

AUTOMATED FAULT LOCATION IN SMART DISTRIBUTION SYSTEMS

A Dissertation

by

SAEED LOTFIFARD

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2011

Major Subject: Electrical Engineering

Automated Fault Location in Smart Distribution Systems

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ABSTRACT

Automated Fault Location in Smart Distribution Systems. (August 2011)

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When a fault occurs in power distribution systems, it should be pinpointed and isolated as soon as possible. In automated power distribution systems, subsequent to pinpointing the fault, distribution systems reconfiguration and restoration tasks are executed so that the electricity could be provided to fault-free areas. Therefore, accurate and fast fault location methods are critical components for realization of fault tolerant power systems.

As distribution systems are gradually evolving into smart distribution systems, implementation of more accurate fault location methods by using available data and communication systems is feasible. To reach this goal, the following tasks are carried out:

- 1) Existing fault location methods in distribution systems are surveyed and their strength and caveats are studied.
- 2) Characteristics of IEDs in distribution systems are studied and their impacts on fault location method selection and implementation are detailed.

- 3) A systematic approach for selecting optimal fault location method is proposed and implemented to pinpoint the most promising algorithms for a given set of application requirements.
- 4) An enhanced fault location method using voltage sag data captured by IEDs that are installed at select location throughout the network is developed. The method solves the problem of multiple fault location estimations and produces more robust results.
- 5) An optimal IED placement approach for the enhanced fault location method is developed and practical considerations for its implementation are detailed.

DEDICATION

To My Mother and Memory of My Father

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1. INTRODUCTION*

1.1 Problem Statement

Different fault location algorithms have been developed for distribution systems in the past. A systematic approach needs to be developed to select the most suitable fault location method that matches predefined criteria such as availability of the required data, robustness of the method, and feasibility of implementation.

In modern distribution systems Intelligent Electronic Devices (IEDs) are deployed at different locations throughout the network. These IEDs have different functionalities. For instance, Power Quality Meters (PQM), are installed to capture harmonics and certain disturbances for analyzing the power quality indices. Digital Protective Relays are utilized to detect occurrence of the faults and isolate faulted section as fast as possible. Digital Fault Recorders (DFR) capture different voltage and/or current signal as well as output of the relays for further analysis of the power systems equipment performances.

In smart distribution systems, the communication systems will be expanded so that

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more information about different sections of the network becomes available. This information can be utilized for a variety of applications such as demand response management, optimal network reconfigurations, etc. Availability of the data in smart distribution systems provides the opportunity to develop more accurate fault location method.

It should be noted that a systematic method needs to be developed to determine what kind of fault location method should be implemented in each network, depending on the configuration of the network, availability of the data and type of the communication systems. Following the selection of a suitable fault location method, appropriate methods should be proposed to take full advantage of availability of the data from IEDs in smart distribution systems to overcome potential drawbacks of the selected method. Finally, a systematic optimal IED placement should be developed.

1.2 Existing Solutions

As detailed in [1], “Different fault location methods have been proposed for distribution systems.

In [2-6], the apparent impedance, which is defined as the ratio of selected voltage to selected current based on the fault type and faulted phases, is utilized. This category of methods results in multiple fault location estimations as they only use measured voltage and current signals at the substation. In [4-5], data collected from fault indicators throughout the network, which determine the direction of the fault, are utilized to solve

the multiple fault location estimation problem. Installation of fault indicators at the beginning of each tap increases the implementation cost.

In [7-9], a method based on direct circuit analysis, is proposed. Although it suitable for unbalanced distribution systems, it does not yield unique fault location estimate.

In [10-11], a method using superimposed components of the voltages and currents is proposed. In this method, an assumed fault point is varied systematically until the actual fault point is found. In this method, the problem of multiple fault location estimates exists as well.

In [12-17], methods based on traveling waves generated by the fault have been suggested. These methods require high frequency sampling depending on the power system configuration and required accuracy. Presence of laterals and load taps that reflect traveling waves may reduce the accuracy of these method. These methods are more suitable for transmission lines [14].

Methods based on intelligent systems are presented in [18-22]. In [18], to detect faulted area an ANFIS (Adaptive Neuro-Fuzzy Inference System) is utilized. In [20] using the LAMDA (Learning Algorithm for Multivariable Data analysis) classification technique, multiple fault location estimation problem is solved. This method need a training process and a re-training if the network configuration changes”.

1.3 Unresolved Issues

- A) A number of methods have been proposed for fault location on the distribution systems in the past. A systematic approach needs to be developed to select the optimal fault location method that matches predefined criteria such as availability of the required data, robustness of the method, and feasibility of implementation.
- B) As a part of smart grid deployment projects, Intelligent Electronic Devices for monitoring, protection and other purposes are installed throughout the power systems. Different types of IEDs with different characteristics may affect the fault location method selection. Moreover, the type of available data depends on feeder automation architectures as well. Therefore, the issues related to handling the data needs to be addressed. Characteristics of each IED and their impacts on enhancement of fault location methods should be studied as well.
- C) Presence of laterals and sub-laterals in distribution systems causes multiple fault location estimations despite of correct distance calculation. A new fault location method needs to be proposed to eliminate the false fault location estimations and give unique estimation. This method should be aware of availability of data in smart distribution systems and takes advantage of them.
- D) In smart distribution systems, it is possible to use data gathered from different IEDs for fault location purpose. However, a systematic procedure need to be develop to determine how many and where the IEDs should be installed.

1.4 Objectives of an Enhanced Fault Location

The proposed enhanced fault location method should solve the problem of the selected optimal fault location among existing fault location methods. It should also eliminate the multiple fault location estimations, and does not require high sampling frequency or retraining subsequent to changes in power grids. It should be able to take advantage of availability of data in smart distribution systems for the task of fault location. To keep its implementation cost low, it should be able to accomplish the task of fault location by using a few IEDs located along the feeder.

2. PROBLEM FORMULATION

2.1 Multiple Fault Location Estimation

As a result of presence of laterals and sub-laterals in distribution systems, multiple fault location estimations are possible despite of correct distance calculation. Fig. 1 shows this issue. If a fault happens at node A, despite the correct estimation of its distance from substation, the location of the fault cannot be determined uniquely as nodes B and C are at the same distance from the substation as well. To eliminate false fault estimations, traditionally fault indicators are installed at beginning of each lateral and sub-laterals. However, it requires huge number of fault indicators installment.

In smart distribution systems, it is possible to utilize data gathered from IEDs installed along the feeder. New methods should be proposed to take advantage of availability of data in smart distribution systems. The fact that fault cause voltage sags with different characteristics at different nodes along the feeder is utilized in the proposed enhanced fault location method for finding the location of fault. At first, a systematic approach for selecting optimal fault location method among existing ones is developed which is explained in Section 5. To eliminate false fault estimations by the selected fault location method, a few IEDs are installed at select nodes along the feeder and the measured voltage sag data are transferred to control center. In control center, fault at each estimated location (one at a time) is applied in the simulated network and voltage sags are calculated using short-circuit analysis program. The fault location is determined based on the similarity of the simulated and measured voltage sag data

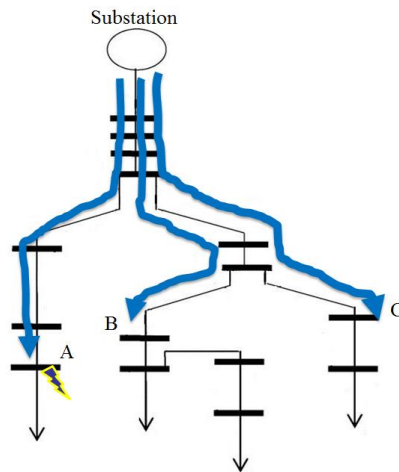


Figure 1 Multiple possible fault location estimation for a fault at node A

captured by the IEDs in the network. The details of the method are presented in Section 6. By using the proposed method false fault location estimations are eliminated and the algorithm gives unique result.

2.2 IED Placement

In the proposed fault location method, voltage sag data are measured at select nodes where the IEDs are installed. To reduce the number of required IEDs while capture enough information, a systematic IED placement should be proposed. The proposed procedure should take into account topology change of the network. The task of determining the optimal number and location of IEDs is formulated as an optimization problem. The proposed IED placement is detailed in section 6

2.3 Smart Distribution Systems Data

In smart distribution systems more data are available in the network. The data can be collected from IEDs with different characteristics located at different locations along the feeder. Different fault location methods have different requirements. Therefore, for each type of IEDs certain fault location methods work better. Another factor that has direct impacts on implementation of fault location method is the feeder automation architectures. Therefore, the characteristics of different types of IEDs need to be studied, such as analog to digital converters (ADC), filtering, sampling rate, triggering method, and IED location on the quality of the records. Moreover, impacts of different types of communication based on feeder automation (FA) architecture on fault location implementation should be addressed. Section 4 discusses these issues in detail.

2.4 Goals of the Dissertation

The dissertation aims at developing an optimal automated fault location by using available data in smart distribution systems. The proposed method should be accurate and precisely pinpoint the location of faults. To reach this goal, a systematic approach for fault location selection is developed. The proposed approach takes into account characteristics of IEDs and the feeder automation architectures. An enhanced fault location method based on voltage sag data gathered at strategic locations throughout the network is proposed to eliminate false fault location estimated by selected impedance-based fault location method. Moreover, a systematic procedure for optimal IED placement is developed to determine number and locations of required IEDs for

implementation of the developed fault location method. The dissertation is organized as follows. In Section 3 existing fault location methods in distribution systems are surveyed and strengths and caveats of them are detailed. In section 4 the impacts of smart distribution technologies on fault location algorithms are studied. In Section 5 a systematic approach for optimal fault location method selection is proposed. In Section 6 a method based on voltage sag data captured at select IEDs along feeder for eliminating false fault estimations is developed. A procedure for optimal IED placement is also proposed which determines number and location of required IEDs. Finally, in section.7 summary and future work are presented.

3. FAULT LOCATION METHODS IN DISTRIBUTION SYSTEMS

3.1 Introduction

In modern power systems with presence of sensitive loads long customer outages are not acceptable. So, if an outage of the line happens due to a fault, it should be pinpointed and the damage should be repaired as quickly as possible.

Distribution systems due to presence of short and heterogeneous lines, laterals, load taps required fault location methods that can consider the peculiarities of the network [23]. In distribution systems even if the distance between the fault point and a node is determined, it is still hard to decide which lateral is involved. As a result, the fault location algorithms may have multiple solutions. In [24], a comparison of impedance based fault location method has been presented. However, a systematic approach for comparison of all types of fault location methods in distribution systems is needed.

Different fault location methods have been proposed for distribution systems [2-4], [7-8], [10-11], [12-14], [18-20].

The detail of above mentioned fault location methods are described briefly in Appendix A.

3.2 Main Requirements of Fault Location Methods

Table 1 summarizes main characteristics of different categories of fault location methods from the requirements point of view.

Table 1 Main requirements of fault location methods

Investigated characteristics	Fault location method										
	Impedance measurement			Direct three-phase circuit analysis	Superimposed components	Traveling wave			Artificial intelligence		
	[1]	[2]	[3]	[6]	[9]	[11]	[12]	[13]	[17]	[18]	[19]
Data Requirements											
• Substation data	×	×	×	×	×	×	×	×	×	×	×
• Feeder data (outside the fence)	-	-	×	-	-	-	-	×	-	-	-
• Voltage signals (abc)	×	×	×	×	×	×	×	×	-	-	×
○ Pre-fault data	×	×	×	-	×	-	-	-	-	-	×
○ During-fault data	×	×	×	×	×	×	×	×	-	-	×
○ Post-fault data	-	-	-	-	-	-	-	-	-	-	×
• Current signals (abc)	×	×	×	×	×	-*	×	-*	×	×	×
○ Pre-fault data	×	×	×	-	×	-	-	-	×	×	×
○ During-fault data	×	×	×	×	×	-	×	-	×	×	×
○ Post-fault data	-	-	-	-	-	-	-	-	×	-	-
• Symmetrical Components	×	-	×	-	-	-	-	-	-	-	-
• Phasor components	-	×	-	×	×	-	-	-	-	-	×
• Time domain	-	-	-	-	-	×	×	×	×	×	-
• High frequency sampling	-	-	-	-	-	×	×	×	-	-	-

Table 1 Continued

Investigated characteristics	Fault location method										
	Impedance measurement			Direct three-phase circuit analysis	Superimposed components	Traveling wave			Artificial intelligence		
	[1]	[2]	[3]	[6]	[9]	[11]	[12]	[13]	[17]	[18]	[19]
Topological and Modeling Requirements											
•Line model (AB or AO)	Short (AO)	Short (AO)	Long (AO)	Short(AO)	Short (AO)	Long (AO)	Long (AO)	Long (AO)	Long (AO)	Short (AO)	Long (AO)
•Load model	Constant	Voltage dependent	Voltage dependent	Constant	Constant	Constant	Constant	Constant	Voltage dependent	Constant	Voltage dependent
• Heterogeneity**	×	×	×	×	×	-	-	-	×	-	×
•Laterals (3-phase or 1 phase branches)	×	×	×	-	-	-	×	-	×	-	×
•Load taps***	×	×	×	×	×	×	×	×	×	×	×
•Communication	-	-	×	-	-	-	-	×	-	-	-
•Expected Accuracy Range****	99%	96.58% to 98.87%	96%	99%	97%	Less than 10 meter error	Less than 10 meter error	Less than 10 meter error	99%		83%
•Field-demonstrated	-	×	-	-	-	-	×	-	-	-	-

Table 1 Continued

Investigated characteristics	Fault location method					
	Impedance measurement			Direct three-phase circuit analysis	Superimposed components	
	[1]	[2]	[3]	[6]	[9]	
Top 3 Strengths	1. Easy to implement 2. Just needs substation data 3. Considers load variation	1. Easy to implement 2. Just needs substation data 3. Considers load variation	1. Easy to implement 2. Just needs substation data 3. Considers load variation	1. Applicable in unbalanced systems 2. Easy to implement 3. Just needs substation data	1. Applicable in unbalanced systems 2. Just needs substation data 3. Considers load variation	
Top 3 Caveats	1. Multiple estimation 2. Dependence on network parameters 3. Need to iteration on unbalanced system	1. Multiple estimation 2. Dependence on network parameters 3. Need to iteration on unbalanced system	1. Multiple estimation 2. Dependence on network parameters 3. Need to iteration on unbalanced system	1. Multiple estimation 2. Dependence on network parameters 3. Does not considers load variation	1. Multiple estimation 2. Dependence on network parameters 3. Huge mathematical calculations	
	Traveling wave			Artificial intelligence		
	[11]	[12]	[13]	[17]	[18]	[19]
Top 3 Strengths	1. Precision 2. Does not need iteration 3. Does not need huge calculation	1. Precision 2. Does not need iteration 3. Does not need huge calculation	1. Precision 2. Does not need iteration 3. Does not need huge calculation	1. Unique estimation 2. Just needs substation data 3. Just needs current signal	1. Unique estimation 2. Just needs substation data 3. Just needs current signal	1. Unique estimation 2. Just need substation data 3. Does not need extra installations
Top 3 Caveats	1. Need to high frequency sampling 2. Prone to mistake in algorithm 3. Dependence on network parameters	1. Need to high frequency sampling 2. Prone to mistake in algorithm 3. Dependence on network parameters	1. Need to high frequency sampling 2. Prone to mistake in algorithm 3. Dependence on network parameters	1. Need to huge number of simulation 2. Need to retraining in different network 3. need to retraining with change in the network	1. Need to huge number of simulation 2. Need to retraining in different network 3. need to retraining with change in the network	1. Need to huge number of simulation 2. Need to retraining in different network 3. need to retraining with change in the network

× Yes /Applicable

- No/ Not Applicable

* Current signal is not required for fault location but is required for fault detection.

*** It means conductors with different values

*** “Load taps” are loads directly connected to the feeder nodes and “laterals” could be three or single-phase line stems from main feeder

**** The values are based on the accuracy reported by the authors of the methods

In this table the type of input data and topology of distribution system as well as need to utilize a communication system have been investigated.

3.3 Conclusions

In this section the most common approaches for fault location in distribution systems were reviewed. The strengths and caveats of the methods were discussed qualitatively. This review is the base for selection of the most suitable methods for pinpointing faults in distribution systems based on available data. When it comes to choosing the most suitable method, it is necessary to have quantitative criterion that can rank the methods systematically. In section 5, a systematic approach for achieving this goal is developed.

4. IMPACT OF SMART DISTRIBUTION ON FAULT LOCATION ALGORITHMS

4.1 Introduction

Different categories of fault location for distribution systems were discussed in the previous Section. Development of communication systems and widespread use of Intelligent Electronic Devices (IEDs) along the feeders in smart grids made it possible to collect more information for finding the location of the fault.

It is important that fault location methods be aware of availability of more data in smart distribution systems. Moreover, the proposed fault location methods should take into account the suitability and sufficiency of the captured data by the IEDs. In [25] typical time frames of different events in power systems are studied.

For instance, if the method is based on features produced by relays and breaker operations, the IED that provides the input data for the method should be able to capture the data in the time frame of seconds and have enough selectivity to detect such events. In this section different aspects of IEDs in smart distribution systems that can affect fault location methods such as analog to digital conversion (ADC), filtering, sampling rate, triggering method, and location of IED are studied. Some scenarios to show how the result of these discussions can be used to select a fault location method are presented.

4.2 Characteristic of IEDs

4.2.1 Sampling Method

As in power systems a variety of IEDS are installed at different time, the sampling methods utilized in the IEDs may be different. Different types of sampling methods have been discussed in [26-28]. In the scanning approach each input channel is sampled one at a time and converted into digital words. This method causes time skewness between input data. In synchronous method, all the input channels are sampled simultaneously. Therefore in this method no time skewness is created between input data [26-28].. In some synchronous sampling methods, one S/H (sampling and hold) and one A/D (Analog to Digital Converter) is assigned to each channel. In other configurations, for each input channel one S/H is assigned and all the inputs are fed into one A/D converter through a multiplexer.

The type of utilized sampling methods depends on the applications that they are used. For example, in the case of differential protection, the input samples are compared at the same time to create a differential scheme. Therefore, a synchronous sampling method needs to be utilized [26]

In implementing fault location methods in distribution systems it is important to take into account the utilized sampling methods in the available IEDs. For instance, RTUs (Remote Terminal Units) in SCADA (Supervisory Control and Data Acquisition) systems usually utilize scanning methods and DPR (Digital Protective Relays) use synchronous methods [28]. Therefore, if the available data is provided by RTUs, fault location methods that operate based on direct comparison of the input samples cannot be

utilized. However, if the data could be gathered from DPR or Digital Fault Recorders (DFR) this type of fault location method can be utilized [28]

4.2.2 Anti-aliasing Filters

According to Nyquist theorem, frequencies higher than half of the sampling frequency should be removed from the signal so that the aliasing phenomena are prevented [29-30]. Butterworth and Chebyshev filters are common low pass filter used in IEDs.

In [31], the frequency and step response of the Butterworth filters and type I and type II second order Chebyshev filter have been studied. According to [31], if the cut-off frequency of the anti-aliasing filter reduces the distortions in the input signals have fewer impacts on a digital algorithm. However, the step response delay of the anti-aliasing filter increases as the cut-off frequency of the anti-aliasing filters reduces.

The anti-aliasing filter should have an acceptable steady-state response, while having the least effect on transient characteristics. Therefore selecting cut-off frequency is tradeoff between accuracy and speed [31].

According to above discussions, the characteristics of anti-aliasing filters have more impact on transient conditions rather steady state conditions. Therefore steady state condition based fault location methods like impedance based methods are less affected by difference in characteristics of anti-aliasing filter of IEDs [28].

4.2.3 Resolution of A/D Conversion

One of the sources of inaccuracies in the input data for fault location methods is the errors due to the Analog to Digital (A/D) converters. In general the error of A/D converters can be represented as follows [26]:

$$q = \frac{V}{2 \times 2^{N-2}} = 2^{-N} V \quad (4.1)$$

In which N is the word length of A/D convertor, V is the maximum input signal

According to (4.1) the IEDs that their A/D converters have longer word length (bigger N) have less error. For example the word length of power quality meters is bigger compared to digital protective relays. Therefore, to increase the accuracy of the fault location algorithms utilization of IEDs with longer word length are preferred [28].

4.2.4 Sampling Frequency

Sampling frequency has direct impacts on the quality of recorded data. The sampling frequency should be high enough to not lose any information between two samples. On the other hand, the higher the sampling frequency, the higher implementation costs. Therefore, sampling frequency of the IEDs is selected based on the application of the IEDs. For instance, PQMs need high sampling frequency because they should be able to capture harmonics. Protective relays that work based on fundamental frequency of the signals, like over-current relays, do not require high sampling frequency. DFRs typically need high sampling frequency because they are used to track details of the signal transients.

The spacing of samples in a IEDs could be different. For instance, if the IED uses a fixed sampling frequency, they will take fixed number of samples per cycle. Therefore, if the frequency of the system changes, the time intervals between consecutive samples changes as well [32]. In another approach, the IED may use constant spacing intervals between the samples, which will lead to variable sampling frequency if the power system frequency changes.

Different fault location methods have different sampling frequency requirements. For example, impedance based fault location methods does not require high sampling rate while traveling wave fault location methods require high sampling rate. Therefore, sampling frequency of the available IEDs has direct impacts on the selection of the suitable fault location method [28].

4.2.5 Clock Signal for Synchronization

The presence of Global Positioning System (GPS), has provided the opportunity to take the data samples in power systems synchronously. The GPS signal can be provided to the IEDs through receivers so that the IEDs can sample the data synchronously.

Some fault location methods require collection of data from different IEDs and direct comparison of the data. In such algorithms the data should be synchronized. However, in some other methods the fault location methods do not require synchronized sampling. Therefore, the type of available IEDs should be considered when one a fault location method is selected [28]

4.3 Application of IEDs

4.3.1 Location of IEDs

The location in which the IED is installed should also be studied. For instance, usually DPRs (Digital Protective Relays) are installed at substations and responsible for one feeder, DFRs (Digital Fault Recorders) are installed at substations and responsible for all feeders (usually one DFR for whole substation), PQMs are installed at substations, load centers and end consumer, and revenue meters at end consumer. The location of the installed IED should be considered in implementation of the fault location methods. If all the IEDs are located in substation it would not be possible to select a fault location method that works based on gathered data from IEDs installed throughout the network.

4.3.2 Data Content

When data from different IEDs are utilized for fault location methods, the characteristics and functionalities of the IEDs should be taken into account. Some IEDs, such as Digital Fault Recorders, are used to directly collect the input data. However, some other IEDs such as Digital Protective Relays, apply pre-processing procedure to the data and work based on the filtered data [28]. As demonstrated in [32], the filtered data may not contain all components of the data such as DC components and etc.

According to above discussion, when data are collected for locating faults, the characteristics and content of the data should be studied. For example, if a fault location

method is requires all content of the sampled data, the IEDs that apply the filtering should not be used or the type of fault location should be changed.

4.3.3 Triggering Methods

To reduce the volume of recorded data, each IED has its own method of triggering. Some methods use change in the amplitude of sampled signal while others may use the rate of change of certain signals and so on.

Some IEDs are only for recoding certain disturbances and are only triggered to record certain disturbances. Therefore, if recording the disturbances due to fault occurrence is not among the tasks of the installed IED, the data collected from this IED cannot be used for fault location task [28].

4.4 Implementation in Selected Feeder Automation Solutions

4.4.1 Feeder Automation Architecture

There are different types of communication based on feeder automation (FA) architecture [33]:

- Centralized Feeder Automation: In this method the data is collected from different IEDs along the feeder through SCADA system and processed.
- Substation Centered Approach: In this configuration the data is collected from the feeder and processes at substation.

- Peer-to-Peer Arrangement: In this configuration the data is exchanged locally through peer-to-peer communications no SCADA-based central station is needed.

The distribution systems automation structure has direct impact on the utilized fault location algorithms. The fault location method that is based on collecting all feeder data, cannot be applied to the system that does not have centralized feeder automation. Therefore, when a fault location method is implemented the type of feeder automation needs to be taken into account.

4.4.2 Advantages and Disadvantages of Different Approaches

The following is advantage and disadvantages of each of feeder automation architectures that are discussed in [33]:

- Central Scheme

Advantage:

Operators are always aware of the condition of the network

The abnormal conditions can be managed more efficiently with more flexibility

It provides the base for implementing more functionality such as demand side management

Disadvantage:

Requires a distribution SCADA system

The implementation cost is higher as need more sophisticated communication infrastructure

It needs to update the electrical model of the power grids

- Substation Centered

Advantage:

It is easy to be implemented

It does not need to have central SCADA system

The implementation cost is not high

Disadvantage:

This configuration limits the distribution systems maneuver

In this scheme the control over the power systems components is limited

- Peer-to-Peer Arrangement

Advantage:

The implementation cost is low as doesn't require central SCADA system and sophisticated communications infrastructure

It provides fast operation (30 seconds or less)

Disadvantage:

The operator does not have full control over the network

It is more expensive compared to substation centered approach

4.4.3 Scenarios

In this section the impact of above mentioned factors on fault location methods are discussed. According to previous Section the following methods are selected:

- A) Impedance based fault location [3]
- B) Direct three-phase circuit analysis-based techniques [7]
- C) Superimposed components-based techniques [10]
- D) Traveling wave techniques [14]
- E) Artificial intelligence-based techniques [18]

Scenario 1

In this case there is no communication infrastructure and available data are provided by DFR and DPR at substation.

Method D needs data along the feeder and high frequency sampling. Therefore, D is not applicable. DFR provides data with higher quality compared to DPR. Therefore, DPR data can be used as back up. Now sources of errors should be taken into account. Both devices use synchronous sampling, so there is no phase shift error. Usually sampling rate of DFRs is higher than DPRs. Therefore DFRs have better “horizontal” resolutions defined by the sampling rate. If the methods work properly for “horizontal” resolution of DPRs they definitely can work for that of DFRs but the reverse may not be true.

According to eq. (4.1) the resolution of the devices can be calculated and then the methods are examined for that accuracy using simulation results. The same process is carried out for anti-aliasing filter. If the data from DPR are used it should be considered whether the data was reordered before or after digital pre-filtering. Accuracy of methods B, C are more affected than others because pre-filtering may remove some features that they are developed based on.

Scenario 2

This scenario assumes that there are communication structure, as well as DFR, and DPR at substation. Except method D that needs high frequency sampling other methods can be implemented. The same discussion about source of errors holds here.

Performances of methods A-C and E are evaluated using simulation results to determine how much they are affected by the factors discussed above. Table 2 summarizes the above discussions.

4.5 Conclusions

The factors that can affect quality of recorded data in IEDs such as ADC resolution, filtering, sampling implementation, sampling rate, and triggering method were studied in this Section. Moreover, impact of IED location and data content, as well as FA architecture and related scenarios for fault location algorithm selection were discussed. As a result, it was concluded that the following factors should be taken into account when selecting a fault location method:

- Sampling method (synchronous or scanned method)
- Sampling frequency (horizontal resolution) and ADC resolution (vertical resolution)
- The criteria that is selected to trigger the recording for specific event (Triggering method)
- The type and cut-off frequency of anti-aliasing filter

Table 2 Summary of two scenarios

	A	B	C
Scenario 1	<ul style="list-style-type: none"> Accuracy is checked by simulation results 	<ul style="list-style-type: none"> Accuracy is checked by simulation results 	<ul style="list-style-type: none"> Accuracy is checked by simulation results
Scenario 2	<ul style="list-style-type: none"> Communication is not needed Does not use IEDs along the feeder Accuracy is checked by simulation results 	<ul style="list-style-type: none"> Communication is not needed Does not use IEDs along the feeder Accuracy is checked by simulation results 	<ul style="list-style-type: none"> Does not need communication Does not use IEDs along the feeder Accuracy is checked by simulation results

Table 2 continued

	D	E
Scenario 1	<ul style="list-style-type: none"> It is not possible to implement because high frequency sampling is needed 	<ul style="list-style-type: none"> Accuracy is checked by simulation results
Scenario 2	<ul style="list-style-type: none"> It is not possible to implement because high frequency sampling is needed 	<ul style="list-style-type: none"> Communication is not needed Does not use IEDs along the feeder Accuracy is checked by simulation results

- Location of the installed IED
- Data content
- Feeder automation architecture (substation centered approach, centralized feeder automation or peer-to-peer arrangement)

Some scenarios were assumed to show application of the above criteria when selecting a fault location method. Knowing characteristics of IEDs can help to know what kind of data could be expected. This knowledge is useful for potential implementation of IED- or system-wide based fault location methods. This leads to development of a fault location method that is feasible and can be implemented in practice by using the available IEDs in the network under study.

5. FAULT LOCATION METHOD SELECTION

5.1 Introduction

Previous Sections summarized the fault location algorithms and related implementation issues. It was noticed that the results of fault location methods are affected by their input parameters. Estimated phasors depend on accuracy of transducers and circuitry that samples and converts voltages and currents, as well as the estimation algorithm. Resistivity of the soil and the temperature, among others, affect line parameters. Load estimation approach affects accuracy of the estimated loads [1]. One important criterion for ranking the fault location methods and selecting the most appropriate one is robustness of the algorithm against uncertainties in the inputs. To demonstrate this criterion quantitatively, uncertainty analysis is conducted in this Section. Uncertainty study quantifies uncertainty in model output due to those of inputs [34-36]. The uncertainty analysis is used for ranking the fault location methods.

5.2 Problem Formulation

Depending upon which fault location method is selected, the estimated location of the fault is function of one or several factors such as follows:

- Parameters of the lines
- Parameters of the loads
- Fault impedance
- IEDs characteristics (Accuracy of measuring devices)

It is possible to express fault location methods as follow:

$$D = f(x_1, x_2, \dots, x_n) \quad (5.1)$$

Where

D: is the estimated location of fault

x_i : Factor that affects the output D (some of them were mentioned above)

$f(\cdot)$: is the function relates the input factors(x_i) to the output (estimated fault location)

for which it is usually difficult to find a close form.

Now the question is” How the uncertainty in the input factors affects the output”.

A method that is able to estimate the fault location more accurately, despite of these uncertainties, is more robust and desirable.

For instance, impedance based fault location method in [4-5] can be expressed as follow:

$$D = f(x_1, x_2, x_3, x_4, x_5) \quad (5.2)$$

where

x_1 : is measured voltage at the substation

x_2 : is measured current at the substation

x_3 : is parameter of the lines

x_4 : is estimated load at each node

x_5 : is fault impedance

Each input has its own uncertainties. For example, parameters of the lines may change as the resistivity of the soil changes. As discussed in section 5, IEDs have uncertainties as well. Accuracy of the estimated load depends on that of utilized approach for load estimation which causes uncertainties. This Section aims at developing an approach to quantitatively measure impacts of these uncertainties in the inputs on the output (estimated fault location).

5.3 Point Estimate Approach

This approach gives the probability density function (PDF) of $z=h(x)$ when PDF of x is known. The details of this method can be found in [37-41]. The following section is a brief summary of the method taken from [37-41].

According to [37-38] knowing x_- , x_+ , p_- , p_+ produces the two estimate of the z , z_- and z_+ . In fact, x_- , x_+ , p_- , p_+ are transformed through the function $h(x)$ to provide the two values of z_- and z_+ . In [37], the followings have been shown:

$$E(z) = \bar{z} = p_- z_- + p_+ z_+ \quad (5.3)$$

$$E(z^2) = p_- z_-^2 + p_+ z_+^2 \quad (5.4)$$

Or in general

$$E(z^M) = p_- z_-^M + p_+ z_+^M \quad (5.5)$$

It is notable that M cannot be greater than the number of known moments of x . The following process shows how to calculate x_- , x_+ , p_- , p_+ [38].

In the following equations, μ_x , σ_x are the mean and standard deviation of X (for our application X was defined in (5.1)).

The Taylor series expansion of $h(X)$ about μ_x is [38]:

$$h(x) = h(\mu_x) + \sum_{i=1}^{\infty} \frac{1}{i!} h^{(i)}(\mu_x) (x - \mu_x)^i \quad (5.6)$$

where $h^{(i)}(\bullet)$, $i = 1, 2, \dots$ is the i th derivative of $h(\bullet)$ with respect to x . The mean value of Z is calculated as follow [38]

$$\mu_z = E(h(x)) = \int_{-\infty}^{+\infty} h(x) f(x) dx = h(\mu_x) + \sum_{i=1}^{\infty} \frac{1}{i!} h^{(i)}(\mu_x) \lambda_{x,i} \sigma_x^i \quad (5.7)$$

where $E(\bullet)$ denotes the expectation.

Now, let $x_i = \mu_x + \xi_i \sigma_x$, $i = 1, 2$, the following holds [38]:

$$\mu_z = p_1 h(x_1) + p_2 h(x_2) + \sum_{i=4}^{\infty} \frac{1}{i!} h^{(i)}(\mu_x) (\lambda_{x,i} - (p_1 \xi_1^i + p_2 \xi_2^i)) \sigma_x^i \quad (5.8)$$

Where p_i is probability concentration at location x_i , $i = 1, 2$ and $k = 2$.

According to [38], the p_i and ξ_j , $j = 1, 2$ are calculated as follows [38]

$$\xi_j = \frac{\lambda_{x,3}}{2} + (-1)^{3-j} \sqrt{1 + \left(\frac{\lambda_{x,3}}{2}\right)^2} \quad j=1,2 \quad (5.9)$$

$$p_j = \frac{(-1)^j \xi_{3-j}}{\zeta} \quad j=1,2 \quad (5.10)$$

Where

$$\zeta = \xi_1 - \xi_2 = 2 \sqrt{1 + \left(\frac{\lambda_{x,3}}{2}\right)^2} \quad (5.11)$$

Therefore,

$$\mu_z \cong p_1 h(x_1) + p_2 h(x_2)$$

Which is a third order approximation of μ_z .

If $h^{(i)}(\bullet)$, $i = 4, 5, \dots$, are equal to zero (e.g. when $h(X)$ is a third order polynomial), the two-point estimate approach gives the exact solution to z [38]

In general for m point concentrations with probability concentrations p_i at location x_i , $x_i = m_x + \xi_i \sigma_x$, $i = 1, 2, \dots, m$, the following holds [38]

$$\mu_z = \sum_{j=1}^m p_j h(x_j) + \sum_{i=2}^{\infty} \frac{1}{i!} h^{(i)}(\mu_x) (\lambda_{x,i} - \sum_{j=1}^m p_j \xi_j^i) \sigma_x^i \quad (5.12)$$

And its approximation can be represented as follows [38]

$$\mu_z \cong \sum_{j=1}^m p_j h(x_j) \quad (5.13)$$

Which is a $(2m-1)$ th order approximation

5.3.1 Function of Several Variables

In the case of $z = h(X) = h(x_1, x_2, \dots, x_n)$, (for our application Z , and $h(X)$ were defined in (4.1) denoted by D and $f(x)$ respectively) where X is the set of random variables X_k , $k = 1, 2, \dots, n$ [38]

$$\xi_{k,i} = \frac{\lambda_{k,3}}{2} + (-1)^{3-i} \sqrt{n + \left(\frac{\lambda_{k,3}}{2}\right)^2} \quad i=1, 2 \quad k=1, 2, \dots, n \quad (5.14)$$

And

$$p_{k,i} = \frac{1}{n} (-1)^i \frac{\xi_{k,3-i}}{\xi_k} \quad (5.15)$$

Where

$$\zeta_k = 2\sqrt{n + \left(\frac{\lambda_{k,3}}{2}\right)^2} \quad (5.16)$$

When $\rho_{ij} \neq 0$, the correlated variables are transformed into uncorrelated set of random variables as discussed in [38].

It should be noted in eq.(5.14) the standard locations $\xi_{k,i}$ is a function of number of input random variables. For large number of inputs the method will have inaccuracies [39]. To solve this problem, 2m+1 scheme has been proposed in [40] which is explained as follows:

locations $\xi_{k,i}$ sets to zero.

If $\xi_{k,3} = 0$ the standard locations and weights are as follows [40]:

$$\xi_{k,i} = \frac{\lambda_{k,3}}{2} + (-1)^{3-i} \sqrt{\lambda_{k,4} - \frac{3}{4}\lambda_{k,3}^2} \quad i=1,2 \quad \xi_{k,3} = 0 \quad (5.17)$$

$$p_{k,i} = \frac{(-1)^{3-i}}{\xi_{k,i}(\xi_{k,1} - \xi_{k,2})} \quad i=1,2 \quad (5.18)$$

$$p_{k,3} = \frac{1}{n} - \frac{1}{\lambda_{k,4} - \lambda_{k,3}^2} \quad (5.19)$$

Setting $\xi_{k,3} = 0$ yields $x_{k,3} = \mu_k$. So, n of 3n locations are the same point $(\mu_1, \mu_2, \dots, \mu_k, \dots, \mu_{n-1}, \mu_n)$ [40]. It is enough to run only one evaluation of function at this location, provided that the corresponding weight is updated as follow [40]:

$$p_0 = \sum_{k=1}^m p_{k,3} = 1 - \sum_{k=1}^m \frac{1}{\lambda_{k,4} - \lambda_{k,3}^2} \quad (5.20)$$

From eq. (5.17), unlike 2n point estimate method, the standard location values of the scheme 2n+1 does not depend on the number n of input random variables [40].

Having the $P_{k,i}$ and $x_{k,i}$ estimated the jth raw moment of the output random variables is defined as follows [40]:

$$E(z^j) \cong \sum_{k=1}^n \sum_{i=1}^m P_{k,i} \times (h(\mu_1, \mu_2, \dots, x_{k,i}, \dots, \mu_{n-1}, \mu_n))^j \quad (5.21)$$

5.4 Fault Location Selection

5.4.1 Qualitative Procedure

According to Section 3 distribution fault location methods could be categorized as follows

- Apparent Impedance based fault location method
- Direct three-phase circuit based fault location method
- Superimposed signal based fault location method
- Traveling waves based fault location method
- Artificial intelligent based fault location method

to select the optimal fault location method, at first qualitative study should be conducted. The qualitative comparison of the fault location methods has been presented in Table 1. In addition to that, the following are also some conclusions that can be made out of that study which states the impedance based fault location methods are more attractive than other methods for the typical distribution systems (having IEDs with medium sampling rate ad substation/control center based communication)

- Traveling wave based methods need high frequency sampling
- Artificial intelligent methods require generation of training data and re-training process if the configuration of the network changes.
- Superimposed components and direct three-phase circuit analysis are very dependent on power system configurations and data acquisition process.
- Among impedance fault location methods, some of them do not consider heterogeneity of the lines, presence of laterals and sub-laterals which makes them inaccurate. In [3-4], these factors have been taken into account. Therefore, they are potential candidates for optimal fault location method. The next section shows how the most appropriate fault location method can be selected quantitatively among the candidate methods.

5.4.2 Quantitative Procedure

In this section a systematic quantitative method for selecting the most suitable fault location method for a given network is proposed. The method is based on uncertainty analysis. The method that has the least uncertainty in pinpointing the faults is selected as the optimal fault location method. To calculate the uncertainty of the method in detecting location of the fault, uncertainties in the input parameters to fault location method are provided. For instance, there are uncertainties in the measured data due to noise and there are also uncertainties in value of parameters of the network. To select the optimal fault location method among the candidate methods selected by using qualitative procedure, they are implemented in the MATLAB software first. The $2n+1$ point

estimate approach is used to quantify the difference between estimated and actual distance from the substation. The $2n+1$ point estimate approach gives μ and σ of the output (error of the fault location method). Knowing these parameters it is possible to define a criterion function to estimate the uncertainty of the output.

$$X_{threshold} = \mu + C\sigma \quad (5.22)$$

According to Chebyshev's inequality [42], the following holds:

$$p[\mu - C\sigma \leq X \leq \mu + C\sigma] \geq 1 - \frac{1}{C^2} \quad (5.23)$$

Using 95% confidence interval criterion C would be 4. Therefore (5.22) becomes as follow:

$$X_{threshold} = \mu + 4\sigma \quad (5.24)$$

The method that has smaller $X_{threshold}$ is more desirable. Because it means less error

5.5 Conclusions

A procedure for optimal fault location method selection was developed in this Section. At first, qualitatively potential candidate methods were selected among pool of fault location methods. It was pointed out that impedance based fault location methods are promising methods for distribution system applications. Among them, two methods that consider peculiarities of the distribution systems including heterogeneity of the lines, and presence of laterals and sub-laterals were selected. A quantitative approach for selecting the optimal fault location by using $2n+1$ point estimation method was also

proposed. In section 7, the performance of proposed quantitative will be demonstrated numerically for Saskatchewan Power System model.

A main drawback of the substation based fault location methods is multiple fault location estimations. To solve this problem, in the next Section, an approach by using gathered data from IEDs throughout the network is proposed.

6. ENHANCED FAULT LOCATION METHOD AND OPTIMAL IED PLACEMENT*

6.1 Introduction

Development of communication systems and ever increasing utilization of Intelligent Electronic Devices (IEDs) along the feeders have made it possible to collect more information for finding the location of the fault. To take full advantage of such data, suitable fault location methods should be developed. According to previous Section, impedance based fault location methods are the most attractive methods for fault location. However, they suffer from multiple fault location estimations. In this Section, a method based on gathered voltage sag data from a few IEDs installed along the feeder is developed to eliminate false fault location estimations. Moreover, a systematic approach for IED placement for fault location implementation is developed which determines number and location of required IEDs.

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6.2 Fault Location Method Based on Voltage Sag Data

As detailed in [1], “the fact that the fault causes voltage sags with different characteristics at different nodes throughout the network is utilized for fault location purpose. The fault location method is based on gathered data from IEDs installed at some strategic points along the

feeder. These IEDs should be able to capture voltage phasors such as power quality meters. The method can pinpoint the fault quickly and precisely and does not suffer from multiple fault location estimation.

Pre-fault and during-fault voltage and current phasors at the root node (substation), as well as knowledge about faulted phase(s) and fault type are utilized. In [43-47] methods for fault classification have been proposed. Pre-fault measurements are used for estimating load variations and updating load models. During-fault data is used for finding the location of the fault. Voltage sags are also gathered from IEDs installed at some selected nodes along the feeder.

At first potential location of fault are detected by apparent impedance based fault location method presented in [3]. Voltage sags at location of installed IEDs are calculated using a load flow program for the faults at each potential locations of the fault estimated by [3]. The fault location is determined by comparing how well each calculated case matches up to what was actually observed by the IEDs in the network. The case that shows the highest similarity is considered the location of the fault.

In implementing this method, several issues should be addressed, which are discussed in the following sections.

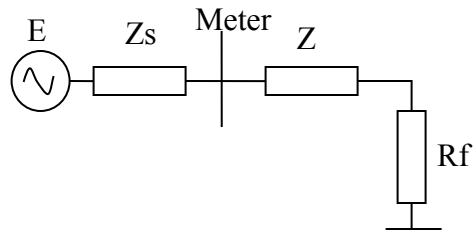


Figure 2 Simple faulted network model [1] © [2011] IEEE

6.2.1 Voltage Sag Characterization

Faults at different locations on the feeder produce voltage sags with different magnitudes which is utilized for fault location in [48-49]. However, in some cases, they may produce voltage sags with the same magnitude.

Fig. 2 shows a simple model of a faulted network. Z_s is the source impedance seen at the meter location. Z is the impedance between meter location and the fault. R_f is the fault resistance. Voltage sag is captured at Meter location. Two cases are assumed for further analysis. A fault occurs at a location where

$$\begin{aligned} Z &= Z_1 \\ R_f &= R_{f1} \end{aligned} \tag{6.1}$$

And in another case, fault is characterized with

$$\begin{aligned} Z &= Z_2 \\ R_f &= R_{f2} \end{aligned} \tag{6.2}$$

In eq. (6.2) $Z_2 > Z_1$, which means farther from the Meter location. According to Fig. 2, voltage phasors captured by the Meter are

$$V_{meter(1)} = \frac{E(Z_1 + R_{f1})}{(Z_s + Z_1 + R_{f1})} \quad (6.3)$$

$$V_{meter(2)} = \frac{E(Z_2 + R_{f2})}{(Z_s + Z_2 + R_{f2})} \quad (6.4)$$

Some values of R_{f1} and R_{f2} may exist so that

$$|V_{meter(1)}| = |V_{meter(2)}| \quad (6.5)$$

In fact, if R_{f2} is smaller than R_{f1} such that voltage drop on R_{f2} and Z_2 equals to that of R_{f1} and Z_1 , magnitude of $V_{meter(1)}$ will be equal to $V_{meter(2)}$. While voltage amplitudes can be equal, the phase angles are not the same. As the fault is mainly affected by the resistive part, it produces different angle shift in comparison with line impedance. Because, line impedance also has an inductive part which is usually bigger/equal to resistive part.

Using phase angle shifts in addition to voltage sag magnitudes doubles the volume of the required data. For instance, in case of a single-phase fault in addition to transmitting voltage sag magnitude to the distribution control center, phase angle shift of the faulted phase should be transmitted as well. In the case of three-phase faults, the phase angle shifts for all three phases are required. Therefore, a method should be used to reduce the volume of the required data while preserving the required information.

In [50] a method for three-phase voltage sag characterization has been proposed. A brief description of the method is as follows [50]:

1) The sag type is determined. In [50] each type has been explained in detail. The basic distinction is between types A, C and D. Type A is an equal drop in three phases,

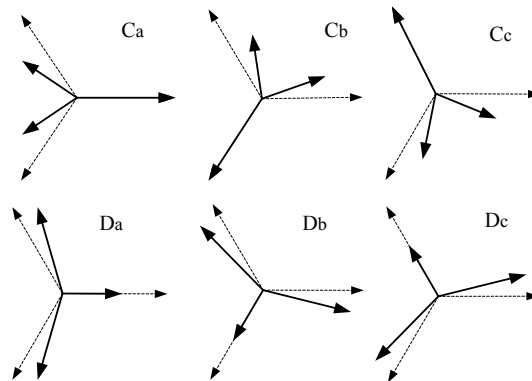


Figure 3 Types C and D voltage sags for different phases [51] © [2003] IEEE

type C is a drop in two phases, and type D is a large drop in one phase with a small drop in the other two phases.

For types C and D, a further subdivision is needed to include the symmetrical phase (the phase with the large voltage drop for type D, the phase without voltage drop for type C). The resulting six types of three-phase unbalanced sags are shown in Fig. 3 [51]. Type Da is a drop in phase a, type Ca is a drop in phases b and c and so on. Voltage dip type is determined using the phase angle obtained from measurements [51]

$$T = \frac{1}{60^\circ} \times \arctan \left\{ \frac{V_{neg}}{1 - V_{pos}} \right\} \quad (6.6)$$

Where T is rounded to the nearest integer number and V_{pos} and V_{neg} are the positive and negative sequence voltages, respectively. T can be a number from 0 to 5 that implies the type Ca, Dc, Cb, Da, Cc, and Db, respectively.

2) The characteristic voltage (\bar{V}) is calculated which is a phasor that quantifies the severity of the voltage sag. It is defined as

$$\bar{V} = \bar{V}_{pos} - \bar{V}'_{neg} \quad (6.7)$$

Where

$$\bar{V}'_{neg} = \bar{V}_{neg} e^{-jT60^\circ} \quad (6.8)$$

3) The positive and negative factor (\bar{F}) is defined as:

$$\bar{F} = \bar{V}_{pos} + \bar{V}'_{neg} \quad (6.9)$$

If the negative and positive sequence impedances are equal, \bar{F} is close to unity in all cases. The phasor diagrams in Fig. 3 are given for $\bar{V}=0.5$ and $\bar{F}=1$.

The absolute value and the argument of the characteristic voltage \bar{V} are referred to as “magnitude” and “phase-angle jump” of the voltage dip, respectively.

Knowing \bar{F} and \bar{V} , it is possible to rebuild the three-phase value of the voltage sag. However, in the fault location method the decision is made based on the comparison of recorded and calculated voltage sag data. This comparison can be done based on \bar{V} which has enough information about amplitude and phase angle jump of the voltage sag. So, \bar{V} is the only required data that should be transferred to the distribution control center.

6.2.2 Fault Resistance Estimation

To estimate the fault resistance, the following procedure at each potential location of fault (one at a time) should be carried out.

First, a fault with $R_f=0$ is applied at an assumed faulted location and the steady state fault current at the root node (substation) is calculated using short circuit analysis method [52]. This calculated fault current is compared with the recorded current at the substation.

$$\varepsilon = |I_{calculated}| - |I_{recorded}| \quad (6.10)$$

where

$|I_{calculated}|$ is the amplitude of the calculated current phasor at the substation.

$|I_{recorded}|$ is the amplitude of the recorded current phasor at the substation.

If the amplitude of the calculated current is smaller than that of the recorded current, the assumed node cannot be the candidate location for the fault. This is because, when the fault with $R_f=0$ at that location cannot produce the same amount of current recorded at the substation, for $R_f>0$ it definitely cannot do so. If ε does not fall within the convergence tolerance, R_f must be increased (say $R_f=20 \Omega$) and another iteration should be performed. By extrapolating/ interpolating the two solutions, closer estimate to the actual value of R_f is reached as shown in Fig. 4. By continuing the process, the R_f for which ε falls within the convergence tolerance can be determined.

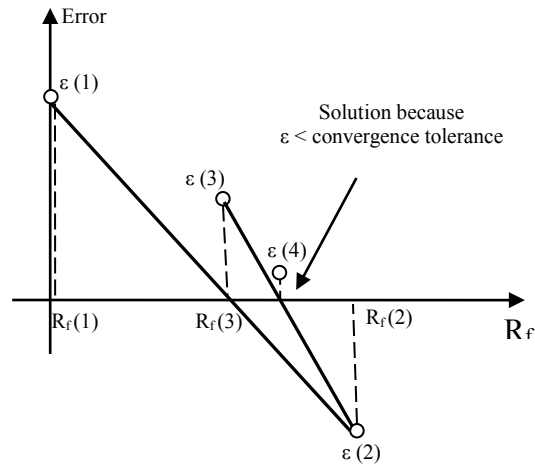


Figure 4 Rf estimation procedure [1] © [2011] IEEE

6.2.1 Load Variation

In order to take into account the variation of the loads, in [10] a method has been suggested. It neglects power losses in the lines, which makes it inaccurate. Here, a method based on the captured data at the substation that considers power losses in the lines is suggested. Load factor is defined as:

$$L_{factor} = \frac{S_{pre-fault}}{S_{Lmax}} \quad (6.11)$$

Where

$$S_{Lmax} = (M_1 + M_2 + \dots + M_N) \quad (6.12)$$

N is the number of load taps and M is their nominal transformer rating.

$S_{pre-fault}$ is the pre-fault apparent power of the loads calculated at the substation, defined as follows:

$$S_{pre-fault} = |S_{substation} - S_{line}| \quad (6.13)$$

where

$$S_{substation} = \sqrt{3} \times V_{Lsubstation} \times I_{Lsubstation}^* \quad (6.14)$$

where $V_{Lsubstation}$ and $I_{Lsubstation}$ are the pre-fault line voltage and current at the substation calculated using a load flow program. And

$$S_{line} = U \times Z \times I^2 \times U^T \quad (6.15)$$

Where Z is a diagonal matrix whose diagonal elements are impedance of each line, and I is the line currents calculated using pre-fault load flow program. U is a row-matrix whose elements are 1 and U^T is the transpose of the U matrix

Now load at each tap is estimated as

$$S_i = L_{factor} * M_i \quad (6.16)$$

Knowing new S for each load, pre-fault load flow is conducted and eq. (6.10), (6.13-6.15) are updated until S converges which means

$$|S_{Line(k)} - S_{Line(k-1)}| < \varepsilon \quad (6.17)$$

Where, ε is convergence tolerance and k is iteration number.

6.3 Implementation of the Method

The characteristic voltage (\bar{V}) of the voltage sag, captured at some nodes along the feeder, is sent to the distribution control center. In the distribution control center, the pre-fault data recorded at the root node (substation) is used for updating load models. The

measured during-fault characteristic voltage ($\bar{V}_{recorded}$), which was sent to the control center, and the calculated characteristic voltage ($\bar{V}_{calculated}$) obtained using short circuit analysis program are compared. To calculate the characteristic voltage ($\bar{V}_{calculated}$) at the control center, the fault at potential location of fault is applied one at a time with the Rf values estimated using the developed method. The node at which applying the fault produces the best match between the calculated and the recorded characteristic voltages is the actual location of fault.

The following equation quantifies similarity between calculated and recorded voltage sag data:

$$Error = \mathcal{E}_{amplitude(V)}^2 + \mathcal{E}_{phase(V)}^2 + \mathcal{E}_{phase(I)}^2 \quad (6.18)$$

where

$\mathcal{E}_{amplitude(V)}$ is the difference between the amplitude of the characteristic voltage of recorded ($\bar{V}_{recorded}$) and calculated voltage sags ($\bar{V}_{calculated}$)

$\mathcal{E}_{phase(V)}$ is the difference between the phase angle of the characteristic voltage of recorded ($\bar{V}_{recorded}$) and calculated voltage sags ($\bar{V}_{calculated}$)

$\mathcal{E}_{phase(I)}$ is difference between phase angle of recorded and calculated current at root node.

The following criterion is defined for faulted node detection

$$Flag = \frac{1}{Error + \Delta} \quad (6.19)$$

where Error is defined in eq. (6.18) and Δ is a small number just to prevent division by zero in eq. (6.19). The location that has the largest Flag value in eq. (6.19) (or smallest Error) is the faulted location.

Fig. 5 shows the flowchart of the proposed algorithm. At first the measured

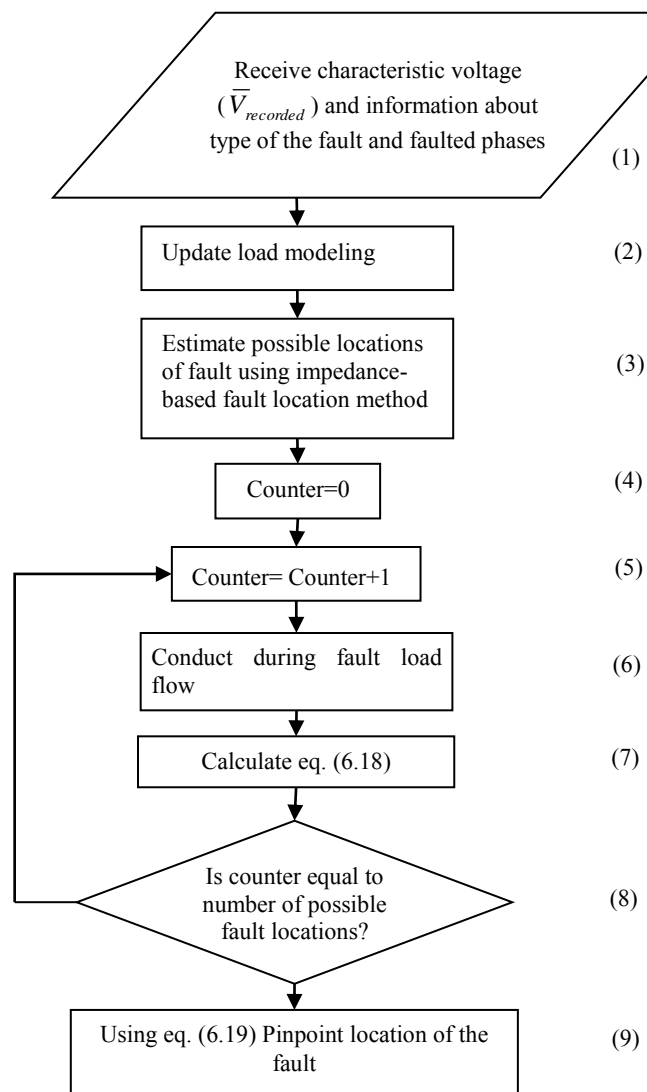


Figure 5 Flow chart of the fault location algorithm [1] © [2011] IEEE

characteristic voltage ($\bar{V}_{recorded}$) and detected fault type and faulted phases are provided to the fault location method. Moreover, the load values are updated. The possible locations of the fault are estimated by impedance based fault location method. The “Counter” checks if all possible location of the fault are examined.

Steps (7) quantify the similarity between the calculated and recorded voltage sag data. Step (8) checks whether the process has been conducted for each possible location of the fault. Finally, the fault location is pinpointed at step (9).”

6.4 IED Placement

6.4.1 Principle of the Proposed Method

As explained in previous section, in the fault location method voltage sag data captured from few IEDs installed throughout the network are gathered in control center and the task of pinpointing the fault location is executed. A question that needs to be answered is how many and where these IEDS should be installed such that with minimum number of IEDs the required information is captured so that the fault location method be able to uniquely estimate location of the fault. In the fault location method, each pair of i and j locations with the same distance from the root node (substation) should be discriminated from each other. As the voltage sag data based fault location is based on data gathered from IEDs installed along the feeder, enough information should be provide to the method by installing IEDs. The required information is voltage sag data that have different characteristics due to fault at location i from fault at location j .

6.4.2 Problem Formulation

In the IED placement procedure the objective is to capture enough information so that the faults at locations that are at the same distance from the substation can be distinguished. Depending on the relative location of the installed IEDs to the fault location, voltage sags with different characteristics (voltage amplitude and/or phase angle shift) are observed. Therefore, to distinguish a fault at location i from a fault at location j , at least one IED should exist that capture different characteristics. If all the IEDs capture the same voltage sag characteristics due to faults at locations i and j , these fault locations are not distinguishable. Therefore, for each pair of fault locations that are at the same distance from the substation, short circuit fault analysis is conducted and the observed voltage sags at different nodes of the network are recorded. The nodes that observe different voltage sag characteristics for fault at different locations are potential candidates for IED placement.

6.4.3 Optimal IED Placement

In this section the optimal IED placement is formulated as an optimization problem. X vector is defined a vector whose x_i is the following

$$x_i = \begin{cases} 1 & \text{If an IED is needed at node } i \\ 0 & \text{otherwise} \end{cases} \quad (6.20)$$

Now the optimization problem is defined as follow:

$$\text{Min } \sum_i x_i \quad (6.21)$$

Subject to

$$\sum_i x_i + \sum_i \sum_k x_i x_k + \dots \geq 1 \quad (6.22)$$

The constraint (6.22) is written for every pairs of nodes that are at the same distance from the substation. For example if nodes a and b are at the same distance from substation, a and b constitute one pair of nodes that should be discriminated from each other.

In (6.22), x_i s are the locations for IEDs placement to j th pair of fault locations that are at the same distance from the root node of the feeder (substation) . The term $x_i x_k$ implies that to distinguish the j th pair of faults two IEDs are needed to be located at nodes i and k .

The constraint (6.22) is non-linear. To make it linear, the optimization problem is formulated as follows:

$$\text{Min } \sum_i x_i \quad (6.23)$$

$$\sum_{k_j} Y_{jk_j} \geq 1 \quad \forall j \quad (6.24)$$

$$\sum_{i \in k_j} x_i \geq |k_j| \times Y_{jk_j} \quad \forall j, k_j \quad (6.25)$$

$$x_i, Y_{jk_j} \in \{0, 1\}$$

where

Y_{jk_j} is kth set if required IEDs to distinguish faults at jth pair of nodes that are located at the same distance from the substation. Y_{jk_j} is 1 if k_j set if IEDs is used to discriminate faults at jth pair.

k_j is set of IEDs to discriminate faults at jth pair

$|k_j|$ is number of required IEDs at k_j set of IEDs to distinguish faults at jth pair

Solving the above binary linear programming problem determines the number and location of required IEDs.

6.4.4 Topology Change

The topology of the power systems may change due to power systems reconfiguration process or due to damage to a certain section of the network. Therefore, in the process of optimal IED placement this issue needs to be taken into account. The power grid is divided into different subareas based on the location of the switches. The pair of fault location that need to be distinguished from each other should have associated IEDs inside the same subarea. If both fault locations that need to be discriminated from each other fall into two different subareas, the IDS can be installed at both subareas.

As shown in Fig. 6, two distinguish faults at node A and B, the IEDs can be installed at subsection 1. However, to distinguish fault and nodes C and D, the IEDs can be installed at subsections 1 and 2.

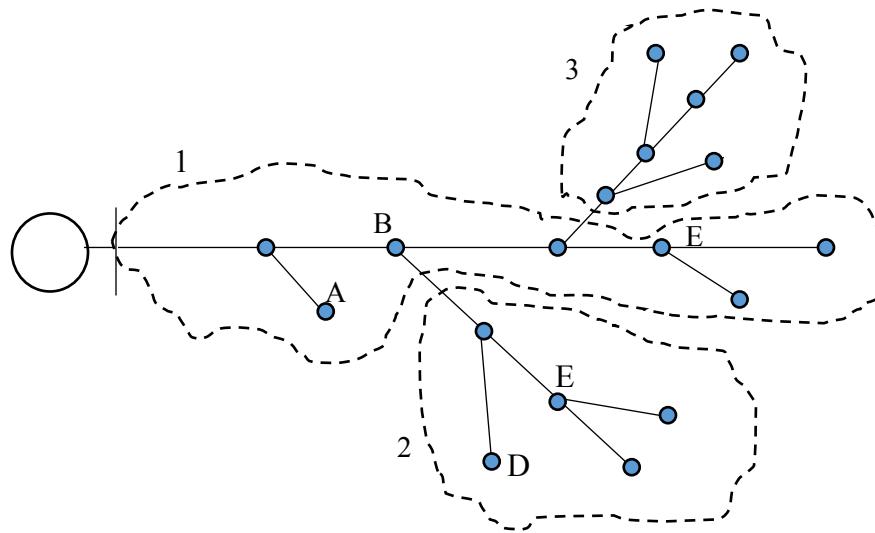


Figure 6 A distribution systems with three subareas

It is notable that some subsections are dependent on each other. It means that a given subsection is connected to the substation through another subsection. In this case, to distinguish faults at dependent subsection the IED can be installed at both subsections. For example, in Fig. 6, subsection 2 is dependent on subsection 1. Therefore, to distinguish faults at node E from faults at node D, IEDs can be installed at both subsection 1 and subsection 2.

6.5 Conclusions

In this Section, a method for eliminating multiple fault location estimations was developed. The method utilizes voltage sag data captured by IEDs at select location throughout the network to eliminate multiple fault location estimates by impedance based fault location method. Moreover, a systematic procedure for IED placement was

developed. The proposed optimal IED placement procedure determines required number of IEDs and their locations.

7. CASE STUDY

7.1 Introduction

In this section performance of proposed fault location method is demonstrated. In the proposed fault location at first possible locations of fault are determined by impedance based fault location method. Based on qualitative study in section 5, [3-4] are the most suitable candidates. In this section, by using quantitative approach presented in section 5, the optimal fault location is selected. Moreover, the performance of developed voltage sag data based fault location for eliminating false fault location estimation is demonstrated.

7.2 Optimal Fault Location Selection

In this section the case study results for two candidate fault location methods [3-4] selected by the qualitative procedure is presented. The mathematical formulation of the fault location algorithms in [3-4] are executed in MATLAB software. The SaskPower [24], is also simulated in ATP software and the generated voltage and current signals are sent to MATLAB software. The parameters of the network are presented in [4] and [24]. Tables 3-8 show the error of the methods defined as follow:

$$error = \frac{| \text{actual fault location} - \text{estimated fault location} |}{\text{total line length}} \quad (7.1)$$

In tables 7-8 the measurement error is 5 percent.

Table 3 Error of the method [3] for a-g fault

Location of the fault	Node# 1				Middle of line 7-8				Node# 13			
Incidence angle	0 deg.		90 deg.		0 deg.		90 deg.		0 deg.		90 deg.	
Measurement error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error
Rf=0 Ω	0.0091	0.0673	0.0091	0.0584	0.0041	0.1013	0.0061	0.1085	0.0003	0.0124	0.0002	0.0203
Rf=10 Ω	0.1017	0.1032	0.1071	0.1082	0.0287	0.0045	0.0263	0.0052	0.0361	0.0305	0.0361	0.031

Table 4 Error of the method [3] for b-c fault

Location of the fault	Node# 1				Middle of line 7-8				Node# 9			
Incidence angle	0 deg.		90 deg.		0 deg.		90 deg.		0 deg.		90 deg.	
Measurement error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error
Rf=0 Ω	0.0091	0.0611	0.008	0.061	0.0031	0.0472	0.0035	0.0463	0.0022	0.0120	0.0019	0.0142
Rf=10 Ω	0.1066	0.1068	0.1038	0.1053	0.0287	0.0164	0.0287	0.0186	0.0265	0.0217	0.0277	0.0217

Table 5 Error of the method [3] for a-b-c fault

Location of the fault	Node# 1				Middle of line 7-8				Node# 9			
Incidence angle	0 deg.		90 deg.		0 deg.		90 deg.		0 deg.		90 deg.	
Measurement error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error
Rf=0 Ω	0.0081	0.0587	0.0081	0.0561	0.008	0.039	0.008	0.041	0.00453	0.0305	0.00462	0.0341
Rf=10 Ω	0.0210	0.0733	0.0181	0.0742	0.0092	0.0574	0.0092	0.0592	0.0044	0.0313	0.0044	0.0334

Table 6 Error of the method [4] for a-g fault

Location of the fault	Node# 1				Middle of line 7-8				Node# 13			
Incidence angle	0 deg.		90 deg.		0 deg.		90 deg.		0 deg.		90 deg.	
Measurement error	Without error	With Error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error
Rf=0 Ω	0.0079	0.0621	0.0081	0.065	0.0988	0.1290	0.0981	0.121	0.0801	0.0591	0.0852	0.0604
Rf=10 Ω	0.0439	0.007	0.0452	0.007	0.0944	0.1238	0.0944	0.1242	0.0741	0.0469	0.0783	0.0472

Table 7 Error of the method [4] for a-b fault

Location of the fault	Node# 1				Middle of line 7-8				Node# 9			
Incidence angle	0 deg.		90 deg.		0 deg.		90 deg.		0 deg.		90 deg.	
Measurement error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error
Rf=0 Ω	0.0087	0.0592	0.0085	0.0602	0.1116	0.1205	0.11361	0.1259	0.0096	0.0498	0.0092	0.0475
Rf=10 Ω	0.0414	0.0610	0.0483	0.1014	0.1120	0.1210	0.1037	0.1271	0.0005	0.0502	0.0005	0.0518

Table 8 Error of the method [4] for a-b-c fault

Location of the fault	Node# 1				Middle of line 7-8				Node# 9			
Incidence angle	0 deg.		90 deg.		0 deg.		90 deg.		0 deg.		90 deg.	
Measurement error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error	Without error	With error
Rf=0 Ω	0.0074	0.0621	0.0079	0.0653	0.0992	0.1243	0.0968	0.1261	0.0698	0.0399	0.07023	0.0401
Rf=10 Ω	0.0663	0.1160	0.0692	0.1123	0.0872	0.1291	0.0881	0.1273	0.0635	0.0312	0.0684	0.0391

By using $2n+1$ point estimation method the $X_{threshold}$ in eq. (5.24) for method [3] is 0.1138 and for method [4] is 0.1326 which means the method [3] is more appropriate fault location method for the simulated network (SaskPower)

7.3 False Fault Location Elimination

As discussed in section 6, few IEDs need to be installed throughout the network to capture voltage sag data. In section 6, an optimal IED placement procedure was also proposed. In the case of Fig. 3 of [24], IEDs should be installed at nodes 8, 11, and 17.

Now, three different scenarios are implemented to demonstrate performance of the proposed fault location method. The locations with highest value of η is the selected location of the fault. Therefore, as Table 9 shows in all cases the fault location is pinpointed precisely.

Table 9 False fault location estimation elimination results

Scenario	Fault type	Actual location	Possible locations	η	Final estimation
1	b-g (5 Ω)	node# 10 (30.093km)	node #10 (29.96 km)	1.3×10^{-2}	node# 10
			Node#7 (29.94 km)	2.0×10^{-3}	
2	a-b (10 Ω)	node# 4 (20.92 km)	node #4 (20.68 km)	1.0×10^{-2}	node# 4
			Line between node 3 and 5 (20.73km)	3.2×10^{-3}	
3	a-c-g (5 Ω)	node# 4 (20.92 km)	node #4 (20.70 km)	1.1×10^{-2}	node# 4
			line between node 3 and 5 (20.75 km)	3.4×10^{-3}	

7.4 Conclusions

The proposed approach for selecting the most appropriate fault location method for a given network is presented. In the proposed approach at first a according to qualitative study a short list of fault location methods is generated. This qualitative study is based on the requirements of the algorithm and the characteristics of the network under study. In the second step, the most appropriate fault location is selected quantitatively. A criterion function based on Chebyshev's inequality is defined that quantifies inaccuracy of fault location methods. The impacts of the inaccuracies and uncertainties in the inputs of the fault location algorithms were quantified using uncertainty analysis. In distribution systems due to presence of laterals and sub-laterals fault location methods may lead to multiple-fault location estimations. As discussed in previous section, a systematic approach for eliminating false fault location estimations can be developed based on collected voltage sag data along the feeder.

In this section the proposed method for eliminating multiple fault location estimations were numerically demonstrated. Two qualitatively selected candidates [3-4] for optimal fault location method that consider peculiarities of the distribution systems were selected. The Saskatchewan Power System model was used to simulate faults in ATP software and the modeling and simulation methods were implemented in MATLAB software.

According to proposed quantitative procedure in section 5, method [3] selected as optimal fault location method. It was also demonstrated that the developed method in section 6 based on voltage sag data captured by few IEDs located at strategic locations

along the feeder is able to eliminate false fault locations successfully and gives unique result.

8. SUMMARY AND FUTURE WORK

8.1 Summary

The demand and importance for a cost effective and reliable method for accurately locating faults on distribution systems, essentially to expedite the restoration of service, has increased greatly. Therefore, a lot of methods have been suggested for fault location in distribution networks in the past. On the other hand, smart distribution systems add unique information technologies to the existing networks. The data can be collected from different IEDs along the feeder and utilized for fault location purpose. Therefore, it is possible to develop more accurate fault location methods in the smart distribution systems. To reach this goal, an enhanced fault location method for smart distribution systems was developed. At first a systematic approach for selecting the most appropriate fault location method among existing methods was proposed. Voltage sag data are captured at select locations throughout the network to solve the problem of multiple fault location estimations. Moreover, a probabilistic approach for IED placement in distribution system was proposed that determines number and locations of required IEDs. Specifically each section focused on addressing one aspects of the explained procedure.

Section 3 surveyed existing fault location methods and their strengths and caveats. The section 4 studied characteristics of IEDs that may be used in fault location as well as their impacts on the fault location method implementation. Distribution fault location methods were categorized as follows:

- Apparent Impedance based fault location method
- Direct three-phase circuit based fault location method
- Superimposed signal based fault location method
- Traveling waves based fault location method
- Artificial intelligent based fault location method

According to the conducted survey, the impedance based fault location methods are the most prospective methods. The followings are some reasons that make other methods unattractive

- Traveling wave based method needs high frequency sampling
- Artificial intelligent method requires a training process and a re-training process if the structure of the network changes.
- Superimposed component based method and the direct three-phase circuit analysis based method are very dependent on power system configurations and data acquisition process

Although impedance based fault location methods have been widely utilized for locating the faults they may lead to multiple fault location estimates.

In section 5, a quantitative approach for evaluating and ranking the fault location methods that qualitatively discussed in the section 3 was proposed. The proposed approach ranks the existing fault location methods based on their robustness against uncertainties in the parameters of the network. Fault location estimation was formulized as an uncertainty analysis problem. $2n+1$ point estimation method as a computationally efficient method was utilized to estimate statistical moments of the error of fault location

methods. Finally, by using Chebyshev's inequality a criterion function was defined to quantitatively rank the fault location method.

In section 6, a method was developed to eliminate false fault location estimations by impedance based fault location method. The method utilizes voltage sag data captured at select IEDs installed throughout the network. Voltage sags at location of installed IEDs are calculated using short-circuit analysis program for the faults at each potential locations for the fault that are estimated by impedance based fault location method. The actual location of the fault is detected based on comparison of the measured and calculated voltage sag data. The fault that causes highest similarity between calculated and measured voltage sag is determined as the actual location of the fault.

In addition to that, an approach was proposed for IED placement. The optimal meter placement was formulized as an optimization problem (Binary Integer Programming). The method determines number and location of required IEDs. Finally, the suitability and performance of the method was demonstrated by using simulation results.

8. 2 Dissertation Contribution

An automated fault location method in smart distribution systems was developed. The method utilizes voltage sag data gathered from a select IEDs installed throughout the network to eliminate multiple false fault location estimations.

A systematic optimal fault location method selection was developed. At first the existing methods were studied qualitatively and their caveats and strengths were detailed. Based on algorithm requirements and feasibility of implementation the most

appropriate category of fault location method was selected. A systematic fault location method selection was proposed that ranks the methods quantitatively.

A method based on voltage sag data captured by select IEDs installed throughout the network was developed. The method eliminates false fault location estimations and gives unique result

An optimal IED placement was proposed that determines the number and the location of required IEDs for the purpose of fault location.

8.3 Future Work

The main focus of the dissertation was on radial distribution systems that is the case most of the time in present distribution systems. Even if the distribution systems are planned as mesh systems, they are operated in radial configuration by keeping open a normally open switch along the feeder. However in future smart distribution systems, distribution systems will be operated in mesh configuration. Moreover, distributed Generations (DGs) are connected different locations of the network. Therefore, the proposed fault location method should be modified or new fault location method should be proposed to address this issue.

Outage management has several steps, including fault detection, fault classification, fault location, and system restoration. In the proposed method, it is assumed that the fault detection and classification are already done and the information about fault occurrence and type of the fault is available by using existing methods. However, smart grids add new information technologies that could be utilized for fault detection and

classification purpose. New methods should be proposed that utilize data gathered along the feeder. The proposed methods should take into account the feeder automation architectures as well. For different type of feeder automation architectures (Centralized Feeder Automation, Substation Centered Approach, Peer-to-Peer Arrangement) different methods should be developed.

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APPENDIX A

In this section, a brief review of fault location methods in distribution systems is presented.

A.1 Impedance-based measurement techniques

Apparent impedance is the ratio of the selected voltage over selected current based on the fault type and faulted phases. When a fault occurs, apparent impedance is calculated and the fault location is determined by comparing apparent impedance with the pre-known line data.

Comprehensive study and discussion about impedance based fault location methods has been presented in [24]. In this section, the following methods are discussed:

- In sequence domain [2]
- In three phase domain and using information from protective devices [3]
- In sequence domain and using fault indicators [4-5]

A.1.1 In sequence domain [2]

This method classifies the fault types based on the magnitude change of current phasor. The phase with biggest magnitude change is used as a reference. The ratio of current magnitude change of each phase over the reference magnitude is calculated. If this ratio is bigger than or equal to 0.75 the phase is determined as faulted phase.

Once the faulted phase is determined, the apparent impedance is defined as follow [2]:

$$Z_{app} = \frac{V_{select}}{I_{select}} = R_{app} + jX_{app} \quad (A.1)$$

where

R_{app} is the apparent resistance seen at the recording device

X_{app} is the apparent reactance seen at the recording device.

V_{select} and I_{select} depend on the type of fault. For example for phase a to ground fault

$$V_{select} = V_a \text{ and } I_{select} = I_a + kI_0 \text{ where } K = \frac{Z_0 - Z_1}{Z_1}$$

According to [2], for fault with distance of D from the measuring point the following holds [2]

$$Z_{app} = Dz_1 + \frac{I_{compensation}R_f}{(I_a + kI_0)} \quad (A.2)$$

Where Dz_1 is the total positive sequence impedance to the fault point, and $I_{compensation}$ is $3I_0$ [2]. In (A.2) the unknown variables are R_f and D . Solving real and imaginary parts of the (A.2) provides the following equation for the distance of the fault [2]

$$D = \frac{(R_{app}M - X_{app}L)}{(R_1M - X_1L)} \quad (A.3)$$

Where

$$L = \frac{(I_d I_{s1} + I_q I_{s2})}{(I_{sm}^2)}, \quad M = \frac{(-I_d I_{s2} + I_q I_{s1})}{(I_{sm}^2)}, \quad I_{comp} = I_d + jI_q, \quad I_{sm}^2 = I_{s1}^2 + I_{s2}^2$$

I_d and I_q are real and imaginary parts of the $I_{\text{compensation}}$ and I_{s1} and I_{s2} are real and imaginary parts of I_{selected} .

Based on presented evaluation results this method can locate the fault with 99 percent precision (one percent error). This method suffers from multiple fault location estimation in case of laterals. This method needs knowledge of the network topology including lines and loads parameters. Moreover, it requires iterative calculations, which means delay in locating the fault.

A.1.2 In three phase domain and using information from protective devices [3]

In this method the fault is located in three phase domain. For instance for the single line to ground fault the following holds: [3]

$$V_a = D(z_{aa}I_a + z_{ab}I_b + z_{ac}I_c) + I_f R_f \quad (\text{A.4})$$

Where

D is the fault distance

I_f is the fault current

R_f is the fault resistance

$$I_f = I_a - I'_a \quad (\text{A.5})$$

Where I'_a is the remote-end current infeed and is determined by load flow and is function of voltages at the fault point [3]

$$I'_a = F(V'_a, V'_b, V'_c) \quad (\text{A.6})$$

Moreover, the voltage at fault location is [3]

$$\begin{bmatrix} V_a' \\ V_b' \\ V_c' \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - D \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (\text{A.7})$$

the fault distance is calculated using the following iterative approach:

An initial fault current is assumed as follows [3]:

$$I_f = I_a - I_{a_{pre}} \quad (\text{A.8})$$

where $I_{a_{pre}}$ is the pre-fault current on the faulted phase. Having the fault current estimated, the fault distance and fault resistance are calculated by using (A.4). Having the fault distance estimated, the voltage vector at the fault point is calculated using equation (A.7). Having the voltage vector estimated at fault location, the remote-end current infeed is obtained by applying the radial power flow algorithm as (A.6).

The above steps are repeated until the method converges, which means the following holds [3]

$$\left| D^{k+1} - D^k \right| \leq \varepsilon \quad (\text{A.9})$$

In the explained procedure, it is assumed that voltage and current vectors at the sending-end of the faulted line segment is available. In [3] a systematic approach is proposed to calculate the sending end of faulted section.

It is notable that using only the substation data could lead to multiple fault locate estimations. To eliminate multiple fault location estimations, [3] has utilized the fact that measured voltage and current signals at substation would have different characteristics based on which protective relays have operated along the feeder. Therefore, for each estimated fault location, fault analysis is carried out and measured signals are compared

with simulated signals. In the simulated scenarios the operation of the protective relays due to faults lead to observation of different voltage and current characteristics at substation. The scenario that has the highest similarity with the measured signals is considered as the actual fault location.

Based on presented evaluation results in [3], error of the fault distance estimation is between 1.13% and 3.42%.

A.1.3 In sequence domain and using fault indicators [4-5]

In this method at first the faulted section is determined. The apparent reactance of observed at substation is calculated by using measured voltage and currents at substation. To calculate the reactance between substation and faulted location, modified reactance of each line sections are calculated. For instance in the case of single phase to ground fault (a-g) the following equation holds for reactance between nodes M and node R [4-5] ,

$$X_{mr}^m = X_{1mr} + \frac{X_{0mr} - X_{1mr}}{3} \quad (\text{A.10})$$

where, X_{0mr} and X_{1mr} are the zero and positive sequence reactance of the section between nodes M and R .

For each section the modified reactance is calculated and is summed up with previous calculated value. This procedure continues until total modified reactance becomes bigger than the apparent reactance. Therefore, the fault location between nodes

x and $x+1(= y)$, is estimated. In this procedure the laterals are ignored. The loads are modeled using Static response type models [4-5]

After detecting the fault section, the voltage and current at the beginning of the faulted section, at fault location, and at the end of faulted section are calculated using the procedure explained in [4-5]. Having the above values estimated, the impedance of the fault is estimated [4-5]. Assuming that the fault has resistive nature, the following holds [4-5]

$$s = \frac{K_{AR} K_{CI} - K_{AI} K_{CR}}{(K_{CR} K_{BI} - K_{CI} K_{BR}) + (K_{DR} K_{AI} - K_{DI} K_{AR})} \quad (\text{A.11})$$

Where (s) denotes a fraction of the faulted section and parameters Ks are detailed in [4-5].

The above procedure is also carried out for sections between node $x-1$ and node x and also nodes $x+1$ and $x+2$ to consider the possible errors in estimating the faulted section.

To eliminate multiple fault estimations due to laterals, in [4-5] fault indicators are installed at the beginning of each taps. The fault indicators indicate if faults have happened in downstream sections.

The presented evaluation results in [4-5] indicate that the error of this method is less than 4%.

A.2 Direct three-phase circuit analysis-based techniques [7-8]

If the network is not balance, their sequence networks are not independent and are coupled. Therefore, the fault location methods that assume the sequence networks are independent from each other cannot be applied.

In [7-8], a fault location algorithm based on the direct circuit analysis is proposed. This method can be applied to any power distribution networks whether they are balanced or not.

This method directly uses three phase parameters of the network to estimate the fault location. For example in case of phase a to ground fault the following holds [7]

$$V_{Sa} = (1-d)(Zl_{aa}I_{Sa} + Zl_{ab}I_{Sb} + Zl_{ac}I_{Sc}) + I_f R_f \quad (\text{A.12})$$

where V_{Sa} is a-phase voltage at sending end of the line, I_{Sa} , I_{Sb} and I_{Sc} are phase current at phase A, I_f is the fault current, and R_f is the fault resistance, and Zl_{aa} , Zl_{ab} , and Zl_{ac} are the line impedances, and d is the distance of the fault from sending end. Using matrix inverse lemma I_f is estimated and replaced in (A.12) to reach the following equation [7]

$$d^2(a_r + ja_i) + d(b_r + jb_i) + c_r + jc_i + R_f(d_r + jd_i) = 0 \quad (\text{A.13})$$

Where $a_r, a_i, b_r, b_i, c_r, c_i, d_r, d_i$, are detailed in [7]

By calculating real part of (A.13) and replacing in the imaginary part of (A. 13) the following is derived [7]

$$d^2(a_r - \frac{d_r}{d_i} a_i) + d(b_r - \frac{d_r}{d_i} b_i) + c_r - \frac{d_r}{d_i} c_i = 0 \quad (\text{A.14})$$

Based on which the fault distance (d) can be estimated.

Based on presented evaluation results in [7-8], error of the fault distance computation is less than 0.1 %.

A.3 Superimposed components-based techniques [10-11]

These algorithms [10-11] are based on utilizing superimposed voltages and currents. In these methods the assumed fault point is moved along the feeder systematically until the actual fault point is pinpointed.

Assuming a lumped parameter model of the line, the total voltage, V_f at the fault is related to the measured voltages and currents by the following equation [10-11]

$$\begin{bmatrix} V_{fa}(\beta) \\ V_{fb}(\beta) \\ V_{fc}(\beta) \end{bmatrix} = \beta \underbrace{\begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix}}_{Z_\beta} \begin{bmatrix} I_{Sa} \\ I_{Sb} \\ I_{Sc} \end{bmatrix} + \begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix} \quad (\text{A.15})$$

where β is the assumed fault position, a is the actual fault position, and Z_s, Z_m are the line self and mutual impedances/unit length, respectively.

Superimposed voltages and currents at assumed fault location, which are difference between the fault and pre-fault fundamental phasors, are calculated. The pre-fault voltage at the assumed fault position is given by [10-11]

$$[V_{fa,b,c(ss)}] = [Z_\beta] \times [I_{Sa,b,c(ss)}] + [V_{Sa,b,c(ss)}] \quad (\text{A.16})$$

The assumed fault position β is varied systematically so that provide minimum values of the unfaulted phase fault path currents [10-11].

Based on presented evaluation results, error of the fault distance computation is less than 3%.

A.4 Traveling wave techniques

In this type of methods the traveling waves generated by the fault is captured and the time difference between the first arrival of the traveling wave and the one reflected from the fault location is used to pinpoint the fault.

Knowing this time delay and the traveling wave velocity the fault is pinpointed. In three-phase networks, the traveling waves are mutually coupled. As a result, a single traveling wave velocity is not defined. Therefore, by using the modal transformation matrices the phase domain signals are decomposed into their modal components and each uncoupled mode is studied independently.

An important requirement of this type of algorithm is accurate detection of extracting the desired component of the measured signals, which indicates the traveling of the waves. Cross-correlation [53], wavelet transform [54], and mathematical morphology [55] are some of the methods utilized in this respect.

One of the main difficulties of implementing this type of algorithms is the need for high sampling frequency. For instance, in the case study in [55] propagation velocity is 1.8182×10^5 miles/sec, so a sampling time of $10 \mu\text{s}$ is used.

In the following subsections, advantages and disadvantages of this category of methods are discussed.

A.4.1 Using band-pass filters [12]

This method is based on the successive arrival of the traveling waves of voltage signals.

According to the Lattice diagram [12] of traveling wave generated by fault, x of the fault from bus-bar R is given by [12]

$$x = \frac{v * tr2}{2} \quad (A.17)$$

where v is the signal traveling velocity on the line, the signal $Vr2$ is captured at $tr2 = 2 * tr1$ seconds after the arrival of the first traveling signal $Vr1$, A value of x less than the line length Lp would indicate a fault on the line.

If the measuring device is located at end S of the line (farther away from the fault location), the fault-generated wave measured at end S, which is indicated by $Vs1$, arrives at time $ts1$. The reflected wave from R arrives at S at time $ts2$ sooner than the actual wave, $Vs3$ that reflected from fault location, which arrives at $ts3$. In this case, if eq. (A. 17) is used to calculate the fault location and using the time difference between $Vs1$ and $Vs2$ will give an incorrect result.

In this case the following holds [12]

$$\begin{aligned} x &= \frac{v * ts2}{2} \\ y &= L_p - \frac{v * ts2}{2} \end{aligned} \quad (A.18)$$

Therefore, it is necessary to discriminate the reflected wave from the fault point and the one is reflected from the remote end.

In the method presented in [12], high-frequency voltage signals at the range of 1 to 10MHz are captured. The bus-bar impedance at this range represents capacitive characteristic. Therefore, the step changes in the incident wave is reflected with opposite sign [12]. According to [11], the reflected wave from the remote bus-bar have the opposite polarity compared the signals reflected from the fault point. Therefore, these two waveforms can be differentiated.

In [12] modal transforms are used to extract the aerial mode and ground mode signals so that the method could be applied for three-phase systems. Digital band pass filters capture the high frequency components needed for the task of locating the fault.

In [12] the accuracy of the proposed fault location scheme with respect to digital sampling rate is discussed. The accuracy of the fault location method is directly proportional to the waveform-sampling rate of the fault locator. Accuracy of $\pm 10\text{m}$ could be reached at a sampling rate of 20MHz.

In [12] it is demonstrated that the generated high-frequency transients due to faults are not affected by the fault type or fault impedance.

The need to have high frequency sampling devices and existence of multiple reflections in the presence of load taps makes are among the difficulties of implementation of this type of method.

A.4.2 Using cross-correlation [13]

In this method the modal voltage V_m and current I_m are calculated as follows [13]:

$$\begin{aligned} [V_m] &= [S]^{-1} [V_{ph}] \\ [I_m] &= [Q]^{-1} [I_{ph}] \end{aligned} \quad (\text{A.19})$$

where V_{ph} and I_{ph} are the phase voltages and phase currents respectively. [S] and [Q] are the voltage and current transformation matrices. If the lines are transposed the [S] and [Q] are as follow [13]:

$$[S] = [Q] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & -2 \\ 1 & -1 & 1 \end{bmatrix} \quad (\text{A.20})$$

The following holds between modal transient voltage and current

$$V_m = \pm Z_m I_m \quad (\text{A.21})$$

where Z_m is the surge impedance of the mode, and the sign is determined based on the direction of transients propagation with respect to the defined direction of positive current.

Once the voltage and current transient amplitudes are known the incident S_1 , and reflected S_2 waves on the faulted line are defined as follow[13]:

$$\begin{aligned} S_1(t) &= Z_m I_m(t) - V_m(t) \\ S_2(t) &= Z_m I_m(t) + V_m(t) \end{aligned} \quad (\text{A.22})$$

The discrete normalized cross-correlation function of the S_1 and S_2 are calculated as is described in [13].

The cross-correlation of the reflected transient and the incident transient is calculated. The peaks in the cross-correlations implies the arrival time of the first (t_1) and second (t_2) incident wave. Finally the fault location is calculated as follows[13]:

$$x = \frac{v^*(t_2 - t_1)}{2} \quad (\text{A.23})$$

where v is the signal traveling velocity on the line.

A.4.3 Using Wavelet transform [14]

In this method Fault Transient Detectors (FTD) are installed at substation and remote end of the line as well as loads terminals.

The modal components of the phase voltage signals are calculated as follows [14]

$$S_{\text{mode}} = TS_{\text{phase}} \quad (\text{A.24})$$

where

$$T = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & \sqrt{3} \end{bmatrix}$$

is Clarke's transformation matrix.

The first mode is the ground mode and is related to earth faults. The second mode, called aerial mode, is related to other types of faults. After decomposing the three-phase signals to modal components, high frequency components of the signals are extracted using wavelet transform and are utilized to detect arrival time of fault-generated transients. The fault distance is calculated as follow [14]:

$$x = \frac{L_{AB} - vt_d}{2} = \frac{L_{AB} - v(t_B - t_A)}{2} \quad (\text{A.25})$$

Where A indicates the local substation and B indicates either remote end of the line or each load terminals v is the signal traveling velocity on the line.

The longest distance among all the estimated distances indicates the actual location of the fault.

A.5 Artificial intelligence-based techniques

In [18-20] application of intelligent methods based fault location methods have been proposed which are summarized as follows:

A.5.1 Using ANFIS Nets and Current Patterns [18]

In this method Adaptive Neuro-Fuzzy Inference System (ANFIS) nets are utilized to pinpoint the fault location. The current signals collected at substation and the parameters of the network, i.e. protective device settings, are used to train the ANFIS.

Wave shape of current waveform changes as a result of the protective relaying operation. Specifically, the fault duration depends on the type of the protective device that clear the fault. For example, the waveforms due to operation of fuse saving protective schemes have several intervals with different current waveform shape. In this scheme, reclosers generate one or more fast and slow trips to clear transient faults. In case of permanent faults, fuses operate to clear faults downstream of their location.

In [18] by applying wavelet transform the duration of these intervals are determined. Some intervals correspond the fault overcurrent and some others correspond to time period in which the recloser isolates the fault. The last intervals correspond to the operation of fuses.

These intervals show the fault characteristics and the protective devices operation time during a fault. In order to capture required training data for the ANFIS, different fault types with different impedances at different places in the networks are simulated and the ANFIS is trained based on the features detailed in [18].

Simulation results show that the method can locate faulted zones with errors lower than 1%.

A.5.2 Using Neural Eigenvalue Algorithm [19]

In this method line currents are transformed into " $\alpha\beta 0$ " current components by applying Clarke-Concordia transform as follow [19]:

$$\begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix} = [T_C] \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (\text{A.26})$$

where [19]

$$[T_C] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

In the $\alpha\beta$ plane, I_α , I_β and I_0 make a circular shape. The radius of the circle is proportional to the magnitude of the phase current [19]. For asymmetric fault cases the curve becomes an ellipse. The direction of the main axis of the ellipse specifies the fault. The distance closer to the measuring device cause higher fault current magnitude and as a result the main direction of the ellipse become larger.

In [19] an eigenvalue based method is proposed to quantify the above mentioned features. In [19], it is shown that the Eigenvalues ($\lambda_\alpha, \lambda_\beta, \lambda_0$) are non-linearly related to the distance of the fault from the substation.

An Artificial Neural Network (ANN) is utilized to represent this relationship. Eigenvalue data “ λ ” and fault type vector “ k_f ” are provided to the ANFIS as inputs and the distance of the fault (m) as output [19].

It is notable that in [19], the occurrence of the fault is detected by comparing eigenvalues characteristics for fault and pre-fault. In normal situation the curve in $\alpha\beta$ plane is a circle while in fault condition it is an ellipse.

A.5.3 Using a Learning Algorithm for Multivariable Data Analysis (LAMDA) [20]

In this method the problem of multiple fault location estimation by impedance based fault location is solved using Learning Algorithm for Multivariable Data Analysis (LAMDA). In this method at first impedance based fault location method presented in [8] is utilized to find the fault location. In order to solve the problem of multiple fault location estimation, an intelligent system is used to detect the faulted zone. Different signals are utilized to capture the fault characteristics which are detailed in [20]. Examples of such signals are Voltage sag magnitude on each phase, current increase on each phase, fall slope on each phase, and so on [20]

PCA (Principal Component Analysis) is then used to extract suitable features for fault location. Finally LAMDA is trained based on these extracted feature to eliminate false fault location estimations [20].

In this method, the zone in which fault has happened is detected with 83% accuracy.

VITA

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