2019

FAULT LOCATION TECHNIQUES USING THE TRAVELING WAVE METHOD AND THE DISCRETE WAVELET TRANSFORM

Wesley Fluty
University of Kentucky, wes.fluty@gmail.com
Author ORCID Identifier:
https://orcid.org/0000-0002-0044-3886
Digital Object Identifier: https://doi.org/10.13023/etd.2019.443

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained needed written permission statement(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine) which will be submitted to UKnowledge as Additional File.

I hereby grant to The University of Kentucky and its agents the irrevocable, non-exclusive, and royalty-free license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless an embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student's advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student's thesis including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Wesley Fluty, Student

Dr. Yuan Liao, Major Professor

Dr. Aaron Cramer, Director of Graduate Studies

FAULT LOCATION TECHNIQUES USING THE TRAVELING WAVE METHOD
AND THE DISCRETE WAVELET TRANSFORM

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Electrical Engineering
in the College of Engineering
at the University of Kentucky

By

Wesley Fluty

Lexington, Kentucky

Director: Dr. Yuan Liao, Professor of Electrical and Computer Engineering

Lexington, Kentucky

2019

https://orcid.org/0000-0002-0044-3886

ABSTRACT OF THESIS

FAULT LOCATION TECHNIQUES USING THE TRAVELING WAVE METHOD AND THE DISCRETE WAVELET TRANSFORM

Fault location within electric power systems is an important topic that helps reduce outage duration and increases reliability of the system. This paper explores the topic of fault location using traveling waves generated by fault conditions and the discrete wavelet transform used for time-frequency analysis. The single-ended and double-ended traveling wave methods are presented and evaluated on a single circuit and double circuit 500kV system modeled using MATLAB SIMULINK. Results are compared on the basis of wavelet used for analysis, sampling rate, and fault resistance.

KEYWORDS: Fault Location, Traveling Waves, Single-Ended, Double-Ended, Discrete Wavelet Transform

Wesley Fluty
(Name of Student)

12/1/2019
Date

FAULT LOCATION TECHNIQUES USING THE TRAVELING WAVE METHOD AND THE DISCRETE WAVELET TRANSFORM

By

Wesley Fluty

Dr. Yuan Liao

Director of Thesis

Dr. Aaron Cramer

Director of Graduate Studies

12/1/2019

Date

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Yuan Liao, for his guidance in the research process and in the completion of this thesis.

I would also like to thank Dr. Cai-Cheng Lu and Dr. Aaron Cramer, for serving as my committee members, and for their feedback.

Lastly, I would like to thank my family and friends for their love and support in my desire to pursue graduate school.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background

Electric power systems are composed of three main parts: generation, transmission, and distribution. Generation is where the electric power is generated, transmission consists of high voltage lines that deliver electric power from the point of generation to load centers or substations, and distribution consists of lower voltage lines that deliver electric power from the substation to the customer. Over the past few decades electric power systems have grown increasingly complex with hundreds of generation stations, and hundreds of thousands of miles of transmission and distribution lines. Along with the increase of total transmission line mileage on the electric grid also comes the increased exposure to line faults.

In an electric power system faults are disturbances that interfere with the normal flow of current. Their causes can range from natural phenomena such as lighting strikes to short circuited equipment within a substation caused by local wildlife. Fault durations can also vary from long-lasting, such as a failed cross arm on a transmission pole that requires a prolonged outage to fix, or transient, such as a tree making contact to an energized conductor before falling to the ground. The one thing in common for all faults is that they disrupt transmission service and can potentially be harmful to surrounding people and equipment.

In order to minimize the impact of faults on transmission lines and customer service, it becomes increasingly important to quickly and accurately pinpoint the location of a fault for isolation and repair.

1.2 Fault Location Methods

Two of the most common methods used for fault location are the impedance-based method and the traveling wave method. The impedance-based method uses phasor voltages and currents captured by fault recorders and known system parameters of the line to calculate the fault location. Reference [1] introduces the digital fault locator, which measures the ratio of reactance of a line from the point of the fault to the device. The line impedance per unit length can then be used to calculate the distance to the fault. Fault resistance though can impact the accuracy of this method with higher resistances affecting precision. Reference [2] builds on this method by measuring the reactance at one end of the line and calculating phase shift between total current flow from one end of the line and current flow through fault resistance. Other research on the impedance based method utilizes both voltage and current measurements for fault location on distribution systems [3-4] and single circuit and parallel transmission lines [5-6] using the bus impedance matrix.

This thesis will focus on the traveling wave method made popular by Bewley [7]. The traveling wave method utilizes high frequency electromagnetic impulses generated by sudden change in voltage and current caused by a fault. These waves propagate away from the fault in both directions and travel along transmission lines until eventually attenuating. The traveling wave method uses the time stamp of the arrival of these waves to busses with appropriate fault locators along with line characteristics to calculate the distance to fault. The two main traveling wave fault location algorithms include the single-ended method and the double-ended method.

The single-ended method utilizes the initial time stamp of the traveling wave caused by a fault to the bus terminal, and the time stamp of the reflected wave from either the fault itself or the far side bus, depending on the fault location in relation to total line length. This method requires less equipment and is thus cheaper, but the reflection waves can be difficult to identify. Reference [8] introduces single-ended techniques that help with the identification of reflection waves and can serve as an introduction to the topic of traveling wave fault location.

The double-ended method utilizes the time stamps from the initial wave to both busses on either side of the fault to calculate fault location. This method requires a communication link to get arrival information from both buses, often using Global Positioning Systems (GPS) for time coordination. The double-ended method is more expensive than the single-ended method, as it requires more equipment and coordination, but a benefit is that the method doesn't rely on accurately identifying reflections of a traveling wave.

Advantages of using the traveling wave method over impedance-based methods are that they are indifferent to fault type, fault resistances, and most fault-inception angles [9]. Disadvantages of using the traveling wave method include traveling wave propagation along transmission lines can be affected by system parameters and network configuration [10] and traveling wave methods can be difficult to use to locate faults near busses and faults with 'near-zero' fault inception angles [11].

1.3 Research Motivation and Objective

This thesis seeks to explore the impact of wavelets used on fault location results by comparing results of the 'db4', 'coif4', and 'sym4' wavelets at a common sampling rate of 1 MHz. The impact of sampling rate on fault location results is also explored by comparing results with sampling rates of 10kHz, 100kHz, 300kHz, 500kHz, and 1MHz. A minimum sampling rate to calculate fault location results to within 1000m, 100m, and 10m of the actual fault is also attempted. The impact of fault resistance is also tested at a common sampling rate of 1 MHZ to determine the resilience of the traveling wave method. Lastly, this thesis seeks to serve as a guide for others who would like to explore the traveling wave method of fault location. For this reason, the single-ended and double-ended traveling wave techniques are both explored on a single circuit and double circuit 500kV power system modeled using MATLAB SIMULINK. Also included are MATLAB SIMULINK modeling requirements and useful functions for discrete wavelet transform analysis.

1.4 Thesis Organization

This thesis is designed to explore the traveling wave method of fault location using the discrete wavelet transform.

Chapter 2 explains the principles of how traveling waves form and their propagation along both lossy and lossless transmission lines. The reflection and refraction of electromagnetic waves is reviewed, and the Bewley Lattice diagram is introduced for a visual representation of initial and reflected traveling wave arrival times. Finally, the single-ended method and double-ended method of fault location using traveling waves is reviewed and discussed.

Chapter 3 introduces the time-frequency domain and the use of the discrete wavelet transform for time localization of high frequency signal components. The Clarke transformation is discussed as a method for modal analysis of three phase signals and the specific MATLAB functions within the Wavelet Analysis Toolkit needed are introduced. The importance of sampling rate for fault location precision is also mentioned and a sampling circuit used in the study is introduced. The signal processing technique used in the evaluation studies is explained and given in the form of a flowchart.

Chapter 4 consists of an evaluation study for a three-phase 500kV single circuit. The single-ended method and double-ended method are both explored through examples and fault location results evaluated using different wavelets, sampling rates, and fault resistances.

Chapter 5 consists of an evaluation study for a three-phase 500kV double circuit. Mutual impedances are added to the distributed parameter line for electromagnetic coupling between circuits. The single-ended method and double-ended method are both explored through examples and evaluated using different wavelets, sampling rates, and fault resistances.

Chapter 6 consists of conclusions gathered from the evaluation studies and suggestions for future work.

2.1 Transmission Line Equation

A power transmission line will have parameters of resistance (R), conductance (G), inductance (L), and capacitance (C), all in per unit length. A segment of this line, dx, will have line constants of Rdx, Gdx, Ldx, and Cdx. Figure 1 shows a simplified model for a single-phase transmission line for analysis. Electric flux ($\boldsymbol{\psi}$) and magnetic flux ($\boldsymbol{\phi}$) created by an electromagnetic wave traveling along the line gives the instantaneous voltage ***u(x,t)*** and instantaneous current ***i(x,t)***. The equations for which are

$$\boldsymbol{d\psi(t) = u(x,t)\ C\ dx} \tag{2.1}$$

$$\boldsymbol{d\phi(t) = i(x,t)\ L\ dx} \tag{2.2}$$

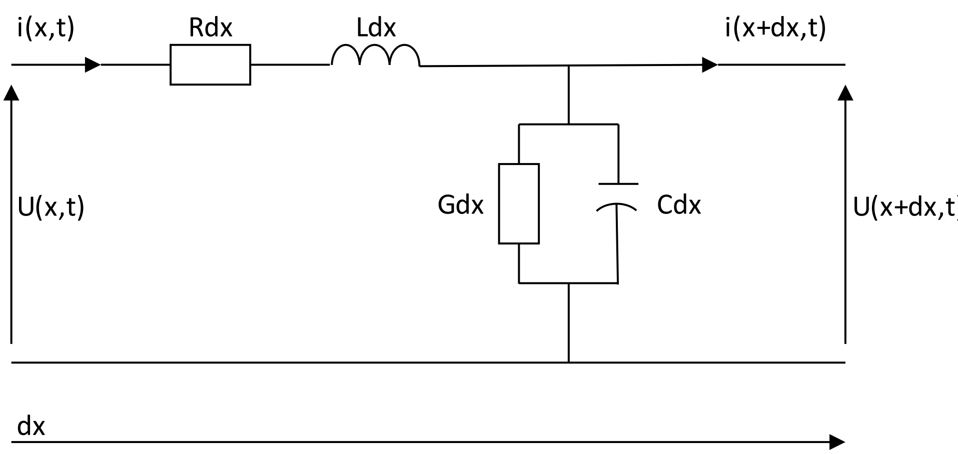

Figure 1: Single-Phase Transmission Line Model

It is possible to calculate the voltage drop in the positive direction of x of the total distance dx by using KVL to obtain:

$$\boldsymbol{\frac{\partial u(x,t)}{\partial x} = -R\ i(x,t) - L\frac{\partial i(x,t)}{\partial t}} \tag{2.3}$$

Likewise, it is possible to use KCL to obtain the instantaneous current.

$$\boldsymbol{\frac{\partial i(x,t)}{\partial x} = -G\ u(x,t) - C\ \frac{\partial u(x,t)}{\partial t}} \tag{2.4}$$

Equations (2.3) and (2.4) can be rewritten into the phasor domain, assuming the equations are time-harmonic, to resemble

$$\frac{d\boldsymbol{V}(\boldsymbol{x})}{d\boldsymbol{x}} = -\boldsymbol{Z}\,\boldsymbol{I}(\boldsymbol{x}) \tag{2.5}$$

$$\frac{d\boldsymbol{I}(\boldsymbol{x})}{d\boldsymbol{x}} = -\boldsymbol{Y}\,\boldsymbol{V}(\boldsymbol{x}) \tag{2.6}$$

where

$$\boldsymbol{Z} = \boldsymbol{R} + \boldsymbol{j\omega L} \tag{2.7}$$

$$\boldsymbol{Y} = \boldsymbol{G} + \boldsymbol{j\omega C} \tag{2.8}$$

Taking the derivative of Equation (2.5) and substituting (2.6), and likewise, taking the derivative of Equation (2.6) and substituting (2.5) gives

$$\frac{d^2\boldsymbol{V}(\boldsymbol{x})}{d\boldsymbol{x}^2} = \boldsymbol{Z}\,\boldsymbol{Y}\,\boldsymbol{V}(\boldsymbol{x}) \tag{2.9}$$

$$\frac{d^2\boldsymbol{I}(\boldsymbol{x})}{d\boldsymbol{x}^2} = \boldsymbol{Y}\,\boldsymbol{Z}\,\boldsymbol{I}(\boldsymbol{x}) \tag{2.10}$$

These equations can then be simplified by defining a new term, $\boldsymbol{\gamma}$, and substituting to get

$$\frac{d^2\boldsymbol{V}(\boldsymbol{x})}{d\boldsymbol{x}^2} = \boldsymbol{\gamma}^2\,\boldsymbol{V}(\boldsymbol{x}) \tag{2.13}$$

$$\frac{d^2\boldsymbol{I}(\boldsymbol{x})}{d\boldsymbol{x}^2} = \boldsymbol{\gamma}^2\,\boldsymbol{I}(\boldsymbol{x}) \tag{2.14}$$

Gamma, $\boldsymbol{\gamma}$, in these equations, represents a complex quantity called the propagation constant.

$$\boldsymbol{\gamma} = \sqrt{\boldsymbol{ZY}} = \boldsymbol{\alpha} + \boldsymbol{j\beta} \tag{2.15}$$

Alpha, $\boldsymbol{\alpha}$, represents the real part of the propagation constant and is referred to as the attenuation constant, as it primarily deals with the amplitude of the traveling wave. Beta, $\boldsymbol{\beta}$, represents the imaginary part of the propagation constant and is referred to as the phase constant, as it primarily influences the phase shift of the traveling wave.

Equation (2.13) and Equation (2.14) can be solved in the form of two arbitrary functions that satisfy the partial differential equations and rewritten in the time domain to resemble

$$\boldsymbol{u}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{A_1}(\boldsymbol{t})\boldsymbol{e}^{\boldsymbol{\gamma x}} + \boldsymbol{A_2}(\boldsymbol{t})\boldsymbol{e}^{-\boldsymbol{\gamma x}} \tag{2.16}$$

$$\boldsymbol{i}(\boldsymbol{x},\boldsymbol{t}) = \frac{\boldsymbol{1}}{\boldsymbol{Z}}[\boldsymbol{A_1}(\boldsymbol{t})\boldsymbol{e}^{\boldsymbol{\gamma x}} - \boldsymbol{A_2}(\boldsymbol{t})\boldsymbol{e}^{-\boldsymbol{\gamma x}}] \tag{2.17}$$

where Z is the characteristic impedance of the line and is calculated by

$$\boldsymbol{Z} = \sqrt{\frac{\boldsymbol{R} + \boldsymbol{j\omega L}}{\boldsymbol{G} + \boldsymbol{j\omega C}}} \tag{2.18}$$

and A_1 and A_2 are arbitrary functions, independent of x. The forward traveling wave is identified by the $e^{-\gamma x}$ and the backward traveling wave by the $e^{\gamma x}$. Note that the characteristic impedance of a 'lossy' line is complex.

2.2 Lossless Line

It can sometimes be simpler to think of a single phase, lossless transmission line when thinking about traveling waves. In this new scenario, resistance (R) and conductance (G) are zero and the inductance (L) and capacitance (C) are constants. The transmission line equations now become

$$\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{x}} = -\boldsymbol{L}\frac{\partial \boldsymbol{i}}{\partial \boldsymbol{t}} \tag{2.19}$$

$$\frac{\partial \boldsymbol{i}}{\partial \boldsymbol{x}} = -\boldsymbol{C}\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{t}} \tag{2.20}$$

A steady state equation is substituted, $\boldsymbol{u = Z_0\, i}$, because of the lack of dampening of the wave into Equation (2.19) and (2.20) to yield

$$\boldsymbol{Z_0}\frac{\partial \boldsymbol{i}}{\partial \boldsymbol{x}} = -\boldsymbol{L}\frac{\partial \boldsymbol{i}}{\partial \boldsymbol{t}} \tag{2.21}$$

$$\frac{\partial \boldsymbol{i}}{\partial \boldsymbol{x}} = -\boldsymbol{Z_0 C}\frac{\partial \boldsymbol{i}}{\partial \boldsymbol{t}} \tag{2.22}$$

Dividing Equation (2.21) by Equation (2.22) gives

$$\boldsymbol{Z_0} = \sqrt{\frac{\boldsymbol{L}}{\boldsymbol{C}}} \tag{2.23}$$

Where Z_0 is the characteristic impedance of the lossless line.

The solutions to the voltage and current waves in the time domain can be satisfied by the general solutions

$$\boldsymbol{u(x,t)} = \boldsymbol{A_1}\left(\boldsymbol{t} + \frac{\boldsymbol{x}}{\boldsymbol{v}}\right) + \boldsymbol{A_2}\left(\boldsymbol{t} - \frac{\boldsymbol{x}}{\boldsymbol{v}}\right) \tag{2.24}$$

$$\boldsymbol{i(x,t)} = \frac{\boldsymbol{1}}{\boldsymbol{Z_0}}\left[\boldsymbol{A_1}\left(\boldsymbol{t} + \frac{\boldsymbol{x}}{\boldsymbol{v}}\right) - \boldsymbol{A_2}\left(\boldsymbol{t} - \frac{\boldsymbol{x}}{\boldsymbol{v}}\right)\right] \tag{2.25}$$

In these expressions, $\boldsymbol{A_1}\left(\boldsymbol{t}+\frac{x}{v}\right)$ is a function describing wave propagation in the negative x-direction, and $\boldsymbol{A_2}\left(\boldsymbol{t}-\frac{x}{v}\right)$ is a function describing wave propagation in the positive x-direction. A common way of referencing these waves are the backward and forward traveling wave.

2.3 Propagation Speed

The propagation speed of a traveling wave along a transmission line is impacted by the line characteristics of inductance (L) and capacitance (C). This relationship can be seen in Equation (2.26).

$$\boldsymbol{v}=\frac{\mathbf{1}}{\sqrt{\boldsymbol{LC}}} \tag{2.26}$$

Propagation speed of a traveling wave can approach the speed of light and thus can require a high sampling rate for detection. In this thesis, positive sequence line impedances are used for propagation speed of the traveling wave. Propagation speeds can also be calculated for zero sequence components of transmission lines but has the condition that they may only be used for the location of grounded faults.

2.4 Reflection and Refraction of Waves

When electromagnetic waves propagate down a transmission line there is a fixed relation between the current and voltage waves due to the characteristic impedance of the line. When these waves hit a discontinuity, such as an open circuit, short circuit, or a change in impedance, then part of the energy of the wave is transmitted (refracted) through the discontinuity while a portion is reflected back.

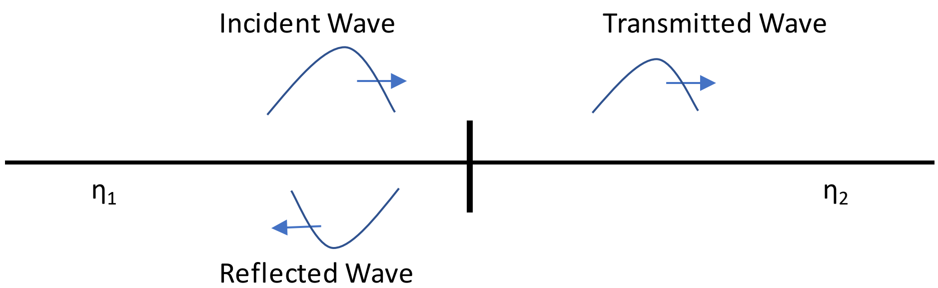

Figure 2: Visual Representation of Transmission and Reflection of Waves at a Discontinuity

The reflection coefficient of a current traveling wave is calculated as

$$\boldsymbol{\Gamma} = \frac{\boldsymbol{\eta_1} - \boldsymbol{\eta_2}}{\boldsymbol{\eta_1} + \boldsymbol{\eta_2}} \tag{2.27}$$

Where $\boldsymbol{\eta_2}$ is the termination impedance and $\boldsymbol{\eta_1}$ is the characteristic impedance of the line.

The transmission coefficient of a current traveling wave is calculated as

$$\boldsymbol{T} = \frac{\boldsymbol{2\eta_1}}{\boldsymbol{\eta_2} + \boldsymbol{\eta_1}} = \boldsymbol{\Gamma} + \boldsymbol{1} \tag{2.28}$$

2.5 Single-Ended Fault Location Method

The single-ended fault location method using traveling waves requires only one fault locator device located at the end of the line. This method eliminates the need for communication between busses and as a result has a lower cost than double-ended methods. The single-ended method requires identifying the arrival of the initial traveling wave generated by a fault on the line and then also properly identifying the reflection of the initial wave from the fault point itself. The timing between the initial wave and the reflection wave can be used to calculate the location of the fault.

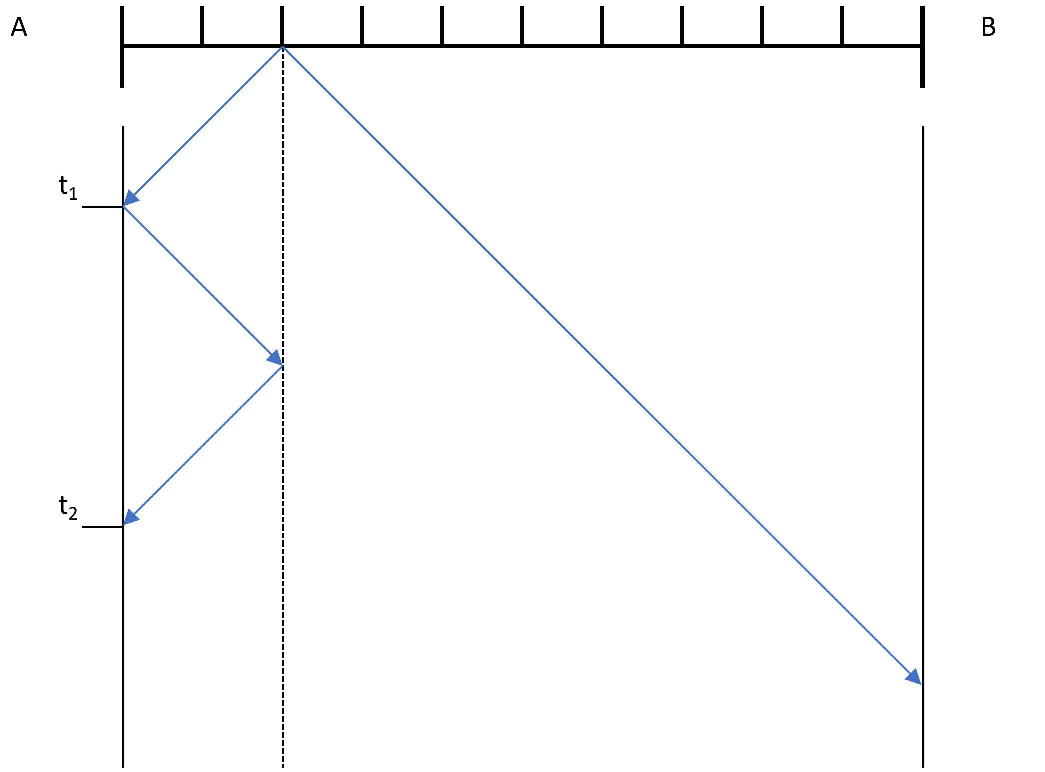

Figure 3: Single-Ended Bewley Lattice Diagram for Fault in First Half of Line

Figure 3 shows the Bewley Lattice Diagram for a fault located in the first half of a line. For faults at less than half-way of the total distance of the line, the fault location equation is given by

$$\boldsymbol{X = \frac{1}{2} v\, \tau\, (t_2 - t_1)} \tag{2.29}$$

Where v is the wave velocity, τ is the inverse of the sampling rate, t_1 is the timing of the initial wave, and t_2 is the timing of the reflection from the fault point.

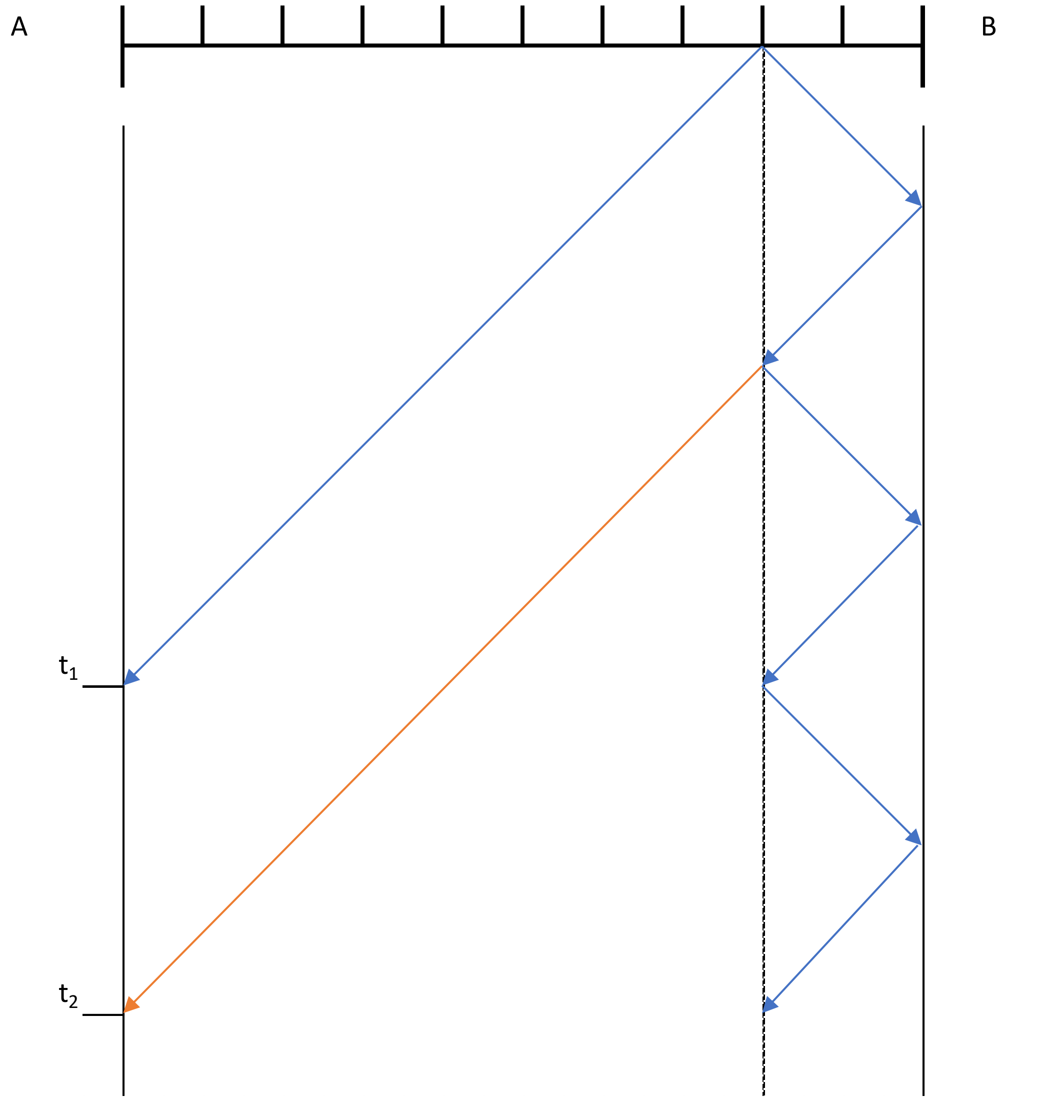

Figure 4: Single-Ended Bewley Lattice Diagram for Fault in Second Half of Line

Figure 4 shows the Bewley Lattice Diagram for a fault in the second half of a line. For faults greater than half-way of the total distance of the line, the fault location equation is given by

$$\boldsymbol{X = L - \frac{1}{2} v\, \tau\, (t_2 - t_1)} \tag{2.30}$$

Where v is wave velocity, τ is the inverse of the sampling rate, t_1 is the arrival of the initial wave, t_2 is the arrival of the reflection waves from the far side bus, and L is the total length of the transmission line.

2.6 Double-Ended Fault Location Method

The double-ended method of fault location requires the use of multiple traveling wave recorders at different busses and a signal relay for communication. This method requires capturing the initial traveling caused by the fault at both busses and using the time delay to calculate the distance to fault.

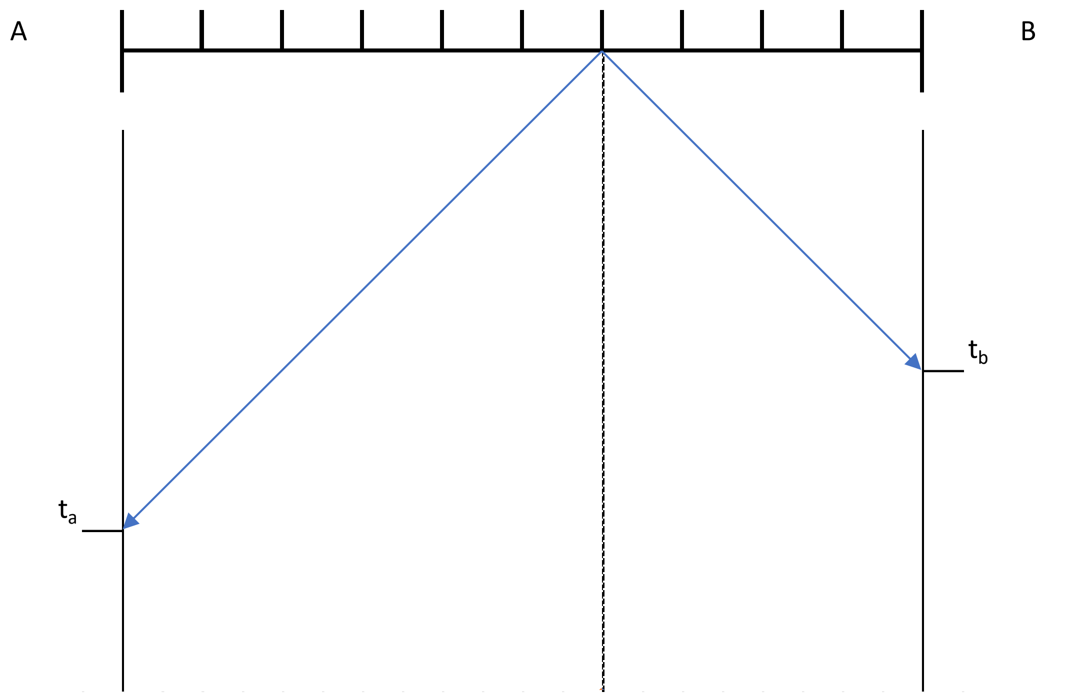

Figure 5: Double-Ended Bewley Lattice Diagram for Fault on Line

Figure 5 shows the Bewley Lattice Diagram for a fault on a transmission line and arrival of the initial traveling waves to both Busses A and B. The double-ended fault location equation is given by

$$\boldsymbol{X = \frac{1}{2}[L + v\,\tau\,(t_a - t_b)]} \tag{2.31}$$

where L is the total length of the line, v is the traveling wave velocity, τ is the inverse of the sampling rate, and t_a and t_b are the arrival times of the initial traveling wave caused by the fault to their respective busses.

CHAPTER 3. SIGNAL PROCESSING TECHNIQUES FOR TRAVELING WAVE FAULT LOCATION

3.1 Time-Frequency Domain

Traveling wave fault locators use high frequency signal components to determine fault location. The Fourier Transform (FT) and the Discrete Fourier Transform (DFT) are commonly used techniques for frequency domain analysis of time domain signals, however, analysis in the frequency domain cannot provide any information about changes of frequency with respect to time. The Short Time Fourier Transform (STFT) and the Wavelet Transform were created to represent a signal in both time and frequency domain through time windowing function. This thesis will focus on the use of the Wavelet Transform for signal analysis.

3.1.1 Wavelets

Wavelets are functions that can be useful for time and frequency localization. Wavelets have the three qualities of being oscillatory, must decay quickly to zero, and have an average value of zero. Daubechies wavelets are often used for the analysis of traveling waves as they are more localized in time making them useful for transient analysis [12]. There are many types of wavelets, but this thesis focuses on the use of Daubachies, Coiflets, and Symlets, specifically their variations with four vanishing moments (‘db4’, ‘coif4’, and ‘sym4’) for fault location. Figure 6 shows the graphical representation of the wavelets used in this thesis.

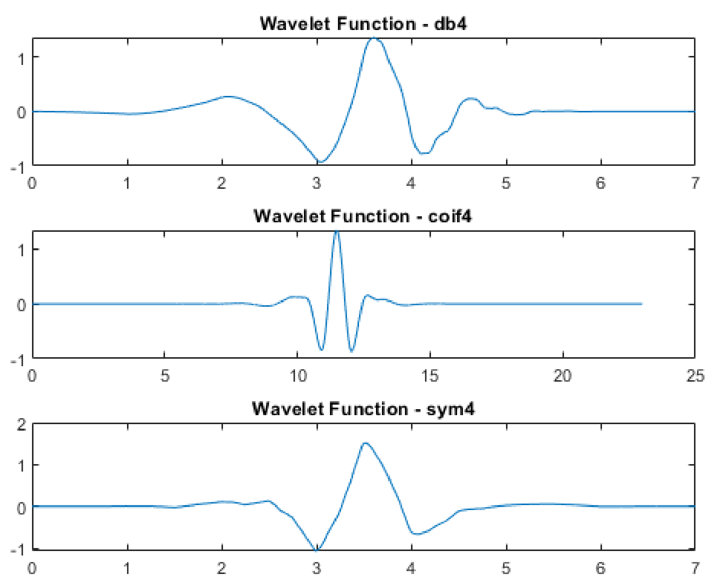

Figure 6: Graphical Representation of the ‘db4’, ‘coif4’ and ‘sym4’ Wavelets

3.1.2 Wavelet Transform

The wavelet transform can provide multiple resolutions in the time and frequency domain, making them a powerful tool for signal analysis. Wavelet analysis works by decomposing a signal into scales of a wavelet analyzing function called a ‘mother wavelet’. The result of which allows the time localization of frequency components within the signal. Windowing used by the transform adjusts for low and high frequencies by using short-time intervals for high frequency components and long-time intervals for low frequency components. Because the wavelet transform can apply to irregular waveforms, it is used within this thesis for analysis of current traveling waves.

The Continuous Wavelet Transform (CWT) can be a useful tool for signal analysis but to reduce computational requirements, the Discrete Wavelet Transform (DWT) is used more frequently. The function for the DWT is given by

$$\boldsymbol{DWT(k,n,m)} = \frac{\mathbf{1}}{\sqrt{\boldsymbol{a_0^m}}} \sum_{\boldsymbol{n}} \boldsymbol{x[n]}\, \boldsymbol{\Psi}\left(\frac{\boldsymbol{k - nb_0a_0^m}}{\boldsymbol{a_0^m}}\right) \tag{3.1}$$

Where $\Psi(t)$ is the mother wavelet, and scaling and translation parameters are $\boldsymbol{a_0^m}$ and $\boldsymbol{nb_0a_0^m}$.

When a signal is translated using the DWT, it is decomposed into its approximate coefficients by convolving with a low pass filter, and its detail coefficients by convolving with a high pass filter. The approximate coefficients end up resembling a “smoothed out” version of the original signal while the detail coefficients resemble spikes that show discontinuities. If a signal is processed enough times using a dyadic wavelet transform then the output signal will be eventually become a DC signal.

3.2 Clarke Transformation

The Clarke Transformation [13] is a useful tool for modal analysis of power systems for a fully transposed line. It works by transforming a three phase *abc* reference frame into an *αβ0* reference frame. This removes the mathematical complications due to electromagnetic coupling between conductors. Equation (3.2) reflects the Clarke Transformation as applied by the MATLAB SIMULINK block.

$$\begin{bmatrix} \boldsymbol{I_\alpha} \\ \boldsymbol{I_\beta} \\ \boldsymbol{I_0} \end{bmatrix} = \frac{\mathbf{2}}{\mathbf{3}} \begin{bmatrix} \mathbf{1} & -\frac{\mathbf{1}}{\mathbf{2}} & -\frac{\mathbf{1}}{\mathbf{2}} \\ \mathbf{0} & \frac{\sqrt{\mathbf{3}}}{\mathbf{2}} & -\frac{\sqrt{\mathbf{3}}}{\mathbf{2}} \\ \frac{\mathbf{1}}{\mathbf{2}} & \frac{\mathbf{1}}{\mathbf{2}} & \frac{\mathbf{1}}{\mathbf{2}} \end{bmatrix} \begin{bmatrix} \boldsymbol{I_a} \\ \boldsymbol{I_b} \\ \boldsymbol{I_c} \end{bmatrix} \tag{3.2}$$

After applying the Clark Transformation, the traditional three phase *abc* reference frame changes from three phases each 120 degrees out of synch into two phases each 90 degree out of synch (aerial modes) and a null signal (ground mode). The aerial modes can then be studied using the discrete wavelet transform for fault analysis. For this thesis, the alpha and beta aerial modes are used for fault analysis.

3.3 MATLAB Functions

In order to perform discrete wavelet analysis of the current signals, some functions found within the Wavelet Toolbox of MATLAB are required [14]. The ***wavedec*** function returns the wavelet decomposition of a signal x, at a level n, using the wavelet specified by 'wname' as seen in Equation (3.3).

$$[\boldsymbol{c}, \boldsymbol{l}] = \boldsymbol{wavedec}(\boldsymbol{x}, \boldsymbol{n}, '\boldsymbol{wname}') \tag{3.3}$$

The outputs c and l contain the decomposition vector and bookkeeper vector respectively. The ***detcoef*** function can then used to retrieve the detail coefficients from the c and l decomposition values at level n obtained from the ***wavedec*** function as seen in Equation (3.4).

$$\boldsymbol{D} = \boldsymbol{detcoef}(\boldsymbol{c}, \boldsymbol{l}, \boldsymbol{n}) \tag{3.4}$$

The detail coefficients can then be plotted and the time-frequency indices of the signal peaks modulus maxima can be used to calculate the fault location. An example of the ***wavedec*** and ***detcoef*** functions being used for fault location analysis will be shared in Appendix A.

3.3.1 Filter Bank

The DWT can analyze a signal at different frequency bands with different resolutions by decomposing the signal into approximate and detail information using scaling and wavelet functions. The MATLAB algorithm for DWT works by convolving the original signal with a high-pass and low-pass filter, then down sampling the signal by keeping the even indexed elements to obtain the level one approximate and detail coefficients. If further decomposition is required, the level one approximation coefficients will then be passed through the same high-pass and low-pass filters and down sampled once again to obtain the level two approximate and detail coefficients.

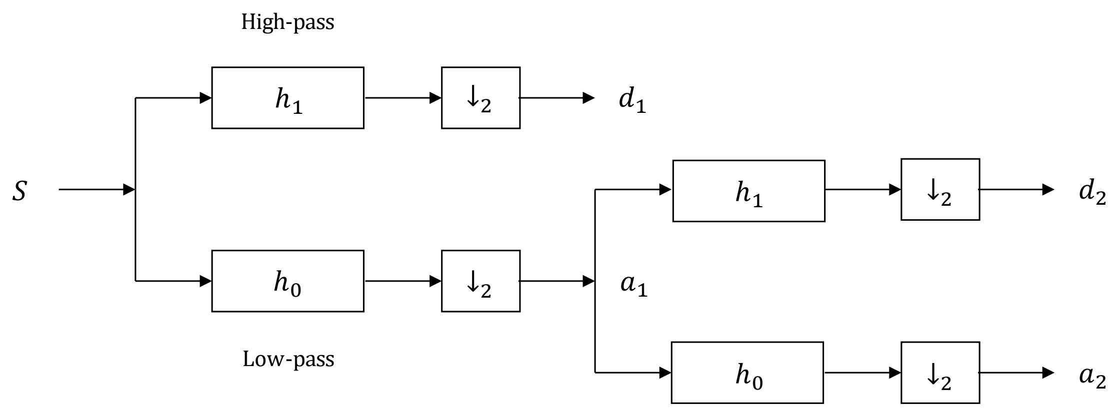

Figure 7: Filter Bank as Applied by MATLAB Wavedec Function [13]

Figure 7 shows a filter bank using two levels of decomposition. This thesis focuses on the level one detail coefficients as they are the most localized in time.

3.4 Sampling Rate

The sampling rate of the signal can influence the accuracy of the fault location estimate when using the traveling wave method. Lower sampling rates require less computational power but will result in larger errors in the fault location estimate compared to higher sampling rates. This thesis will explore the impact of sampling rate on the accuracy of the fault location estimate for both the single-ended method and double-ended method by comparing sampling rates of 10kHz, 100kHz, 300kHz, 500kHz, and 1MHz. The sampling frequency requirement for location accuracy will also be provided to within 1000m, 100m, and 10m when possible. Figure 8 shows the implementation circuit for the Clarke Transformation and sampling of alpha/beta aerial mode current signals used within the evaluation studies. After conversion of the current signals to aerial modes and being sampled, the signals are sent to the workspace for wavelet analysis.

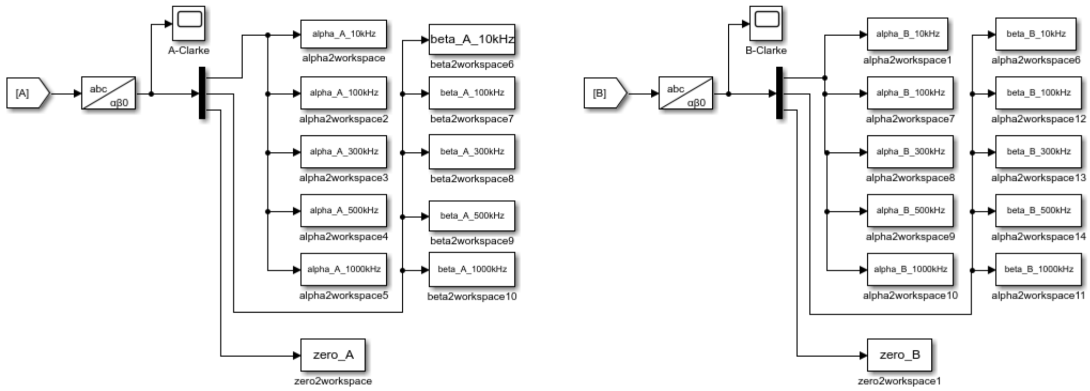

Figure 8: MATLAB SIMULINK Sampling Circuit

3.5 Signal Processing

The signal processing techniques discussed earlier in this chapter can now be combined in order to calculate the fault location estimate. For simplicity, all fault simulations are 0.2 seconds in total length with the fault being switched in at 0.1 seconds and switched out at 0.105 seconds. The fault location has already been applied by modifying the line length for each section of the distributed parameter line block on either side of the fault with both line sections totaling 100km.

First, faulted three phase current signals for both Bus A and Bus B are transformed using the Clarke Transformation block within MATLAB SIMULINK. The resulting alpha and beta signals are then sampled using the sampling circuit at different sampling rates and resulting signals are sent to the workspace. From the workspace, the MATLAB wavedec function is applied to the sampled signal and the level one detail coefficients calculated and plotted. The time-frequency indices for the appropriate peak modulus maxima are then multiplied by two in order to calculate the arrival time of the traveling waves and then plugged into the fault location formula. Figure 9 contains the flowchart of the signal processing technique used in the evaluation studies.

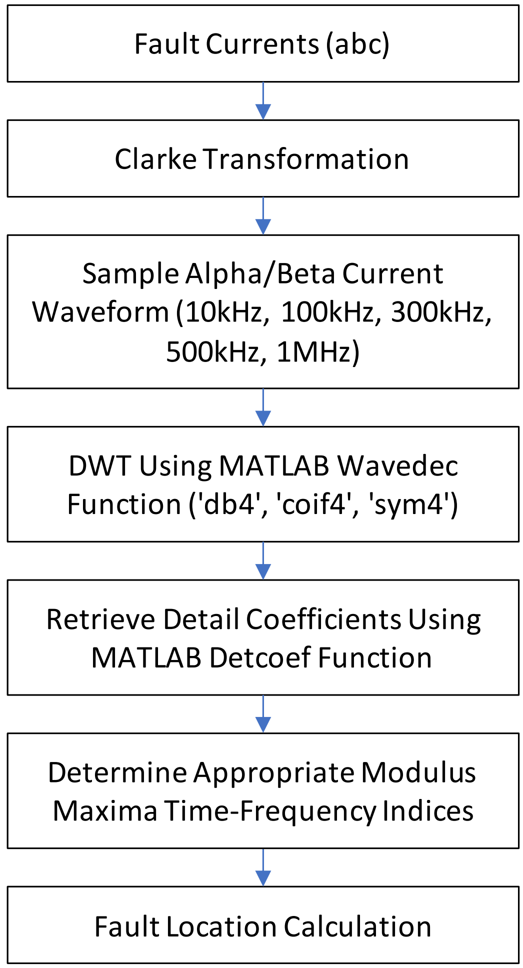

Figure 9: Flowchart of Fault Location Signal Processing Using Discrete Wavelet Transform

4.1 Single Circuit Power System

In this chapter, a single circuit three-phase power system was simulated in MATLAB SIMULINK for fault location testing using traveling waves and the discrete wavelet transform. The system features two 500kV busses, Bus A and Bus B, with attached generators and a transmission line modeled using distributed parameters. Line characteristics on both ends of the fault were held constant with the exception of line length, which was used to change fault location. The single circuit 500kV system can be seen in Figure 10.

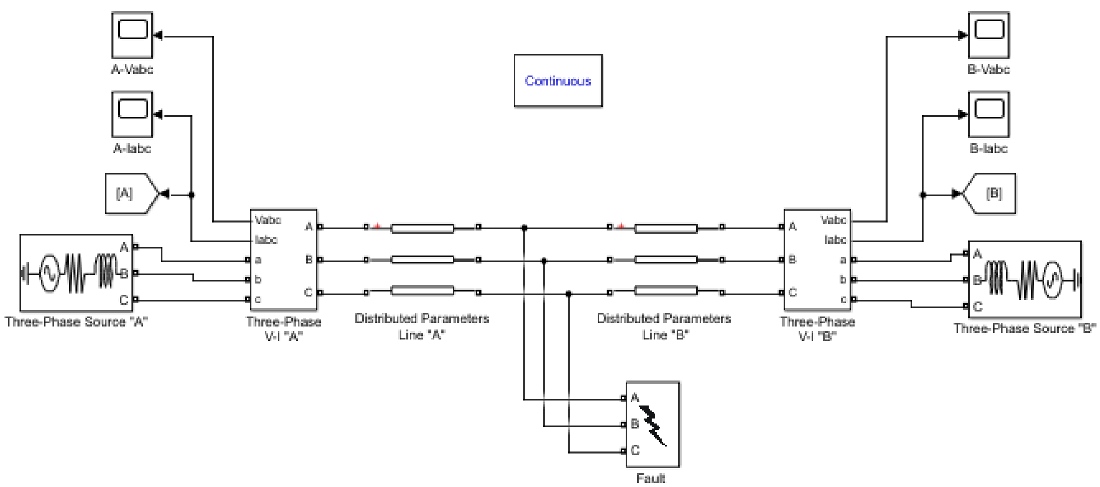

Figure 10: Single Circuit Power System Modeled Using MATLAB SIMULINK

System Parameters:

System Base Voltage: 500 kV

System Base Power: 100 MVA

System Frequency: 60 Hz

Number of Phases: 3

Source ‘A’ Internal Resistance: 0.8929 Ohms

Source ‘A’ Internal Inductance: 16.58e-3 H

Source ‘B’ Internal Resistance: 0.9375 Ohms

Source ‘B’ Internal Inductance: 17.41e-3 H

Positive Sequence Line Resistance: 0.01273 Ohms/km

Zero Sequence Line Resistance: 0.3864 Ohms/km

Positive Sequence Line Inductance: 0.9337e-3 H/km

Zero Sequence Line Inductance: 4.1264e-3 H/km

Positive Sequence Line Capacitance: 12.74e-9 F/km

Zero Sequence Line Capacitance: 7.751e-9 F/km

Total Line Length: 100 km

4.2 Methodology

The sequence used for fault location is covered in Chapter 3 with a flowchart mapped in Figure 10. The types of faults used in the evaluation studies include single phase to ground, double line ungrounded, double line to ground, and three phase to ground. In addition to studying different types of faults, different fault levels were also studied in order to test the traveling wave methods. Fault resistances of 1Ω, 5Ω, 10Ω, 50Ω, and 100Ω were studied for single phase to ground faults. Fault resistances of 1Ω, 5Ω, and 10Ω were studied for double line ungrounded and grounded faults, and three phase to ground faults. The following are examples using both the single-ended and double-ended method for the single circuit system.

In this example, a 1Ω single phase to ground fault occurred at 20km from Bus A of a total 100km line section. The current signal has already been transformed into the αβ0 reference frame using the Clarke Transformation and sampled at 1 MHz. The wavedec function specified to perform the discrete wavelet transform at level 1 using the ‘db4’ wavelet, and the detcoef function retrieves the detail coefficients which are plotted in Figure 11.

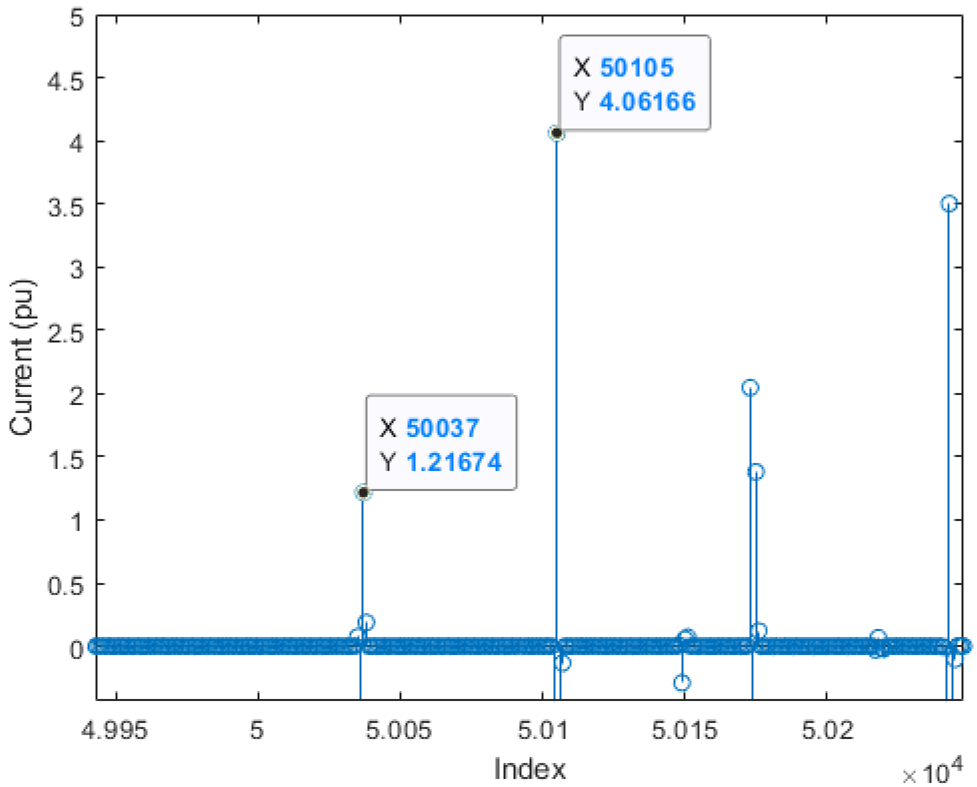

Figure 11: Wavelet Modulus Maxima for Current Signal with 1Ω AG Fault at 20km from Bus A on Single Circuit (1 MHz)

In order to determine the fault location, the velocity of the traveling wave must be calculated based on the line parameters of the circuit. In this case, the velocity of the traveling wave is based on the positive sequence line inductance and line capacitance. Plugging these numbers into Equation (2.25)

$$\boldsymbol{v = \frac{1}{\sqrt{LC}}}$$

$$\boldsymbol{v = \frac{1}{\sqrt{(9.337e-4)(1.274e-8)}}}$$

$$\boldsymbol{v = 289942\ km/s}$$

The index for the initial traveling for the fault to bus A is 50037 and the reflection wave from the fault location is 50105. Multiplying these numbers by two and plugging them into Equation (2.30)

$$X = \frac{1}{2} v\, \tau\, (t_2 - t_1)$$

$$X = \frac{1}{2}(289942)\left(\frac{1}{1000000}\right)\left((2 * 50105) - (2 * 50037)\right)$$

$$X = 19.72\ km$$

Calculating the error of the result yields

$$Error = \left|\frac{Estimate - Actual}{100}\right| * 100\%$$

$$Error = \left|\frac{19.72 - 20}{100}\right| * 100\%$$

$$Error = 0.28\%$$

For a fault beyond the halfway mark of a transmission line, a similar method is employed but with a slightly modified distance equation. In this next example, a 1Ω ABG fault occurs at 70km from Bus A of a total 100km line section. The same velocity can be used as calculated before due to the line characteristics remaining the same. Figure 12 shows the detail coefficients for the ‘db4’ wavelet plotted for this scenario.

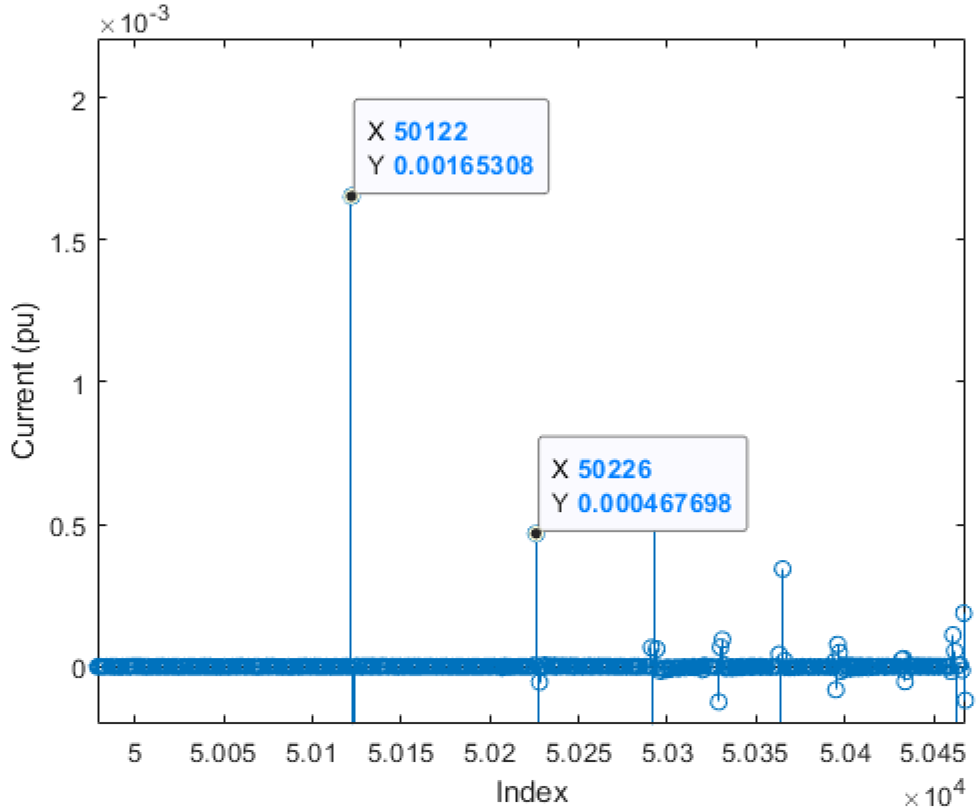

Figure 12: Wavelet Modulus Maxima for Current Signal with 1Ω ABG Fault at 70km from Bus A on Single Circuit (1 MHz)

The index for the initial traveling for the fault to Bus A is 50122 and the reflection wave from Bus B is 50226. Multiplying these numbers by two and plugging them into Equation (2.31)

$$\boldsymbol{X = L - \frac{1}{2} v\, \tau\, (t_2 - t_1)}$$

$$\boldsymbol{X = 100 - \frac{1}{2}(289942)\left(\frac{1}{1000000}\right)\big((2 * 50226) - (2 * 50122)\big)}$$

$$\boldsymbol{X = 69.85\ km}$$

Calculating the error of the result yields

$$\boldsymbol{Error = \left|\frac{Estimate - Actual}{100}\right| * 100\%}$$

$$\boldsymbol{Error = \left|\frac{69.85 - 70}{100}\right| * 100\%}$$

$$\boldsymbol{Error} = \mathbf{0.15\%}$$

Next, an example of using the double-ended method for the same circuit will be explained. Velocity can be kept the same as the line characteristics have not changed, but now the arrival time for the initial traveling wave for both Bus A and Bus B will be needed for the calculation. A 1Ω AB fault is applied at 40km from Bus A of a total 100km line. Figure 13 shows the 'db4' level one detail coefficients for both Bus A and Bus B.

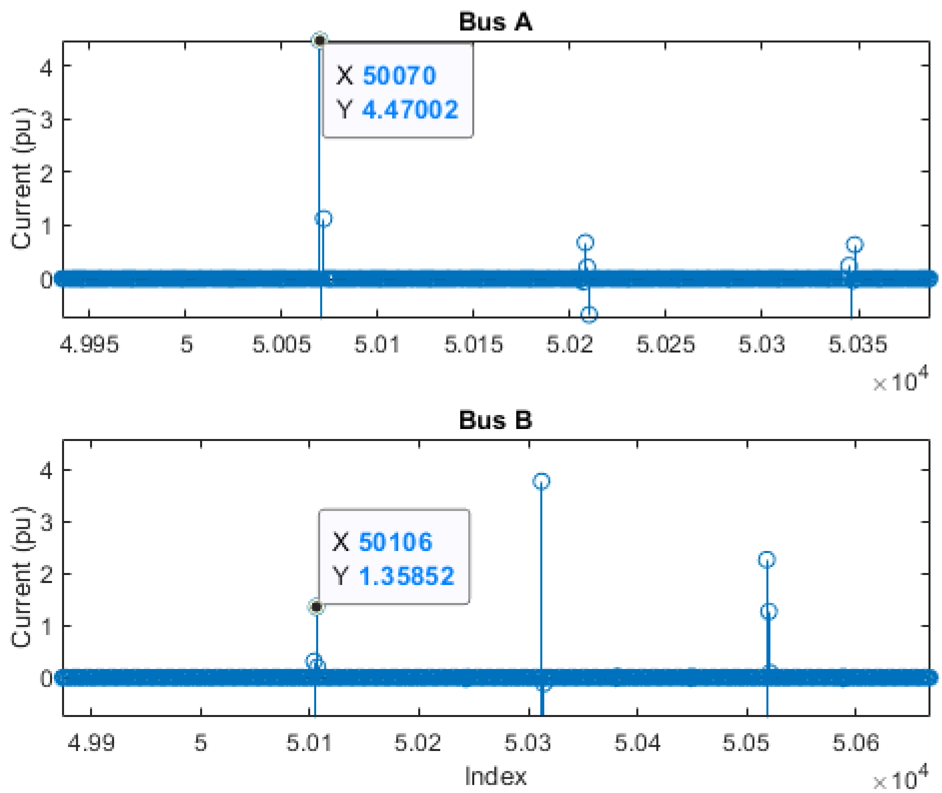

Figure 13: Wavelet Modulus Maxima for Current Signal with 1Ω AB Fault at 40km from Bus A for both Bus A and Bus B on Single Circuit (1 MHz)

The index for the initial traveling wave for the fault to bus A is 50070 and Bus B is 50106. Multiplying both numbers by two and plugging them into Equation (2.32) yields

$$\boldsymbol{X} = \frac{\mathbf{1}}{\mathbf{2}}[\boldsymbol{L} + \boldsymbol{v}\,\boldsymbol{\tau}\,(\boldsymbol{t_a} - \boldsymbol{t_b})]$$

$$\boldsymbol{X} = \frac{\mathbf{1}}{\mathbf{2}}\left[\mathbf{100} + (\mathbf{289942})\left(\frac{\mathbf{1}}{\mathbf{1000000}}\right)\left((\mathbf{2} * \mathbf{50070}) - (\mathbf{2} * \mathbf{50106})\right)\right]$$

$$\boldsymbol{X} = \mathbf{39.56}\ \boldsymbol{km}$$

Calculating the error of the result yields

$$\boldsymbol{Error} = \left|\frac{\boldsymbol{Estimate} - \boldsymbol{Actual}}{\mathbf{100}}\right| * \mathbf{100}\%$$

$$\boldsymbol{Error} = \left|\frac{\mathbf{39.56} - \mathbf{40}}{\mathbf{100}}\right| * \mathbf{100}\%$$

$$\boldsymbol{Error} = \mathbf{0.44}\%$$

4.3 Single-Ended Method Results

4.3.1 Comparison of Wavelets

In this section, the single ended method fault location error results of the three wavelets (‘db4, ‘coif4’, and ‘sym4’) are compared for different types of faults at 10km increments. All testing was performed on the single circuit presented earlier in the chapter, all with a sampling frequency of 1 MHz.

Table 4.1: Single-Ended Fault Location Results for 1 Ohm Single Phase to Ground (AG) Fault on Single Circuit (1 MHz)

	‘db4’		‘coif4’		‘sym4’	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.15	0.15	9.86	0.14	10.44	0.44
20	20.30	0.30	19.72	0.28	20.30	0.30
30	30.44	0.44	30.44	0.44	30.44	0.44
40	40.30	0.30	40.30	0.30	40.30	0.30
50	49.87	0.13	49.58	0.42	50.16	0.16
60	59.99	0.01	59.99	0.01	60.28	0.28
70	69.85	0.15	69.85	0.15	70.14	0.14
80	79.99	0.01	79.99	0.01	79.99	0.01
90	90.14	0.14	90.43	0.43	89.85	0.15
Average		0.18		0.24		0.25

Table 4.1 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AG fault on a single circuit sampled at 1MHz. The wavelet with the

lowest average error is ‘db4’ with 0.18%. Both ‘coif4’ and ‘sym4’ have similar averages of 0.24% and 0.25%. The largest error never exceeds 0.44% for this reported scenario.

Table 4.2: Single-Ended Fault Location Results for 1 Ohm Double Line Ungrounded (AB) Fault on Single Circuit (1 MHz)

	‘db4’		‘coif4’		‘sym4’	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.15	0.15	10.15	0.15	10.15	0.15
20	19.72	0.28	19.72	0.28	19.72	0.28
30	29.57	0.43	29.28	0.72	29.57	0.43
40	40.30	0.30	39.72	0.28	39.72	0.28
50	50.16	0.16	50.16	0.16	50.16	0.16
60	60.28	0.28	59.70	0.30	59.70	0.30
70	70.43	0.43	70.72	0.72	70.43	0.43
80	79.70	0.30	80.28	0.28	80.28	0.28
90	89.85	0.15	89.85	0.15	89.85	0.15
Average		0.28		0.34		0.27

Table 4.2 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AB fault on a single circuit sampled at 1MHz. The wavelet with the lowest average error is ‘sym4’ with 0.27% followed closely by ‘db4’ with 0.28%. The ‘coif4’ wavelet comes last with an average error of 0.34%. The largest error never exceeds 0.72% for this reported scenario.

Table 4.3: Single-Ended Fault Location Results for 1 Ohm Double Line to Ground (ABG) Fault on Single Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.15	0.15	10.15	0.15	10.15	0.15
20	19.72	0.28	19.72	0.28	19.72	0.28
30	29.57	0.43	29.28	0.72	29.57	0.43
40	40.30	0.30	39.72	0.28	39.72	0.28
50	50.16	0.16	50.16	0.16	50.16	0.16
60	60.28	0.28	59.70	0.30	59.70	0.30
70	70.43	0.43	70.72	0.72	70.43	0.43
80	79.70	0.30	80.28	0.28	80.28	0.28
90	89.85	0.15	89.85	0.15	89.85	0.15
Average		0.28		0.34		0.27

Table 4.3 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABG fault on a single circuit sampled at 1MHz. The wavelet with the lowest average error is 'sym4' with 0.27% followed by 'db4' at 0.28%. The 'coif4' wavelet comes last with an average error of 0.34%. The largest error never exceeds 0.72% for this reported scenario.

Table 4.4: Single-Ended Fault Location Results for 1 Ohm Three Phase to Ground (ABCG) Fault on Single Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.15	0.15	9.86	0.14	10.44	0.44
20	20.30	0.30	19.72	0.28	20.30	0.30
30	30.44	0.44	30.15	0.15	30.15	0.15
40	39.72	0.28	39.72	0.28	40.30	0.30
50	50.16	0.16	49.87	0.13	50.45	0.45
60	59.99	0.01	59.99	0.01	60.28	0.28
70	69.85	0.15	69.85	0.15	70.14	0.14
80	80.57	0.57	80.57	0.57	79.99	0.01
90	90.14	0.14	90.43	0.43	89.85	0.15
Average		0.24		0.24		0.25

Table 4.4 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABCG fault on a single circuit sampled at 1MHz. The wavelets with the lowest average error are 'db4' and 'coif4' at 0.24% followed by 'sym4' at 0.25%. The largest error never exceeds 0.57% for this reported scenario.

4.3.2 Comparison of Sampling Rate

In this section, the single-ended fault location results for the three wavelets ('db4', 'coif4', and 'sym4') are compared across five different sampling rates (10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1 MHz) using different fault types.

Table 4.5: Single-Ended Fault Location Results for 1 Ohm Single Phase to Ground (AG) Fault on Single Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	86.98	66.98	86.92	66.98	86.98	66.98
	40	57.99	17.99	57.99	17.99	57.99	17.99
	60	13.02	46.98	13.02	46.98	42.01	17.99
100	20	23.20	3.20	17.40	2.60	23.20	3.20
	40	43.49	3.49	40.59	0.59	43.49	3.49
	60	62.31	2.31	65.21	5.21	59.41	0.59
300	20	20.30	0.30	19.33	0.67	21.26	1.26
	40	41.56	1.56	40.59	0.59	40.59	0.59
	60	59.41	0.59	58.44	1.56	60.37	0.37
500	20	20.30	0.30	19.72	0.28	20.88	0.88
	40	40.59	0.59	39.43	0.57	40.59	0.59
	60	59.99	0.01	59.99	0.01	59.99	0.01
1000	20	20.30	0.30	19.72	0.28	20.30	0.30
	40	40.30	0.30	40.30	0.30	40.30	0.30
	60	59.99	0.01	59.99	0.01	60.28	0.28

Table 4.5 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 66.98% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins as early as 100 kHz but becomes much more consistent at 300 kHz. The sampling rate requirement to get within 100m of the actual fault location requires at least 500 kHz with not much improvement in error when moving up to 1000 kHz.

Table 4.6: Single-Ended Fault Location Results for 1 Ohm Double Line Ungrounded (AB) Fault on Single Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	115.98	95.98	115.98	95.98	115.98	95.98
	40	57.99	17.99	57.99	17.99	57.99	17.99
	60	13.02	46.98	13.02	46.98	13.02	46.98
100	20	17.40	2.60	23.20	3.20	17.40	2.60
	40	40.59	0.59	37.69	2.31	37.69	2.31
	60	62.31	2.31	56.51	3.49	62.31	2.31
300	20	21.26	1.26	22.23	2.23	20.30	0.30
	40	38.66	1.34	40.59	0.59	39.63	0.37
	60	59.41	0.59	59.41	0.59	60.37	0.37
500	20	20.30	0.30	20.30	0.30	20.30	0.30
	40	39.43	0.57	39.43	0.57	39.43	0.57
	60	61.15	1.15	60.57	0.57	60.57	0.57
1000	20	19.72	0.28	19.72	0.28	19.72	0.28
	40	40.30	0.30	39.72	0.28	39.72	0.28
	60	60.28	0.28	59.70	0.30	59.70	0.30

Table 4.6 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AB fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 95.98% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins as early as 100 kHz but becomes much more consistent at 300 kHz. The sampling rate requirement to get within 100m or 10m of the actual fault location is not seen under this fault condition.

Table 4.7: Single-Ended Fault Location Results for 1 Ohm Double Line to Ground (ABG) Fault on Single Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	115.98	95.98	115.98	95.98	115.98	95.98
	40	57.99	17.99	57.99	17.99	57.99	17.99
	60	13.02	46.98	13.02	46.98	13.02	46.98
100	20	17.40	2.60	23.20	3.20	17.40	2.60
	40	40.59	0.59	37.69	2.31	37.69	2.31
	60	62.31	2.31	56.51	3.49	62.31	2.31
300	20	21.26	1.26	22.23	2.23	20.30	0.30
	40	38.66	1.34	40.59	0.59	39.63	0.37
	60	59.41	0.59	59.41	0.59	60.37	0.37
500	20	20.30	0.30	20.30	0.30	20.30	0.30
	40	39.43	0.57	39.43	0.57	39.43	0.57
	60	61.15	1.15	60.57	0.57	60.57	0.57
1000	20	19.72	0.28	19.72	0.28	19.72	0.28
	40	40.30	0.30	39.72	0.28	39.72	0.28
	60	60.28	0.28	59.70	0.30	59.70	0.30

Table 4.7 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 95.98%, similar to the AB fault, indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins as early as 100 kHz but becomes much more consistent at 300 kHz. The sampling rate requirement to get within 100m or 10m of the actual fault location is not seen under this fault condition.

Table 4.8: Single-Ended Fault Location Results for 1 Ohm Three Phase to Ground (ABCG) Fault on Single Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	57.99	37.99	86.98	66.98	86.98	66.98
	40	57.99	17.99	57.99	17.99	57.99	17.99
	60	13.02	46.98	42.01	17.99	42.01	17.99
100	20	23.20	3.20	17.40	2.60	23.20	3.20
	40	43.49	3.49	40.59	0.59	43.49	3.49
	60	62.31	2.31	62.31	2.31	62.31	2.31
300	20	20.30	0.30	19.733	0.67	21.26	1.26
	40	40.59	0.59	40.59	0.59	40.59	0.59
	60	59.41	0.59	60.37	0.37	60.37	0.37
500	20	20.30	0.30	19.72	0.28	20.88	0.88
	40	40.59	0.59	39.43	0.57	40.59	0.59
	60	59.99	0.01	59.99	0.01	59.99	0.01
1000	20	20.30	0.30	19.72	0.28	20.30	0.30
	40	39.72	0.28	39.72	0.28	40.30	0.30
	60	59.99	0.01	59.99	0.01	60.28	0.28

Table 4.8 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABCG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 66.98%, indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins as early as 100 kHz but becomes much more consistent at 300 kHz. The sampling rate requirement to get within 100m and 10m of the actual fault location can be seen at sampling rates of 500 kHz and 1000 kHz.

4.3.3 Comparison of Fault Resistances

In this section, the single ended fault location results for the three wavelets (‘db4’, ‘coif4’, and ‘sym4’) are compared using different fault resistances up to 100 Ohms with a sampling rate of 1 MHz.

Table 4.9: Single-Ended Fault Location Results for Single Phase to Ground (AG) Fault on Single Circuit at Various Fault Resistances (1 MHz)

		‘db4’		‘coif4’		‘sym4’	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.44	0.44	30.44	0.44	30.44	0.44
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	69.85	0.15	69.85	0.15	70.14	0.14
5	30	30.44	0.44	30.44	0.44	30.44	0.44
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	69.85	0.15	69.85	0.15	70.14	0.14
10	30	30.44	0.44	30.44	0.44	30.44	0.44
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	69.85	0.15	69.85	0.15	70.14	0.14
50	30	30.44	0.44	30.44	0.44	30.44	0.44
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	69.85	0.15	69.85	0.15	70.14	0.14
100	30	30.44	0.44	30.44	0.44	30.44	0.44
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	69.85	0.15	69.85	0.15	70.14	0.14

Table 4.9 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AG fault on a single circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 4.10: Single-Ended Fault Location Results for Double Line Ungrounded (AB) Fault on Single Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	29.57	0.43	29.28	0.72	29.57	0.43
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	70.43	0.43	70.72	0.72	70.43	0.43
5	30	29.57	0.43	29.28	0.72	29.57	0.43
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	70.43	0.43	70.72	0.72	70.43	0.43
10	30	29.57	0.43	29.28	0.72	29.57	0.43
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	70.43	0.43	70.72	0.72	70.43	0.43

Table 4.10 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AB fault on a single circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 4.11: Single-Ended Fault Location Results for Double Line to Ground (ABG) Fault on Single Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	29.57	0.43	29.28	0.72	29.57	0.43
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	70.43	0.43	70.72	0.72	70.43	0.43
5	30	29.57	0.43	29.28	0.72	29.57	0.43
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	70.43	0.43	70.72	0.72	70.43	0.43
10	30	29.57	0.43	29.28	0.72	29.57	0.43
	50	50.16	0.16	50.16	0.16	50.16	0.16
	70	70.43	0.43	70.72	0.72	70.43	0.43

Table 4.11 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABG fault on a single circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 4.12: Single-Ended Fault Location Results for Three Phase to Ground (ABCG) Fault on Single Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.44	0.44	30.15	0.15	30.15	0.15
	50	50.16	0.16	49.87	0.13	50.45	0.45
	70	69.85	0.15	69.85	0.15	70.14	0.14
5	30	30.44	0.44	30.15	0.15	30.15	0.15
	50	50.16	0.16	49.87	0.13	50.45	0.45
	70	69.85	0.15	69.85	0.15	70.14	0.14
10	30	30.44	0.44	30.15	0.15	30.15	0.15
	50	50.16	0.16	49.87	0.13	50.45	0.45
	70	69.85	0.15	69.85	0.15	70.14	0.14

Table 4.12 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABCG fault on a single circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

4.4 Double-Ended Method Results

4.4.1 Comparison of Wavelets

In this section, the double-ended method fault location results of the three wavelets ('db4, 'coif4', and 'sym4') are compared for different types of faults at 10km increments along the single circuit presented earlier in the chapter, all with a sampling frequency of 1 MHz.

Table 4.13: Double-Ended Fault Location Results for 1 Ohm Single Phase to Ground (AG) Fault on Single Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	9.99	0.01	9.99	0.01	9.99	0.01
20	20.14	0.14	20.14	0.14	20.14	0.14
30	29.99	0.01	29.99	0.01	29.99	0.01
40	39.85	0.15	39.85	0.15	39.85	0.15
50	50.00	0.00	50.00	0.00	50.00	0.00
60	60.15	0.15	60.15	0.15	60.15	0.15
70	70.01	0.01	70.01	0.01	70.01	0.01
80	79.86	0.14	79.86	0.14	79.86	0.14
90	90.01	0.01	90.01	0.01	90.01	0.01
Average		0.07		0.07		0.07

Table 4.13 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm AG fault on a single circuit sampled at 1MHz. All three wavelets share the lowest average error of 0.07% in this scenario. The largest error never exceeds 0.15%.

Table 4.14: Double-Ended Fault Location Results for 1 Ohm Double Line Ungrounded (AB) Fault on Single Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	9.99	0.01	9.99	0.01	9.99	0.01
20	20.43	0.43	20.14	0.14	19.56	0.44
30	29.99	0.01	29.99	0.01	29.99	0.01
40	39.56	0.44	40.43	0.43	40.43	0.43
50	50.00	0.00	50.00	0.00	50.00	0.00
60	60.44	0.44	59.57	0.43	59.57	0.43
70	70.01	0.01	70.01	0.01	70.01	0.01
80	79.57	0.43	79.86	0.14	80.15	0.15
90	90.01	0.01	90.01	0.01	90.01	0.01
Average		0.20		0.13		0.17

Table 4.14 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm AB fault on a single circuit sampled at 1MHz. The wavelet with the lowest average error is 'coif4' with 0.13% followed by 'sym4' at 0.17%. The 'db44' wavelet comes last with an average error of 0.20%. The largest error never exceeds 0.44% for this reported scenario.

Table 4.15: Double-Ended Fault Location Results for 1 Ohm Double Line to Ground (ABG) Fault on Single Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	9.99	0.01	9.99	0.01	9.99	0.01
20	20.43	0.43	20.14	0.14	19.56	0.44
30	29.99	0.01	29.99	0.01	29.99	0.01
40	39.56	0.44	40.43	0.43	40.43	0.43
50	50.00	0.00	50.00	0.00	50.00	0.00
60	60.44	0.44	59.57	0.43	59.57	0.43
70	70.01	0.01	70.01	0.01	70.01	0.01
80	79.57	0.43	79.86	0.14	80.15	0.15
90	90.01	0.01	90.01	0.01	90.01	0.01
Average		0.20		0.13		0.17

Table 4.15 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm ABG fault on a single circuit sampled at 1MHz. The wavelet with the lowest average error is 'coif4' with 0.13% followed by 'sym4' at 0.17%. The 'db44' wavelet comes last with an average error of 0.20%. The largest error never exceeds 0.44% for this reported scenario.

Table 4.16: Double-Ended Fault Location Results for 1 Ohm Three Phase to Ground (ABCG) Fault on Single Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	9.99	0.01	9.99	0.01	9.99	0.01
20	20.43	0.43	19.56	0.44	20.14	0.14
30	29.99	0.01	29.99	0.01	29.99	0.01
40	40.43	0.43	40.43	0.43	39.85	0.15
50	50.00	0.00	50.00	0.00	50.00	0.00
60	59.57	0.43	59.57	0.43	60.15	0.15
70	70.01	0.01	70.01	0.01	70.01	0.01
80	80.44	0.44	80.44	0.44	79.86	0.14
90	90.01	0.01	90.01	0.01	90.01	0.01
Average		0.20		0.20		0.07

Table 4.16 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm ABCG fault on a single circuit sampled at 1MHz. The wavelet with the lowest average error is 'sym4' with 0.07% followed by both 'db4' and 'coif4' at 0.20%. The largest error never exceeds 0.44% for this reported scenario.

4.4.2 Comparison of Sampling Rate

In this section, the double-ended fault location results for the three wavelets ('db4', 'coif4', and 'sym4') are compared across five different sampling rates (10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1 MHz).

Table 4.17: Double-Ended Fault Location Results for 1 Ohm Single Phase to Ground (AG) Fault on Single Circuit at Various Sampling Rates

		‘db4’		‘coif4’		‘sym4’	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	21.01	1.01	21.01	1.01	21.01	1.01
	40	50.00	10.00	21.01	18.99	21.01	18.99
	60	50.00	10.00	78.99	18.99	50.00	10.00
100	20	21.01	1.01	23.91	3.91	18.11	1.89
	40	38.40	1.60	35.50	4.50	41.30	1.30
	60	61.60	1.60	58.70	1.30	58.70	1.30
300	20	20.04	0.04	20.04	0.04	20.04	0.04
	40	40.34	0.34	40.34	0.34	40.34	0.34
	60	59.66	0.34	59.66	0.34	59.66	0.34
500	20	20.43	0.43	21.01	1.01	19.85	0.15
	40	40.14	0.14	40.14	0.14	40.14	0.14
	60	59.86	0.14	59.86	0.14	59.86	0.14
1000	20	20.14	0.14	20.14	0.14	20.14	0.14
	40	39.85	0.15	39.85	0.15	39.85	0.15
	60	60.15	0.15	60.15	0.15	60.15	0.15

Table 4.17 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm AG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 18.99% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins and is consistent as early as 300 kHz. The sampling rate requirement to get within 100m or 10m of the actual fault location is not seen in this analysis.

Table 4.18: Double-Ended Fault Location Results for 1 Ohm Double Line Ungrounded (AB) Fault on Single Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	21.01	1.01	21.01	1.01	21.01	1.01
	40	78.99	38.99	21.01	18.99	50.00	10.00
	60	50.00	10.00	78.99	18.99	50.00	10.00
100	20	18.11	1.89	15.21	4.79	21.01	1.01
	40	35.50	4.50	44.20	4.20	38.40	1.60
	60	64.50	4.50	55.80	4.20	61.60	1.60
300	20	18.11	1.89	20.04	0.04	20.04	0.04
	40	42.27	2.27	41.30	1.30	40.34	0.34
	60	57.73	2.27	58.70	1.30	59.66	0.34
500	20	19.85	0.15	19.27	0.73	19.27	0.73
	40	39.56	0.44	40.14	0.14	40.14	0.14
	60	60.44	0.44	59.86	0.14	59.86	0.14
1000	20	20.43	0.43	20.14	0.14	19.56	0.44
	40	39.56	0.44	40.43	0.43	40.43	0.43
	60	60.44	0.44	59.57	0.43	59.57	0.43

Table 4.18 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm AB fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 38.99% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins as early as 300 kHz but is more consistent at 500 kHz. The sampling rate requirement to get within 100m or 10m of the actual fault location is not seen in this analysis.

Table 4.19: Double-Ended Fault Location Results for 1 Ohm Double Line to Ground (ABG) Fault on Single Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	21.01	1.01	21.01	1.01	21.01	1.01
	40	78.99	38.99	21.01	18.99	50.00	10.00
	60	50.00	10.00	78.99	18.99	50.00	10.00
100	20	18.11	1.89	15.21	4.79	21.01	1.01
	40	35.50	4.50	44.20	4.20	38.40	1.60
	60	64.50	4.50	55.80	4.20	61.60	1.60
300	20	18.11	1.89	20.04	0.04	20.04	0.04
	40	42.27	2.27	41.30	1.30	40.34	0.34
	60	57.73	2.27	58.70	1.30	59.66	0.34
500	20	19.85	0.15	19.27	0.73	19.27	0.73
	40	39.56	0.44	40.14	0.14	40.14	0.14
	60	60.44	0.44	59.86	0.14	59.86	0.14
1000	20	20.43	0.43	20.14	0.14	19.56	0.44
	40	39.56	0.44	40.43	0.43	40.43	0.43
	60	60.44	0.44	59.57	0.43	59.57	0.43

Table 4.19 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm ABG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 36.99% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins as early as 300 kHz but is more consistent at 500 kHz. The sampling rate requirement to get within 100m or 10m of the actual fault location is not seen in this analysis.

Table 4.20: Double-Ended Fault Location Results for 1 Ohm Three Phase to Ground (ABCG) Fault on Single Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	21.01	1.01	21.01	1.01	-7.99	27.99
	40	50.00	10.00	21.01	18.99	50.00	10.00
	60	50.00	10.00	78.99	18.99	78.99	18.99
100	20	21.01	1.01	23.91	3.91	18.11	1.89
	40	38.40	1.60	35.50	4.50	41.30	1.30
	60	61.60	1.60	64.50	4.50	58.70	1.30
300	20	20.04	0.04	20.04	0.04	20.04	0.04
	40	40.34	0.34	40.34	0.34	40.34	0.34
	60	59.66	0.34	59.66	0.34	59.66	0.34
500	20	20.43	0.43	21.01	1.01	19.85	0.15
	40	40.14	0.14	40.14	0.14	40.14	0.14
	60	59.86	0.14	59.86	0.14	59.86	0.14
1000	20	20.43	0.43	19.56	0.44	20.14	0.14
	40	40.43	0.43	40.43	0.43	39.85	0.15
	60	59.57	0.43	59.57	0.43	60.15	0.15

Table 4.20 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm ABCG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 27.99% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins as early as 300 kHz and is consistent at that same time. The sampling rate requirement to get within 100m of the actual fault location is seen when using the 300 kHz sampling rate at fault location of 20km, but nowhere else.

4.4.3 Comparison of Fault Resistances

In this section, the double-ended fault location results for the three wavelets ('db4', 'coif4', and 'sym4') are compared using different fault resistances up to 100 Ohms using a 1 MHz sampling rate.

Table 4.21: Double-Ended Fault Location Results for Single Phase to Ground (AG) Fault on Single Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
5	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
10	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
50	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
100	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01

Table 4.21 compares the fault location results of the three wavelets using the double-ended method for an AG fault on a single circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 4.22: Double-Ended Fault Location Results for Double Line Ungrounded (AB) Fault on Single Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
5	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
10	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01

Table 4.22 compares the fault location results of the three wavelets using the double-ended method for an AB fault on a single circuit at various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 4.23: Double-Ended Fault Location Results for Double Line to Ground (ABG) Fault on Single Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
5	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
10	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01

Table 4.23 compares the fault location results of the three wavelets using the double-ended method for an ABG fault on a single circuit at various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 4.24: Double-Ended Fault Location Results for Three Phase to Ground (ABCG) Fault on Single Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
5	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01
10	30	29.99	0.01	29.99	0.01	29.99	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	70.01	0.01	70.01	0.01	70.01	0.01

Table 4.24 compares the fault location results of the three wavelets using the double-ended method for an ABCG fault on a single circuit at various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

5.1 Double Circuit Power System

In this chapter, a three-phase double circuit power system was simulated in MATLAB SIMULINK for fault location testing using traveling waves and the discrete wavelet transform. The double circuit consists of two parallel 500kV lines that share the same Bus A and Bus B terminal ends. Mutual zero sequence line resistance, inductance, and capacitance have been added to the distributed parameter line characteristics to simulate electromagnetic coupling between circuits. One three phase circuit has been designated 'unhealthy' indicating presence of a fault, while the other circuit is 'healthy' without a fault. The double circuit 500kV system can be seen in Figure 14.

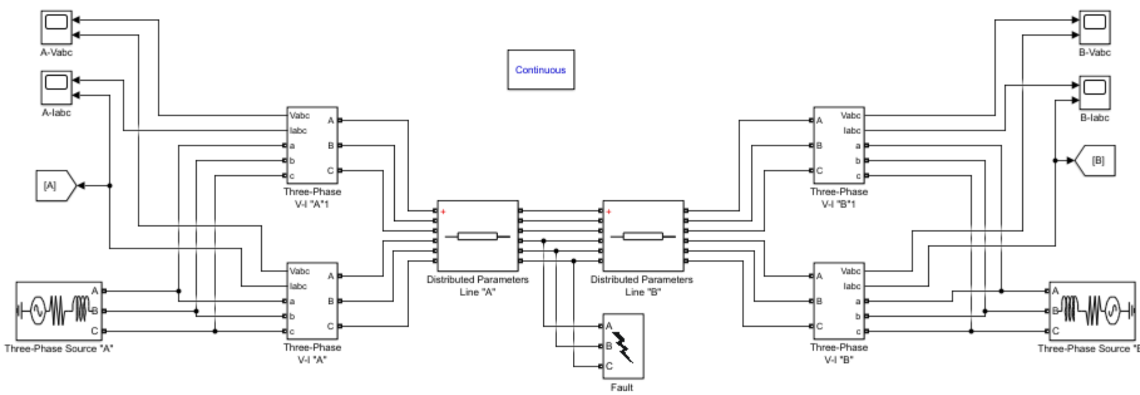

Figure 14: Double Circuit Power System Modeled Using MATLAB SIMULINK

System Parameters:

System Base Voltage: 500 kV

System Base Power: 100 MVA

System Frequency: 60 Hz

Number of Phases: 6

Source ‘A’ Internal Resistance: 0.8929 Ohms

Source ‘A’ Internal Inductance: 16.58e-3 H

Source ‘B’ Internal Resistance: 0.9375 Ohms

Source ‘B’ Internal Inductance: 17.41e-3 H

Positive Sequence Line Resistance: 0.0061 Ohms/km

Zero Sequence Line Resistance: 0.268 Ohms/km

Mutual Zero Sequence Line Resistance: 0.23 Ohms/km

Positive Sequence Line Inductance: 1.19e-3 H/km

Zero Sequence Line Inductance: 3.301e-3 H/km

Mutual Zero Sequence Line Inductance: 2.008e-3 H/m

Positive Sequence Line Capacitance: 1.4833e-8 F/km

Zero Sequence Line Capacitance: 8.6001e-9 F/km

Mutual Zero Sequence Line Capacitance: -5.1699e-9 F/km

Total Line Length: 100 km

5.2 Methodology

The sequence used for fault location is covered in Chapter 3 with a flowchart mapped in Figure 10. The types of faults studied during this thesis include single phase to ground, double line ungrounded, double line to ground, and three phase to ground. In addition to studying different types of faults, different fault levels were also studied in order to test the traveling wave methods. Fault resistances of 1Ω, 5Ω, 10Ω, 50Ω, and 100Ω were studied for single phase to ground faults. Fault resistances of 1Ω, 5Ω, and 10Ω were studied for double line ungrounded and grounded faults, and three phase to ground faults. The following are examples using both the single-ended and double-ended method for the double circuit system.

In this example, a 1Ω single phase to ground (AG) fault occurs at 30km from Bus A on the 'unhealthy' circuit of a total 100km line section. The current signal has already been transformed into the αβ0 reference frame using the Clarke Transformation and sampled at 1MHz. The wavedec function specified to perform the discrete wavelet transform at level 1 using the 'db4' wavelet, and the detcoef function retrieves the detail coefficients which are plotted in Figure 15.

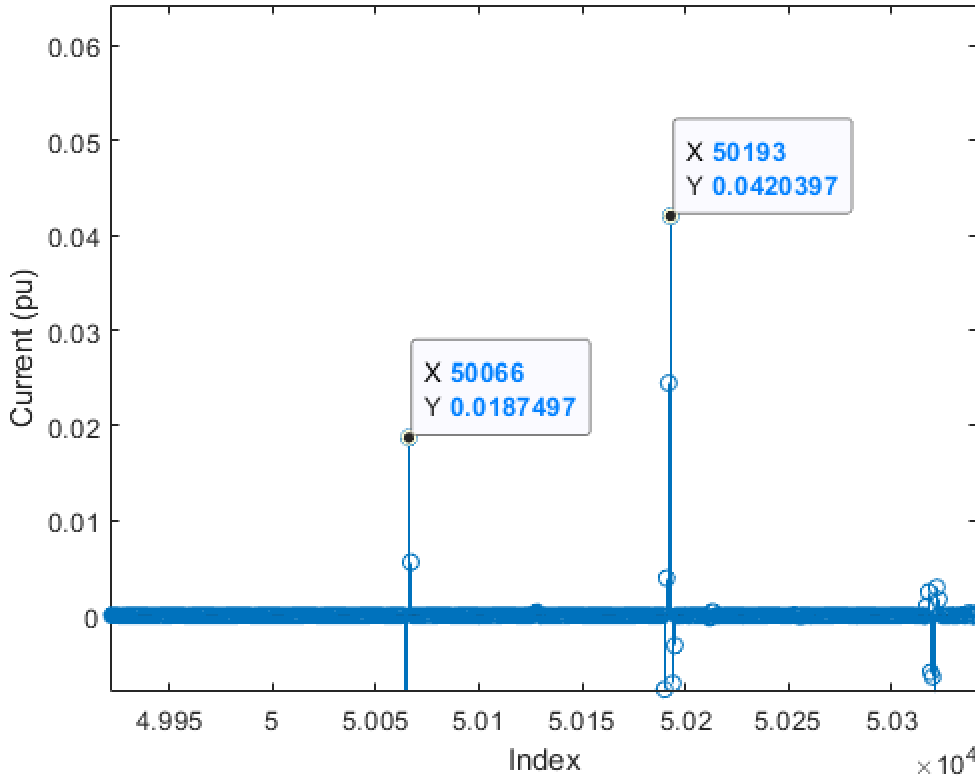

Figure 15: Wavelet Modulus Maxima for Current Signal with 1Ω AG Fault at 30km from Bus A on Double Circuit (1 MHz)

In order to determine the fault location, the velocity of the traveling wave must be calculated based on the line parameters of the circuit. In this case, the velocity of the traveling wave is based on the positive sequence line inductance and line capacitance. Plugging these numbers into Equation (2.25)

$$\boldsymbol{v = \frac{1}{\sqrt{LC}}}$$

$$\boldsymbol{v = \frac{1}{\sqrt{(1.19e-3)(1.4833e-8)}}}$$

$$\boldsymbol{v = 238019\ km/s}$$

The index for the initial traveling for the fault to bus A is 50066 and the reflection wave index from the fault location is 50193. Multiplying these numbers by two and plugging them into Equation (2.30)

$$\boldsymbol{X = \frac{1}{2} v\, \tau\, (t_2 - t_1)}$$

$$\boldsymbol{X = \frac{1}{2}(238019)\left(\frac{1}{1000000}\right)\left((2 * 50193) - (2 * 50066)\right)}$$

$$\boldsymbol{X = 30.23\ km}$$

Calculating the error of the result yields

$$\boldsymbol{Error = \left|\frac{Estimate - Actual}{100}\right| * 100\%}$$

$$\boldsymbol{Error = \left|\frac{30.23 - 30}{100}\right| * 100\%}$$

$$\boldsymbol{Error = 0.23\%}$$

For a fault beyond the halfway mark to Bus A, a similar method is employed but with a slightly modified distance equation. In this next example, a 1Ω ABG fault occurs at 80km from Bus A of a total 100km line section. The same velocity can be used as before as the line characteristics are unchanged. Figure 16 shows the detail coefficients plotted for this scenario.

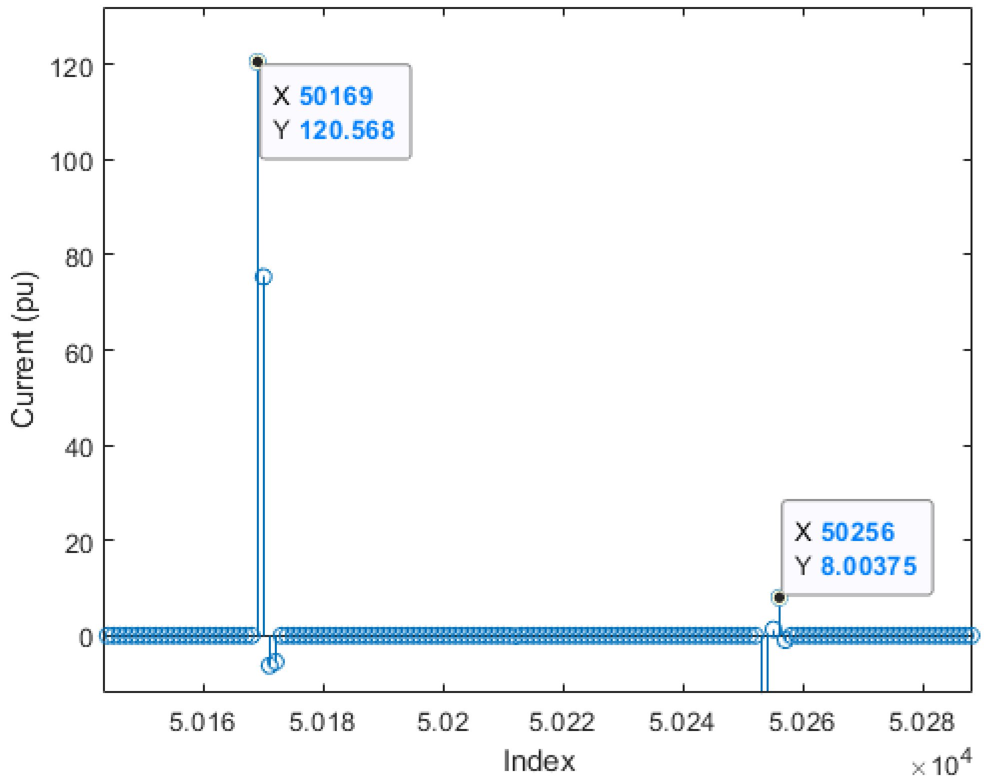

Figure 16: Wavelet Modulus Maxima for Current Signal with 1Ω ABG Fault at 80km from Bus A on Double Circuit (1 MHz)

The index for the initial traveling for the fault to Bus A is 50169 and the reflection wave index from Bus B is 50256. Multiplying these numbers by two and plugging them into Equation (2.31)

$$X = L - \frac{1}{2} v\, \tau\, (t_2 - t_1)$$

$$X = 100 - \frac{1}{2}(238019)\left(\frac{1}{1000000}\right)\left((2 * 50256) - (2 * 50169)\right)$$

$$X = 79.29\ km$$

Calculating the error of the result yields

$$Error = \left|\frac{Estimate - Actual}{100}\right| * 100\%$$

$$Error = \left|\frac{79.29 - 80}{100}\right| * 100\%$$

$$Error = 0.71\%$$

Next, an example of using the double-ended method for the same circuit will be explained. Traveling wave velocity is unchanged but now the arrival time of the initial traveling wave for both Bus A and Bus B will be needed for the calculation. A 1Ω AB fault is applied at 60km from Bus A on the 'unhealthy' circuit of the modeled double circuit. Figure 17 shows the 'db4' level one detail coefficients for both Bus A and Bus B.

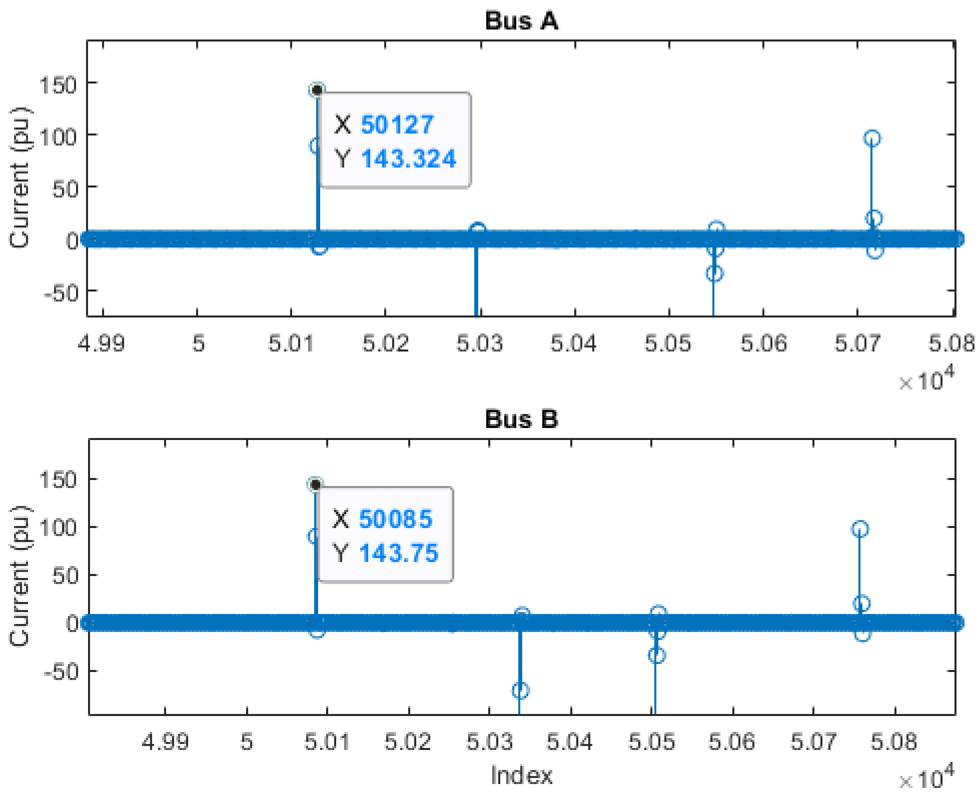

Figure 17: Wavelet Modulus Maxima for Current Signal with 1Ω AB Fault at 60km from Bus A for both Bus A and Bus B on Double Circuit (1 MHz)

The index for the initial traveling wave for the fault to Bus A is 50127 and Bus B is 50085. Multiplying these numbers by two and plugging them into Equation (2.32)

$$\boldsymbol{X = \frac{1}{2}[L + v\,\tau\,(t_a - t_b)]}$$

$$\boldsymbol{X = \frac{1}{2}\left[100 + (238019)\left(\frac{1}{1000000}\right)\left((2*50127) - (2*50085)\right)\right]}$$

$$\boldsymbol{X = 60.00\ km}$$

Calculating the error of the result yields

$$\boldsymbol{Error} = \left|\frac{\boldsymbol{Estimate - Actual}}{\mathbf{100}}\right| * \mathbf{100}\%$$

$$\boldsymbol{Error} = \left|\frac{\mathbf{60 - 60}}{\mathbf{100}}\right| * \mathbf{100}\%$$

$$\boldsymbol{Error} = \mathbf{0.00}\%$$

5.3 Single-Ended Method Results

5.3.1 Comparison of Wavelets

Table 5.1: Single-Ended Fault Location Results for 1 Ohm Single Phase to Ground (AG) Fault on Double Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.00	0.00	9.52	0.48	9.28	0.72
20	19.76	0.24	19.99	0.01	19.99	0.01
30	30.23	0.23	30.23	0.23	30.23	0.23
40	40.46	0.46	39.99	0.01	39.75	0.25
50	49.75	0.25	49.75	0.25	49.75	0.25
60	60.25	0.25	60.25	0.25	60.25	0.25
70	70.25	0.25	70.25	0.25	70.25	0.25
80	80.24	0.24	80.24	0.24	80.24	0.24
90	90.48	0.48	90.24	0.24	90.24	0.24
Average		0.27		0.22		0.27

Table 5.1 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AG fault on a double circuit sampled at 1 MHz. The wavelet with the lowest average error is 'coif4' with 0.22% followed by both 'db4' and 'coif4' at 0.27%. The largest error never exceeds 0.72% for this reported scenario.

Table 5.2: Single-Ended Fault Location Results for 1 Ohm Double Line Ungrounded (AB) Fault on Double Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.00	0.00	9.76	0.24	10.23	0.23
20	20.23	0.23	20.23	0.23	20.23	0.23
30	30.47	0.47	30.47	0.47	30.47	0.47
40	40.94	0.94	40.23	0.23	39.99	0.01
50	50.70	0.70	50.22	0.22	50.22	0.22
60	59.06	0.94	59.77	0.23	59.77	0.23
70	69.30	0.70	69.77	0.23	69.77	0.23
80	79.29	0.71	79.77	0.23	79.77	0.23
90	89.53	0.47	89.77	0.23	89.77	0.23
Average		0.57		0.26		0.23

Table 5.2 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AB fault on a double circuit sampled at 1 MHz. The wavelet with the lowest average error is 'sym4' with 0.23% followed by 'coif4' at 0.26%. The 'db4' wavelet trails at 0.57% average error. The largest error never exceeds 0.94% for this reported scenario.

Table 5.3: Single-Ended Fault Location Results for 1 Ohm Double Line to Ground (ABG) Fault on Double Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.00	0.00	9.76	0.24	10.23	0.23
20	20.23	0.23	20.23	0.23	20.23	0.23
30	30.47	0.47	30.47	0.47	30.47	0.47
40	40.94	0.94	40.23	0.23	39.99	0.01
50	50.70	0.70	50.22	0.22	50.22	0.22
60	59.06	0.94	59.77	0.23	59.77	0.23
70	69.30	0.70	69.77	0.23	69.77	0.23
80	79.29	0.71	79.77	0.23	79.77	0.23
90	89.53	0.47	89.77	0.23	89.77	0.23
Average		0.57		0.26		0.23

Table 5.3 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABG fault on a double circuit sampled at 1 MHz. The wavelet with the lowest average error is 'sym4' with 0.23% followed by 'coif4' at 0.26%. The 'db4' wavelet trails at 0.57% average error. The largest error never exceeds 0.94% for this reported scenario.

Table 5.4: Single-Ended Fault Location Results for 1 Ohm Three Phase to Ground (ABCG) Fault on Double Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	9.76	0.24	9.28	0.72	9.52	0.48
20	19.76	0.24	19.76	0.24	19.76	0.24
30	29.75	0.25	29.75	0.25	29.75	0.25
40	39.75	0.25	39.75	0.25	39.75	0.25
50	49.75	0.25	49.75	0.25	49.75	0.25
60	60.25	0.25	60.25	0.25	60.25	0.25
70	70.25	0.25	70.25	0.25	70.25	0.25
80	80.24	0.24	80.24	0.24	80.24	0.24
90	90.24	0.24	90.24	0.24	90.24	0.24
Average		0.25		0.30		0.27

Table 5.4 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABCG fault on a double circuit sampled at 1 MHz. The wavelet with the lowest average error is 'db4' with 0.25% followed by 'sym4' at 0.27%. The 'coif4' wavelet trails closely at 0.30% average error. The largest error never exceeds 0.72% for this reported scenario.

5.3.2 Comparison of Sampling Rate

Table 5.5: Single-Ended Fault Location Results for 1 Ohm Single Phase to Ground (AG) Fault on Double Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	95.21	75.21	95.21	75.21	95.2	75.21
	40	47.60	7.60	95.21	55.21	47.60	7.60
	60	28.59	31.41	52.40	7.60	52.40	7.60
100	20	21.42	1.42	21.42	1.42	21.42	1.42
	40	38.08	1.92	38.08	1.92	42.84	2.84
	60	64.30	4.30	61.92	1.92	61.92	19.2
300	20	20.63	0.63	19.83	0.17	19.83	0.17
	40	39.67	0.33	39.67	0.33	41.26	1.26
	60	59.54	0.46	59.54	0.46	59.54	0.46
500	20	19.99	0.01	19.04	0.96	19.99	0.01
	40	39.99	0.01	39.99	0.01	39.99	0.01
	60	60.49	0.49	60.49	0.49	60.49	0.49
1000	20	19.76	0.24	19.99	0.01	19.99	0.01
	40	40.46	0.46	39.99	0.01	39.75	0.25
	60	60.25	0.25	60.25	0.25	60.25	0.25

Table 5.5 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AG fault on a double circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 75.21% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins at 300 kHz. The sampling rate requirement to get within 100m of the actual fault location requires at least 500 kHz. The sampling rate requirement to get with 10m of actual fault is seen only for 500 kHz and 1000 kHz for faults less than halfway of the total line length.

Table 5.6: Single-Ended Fault Location Results for 1 Ohm Double Line Ungrounded (AB) Fault on Double Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	95.24	75.21	95.21	75.21	95.21	75.21
	40	71.41	31.41	47.60	7.60	47.60	7.60
	60	52.40	7.60	52.40	7.60	52.40	7.60
100	20	23.80	3.80	16.66	3.34	16.66	3.34
	40	40.46	0.46	40.46	0.46	40.46	0.46
	60	59.54	0.46	54.78	5.22	54.78	5.22
300	20	19.04	0.96	21.42	1.42	21.42	1.42
	40	40.46	0.46	40.46	0.46	40.46	0.46
	60	59.54	0.46	57.95	2.05	57.95	2.05
500	20	20.95	0.95	19.52	0.48	19.52	0.48
	40	40.46	0.46	40.46	0.46	40.46	0.46
	60	59.06	0.94	59.54	0.46	59.54	0.46
1000	20	20.23	0.23	20.23	0.23	20.23	0.23
	40	40.94	0.94	40.23	0.23	39.99	0.01
	60	59.06	0.94	59.77	0.23	59.77	0.23

Table 5.6 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AB fault on a double circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 75.21% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins at 100 kHz but is more consistent at 500 kHz. The sampling rate requirement to get within 100m of the actual fault location is only seen once for the 'sym4' wavelet at a fault location of 40km and sampling rate of 1000 kHz.

Table 5.7: Single-Ended Fault Location Results for 1 Ohm Double Line to Ground (ABG) Fault on Double Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	95.24	75.21	95.21	75.21	95.21	75.21
	40	71.41	31.41	47.60	7.60	47.60	7.60
	60	52.40	7.60	52.40	7.60	52.40	7.60
100	20	23.80	3.80	16.66	3.34	16.66	3.34
	40	40.46	0.46	40.46	0.46	40.46	0.46
	60	59.54	0.46	54.78	5.22	54.78	5.22
300	20	19.04	0.96	21.42	1.42	21.42	1.42
	40	40.46	0.46	40.46	0.46	40.46	0.46
	60	59.54	0.46	57.95	2.05	57.95	2.05
500	20	20.95	0.95	19.52	0.48	19.52	0.48
	40	40.46	0.46	40.46	0.46	40.46	0.46
	60	59.06	0.94	59.54	0.46	59.54	0.46
1000	20	20.23	0.23	20.23	0.23	20.23	0.23
	40	40.94	0.94	40.23	0.23	39.99	0.01
	60	59.06	0.94	59.77	0.23	59.77	0.23

Table 5.7 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABG fault on a double circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 75.21% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins at 100 kHz but is more consistent at 500 kHz. The sampling rate requirement to get within 100m of the actual fault location is only seen once for the 'sym4' wavelet at a fault location of 40km and sampling rate of 1000 kHz.

Table 5.8: Single-Ended Fault Location Results for 1 Ohm Three Phase to Ground (ABCG) Fault on Double Circuit at Various Sampling Rates

		‘db4’		‘coif4’		‘sym4’	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	95.21	75.21	95.21	75.21	95.21	75.21
	40	47.60	7.60	47.60	7.60	47.60	7.60
	60	28.59	31.41	52.40	7.60	52.40	7.60
100	20	21.42	1.42	21.42	1.42	21.42	1.42
	40	38.08	1.92	40.46	0.46	38.08	1.92
	60	64.30	4.30	61.92	1.92	61.92	1.92
300	20	19.83	0.17	19.04	0.96	19.04	0.96
	40	38.88	1.12	38.88	1.12	38.88	1.12
	60	59.54	0.46	59.54	0.46	59.54	0.46
500	20	19.52	0.48	19.99	0.01	19.99	0.01
	40	39.51	0.49	39.99	0.01	39.51	0.49
	60	60.49	0.49	60.49	0.49	60.49	0.49
1000	20	17.76	0.24	19.76	0.24	19.76	0.24
	40	39.75	0.25	39.75	0.25	39.75	0.25
	60	60.25	0.25	60.25	0.25	60.25	0.25

Table 5.8 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABCG fault on a double circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 75.21% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location is consistent at 300 kHz. The sampling rate requirement to get within 100m and 10m of the actual fault location is only seen for the ‘coif4’ and ‘sym4’ wavelet at fault locations of 20km & 40km with sampling rate of 500 kHz.

5.3.3 Comparison of Fault Resistances

Table 5.9: Single-Ended Fault Location Results for Single Phase to Ground (AG) Fault on Double Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.23	0.23	30.23	0.23	30.23	0.23
	50	49.75	0.25	49.75	0.25	49.75	0.25
	70	70.25	0.25	70.25	0.25	70.25	0.25
5	30	30.23	0.23	30.23	0.23	30.23	0.23
	50	49.75	0.25	49.75	0.25	49.75	0.25
	70	70.25	0.25	70.25	0.25	70.25	0.25
10	30	30.23	0.23	30.23	0.23	30.23	0.23
	50	49.75	0.25	49.75	0.25	49.75	0.25
	70	70.25	0.25	70.25	0.25	70.25	0.25
50	30	30.23	0.23	30.23	0.23	30.23	0.23
	50	49.75	0.25	49.75	0.25	49.75	0.25
	70	70.25	0.25	70.25	0.25	70.25	0.25
100	30	30.23	0.23	30.23	0.23	30.23	0.23
	50	49.75	0.25	49.75	0.25	49.75	0.25
	70	70.25	0.25	70.25	0.25	70.25	0.25

Table 5.9 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AG fault on a double circuit with various fault resistances. The fault location results remain unchanged when increasing the resistance of the fault.

Table 5.10: Single-Ended Fault Location Results for Double Line Ungrounded (AB) Fault on Double Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.47	0.47	30.47	0.47	30.47	0.47
	50	50.70	0.70	50.22	0.22	50.22	0.22
	70	69.30	0.70	69.77	0.23	69.77	0.23
5	30	30.47	0.47	30.47	0.47	30.47	0.47
	50	50.70	0.70	50.22	0.22	50.22	0.22
	70	69.30	0.70	69.77	0.23	69.77	0.23
10	30	30.47	0.47	30.47	0.47	30.47	0.47
	50	50.70	0.70	50.22	0.22	50.22	0.22
	70	69.30	0.70	69.77	0.23	69.77	0.23

Table 5.10 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm AB fault on a double circuit with various fault resistances. The fault location results remain unchanged when increasing the resistance of the fault.

Table 5.11: Single-Ended Fault Location Results for Double Line to Ground (ABG) Fault on Double Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.47	0.47	30.47	0.47	30.47	0.47
	50	50.70	0.70	50.22	0.22	50.22	0.22
	70	69.30	0.70	69.77	0.23	69.77	0.23
5	30	30.47	0.47	30.47	0.47	30.47	0.47
	50	50.70	0.70	50.22	0.22	50.22	0.22
	70	69.30	0.70	69.77	0.23	69.77	0.23
10	30	30.47	0.47	30.47	0.47	30.47	0.47
	50	50.70	0.70	50.22	0.22	50.22	0.22
	70	69.30	0.70	69.77	0.23	69.77	0.23

Table 5.11 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABG fault on a double circuit with various fault resistances. The fault location results remain unchanged when increasing the resistance of the fault.

Table 5.12: Single-Ended Fault Location Results for Three Phase to Ground (ABCG) Fault on Double Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	29.75	0.25	29.75	0.25	29.75	0.25
	50	49.75	0.25	49.75	0.25	49.75	0.25
	70	70.25	0.25	70.25	0.25	70.25	0.25
5	30	29.75	0.25	29.75	0.25	29.75	0.25
	50	49.75	0.25	49.75	0.25	49.75	0.25
	70	70.25	0.25	70.25	0.25	70.25	0.25
10	30	29.75	0.25	29.75	0.25	29.75	0.25
	50	49.75	0.25	49.75	0.25	49.75	0.25
	70	70.25	0.25	70.25	0.25	70.25	0.25

Table 5.11 compares the fault location results of the three wavelets using the single-ended method for 1 Ohm ABCG fault on a double circuit with various fault resistances. The fault location results remain unchanged when increasing the resistance of the fault.

5.4 Double-Ended Method Results

5.4.1 Comparison of Wavelets

Table 5.13: Double-Ended Fault Location Results for 1 Ohm Single Phase to Ground (AG) Fault on Double Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.01	0.01	10.01	0.01	10.01	0.01
20	20.01	0.01	20.01	0.01	20.01	0.01
30	30.01	0.01	30.01	0.01	30.01	0.01
40	40.00	0.00	40.00	0.00	40.00	0.00
50	50.00	0.00	50.00	0.00	50.00	0.00
60	60.00	0.00	60.00	0.00	60.00	0.00
70	69.99	0.01	69.99	0.01	69.99	0.01
80	79.99	0.01	79.99	0.01	79.99	0.01
90	89.99	0.01	89.99	0.01	99.99	0.01
Average		0.01		0.01		0.01

Table 5.13 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm AG fault on a double circuit sampled at 1 MHz. All three wavelets share the lowest average error of 0.01% in this scenario. The largest error never exceeds 0.01%.

Table 5.14: Double-Ended Fault Location Results for 1 Ohm Double Line Ungrounded (AB) Fault on Double Circuit (1MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.01	0.01	10.01	0.01	10.01	0.01
20	20.01	0.01	20.01	0.01	20.01	0.01
30	30.01	0.01	30.01	0.01	30.01	0.01
40	40.00	0.00	40.00	0.00	40.00	0.00
50	50.00	0.00	50.00	0.00	50.00	0.00
60	60.00	0.00	60.00	0.00	60.00	0.00
70	69.99	0.01	69.99	0.01	69.99	0.01
80	79.99	0.01	79.99	0.01	79.99	0.01
90	89.99	0.01	89.99	0.01	99.99	0.01
Average		0.01		0.01		0.01

Table 5.14 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm AB fault on a double circuit sampled at 1 MHz. All three wavelets share the lowest average error of 0.01% in this scenario. The largest error never exceeds 0.01%.

Table 5.15: Double-Ended Fault Location Results for 1 Ohm Double Line to Ground (ABG) Fault on Double Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.01	0.01	10.01	0.01	10.01	0.01
20	20.01	0.01	20.01	0.01	20.01	0.01
30	30.01	0.01	30.01	0.01	30.01	0.01
40	40.00	0.00	40.00	0.00	40.00	0.00
50	50.00	0.00	50.00	0.00	50.00	0.00
60	60.00	0.00	60.00	0.00	60.00	0.00
70	69.99	0.01	69.99	0.01	69.99	0.01
80	79.99	0.01	79.99	0.01	79.99	0.01
90	89.99	0.01	89.99	0.01	99.99	0.01
Average		0.01		0.01		0.01

Table 5.15 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm ABG fault on a double circuit sampled at 1 MHz. All three wavelets share the lowest average error of 0.01% in this scenario. The largest error never exceeds 0.01%.

Table 5.16: Double-Ended Fault Location Results for 1 Ohm Three Phase to Ground (ABCG) Fault on Double Circuit (1 MHz)

	'db4'		'coif4'		'sym4'	
Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	10.01	0.01	10.01	0.01	10.01	0.01
20	20.01	0.01	20.01	0.01	20.01	0.01
30	30.01	0.01	30.01	0.01	30.01	0.01
40	40.00	0.00	40.00	0.00	40.00	0.00
50	50.00	0.00	50.00	0.00	50.00	0.00
60	60.00	0.00	60.00	0.00	60.00	0.00
70	69.99	0.01	69.99	0.01	69.99	0.01
80	79.99	0.01	79.99	0.01	79.99	0.01
90	89.99	0.01	89.99	0.01	89.99	0.01
Average		0.01		0.01		0.01

Table 5.16 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm ABCG fault on a double circuit sampled at 1 MHz. All three wavelets share the lowest average error of 0.01% in this scenario. The largest error never exceeds 0.01%.

5.4.2 Comparison of Sampling Rate

Table 5.17: Double-Ended Fault Location Results for 1 Ohm Single Phase to Ground (AG) Fault on Double Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	-21.41	41.41	-21.41	41.41	26.20	6.20
	40	50.00	10.00	73.80	33.80	73.80	33.80
	60	50.00	10.00	50.00	10.00	73.80	13.80
100	20	19.06	0.94	19.06	0.94	21.44	1.44
	40	38.10	1.90	40.48	0.48	35.72	4.28
	60	61.90	1.90	59.52	0.48	64.28	4.28
300	20	19.06	0.94	19.85	0.15	19.85	0.15
	40	41.27	1.27	41.27	1.27	39.69	0.31
	60	58.73	1.27	58.73	1.27	60.31	0.31
500	20	20.01	0.01	20.01	0.01	20.01	0.01
	40	40.00	0.00	40.00	0.00	40.00	0.00
	60	60.00	0.00	60.00	0.00	60.00	0.00
1000	20	20.01	0.01	20.01	0.01	20.01	0.01
	40	40.00	0.00	40.00	0.00	40.00	0.00
	60	60.00	0.00	60.00	0.00	60.00	0.00

Table 5.17 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm AG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 41.41% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins at 300 kHz but is consistent at 500 kHz. The sampling rate requirement to get within 100m and 10m of the actual fault location is seen at 500 kHz and 1000 kHz, without much change between the two rates.

Table 5.18: Double-Ended Fault Location Results for 1 Ohm Double Line Ungrounded (AB) Fault on Double Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	-21.41	41.41	50.00	30.00	50.00	30.00
	40	73.80	33.80	2.40	37.60	50.00	10.00
	60	26.20	33.80	73.80	13.80	50.00	10.00
100	20	16.68	3.32	23.82	3.82	23.82	3.82
	40	35.72	4.28	42.86	2.86	42.86	2.86
	60	64.28	4.28	57.14	2.86	57.14	2.86
300	20	21.44	1.44	19.06	0.94	19.06	0.94
	40	38.89	1.11	41.27	1.27	41.27	1.27
	60	61.11	1.11	58.73	1.27	57.73	1.27
500	20	20.01	0.01	20.01	0.01	20.01	0.01
	40	40.00	0.00	40.00	0.00	40.00	0.00
	60	60.00	0.00	60.00	0.00	60.00	0.00
1000	20	20.01	0.01	20.01	0.01	20.01	0.01
	40	40.00	0.00	40.00	0.00	40.00	0.00
	60	60.00	0.00	60.00	0.00	60.00	0.00

Table 5.18 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm AB fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 41.41% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins at 300 kHz but is consistent at 500 kHz. The sampling rate requirement to get within 100m and 10m of the actual fault location is seen at 500 kHz and 1000 kHz, without much change between the two rates.

Table 5.19: Double-Ended Fault Location Results for 1 Ohm Double Line to Ground (ABG) Fault on Double Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	-21.41	41.41	50.00	30.00	50.00	30.00
	40	73.80	33.80	2.40	37.60	50.00	10.00
	60	26.20	33.80	73.80	13.80	50.00	10.00
100	20	16.68	3.32	23.82	3.82	23.82	3.82
	40	35.72	4.28	42.86	2.86	42.86	2.86
	60	64.28	4.28	57.14	2.86	57.14	2.86
300	20	21.44	1.44	19.06	0.94	19.06	0.94
	40	38.89	1.11	41.27	1.27	41.27	1.27
	60	61.11	1.11	58.73	1.27	57.73	1.27
500	20	20.01	0.01	20.01	0.01	20.01	0.01
	40	40.00	0.00	40.00	0.00	40.00	0.00
	60	60.00	0.00	60.00	0.00	60.00	0.00
1000	20	20.01	0.01	20.01	0.01	20.01	0.01
	40	40.00	0.00	40.00	0.00	40.00	0.00
	60	60.00	0.00	60.00	0.00	60.00	0.00

Table 5.19 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm ABG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 41.41% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins at 300 kHz but is consistent at 500 kHz. The sampling rate requirement to get within 100m and 10m of the actual fault location is seen at 500 kHz and 1000 kHz, without much change between the two rates.

Table 5.20: Double-Ended Fault Location Results for 1 Ohm Three Phase to Ground (ABCG) Fault on Double Circuit at Various Sampling Rates

		'db4'		'coif4'		'sym4'	
Sampling Rate (kHz)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
10	20	-21.41	41.41	26.20	6.20	-21.41	41.41
	40	50.00	10.00	73.80	33.80	73.80	33.80
	60	50.00	10.00	73.80	13.80	50.00	10.00
100	20	19.06	0.94	19.06	0.94	16.68	3.32
	40	38.10	1.90	40.48	0.48	35.72	4.28
	60	61.90	1.90	59.52	0.48	64.28	4.28
300	20	19.06	0.94	19.85	0.15	19.85	0.15
	40	42.07	2.07	41.27	1.27	39.69	0.31
	60	58.73	1.27	58.73	1.27	60.31	0.31
500	20	20.01	0.01	20.01	0.01	20.01	0.01
	40	40.00	0.00	40.00	0.00	40.00	0.00
	60	60.00	0.00	60.00	0.00	60.00	0.00
1000	20	20.01	0.01	20.01	0.01	20.01	0.01
	40	40.00	0.00	40.00	0.00	40.00	0.00
	60	60.00	0.00	60.00	0.00	60.00	0.00

Table 5.20 compares the fault location results of the three wavelets using the double-ended method for 1 Ohm ABCG fault on a single circuit sampled at 10 kHz, 100 kHz, 300 kHz, 500 kHz, and 1000 kHz. The error of the 10 kHz sample rate goes as high as 41.41% indicating an inadequate sampling rate for fault location. The sampling rate requirement to get within 1000m of the actual fault location begins at 300 kHz but is consistent at 500 kHz. The sampling rate requirement to get within 100m and 10m of the actual fault location is seen at 500 kHz and 1000 kHz, without much change between the two rates.

5.4.3 Comparison of Fault Resistances

Table 5.21: Double-Ended Fault Location Results for Single Phase to Ground (AG) Fault on Double Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
5	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
10	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
50	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
100	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01

Table 5.21 compares the fault location results of the three wavelets using the double-ended method for an AG fault on a double circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 5.22: Double-Ended Fault Location Results for Double Line Ungrounded (AB) Fault on Double Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
5	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
10	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01

Table 5.22 compares the fault location results of the three wavelets using the double-ended method for an AB fault on a double circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 5.23: Double-Ended Fault Location Results for Double Line to Ground (ABG) Fault on Double Circuit at Various Fault Resistances (1 MHz)

		'db4'		'coif4'		'sym4'	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
5	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
10	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01

Table 5.23 compares the fault location results of the three wavelets using the double-ended method for an ABG fault on a double circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

Table 5.24: Double-Ended Fault Location Results for Three Phase to Ground (ABCG) Fault on Double Circuit at Various Fault Resistances (1 MHz)

		‘db4’		‘coif4’		‘sym4’	
Fault Resistance (Ohm)	Actual (km)	Estimate (km)	Error (%)	Estimate (km)	Error (%)	Estimate (km)	Error (%)
1	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
5	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01
10	30	30.01	0.01	30.01	0.01	30.01	0.01
	50	50.00	0.00	50.00	0.00	50.00	0.00
	70	69.99	0.01	69.99	0.01	69.99	0.01

Table 5.24 compares the fault location results of the three wavelets using the double-ended method for an ABCG fault on a double circuit with various fault resistances with a sampling rate of 1 MHz. The fault location results remain unchanged when increasing the resistance of the fault.

CHAPTER 6. CONCLUSION

The purpose of this thesis is to present the topic of fault location techniques using the traveling wave method and the discrete wavelet transform. The principles of traveling waves and the single-ended and double-ended fault location methods are explored. Signal processing techniques required for traveling wave analysis using the discrete wavelet transform in MATLAB SIMULINK are also covered. An evaluation study on a single circuit and double circuit 500kV line are performed and fault location results using three different wavelets are compared, along with sampling rate, and fault resistance analysis.

Results of the wavelet comparison analysis using the 'db4', 'coif4', and 'sym4' wavelets with a common sampling rate of 1 MHz are inconclusive, as there wasn't a wavelet that consistently gave lower average errors across all tested scenarios. It is possible that the sampling rate had a much more significant impact than wavelet used for analysis in this portion of the study.

Results of the sampling rate comparison analysis indicate the 10 kHz sampling rate being inadequate for traveling wave methods for fault location. Results to get within 1000m, 100m, and 10m of the actual fault location varied throughout the analysis depending on circuit, fault type, and fault location method. It is recommended that a sampling rate of 300 kHz is used for the single-ended method and a sampling rate of 500 kHz is needed for the double-ended method to get within 1000m of actual fault location. Sampling rate results to get within 100m or 10m of actual fault location are too inconsistent within this study for recommendation and requires more analysis. An interesting result of this analysis is that there was not much of an improvement in error when comparing the 500 kHz and 1 MHz sampling rate results for the cases where location estimates were within 100m and 10m.

Results of the fault resistance comparison indicate consistent fault location results regardless of resistance value. This is consistent with literature of the resiliency of the traveling wave method.

For future work,

- Additional wavelet analysis to try to determine an optimum wavelet for fault location
- Additional sampling rate analysis to better determine requirements for fault location estimates within 1000m, 100m, and 10m of actual fault
- Techniques to improve fault location results at lower sampling rates
- Additional fault location analysis with faults occurring between the 'healthy' and 'unhealthy' circuits of a double circuit line
- Additional fault location analysis on T-intersection transmission lines
- Additional analysis with modeled current transformers

APPENDIX

```
% Example
% Perform DWT on ‘alpha_A_1000kHz’ signal using ‘db4’ wavelet at level ‘1’
[c_alpha_A_1000kHz,l_alpha_A_1000kHz]=wavedec(alpha_A_1000kHz,1,'db4');
% Retrieve Detail coefficients at level ‘1’
[cd1_alpha_A_1000kHz]=detcoef(c_alpha_A_1000kHz,l_alpha_A_1000kHz,1);
% Plot Detail coefficients in Figure 1
figure(1);
stem(cd1_alpha_A_1000kHz)
```

REFERENCES

1. M.T. Sant, Y.G. Paithankar, “Online digital fault locator for overhead transmission line,” Proceedings of the Institution of Electrical Engineers, vol. 126, no. 11, Nov. 1979, pp. 1181-1185.

2. A. Wiszniewski, “Accurate fault impedance locating algorithm,” IEE Proceedings C-Generation, Transmission and Distribution, vol. 130, no. 6, Nov. 1983, pp. 311-314.

3. W. Xiu and Y. Liao, "Fault location observability analysis on power distribution systems," Electric Power Components and Systems, vol. 42, no. 16, 2014, pp 1862-1871.

4. Y. Liao, "A novel method for locating faults on distribution systems," Electric Power Systems Research Journal, vol. 117, Dec. 2014, pp. 21-26.

5. Y. Liao, "Fault location for single-circuit line based on bus impedance matrix utilizing voltage measurements," IEEE Transactions on Power Delivery, vol. 23, no. 2, Apr. 2008, pp. 609-617.

6. W. Xiu and Y. Liao, "Fault location for parallel transmission lines with limited voltage and current measurements," International Journal of Emerging Electric Power Systems, vol. 14, no. 3, June 2013, pp. 265-274.

7. L.V. Bewley, “Traveling waves on transmission systems,” Transactions of the American Institute of Electrical Engineers, vol. 50, no. 2, June 1931, pp. 532-550.

8. A. Guzmán, B. Kasztenny, Y. Tong, M. V. Mynam, "Accurate and economical traveling-wave fault locating without communications," 2018 71st Annual Conference for Protective Relay Engineers (CPRE), College Station, Texas, USA, March 26-29, 2018.

9. M. M. S., Jan Izykowski and E. Rosolowski, Fault Location on Power Networks, Springer, 2010.

10. M. H. Idris, M. W. Mustafa, Y. Yatim, “Effective Two Terminal Single Line to Ground Fault Location Algorithm,” 2012 IEEE International Power Engineering and Optimization Conference (PEDCO) Melaka, June 6-7, 2012, pp. 246-251.

11. T. Kawady and J. Stenzel. “Investigation of practical problems for digital fault location algorithms based on EMTP simulation,” Asia-Pacific Transmission and Distribution Conference and Exhibition, vol. 1, 2002, pp.118-123.

12. I. Daubechies, “Ten lectures on wavelets,” Society for Industrial and Applied Mathematics, Philadelphia, PA, 1992.

13. E. Clarke, “Circuit analysis of AC power systems: symmetrical and related components,” Wiley, New York, 1943.

14. MATLAB Wavelet Toolbox User’s Guide, the Math Works Inc., Natick, MA, 2019

VITA

Author:

Name: Wesley Fluty

Education:

Bachelor of Science in Electrical Engineering, 2015

Bachelor of Arts in Economics, 2010

University of Kentucky

Professional Positions:

Engineer II, Protection and Control

Power Grid, LLC.

November 2019 – Present

Engineer, Transmission Planning

East Kentucky Power Cooperative

June 2015 – October 2019

Awards:

Undergraduate Certificate in Power and Energy (PEIK)