and frequency (spectral) domain-based fault-location methods—being unable to determine location of temporary events—cannot be used for sub-cycle fault events. The suitability of an arc voltage-based algorithm for determining the location of self-clearing fault events, well ahead in time before they turn permanent, is demonstrated. The average percentage error for all the analyzed cases is found to be less than 10%, indicating the accuracy with which self-clearing faults can help in averting permanent faults. The impact of the number of samples per window on the fault-location estimates is discussed in detail. Finally, SLG faults evolving into multi-phase faults are analyzed. Preliminary results prove the applicability of an arc-voltage algorithm for detecting multi-phase evolving faults. Future work involves

investigating multi-phase self-clearing and sustained faults. An arc voltage-based technique will be extended to locate such faults accurately.

6

ARC VOLTAGE-BASED FAULT-LOCATING METHOD CONSIDERING CABLE CAPACITANCES

Introduction

An algorithm to estimate the reactance and resistance to fault based on the voltage and current data recorded at a monitoring site was presented in Chapter 3. This algorithm takes into account the arc voltage in calculating the impedance-to-fault location, while the capacitance of the line is neglected. However, the line capacitance can be significant in the case of underground cables. In this chapter, a new algorithm is proposed to take into account the capacitance of the transmission line or cable along with the resistance and reactance. It is expected that this new algorithm will improve the accuracy of the results obtained.

This chapter begins with the derivation of the arc voltage-based fault-location algorithm considering cable capacitance. The efficacy of the new algorithm is tested using a number of simulation models in PSCAD/EMTDC. The impedance-to-fault estimates from the new algorithm are compared with those from the arc voltage-based algorithm from Chapter 3. This is followed by the application of the proposed algorithm to estimate fault distances using waveforms from the power quality monitors.

Derivation

Consider that a single-line-to-ground fault occurs on an underground cable. The cable as seen from the monitoring site can be represented by an equivalent pi model as shown in Figure 6-1[40].

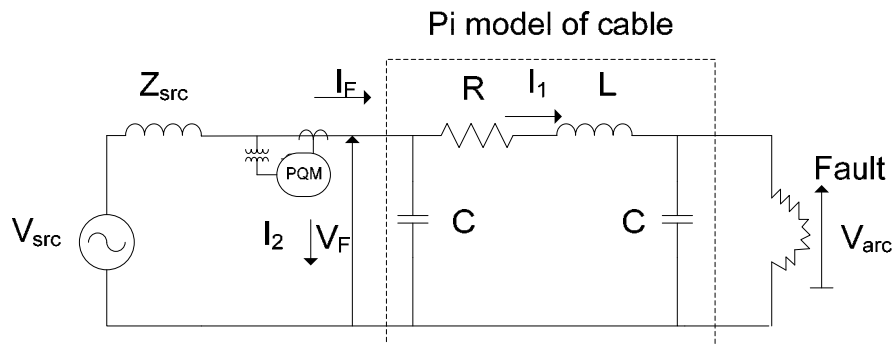


Figure 6-1
Equivalent Pi Model Representation of Cable during a Single-Line-to-Ground Fault

The following notations are used in describing the capacitance estimation in addition to the resistance and reactance estimations:

V_{src} is the equivalent source voltage

Z_{src} is the equivalent source impedance

V_F and I_F are the measured faulted phase voltage and current at the monitoring location

L , R , and C are the cable inductance, resistance, and capacitance, respectively

V_{arc} is the arc voltage at the fault location

I_1 is the current that flows through the line resistance and reactance

I_2 is the current that flows through the capacitance on the left of the pi model

To simplify the analysis, an assumption was made that the fault impedance is very small and hence can be neglected. As a result, the capacitor on the load side of the pi model is essentially shorted by the fault. Now the fault circuit consists only of R , L , and C on the source side, and is depicted in Figure 6-2.

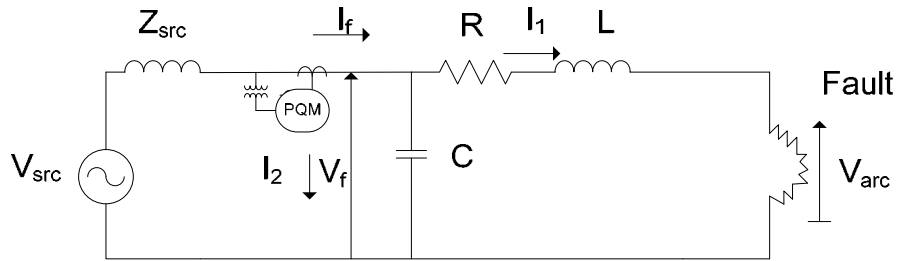


Figure 6-2
Simplified Representation of Cable during a Single-Line-to-Ground Fault

The faulted phase voltage measured at the monitoring station can be written as given in Eq. 6-1, while the currents I_1 and I_2 are represented in Eq. 6-2 and Eq. 6-3, respectively.

$$V_F = R.I_1 + L \frac{dI_1}{dt} + V_{arc} \text{sign}(I_1) \quad \text{Eq. 6-1}$$

$$I_1 = I_F - I_2 \quad \text{Eq. 6-2}$$

$$I_2 = C \frac{dV_F}{dt} \quad \text{Eq. 6-3}$$

By using Eq. 6-2 and Eq. 6-3, Eq. 6-1 can be expanded into Eq. 6-4.

$$V_F = R.I_F - R.C \frac{dV_F}{dt} + L \frac{dI_F}{dt} - L.C \frac{d^2V_F}{dt^2} + V_{arc} \text{sign}(I_F - I_2) \quad \text{Eq. 6-4}$$

The fault current I_F is much greater than the current through the capacitance, I_2 . Hence, only the *sign* of I_F is calculated in the last term, which will not affect the result. The final expression that represents the SLG fault is given in Eq. 6-5.

$$V_F = R.I_F - R.C \frac{dV_F}{dt} + L \frac{dI_F}{dt} - L.C \frac{d^2V_F}{dt^2} + V_{arc} \text{sign}(I_F) \quad \text{Eq. 6-5}$$

Equation 6-5 can be rewritten in a format that makes it easier to solve, as given in Eq. 6-6

$$\begin{aligned} Ax &= b \\ \text{where} \\ a_1 &= I_F \\ a_2 &= -\frac{dV_F}{dt} \\ a_3 &= \frac{dI_F}{dt} \\ a_4 &= -\frac{d^2V_F}{dt^2} \\ a_5 &= \text{sign}(I_F) \\ A &= [a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5] \\ x &= [R \quad R.C \quad L \quad L.C \quad V_{arc}]^T \\ b &= V_F \end{aligned} \quad \text{Eq. 6-6}$$

The above expression is true at every point in the waveform of the current and voltage. Hence, depending on the sampling rate, there will be 128 or 256 equations per cycle, with five unknowns. This is an over-determined system of equation that is solved by using the non-negative least-square-error method. A routine to implement the non-negative least-square-error method is available from off-the-shelf commercial scientific software packages such as Matlab and R [35] [36], to mention just a few. The voltage and current data obtained from the monitoring station is read by the program, and the faulted phase voltage, V_F , is identified. As mentioned in the Chapter 3, the neutral current is used as the fault current. The coefficients a_1 to a_5 are calculated from the voltage and current data. The preprocessing of the voltage and current waveforms is carried out as explained in Chapter 3. In addition, a smoothing spline-based curve fitting differentiation technique is used for finding the derivatives. After running an iterative solution, to minimize the least-square error, only the positive values of V_{arc} , L , C , and R are accepted. Capacitance can be estimated from a_2 and a_4 , and for most of the cases, the value of C obtained from both was nearly the same.

The accuracy of the new algorithm is validated with the help of a simplified time-domain simulation model. The application to real-world data is explored in the subsequent sections of this chapter.

PSCAD Simulation and Validation

A model of a simple 12.47-kV distribution feeder was created in PSCAD/EMTDC on the lines of Figure 6-2. A permanent single-line-to-ground fault occurs on phase A at $t=0.1$ sec. The fault impedance is negligible. The simulation ends at $t=0.2$ sec. The three-phase currents and voltages are sampled at the rate of 256 samples per cycle. The data window used is equal to the sampling rate. The value of the line resistance, R , is $0.35\ \Omega$, while that of the line reactance, X_L , is $0.44\ \Omega$. However, the value of the line capacitance is varied, $C=50\ \mu\text{F}$ and $C=120\ \mu\text{F}$, to verify the proposed algorithm. The PSCAD simulation model for $C=50\ \mu\text{F}$ is shown in Figure 6-3. It should be noted that the simulation model is three-phase and Figure 6-3 shows only the equivalent single-line diagram.

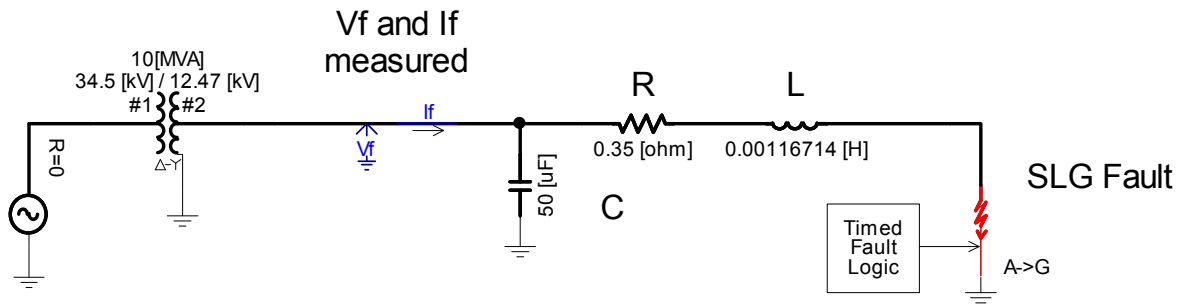


Figure 6-3
PSCAD Simulation of SLG Fault on a Cable

The voltage and current waveforms are shown in Figure 6-4, while the estimate of R , X_L , and C is shown in Figure 6-5.

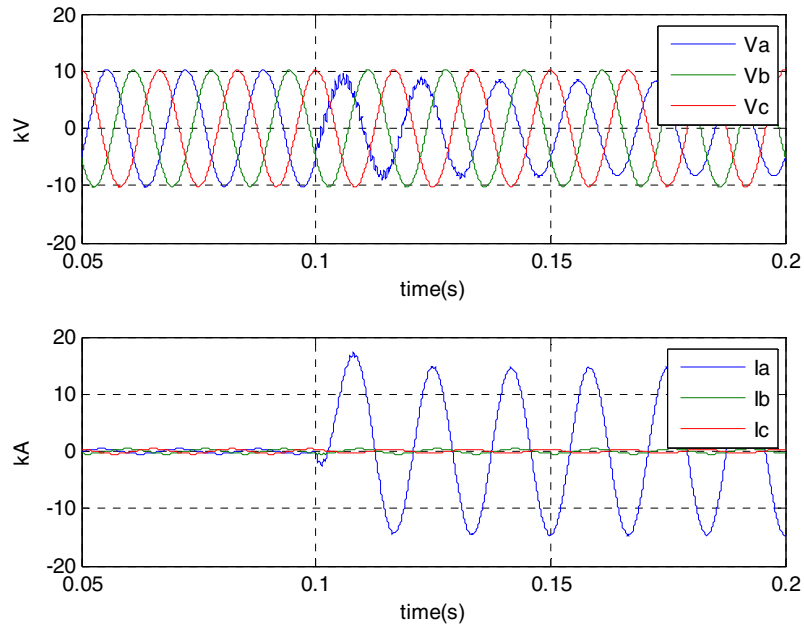


Figure 6-4
Voltage and Current Waveforms for $C=50 \mu F$

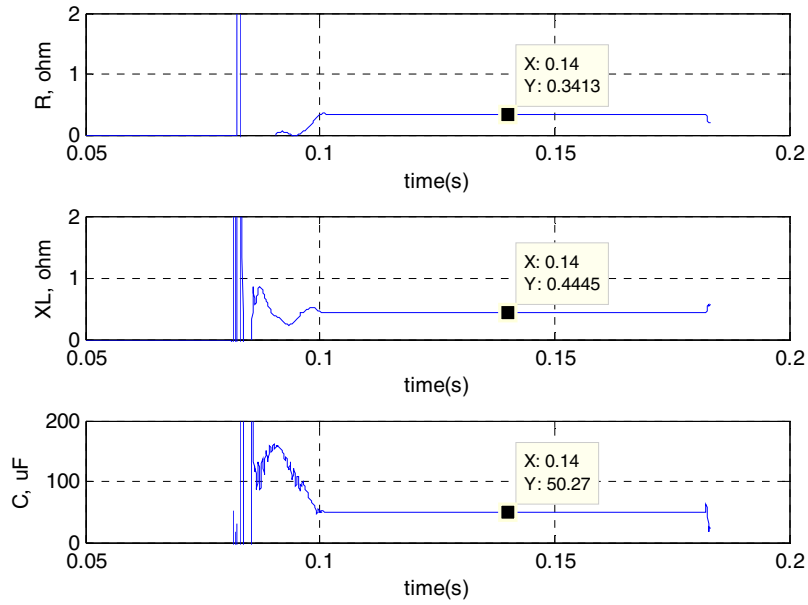


Figure 6-5
Estimated Values of R , X_L , and C for $C=50 \mu F$

It can be seen from Figure 6-5 that the proposed algorithm accurately estimates not only the value of the capacitance but also the value of the line reactance and resistance. The values of $R=0.34 \Omega$, $X_L=0.44 \Omega$, and $C=50.27 \mu F$ are obtained, which are very close to the circuit parameters implemented in the simulation model. Another observation is that the algorithm starts

the estimation process only after the inception of the fault and is applicable only when the fault is in the system. In addition, the estimates of R , X_L , and C are stable during the fault, which indicates that they are reasonably accurate. From the above simulation results it can be concluded that the assumptions made during the development of the algorithm are valid and do not significantly affect the results.

For the case with $C=120\text{ }\mu\text{F}$, it was observed that the algorithm estimates the values of $R=0.331\text{ }\Omega$, $X_L=0.44\text{ }\Omega$, and $C=119.9\text{ }\mu\text{F}$, which match the circuit parameters used in PSCAD simulation. Furthermore, the estimates are stable for the duration of the fault.

In the final simulation, the capacitance value is left unchanged at $120\text{ }\mu\text{F}$; however, the fault starting at $t=0.1\text{ sec}$ has a duration of one cycle. The voltage and current waveforms are shown in Figure 6-6, while the estimate of R , X_L , and C is shown in Figure 6-7. The line parameter estimates have been zoomed around the fault for better visualization.

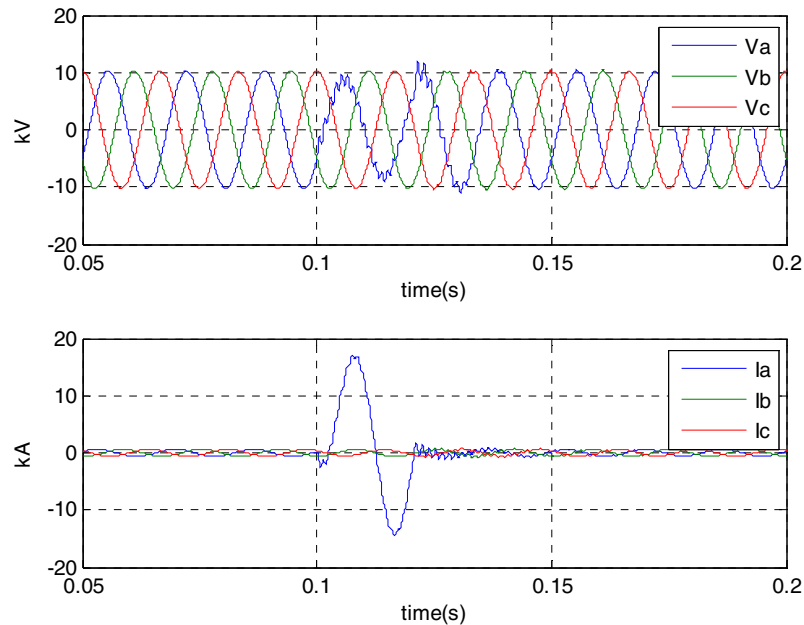


Figure 6-6
Voltage and Current Waveforms for $C=120\text{ }\mu\text{F}$ and Fault Duration of One Cycle

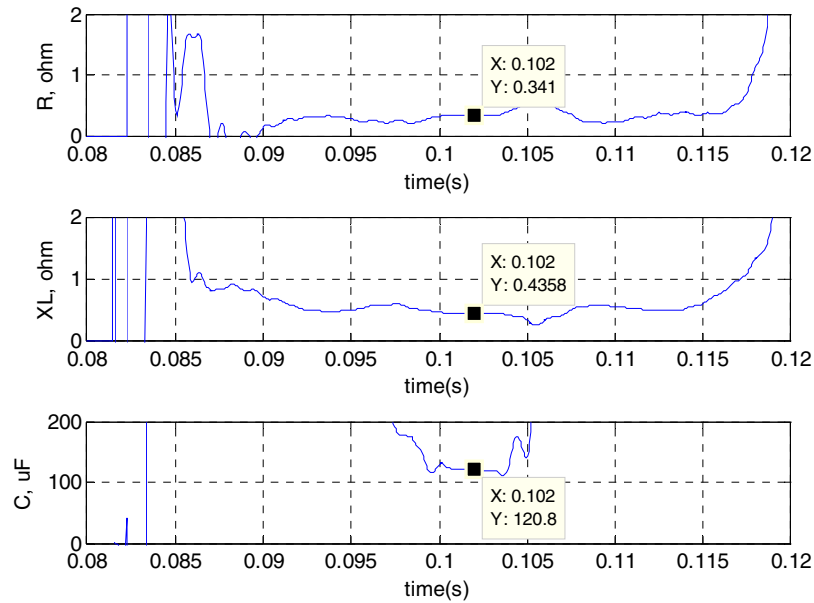


Figure 6-7
Estimated Values of R , X_L , and C for $C=120\text{ }\mu\text{F}$ for a Fault Duration of One Cycle (Zoomed in the Faulted Portion)

It can be seen from Figure 6-7 that the proposed algorithm accurately estimates the value of the capacitance, line reactance, and resistance for the duration of the fault. The values of $R=0.34\text{ }\Omega$, $X_L=0.43\text{ }\Omega$, and $C=120.8\text{ }\mu\text{F}$ are obtained, which are very close to the circuit parameters implemented in the simulation model. Additionally, the estimates are stable for the fault duration.

In the next section, the proposed algorithm is compared with the arc voltage-based fault-location method proposed in Chapter 3 using PSCAD simulation.

Comparison of Fault-Location Algorithms with and without Cable Capacitance Using PSCAD Simulations

The simulation model used in this section to test the proposed algorithm is shown in Figure 6-8. The model is more complex than the one in Figure 6-3, and it resembles the real-world substation arrangement. The load has been modeled using a current source, so that the load current continues to flow during the fault. In addition, a neutral reactor of $1\text{ }\Omega$ is present at the transformer. For this model, the distribution voltage level has been chosen to be 13.8 kV , while the value of the line resistance, R , is $0.15\text{ }\Omega$, and value of the line reactance, X_L , is $0.44\text{ }\Omega$. The three-phase currents and voltages are sampled at the rate of 256 samples per cycle.

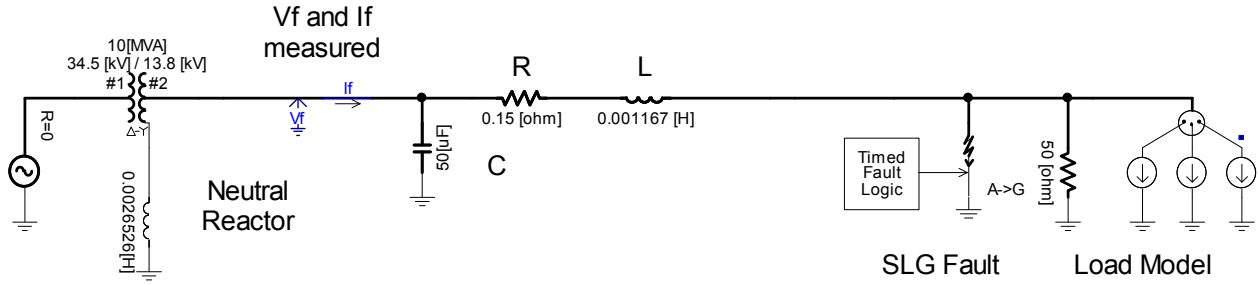


Figure 6-8
PSCAD Simulation Model for Comparison of Fault-Distance-Estimation Algorithms

A single-line-to-ground fault is simulated on phase A at $t=0.089$ sec and lasts one cycle. The three-phase voltage and current waveforms are shown in Figure 6-9.

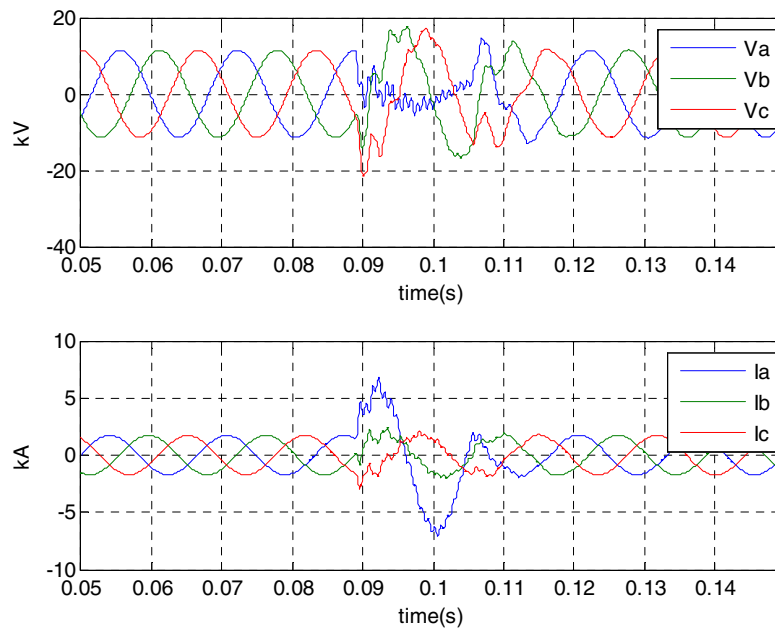


Figure 6-9
Voltage and Current Waveform of PSCAD Simulation: One-Cycle Fault

The two distance-estimation algorithms are applied to the data obtained from the simulation. The window length used in the implementation of both algorithms is 128 samples, according to the discussion in Chapter 1. The reactance to fault from the monitoring station was estimated using the arc voltage-based algorithm from Chapter 3 and is shown in Figure 6-10. The results obtained from the algorithm proposed in this chapter are shown in Figure 6-11. The plots are zoomed near the fault period for better comprehension.

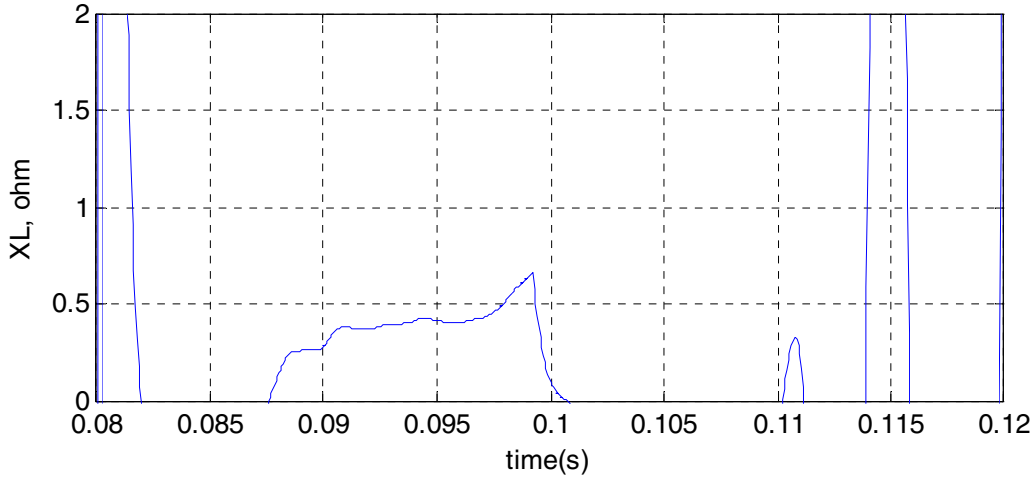


Figure 6-10
One-Cycle Fault: Reactance to Fault from the Arc-Voltage Distance-Estimation Algorithm without Capacitance

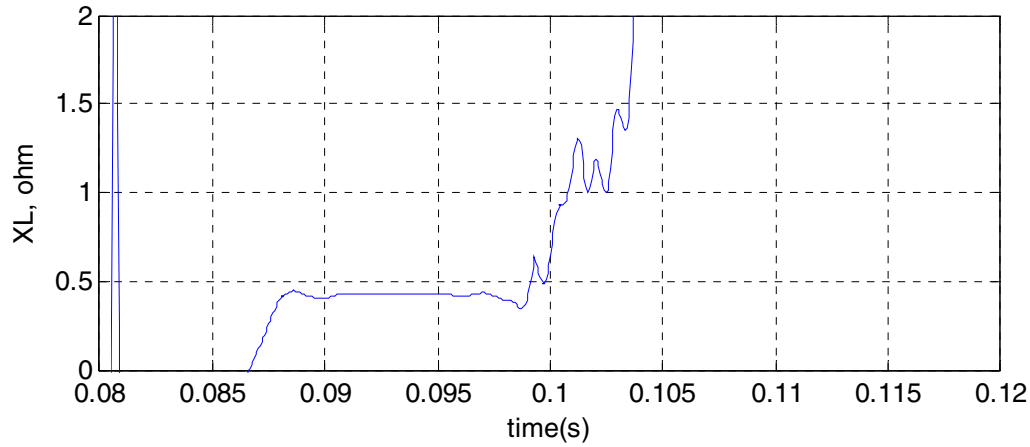


Figure 6-11
One-Cycle Fault: Reactance to Fault from the Arc-Voltage Distance-Estimation Algorithm with Capacitance

The median value of the reactance to fault obtained from the arc voltage-based algorithm is $X_L = 0.3757 \Omega$ (-14.6136% error). On the other hand, the algorithm using capacitance estimates a median of $X_L = 0.4274 \Omega$ (-2.863% error). As described in Chapter 3, one of the techniques to obtain the best estimate of the reactance to fault is by taking the median of all the estimates during the fault. The median method has been employed for this example. It can be seen that the fault-distance algorithm considering the cable capacitance has much less error in the estimate of reactance to fault compared with the traditional method.

For the next case, the single-line-to-ground fault simulated on phase A has a duration of one-half cycle. The three-phase voltage and current waveforms are shown in Figure 6-12.

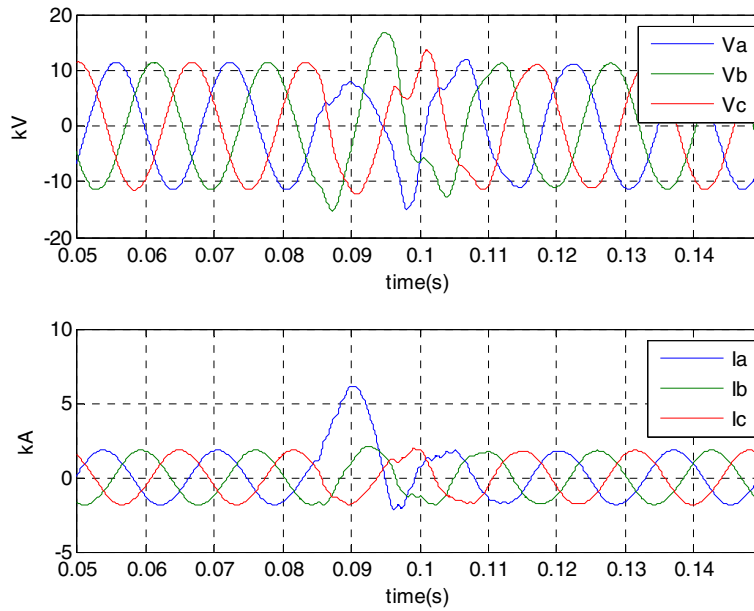


Figure 6-12
Voltage and Current Waveform of PSCAD Simulation: Half-Cycle Fault

The window length used for both algorithms is now 64 samples. The value of reactance to fault from the monitoring station estimated by the original arc-voltage algorithm is shown in Figure 6-13. The result obtained from the algorithm proposed in this chapter is shown in Figure 6-14.

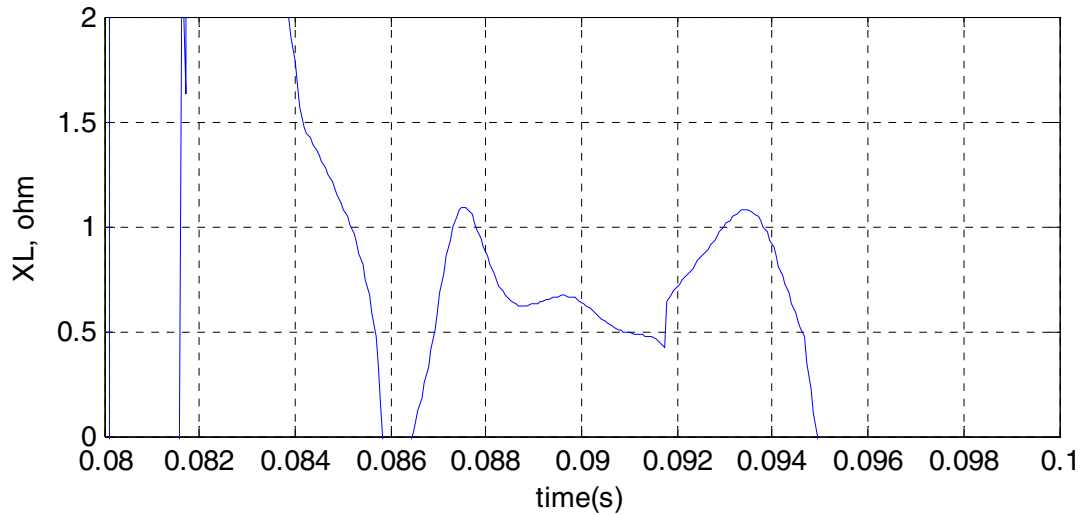


Figure 6-13
Half-Cycle Fault: Reactance to Fault from the Arc-Voltage Distance-Estimation Algorithm without Capacitance

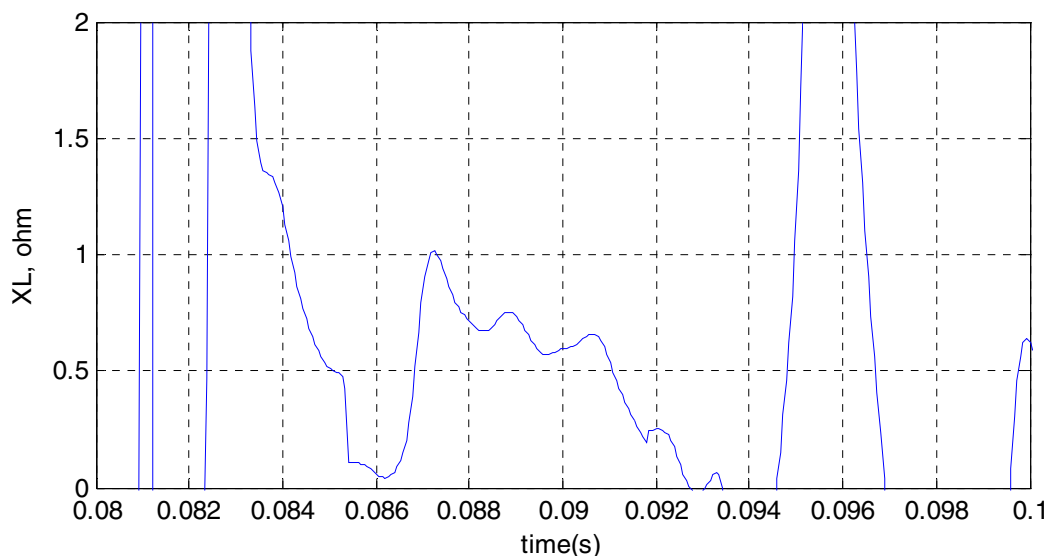


Figure 6-14
Half-Cycle Fault: Reactance to Fault from the Arc-Voltage Distance-Estimation Algorithm with Capacitance

The median value of the reactance to fault obtained from the arc voltage-based algorithm is $X_L = 0.6651 \, \Omega$ (51.1591% error). On the other hand, the algorithm using capacitance estimates a median of $X_L = 0.4246 \, \Omega$ (-3.5% error). In this example as well, the best estimate of the reactance to fault is obtained by using the median method described in Chapter 3. Additionally, the fault-distance algorithm considering the cable capacitance has a more accurate estimate of reactance to fault compared with the traditional method.

The application of this proposed algorithm is now demonstrated using the actual data recorded by power quality monitors from participating electric utility companies.

Application of Fault Location Algorithm to Field Measurement Data

The layout of the distribution network for this example consists of a substation, which has a number of distribution feeders connected to it. A power quality monitor is located at the substation. From the line-charging kvars of the feeders, the average capacitance was calculated to be $8.4 \, \mu\text{F}$. A few cases of faults recorded by the power quality monitor on the substation are analyzed in this section, and the capacitance of the line is estimated using the algorithm proposed.

Figure 6-15 shows the voltage and current waveform for the first case of a fault recorded at the substation. The estimated value of the capacitance is shown in Figure 6-16 and is found between $4 \, \mu\text{F}$ and $5 \, \mu\text{F}$.

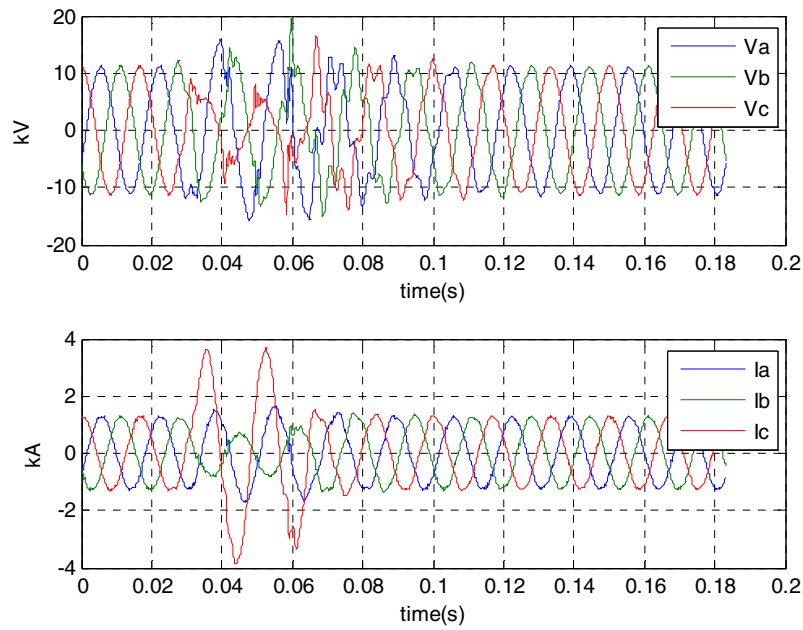


Figure 6-15
Voltage and Current Waveform at Substation: Case 1

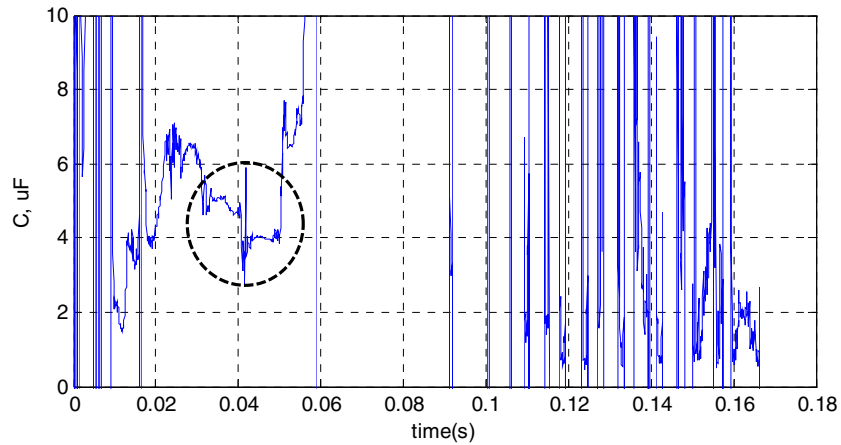


Figure 6-16
Estimated Capacitance: Case 1

Four other fault cases recorded by the monitor at the substation were analyzed (waveforms not shown), and the values of the capacitance were found to be 6 μF , 2.5 μF , and 1.5 μF , respectively. Two of these values are rather inaccurate, while the first is relatively accurate and close to the known capacitance value of 8.4 μF . Hence, this example proves that the algorithm may work in certain conditions. It needs more work to improve the accuracy of the capacitance estimate.

Another important validation that needs to be done is to check whether this new algorithm accurately estimates the value of the reactance (X_L) and resistance (R) to fault. Figure 6-17 shows the voltage and current waveforms of a cable fault on a distribution feeder at another location in

the same utility. The estimated reactance to fault (X_L) and resistance to fault (R) are shown in Figure 6-18, while the estimated capacitance is shown in Figure 6-19.

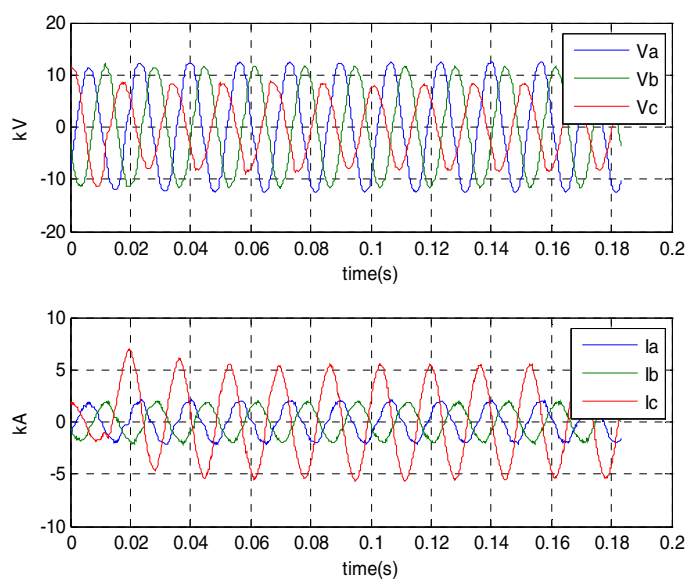


Figure 6-17
Voltage and Current Waveform for Cable Fault

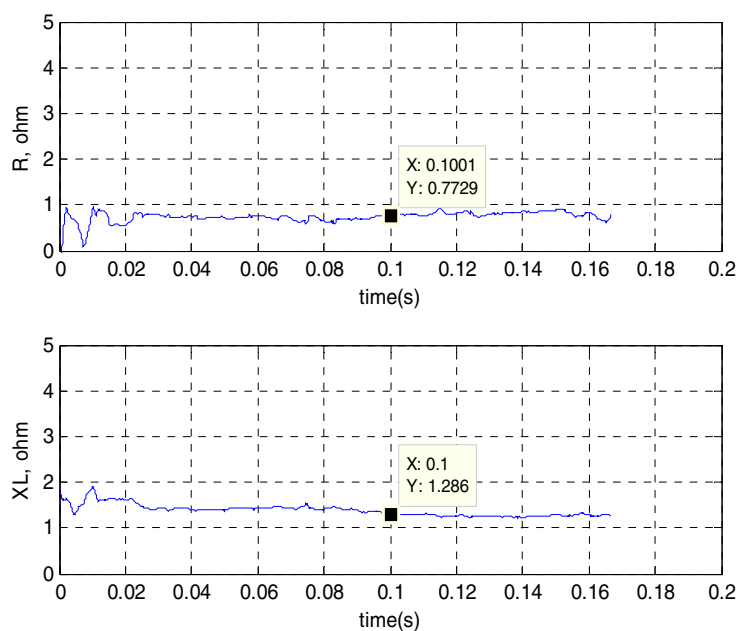


Figure 6-18
Estimated Resistance and Reactance to Fault

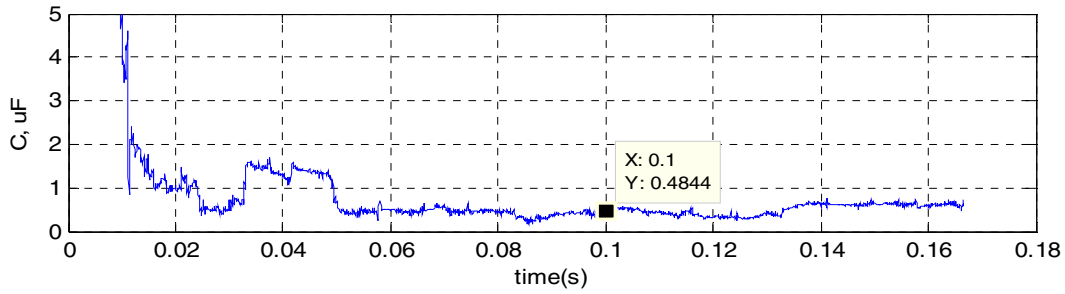


Figure 6-19
Estimated Capacitance of the Line

The actual value of the impedance was $0.72+1.33i \Omega$, which agrees with $R_{estimated} = 0.77 \Omega$ and $X_{estimated} = 1.28 \Omega$. There is no information available to corroborate the value of the capacitance estimate, $C_{estimated} = 0.48 \mu\text{F}$. The results of the reactance to fault obtained from four cases are summarized in Figure 6-20. It is evident that the new algorithm is still able to estimate the fault reactance accurately, along with the addition of the capacitance.

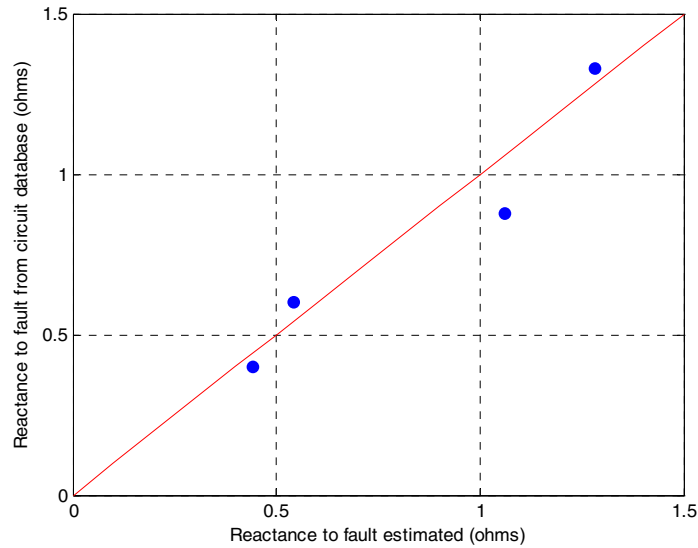


Figure 6-20
Reactance and Resistance to Fault Estimates Calculated from New Algorithm

In the final step of the validation process of the new algorithm, a comparison was made between the results obtained from the arc voltage-estimation algorithm described in Chapter 3. Consider the case with a permanent single-line-to-ground fault in phase B, as shown in Figure 4-17. The reactance to fault estimated by the arc-voltage algorithm was 1.095Ω . The new algorithm is applied to the same fault data, and the results of the resistance and reactance to fault are shown in Figure 6-21.

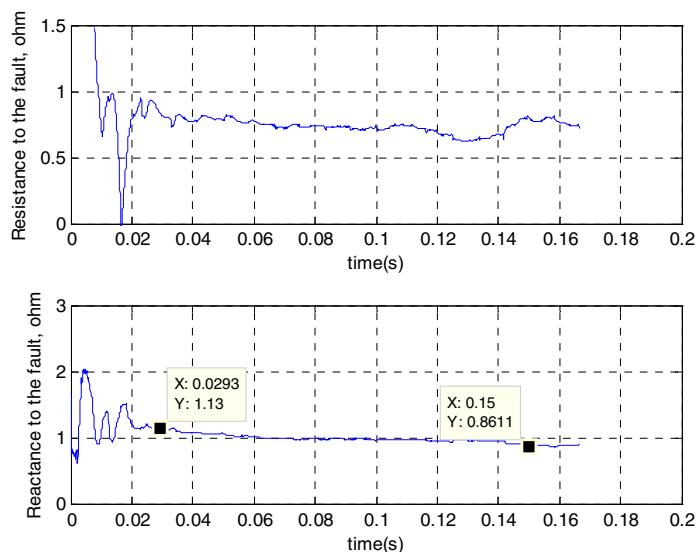


Figure 6-21
Reactance and Resistance to Fault Estimates Calculated from New Algorithm for Event
Shown in Figure 4-17

The value of the reactance estimated using the proposed algorithm obtained by simple averaging of the results shown in Figure 6-21 is 0.995 Ω . The value is very close to that obtained from the original algorithm that does not take into account the line capacitance. This case further confirms that the addition of the capacitance term in the arc voltage-estimation algorithm does not alter the results of the resistance and reactance to fault. On the contrary, the new algorithm provides the value of the line capacitance in addition to the other results.

Summary

The algorithm proposed in this Chapter is a modified version of the arc voltage-based fault-distance estimation method described in Chapter 3. A simplified pi model of the distribution cable is used while deriving the algorithm where the line capacitance is taken into account along with the reactance (X_L) and resistance (R). In order to verify the new algorithm, a simplified distribution feeder fault was simulated in PSCAD/EMTDC software. The algorithm is able to accurately estimate the values of R , X_L , and C during sustained as well as temporary faults. Data generated from preliminary simulation models shows that the proposed algorithm is able to obtain better results than the traditional arc voltage-based distance-estimation algorithm. In the next step of the verification process, the algorithm is shown to estimate the values of feeder capacitance accurately. Results are mixed. There are cases where the algorithm is able to provide relatively accurate estimates, while there are cases where the algorithm fails. Another important confirmation step that was needed to be performed was to verify whether the new algorithm accurately estimates the value of the reactance (X_L) and resistance (R) to fault. This was carried out by comparing the fault-distance estimates from the new algorithm with those obtained from the basic arc voltage-based algorithm described in Chapter 3. Fault-impedance estimates match relatively well.

In a nutshell, the main advantage is expected to improve impedance-to-fault location estimates in underground cable systems where transient oscillations may occur while the fault is on the system. Further study needs to be carried out to improve the proposed algorithm.

7

CABLE FAULTS

Introduction

As a part of an effort to expedite service restoration, fault waveforms are analyzed to determine their root causes. Characteristics of a fault waveform provide clues about the nature of the fault. Cable faults have different characteristics compared with other types of faults. Therefore, the goal is to determine common and unique (differentiating) waveform characteristics that can be used to estimate different fault types. In this chapter, waveform characteristics of cable faults (cable, joint or splice, and termination failures) are discussed and presented. In later chapters, characteristics of animal- and tree-contact faults, lightning-induced faults, and other faults cleared by current-limiting fuses are presented.

Cable faults are typically single-line-to-ground faults, and the faults considered can fall into more than one of the following categories,

- Sustained or temporary (self-clearing),
- Fault located at the terminator, splice, or in the cable
- Fault caused by moisture, water treeing, or tracking (or electrical treeing)

Before covering these categories, the cable construction is described. The cause of cable failure is then described in more detail, and waveforms of these events are examined so that the unique characteristics from these events can be extracted.

Underground Cable Construction

Even though there are a variety of underground cables, all cables have the following components:

- Phase conductor – The center of the cable that is the electrical conducting path of the cable.
- Insulation – Insulation prevents the phase conductor from coming into direct contact with other objects and arcing that occurs because of the close proximity of the underground cable components.
- External protection – This prevents moisture from entering, mechanical damage, chemical or electrochemical attack, fire, and any other harmful influences that could cause harm to the cable itself [41].

Cables can be classified into two groups, cables with solid dielectric insulation and cables that are pressurized with oil or gas. The pressurized cables can be either high-pressure fluid-filled pipe-type cables or a self-contained fluid-filled cable that uses a paper tape insulation. One type of solid dielectric type of cable is cross-linked polyethylene or XLPE cable. XLPE cables do not

require insulating fluids, which is one advantage of solid dielectric cables over pressurized cables.

An example of a solid dielectric cable, a concentric-neutral cable, is described below [42]. In addition to the above components, this type of cable has additional components shown in Figure 7-1. The *conductor* is covered in a *conductor shield*, which is used to prevent excessive electrical stress in *voids* that may appear in the insulation [41]. Voids are air gaps inside the cable insulation, which could lead to cable failure. Advancements in cable construction have led to the reduction of voids, making solid dielectric cables more popular [43]. Outside the conductor shield is the *insulation*, which is covered by an *insulation shield*. A *concentric neutral*, consisting of several copper wires, is concentrically wound around the insulation shield. Outside the concentric neutral is the *PE jacket*, which is the outermost layer of the cable. Underground residential distribution (URD) typically uses concentric-neutral cables [42]. The *external protection* covers the outside of the cable and protects the cable against mechanical damage or stresses [41].

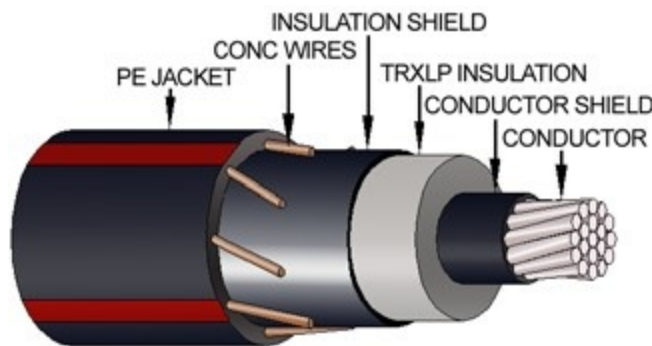


Figure 7-1
Concentric-Neutral Cable with Labeled Components (from
<http://www.mahanson.com/images/Hendrix%20Cable.jpg>)

Joints or splices and cable terminations are where many cable failures occur. Splices or joints connect two separate pieces of conductor. Splices are needed because there are limits to how much cable can be wound around a spool and to how much cable can be pulled through a pipe [44]. Terminations are used when the underground cable is brought above ground. A porcelain insulation or housing, often called “potheads,” protects the connections between the underground and above-ground cable [44]. Terminations also keep moisture from entering the underground cables.

Causes of Cable Failure

A cable fault is any problem in a cable that affects the performance of the cable and includes contact faults, ground contact faults, breaks, ingress of moisture, crimping, cross-talking, flashing fault, transitory, and partial discharge [45].

Temporary or self-clearing cable faults do not usually occur on underground cable systems. Occasionally animals or water can temporarily cause a fault through a piece of energized equipment [42]. Another type of self-clearing fault can occur on the splice of a cable. This type of fault occurs when water enters the cable splice and breaks down the insulation of the cable.

The arc energy melts the water and creates vapor at high pressure, which eventually extinguishes the arc [42].

Treeing is the general term used to describe the type of electrical breakdown that occurs in solid dielectric insulation of the cable. Treeing may not necessarily cause a fault. However, because failures are often preceded by fissures in the insulation, treeing is a potential hazard [41]. There are three types of treeing:

1. Water trees
2. Electrical trees
3. Electrochemical trees

Water trees, which are caused by water coming into contact with the insulation, accelerate the failure of the cable [41]. The formation of water trees does not mean that the cable will fail, as stated above. However, failure occurs when water treeing converts to an electrical tree, or tracking [42].

Electrical trees and electrochemical trees differ significantly in appearance from water trees. Electrochemical trees are caused by the water in the insulation containing solute ions. Moisture or an electrolyte allows water trees or electrochemical treeing to occur at a much lower voltage than is needed for electrical treeing.

Electrical trees, sometimes referred to as *tracking*, are the resulting voids or pockets of air found in the insulation. These pockets of air are caused by the thermal expanding and contracting that occur during changes in load. Voids tend to ionize and cause corona discharge, which scorches and carbonizes surrounding insulation. When enough air pockets form, tracking or a charred path forms where the insulation breaks down, causing cable failure [46].

In the next sections, underground cable failures are grouped by cable component failure or by the cause of the fault. The grouping is based on characteristics extracted from the voltage and current waveforms recorded during these events. The following section describes the characteristics seen in waveforms from these events.

Waveform Characteristics of Cable Faults

In this section, the voltage and current waveforms recorded during an underground cable fault event are used to classify the events. The waveforms were selected from a database of events provided by participating utilities. Only the waveforms that contained detailed written information about the cause of the event were analyzed. This includes information about where the fault occurred on the cable and in some cases what caused the cable to fail. The database contains more cable fault events; however, these events do not contain information or contain insufficient information about the cause of the fault that would help our analysis. Therefore, the results discussed in this chapter are preliminary and can be improved upon once more information is provided by the utilities.

The events in this chapter are classified based on the following categories. First, the event is classified by underground cable component failure, either the cable itself, the splice or joint, or the termination. These components were described in the previous section. Next, the event is

classified based on the cause of the fault or failure. These categories include treeing, tracking, or moisture.

Some characteristics that are common to most cable failures are discussed below. However, it is difficult to find unique characteristics that are common to all the event waveforms because of the possibility of the network conditions having a strong influence on the waveforms rather than the cable failure itself. For this reason, identifying the root cause of cable failure can be challenging. Characteristics that stood out include short-duration impulses or high-frequency oscillations that occur once each half cycle. The impulses or oscillations typically occur at the same instant as the zero crossing of the faulted phase current. If an oscillation is present, the oscillation frequency is from 0.9 to 4.0 kHz. In the case of underground cable faults that occur at the joint and are caused by tracking, the frequency of the oscillations is in the range of 1.3 to 1.9 kHz. Not enough information is available to determine the range of frequencies for other event types. The oscillations can be seen for the joint fault with tracking in Figure 7-2 below.

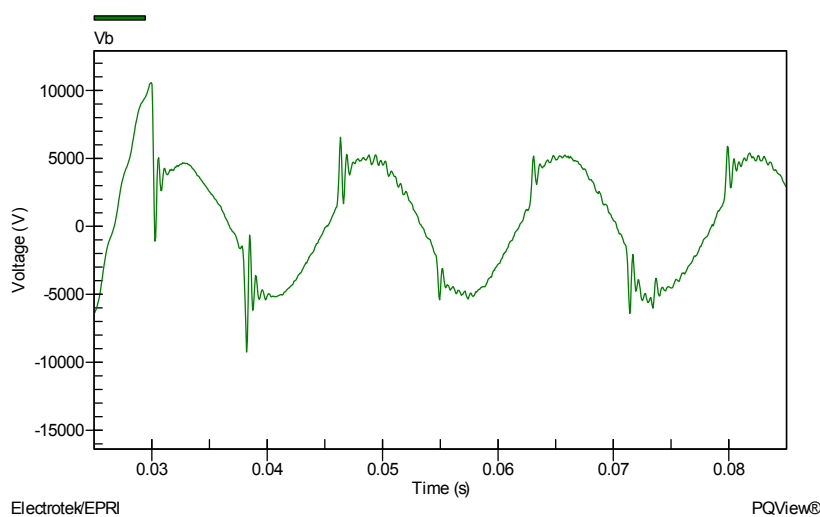


Figure 7-2
Oscillation of 1.9 kHz in the Voltage Waveform during a Cable Fault in the Joint with Tracking

In a few cases, oscillations or impulses appear at different instants of the event. Sometimes the impulses occur only at the beginning of the event before disappearing, occurring only 2 or 3 times through the duration of the event. Sometimes the impulses continue through the duration of the event or sometimes the impulses appear only near the middle or end of the event. Examples of the impulses showing up at different sections of the event are shown in Figure 7-3, Figure 7-4, and Figure 7-5. All three of the examples are for faults that are located at the cable.

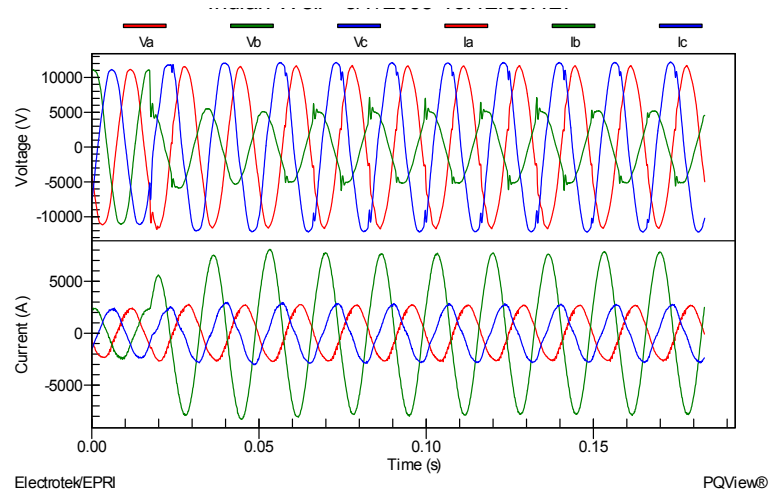


Figure 7-3
Oscillations Begin to Show Up Near the Middle of the Underground Cable Fault Event Duration

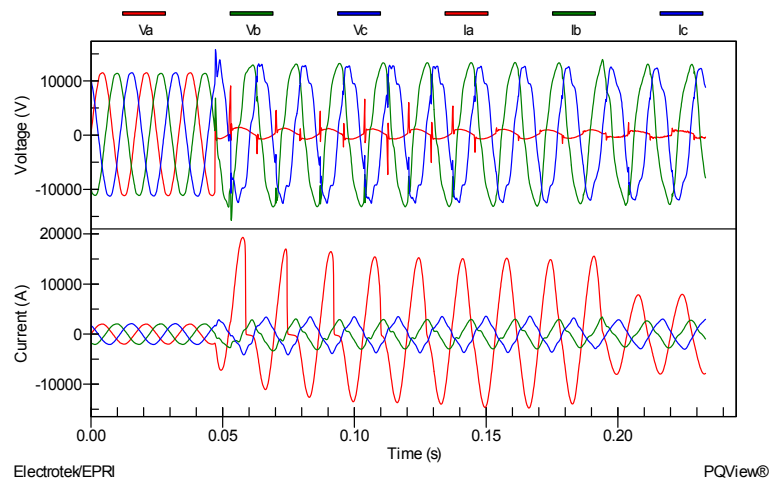


Figure 7-4
Oscillations Last Throughout the Duration of the Underground Cable Fault Event

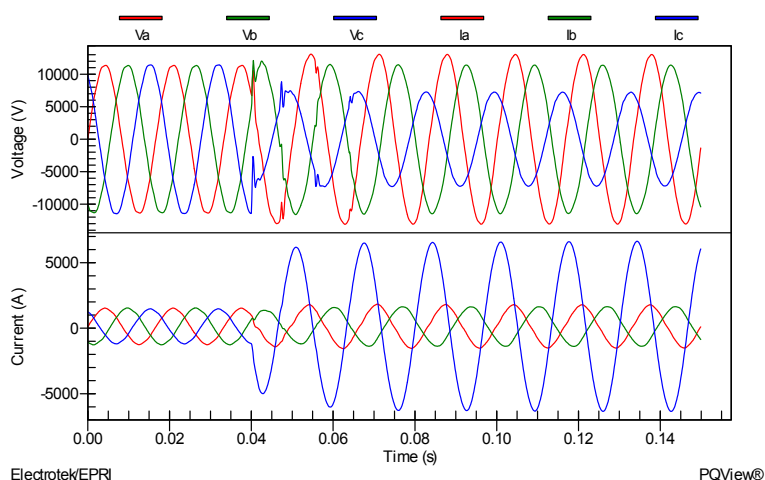


Figure 7-5
Impulses Show Up Only Near the Start of the Underground Cable Fault Event

Waveform Characteristics Extracted Using Wavelet Transform

The squared wavelet transform coefficients (WTC) for the faulted phase voltage are examined in this section. The wavelet-transform algorithm is described in the appendix. The squared WTC1, WTC2, and WTC3 are examined to see if the cause of a cable failure or if the location of the cable failure at the underground cable has an impact on the squared WTCs' amplitudes.

Two examples are used to determine whether WTCs are a good tool to help classify underground cable faults. In both examples, the fault occurred on the splice of the cable and there was tracking on the sleeve of the cable. In Figure 7-6 is the faulted voltage waveform for the first example. The wavelet transform for this example is shown in Figure 7-7.

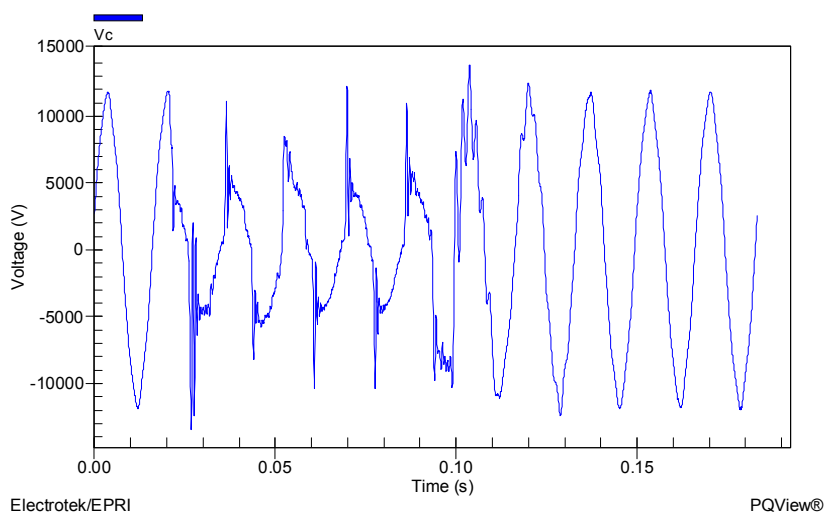


Figure 7-6
Faulted Phase Voltage Waveform for a Cable Fault Located at the Splice with Tracking on the Sleeve

In Figure 7-7, the scale of the squared WTCs reach 0.02 pu^2 for WTC1, 0.25 pu^2 for WTC2, and 2.0 pu^2 for WTC3. However, it should be noted that the WTCs also indicate the change from nominal voltage to the start of the fault seen in the voltage waveform as well as the oscillations unique to cable faults. The WTCs of the fault initiation can be very high and mask the statistical behavior of WTCs of the fault event. For this reason, because signatures during the fault are of interests, the high-amplitude WTCs indicating the start of the fault in the WTCs were removed.

In order to select which points to remove, the average and the standard deviation of all the peaks in the WTCs were taken. If any of the peaks were greater than three times the standard deviation, that peak was removed, and then the WTCs were re-plotted. If necessary, the process was repeated to make sure that the peaks caused by the fault start were removed. Once the WTCs were re-plotted, the new range of the squared WTCs were 0.01 pu^2 for WTC1, 0.16 pu^2 for WTC2, and 1.0 pu^2 for WTC3. Figure 7-8 shows WTC1 after the peaks indicating the start of the event were removed and re-plotted.

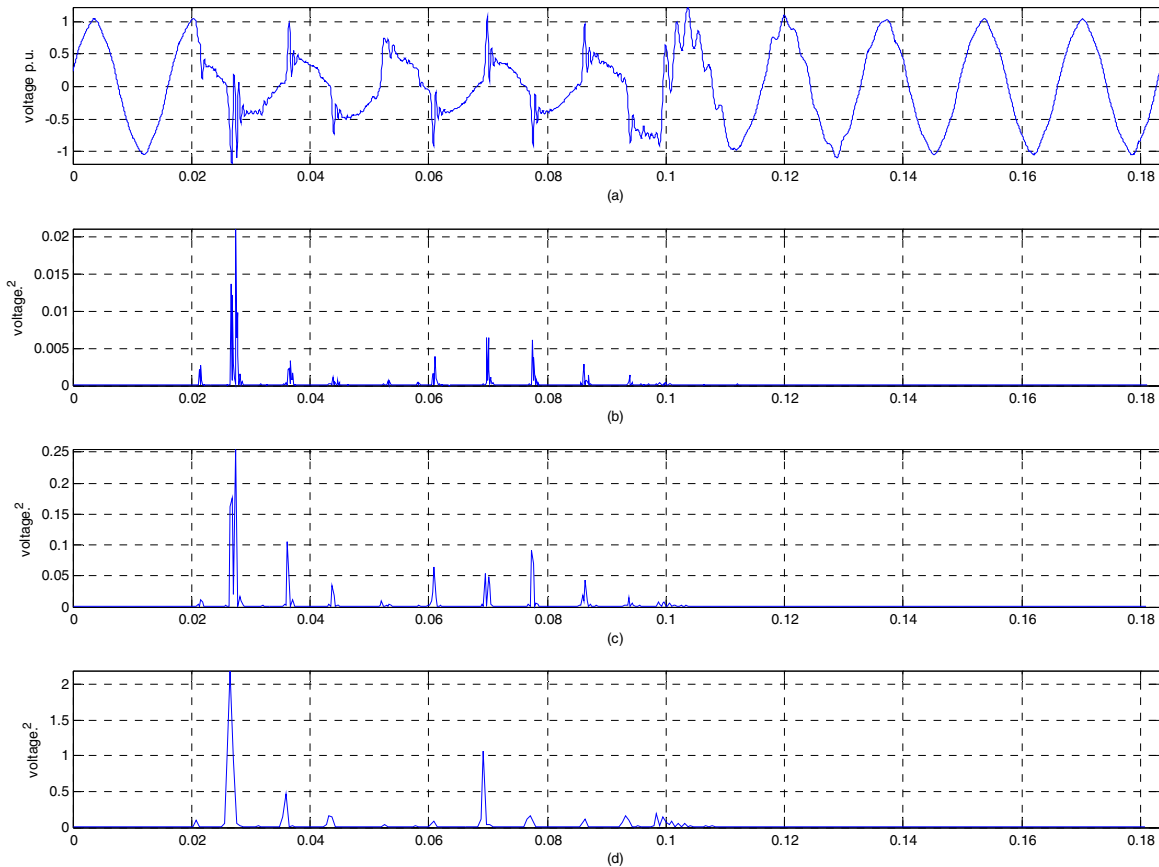


Figure 7-7
Wavelet-Transform Coefficients for Voltage Cable Fault Located at the Splice with Tracking

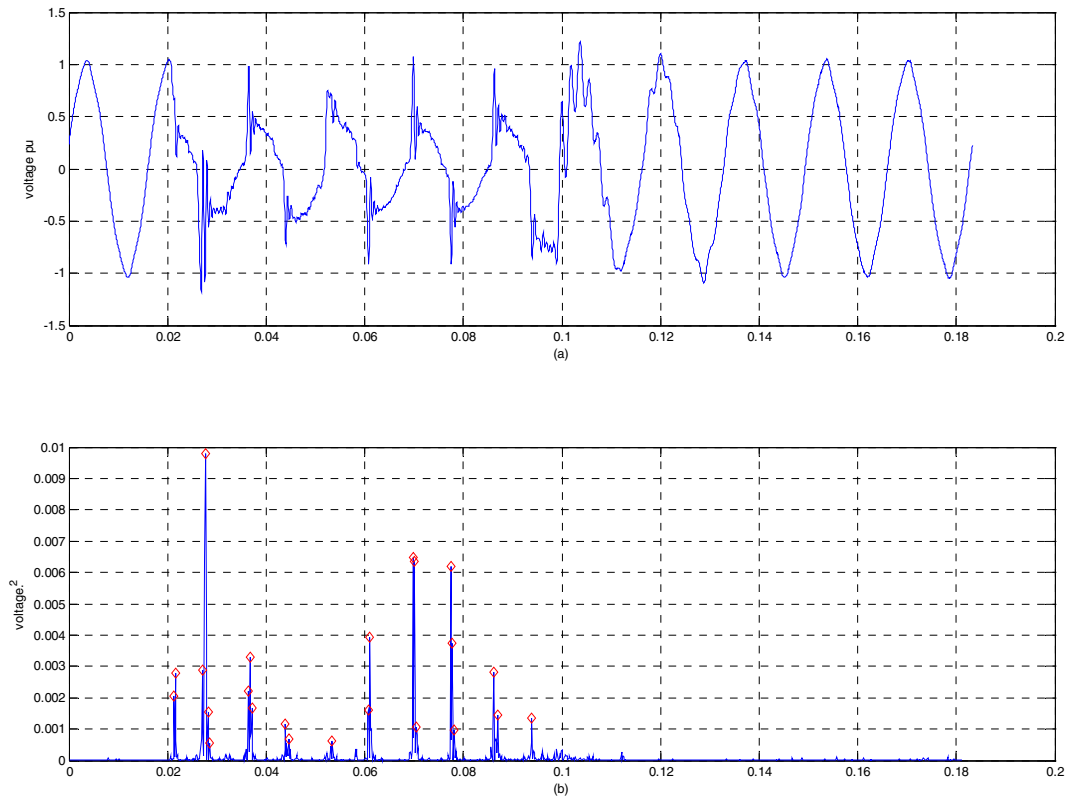


Figure 7-8
The Faulted Voltage Waveform and the Squared WTC1 After the Peaks Indicating the Start of the Event Were Removed

The second example is examined in Figure 7-9 and Figure 7-10 below. In this case, the peaks in the WTCs caused by the fault start do not dominate other WTCs; thus they do not need to be removed. The scale of the amplitude for squared WTC's is 0.01 pu^2 for WTC1, 0.11 pu^2 for WTC2, and 0.8 pu^2 for WTC3. This range is similar to the previous case.

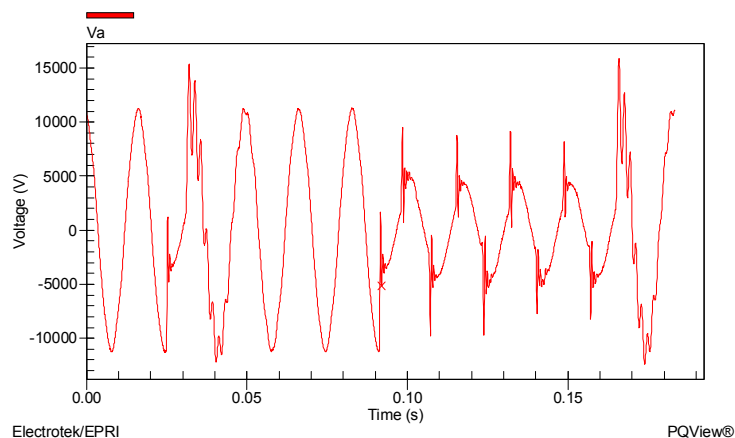


Figure 7-9
Faulted Phase Voltage Waveform for a Cable Fault Located at the Splice with Tracking on the Sleeve

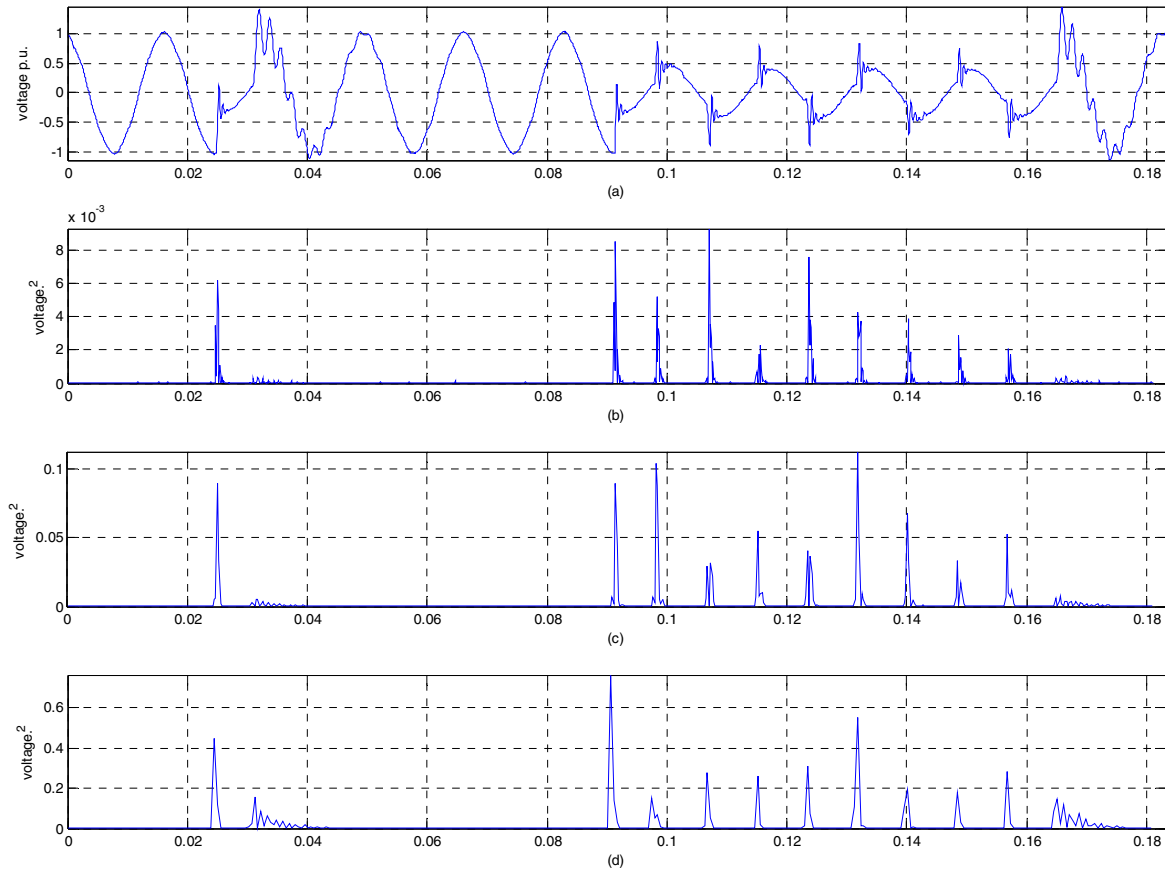


Figure 7-10
Wavelet-Transform Coefficients for Voltage Cable Fault Located at the Splice with Tracking

To show that this range is unique to faults located at the joint or to tracking on the sleeve, more underground cable faults were examined. The following examples are faults located on the cable, faults that contained moisture or treeing in the cable insulation when the utility crew located the fault. In Figure 7-11, the fault was located at the cable and contained treeing. The squared WTCs are plotted in Figure 7-12. The ranges of the squared WTCs are 0.0015 pu^2 for WTC1, 0.02 pu^2 for WTC2, and 0.15 pu^2 for WTC3. The peaks are all significantly lower in this case compared to the squared WTCs for events located at the joint that are caused by tracking.

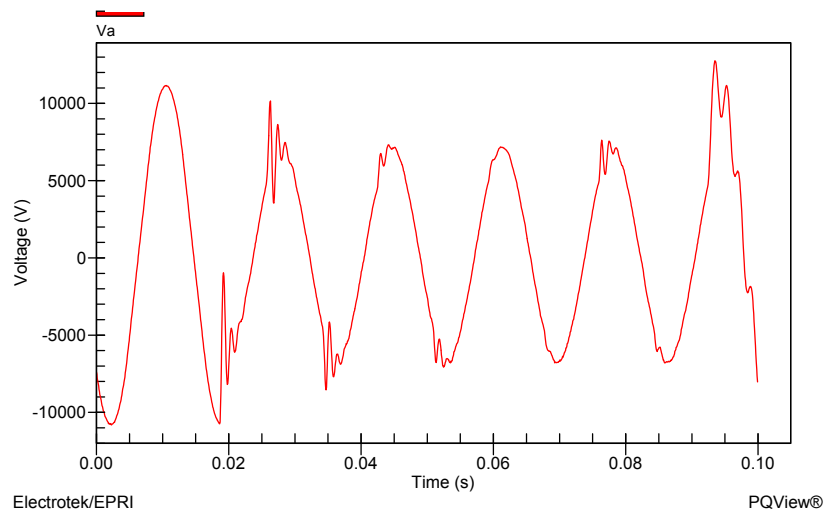


Figure 7-11
Faulted Voltage Waveform for a Fault Located at the Cable with Treeing

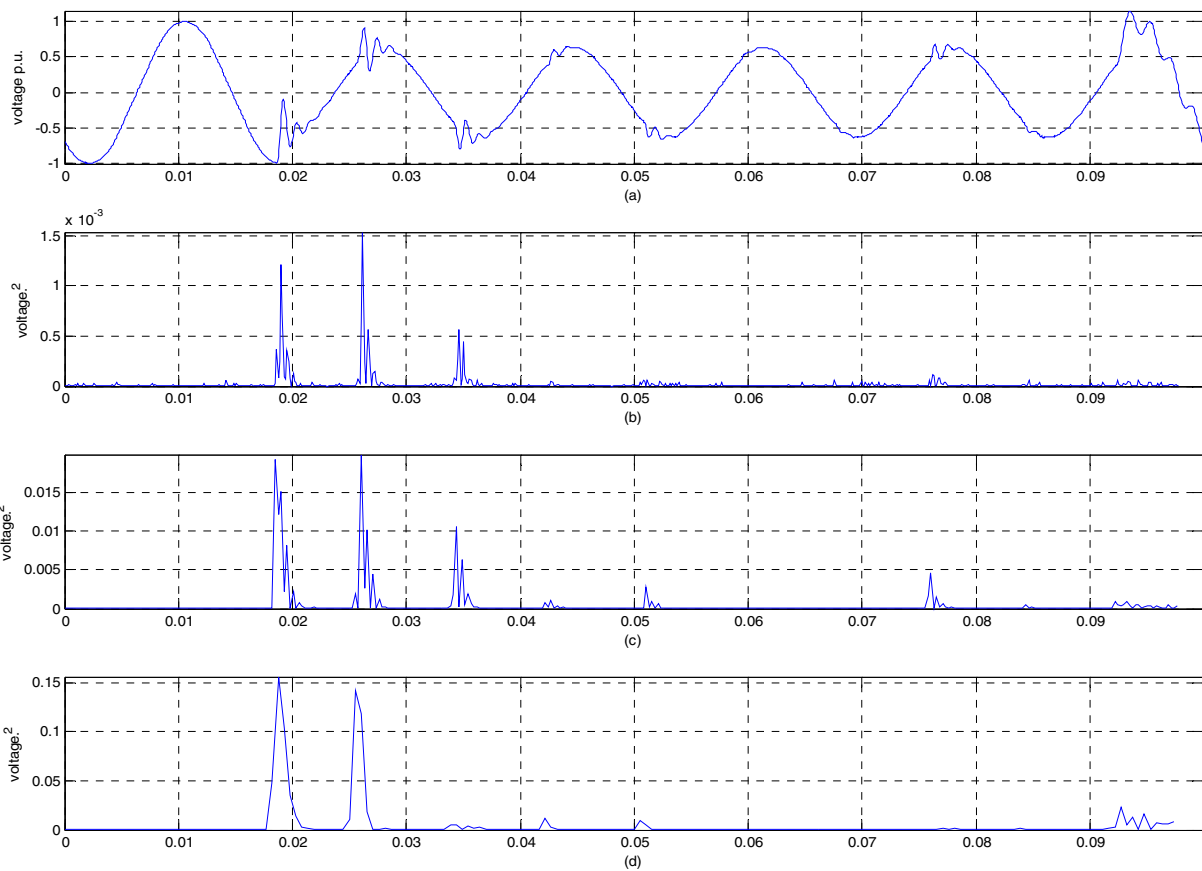


Figure 7-12
Wavelet-Transform Coefficients for a Fault Located at the Cable with Treeing

Another example is examined in Figure 7-13. In this case, the fault is also located at the cable but water was found inside the cable. The faulted phase voltage is shown in Figure 7-13, and the WTCs are plotted in Figure 7-14.

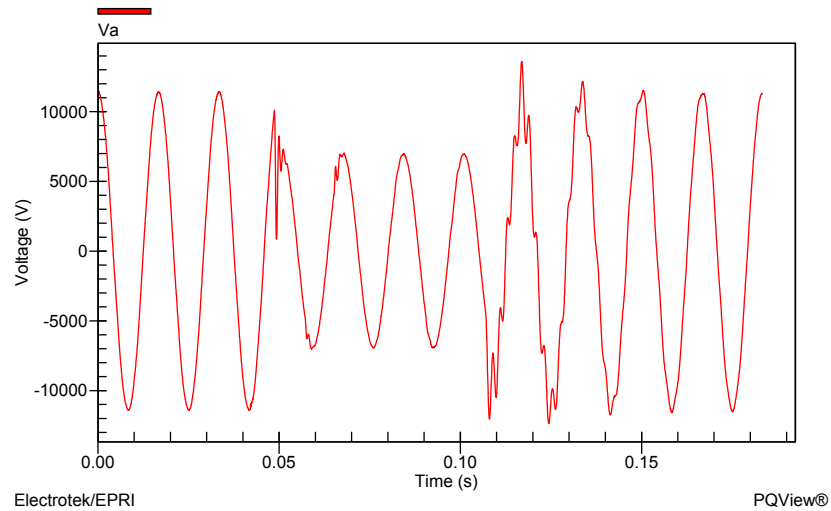


Figure 7-13
Faulted Voltage Waveform for a Fault Located at the Cable with Moisture

The range of the WTCs is very small, and the only peak found in the WTC's is an indicator of the change from nominal voltage to the faulted voltage. If the only peak is removed, the remaining peaks are too small to be used as an indicator of impulses or oscillations in the faulted portion of the voltage waveform. Even from visual inspection it is easy to tell that the faulted portion of the voltage waveform is fairly smooth and free of impulses and oscillations.

In conclusion, the squared-transform WTCs appear to be unique to different underground cable events. By analyzing the statistical behavior and magnitude variations from one scale to another, the wavelet transform may be an effective tool to distinguish faults located at the cable joint with tracking on the sleeve from the WTCs for faults located at the cable with treeing and with moisture in the cable. However, because the number of event waveforms that contained information about the cause of the fault is limited, more events are needed to obtain a better definition of the range of WTCs by event cause.

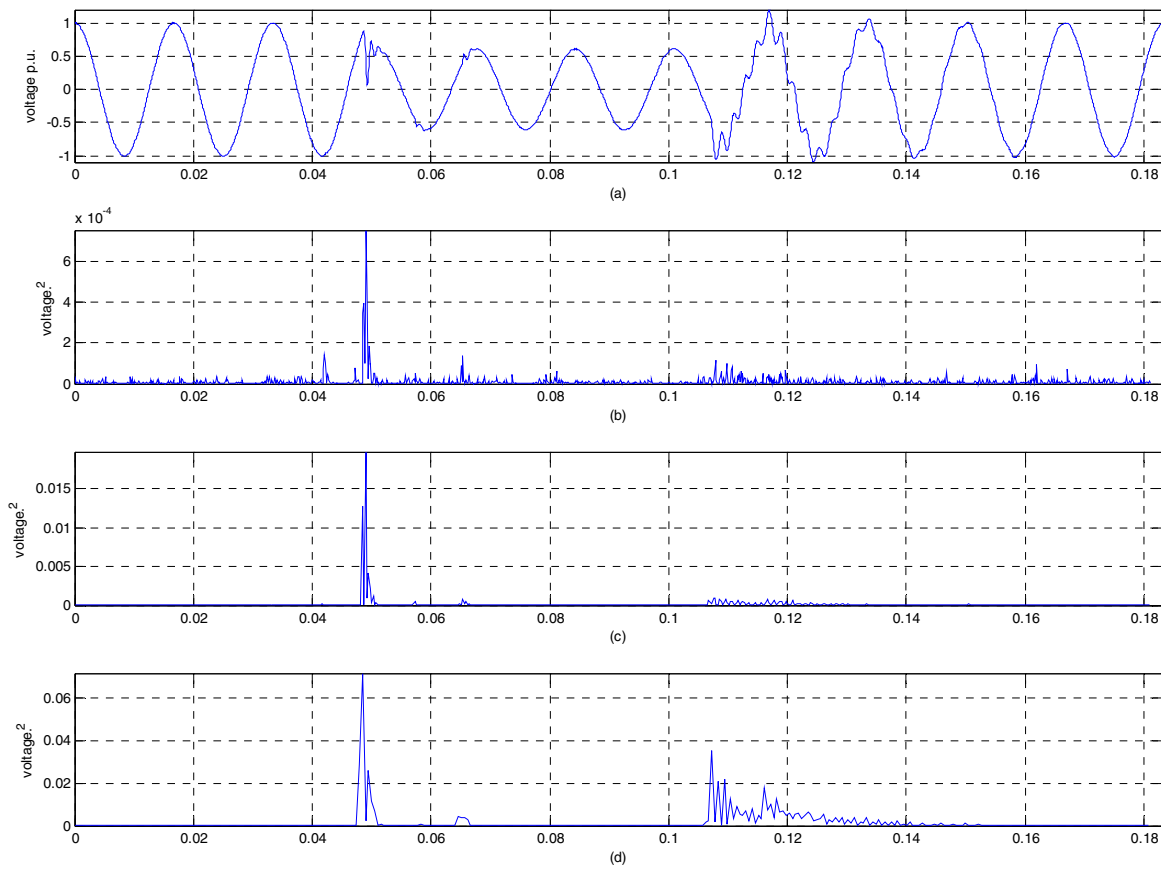


Figure 7-14
Wavelet-Transform Coefficients for a Fault Located at the Cable with Moisture

Waveform Characteristics of Cable Joint or Splice Failures

In this section, common characteristics seen in cable joint or splice failures are examined. The classification is based on their voltage waveforms. The waveforms for faults located at the joint or splice of the cable are shown in Figure 7-15 and Figure 7-16. During the fault, small-magnitude impulses are seen in the faulted phase voltage. These impulses occur during the zero-crossings in the faulted phase current waveform. The impulses do not last the whole event and eventually stop appearing after only two cycles.

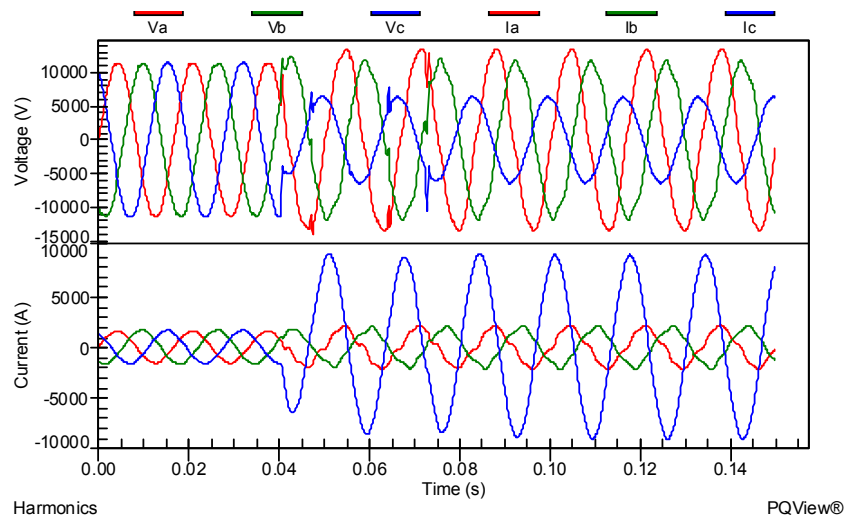


Figure 7-15
Voltage and Current Waveforms for a Cable Fault Located at the Joint

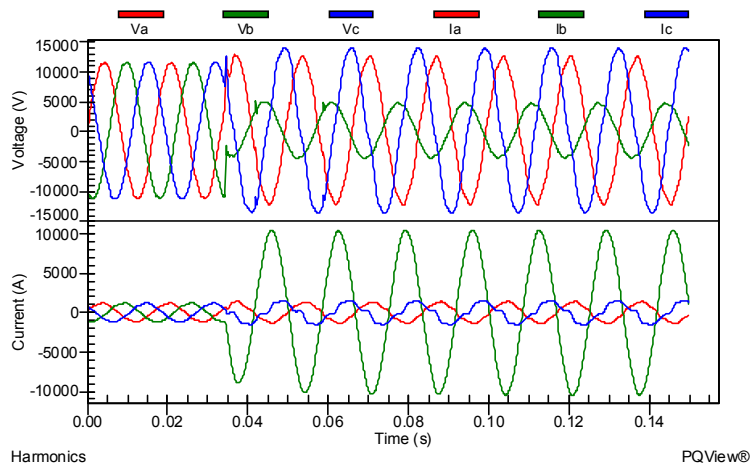


Figure 7-16
Voltage and Current Waveforms for a Cable Fault Located at the Joint

Waveform Characteristics of Cable Termination Failures

The waveforms for faults located at the termination of the cable are shown in the figures below. Even though the faulted phase voltage waveform in this example has impulses located at the start of the event, not all termination faults have impulses located in the faulted phase voltage waveform. An example of the lack of impulses is shown in Figure 7-18 and Figure 7-19.

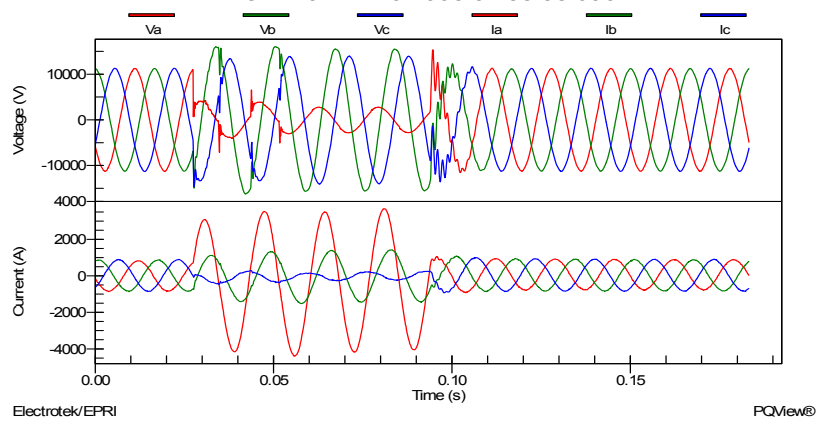


Figure 7-17
Waveforms for Fault Located at the Cable Termination with Impulses in the Voltage

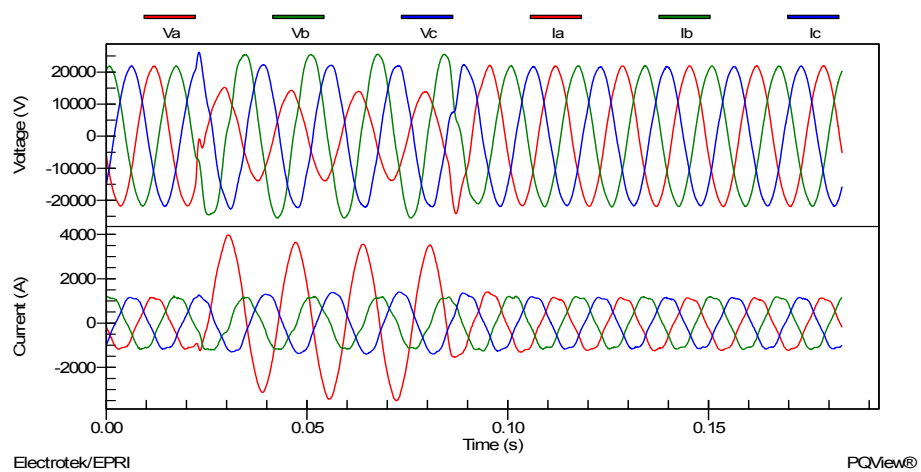


Figure 7-18
Waveforms for Fault Located at the Cable Termination without Impulses in the Voltage

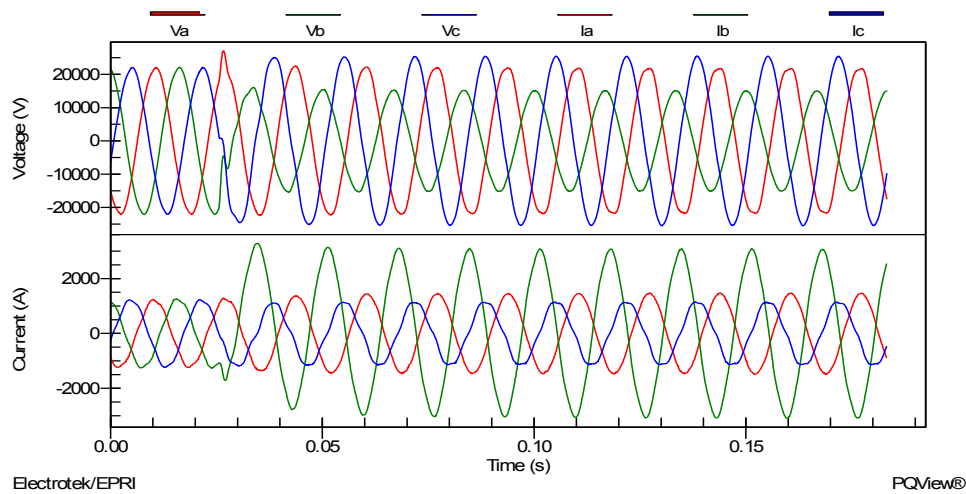


Figure 7-19
Waveforms for Fault Located at the Cable Termination without Impulses in the Voltage

Waveform Characteristics of Cable Failures

The waveforms for faults located at the cable are shown below. For underground cable faults, the fault typically is single-phase and may evolve into two or three phases. In Figure 7-20, the impulses seen in the faulted phase voltage are very high and occur throughout the duration of the fault. Near the end of the event window, the voltage waveform begins to take on a square waveform and looks very similar to an arc voltage waveform. Arcing in cables is covered in a later section of this chapter.

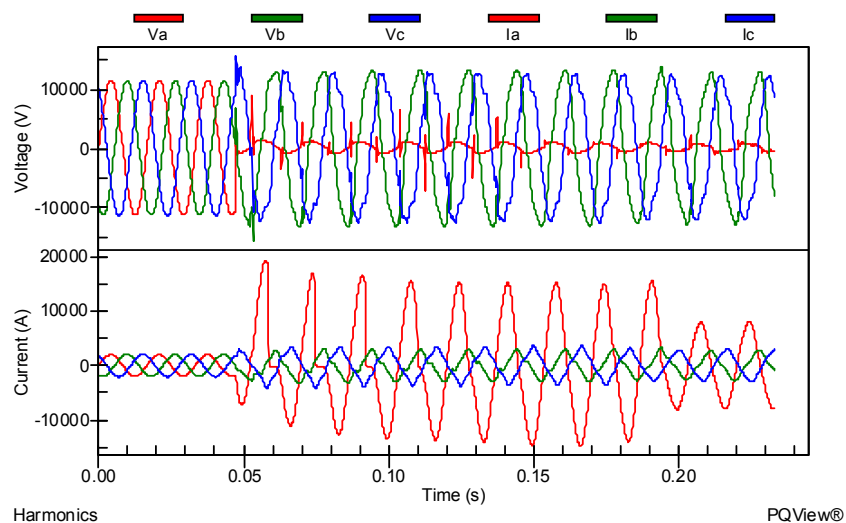


Figure 7-20
Voltage and Current Waveforms for an Underground Fault Located at the Cable

In Figure 7-21, the impulses last through the duration of the event that is captured in the recorded window.

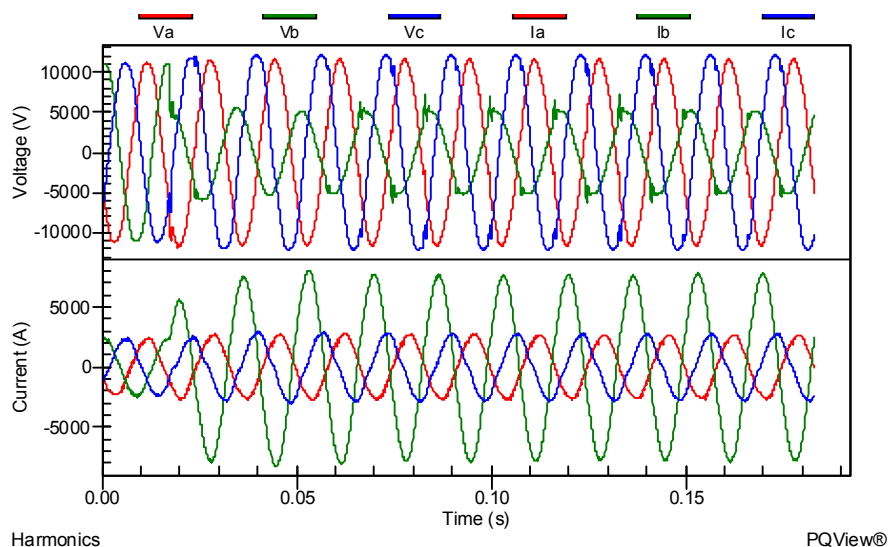


Figure 7-21
Voltage and Current Waveforms for an Underground Fault Located at the Cable

The above discussions covered similarities shared by a few of the waveforms from the same event types broken down in the categories listed at the beginning of the chapter. However, not all of the events share the same characteristics. Therefore, it is difficult to classify the events based on where the cable fault is located and by the cause of the event, such as tracking, treeing, or moisture. Further research and data, including information about the cause of the fault, are needed. The following section covers arcing in underground cables that may reveal more characteristics to help identify where the cable fault is located.

Arcing in Underground Cable Systems

The estimated arc voltage for cable faults is examined in this section. The arc voltage can be used to help categorize events. The arc voltage is estimated using the method described in Chapter 3. In this section, it is shown that the arc-voltage estimate can be first used to determine whether the fault is a cable fault or a fault caused by tree or animal contact. Afterwards, the estimated arc voltage can be used to help determine whether the recorded event is an underground cable fault, and it can also be used to help determine which failed component caused the cable fault. One type of cable failure, tracking on the joint of the cable, is also examined.

An example of an underground cable fault and the estimated arcing voltage for the fault are shown in Figure 7-22 and Figure 7-23. The event is labeled as an underground cable fault and is a sustained single-line-to-ground fault.

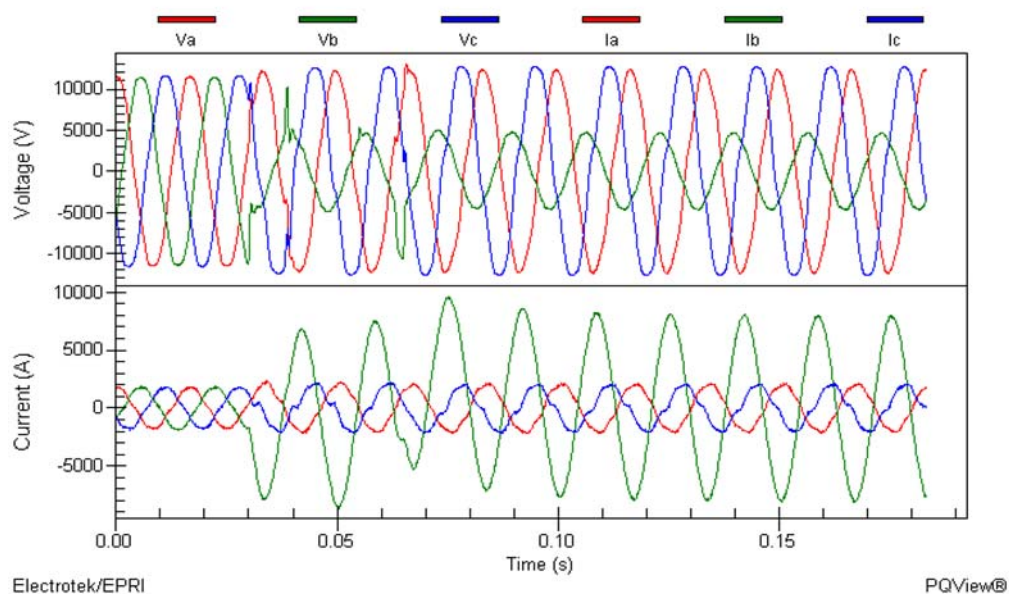


Figure 7-22
Example of Voltage and Current Waveforms for an Underground Cable Fault

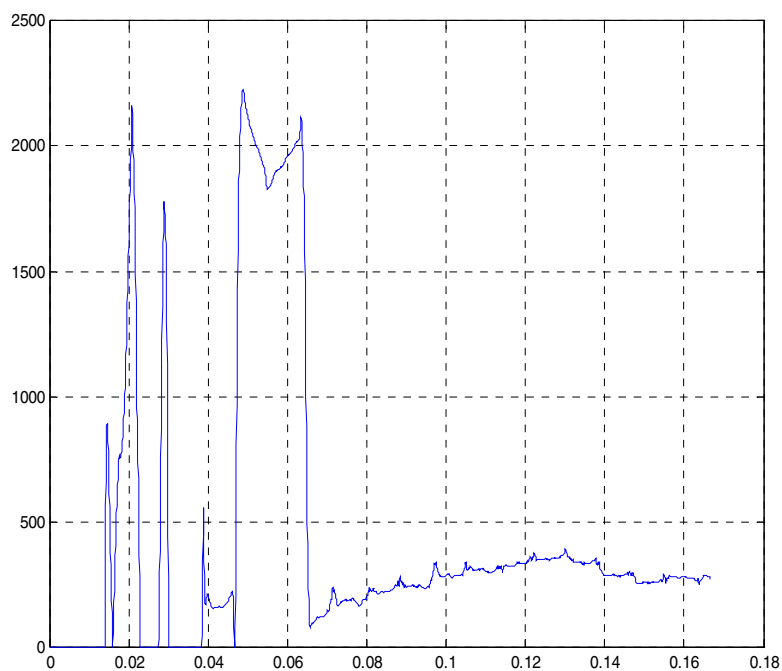


Figure 7-23
The Estimated Arc Voltage for the Underground Cable Fault in Figure 7-22

To show that the arc voltage can be used to differentiate a cable fault from other types of faults, the arc voltage was estimated for a variety of cases, including 20 animal-contact cases, 25 underground cable failure cases, 8 lightning cases, and 24 tree-contact cases. Each value of the estimated arc voltage is grouped by type of failure, normalized, and plotted in Figure 7-25. To interpret the graph below, it is easiest to look at the 0.90 mark on the Y axis. This means that 90% of the arc voltage is below 250 V for cable failures, and approximately 90% of the arc voltage for lightning-induced arcing is below 550 V. Also, 90% of the arcing caused by animal contacts and tree contacts falls below approximately 1500 V. This means that it might be easier to pick out cable failures from animal or tree contacts by examining the arc voltage. However, it may be difficult to distinguish cable failures from lightning failures based on arc voltage. Other characteristics can be used to differentiate between the two events.

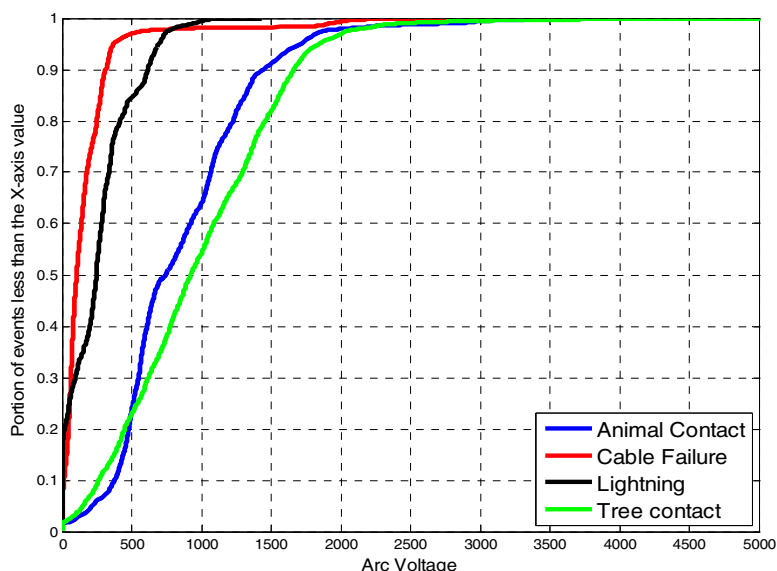


Figure 7-24
Comparison of the Arc Voltage for Underground Cables to the Arc Voltage of Animal Contact, Lightning, and Tree Contact

The same method is used to differentiate between cable component failures such as joint, cable, and termination. A number of cases were examined such as 25 joint failures, 22 cable failures, and 16 termination failures. If a voltage is selected along the X axis, it can be seen from the plots what percentage of the arc voltage falls under the selected voltage. For example, in Figure 7-25, if 500 V is selected, that means 50% of the arc voltage for joint failures, 62% of the arc voltage for termination failures, and 85% of arc voltage for cable failures are under 500 V. Or it could be thought of as a certain percentage of the waveform being above the selected voltage on the X axis. The steeper the plot, the lower the values of the estimated arc voltage are likely to be.

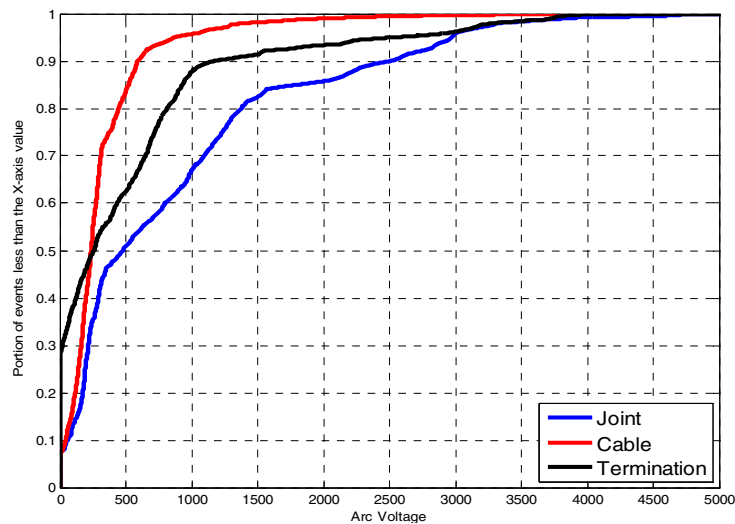


Figure 7-25
Comparison of the Arc Voltage for Joint, Cable, and Termination Failures on Underground Cables

If the cause of the failure is examined, it can be seen in Figure 7-26 that some types of joint failures are similar to termination failures. When a joint failure with tracking occurs, the values of the estimated arc voltage tend to be larger than the arc voltage for a joint failure without tracking.

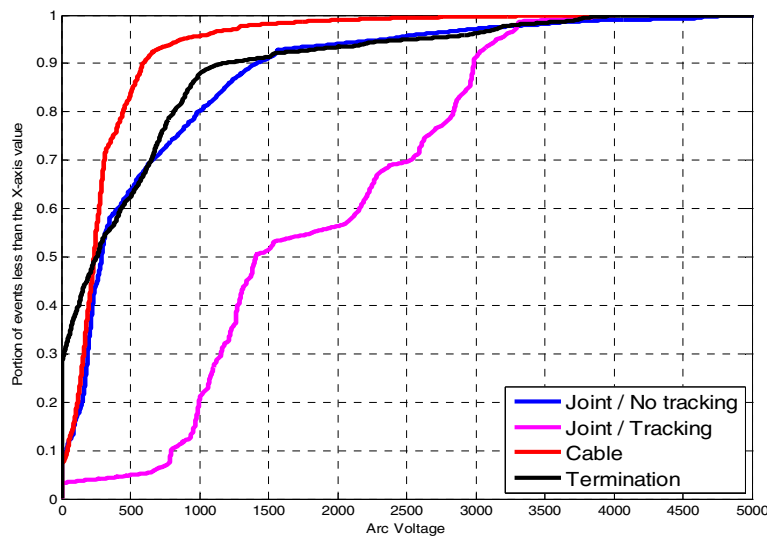


Figure 7-26
Comparison of the Arc Voltage for Failures on the Joint of Underground Cables with Tracking and without Tracking

Even though the arc voltage cannot always be used to determine the cause or locate the failed component that caused the fault to occur, it can be used along with the previous characteristics to categorize underground cable faults.

Summary

In this chapter, underground power cables and the characteristics seen in current and voltage waveforms caused by faulted underground cables were described. Underground power cables consist of a phase conductor surrounded by insulation and external protection to prevent damage to the cable. Joints or splices and cable terminations are where many cable failures occur. A cable joint or splice connects two separate phase conductors. A cable termination connects the underground cables to above-ground cables. Voids in the insulation may lead to treeing and eventually tracking, which can cause cable failure. The presence of moisture in the cable can escalate underground cable failure. Event data recorded at monitoring stations located above stream from the fault and by crews sent to repair underground cable faults were provided by utilities. The data contained three phase voltage and current waveforms, information on the failed cable component (joint, termination, or cable), and information on the cause of the cable failure. However, some events do not contain information or contain insufficient information about the cause of the fault that would help our analysis. Therefore, the results discussed in this chapter are preliminary and can be improved upon once more information is provided by the utilities.

In most underground cable faults, impulses or short oscillations appear in the faulted phase voltage waveform. If oscillations are present, the frequency of the oscillation was calculated. The wavelet transform is also applied to the faulted phase voltage waveform and the magnitudes of the squared wavelet transform coefficients (WTC) are examined. A few examples of one type of cable fault, a fault occurring on the joint with tracking on the sleeve, are used to show that the range of the frequency of oscillations and the magnitudes of the WTCs are similar and can be used to classify other events as well. The voltage and current waveform characteristics are listed for cable joint or splice failures, cable termination failures, and cable failures. Another unique characteristic that can be used to categorize an underground cable fault is the estimated arc voltage. From a variety of events taken from the database, the arc voltage is used to distinguish an underground cable fault from animal- and tree-contact events. The arc voltage is also used to determine the likelihood of an underground cable fault component failure.

8

WAVEFORM CHARACTERIZATION OF FAULTS DUE TO ANIMAL CONTACTS, TREE CONTACTS, AND LIGHTNING

Introduction

Power quality disturbances on distribution lines are caused by a number of factors [42]. Such events can be internal or external. Internal events are mainly the result of equipment malfunction or failure. On the other hand, external disturbances occur mainly due to animal and bird contacts, tree contacts, vehicle accidents, as well as natural phenomena such as lightning. These causes are primarily for overhead transmission lines. Such power quality disturbances cause a deviation from the normal operating voltage and current values. The power quality monitoring stations that detect these deviations store a snapshot of the voltage and current waveforms. This power quality disturbance data possesses a huge amount of information that can be analyzed to identify the cause of the said disturbance.

There are numerous benefits of identifying the causes of power quality disturbances recorded by the monitors. Some of these are mentioned below:

- Permanent faults are cleared by the operation of an overcurrent protective device, such as a fuse or a reclosure. This may result in a distribution line being temporarily out of service. For example, a tree branch can fall on the lines, shorting one, two, or all three phases. If the branch does not fall down on its own after burning out, the fault becomes permanent. In this case the linemen need to physically go to the location of the fault and remove the branch before the line can be reenergized. Identifying the cause of the fault, based on the monitoring station data, will save time in speculations about the cause and aid in quick restoration of supply to the affected consumers.
- Temporary faults may have a duration anywhere from a quarter of a cycle to a few cycles. Generally, protective devices do not operate during such faults because they self-clear. For example, a tree branch can fall on the distribution lines, shorting the phase and neutral and causing a single-line-to-ground fault. The recloser present upstream from the fault will detect it and initially open the line. Consequently, the recloser will close onto the fault, and if the resulting arc burns out the branch and it falls to the ground, the fault is self-cleared and there is no need for the recloser to open permanently. If one is able to identify the cause of the disturbance based on the power quality data, the recurrence of the event may be prevented in the future. In addition, temporary faults could be an indication of an impending permanent fault. In this example, if the tree is trimmed in a timely manner, it will not cause a fault at the same location.

- Every electric power utility has the propensity for power quality disturbances based on the geographical location. In addition, the weather conditions and the time of day also play a vital role in the type of the fault. Power quality disturbance characterization can help the utility in improving the operations by having the knowledge of when and where the probability of a particular disturbance occurring is high.

In this chapter, the analysis of the power quality disturbance waveforms recorded at monitoring stations in a particular utility is carried out for known events due to animal contacts, tree contacts, and lightning strikes. A discussion on the unique signatures in each category of events that can be used to distinguish it from other power quality disturbances is presented. These signatures are used to classify disturbances due to animal contact, tree contact, and lightning.

Characteristic Signatures and Data Sources of Power Quality Disturbances

In the literature, a number of methods have been proposed that recognize power quality disturbances using artificial neural networks [14] [47] [48], wavelet domain analysis [49], as well as statistical techniques. These methods scan the waveforms to identify certain signatures that are characteristic of the disturbance. Some of these signatures for animal contact, tree contact, and lightning are discussed below. Certain signatures can be applicable to all of these categories, while some are useful only for one of the above categories of disturbances.

The power quality disturbance data analyzed in this chapter was obtained from participating utilities. They primarily consist of overhead power lines and also some underground cables. The disturbance data obtained consists of 143 tree-contact cases, 66 animal-contact cases, and 28 lightning-induced cases. As seen in Figure 8-1, tree-contact cases occupy 60% of all the disturbances. In addition, only three bird-contact cases were reported, and they are excluded because they are too few to draw a valid statistical interpretation.

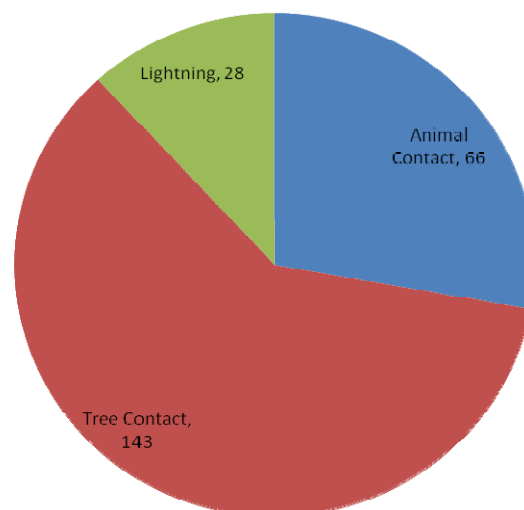


Figure 8-1
Pie Chart for Animal-Contact, Tree-Contact, and Lightning-Induced Events

The power quality monitoring station data for the given utility was analyzed based on the characteristic signatures in the manner explained in the following sections.

Characteristic Signature Based on Time of Day

The first signature is the time of occurrence of the disturbance. The information obtained from the power quality monitoring stations has a time stamp attached to it that can be used to extract not only the time of day but also the time of the year when a particular event has occurred. This analysis is vital, considering that power quality disturbances are influenced by the weather conditions, seasons, and the diurnal cycle. For example, lightning is associated with seasonal thunderstorms, which generally occur in late spring and summer. Animal and bird contacts associated with the power lines are more common during the migratory season. A similar analysis for animal contact events was presented as a part of [50].

The month and the time of day are separated from the time stamp. Based on the month of occurrence, the events are classified into four types, namely, summer (June to August), fall (September to November), winter (December to February), and spring (March to May). In addition, disturbances taking place between 6:00 am in the morning and 7:00 pm in the evening are categorized as *daytime* events, while *night time* events are those that occur between 7:00 pm in the evening and 6:00 am in the morning.

Figure 8-2 shows the normalized classification of the animal-contact, tree-contact, and lightning events, based on the month of occurrence, into four seasons.

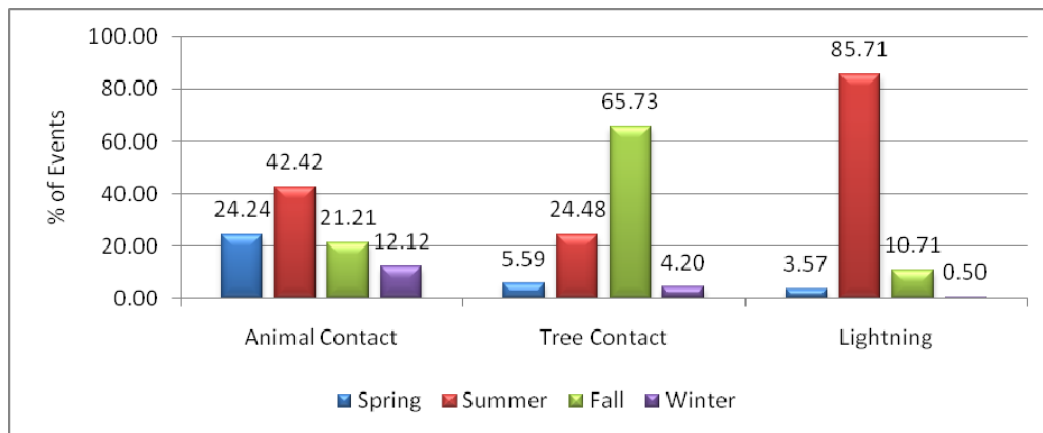


Figure 8-2
Seasonal Distribution of Animal-Contact, Tree-Contact, and Lightning Events

It can be seen that about 85% of lightning-induced disturbances occur in the summer, which happens to be the time of the year when thunderstorms are common. On the contrary, the lightning-induced events occurring in the winter are nearly zero. In addition, 65% of the tree-contact events occur during the fall when the wind is generally strong and the trees are losing their leaves. About 25% tree-contact events take place during the summer months, while the percentage in winter and spring is 4.2 and 5.59, respectively. On the other hand, animal-contact events are spread nearly evenly in spring and fall, with the percentage values of 24.24 and 21.21,

respectively. A majority of animal-contact-triggered events, 42.42% occurred in summer, while only 12.12% of the events took place in winter.

These three events can also be classified into *daytime* and *night time*, as shown in Figure 8-3. As mentioned earlier, *daytime* is defined between 6:00 am to 7:00 pm, while *night time* is from 7:00 pm to 6:00 am.

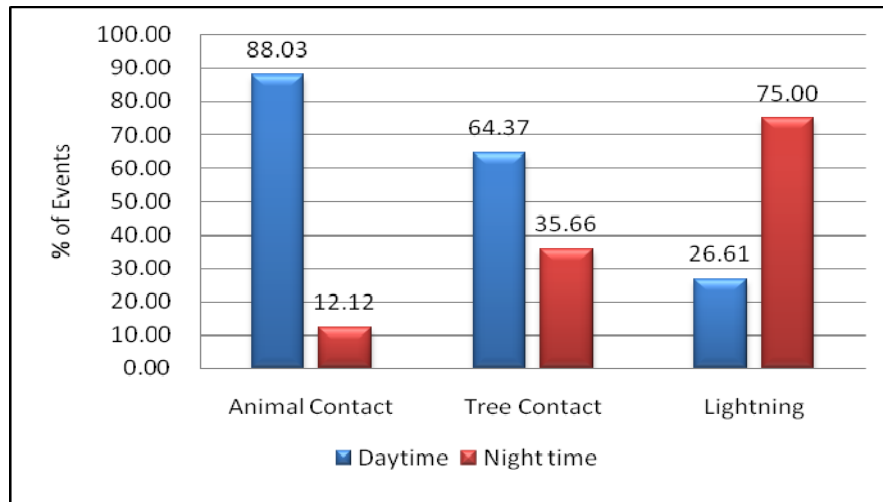


Figure 8-3
Classification of Animal-Contact, Tree-Contact, and Lightning Events into *Daytime* and *Night Time*

It can be seen that nearly 90% of the animal-contact-triggered events occur during the daytime. This depends on the kind of animals present in the geographical region of the utility. If a particular utility has a large presence of nocturnal animals in its region, the graph will be opposite to the one in Figure 8-3. In addition, 64% of the tree contact cases occur when the sun is shining, while three quarters of the lightning-induced disturbances occur when the sun has set.

Characteristic Signature Based on Phase Angles of Fault Events

Fault angle can be defined as the angle of the normal sine wave at the disturbance initiation point. It was construed during the initial part of the analysis that the tree-contact- and animal-contact-triggered power quality events would start around the peak of the sine wave. This premise is primarily based on the fact that the voltage gradient between the animal/tree branch and the power line is maximum at the peak. Figure 8-4 and Figure 8-5 show an animal-contact and tree-contact event, respectively, occurring near the positive peak of the sine wave. For the animal-contact case, the fault occurs in phase A, while in the tree-contact case, phase B is affected. The inception of the fault is characterized by a sudden sag in the voltage and a corresponding rise in the current of the same phase above the normal operating value.

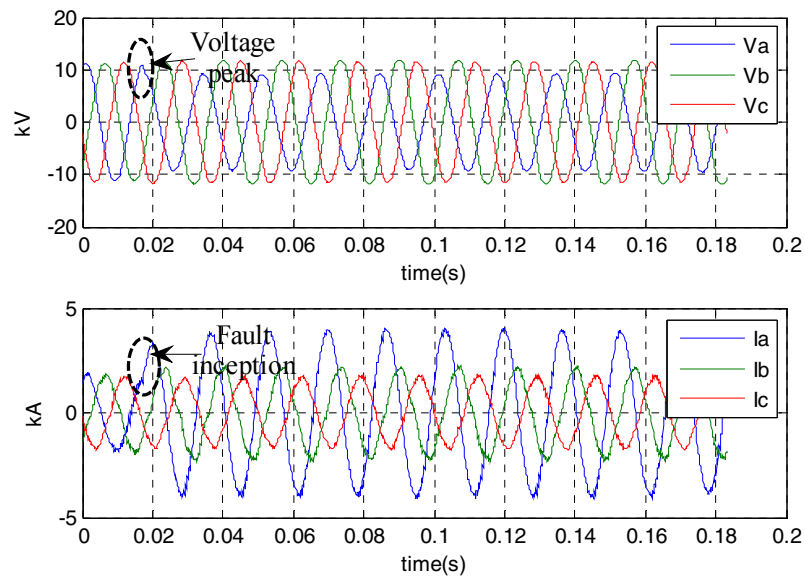


Figure 8-4
Animal-Contact Event Occurring at Voltage Peak

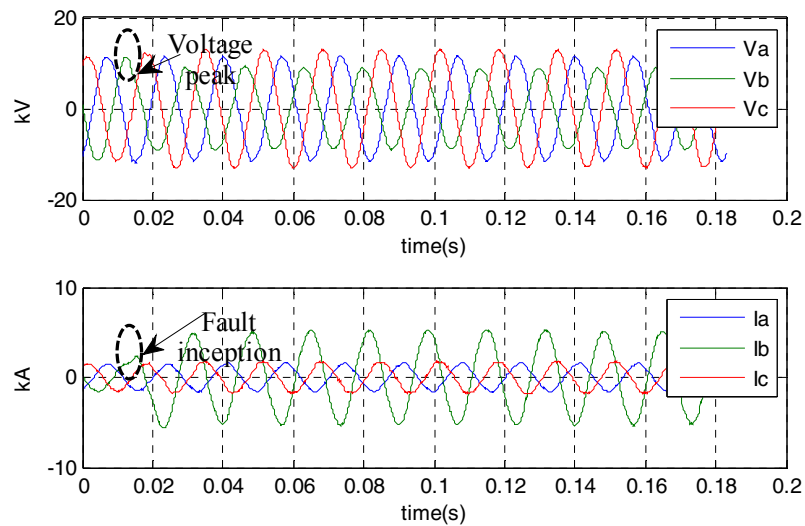


Figure 8-5
Tree-Contact Event Occurring at Voltage Peak

However, it was found that some lightning-induced events also occur at the peak of the sine wave, as shown in Figure 8-6. In this case, the fault inception is at the negative peak of the voltage, and phase C is affected.

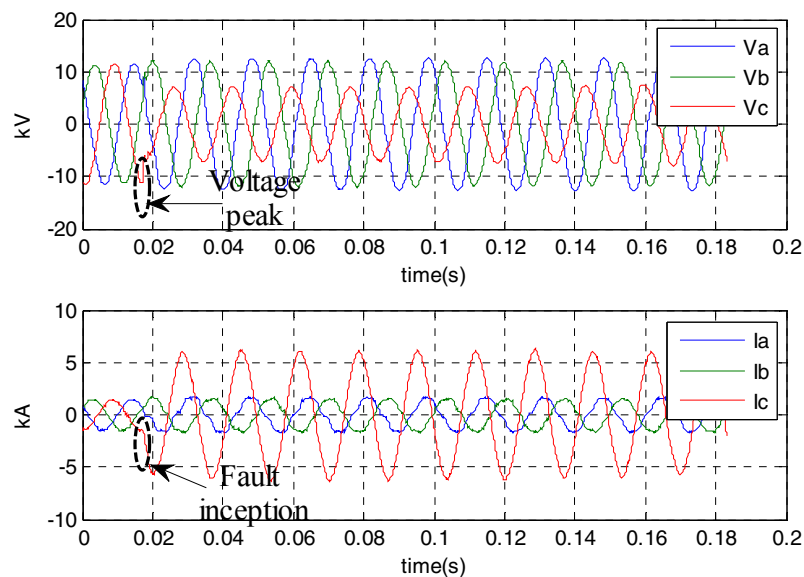


Figure 8-6
Lightning-Induced Event Occurring at Voltage Peak

The total power quality disturbance data was analyzed to find the fault-inception angles for animal-contact, tree-contact and lightning-induced events. The results for a total of 170 cases are summarized in Table 8-1. Sixty-seven cases were found to be ambiguous. Ambiguous cases are mostly those in which the waveform obtained from power quality monitoring station does not contain the beginning of the fault. Hence, it is not possible to find the fault-inception angle. On the other hand, in some cases it is unclear which phase is faulted. If the fault angle as defined at the start of this section is between 15° of the positive or negative peak ($\pm 90^\circ$) of the sine wave, the event is said to have an inception at the peak. All other events have an inception not around the peak.

Table 8-1
Fault-Inception Angle for Animal-Contact, Tree-Contact, and Lightning-Induced Cases

Event	Fault-Inception around Peak	Fault Inception NOT around Peak	Total Cases
Animal Contact	43 (70.5%)	18 (29.5%)	61
Tree Contact	66 (73.33%)	24 (26.67%)	90
Lightning Induced	16 (84.21%)	3 (15.79%)	19

It is seen that 48 out of 61 animal-contact events and 66 out of 90 tree-contact events (i.e. more than 70%) have the fault-inception angle near the peak of the sinusoidal waveform. However, it is observed that 16 out of 19 (or roughly 85%) of the lightning-induced events started near the peak. Thus being initiated around the peak of a sinusoidal wave, with the available data set, does not seem to be a very unique feature of any particular group. Nonetheless, it is also highly possible that these could be isolated cases where the lightning-induced events seem to have been

initiated around the peak of the sinusoidal waveform. Hence, further study needs to be conducted before a conclusion regarding the angle at which a disturbance is initiated can be reached.

Characteristic Signature Based on Number of Phases Involved

A fault can affect one, two, or all three phases of a distribution feeder. The number of phases involved in the fault depends on the cause of the fault. Generally, animal and tree contacts tend to affect only one phase, and hence these events are single-line-to-ground faults. On the contrary, a lightning stroke has the likelihood of affecting all three phases of the power lines. The number of faulted phases was found out for the 170 cases analyzed in the previous section, and the results are given in Table 8-2. A disturbance affecting only one phase is called a *single-phase fault*, while if two or three phases are affected, the event is categorized as a *multi-phase fault*.

Table 8-2
Number of Affected Phases for Animal-Contact, Tree-Contact, and Lightning-Induced Cases

Event	Single-Phase Faults	Multi-Phase Faults	Total Cases
Animal Contact	53 (86.88%)	8 (13.12%)	61
Tree Contact	66 (73.33%)	24 (26.67%)	90
Lightning Induced	8 (42.10%)	11 (57.90%)	19

It is seen that 53 out of 61 animal-contact events and 66 out of 90 tree-contact events (i.e. more than 70%) are single-phase faults. On the other hand, 11 out of 19 lightning-induced events (or roughly 60%) are multiphase. As in the case of the fault-inception angle, the number of phases involved is not a characteristic signature of any particular event. Further research needs to be conducted in order to better utilize this feature.

Characteristic Signature Based on Time Duration

Characteristically, lightning-stroke events are high-frequency transients having higher energy content as compared to contact-triggered events. The AC resistance of an overhead conductor increases with increasing frequency [51]. The line impedance of the conductors is also directly proportional to the frequency, which implies that the opposition to the flow of current in the distribution system increases with the frequency of the current traveling through it. This increased opposition to the flow of higher-frequency currents makes such high-frequency transients die down faster as compared to relatively lower-frequency transients. Thus, lightning-induced disturbances should tend to die down faster as compared to tree/animal-contact-triggered disturbances when traveling through the same distribution network. However, this may not always be the case, as seen in Figure 8-6, where the lightning-induced fault in phase C lasts for several cycles. Figure 8-7 shows a tree-contact event in which the fault in phase A is temporary and has a duration of just one cycle.

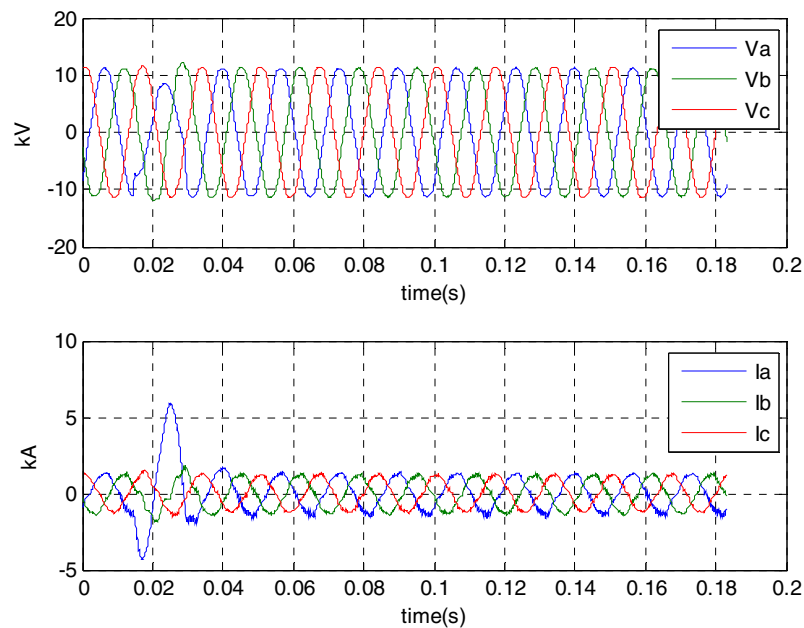


Figure 8-7
Tree-Contact Event Lasting for One Cycle

From the above examples it is clear that the time duration of the fault cannot be said to be a unique characteristic of any event. The duration of the fault is determined by the operation of the overcurrent protective device interrupting the fault. If a protective device detects a fault within the first cycle and opens, the duration is just one cycle. On the contrary, if the settings of the protective device allow it to open after the fault is sustained, then the duration can be several cycles. Thus, the duration of the fault is not necessarily dependent on the factor causing it, but moreover on the settings of the overcurrent protective device interrupting the fault.

Characteristic Signature Based on Arc Voltage

When a tree branch or an animal is about to be in contact with the power lines, there may be an electric arc struck in the medium (generally air) between the object and the line. The characteristics of the arc such as the arc length, arc impedance, and arc voltage hold crucial information about the cause of the disturbance. Arguably, the arc voltage is the most important characteristic out of all the above and can be used as a signature of the power quality disturbance. An algorithm to estimate the arc voltage developed in Chapter 3 is employed in this chapter. It should be noted that the algorithm can only be applied to single-line-to-ground faults and it only calculates the arc voltage of the affected phase. Animal- and tree-contact-triggered events involve a physical contact of an object with the power lines and hence tend to have an arc voltage higher than events induced by lightning strokes. Arc-voltage estimates for animal-contact (Figure 8-4), tree-contact (Figure 8-5), and lightning-induced (Figure 8-6) events are shown in Figure 8-8, Figure 8-9, and Figure 8-10, respectively. It can be seen that the animal- and tree-contact events have an arc voltage that is mostly more than 1 kV. On the contrary, the lightning-induced event has an arc voltage that largely remains much below 1 kV for the duration of the fault. The results obtained from the arc voltage estimation algorithm hold good only for the

duration of the fault. In addition, the arc voltage may not remain stable at one value during the fault because of changes in the fault current and unbalance in the distribution network.

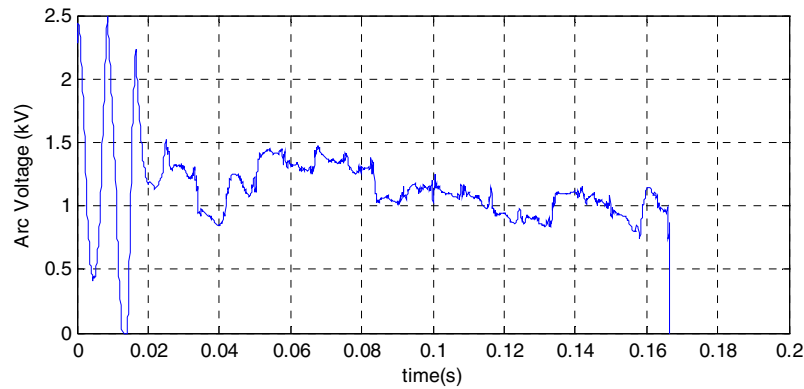


Figure 8-8
Arc Voltage in Phase A for the Animal-Contact Event Shown in Figure 8-4

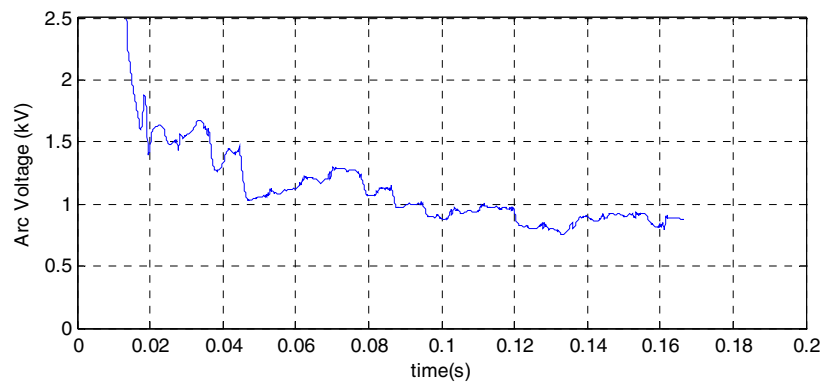


Figure 8-9
Arc Voltage in Phase B for the Tree-Contact Event Shown in Figure 8-5

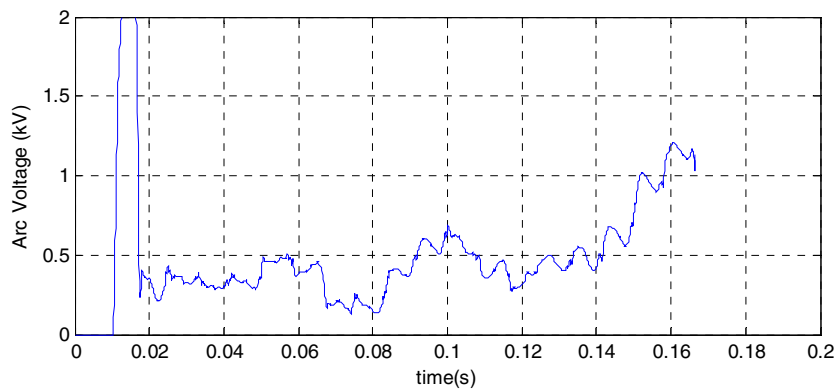


Figure 8-10
Arc Voltage in Phase C for the Lightning-Induced Event Shown in Figure 8-6

Results of arc voltage for all animal-contact, tree-contact, and lightning-induced power quality events in the given utility database are now discussed. As mentioned in the previous paragraph, the arc-voltage-estimation algorithm can be applied only to single-line-to-ground faults. In addition, only the events that have a stable arc voltage value have been selected for analysis, resulting in a total of 20 animal-contact cases, 24 tree-contact cases, and 14 lightning-induced cases. The arc voltage values from all of these cases are plotted in a normalized fashion, as shown in Figure 8-11. Twenty-five cable-failure cases from the same utility are included for the purpose of comparison.

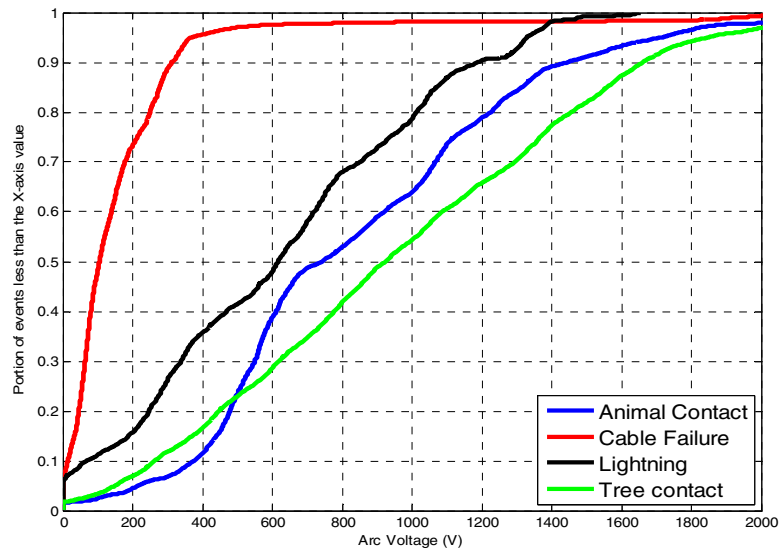


Figure 8-11
Normalized Arc-Voltage Distribution for Animal-Contact, Tree-Contact, and Lightning-Events

It is observed that lightning-induced events have the least arc voltage among the three categories, while tree contact events have the highest arc-voltage values. For the most part, animal-contact events have an arc voltage in between lightning-induced and tree-contact events. Compared with these three events, cable-failure-triggered disturbances have far less arc voltage.

Characteristic Signature Based on Wavelet Transforms

When a lightning event occurs, it comes with one or more current pulses (or strokes). The current stroke penetrates into the power system at the strike point. It may be followed by one or more strokes. The entire flash event occurs in a very short period, usually in a few hundred microseconds. Induced voltage and current transients propagate away from the strike point and are captured by power quality monitors. Regardless of the location of power quality monitors, (upstream or downstream from the lightning current injection), as long as they are located within the affected area, voltage and current waveforms should be captured almost simultaneously by all power quality monitors. Due to inaccuracy in time synchronization among power quality monitors, a one- or two-second difference may occur.

Lightning-induced waveforms may look quite different, depending on the distance between the strike point and a power quality monitor. PQ monitors near the strike point are likely to capture high-frequency oscillations at the initiation of the disturbance. PQ monitors at a different voltage level or some electrical distance apart are unlikely to capture these high-frequency oscillations because overhead lines and transformers are inductive. The following few disturbance waveforms are a result of a single lightning event. These disturbance waveforms were captured at 161 kV and 13.8 kV voltage levels. The lightning event was believed to strike close to a power quality monitor at the 161-kV system.

Figure 8-12 and Figure 8-13 show two sets of three-phase voltage and current waveforms caused by a lightning stroke that occurred at 10:01:22.000. Monitor T did not see the high current, while Monitor W-C saw it. This is because the lightning stroke was upstream from Monitor T but downstream from Monitor W-C. Note that an appreciable oscillatory transient (2.2 kHz) was present during the initiation of the disturbance. These two sets of waveforms were captured by power quality monitors at a 161-kV system. Figure 8-14 shows a set of waveforms due to the same lightning stroke. It was captured by a power quality monitor at a 13.8-kV system. Note that the waveforms (both voltage and current) are smooth and do not have an appreciable oscillatory transient.

These example waveforms indicate lightning-induced waveforms can have a number of wave shapes. Significant oscillatory transients in a voltage waveform may be present when the monitor is close to the lightning event. When the monitor is some distance apart from the strike point or at a different voltage level, the oscillatory transients are likely smoothed out. Based on the time proximity of captured waveforms, a cross-correlation technique could be used to cluster waveforms captured from different power quality monitors. A power quality monitor closest to the strike point would have an appreciable oscillatory transient. This set of three-phase voltage and current waveforms is then used as a reference for other sets captured around the same time.

The wavelet transform can be used to analyze and uncover the spectral content in the time-scale domain. In the following, a dyadic wavelet transform is applied to the above waveforms.

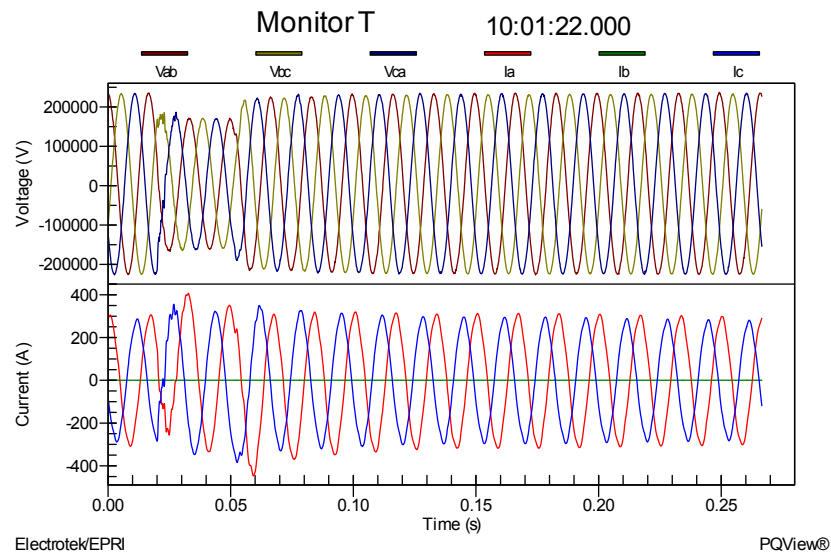


Figure 8-12
Three-Phase Voltage and Current Waveforms of a Lightning Event Captured at a 161-kV System. Monitor T Was Downstream from the Lightning Stroke.

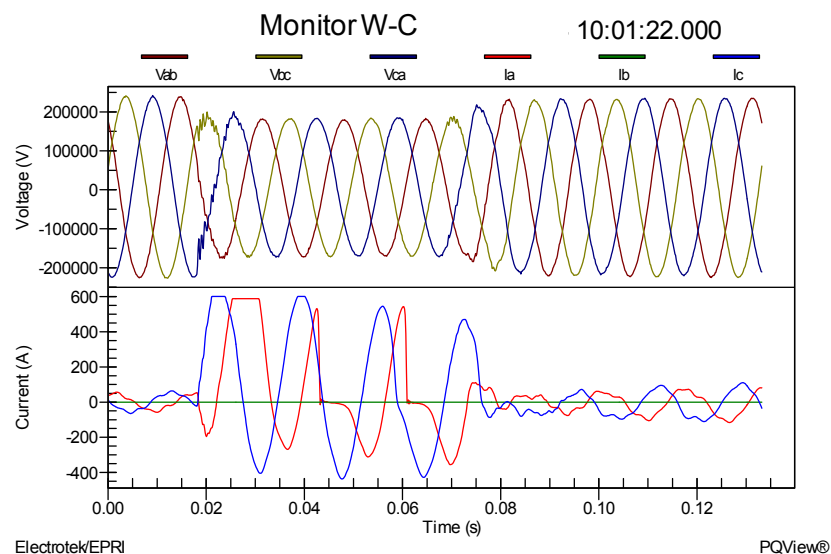


Figure 8-13
Three-Phase Voltage and Current Waveforms of a Lightning Event Captured at a 161-kV System. Monitor W-C Was Upstream from the Lightning Stroke.

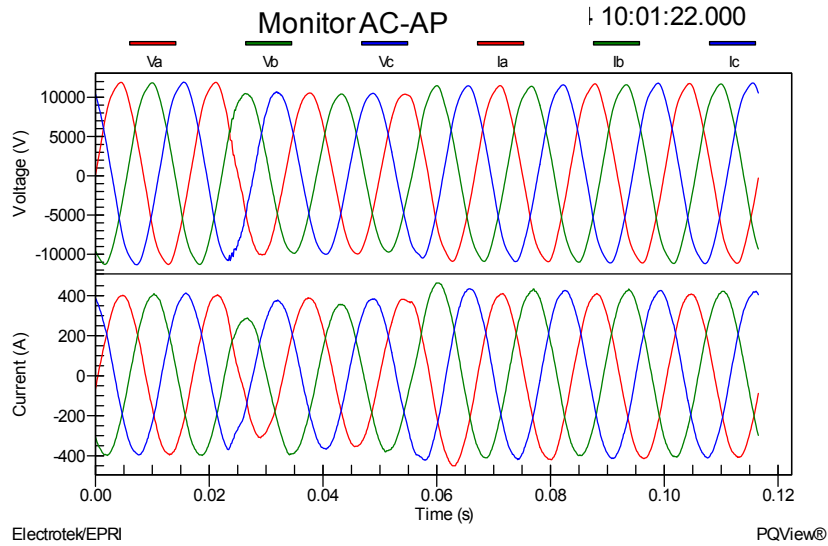


Figure 8-14
Three-Phase Voltage and Current Waveforms of a Lightning Event Captured at a 13.8 kV System

In the above example waveforms, a lightning event results in three-phase voltage sags. However, only one phase is analyzed below using the wavelet transform because results from other phases are similar. The voltage waveform captured by Monitors W-C (161 kV) and AC-AP (13.8 kV) are normalized and decomposed into three wavelet analysis scales. Figure 8-15 and Figure 8-16 show the square of the discrete wavelet transform outputs. They represent the time-scale energy spectra of the time-domain signal. The frequency content of each decomposition scale is as follows:

- Scale 1: frequency from 1920 – 3840 Hz
- Scale 2: frequency from 960 – 1920 Hz
- Scale 3: frequency from 480 – 960 Hz

Based on results shown in Figure 8-15 and Figure 8-16, it is clear that transients with high-frequency contents appear in lower scales, while those with lower-frequency contents appear in higher scales. Comparing the square of the transform outputs on the scale-by-scale basis, for the voltage waveform captured by Monitor W-C, the maximum energies in scales 1, 2, and 3 are 1.7×10^{-2} , 4.3×10^{-2} , and 5.4×10^{-2} , respectively. In contrast, for the voltage waveform captured by Monitor AC-AP, the maximum energies in the first two scales are 2.6×10^{-3} and 7.8×10^{-4} . Its third scale does not contain meaningful maximum energy information. The difference between these results is quite significant. They indicate that lightning-induced waveforms may be identifiable in the wavelet domain if a power quality monitor is near the strike point. For lightning-induced waveforms captured by remote power quality monitors, they can be identified indirectly through the use of time-proximity cross-correlation approach and other identifying signatures described above.

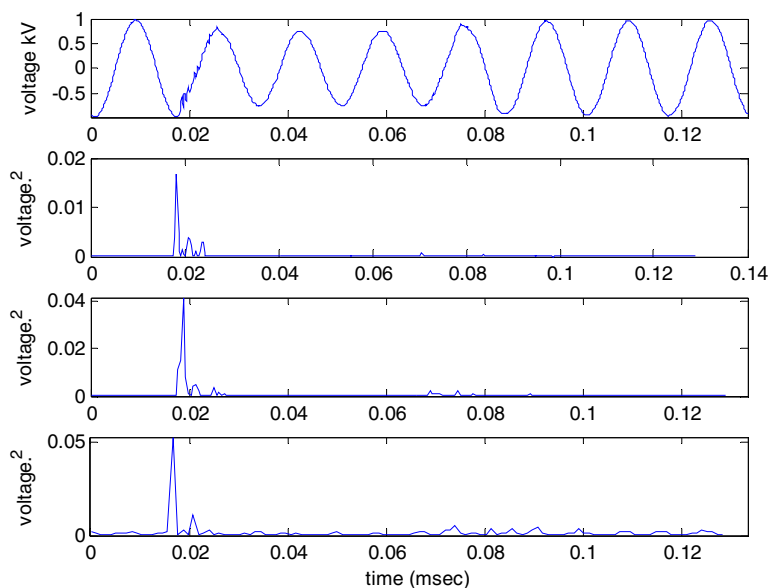


Figure 8-15
A Three-Scale Wavelet Transform of a Lightning-Induced Voltage Waveform Captured by Monitor A-C (161 kV)

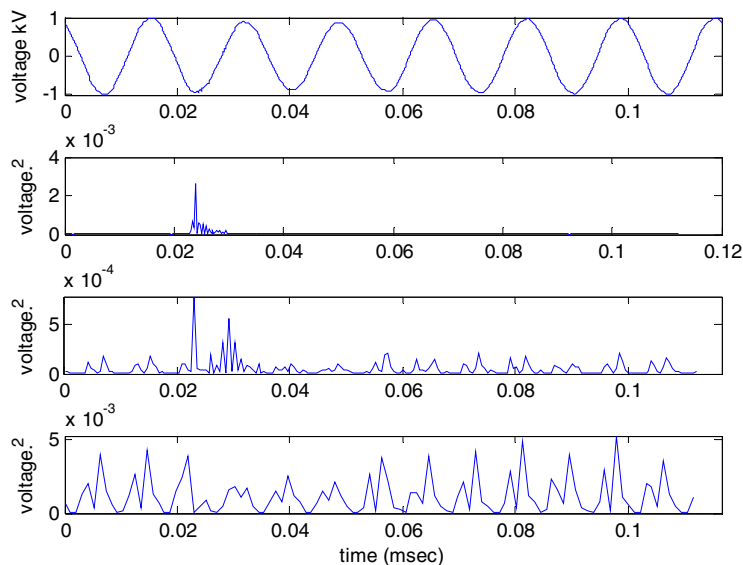


Figure 8-16
A Three-Scale Wavelet Transform of a Lightning-Induced Voltage Waveform Captured by Monitor AC-AP (13.8 kV)

Tree-contact events have a number of wave shapes as well. They are dependent on the voltage level where the tree contact occurs. As pointed out earlier, a tree-contact event is more likely to occur at the peak of the voltage. The following waveforms show near simultaneous tree contacts

believed to occur on a transmission line. They were captured by power quality monitors installed at transmission and distribution systems. Figure 8-17, Figure 8-18, and Figure 8-19 show multiple identical tree contacts captured by Monitor NH (161 kV), CE1 (161 kV), and AC-AP (13.8 kV), respectively. Unlike tree contacts on distribution lines, they do not result in a permanent fault. Waveforms captured at a transmission-system level do possess more significant transients than those captured at a distribution-system level. This is because inductive elements (transformers and overhead lines) of the power system offer higher impedance at a higher frequency.

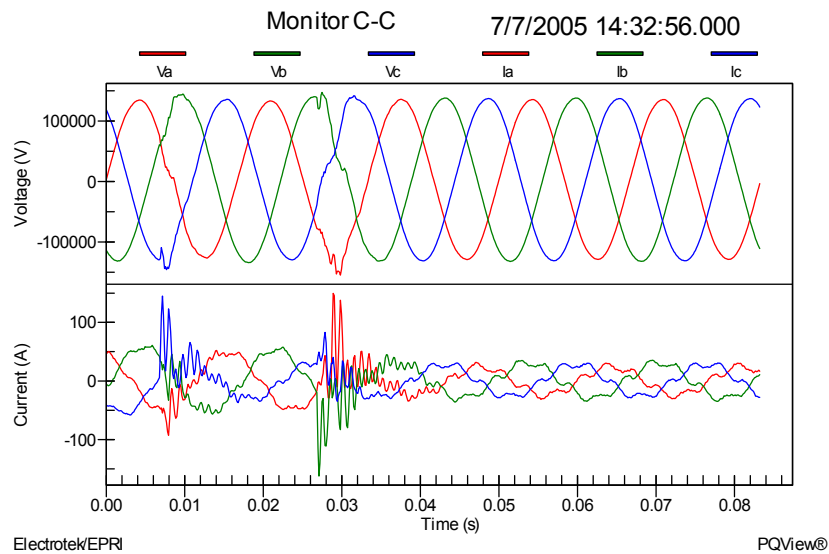


Figure 8-17
Three-Phase Voltage and Current Waveforms of Multiple Tree Contacts Captured at a 161-kV System (Monitor NH)

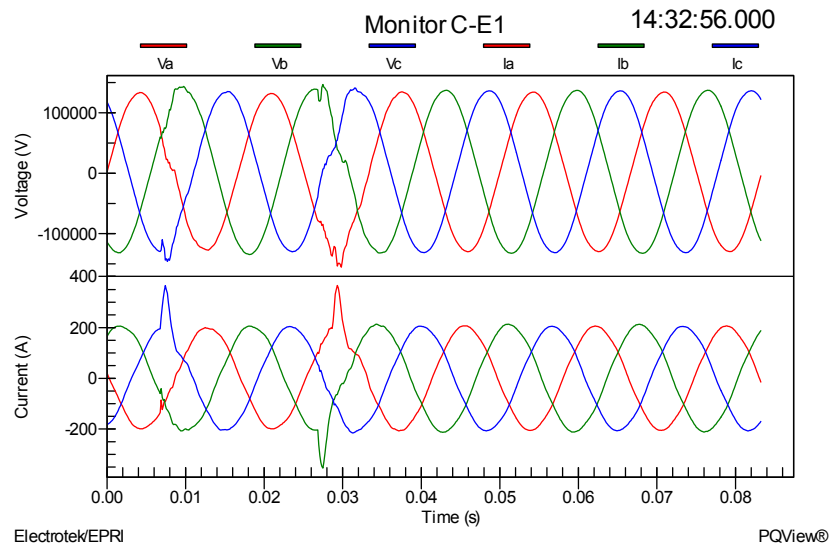


Figure 8-18
Three-Phase Voltage and Current Waveforms of Multiple Tree Contacts Captured at a 161-kV System (Monitor CE1)

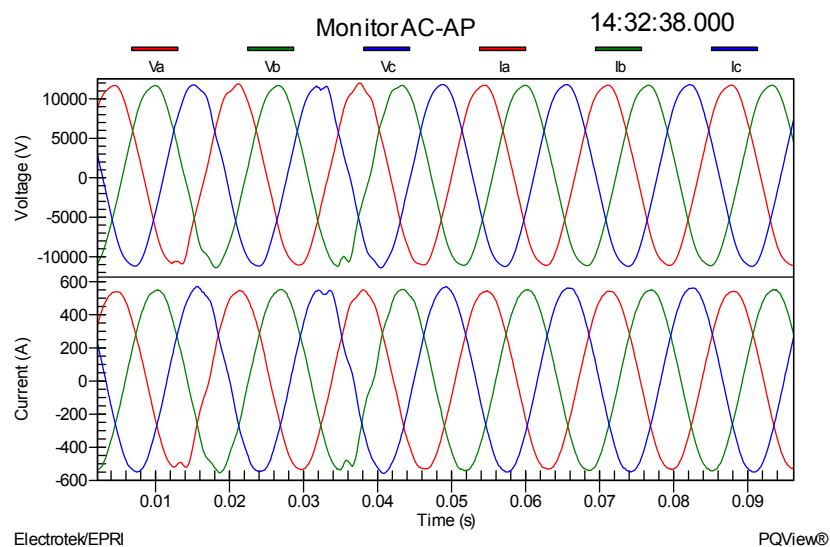


Figure 8-19
Three-Phase Voltage and Current Waveforms of Multiple Tree Contacts Captured at a 13.8-kV System (Monitor AC-AP)

The squared of the wavelet transform output of voltage waveforms captured by Monitors C-C (161 kV) and AC-AP (13.8 kV) are shown in Figure 8-20 and Figure 8-21, respectively. The frequency content of each decomposition scale is the same given for those of lightning-event analysis. For the voltage waveform captured by Monitor C-C (161 kV), the maximum energies in scales 1, 2, and 3 are 2.1×10^{-3} , 1.39×10^{-2} , and 3.3×10^{-2} , respectively. In contrast, for the voltage waveform captured by Monitor AC-AP, the maximum energies in each scale are 9.4×10^{-7} , 1.28×10^{-5} , and 1.2×10^{-4} . Comparing these values to those shown earlier for a lightning event,

scale 1 value for a voltage waveform (captured at 161 kV) caused by a lightning event is approximately 10 times higher than that for a tree-contact event (captured at 161 kV also). For scales 2 and 3 values, they are comparable. Using very limited waveform samples, it is observed that lightning events appear to possess higher-frequency contents than tree-contact events. This is reasonable given the fact that lightning tends to have a higher frequency due to the travelling-wave phenomenon arising from the discontinuity (from a piece of equipment to another) encountered during the pulse propagation.

The above analysis hints that lightning events may be distinguishable from tree contact events in the wavelet domain. This is especially true if events are captured by a nearby power quality monitor. Further investigations are necessary to study the statistical behavior of the wavelet-transform outputs.

Unfortunately, waveforms captured by a distant power quality monitor are difficult to characterize (e.g., transmission-level events captured at a distribution-level power quality monitor). The inductive elements of the power system mellow the oscillatory transients, blurring the unique waveform signatures.

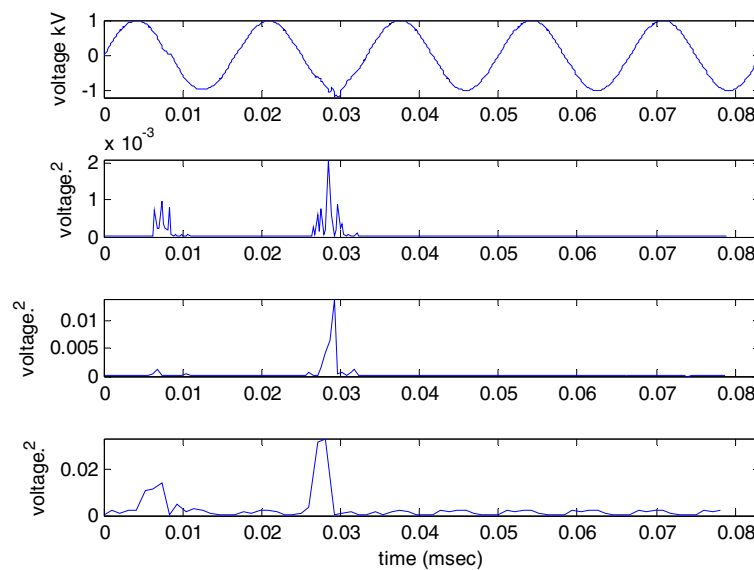


Figure 8-20
Three-Scale Wavelet Decomposition of a Tree-Contact Voltage Waveform Captured by Monitor NH (161 kV)

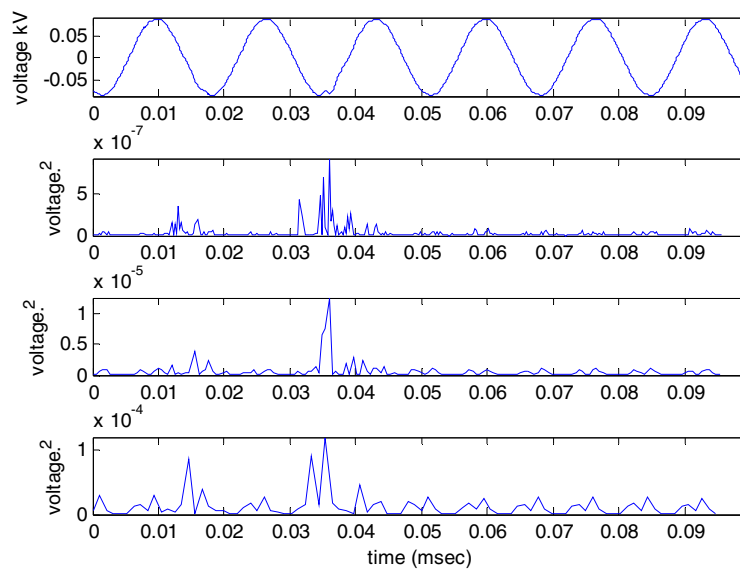


Figure 8-21
Three-Scale Wavelet Decomposition of a Tree-Contact Voltage Waveform Captured by
Monitor AC-AP (161 kV)

Summary

Power quality monitors present in the distribution network record the voltage and current waveforms of the disturbances occurring in the network. These waveforms possess vital information pertaining to the cause of the disturbance. This information was extracted in the form of characteristic signatures, which can be used for event classification. The analyzed signatures included the time of occurrence, fault phase angle, number of affected phases, time duration of the fault, arc voltage, and wavelet-domain analysis. Using the time of occurrence, the events were classified according to the season and also the time of day. It was found that most lightning events took place during the summer months, while a majority of the animal contact events occurred during daytime. Both contact events, animal and tree, were generally affecting only one phase of the distribution line, and these events usually had a fault-inception angle near the peak of the sine wave. On the other hand, the time duration of the fault proved to be an inconclusive characteristic signature. Furthermore, lightning-induced events had an arc voltage that was lower than both the contact events. In addition, it was suggested that lightning events could be distinguishable from tree-contact events in the wavelet domain.

Through the course of this analysis, it was found that no single signature can exclusively identify a given event. However, a combination of these signatures can be used to uniquely characterize the animal-contact, tree-contact, and lightning-induced events. Future work involves studying more disturbance waveform signatures like fault impedance, energy content, and rate of change of power.

9

FAULT EVENTS RESULTING IN CURRENT-LIMITING FUSE OPERATIONS

Unique characteristics buried in voltage and current waveforms are useful to identify the root cause of a fault event. These characteristics can be extracted from the portion of a waveform having a fault. This portion can be oscillatory, sagged, or swelled, or have other abnormal wave shapes. Its duration is determined by the overcurrent protective device interrupting the fault current. It may be a substation circuit breaker, a line recloser, a sectionalizer, or a fuse (either current-limiting or expulsion type). For a fault event isolated by a current-limiting fuse, the time during which the fault is in the system is typically about one-quarter of a cycle. Voltage and current waveform characteristics during the fault are dominated by the arc-extinction process taking place in the current-limiting fuse. They hardly belong to the fault event that gives rise to the high current magnitudes. For this reason, identifying the root cause of a fault event cleared by a current-limiting fuse is impossible. Therefore, the objective of this chapter is to extract voltage and current waveform characteristics to determine whether the fault event results in the operation of a current-limiting fuse.

For a fault event isolated by other protective devices, the time duration of the fault is usually a few cycles. Voltage and current waveforms captured during the fault event provide a wealth of information about the nature of the fault. Earlier chapters describe waveform characteristics of faults cleared by a protective device.

Introduction

Current-limiting fuses are typically used where fault current is often very high and the damage to fuse-protected equipment caused by a fault would result in catastrophic failure [52][53]. Current-limiting fuses attempt to prevent catastrophic failure by forcing fault current to zero in a short time (less than $\frac{1}{2}$ of a cycle). This action significantly reduces the amount of energy dissipated in the faulted equipment. In contrast, an expulsion fuse waits until the current crosses zero, resulting in longer exposure to high fault current. The use of current-limiting fuses has the added benefit of shortening the duration of a voltage sag that occurs during a fault and can improve the power quality of the system.

A current-limiting fuse is made of a coil of thin ribbon element or wire around a form and enclosed in an insulating tube filled with sand. The insulating tube is designed to withstand the pressure build up during the fuse operation without rupturing [52]. During a fault, the fuse element melts, and the time from fault inception to the melting of the fuse element is defined as the *fuse melting time*. Next, the sand inside the insulating tube melts and aids in creating a voltage drop across the fuse, which opposes the flow of current, eventually forcing the current to zero. Figure 9-1 shows the operating principle of the fuse.

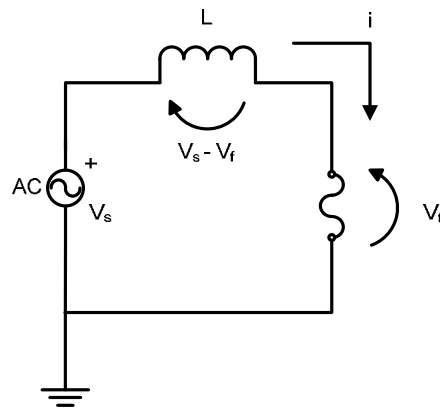


Figure 9-1
Operating Principle of a Current-Limiting Fuse

Where v_f is the voltage at the fuse terminals, v_s is the source voltage, L is the source impedance, and the instantaneous current i is given by Eq. (9.1).

$$i = \int \frac{v_s - v_f}{L} dt$$

Eq. 9-1

The voltage at the fuse terminals appears once the prospective breaking current is reached. The prospective breaking current is the current through the fuse at which the breaking capacity of the fuse is reached. Once the voltage across the fuse exceeds the source voltage v_s , the instantaneous current i begins to decrease until the arc is extinguished. Figure 9-2 illustrates the operation of an ideal current-limiting fuse, where the current is the instantaneous current.

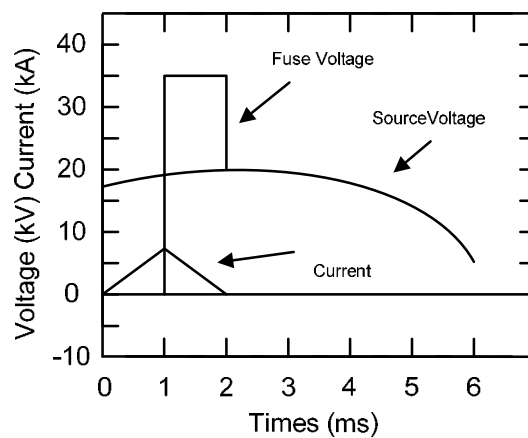


Figure 9-2
Fuse Current, Fuse Voltage, and Source Voltage during the Operation of an Ideal Current-Limiting Fuse

The next sections show examples of current and voltage waveforms and characteristics of the operation of current-limiting fuses to identifying these types of events. The last section identifies and quantifies the unique characteristics of current-limiting fuse operation as seen in the current and voltage waveforms recorded at a monitoring station located upstream from the fault.

Waveforms of Current-Limiting Fuse Operation

The voltage and current waveforms shown below share common characteristics that help identify events as current-limiting fuse operations. Some characteristics include:

- The duration of the event is usually less than $\frac{1}{2}$ a cycle.
- The faulted current waveform during the event rises sharply and drops once the fuse element has melted.

The voltage waveform usually drops below the nominal voltage and stays close to that value until the arc is cleared. Clearing of the arc happens when the current through the fuse is forced to zero; therefore, it does not happen instantaneously. This causes the voltage waveform to look as if a square chunk has been removed. After the arc has been extinguished, the voltage waveform returns to its pre-fault value. Using the above characteristics, it is possible to identify current-limiting fuse operations by visual inspection.

Examples of voltage and current waveforms of current-limiting fuse operations are shown in Figure 9-3, Figure 9-4, and Figure 9-5. The waveforms were recorded upstream from the fault at a monitoring station. In other words, the fault is downstream from the monitoring station. The utility consists of predominantly overhead lines with a voltage level of 13.8 kV.

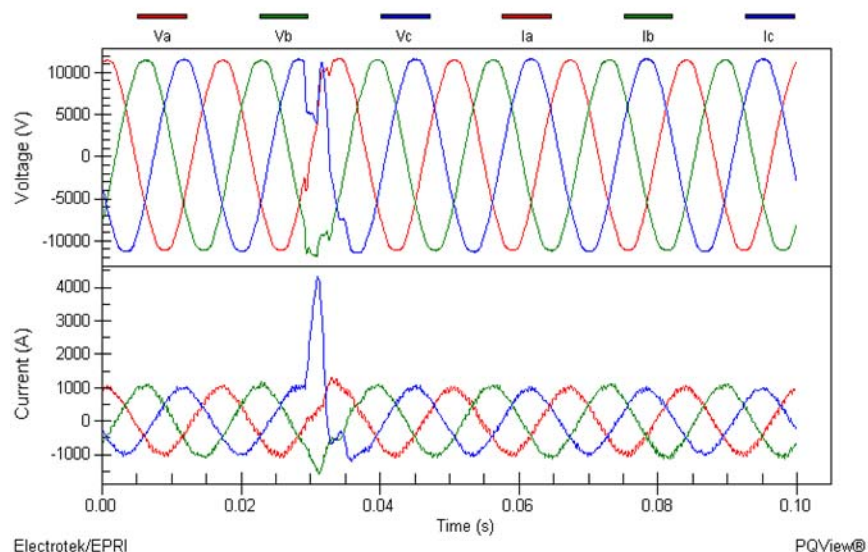


Figure 9-3
First Example of a Current-Limiting Fuse Event Showing Three-Phase Voltage Waveforms and Three-Phase Current Waveforms

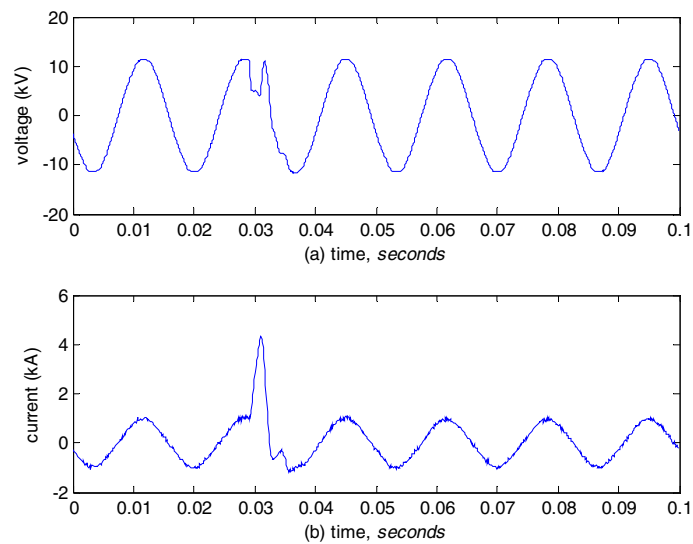


Figure 9-4
First Example of a Current-Limiting Fuse Event Showing (a) Faulted Phase Voltage
Waveform and (b) Faulted Phase Current Waveform

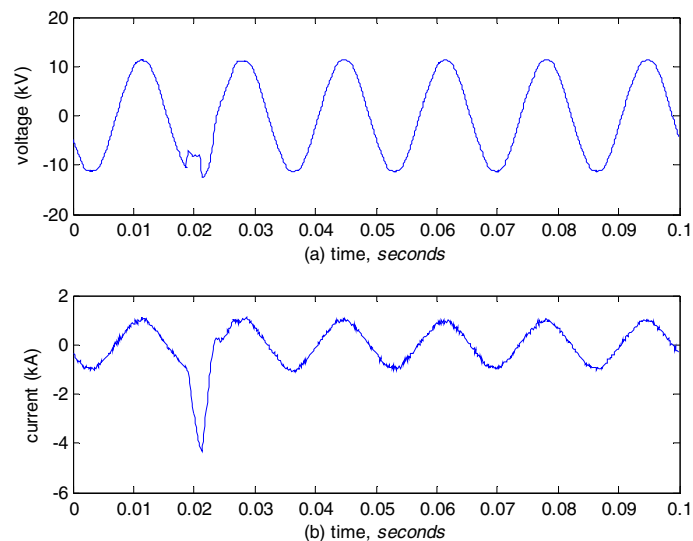


Figure 9-5
Second Example of a Current-Limiting Fuse Event Showing (a) Faulted Phase Voltage
Waveform and (b) Faulted Phase Current Waveform

Waveforms Similar to But Not of Current-Limiting Fuse Operation

There are certain events that when analyzed may appear to be current-limiting fuse (CLF) operations, even though they are not. This is due to a few characteristics that they have in common with current-limiting fuse operations. In this section, the voltage and current waveforms

caused by these non-CLF events are examined. For example, the current waveform in Figure 9-6 looks similar to a current-limiting fuse operation. When the voltage waveform for the same phase is examined, it can be seen that almost immediately after the voltage drops, it begins to rise again to its pre-event value. It can be seen in the other two phases of the voltage waveforms that the voltages also begin to drop towards zero. For a current-limiting fuse operation, only the faulted phase should be affected and the other two phases should not be altered. The event in Figure 9-6 was actually a capacitor bank switching event.

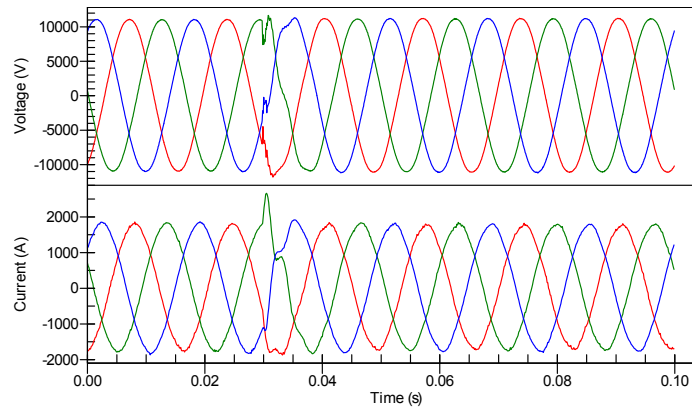


Figure 9-6
First Example of a Non-Current-Limiting Fuse Event Showing Three-Phase Voltage and Current Waveforms

The current waveform in Figure 9-7 below is also similar to the current waveform of a current-limiting fuse operation. However, the faulted phase voltage does not have the same characteristics as a current-limiting fuse operation. The faulted phase voltage drops toward zero but does not stay at that value until the fault is cleared. Instead, the voltage continues to drop. In the following section, a more detailed analysis of the waveforms is carried out. The characteristics are quantified and analyzed for a variety of events.

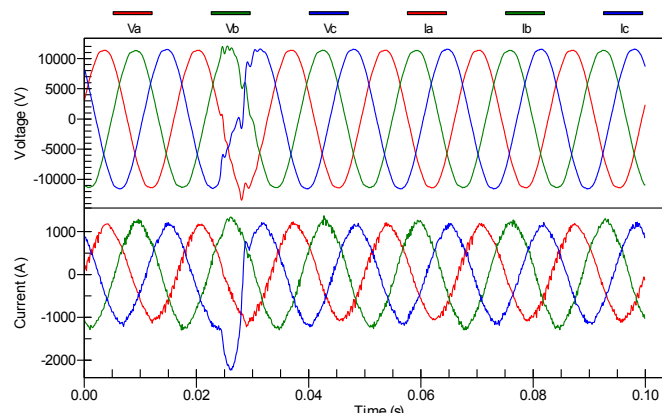


Figure 9-7
Second Example of a Non-Current-Limiting Fuse Event Showing Three-Phase Voltage and Current Waveforms

Unique Characteristics of Waveforms of Current-Limiting Fuse Operation

As mentioned in the previous section, there are some characteristics in the current and voltage waveforms of current-limiting fuse operations that can be identified by visual inspection. Through visual inspection, a number of current-limiting fuse operations were selected from the events database provided participating utilities. A more thorough examination using algorithms described in the appendix is able to identify unique current-limiting fuse operation characteristics and quantified these characteristics. New characteristics were also identified in the current and voltage waveforms through the use of numerical analysis and other techniques used by the algorithms described in the previous chapters.

The first part of the analysis examines the characteristics of the current waveform of the faulted phase. The characteristics of interest are as follows:

- The duration of the event
- The current phase angle at which the event starts
- The current phase angle at which the event ends
- The current rise time from the start of the event to when the fuse melts
- The current fall time after the fuse melts to the end of the event
- The ratio of the peak fault current to the pre-fault load current

The faulted current waveform consists of pre-fault load current, the load current plus the fault current during the event, and the load current after the fault has been isolated by the fuse, as shown in Figure 9-8.

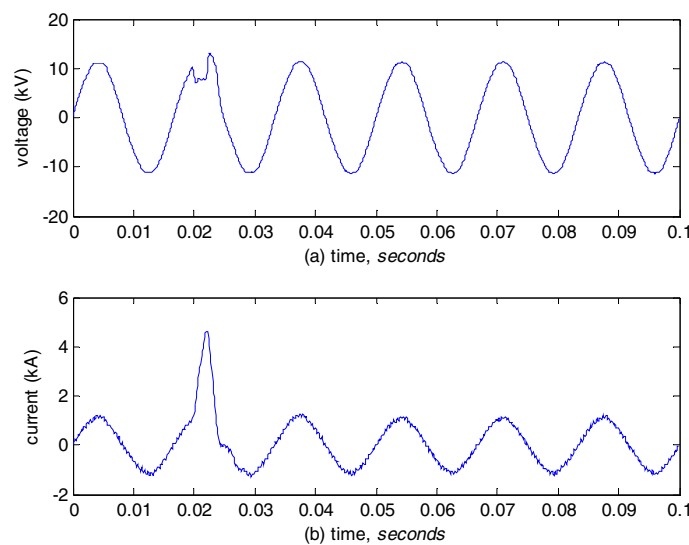


Figure 9-8
Example of Current-Limiting Fuse Operation Used to Examine Characteristics of (a)
Faulted Phase Voltage Waveform and (b) Faulted Phase Current Waveform

In order to extract the characteristics listed above, the fault current needs to be isolated from the current waveform. If it is assumed that the load current does not drastically change during the fault, the fault current can be estimated by taking the difference between the current during the fault and the load current during the fault. The load current during the fault is estimated using Eq. (9.2):

$$i_{\text{replica}} = \sqrt{2} \cdot I_{\text{RMS}} \cdot \sin(2\pi \cdot f \cdot t + \theta) \quad \text{Eq. 9-2}$$

where, I_{RMS} = the RMS current

f = the frequency

θ = the phase angle

i_{replica} = the estimated load current during the fault event

All of the parameters are estimated using the pre-fault portion of the current waveform.

The estimated load current using the equation above is shown in Figure 9-9 along with the actual recorded data i_{measured} . When i_{replica} and i_{measured} are plotted together, by visual inspection it is easy to determine where the event begins and ends.

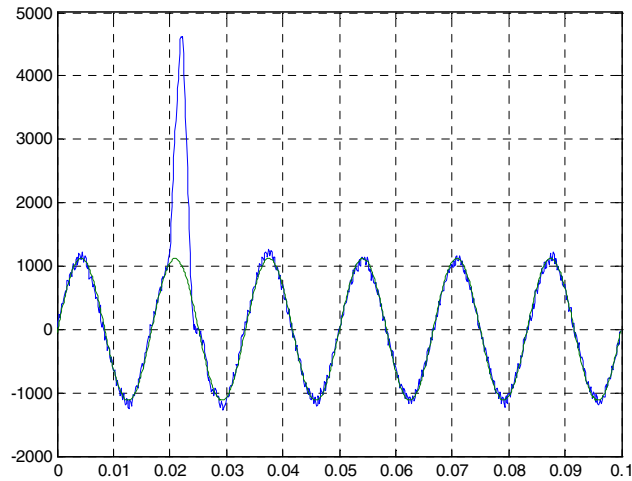


Figure 9-9
Example of Measured Current i_{measured} and Replica Waveform i_{replica} Plotted on the Same Graph

The difference i_{diff} (difference between i_{replica} and i_{measured}) is used as the fault-current estimate and is shown in Figure 9-10.

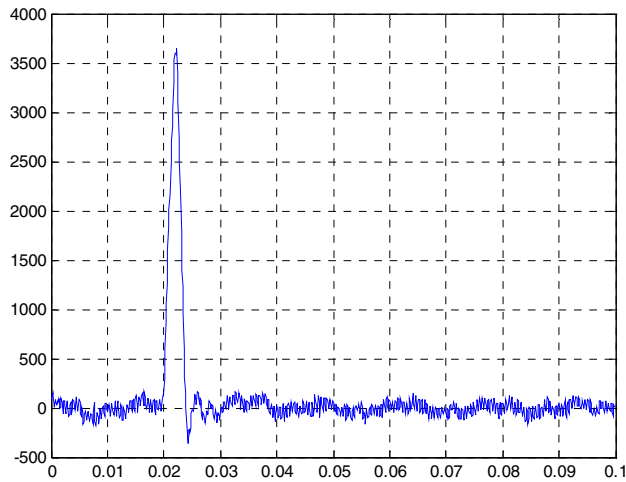


Figure 9-10
Example of Difference Current i_{diff} Which Is Used as the Fault Current Estimate

Because the measured waveform is not perfectly sinusoidal, the estimated load current, or $i_{replica}$, does not exactly match the measured data, $i_{measured}$, as can be seen in the difference current, i_{diff} , in Figure 9-10. This pre- and post-fault noise makes it more difficult to find exactly when the fault event begins and ends. Currently, the noise is not removed and the methods described below are used to estimate the current-limiting fuse characteristics found in the current waveform.

Using, i_{diff} , the fault start time, t_{start} , and fault end time, t_{end} , are estimated using the following method. The peak current, i_{peak} , and the time at which the peak current occurs (t_{peak}) are identified. The first zero crossings before and after the peak current are identified and labeled as the start fault time, t_{start} , and the end fault time, t_{end} . The duration is then calculated by taking the difference between t_{end} and t_{start} . Once the ending and starting times of the event and the peak fault current time have been identified, the rise time and fall time of the fault current can be easily calculated by using Eq. (9.3).

$$\frac{dI}{dt} = \frac{I_{peak} - I_{start/end}}{t_{peak} - t_{start/end}} \text{ A / s} \quad \text{Eq. 9-3}$$

Another characteristic that may help identify current-limiting fuse operations is the point on the current waveform when fault inception occurs. This is useful because most interruptions occur at the voltage peak. The estimated starting time, t_{start} , and ending time, t_{end} , of the event and the estimated phase angle, θ , are used to find the point of the waveform where the event starts and where the event ends. A visual of how the phase angle is estimated is shown in Figure 9-11. The current waveform with the starting and ending times for the event can be seen in the top half of Figure 9-11. The bottom half of the figure shows the phase angle, θ , where the phase angle is zero degrees at a negative-to-positive zero crossing point in the waveform, 90 degrees at the positive peak of the waveform, and so on.

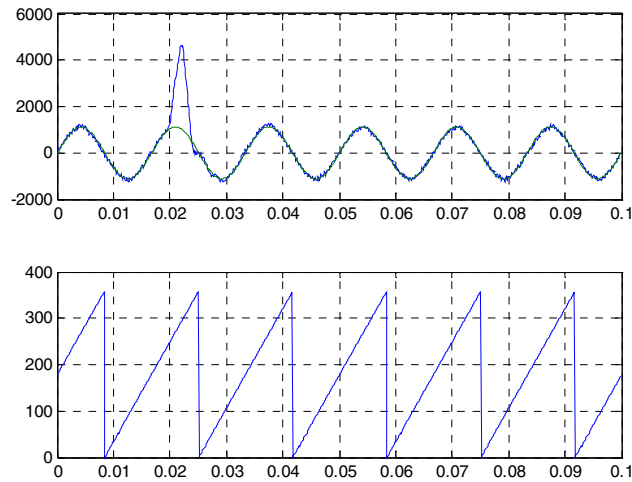


Figure 9-11
Estimation of Starting and Ending Phase Angle of the Event

The ratio between the peak fault current and load current is calculated by taking the ratio of the maximum fault current, i_{peak} , and the value of current from, $i_{replica}$ at the same instant in time, t_{peak} . The thermal energy, or I^2t , is also calculated by integrating the square of the fault current during the estimated event time.

The analysis described above was completed for 38 current-limiting fuse operation waveforms identified from the data collected by a number of utilities. The results from all of the analyses are shown in Table 9-1.

Table 9-1
Current Waveform Characteristics for Current-Limiting Fuse Events in the Events Database

Event No.	Duration (Cycles)	Phase Start	Phase End	dI/dt Start	dI/dt End	Fault/Load	I ² t Total
1	0.3047	104	214	932.500	2125.658	1.840	1.26E+06
2	0.2813	113	214	1045.000	2533.594	2.128	1.07E+06
3	0.2500	107	197	1916.250	2375.000	1.978	1.03E+06
4	0.2734	307	45	1315.385	1716.071	2.217	8.10E+05
5	0.2578	273	6	2792.045	2259.868	3.922	1.29E+06
6	1.7578	264	177	340.972	229.464	1.308	3.55E+06
7	0.2969	276	23	838.235	1637.500	2.047	1.20E+06
8	0.3125	278	31	1192.500	1594.643	2.650	9.66E+05
9	0.3203	248	3	1647.656	1456.500	3.306	1.65E+06
10	0.2969	65	172	1442.647	1648.214	2.961	1.57E+06

Table 9-1 (continued)
Current Waveform Characteristics for Current-Limiting Fuse Events in the Events Database

Event No.	Duration (Cycles)	Phase Start	Phase End	di/dt Start	di/dt End	Fault/Load	I ² t Total
11	0.3203	256	11	1351.974	1960.417	3.462	1.41E+06
12	0.2656	110	205	1857.692	2567.500	3.585	9.52E+05
13	0.4063	31	177	751.210	1935.000	2.909	1.26E+06
14	0.4141	65	214	985.096	1459.722	3.012	2.96E+06
15	0.3438	34	158	1115.625	1434.375	2.942	1.83E+06
16	0.7578	93	6	792.647	1213.043	2.339	3.96E+06
17	0.2734	82	180	1305.882	1943.750	2.675	1.23E+06
18	0.2734	107	205	1862.500	2358.553	2.762	1.24E+06
19	0.2500	281	11	2294.318	2664.706	2.873	1.36E+06
20	0.2813	295	37	1410.577	2439.844	2.455	9.01E+05
21	1.4844	177	352	646.250	685.000	1.188	1.26E+07
22	1.4063	56	203	846.835	2371.500	2.376	2.79E+07
23	0.2891	101	205	980.000	1910.417	2.269	9.36E+05
24	0.3281	267	25	1104.808	1543.965	1.735	1.84E+06
25	0.2813	318	59	1389.844	2957.143	3.323	8.02E+05
26	0.3750	82	217	978.947	1773.214	1.862	3.33E+06
27	0.2813	253	354	1403.906	1841.250	2.328	1.72E+06
28	0.4609	73	239	1268.055	1821.094	2.749	9.12E+06
29	0.3125	276	28	813.971	1423.125	2.535	7.99E+05
30	0.3750	87	222	1203.571	1764.000	2.938	2.90E+06
31	0.3906	79	219	1072.159	1664.423	2.741	2.88E+06
32	0.3438	107	231	1233.088	1741.500	2.403	1.91E+06
33	0.2969	295	42	1856.250	2595.395	2.668	1.87E+06
34	0.2734	113	211	1374.107	2755.147	2.000	1.25E+06
35	0.2813	93	194	1478.571	2566.667	2.088	1.75E+06
36	0.3359	284	45	816.667	1651.875	2.167	1.03E+06
37	0.5703	267	113	1401.562	1081.875	2.910	2.69E+06
48	0.2813	304	45	1400.893	2201.470	2.791	8.03E+05

The results are also plotted in Figure 9-12 and Figure 9-13 in order to provide a visual representation. In Figure 9-12, the average current-limiting fuse event duration is approximately a quarter of a cycle, with a standard deviation of approximately 0.10 cycles.

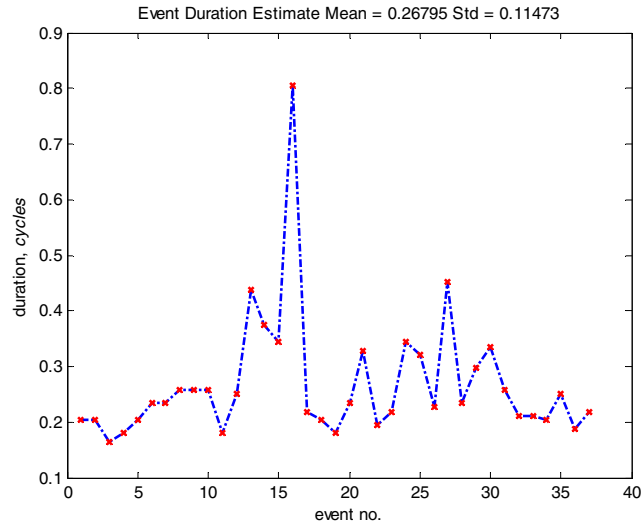


Figure 9-12
Estimates for Current-Limiting Event Durations Using the Current Waveform

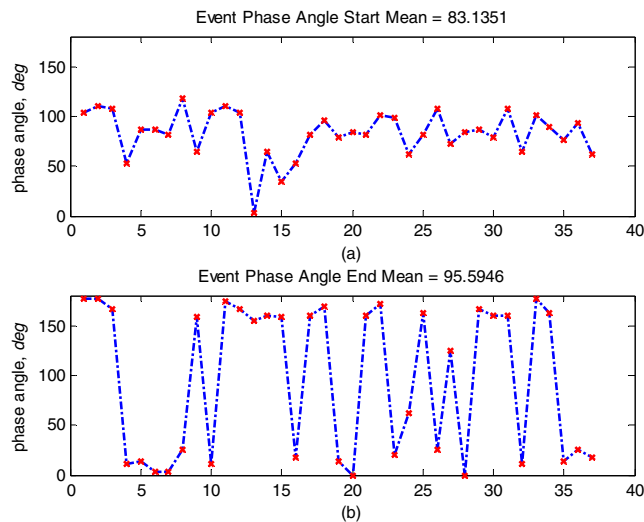


Figure 9-13
Estimates for Current-Limiting Event Phase Angle Showing (a) Starting Phase Angle and (b) Ending Phase Angle

In Figure 9-13, the estimates for the point on the waveform when the event begins and when the event ends is plotted. On average, the fault inception usually begins near the peak of the current waveform. Because it was seen from the duration estimate that current-limiting fuse events last approximately $\frac{1}{4}$ of a cycle, the event should end at or near the zero crossing. This is exactly what is shown in Figure 9-13, where the event ends at either 0° or 180° , depending on whether the event started at the positive or negative peak of the current waveform.

In Figure 9-14, the estimates for the current waveform during the current-limiting fuse event ramp rates are plotted. The average ramp-up rate is lower than the ramp-down rate. The ratio of the peak fault current to the load current is shown in Figure 9-15. The average ratio is

approximately 3.15, and the standard deviation is fairly high, approximately 0.82. However, from the plot, the peak fault current is at least twice the load current.

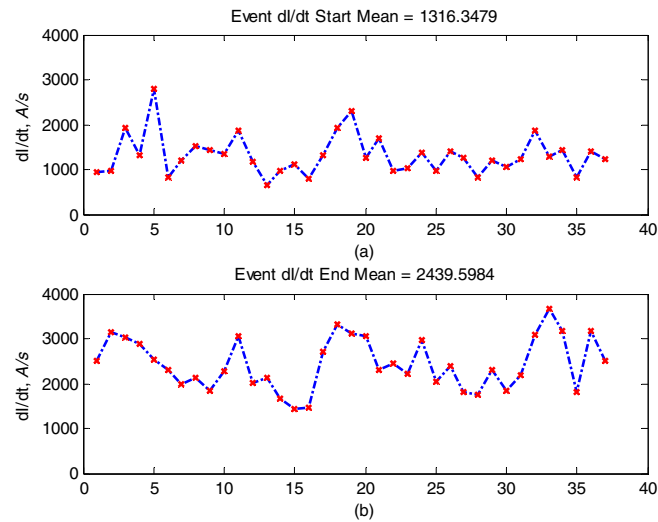


Figure 9-14
Estimates for Current-Limiting Event Current Ramp Rates Showing (a) Ramp-Up Rate and (b) Ramp-Down Rate

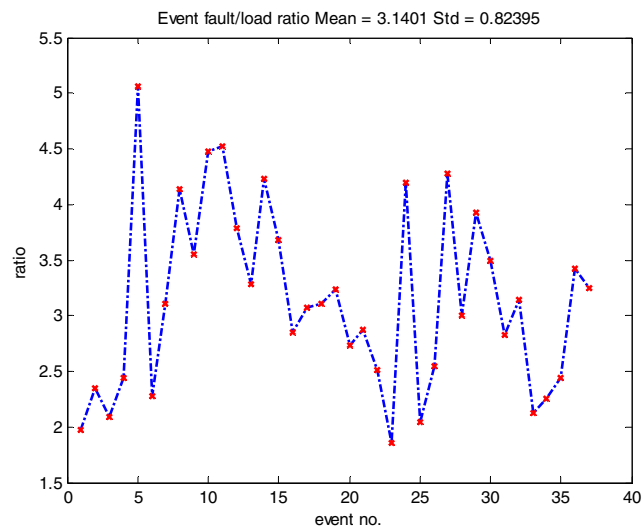


Figure 9-15
Estimates for the Ratio of the Peak Fault Current to the Load Current

The estimates for I^2t are shown in Figure 9-16. However, the range for the estimates varies over a wide range of values, and it is difficult to determine a typical value of I^2t for current-limiting fuse events.

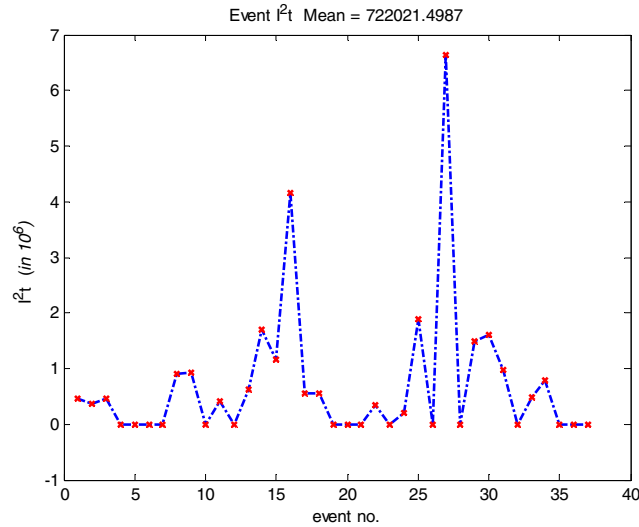


Figure 9-16
Estimates for I^2t

At the end of this chapter, the median, range, and standard deviation of current-limiting fuse event characteristics found in both the current and voltage waveforms are given.

The voltage waveform is also used to find new current-limiting fuse-operation characteristics as well as to validate the accuracy of the event-duration estimate made previously using the current waveform. The characteristics found using the voltage waveform include the following:

- The duration of the event
- The voltage phase angle at which the event starts
- The voltage phase angle at which the event ends
- The voltage drop during arcing that occurs after the fuse melts

Previously, the duration of the current-limiting fuse event was estimated by taking the difference between a replica current waveform and the measured data. For the voltage waveform, a different approach—a wavelet transform—is used to estimate the duration of the event. The algorithm for the wavelet transform is described in the appendix.

The voltage waveform is decomposed into three decomposition scales. These terms of squared wavelet transform coefficients (WTCs) are then utilized to determine the smoothness of the waveform. For example, the starting time of the event t_s can be determined using the squared WTC1, WTC2, and WTC3 plots. The original waveform and the squared wavelet transform coefficients are shown in Figure 9-17.

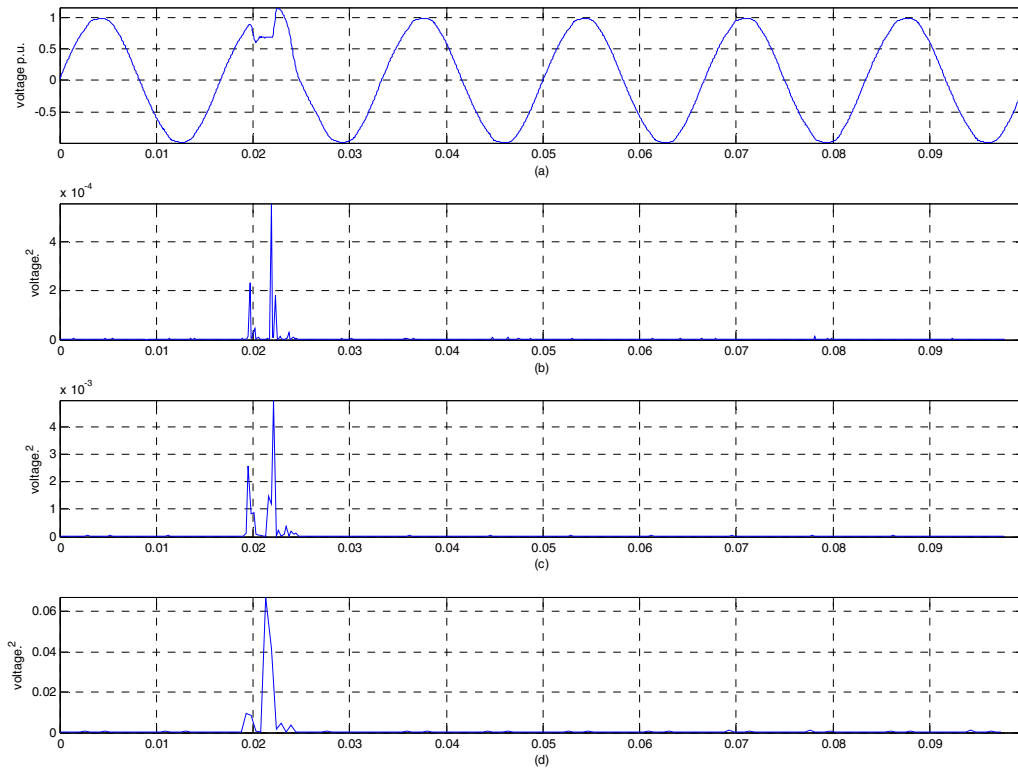


Figure 9-17
The Wavelet Transform of a Current-Limiting Fuse-Operation Voltage Waveform: (a) The Time Domain Signal; (b)-(d) Squared WTCs at Scales 1, 2, and 3, Respectively

The peaks in the squared wavelet transform coefficients indicate abrupt changes in the waveform. In the case of a current-limiting fuse event, the peaks indicate the change from smooth sinusoidal voltage waveform to the sudden drop in voltage that occurs during a fault. The peaks also indicate when the arc has been extinguished and the voltage waveform returns to its pre-fault state. For example, in Figure 9-18, the peaks from squared WTC1 are identified. The first peak is defined as t_s , the last peak is defined as t_e , and the difference, $t_e - t_s$, is the event-duration estimate. The peaks in the squared WTC1 between t_s and t_e are from the jaggedness of the arc voltage. Two more event-duration estimates are made using the same method but applied to WTC2 and WTC3.

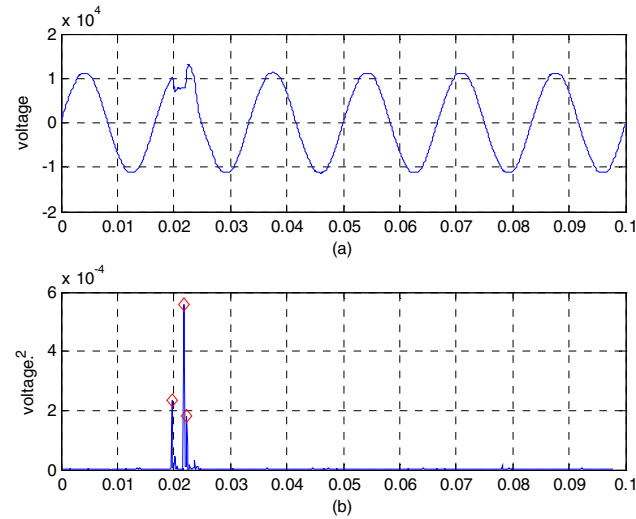


Figure 9-18
The Wavelet Transform of a Current-Limiting Fuse Operation: (a) The Time Domain Signal;
(b) Squared WTC1 with the Peaks Identified

The magnitude peaks of the squared wavelet transform coefficients were also recorded. The results from the wavelet analysis are shown in Table 9-3. Most of the event-duration estimates are approximately $\frac{1}{4}$ of a cycle.

Table 9-2
Estimates for Current-Limiting Fuse-Event Duration Using Wavelet Transformation and the Peak Squared Wavelet Transform Coefficients

Event No.	Duration (Cycles)			Peak Magnitudes (Voltage ²)		
	WTC1	WTC2	WTC3	WTC1	WTC2	WTC3
1	0.2031	0.1250	0.2813	3.0990E-02	3.0729E-02	3.0729E-02
2	0.1406	0.0625	0.0938	2.6563E-02	2.7604E-02	2.7604E-02
3	0.1953	0.2031	0.1563	2.3307E-02	2.5521E-02	2.5521E-02
4	0.2109	0.2188	0.2188	2.0703E-02	2.0573E-02	1.8750E-02
5	0.1016	0.1094	0.0000	2.0703E-02	2.0833E-02	1.8750E-02
6	0.2500	0.0938	0.1563	3.4896E-02	3.4635E-02	3.4375E-02
7	0.2500	0.2656	0.3125	1.7969E-02	1.7448E-02	1.9271E-02
8	0.1563	0.1563	0.1250	2.1875E-02	2.2135E-02	2.1354E-02
9	0.2656	0.2500	0.2188	3.1771E-02	2.9427E-02	3.1250E-02
10	0.1484	0.2500	0.1563	2.0833E-02	1.8490E-02	2.0313E-02
11	0.2266	0.2344	0.2188	2.8906E-02	2.9167E-02	3.0208E-02
12	0.2500	0.1406	0.2188	2.9297E-02	2.9688E-02	2.9167E-02

Table 9-2 (continued)
Estimates for Current-Limiting Fuse-Event Duration Using Wavelet Transformation and the Peak Squared Wavelet Transform Coefficients

Event No.	Duration (Cycles)			Peak Magnitudes (Voltage ²)		
	WTC1	WTC2	WTC3	WTC1	WTC2	WTC3
13	0.2891	0.3906	0.2813	2.9036E-02	2.8906E-02	2.9167E-02
14	0.3125	0.2969	0.2188	3.2422E-02	3.2552E-02	3.2292E-02
15	0.5234	0.5469	0.5313	3.2943E-02	2.4219E-02	2.3958E-02
16	0.2188	0.2500	0.1250	1.6927E-02	1.9531E-02	1.9271E-02
17	0.1484	0.1563	0.1250	2.4089E-02	2.3958E-02	2.3958E-02
18	0.0547	0.2969	0.0000	1.7448E-02	1.7708E-02	1.7188E-02
19	5.1172	0.3281	0.3750	1.7448E-02	1.7708E-02	2.2396E-02
20	0.2031	0.1406	0.1563	3.0990E-02	3.0729E-02	2.8125E-02
21	0.2656	0.2813	0.2188	2.1224E-02	2.1094E-02	2.0313E-02
22	0.7813	0.0000	0.0000	3.4635E-02	2.9427E-02	2.8646E-02
23	0.4766	0.5156	0.5313	3.0339E-02	3.8802E-02	2.9688E-02
24	0.2109	0.2188	0.2188	2.5000E-02	2.8385E-02	2.8125E-02
25	0.3281	0.3438	0.2500	3.1510E-02	3.1250E-02	3.1250E-02
26	0.2344	0.3438	0.3438	1.7448E-02	1.6927E-02	1.6667E-02
27	0.2969	0.2656	0.2188	3.3464E-02	3.3073E-02	3.6979E-02
28	0.2344	0.2500	0.3125	1.9661E-02	1.9271E-02	1.8750E-02
29	0.1328	0.1406	0.0938	3.0990E-02	3.1250E-02	3.2292E-02
30	0.2109	0.2188	0.1563	2.5260E-02	2.3177E-02	2.2917E-02
31	0.1484	0.1563	0.2500	2.0703E-02	2.2656E-02	2.2396E-02
32	0.2891	0.2969	0.2813	3.2682E-02	3.2552E-02	3.1771E-02

Figure 9-19 shows a plot of the event-duration estimates using the wavelet transform used on the voltage waveform. From the figure, most of the event-duration estimates using the wavelet transform fall under $\frac{1}{4}$ of a cycle.

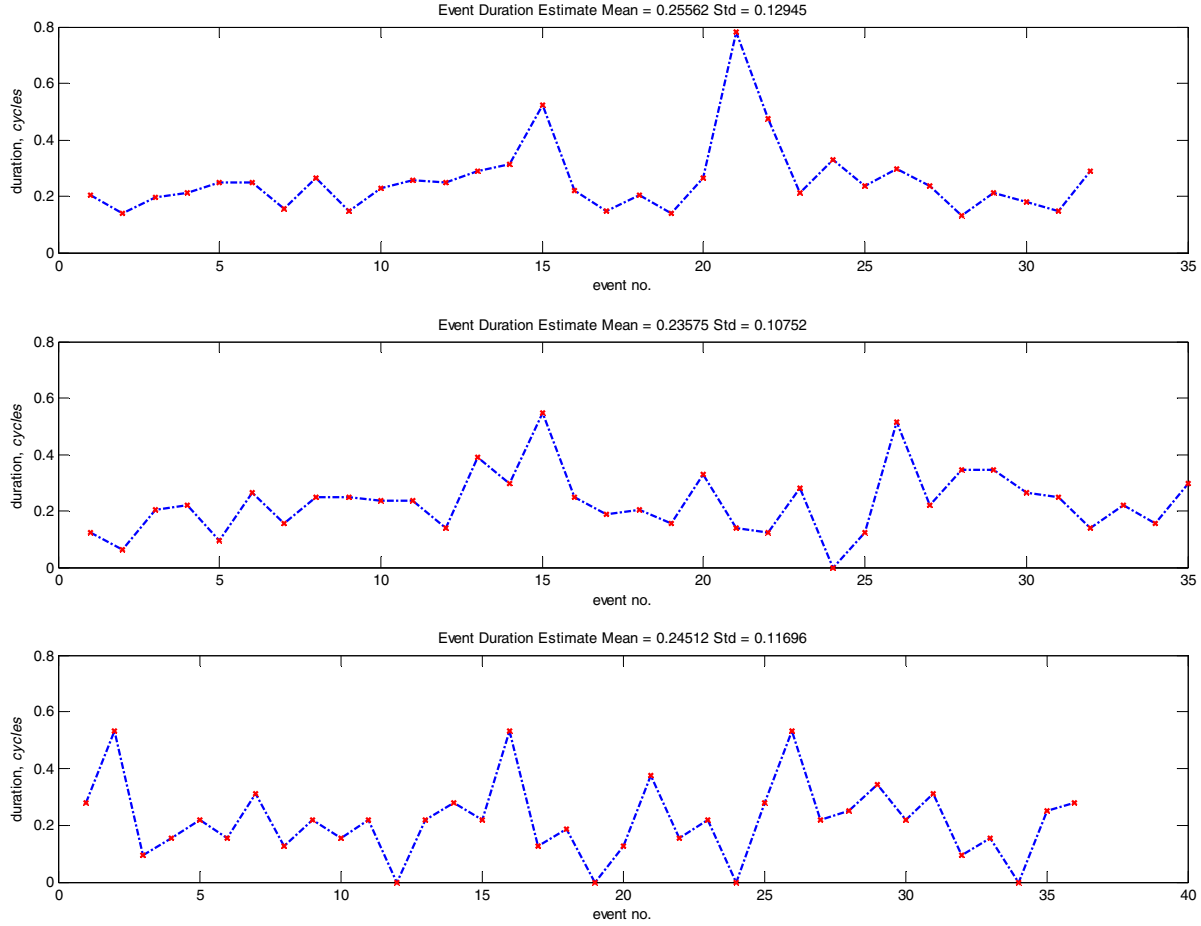


Figure 9-19
Estimates for the Current-Limiting Fuse-Duration Estimate Using the Wavelet Transform
Using (top) Squared WTC1, (middle) Squared WTC2, and (bottom) Squared WTC3

The method for estimating the phase angle of the starting and ending voltages is similar to the method used for the current waveform phase estimates. First, the parameters for Eq. 9-4 are determined, and a replica waveform is created.

$$v_{\text{replica}} = \sqrt{2} \cdot V_{\text{RMS}} \cdot \sin(2\pi \cdot f \cdot t + \theta) \quad \text{Eq. 9-4}$$

The phase angle, θ , and the starting and ending times of the event are used to estimate the starting and ending phase angle of the event. The results from the starting and ending phase-angle estimates are shown in Table 9-3. The average starting phase-angle estimates are close to the peak of the voltage waveform.

Table 9-3
Estimates for the Starting and Ending Phase Angle Using the Voltage Waveform

Event No.	Phase Start	Phase End
1	93	166
2	295	295
3	104	155
4	301	11
5	252	328
6	134	170
7	266	356
8	278	8
9	66	122
10	49	145
11	246	300
12	101	183
13	73	163
14	68	172
15	30	142
16	115	304
17	73	152
18	125	330
19	23	23
20	284	338
21	21	41
22	113	155
23	100	173
24	262	312
25	291	27
26	186	107
27	257	105
28	58	229
29	274	350
30	72	190
31	73	158
32	98	205
33	293	17
34	103	150
35	86	162
36	260	325
37	269	322
38	288	32

Figure 9-20 shows the voltage phase angle of the start of the event. It shows that fault inception happens near the peak of the voltage waveform, which is what is expected because the voltage drop is greatest just before a single-line-to-ground fault occurs.

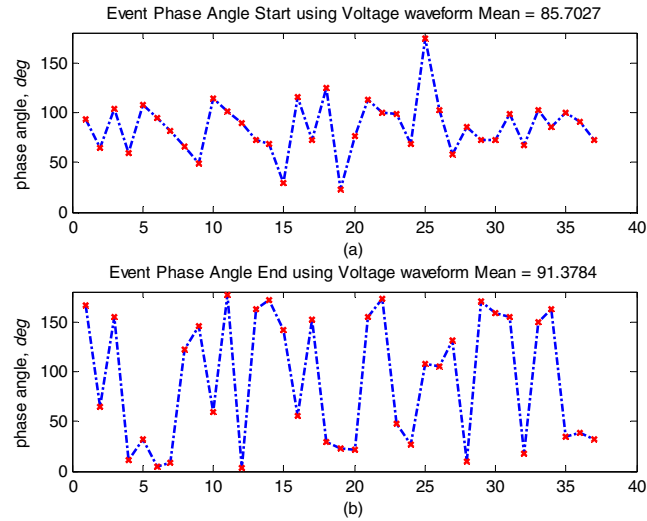


Figure 9-20
Estimates for Current-Limiting Event Phase Angle Using the Voltage Waveform: (a) Starting Phase Angle and (b) Ending Phase Angle

The percentage drop of the voltage seen from the voltage waveform is estimated using the replica voltage waveform method described earlier. The largest drop in voltage during the event is found and compared to the replica waveform at the same instant in time. The percentage drop is then calculated. The results from the analysis are shown in Figure 9-21.

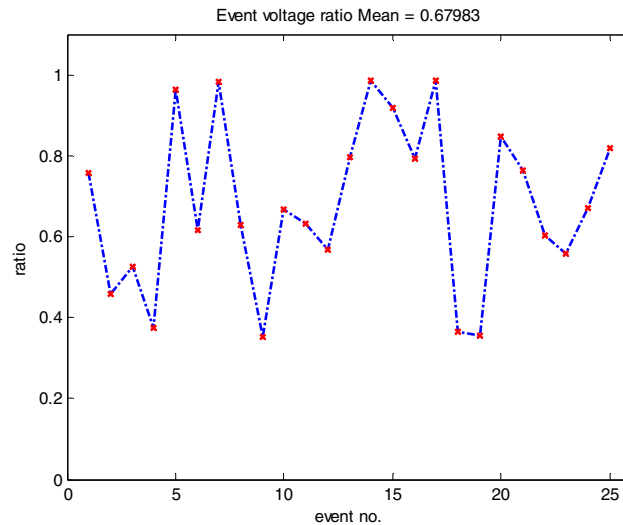


Figure 9-21
Estimates for Current-Limiting Event Voltage Ratio

A summary of the characteristics of current-limiting fuse operations is shown in Table 9-4.

Table 9-4
Summary of the Characteristics of Current-Limiting Fuse Operations

Characteristics of CLF Operations	Mean value
Event duration (replica current method)	0.26795
Phase-angle start (current waveform)	83.1351
di/dt start	1316.35
di/dt end	2439.6
Fault/load current ratio	3.1401
I^2t total	7.2×10^6
Phase start (voltage waveform)	85.7027
Voltage drop ratio	0.67983

Using the results from the current-limiting fuse analysis, it is possible to automatically categorize an event occurring on the system as a current-limiting fuse event or as some other type of event.

Summary

In this chapter, current-limiting fuse (or CLF) operations and the effects on the current and voltage waveforms are described. A current-limiting fuse is used to protect sensitive equipment by forcing the fault current through the fuse to zero in approximately $\frac{1}{4}$ of a cycle. The characteristics for current-limiting fuse operations are described and extracted from current and voltage waveforms recorded at the monitoring station located upstream from the event. The characteristics first used to identify CLF operations through visual inspection include the sudden increase in the faulted current waveform, which lasts less than $\frac{1}{2}$ of a cycle. In the voltage waveform, there is a sudden drop in voltage that remains at that magnitude until the arc across the fuse is extinguished. From the database of power system events provided by utilities, a selection of CLF operation events was chosen based on visual inspection. Unique characteristics were then extracted from the recorded voltage and current waveforms using the algorithms described in this chapter and the appendix. The characteristics include the duration of the event based on the faulted current waveform, duration of the event based on the voltage waveform, the phase angle of the current at the start of the event, the ramp up and ramp down rate of the fault current, the ratio of the peak fault current to the load current, the amount of energy in the fault current, the ratio of the voltage sag to the load voltage, and the phase angle of the voltage at the start of the event. These characteristics were extracted using the replica waveform method and the wavelet transforms, which is described in the appendix. The algorithms were applied to the CLF events selected through visual inspection, and the results were tabulated. In the future, the methods described in this chapter can be used to automatically determine whether recorded events are caused by current-limiting fuse operations.

10

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A

APPENDIX: ALGORITHMS

Power system events are characterized by certain characteristics such as duration, frequency, instantaneous voltage, and current variations, to mention a few [52]. These characteristics vary for each type of event that occurs on the grid. The algorithms containing the numerical methods that extract the unique event characteristics described in the above chapters are covered in this appendix. With the help of these algorithms, it is possible to quantify the event characteristics, which will eventually lead to automatic classification of events as they occur. The algorithms were tested on a database of events. In the following sections, the algorithms are presented and include the wavelet transform and other common functions such as curve fitting and least squares.

Wavelet Transform

A brief overview of the wavelet transformation and the unique characteristics that can be extracted using the wavelet transform are covered in this section. Wavelet transform is a mathematical tool used to decompose a given signal into different levels of resolution in the time and frequency (scale) domains. The level of decomposition depends on the sampling rate of the signal to be transformed. There are two basic types of wavelet transforms: the continuous and discrete wavelet transforms.

Let $x(t)$ be a real finite energy signal; the continuous wavelet transform of $x(t)$ is defined as follows:

$$CWT_{\varphi_x}(a, b) = W_x(a, b) = \int_{-\infty}^{\infty} x(t) \varphi_{a,b}^*(t) dt, \quad \text{Eq. A-1}$$

where, $\varphi_{a,b}(t) = |a|^{-1/2} \varphi\left(\frac{t-b}{a}\right)$.

where $\varphi(t)$ is the base function or the mother wavelet, the asterisk on $\varphi(t)$ denotes a complex conjugate, and $a, b \in \Re$, $a \neq 0$, are the dilation and translation parameters, respectively. It should be noted that only functions with a zero mean average can be used as the mother wavelet.

The continuous wavelet transform works by continuously dilating and translating the mother wavelet, $\varphi(t)$, over the entire range of $x(t)$. As a result, there is a significant amount of redundancy in the wavelet domain. The transformed signals in the continuous wavelet domain are excellent for visualizing time and scale behavior of the time-domain signal. Oftentimes, when visualization is not called for, the continuous dilation and translation of the mother wavelet are replaced with discrete dilation and translation. They can be accomplished by selecting the dilation and translation parameters as follows: $a = a_0^m, b = nb_0 a_0^m$, where a_0 and b_0 are fixed

constants with $a_0 > 1$, $b_0 > 0$, $m, n \in Z$, and Z is the set of positive integers. With this substitution, the discrete wavelet transform of $x(t)$ can be defined as follows:

$$DWT_{\varphi}(m, n) = \int_{-\infty}^{\infty} x(t) \varphi_{a,b}^*(t) dt,$$

$$\text{where, the discretized mother wavelet transform, } \varphi_{a,b}(t) = a_0^{-m/2} \varphi\left(\frac{t - nb_0 a_0^m}{a_0^m}\right).$$

Eq. A-2

Using the values of $a_0 = 2$ and $b_0 = 1$ in Eq. A-2, a special type of discrete wavelet transforms called the *dyadic-orthonormal wavelet transform* is obtained. It eliminates information redundancy among the decomposed signals due to their orthonormal properties. The other importance of this substitution is that an algorithm called the *multi-resolution signal decomposition* (MSD) *technique* can be used to decompose a signal into scales with different time and frequency resolutions [54].

The mother wavelets for the dyadic wavelet transform are mathematically derived to achieve the orthonormal properties. They are called *Daubechies wavelets* after the mathematician who derived them. These wavelets can be constructed from four, six, eight, ten, and so on filter coefficients and are known as *Daub4*, *Daub6*, *Daub8*, and *Daub10 wavelets*, respectively [55]. The choice of the analyzing wavelets plays an important role in detecting and localizing various types of power quality disturbances. This choice becomes all the more important when considering one- or two-scale signal decompositions. The applicability of various mother wavelets in different scenarios is analyzed in [56]. Daub4 and Daub6 wavelets are suitable for short and fast transient disturbances, whereas Daub8 and Daub10 wavelets are suitable for slow transients.

In this report, Daub4 is selected as the mother wavelet because the fast and short transient disturbances get detected at lower decomposition scales, whereas slow and long transients get identified at higher decomposition scales. For this reason, the time-domain signal is decomposed into three decomposition scales with different levels of resolution. For a time-domain signal with a sampling rate of 128 samples/cycle, the frequency resolutions of the transformed signals are as follows:

- Scale 1: Frequency range is between 1920 Hz and 3840 Hz
- Scale 2: Frequency range is between 960 Hz and 1920 Hz
- Scale 3: Frequency range is between 480 Hz and 960 Hz

To examine how event characteristics can be extracted using wavelet transformations, an example of a current-limiting fuse operation is shown in Figure A-1. A current-limiting fuse operation can be seen in the faulted phase of the voltage waveform in Figure A-1.

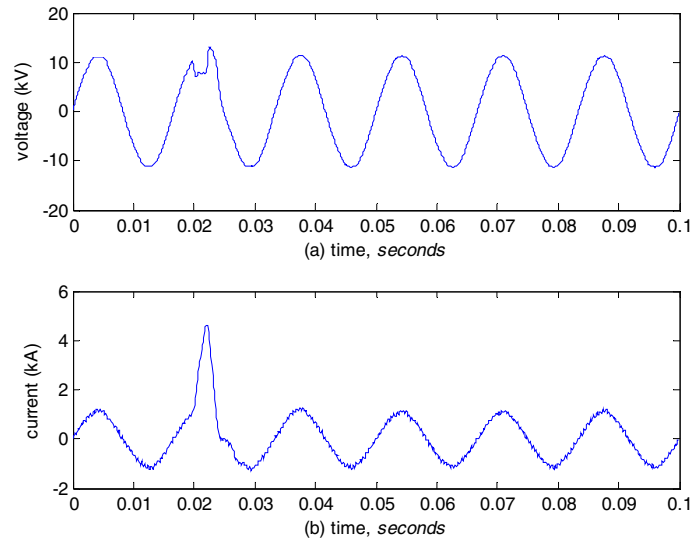


Figure A-1
Example Faulted Waveforms

The waveform before the event is smooth and almost perfectly sinusoidal. When the fuse element melts, the voltage seen at an upstream monitoring station drops and stays at a lower value because of the arc created across the fuse. After the arc is extinguished, the voltage waveform returns to its pre-fault state, smooth and sinusoidal. The wavelet transform variables in terms of squared wavelet transform coefficients (WTCs) are utilized to determine the smoothness of the waveform. In other words, when applying the wavelet transform to the voltage waveform above, the WTC will indicate the start and end of the event. The start and end times are then used to calculate the duration of the event. An example of the wavelet transform applied to a current-limiting fuse-operation voltage waveform is shown in Figure A-2.

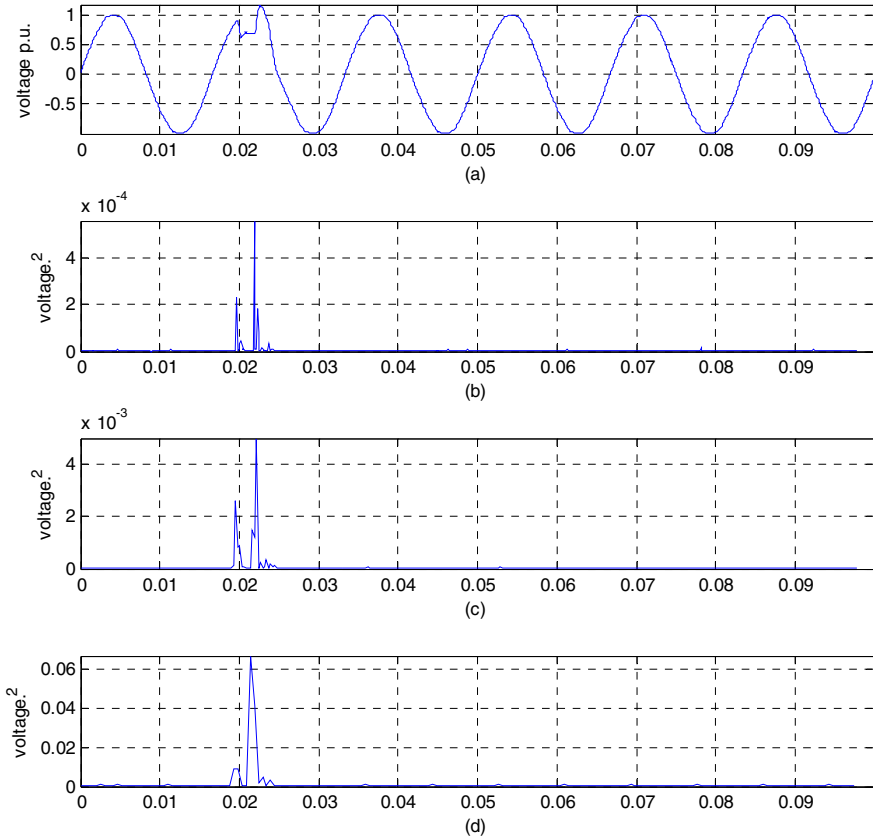


Figure A-2
Wavelet Transform: Applied to the (a) Faulted Voltage Waveform; (b)-(d) the Squared Wavelet Transform Coefficients WTC1, WTC2, and WTC3, Respectively

The WTC at scales 1, 2, and 3 of the transform are shown in Figure A-2 (b)-(d) above. The starting time, t_s , is located by finding the first peak of the squared WTC1. The ending time, t_e , is also found similarly, by finding the last peak of the squared WTC1.

The wavelet transform can also be applied to the current waveform. The WTC at scales 1, 2, and 3 of the transform are shown in Figure A-3 (b)-(d). As can be seen from the squared WTC1, it is not possible to accurately calculate when the event starts or when the event ends because the resolution of the wavelet at scale 1 does not match the time-domain signal. However, squared WTC2 and squared WTC3 can be used to deduce the duration of the transient event.

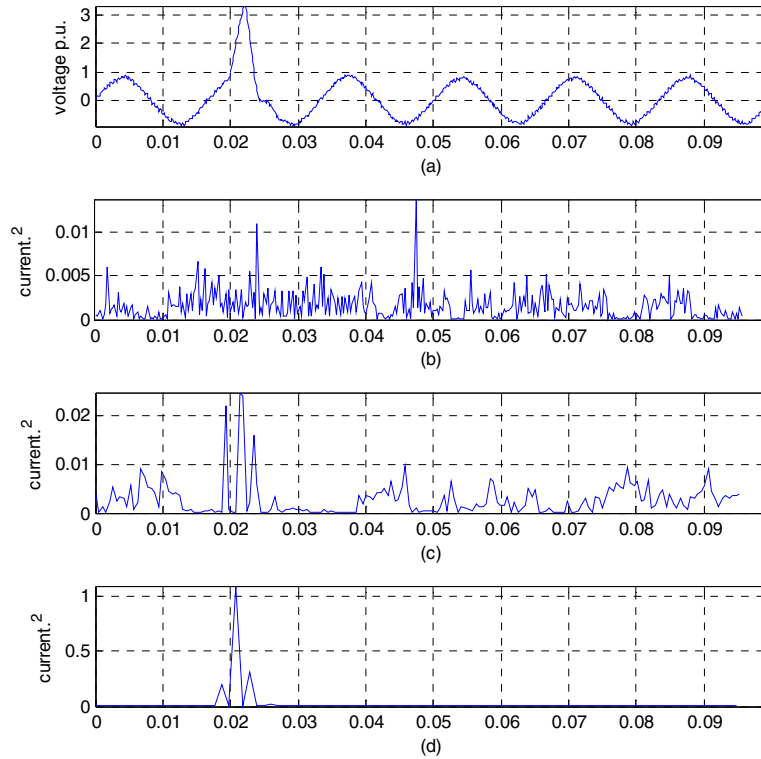


Figure A-3
Wavelet Transform: Applied to the (a) Faulted Current Waveform; (b)-(d) the Squared
Wavelet Transform Coefficients WTC1, WTC2, and WTC3, Respectively

Another example of how the wavelet transformation algorithm is used to extract event characteristics is when it is applied to the voltage waveform during a sustained cable fault. Small impulses appear in the faulted phase voltage waveform during the event. When the wavelet transformation is applied to the waveform, the resulting squared WTCs indicate when the notches occur. The frequency of the impulses in the voltage waveform can be used to categorize the event type. An example of the impulses that occur in the voltage waveform is shown in Figure A-4. The waveforms are for a sustained underground cable fault.

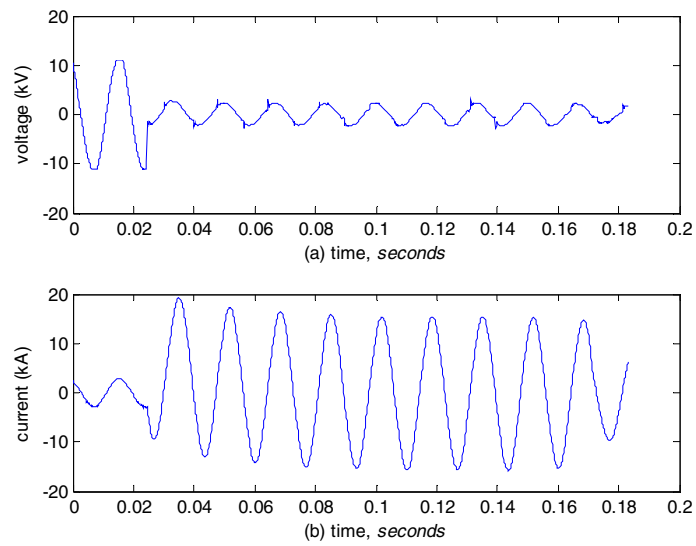


Figure A-4
Example Faulted Waveform

The wavelet transform coefficients resulting from the wavelet transformation of the faulted voltage waveform are shown in Figure A-5. Note that the magnitude of voltage crest during the fault is around 0.2 p.u.

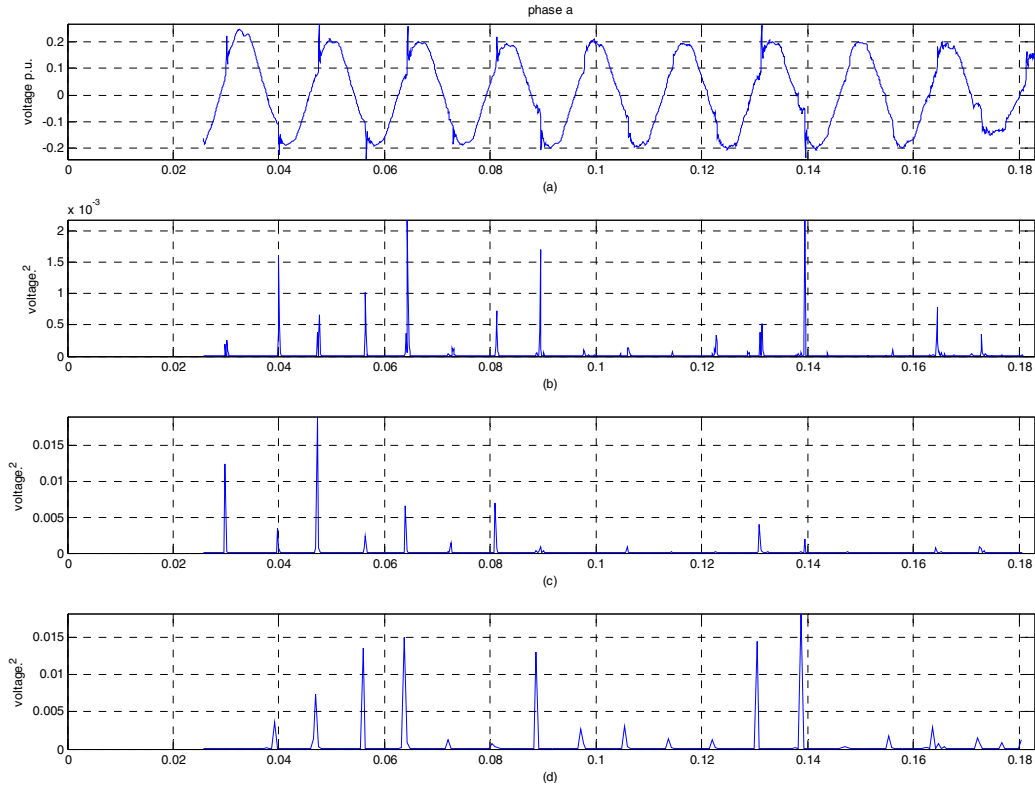


Figure A-5
Wavelet Transform: Applied to the (a) Faulted Voltage Waveform; (b)-(d) the Squared Wavelet Transform Coefficients WTC1, WTC2, and WTC3, Respectively

The peaks of the squared wavelet transformation coefficients WTC1 are labeled in Figure A-6 (b). The times when the peaks occur on the squared WTC1 are plotted on the faulted voltage waveform in order to check whether the wavelet transform algorithm was able to locate all the impulses in the voltage waveform. Figure A-6 (c) shows that the squared WTC1 accurately finds the impulses in the voltage waveform. Sometimes the WTC1 indicates the start and end of the impulse.

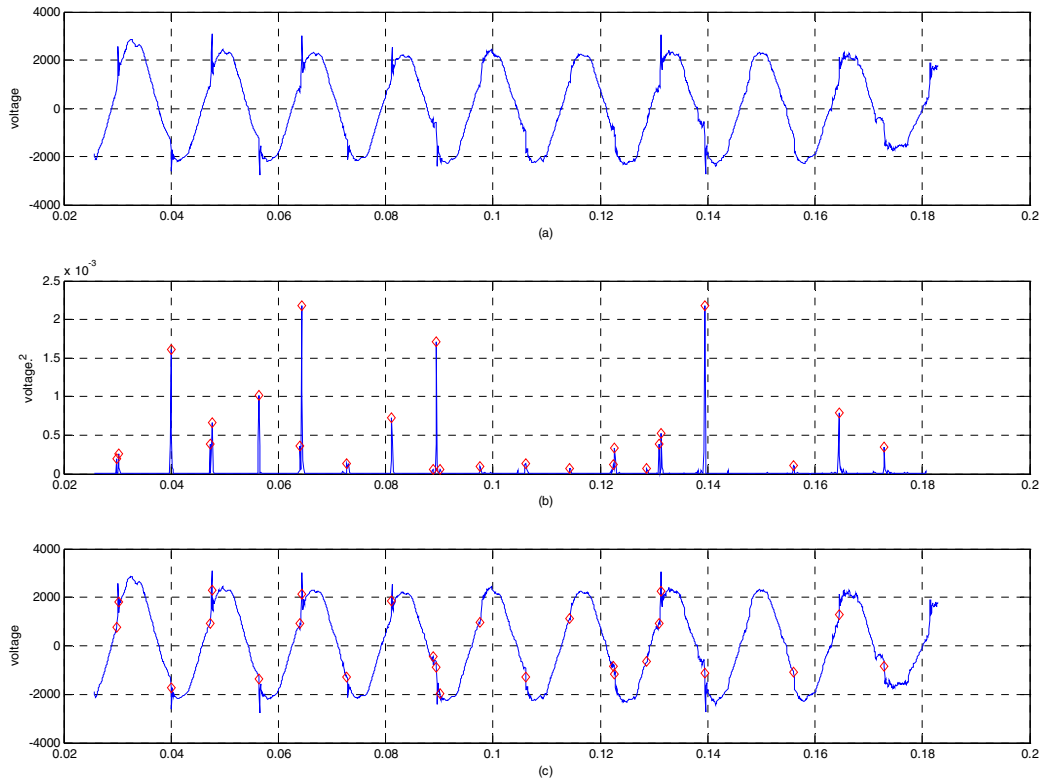


Figure A-6
Faulted Voltage Waveform and Squared WTC1

General Functions

Commonly available functions in commercial software packages were utilized to extract some simple characteristics found in the current and voltage waveforms. These functions include the fast Fourier transform, non-negative least squares, smoothing splines, trapezoidal method, and a curve-fitting method. New functions that were created to use throughout the code include running/moving window and the formation of a replica waveform. The replica waveform function assumes that the load current does not change during the fault and can be thought of as the continuation of the pre-fault voltage and current waveforms. The function creates waveforms that are used to compare instantaneous pre-fault values to the actual faulted waveforms. The replica waveforms are used to estimate fault duration and the phase angle at the start of the fault.

Standard Built-in Functions

Some of the built-in functions are described here. These functions include the non-negative least-squares method, the smoothing-splines curve-fitting method, and the fast Fourier transform (FFT). The non-negative least-squares method is used in the arc voltage-estimation algorithm. As mentioned earlier, the least-squares method is used when trying to solve an over-determined system of equations. The non-negative least-squares method solved for the system of equations by minimizing the norm of the estimate and the actual data.

The smoothing-splines method is a curve-fitting method that is used to smooth out noisy data. The smoothing-splines method finds the best curve fit by minimizing Eq. A-3.

$$p \sum_i w_i (y_i - s(x_i))^2 + (1-p) \int \left(\frac{d^2 s}{dx^2} \right)^2 dx \quad \text{Eq. A-3}$$

In addition to smoothing out the original data, this method also provides a way to increase the number of samples. This proves useful when taking the derivative of the data. When taking the derivative of a signal, the noise in the resulting derivative is amplified. Taking the derivative of the smoothed data and having a smaller time between samples result in the derivative being less noisy.

The fast Fourier transform is used in the algorithm to find the frequency component of the waveform.

Other Custom-Built Functions

The *running window function* is a simple function that captures a selected fraction of the waveform. The window runs along the entire waveform. Each time it moves, the selected analytical method is applied. This function is used by methods that require only a fraction of the waveform, such as just one cycle of data, to do the analysis. The window size can be adjusted, but doing so usually affects the result of the analysis.

The *replica waveform function* creates a waveform based on the pre-fault voltage or current waveform data. It is assumed that the load current does not change during the fault, and therefore the replica waveform is used to recreate the load current waveform during the fault event. The replica waveform function uses the pre-fault waveform to find the parameters given in Eq. A-4.

$$i_{\text{replica}} = \sqrt{2} \cdot I_{\text{RMS}} \cdot \sin(2\pi \cdot f \cdot t + \theta) \quad \text{Eq. A-4}$$

where I_{RMS} is the RMS current, f is the frequency, θ is the phase angle, and i_{replica} is the replica current during the fault event. Using one cycle of the pre-fault data, the RMS value of the waveform is estimated using Eq. A-5.

$$x_{\text{RMS}} = \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2} \quad \text{Eq. A-5}$$

The frequency is estimated by taking one cycle of the pre-fault data and applying the FFT. The phase-angle estimate is made by finding the first zero crossing in the waveform. The replica waveform function can be applied to each phase of the three-phase voltage or current waveforms. An example of the waveforms created using the replica waveform function

compared to the original waveform for a current-limiting fuse event is shown in Figure A-7 and Figure A-8.

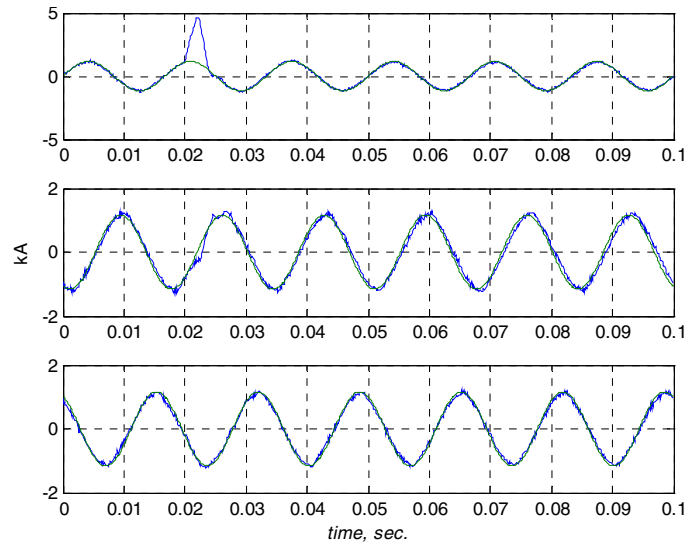


Figure A-7
Example of the Replica Waveform Function Applied to Current Waveforms

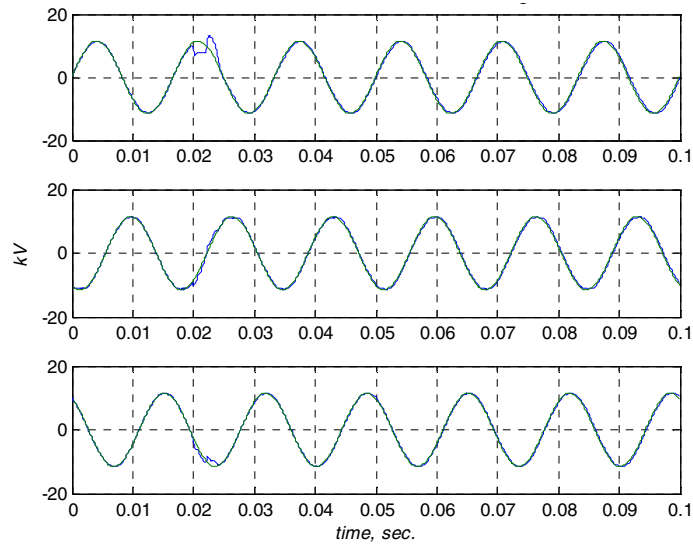


Figure A-8
Example of the Replica Waveform Function Applied to Voltage Waveforms

When the measured waveform is plotted against the replica waveform, it is much easier to see where the fault starts and to see other events that occurred. Not only does the replica waveform provide a useful tool for visual inspection but it is also used to determine which phases or phase is faulted and is used to estimate the duration of the event.

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