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Traveling Wave Fault Location Method for Distribution Systems with Distributed Generation

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TRAVELING WAVE FAULT LOCATION METHOD FOR DISTRIBUTION SYSTEMS WITH DISTRIBUTED GENERATION

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

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2021

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ABSTRACT OF THESIS

TRAVELING WAVE FAULT LOCATION METHOD FOR DISTRIBUTION SYSTEMS WITH DISTRIBUTED GENERATION

Fault location is an important topic within electric power systems, as accurate fault location techniques will improve the reliability of the system and reduce downtime caused by outages. This paper explores fault location in distribution systems with distributed generation using the traveling wave fault location method. The single-ended and double-ended traveling wave methods are evaluated using a single-circuit distribution system which is modeled using MATLAB SIMULINK. The results are compared using a basis of signals and bus pairs across fault types, sampling rates and fault resistances.

KEYWORDS: Fault Location, Traveling Wave, Single-Ended, Double-Ended, Distribution Systems, Distributed Generation

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TRAVELING WAVE FAULT LOCATION METHOD FOR DISTRIBUTION SYSTEMS WITH DISTRIBUTED GENERATION

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CHAPTER 1. INTRODUCTION

1.1 Background

Electric Power systems are composed of electrical components which make up the three main parts, generation, transmission and distribution. Generation broadly refers to power plants that generate electric power e.g., coal plants, natural gas plants, solar PV farms, etc. Transmission mainly consists of high voltage power lines that transport that power from the generation sites to substations which then step down the high voltage to lower voltage levels. The distribution system then steps the voltage down further and with the use of distribution lines, the electric power is then fed to our homes. Due to the emergence of various new technologies like distributed generation/inverter-based generation, smart grid systems, etc. the complexity of our power system has grown and so has the need for accurate and reliable ways to detect faults in our system.

Faults in an electric power system can be defined as any disturbance in the systems current. These faults can be caused by a wide range of things, from naturally occurring phenomena like lightning strikes to wildlife getting caught on a line [1]-[10]. There are different types of faults but regardless of the type of fault, they cause a loss of service to the customers and can be harmful if not cleared. In order for us to reduce the effects of faults in a system, we need to accurately and quickly detect the location of these faults [6][7].

1.2 Fault Location Methods

The two most common methods in which faults are located are the impedance-based method and the traveling wave method [5][6][7][8][9][10]. The impedance-based method is a simple approach where current and voltage signals along with sequence impedance are used in order to determine the location of the fault on a line [7]. Due to the emergence of inverter-based generation like solar PV systems and wind generation systems, which have varied fundamental frequency fault current contributions and no zero and negative sequence fault currents, using this method may not be as accurate as for traditional power systems [6]. Also, an increase in the fault resistance can also affect the accuracy of this method.

This project focuses on the traveling wave method of fault location. This method makes use of the high frequency electromagnetic pulse waves which are generated at the point of a fault by the change in voltage and current. These waves travel in both directions of the distribution line and away from the fault point and eventually attenuate. The traveling wave method uses the time stamps of these waves as they reach the sensors on the bus/busses on either end of the distribution line along with the speed of the wave and a sampling rate in order to pinpoint the location of the fault on the distribution line. The two traveling wave location methods are the single-ended method and the double-ended method.

The single-ended method makes use of the initial wave from the fault location as well as the reflected wave and these timestamps are gotten from a sensor on a single bus in the distribution system. This is the cheaper method as it requires less equipment, but it is also not as accurate as the double-ended method as it is a challenge to properly identify the reflected wave.

The double-ended method makes use of the initial wave at bus A as well as the initial wave at bus B, so no reflected wave timestamp is needed. This method is more expensive as it requires more equipment but eliminates the use of the reflected wave timestamp which makes it more accurate at detecting the fault location.

The main advantages of the traveling wave fault location method as opposed to the impedance-based method are that the results are accurate irrespective of fault type and fault resistance. The traveling wave method may find applications in utility distribution feeders and inside microgrid and for detecting MG islanding, while common islanding methods are referred to [11].

1.3 Motivation and Objective

The aim of this project is to explore the impact of different parameters on fault location using the traveling wave method. Both the single ended and double ended methods are used, and results are compared. The single-ended method is compared on the basis of voltage and current signals: 'sig_V', 'Yhigh_V', 'sig_I', 'Yhigh_I' across different fault types at a sampling rate of 1 MHz. The next step was to then vary the sampling rate between 1 MHz and 10 MHz. Lastly, the impact of fault resistance is also tested at a constant sampling rate of 1 MHz.

The double ended method is compared using 'sig_V' but with varying bus pairs: 'Bus 2 & Bus 4', 'Bus 3 & Bus 4', 'Bus 3 & Bus 5' and 'Bus 2 & Bus 5' across different fault types at a sampling rate of 1 MHz. The next step was to then vary the sampling rate between 1 MHz and 10 MHz. Lastly, the impact of fault resistance is also tested at a constant sampling rate of 1 MHz.

I believe that this project will serve as a solid base for anyone who is interested in the traveling wave fault location method. The single-ended and double-ended method are both explored on a distribution system that was modeled in MATLAB SIMULINK.

1.4 Project Organization

Chapter 2 explains more in depth the single-ended and the double-ended methods of the traveling wave fault location method. A Bewley-Lattice diagram is shown for both methods in order to give a more visual look at the reflection and refraction of the waves.

Chapter 3 is a simulation study for a three-phase distribution system with distributed generation which shows in depth examples and results for both the single-ended and double-ended methods. These results consist of changes to the type of fault, sampling rate and fault resistances.

Chapter 4 is the conclusion after we have taken a look at the results in the previous chapter and also contains recommendations on future work.

CHAPTER 2. CONCEPTS OF TRAVELING WAVE FAULT LOCATION

2.1. Single Ended Fault Location Method

The single ended traveling wave fault location method requires only one sensor at one of the busses in the distribution system. This makes it the cheaper method to implement as it does not need two sensors or a signal relay between busses. The drawback of the lower cost is that the single ended method is less accurate than the double ended method. This method works by identifying two waves. The first wave is the initial traveling wave generated from the fault point to the bus where the sensor is located. The second wave is a reflected wave from the initial fault point. The difference between the time stamps of when both of these waves arrive is used to calculate the location of the fault, along with the velocity of the wave and the sampling frequency.

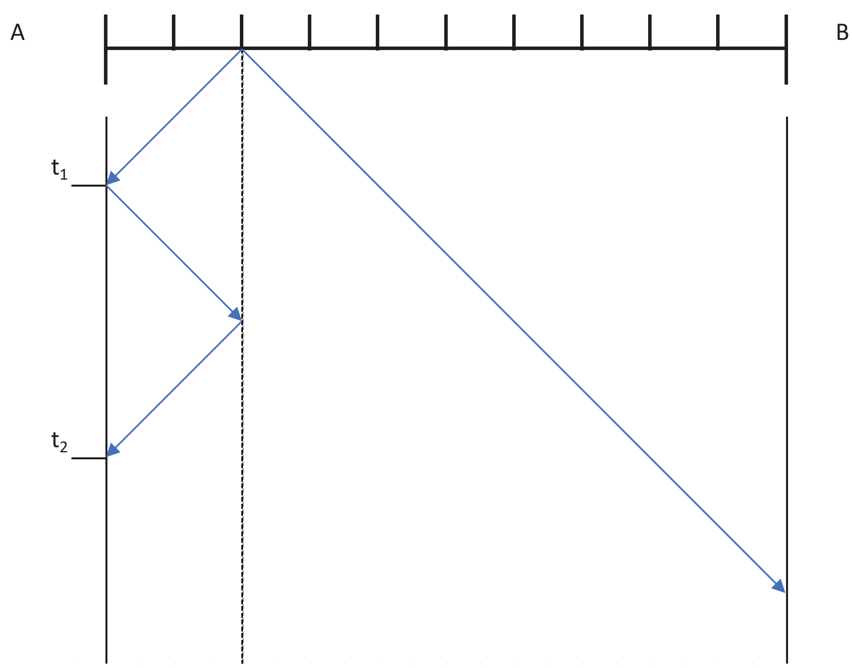

Figure 1: Single-Ended Bewley Lattice Diagram for Fault in First Half of Line

Figure 1 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

$$\boldsymbol{X = \frac{1}{2} v\, \tau\, (t_2 - t_1)} \tag{2.1}$$

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

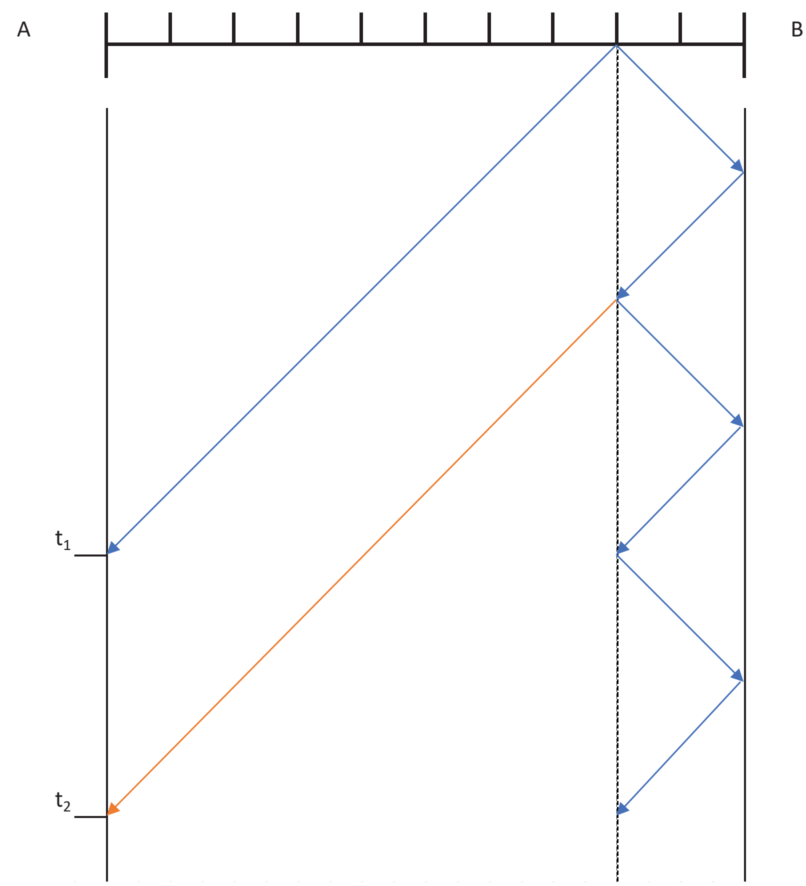

Figure 2: Single-Ended Bewley Lattice Diagram for Fault in Second Half of Line

Figure 2 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

$$\boldsymbol{X = L - \frac{1}{2} v \, \tau \, (t_2 - t_1)} \tag{2.2}$$

Where v is wave velocity, τ is the inverse of the sampling frequency, 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 distribution line.

2.2 Double Ended Fault Location Method

The double ended traveling wave fault location method requires two sensors which are placed on any two busses in the distribution system. This makes it the more expensive method as it requires two sensors and a signal relay for communication between the sensors. The double ended method is more accurate than the single ended method at detecting the location of the fault. This method also works by identifying two waves. It detects the initial waves at both busses and the difference between the time stamps of these waves is used to calculate the fault location.

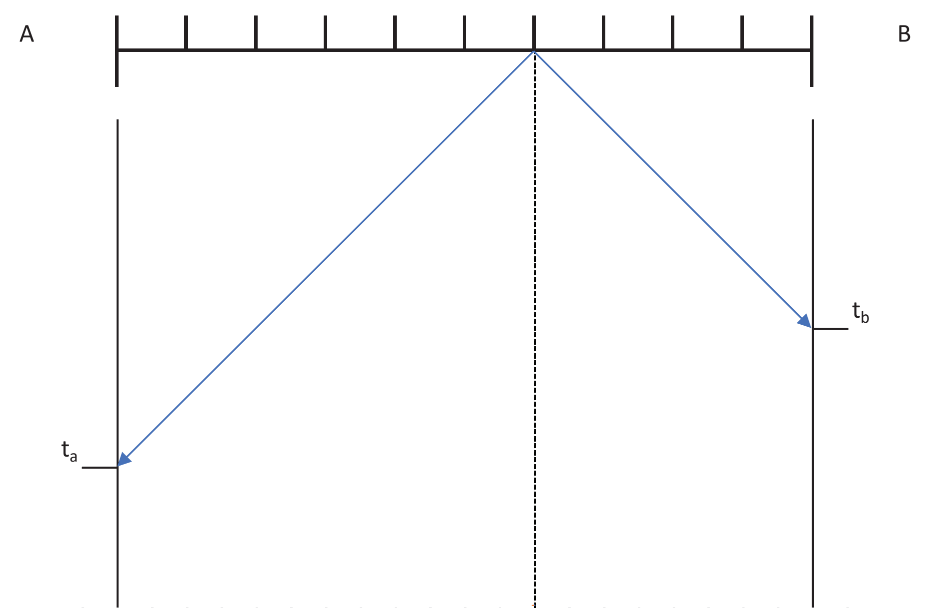

Figure 3: Double-Ended Bewley Lattice Diagram for Fault on Line

Figure 3 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

$$\boldsymbol{X} = \frac{\boldsymbol{1}}{\boldsymbol{2}}[\boldsymbol{L} + \boldsymbol{v}\,\boldsymbol{\tau}\,(\boldsymbol{t_a} - \boldsymbol{t_b})] \tag{2.3}$$

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

3.1 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. The system features seven busses, substation sources, distributed generation sources, various loads and distribution lines 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. This single circuit system can be seen in Figure 4.

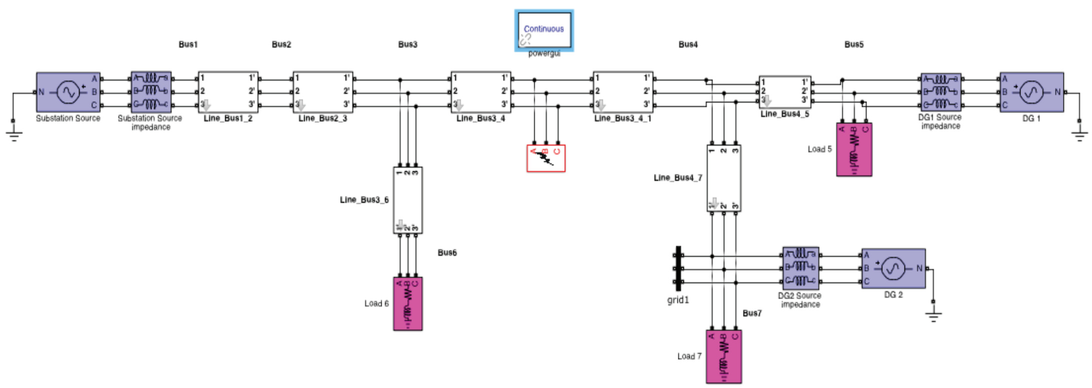

Figure 4: Single Circuit Power System Modeled Using MATLAB SIMULINK provided by Dr. Yuan Liao

System Parameters:

System Base Voltage: 12.47 kV

System Base Power: 1 MVA

System Frequency: 60 Hz

Number of Phases: 3

Substation Source Positive Sequence Resistance: 0.23 Ohms

Substation Source Positive Sequence Inductance: 5.57e-3 H

Substation Source Zero Sequence Resistance: 0.15 Ohms

Substation Source Zero Sequence Inductance: 3.89e-3 H

DG1 Source Positive Sequence Resistance: 1.87 Ohms

DG1 Source Positive Sequence Inductance: 4.82e-2 H

DG1 Source Zero Sequence Resistance: 1.56Ohms

DG1 Source Zero Sequence Inductance: 4.59e-2 H

DG2 Source Positive Sequence Resistance: 1.87 Ohms

DG2 Source Positive Sequence Inductance: 4.82e-2 H

DG2 Source Zero Sequence Resistance: 1.56 Ohms

DG2 Source Zero Sequence Inductance: 4.59e-2 H

Total Line Length: 3 km

3.2 Single Ended Method Results

3.2.1 Comparison of Signals

In this section, the single ended method fault location error results of the four signals (‘sig_V’, ‘Yhigh_V’, ‘sig_I’ and ‘Yhigh_I’) are compared for different types of faults at 0.3km increments. All testing was performed on the single circuit presented earlier in the chapter, with a sampling frequency of 1 MHz. The simulation model shown in Figure 4 was run to generate voltage and current waveforms under various fault cases. Then, the signals sig_V, Yhigh_V, sig_I and Yhigh_I are extracted from the simulated waveforms by MATLAB programs provided by Dr. Yuan Liao [6].

Table 3.1: Single-Ended Fault Location Results for 0.1 Ohm Single Phase to Ground (AG) Fault on Single Circuit (1MHz)

	‘sig_V’		‘Yhigh_V’		‘sig_I’		‘Yhigh_I’	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.40	0.10	0.40	0.10	0.40	0.10	0.40	0.10
0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
0.90	0.80	0.10	0.80	0.10	0.80	0.10	0.80	0.10
1.20	1.21	0.01	1.21	0.01	1.21	0.01	1.21	0.01
1.50	1.74	0.24	1.74	0.24	1.74	0.24	1.74	0.24
1.80	1.66	0.14	1.66	0.14	1.66	0.14	1.66	0.14
2.10	1.93	0.17	1.93	0.17	1.93	0.17	1.93	0.17
2.40	1.53	0.87	1.53	0.87	1.53	0.87	1.53	0.87
2.70	2.60	0.10	2.60	0.10	2.60	0.10	2.60	0.10
Average		0.20		0.20		0.20		0.20

Table 3.1 compares the fault location error results of the four signals using the single ended method for a 0.1 Ohm AG fault sampled at 1MHz. We can see that the results are consistent between all four signals, each with an average error of 0.20 km.

The fault location equation is given by

$$\boldsymbol{X = \frac{1}{2} v\, \tau\, (t_2 - t_1)} \tag{1.1}$$

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.

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 the velocity equation gives us:

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

$$\boldsymbol{v = \frac{1}{\sqrt{(14e-4)(1.0146e-8)}}}$$

$$\boldsymbol{v = 267880\ km/s}$$

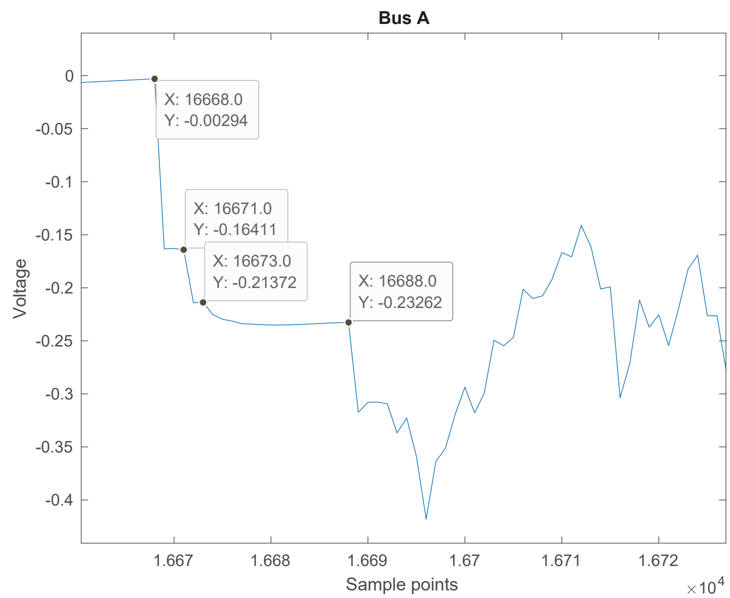

Figure 5: Time indexes for sig_V with 0.1Ω AG Fault at 0.30 km from Bus A on Single Circuit (1 MHz)

Example 1: Focusing on sig_V at 0.30 km at 1 MHz.

The index for the initial traveling for the fault to Bus A is 16668 and the reflection wave from the fault location is 16671. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16671 - 16668)}$$

$$\boldsymbol{X = 0.40\ km}$$

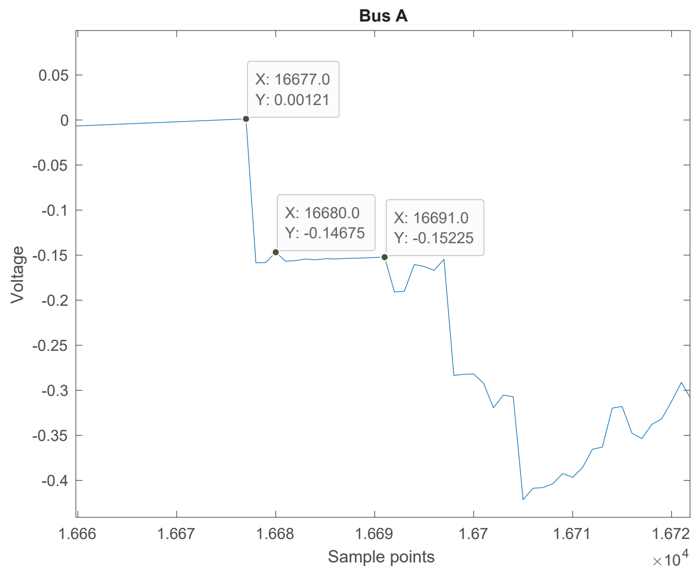

Figure 6: Time indexes for sig_V with 0.1Ω AG Fault at 2.70 km from Bus A on Single Circuit (1 MHz)

Example 2: Focusing on sig_V at 2.70 km at 1 MHz.

The index for the initial traveling for the fault to Bus A is 16677 and the reflection wave from the fault location is 16680. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16680 - 16677)}$$

$$\boldsymbol{X = 2.60\ km}$$

Table 3.2: Single-Ended Fault Location Results for 0.1 Ohm Double Line Ungrounded (AB) Fault on Single Circuit (1MHz)

	'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03
0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
0.90	0.80	0.10	0.80	0.10	0.80	0.10	0.80	0.10
1.20	1.21	0.01	1.21	0.01	1.21	0.01	1.21	0.01
1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
1.80	1.74	0.06	1.74	0.06	1.74	0.06	1.74	0.06
2.10	1.66	0.44	2.14	0.04	1.80	0.30	2.14	0.04
2.40	2.41	0.01	2.41	0.01	2.10	0.30	2.10	0.30
2.70	2.68	0.02	2.68	0.02	1.53	1.17	1.53	1.17
Average		0.09		0.04		0.23		0.20

Table 3.2 compares the fault location error results of the four signals using the single ended method for a 0.1 Ohm AB fault sampled at 1MHz. The results show that signal sig_I has the highest error average of 0.23 km while Yhigh_V performs the best with an average error of 0.04 km.

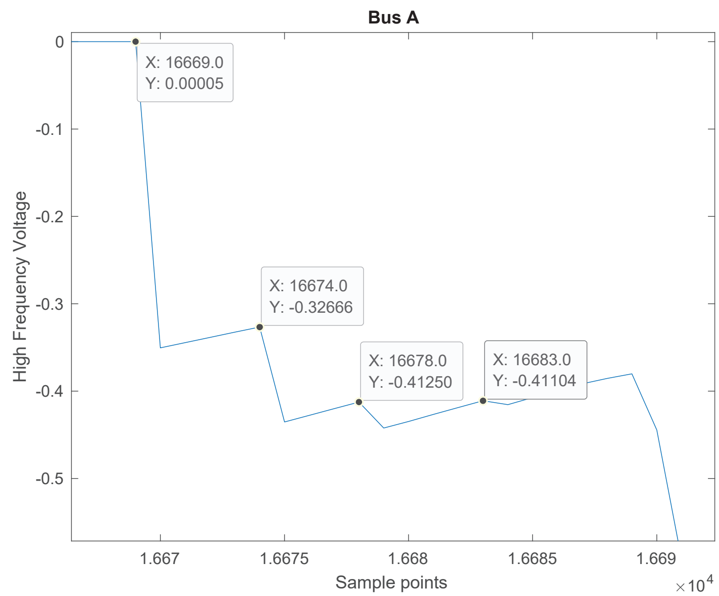

Figure 7: Time indexes for Yhigh_V with 0.1Ω AB Fault at 0.60 km from Bus A on Single Circuit (1 MHz)

Example 3: Focusing on Yhigh_V at 0.60 km at 1 MHz.

The index for the initial traveling for the fault to Bus A is 16669 and the reflection wave from the fault location is 16674. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16674 - 16669)}$$

$$\boldsymbol{X = 0.67\ km}$$

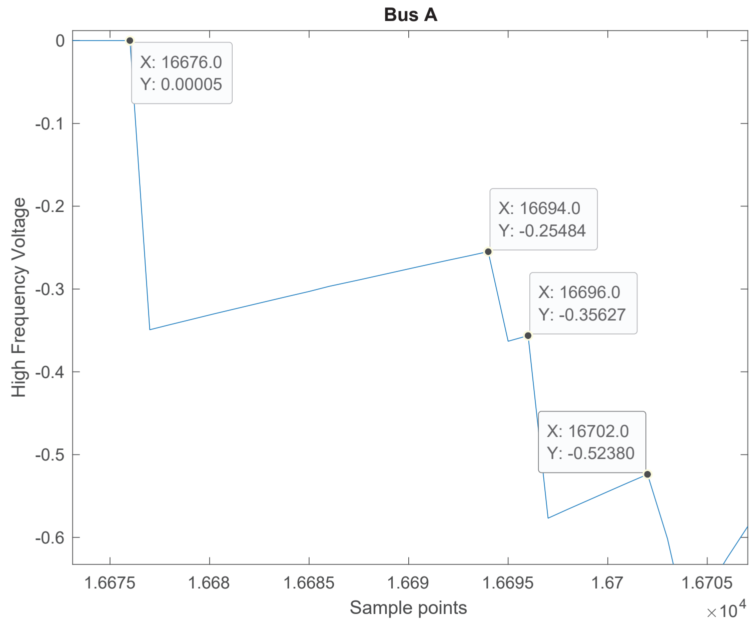

Figure 8: Time indexes for Yhigh_V with 0.1Ω AB Fault at 2.40 km from Bus A on Single Circuit (1 MHz)

Example 4: Focusing on Yhigh_V at 2.40 km at 1 MHz.

The index for the initial traveling for the fault to Bus A is 16676 and the reflection wave from the fault location is 16694. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16694 - 16676)}$$

$$\boldsymbol{X = 0.59\ km}$$

But, after examination of the wavefront polarity, the fault location should be calculated as

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16694 - 16676)}$$

$$\boldsymbol{X = 2.41\ \mathrm{km}}$$

Table 3.3: Single-Ended Fault Location Results for 0.1 Ohm Double Line to Ground (ABG) Fault on Single Circuit (1MHz)

	'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03
0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
0.90	0.80	0.10	0.80	0.10	0.80	0.10	0.80	0.10
1.20	1.21	0.01	1.21	0.01	1.21	0.01	1.21	0.01
1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
1.80	1.79	0.01	1.79	0.01	1.79	0.01	1.79	0.01
2.10	2.06	0.04	2.06	0.04	2.06	0.04	2.06	0.04
2.40	1.66	0.74	1.66	0.74	1.66	0.74	2.41	0.01
2.70	2.73	0.03	2.73	0.03	2.73	0.03	2.73	0.03
Average		0.12		0.12		0.12		0.04

Table 3.3 compares the fault location error results of the four signals using the single ended method for a 0.1 Ohm ABG fault sampled at 1MHz. The results show that signal Yhigh_I performs the best with an average error of 0.04 km.

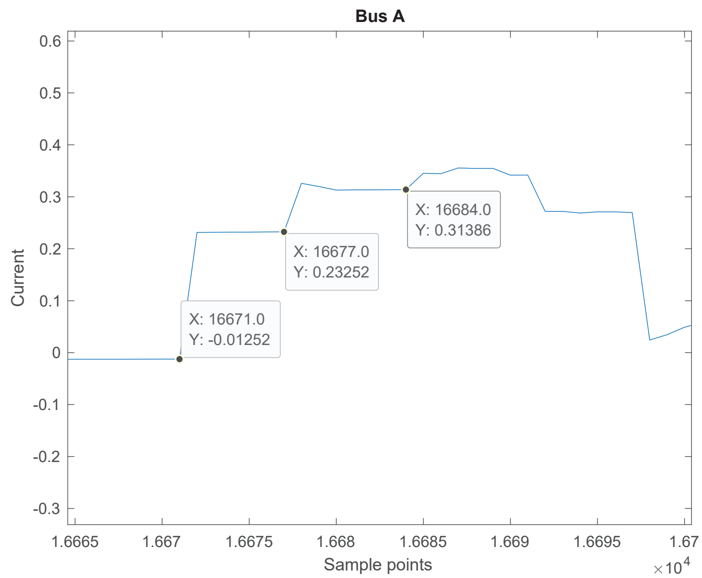

Figure 9: Time indexes for sig_I with 0.1Ω ABG Fault at 0.90 km from Bus A on Single Circuit (1 MHz)

Example 5: Focusing on sig_I at 0.90 km at 1 MHz.

The index for the initial traveling for the fault to Bus A is 16671 and the reflection wave from the fault location is 16677. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16677 - 16671)}$$

$$\boldsymbol{X = 0.80 \; km}$$

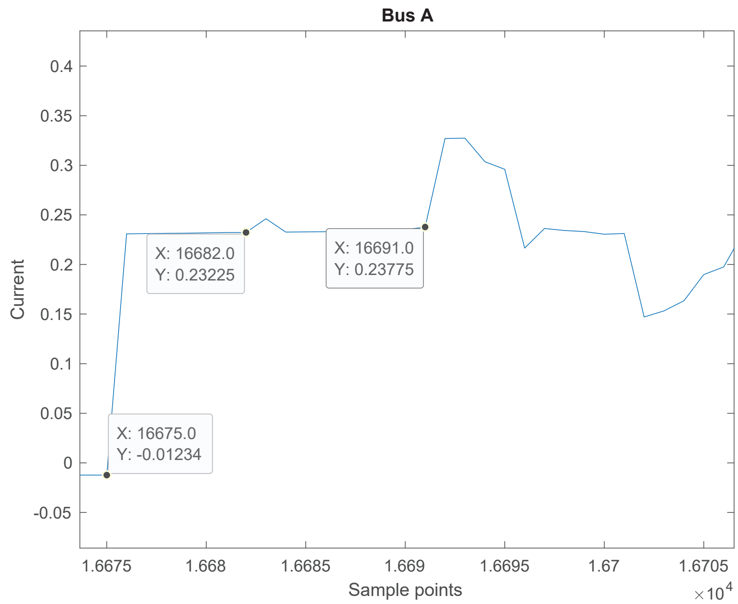

Figure 10: Time indexes for sig_I with 0.1Ω ABG Fault at 2.10 km from Bus A on Single Circuit (1 MHz)

Example 6: Focusing on sig_I at 2.10 km at 1 MHz.

The index for the initial traveling for the fault to Bus A is 16675 and the reflection wave from the fault location is 16682. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16682 - 16675)}$$

$$\boldsymbol{X = \ 2.06\ km}$$

Table 3.4: Single-Ended Fault Location Results for 0.1 Ohm Three Phase to Ground (ABCG) Fault on Single Circuit (1MHz)

	'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.40	0.10	0.40	0.10	0.40	0.10	0.40	0.10
0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
0.90	0.80	0.10	0.80	0.10	0.80	0.10	0.80	0.10
1.20	1.20	0.00	1.20	0.00	1.20	0.00	1.21	0.01
1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
1.80	1.74	0.06	1.74	0.06	1.74	0.06	1.74	0.06
2.10	2.14	0.04	2.14	0.04	2.14	0.04	2.14	0.04
2.40	2.41	0.01	2.41	0.01	2.41	0.01	2.41	0.01
2.70	2.68	0.02	2.68	0.02	2.68	0.02	2.68	0.02
Average		0.05		0.05		0.05		0.05

Table 3.4 compares the fault location error results of the four signals using the single ended method for a 0.1 Ohm ABCG fault sampled at 1MHz. We can see that the results are consistent between all four signals, each with an average error of 0.05 km.

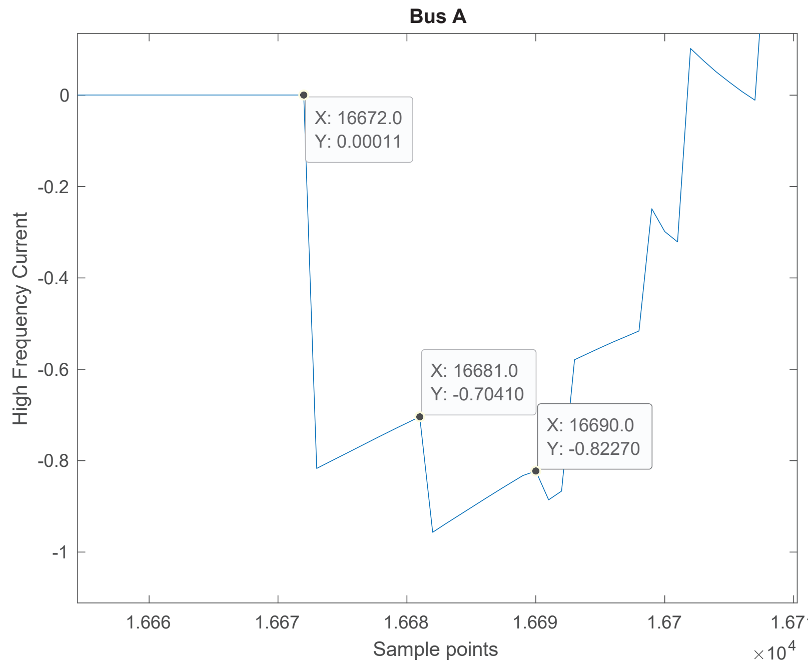

Figure 11: Time indexes for Yhigh_I with 0.1Ω ABCG Fault at 1.20 km from Bus A on Single Circuit (1 MHz)

Example 7: Focusing on sig_V at 1.20 km at 1 MHz.

The index for the initial traveling for the fault to Bus A is 16672 and the reflection wave from the fault location is 16681. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16681 - 16672)}$$

$$\boldsymbol{X = 1.21\ km}$$

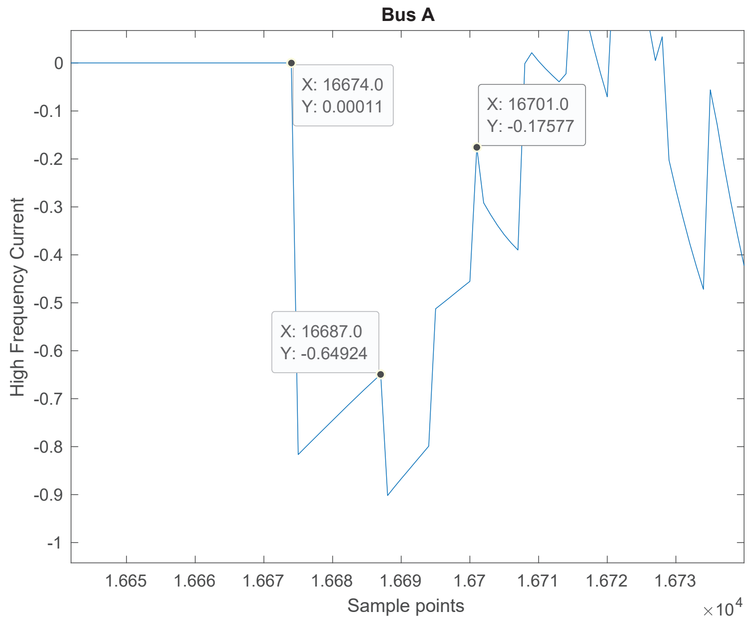

Figure 12: Time indexes for Yhigh_I with 0.1Ω ABCG Fault at 1.80 km from Bus A on Single Circuit (1 MHz)

Example 8: Focusing on Yhigh_I at 1.80 km at 1 MHz.

The index for the initial traveling for the fault to Bus A is 16674 and the reflection wave from the fault location is 16687. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16687 - 16674)}$$

$$\boldsymbol{X = 1.26\ km}$$

3.2.2 Comparison of Sampling Rate

In this section, the single-ended fault location results of the four signals (‘sig_V’, ‘Yhigh_V’, ‘sig_I’, ‘Yhigh_I’) are compared across six different sampling rates (1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz and 10 MHz) using different fault types.

Table 3.5: Single-Ended Fault Location Results for 0.1 Ohm Single Phase to Ground (AG) Fault on Single Circuit at Various Sampling Rates

		'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Sampling Rate (MHz)	Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
1	0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
	1.50	1.74	0.24	1.74	0.24	1.74	0.24	1.74	0.24
	2.40	1.53	0.87	1.53	0.87	1.53	0.87	1.53	0.87
2	0.60	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00
	1.50	1.74	0.24	1.74	0.24	1.74	0.24	1.74	0.24
	2.40	2.33	0.07	2.33	0.07	2.33	0.07	2.33	0.07
3	0.60	0.63	0.03	0.63	0.03	0.63	0.03	0.63	0.03
	1.50	1.79	0.29	1.79	0.29	1.79	0.29	1.79	0.29
	2.40	2.29	0.11	2.29	0.11	2.29	0.11	2.29	0.11
4	0.60	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00
	1.50	1.74	0.24	1.74	0.24	1.74	0.24	1.74	0.24
	2.40	2.30	0.10	2.30	0.10	2.30	0.10	2.30	0.10
5	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.77	0.27	1.77	0.27	1.77	0.27	1.77	0.27
	2.40	2.30	0.10	2.30	0.10	2.30	0.10	2.30	0.10
10	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.77	0.27	1.77	0.27	1.77	0.27	1.77	0.27
	2.40	2.30	0.10	2.30	0.10	2.30	0.10	2.30	0.10

Table 3.5 compares the fault location results of the four signals using the single-ended method for 0.1 Ohm AG fault on a single circuit sampled at 1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz and 10 MHz. The largest error we see is at the 2.40 km point at 1 MHz. As

we increase the sampling frequency, we can see that this is rectified, and better results are obtained for all fault locations.

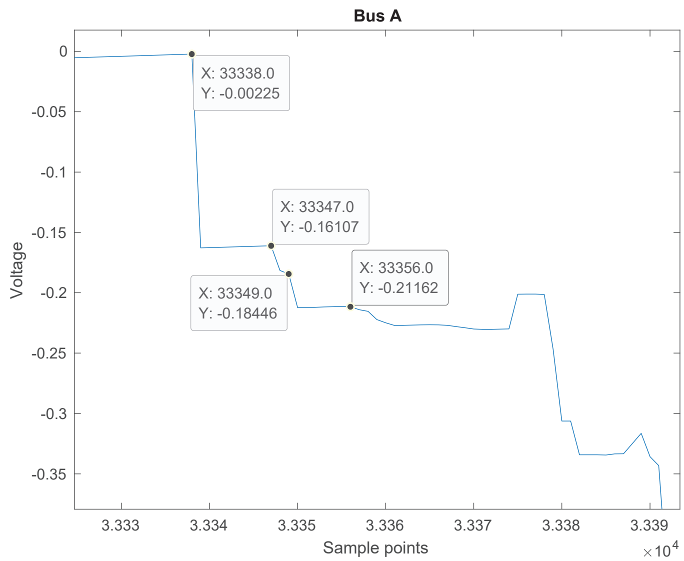

Figure 13: Time indexes for sig_V with 0.1Ω AG Fault at 0.60 km from Bus A on Single Circuit (2 MHz)

Example 9: Focusing on sig_V at 0.60 km at 2 Mhz.

The index for the initial traveling for the fault to Bus A is 33338 and the reflection wave from the fault location is 33347. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{2000000}\right)(33347 - 33338)}$$

$$\boldsymbol{X = 0.60\ km}$$

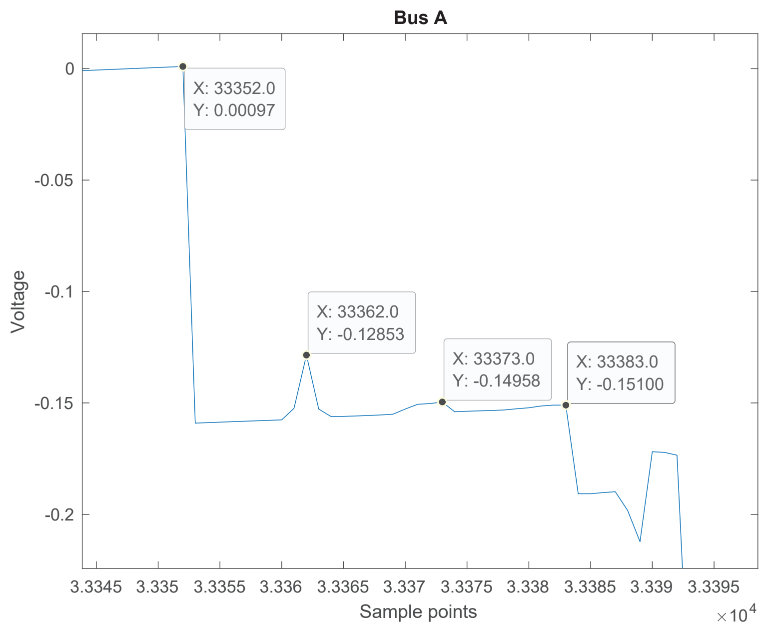

Figure 14: Time indexes for sig_V with 0.1Ω AG Fault at 2.40 km from Bus A on Single Circuit (2 MHz)

Example 10: Focusing on sig_V at 2.40 km at 2 Mhz.

The index for the initial traveling for the fault to Bus A is 33352 and the reflection wave from the fault location is 33362. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{2000000}\right)(33362 - 33352)}$$

$$\boldsymbol{X = 2.33\ km}$$

Table 3.6: Single-Ended Fault Location Results for 0.1 Ohm Double Line Ungrounded (AB) Fault on Single Circuit at Various Sampling Rates

		'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Sampling Rate (MHz)	Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
1	0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.41	0.01	2.41	0.01	2.10	0.30	2.10	0.30
2	0.60	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.41	0.01	2.41	0.01	2.41	0.01	2.41	0.01
3	0.60	0.63	0.03	0.63	0.03	0.63	0.03	0.63	0.03
	1.50	1.52	0.02	1.52	0.02	1.52	0.02	1.52	0.02
	2.40	2.41	0.01	2.41	0.01	2.41	0.01	2.41	0.01
4	0.60	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.41	0.01	2.41	0.01	2.41	0.01	2.41	0.01
5	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.38	0.02	2.38	0.02	2.38	0.02	2.38	0.02
10	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.40	0.00	2.40	0.00	2.40	0.00	2.40	0.00

Table 3.6 compares the fault location results of the four signals using the single-ended method for 0.1 Ohm AB fault on a single circuit sampled at 1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz and 10 MHz. All sampling rates perform well.

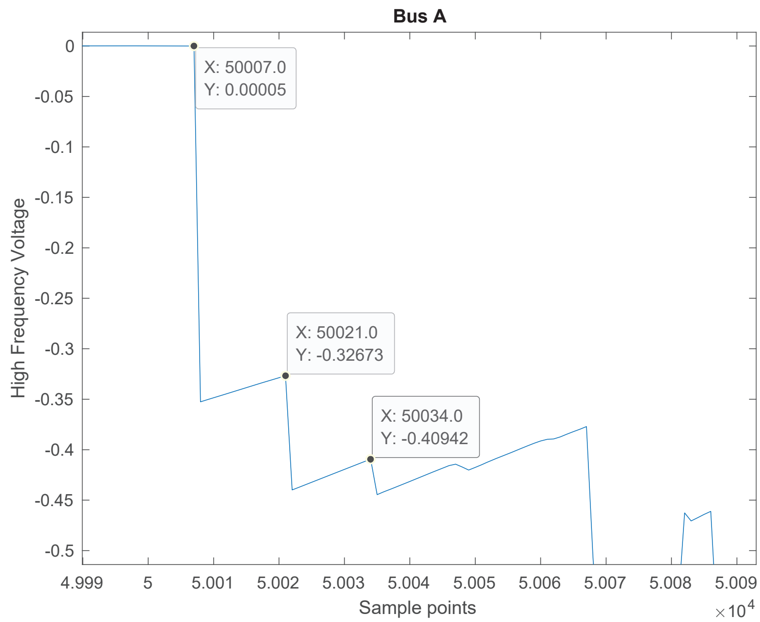

Figure 15: Time indexes for Yhigh_V with 0.1Ω AB Fault at 0.60 km from Bus A on Single Circuit (3 MHz)

Example 11: Focusing on Yhigh_V at 0.60 km at 3 Mhz.

The index for the initial traveling for the fault to Bus A is 50007 and the reflection wave from the fault location is 50021. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{3000000}\right)(50021 - 50007)}$$

$$\boldsymbol{X = 0.63\ km}$$

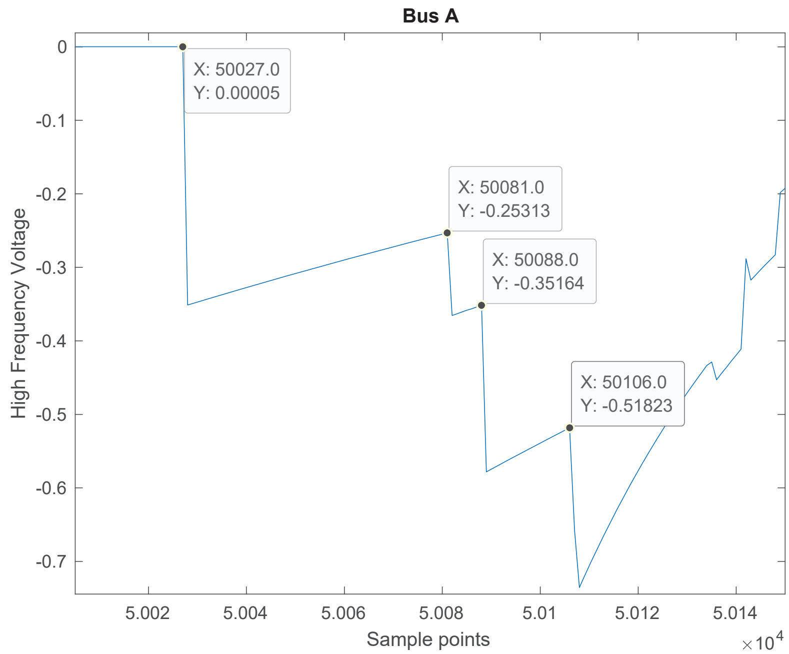

Figure 16: Time indexes for Yhigh_V with 0.1Ω AB Fault at 2.40 km from Bus A on Single Circuit (3 MHz)

Example 12: Focusing on Yhigh_V at 2.40 km at 3 MHz.

The index for the initial traveling for the fault to Bus A is 50027 and the reflection wave from the fault location is 50081. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{3000000}\right)(50081 - 50027)}$$

$$\boldsymbol{X = \ 0.59\ km}$$

Actually, based on polarity analysis, we can see the correct fault location should be:

$$\boldsymbol{X \ = \frac{1}{2}(267880)\left(\frac{1}{3000000}\right)(50081 - 50027)}$$

X = 2.41 km

Table 3.7: Single-Ended Fault Location Results for 0.1 Ohm Double Line to Ground (ABG) Fault on Single Circuit at Various Sampling Rates

		'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Sampling Rate (MHz)	Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
1	0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.33	0.07	1.66	0.74	2.33	0.07	2.41	0.01
2	0.60	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.33	0.07	2.33	0.07	2.40	0.00	2.40	0.00
3	0.60	0.58	0.02	0.58	0.02	0.58	0.02	0.58	0.02
	1.50	1.52	0.02	1.52	0.02	1.52	0.02	1.52	0.02
	2.40	2.37	0.03	2.37	0.03	2.37	0.03	2.37	0.03
4	0.60	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.40	0.00	2.40	0.00	2.40	0.00	2.40	0.00
5	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.41	0.01	2.41	0.01	2.41	0.01	2.41	0.01
10	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.41	0.01	2.41	0.01	2.41	0.01	2.41	0.01

Table 3.7 compares the fault location results of the four signals using the single-ended method for 0.1 Ohm ABG fault on a single circuit sampled at 1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz and 10 MHz. The largest error we see is at the 2.40 km point at 1 MHz at both signals Yhigh_V and Yhigh_I. As we increase the sampling frequency, we can see that this is rectified, and better results are obtained for all fault locations.

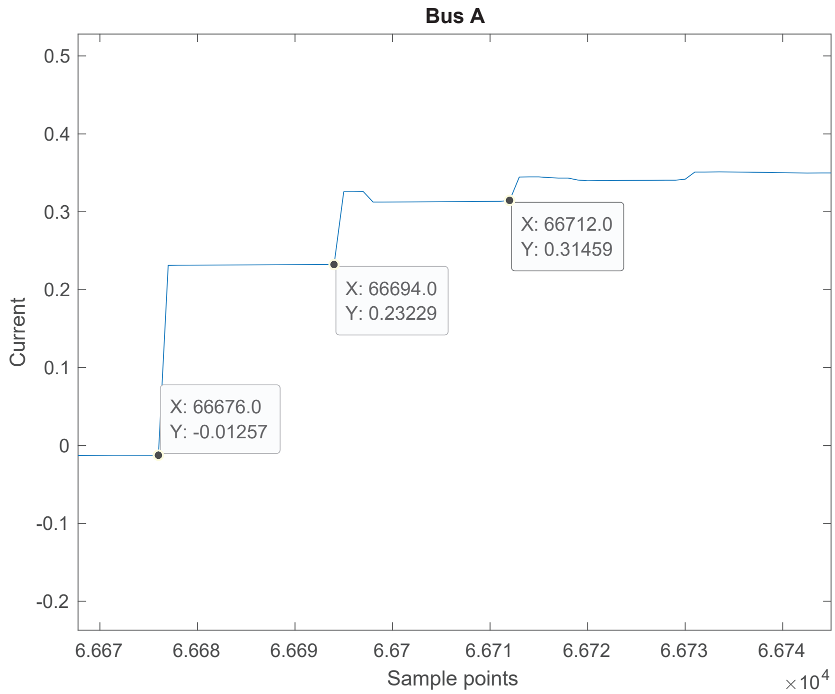

Figure 17: Time indexes for sig_I with 0.1Ω ABG Fault at 0.60 km from Bus A on Single Circuit (4 MHz)

Example 13: Focusing on sig_I at 0.60 km at 4 Mhz.

The index for the initial traveling for the fault to Bus A is 66676 and the reflection wave from the fault location is 66694. Plugging these values into the fault location equation gives us:

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

$$X = \frac{1}{2}(267880)\left(\frac{1}{4000000}\right)(66694 - 66676)$$

$$X = 0.60\ km$$

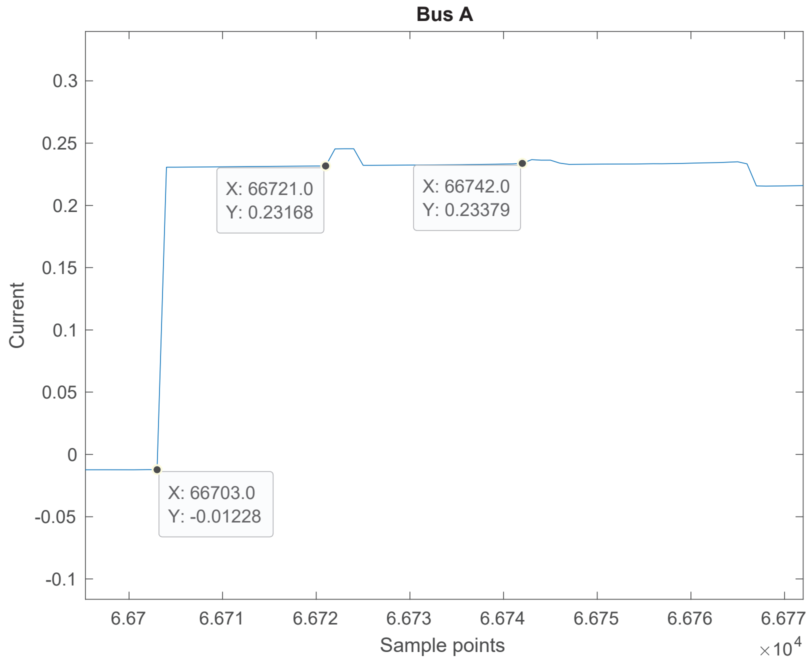

Figure 18: Time indexes for sig_I with 0.1Ω ABG Fault at 2.40 km from Bus A on Single Circuit (4 MHz)

Example 14: Focusing on sig_I at 2.40 km at 4 Mhz.

The index for the initial traveling for the fault to Bus A is 66703 and the reflection wave from the fault location is 66721. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{4000000}\right)(66721 - 66703)}$$

$$\boldsymbol{X = 2.40\ km}$$

Table 3.8: Single-Ended Fault Location Results for 0.1 Ohm Three Phase to Ground (ABCG) Fault on Single Circuit at Various Sampling Rates

		'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Sampling Rate (MHz)	Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
1	0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.41	0.01	2.41	0.01	2.41	0.01	2.41	0.01
2	0.60	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.40	0.00	2.40	0.00	2.40	0.00	2.40	0.00
3	0.60	0.63	0.03	0.63	0.03	0.63	0.03	0.63	0.03
	1.50	1.52	0.02	1.52	0.02	1.52	0.02	1.52	0.02
	2.40	2.41	0.01	2.41	0.01	2.41	0.01	2.41	0.01
4	0.60	0.60	0.00	0.60	0.00	0.60	0.00	0.60	0.00
	1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
	2.40	2.38	0.02	2.38	0.02	2.38	0.02	2.38	0.02
5	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.38	0.02	2.38	0.02	2.38	0.02	2.38	0.02
10	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.40	0.00	2.40	0.00	2.40	0.00	2.40	0.00

Table 3.8 compares the fault location results of the four signals using the single-ended method for 0.1 Ohm ABCG fault on a single circuit sampled at 1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz and 10 MHz. All sampling rates perform well.

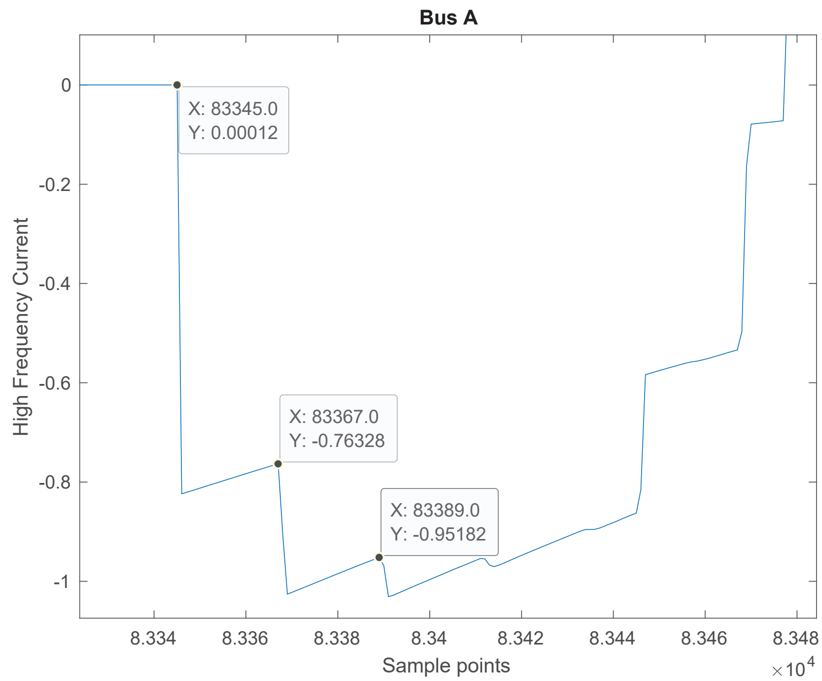

Figure 19: Time indexes for Yhigh_I with 0.1Ω ABCG Fault at 0.60 km from Bus A on Single Circuit (5 MHz)

Example 15: Focusing on Yhigh_I at 0.60 km at 5 Mhz.

The index for the initial traveling for the fault to Bus A is 83345 and the reflection wave from the fault location is 83367. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{5000000}\right)(83367 - 83345)}$$

$$\boldsymbol{X = 0.59\ km}$$

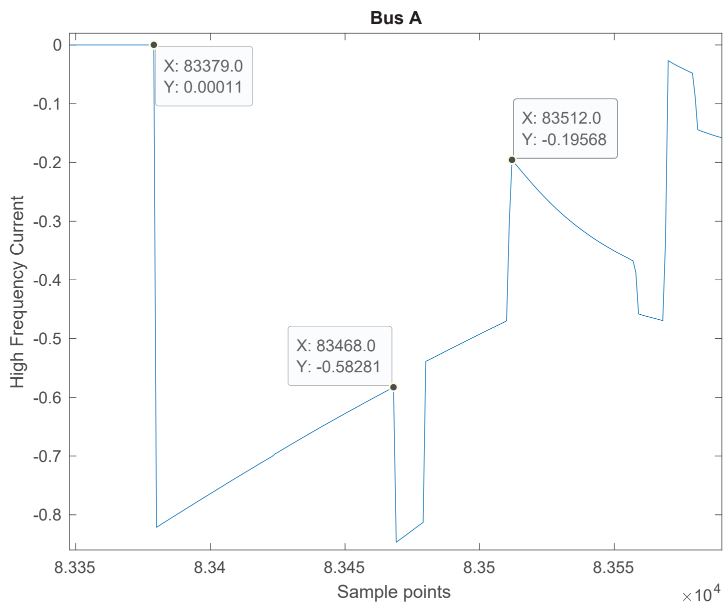

Figure 20: Time indexes for Yhigh_I with 0.1Ω ABCG Fault at 2.40 km from Bus A on Single Circuit (5 MHz)

Example 16: Focusing on Yhigh_I at 2.40 km at 5 MHz.

The index for the initial traveling for the fault to Bus A is 83379 and the reflection wave from the fault location is 83468. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{5000000}\right)(83468 - 83379)}$$

$$\boldsymbol{X = 0.62\ km}$$

The first sight seems tell us that the fault location is wrong. After careful examination of the wave polarity, we find out the reason. The wave from the remote end is negligible due to small resistance, so based on the polarity of the wave, we should use the following equation to calculate the fault location:

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{5000000}\right)(83468 - 83379)}$$

$$\boldsymbol{X = 2.38\ \mathrm{km}}$$

3.2.3 Comparison of Fault and Ground Resistance

In this section, the single ended method fault location error results of the four signals (‘sig_V’, ‘Yhigh_V’, ‘sig_I’ and ‘Yhigh_I’) are compared using different fault resistance (Ron) and ground resistance (Rg) relative to the fault type being analyzed. All testing was performed on the single circuit presented earlier in the chapter, with a sampling frequency of 1 MHz.

Table 3.9: Single-Ended Fault Location Results for Rg = 10 Ohm Single Phase to Ground (AG) Fault on Single Circuit (1MHz)

	‘sig_V’		‘Yhigh_V’		‘sig_I’		‘Yhigh_I’	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03
0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
0.90	0.80	0.10	0.80	0.10	0.80	0.10	0.80	0.10
1.20	1.21	0.01	1.21	0.01	1.21	0.01	1.21	0.01
1.50	1.74	0.24	1.74	0.24	1.74	0.24	1.74	0.24
1.80	1.66	0.14	1.66	0.14	1.66	0.14	1.66	0.14
2.10	1.93	0.17	1.93	0.17	1.93	0.17	1.93	0.17
2.40	2.20	0.20	2.20	0.20	2.20	0.20	2.20	0.20
2.70	2.60	0.10	2.60	0.10	2.60	0.10	2.60	0.10
Average		0.12		0.12		0.12		0.12

Table 3.9 compares the fault location results of the four signals using the single-ended method for an AB fault on a single circuit sampled at 1 MHz with a ground resistance, Rg = 10 Ohm. All signals performed well at all fault locations.

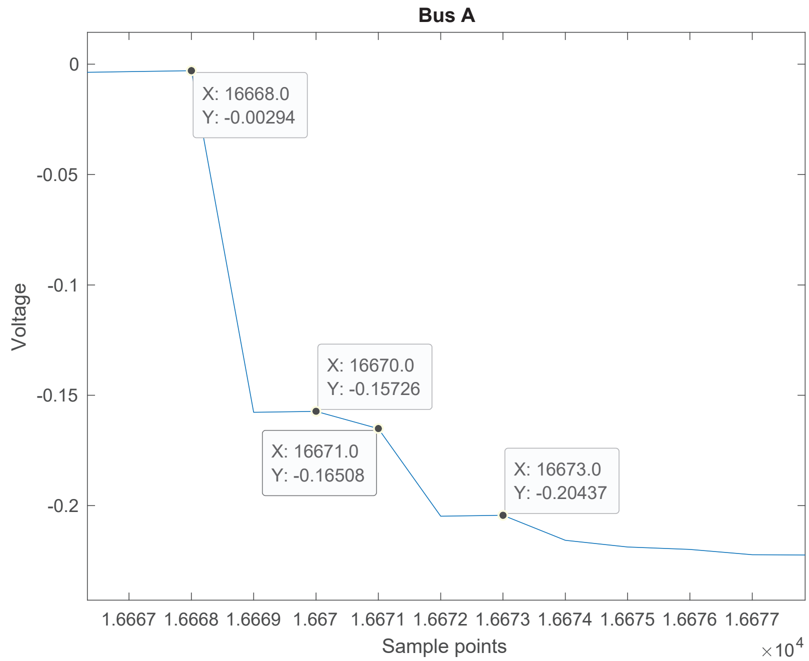

Figure 21: Time indexes for sig_V with Rg = 10 Ohm AG Fault at 0.30 km from Bus A on Single Circuit (1 MHz)

Example 17: Focusing on sig_V at 0.30 km at 1 Mhz.

The index for the initial traveling for the fault to Bus A is 16668 and the reflection wave from the fault location is 16670. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16670 - 16668)}$$

$$\boldsymbol{X = 0.27\ km}$$

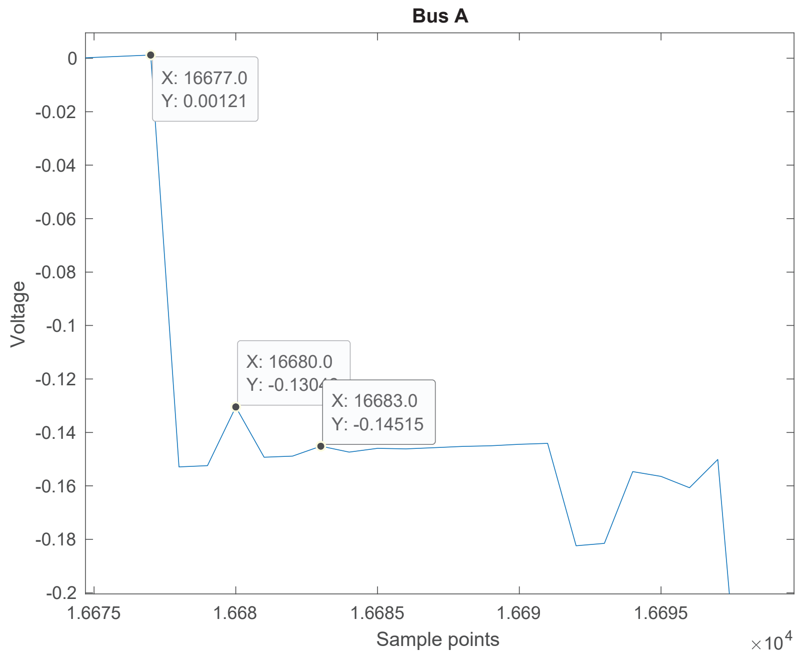

Figure 22: Time indexes for sig_V with Rg = 10 Ohm AG Fault at 2.70 km from Bus A on Single Circuit (1 MHz)

Example 18: Focusing on sig_V at 2.70 km at 1 Mhz.

The index for the initial traveling for the fault to Bus A is 16677 and the reflection wave from the fault location is 16680. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16680 - 16677)}$$

$$\boldsymbol{X = 2.60\ km}$$

Table 3.10: Single-Ended Fault Location Results for Ron = 5 Ohm Double phase Ungrounded (AB) Fault on Single Circuit (1MHz)

	'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.40	0.10	0.40	0.10	0.40	0.10	0.40	0.10
0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
0.90	0.80	0.10	0.80	0.10	0.80	0.10	0.80	0.10
1.20	1.21	0.01	1.21	0.01	1.21	0.01	1.21	0.01
1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
1.80	1.74	0.06	1.74	0.06	1.74	0.06	1.74	0.06
2.10	2.14	0.04	2.14	0.04	2.14	0.04	2.14	0.04
2.40	2.41	0.01	2.20	0.20	2.20	0.20	2.41	0.01
2.70	2.68	0.02	2.68	0.02	2.46	0.24	2.68	0.02
Average		0.05		0.07		0.09		0.05

Table 3.10 compares the fault location results of the four signals using the single-ended method for an AB fault on a single circuit sampled at 1 MHz with a fault resistance, Ron = 5 Ohm. All signals performed well at the different fault points.

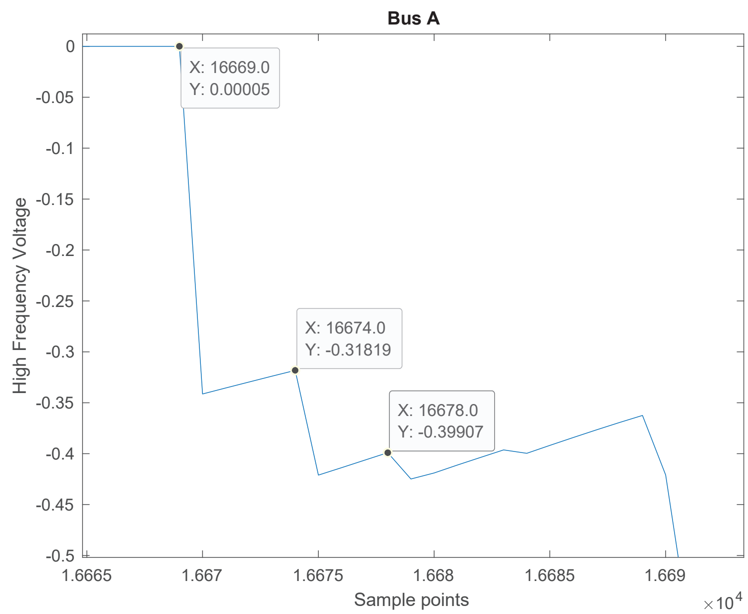

Figure 23: Time indexes for Yhigh_V with Ron = 5 Ohm AB Fault at 0.60 km from Bus A on Single Circuit (1 MHz)

Example 19: Focusing on Yhigh_V at 0.60 km at 1 Mhz.

The index for the initial traveling for the fault to Bus A is 16669 and the reflection wave from the fault location is 16674. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16674 - 16669)}$$

$$\boldsymbol{X = 0.67\ km}$$

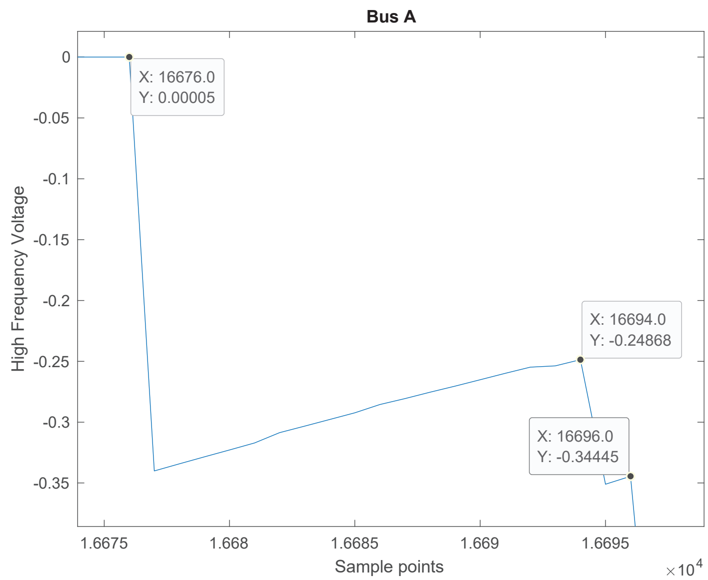

Figure 24: Time indexes for Yhigh_V with Ron = 5 Ohm AB Fault at 2.40 km from Bus A on Single Circuit (1 MHz)

Example 20: Focusing on Yhigh_V at 2.40 km at 1 Mhz.

The index for the initial traveling for the fault to Bus A is 16676 and the index for the wave from the remote end is 16682. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16682 - 16676)}$$

$$\boldsymbol{X = 2.20\ km}$$

Table 3.11: Single-Ended Fault Location Results for Rg = 10 Ohm and Ron = 5 Ohm Double line to Ground (ABG) Fault on Single Circuit (1MHz)

	'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03
0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
0.90	0.80	0.10	0.80	0.10	0.80	0.10	0.80	0.10
1.20	1.21	0.01	1.21	0.01	1.21	0.01	1.21	0.01
1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
1.80	1.79	0.01	1.79	0.01	1.79	0.01	1.79	0.01
2.10	2.06	0.04	2.06	0.04	2.06	0.04	2.06	0.04
2.40	1.66	0.74	2.41	0.01	1.66	0.74	2.41	0.01
2.70	2.73	0.03	2.73	0.03	2.73	0.03	2.73	0.03
Average		0.12		0.04		0.12		0.04

Table 3.11 compares the fault location results of the four signals using the single-ended method for an ABG fault on a single circuit sampled at 1 MHz with a ground resistance, Rg = 10 Ohm and fault resistance, Ron = 5 Ohm. All signals performed well at all fault locations.

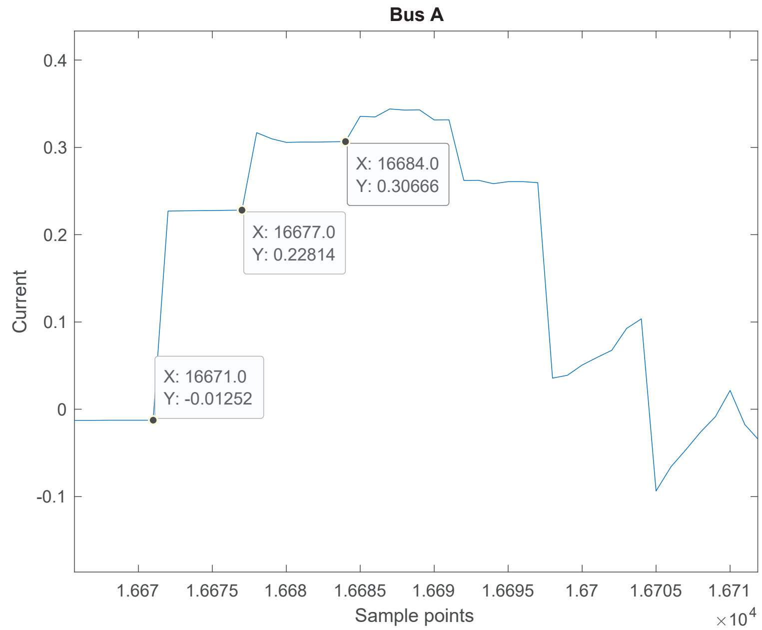

Figure 25: Time indexes for sig_I with Rg = 10 Ohm and Ron = 5 Ohm ABG Fault at 0.90 km from Bus A on Single Circuit (1 MHz)

Example 21: Focusing on sig_I at 0.90 km at 1 Mhz.

The index for the initial traveling for the fault to Bus A is 16671 and the reflection wave from the fault location is 16677. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16677 - 16671)}$$

$$\boldsymbol{X = 0.80\ km}$$

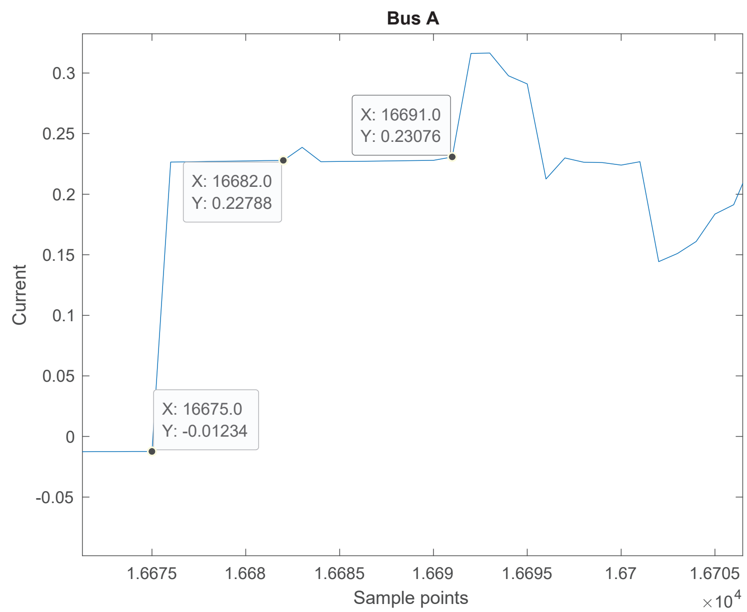

Figure 26: Time indexes for sig_I with Rg = 10 Ohm and Ron = 5 Ohm ABG Fault at 2.10 km from Bus A on Single Circuit (1 MHz)

Example 22: Focusing on sig_I at 2.10 km at 1 Mhz.

The index for the initial traveling for the fault to Bus A is 16675 and the reflection wave from the fault location is 16682. Plugging these values into the fault location equation gives us:

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

$$X = 3 - \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16682 - 16675)$$

$$X = \ 2.06\ km$$

Table 3.12: Single-Ended Fault Location Results for Rg = 10 Ohm and Ron = 5 Ohm
Three phase to Ground (ABCG) Fault on Single Circuit (1MHz)

	'sig_V'		'Yhigh_V'		'sig_I'		'Yhigh_I'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.27	0.03	0.27	0.03	0.27	0.03	0.27	0.03
0.60	0.67	0.07	0.67	0.07	0.67	0.07	0.67	0.07
0.90	0.80	0.10	0.80	0.10	0.80	0.10	0.80	0.10
1.20	1.21	0.01	1.21	0.01	1.21	0.01	1.21	0.01
1.50	1.47	0.03	1.47	0.03	1.47	0.03	1.47	0.03
1.80	2.20	0.40	1.74	0.06	1.74	0.06	1.74	0.06
2.10	1.66	0.44	2.14	0.04	2.14	0.04	2.14	0.04
2.40	2.20	0.20	2.41	0.01	2.14	0.26	2.41	0.01
2.70	2.20	0.50	2.68	0.02	1.88	0.82	2.68	0.02
Average		0.20		0.04		0.16		0.04

Table 3.12 compares the fault location results of the four signals using the single-ended method for an ABCG fault on a single circuit sampled at 1 MHz with a ground resistance, Rg = 10 Ohm and fault resistance, Ron = 5 Ohm.

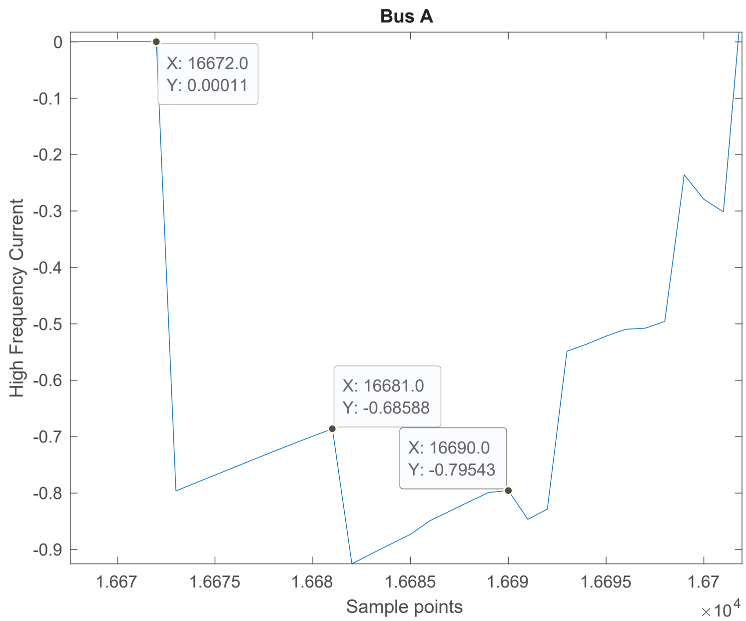

Figure 27: Time indexes for Yhigh_I with Rg = 10 Ohm and Ron = 5 Ohm ABCG Fault at 1.20 km from Bus A on Single Circuit (1 MHz)

Example 23: Focusing on Yhigh_I at 1.20 km at 1 Mhz.

The index for the initial traveling for the fault to Bus A is 16672 and the reflection wave from the fault location is 16681. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16681 - 16672)}$$

$$\boldsymbol{X = 1.21\ km}$$

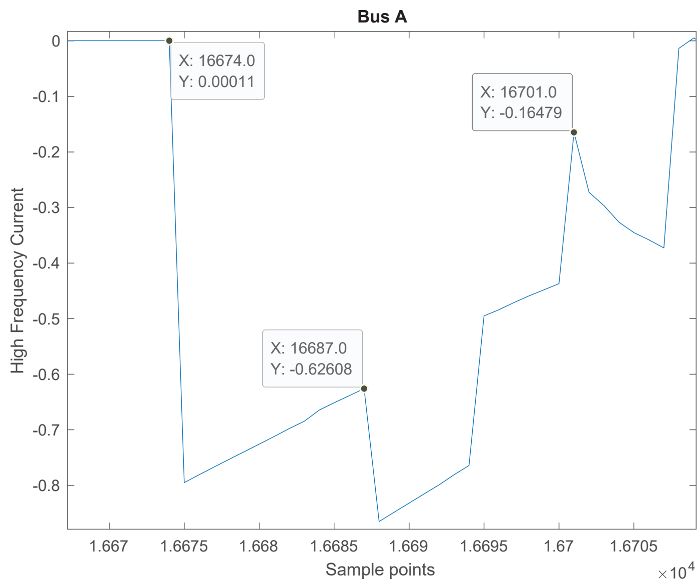

Figure 28: Time indexes for Yhigh_I with Rg = 10 Ohm and Ron = 5 Ohm ABCG Fault at 1.80 km from Bus A on Single Circuit (1 MHz)

Example 24: Focusing on Yhigh_I at 1.80 km at 1 Mhz.

The index for the initial traveling for the fault to Bus A is 16674 and the reflection wave from the fault location is 16687. Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3 - \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16687 - 16674)}$$

$$\boldsymbol{X = 1.26\ km}$$

The first sight seems tell us that the fault location is wrong. After careful examination of the wave polarity, we find out the reason. The wave from the remote end is negligible due to small resistance, so based on the polarity of the wave, we should use the following equation to calculate the fault location:

$$\boldsymbol{X = \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16687 - 16674)}$$

$$\boldsymbol{X = 1.74\ km}$$

3.3 Double Ended Method Results

3.3.1 Comparison of Bus Pairs

In this section, the double ended method fault location error results of the four bus pairs ('Bus 2 & Bus 4', 'Bus 3 & Bus 4', 'Bus 3 & Bus 5' and 'Bus 2 & Bus 5') are compared for different types of faults at 0.3km increments using the 'sig_V' signal. All testing was performed on the single circuit presented earlier in the chapter, with a sampling frequency of 1 MHz.

Table 3.13: Double-Ended Fault Location Results for 0.1 Ohm Single Phase to Ground (AG) Fault on Single Circuit (1MHz)

	'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.30	0.00	0.29	0.01	0.24	0.06	0.24	0.06
0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
0.90	0.83	0.07	0.96	0.06	0.91	0.01	0.78	0.12
1.20	1.24	0.04	1.23	0.03	1.31	0.11	1.32	0.12
1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
1.80	1.77	0.03	1.77	0.03	1.85	0.05	1.85	0.05
2.10	2.04	0.06	2.04	0.06	2.12	0.02	2.12	0.02
2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2.70	2.71	0.01	2.71	0.01	2.65	0.05	2.66	0.04
Average		0.03		0.03		0.05		0.07

Table 3.13 compares the fault location error results of the four bus pairs using the double ended method for a 0.1 Ohm AG fault sampled at 1MHz. We can see that the double ended method performs better on average than the single ended method.

The fault location equation for the double ended method is given by

$$X = L + \frac{1}{2} v \tau (t_a - t_b) \tag{2.0}$$

Where L is the total line length between busses, v is the wave velocity, τ is the inverse of the sampling rate, t_a is the timing of the initial wave at Bus A, and t_b is the timing of the initial wave at Bus B.

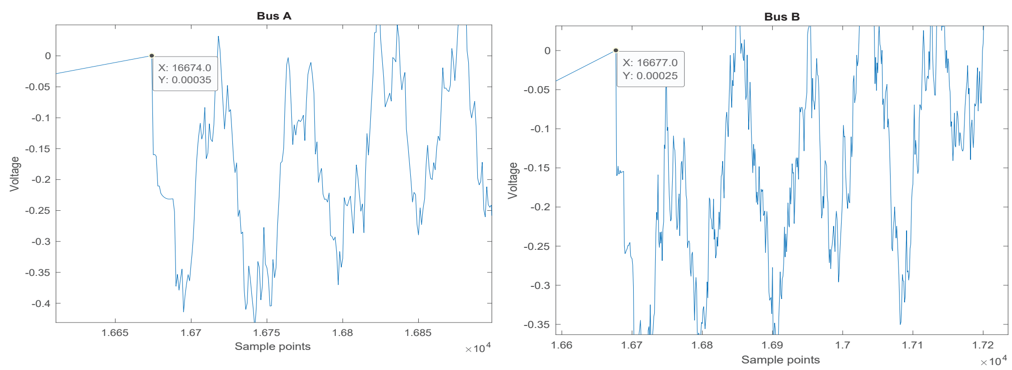

Figure 29: Time indexes for Bus 2 and Bus 4 pair with 0.1Ω AG Fault at 0.30 km from Bus 3 on Single Circuit (1 MHz)

Example 25: Focusing on Bus 2 and Bus 4 pair at 0.30 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 16674 (t_a) and the initial traveling wave for the fault to Bus 4 is 16677 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$X = L + \frac{1}{2} v \tau (t_a - t_b) - Line\_Bus2\_3$$

$$X = 4.6 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16674 - 16677) - 1.6$$

$$X = 0.30\ km$$

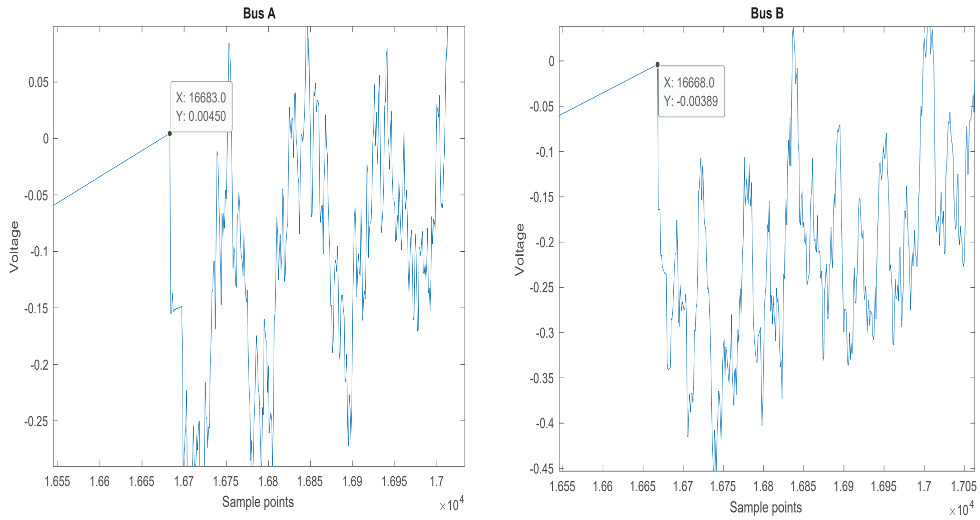

Figure 30: Time indexes for Bus 2 and Bus 4 pair with 0.1Ω AG Fault at 2.70 km from Bus 3 on Single Circuit (1 MHz)

Example 26: Focusing on Bus 2 and Bus 4 pair at 2.70 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 16683 (t_a) and the initial traveling wave for the fault to Bus 4 is 16668 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$X = L + \frac{1}{2} v \, \tau \, (t_a - t_b) - Line\_Bus2\_3$$

$$X = 4.6 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16683 - 16668) - 1.6$$

$$X = 2.71 \; km$$

Table 3.14: Double-Ended Fault Location Results for 0.1 Ohm Single Phase to Ground (AB) Fault on Single Circuit (1MHz)

	'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.30	0.00	0.29	0.01	0.24	0.06	0.24	0.06
0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
0.90	0.83	0.07	0.96	0.06	0.91	0.01	0.78	0.12
1.20	1.24	0.04	1.23	0.03	1.31	0.11	1.32	0.12
1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
1.80	1.77	0.03	1.77	0.03	1.85	0.05	1.85	0.05
2.10	2.04	0.06	2.04	0.06	2.12	0.02	2.12	0.02
2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2.70	2.71	0.01	2.71	0.01	2.65	0.05	2.66	0.04
Average		0.03		0.03		0.05		0.07

Table 3.14 compares the fault location error results of the four bus pairs using the double ended method for a 0.1 Ohm AB fault sampled at 1MHz. We can see that the double ended method performs better on average than the single ended method.

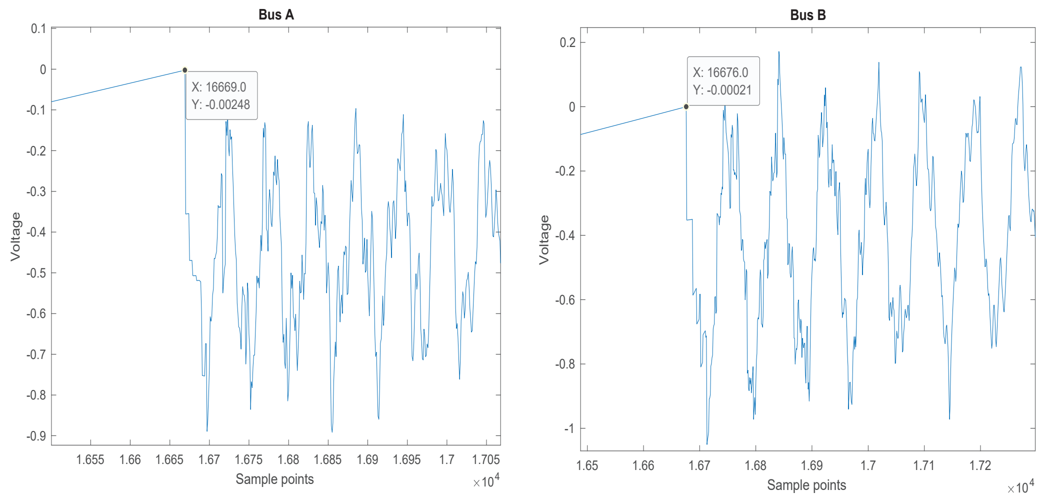

Figure 31: Time indexes for Bus 3 and Bus 4 pair with 0.1Ω AB Fault at 0.60 km from Bus 3 on Single Circuit (1 MHz)

Example 27: Focusing on Bus 3 and Bus 4 pair at 0.60 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 16669 (t_a) and the initial traveling wave for the fault to Bus 4 is 16676 (t_b). Plugging these values into the fault location equation gives us:

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

$$X = 3.0 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16669 - 16676)$$

$$X = 0.56\ km$$

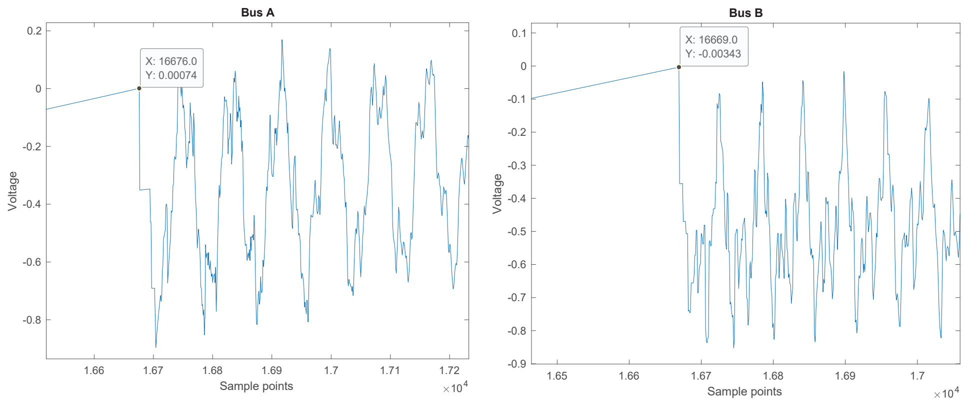

Figure 32: Time indexes for Bus 3 and Bus 4 pair with 0.1Ω AB Fault at 2.40 km from Bus 3 on Single Circuit (1 MHz)

Example 28: Focusing on Bus 3 and Bus 4 pair at 2.40 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 16676 (t_a) and the initial traveling wave for the fault to Bus 4 is 16669 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3.0 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16676 - 16669)}$$

$$\boldsymbol{X = 2.44 \; km}$$

Table 3.15: Double-Ended Fault Location Results for 0.1 Ohm Single Phase to Ground (ABG) Fault on Single Circuit (1MHz)

	'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.30	0.00	0.29	0.01	0.24	0.06	0.24	0.06
0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
0.90	0.83	0.07	0.96	0.06	0.91	0.01	0.78	0.12
1.20	1.24	0.04	1.23	0.03	1.31	0.11	1.32	0.12
1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
1.80	1.77	0.03	1.77	0.03	1.85	0.05	1.85	0.05
2.10	2.04	0.06	2.04	0.06	2.12	0.02	2.12	0.02
2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2.70	2.71	0.01	2.71	0.01	2.65	0.05	2.66	0.04
Average		0.03		0.03		0.05		0.07

Table 3.15 compares the fault location error results of the four bus pairs using the double ended method for a 0.1 Ohm ABG fault sampled at 1MHz. We can see that the double ended method performs better on average than the single ended method.

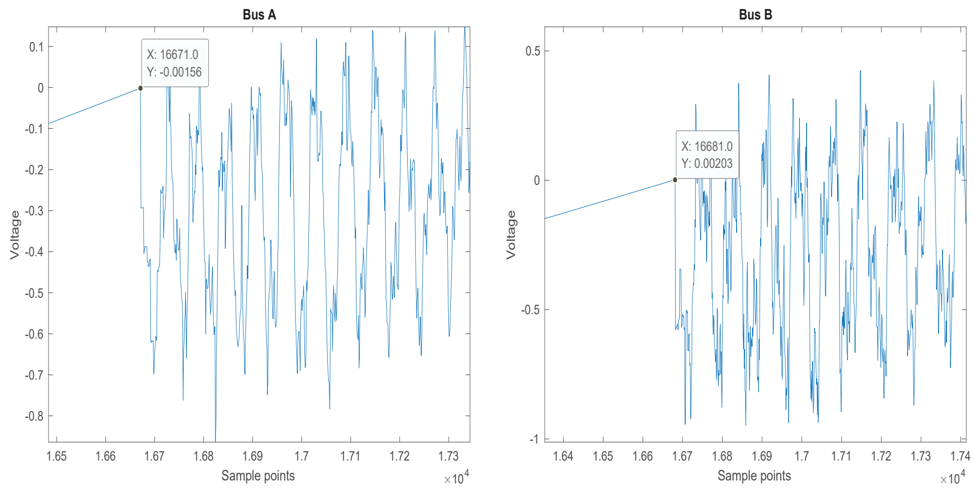

Figure 33: Time indexes for Bus 3 and Bus 5 pair with 0.1Ω ABG Fault at 0.90 km from Bus 3 on Single Circuit (1 MHz)

Example 29: Focusing on Bus 3 and Bus 5 pair at 0.90 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 16671 (t_a) and the initial traveling wave for the fault to Bus 5 is 16681 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 4.5 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16671 - 16681)}$$

$$\boldsymbol{X = 0.91\ km}$$

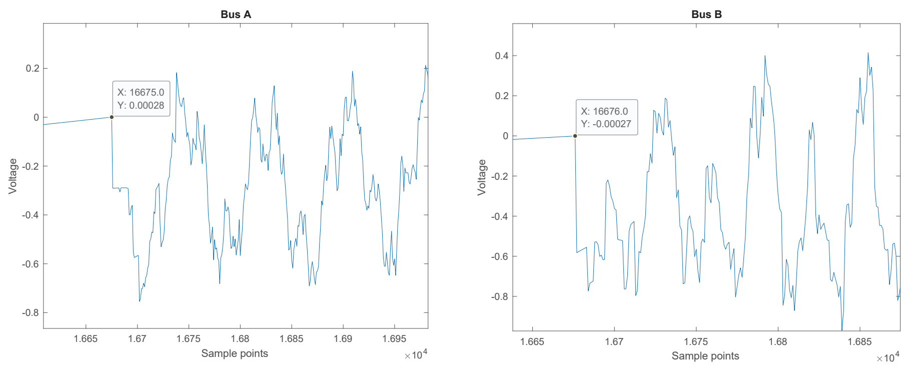

Figure 34: Time indexes for Bus 3 and Bus 5 pair with 0.1Ω ABG Fault at 2.10 km from Bus 3 on Single Circuit (1 MHz)

Example 30: Focusing on Bus 3 and Bus 5 pair at 2.10 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 16675 (t_a) and the initial traveling wave for the fault to Bus 5 is 16676 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 4.5 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16675 - 16676)}$$

$$\boldsymbol{X = 2.12 \; km}$$

Table 3.16: Double-Ended Fault Location Results for 0.1 Ohm Single Phase to Ground (ABCG) Fault on Single Circuit (1MHz)

	'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.30	0.00	0.29	0.01	0.24	0.06	0.24	0.06
0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
0.90	0.83	0.07	0.96	0.06	0.91	0.01	0.78	0.12
1.20	1.24	0.04	1.23	0.03	1.31	0.11	1.32	0.12
1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
1.80	1.77	0.03	1.77	0.03	1.85	0.05	1.85	0.05
2.10	2.04	0.06	2.04	0.06	2.12	0.02	2.12	0.02
2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2.70	2.71	0.01	2.71	0.01	2.65	0.05	2.66	0.04
Average		0.03		0.03		0.05		0.07

Table 3.16 compares the fault location error results of the four bus pairs using the double ended method for a 0.1 Ohm ABCG fault sampled at 1MHz. We can see that the double ended method performs better on average than the single ended method.

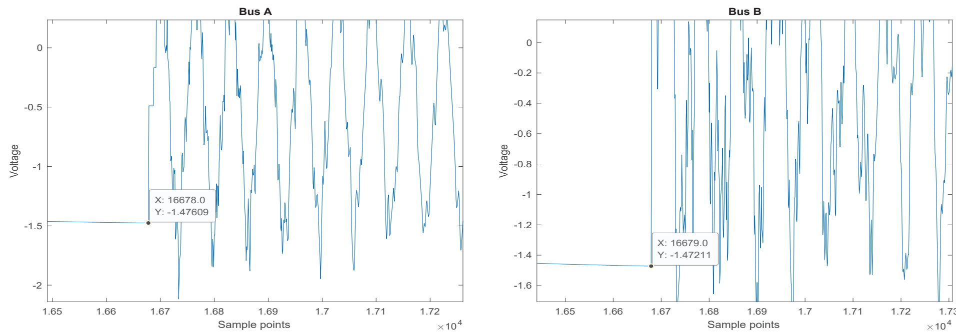

Figure 35: Time indexes for Bus 2 and Bus 5 pair with 0.1Ω ABCG Fault at 1.20 km from Bus 3 on Single Circuit (1 MHz)

Example 31: Focusing on Bus 2 and Bus 5 pair at 1.20 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 16678 (t_a) and the initial traveling wave for the fault to Bus 5 is 16679 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$X = L + \frac{1}{2} v\,\tau\,(t_a - t_b) - Line\_Bus2\_3$$

$$X = 6.1 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16678 - 16679) - 1.6$$

$$X = 1.32\ km$$

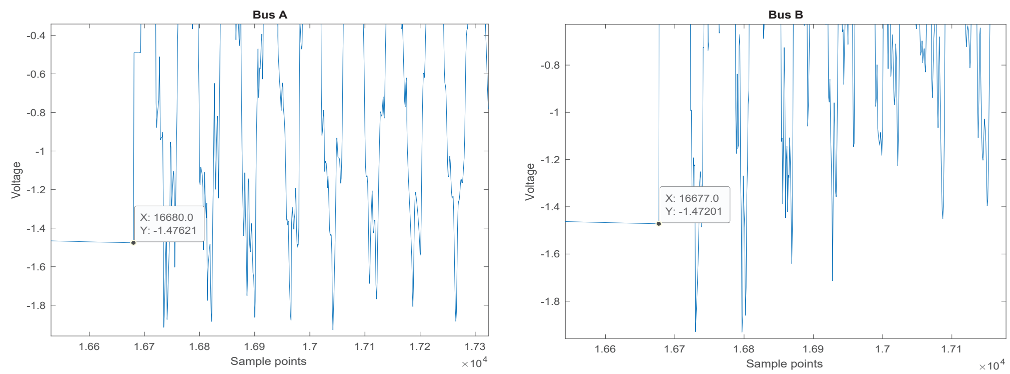

Figure 36: Time indexes for Bus 2 and Bus 5 pair with 0.1Ω ABCG Fault at 1.80 km from Bus 3 on Single Circuit (1 MHz)

Example 32: Focusing on Bus 2 and Bus 5 pair at 1.80 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 16680 (t_a) and the initial traveling wave for the fault to Bus 5 is 16677 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$\boldsymbol{X = L + \frac{1}{2} v\, \tau\, (t_a - t_b) - Line\_Bus2\_3}$$

$$\boldsymbol{X = 6.1 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16680 - 16677) - 1.6}$$

$$\boldsymbol{X = 1.85\ km}$$

3.3.2 Comparison of Sampling Rate

In this section, the double-ended fault location results of the four bus pairs (‘Bus 2 & Bus 4’, ‘Bus 3 & Bus 4’, ‘Bus 3 & Bus 5’ and ‘Bus 2 & Bus 5’) are compared across six different sampling rates (1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz and 10 MHz) using different fault types.

Table 3.17: Double-Ended Fault Location Results for 0.1 Ohm Single Phase to Ground (AG) Fault on Single Circuit at Various Sampling Rates

		'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Sampling Rate (MHz)	Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
1	0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
	1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
	2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2	0.60	0.57	0.03	0.56	0.04	0.58	0.02	0.58	0.02
	1.50	1.50	0.00	1.50	0.00	1.51	0.01	1.52	0.02
	2.40	2.44	0.04	2.44	0.04	2.45	0.05	2.45	0.05
3	0.60	0.61	0.01	0.61	0.01	0.60	0.00	0.60	0.00
	1.50	1.50	0.00	1.50	0.00	1.49	0.01	1.49	0.01
	2.40	2.40	0.00	2.40	0.00	2.38	0.02	2.39	0.01
4	0.60	0.60	0.00	0.60	0.00	0.61	0.01	0.61	0.01
	1.50	1.47	0.03	1.50	0.00	1.51	0.01	1.48	0.02
	2.40	2.41	0.01	2.40	0.00	2.38	0.02	2.39	0.01
5	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.39	0.01	2.41	0.01	2.41	0.01	2.39	0.01
10	0.60	0.59	0.01	0.60	0.00	0.60	0.00	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.39	0.01	2.40	0.00	2.41	0.01	2.40	0.00

Table 3.17 compares the fault location results of the four bus pairs using the double-ended method for 0.1 Ohm AG fault on a single circuit sampled at 1 MHz, 2 MHz, 3

MHz, 4 MHz, 5 MHz and 10 MHz. As we increase the sampling rate there is not much change as the results are very accurate.

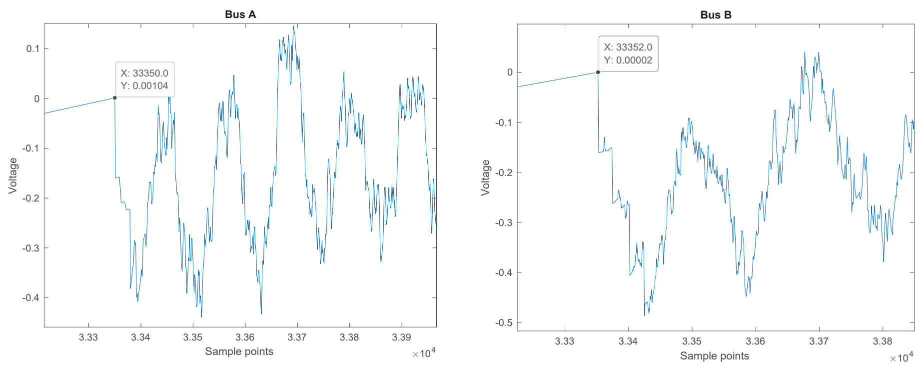

Figure 37: Time indexes for Bus 2 and Bus 4 pair with 0.1Ω AG Fault at 0.60 km from Bus 3 on Single Circuit (2 MHz)

Example 33: Focusing on Bus 2 and Bus 4 pair at 0.60 km at 2 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 33350 (t_a) and the initial traveling wave for the fault to Bus 4 is 33352 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$\boldsymbol{X = L + \frac{1}{2} v\, \tau\, (t_a - t_b) - Line\_Bus2\_3}$$

$$\boldsymbol{X = 4.6 + \frac{1}{2}(267880)\left(\frac{1}{2000000}\right)(33350 - 33352) - 1.6}$$

$$\boldsymbol{X = 0.57\ km}$$

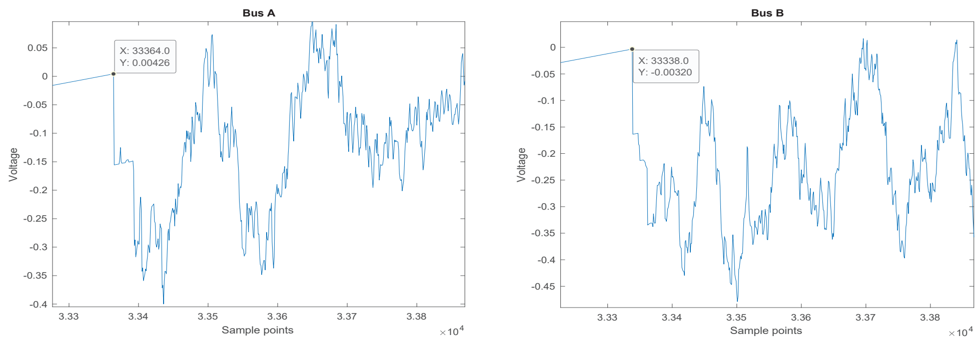

Figure 38: Time indexes for Bus 2 and Bus 4 pair with 0.1Ω AG Fault at 2.40 km from Bus 3 on Single Circuit (2 MHz)

Example 34: Focusing on Bus 2 and Bus 4 pair at 2.40 km at 2 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 33364 (t_a) and the initial traveling wave for the fault to Bus 4 is 33338 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$X = L + \frac{1}{2} v\, \tau\, (t_a - t_b) - Line\_Bus2\_3$$

$$X = 4.6 + \frac{1}{2}(267880)\left(\frac{1}{2000000}\right)(33364 - 33338) - 1.6$$

$$X = 2.44\ km$$

Table 3.18: Double-Ended Fault Location Results for 0.1 Ohm Double Line Ungrounded (AB) Fault on Single Circuit at Various Sampling Rates

		'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Sampling Rate (MHz)	Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
1	0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
	1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
	2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2	0.60	0.57	0.03	0.56	0.04	0.58	0.02	0.58	0.02
	1.50	1.50	0.00	1.50	0.00	1.51	0.01	1.52	0.02
	2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
3	0.60	0.61	0.01	0.61	0.01	0.60	0.00	0.60	0.00
	1.50	1.50	0.00	1.50	0.00	1.49	0.01	1.49	0.01
	2.40	2.40	0.00	2.40	0.00	2.38	0.02	2.39	0.01
4	0.60	0.60	0.00	0.60	0.00	0.61	0.01	0.61	0.01
	1.50	1.47	0.03	1.50	0.00	1.51	0.01	1.48	0.02
	2.40	2.41	0.01	2.40	0.00	2.38	0.02	2.39	0.01
5	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.39	0.01	2.41	0.01	2.41	0.01	2.39	0.01
10	0.60	0.59	0.01	0.60	0.00	0.60	0.00	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.39	0.01	2.40	0.00	2.41	0.01	2.40	0.00

Table 3.18 compares the fault location results of the four bus pairs using the double-ended method for 0.1 Ohm AB fault on a single circuit sampled at 1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz and 10 MHz. As we increase the sampling rate there is not much change as the results are very accurate.

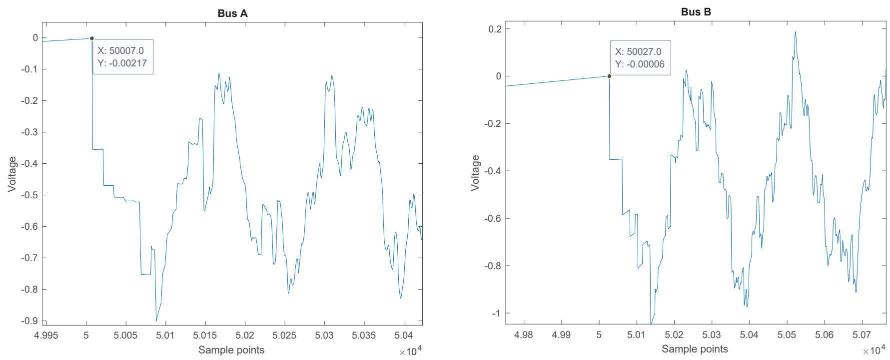

Figure 39: Time indexes for Bus 3 and Bus 4 pair with 0.1Ω AB Fault at 0.60 km from Bus 3 on Single Circuit (3 MHz)

Example 35: Focusing on Bus 3 and Bus 4 pair at 0.60 km at 3 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 50007 (t_a) and the initial traveling wave for the fault to Bus 4 is 50027 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3.0 + \frac{1}{2}(267880)\left(\frac{1}{3000000}\right)(50007 - 50027)}$$

$$\boldsymbol{X = 0.61 \; km}$$

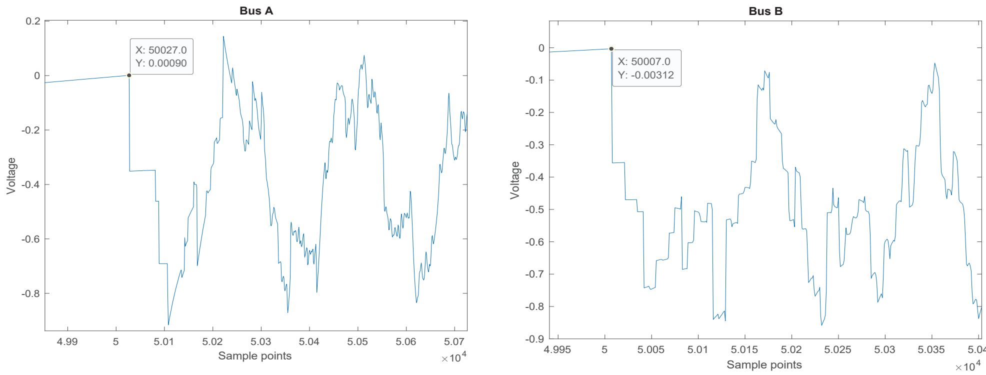

Figure 40: Time indexes for Bus 3 and Bus 4 pair with 0.1Ω AB Fault at 2.40 km from Bus 3 on Single Circuit (3 MHz)

Example 36: Focusing on Bus 3 and Bus 4 pair at 2.40 km at 3 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 50027 (t_a) and the initial traveling wave for the fault to Bus 4 is 50007 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3.0 + \frac{1}{2}(267880)\left(\frac{1}{3000000}\right)(50027 - 50007)}$$

$$\boldsymbol{X = 2.40\ km}$$

Table 3.19: Double-Ended Fault Location Results for 0.1 Ohm Double Line to Ground (ABG) Fault on Single Circuit at Various Sampling Rates

		'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Sampling Rate (MHz)	Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
1	0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
	1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
	2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2	0.60	0.57	0.03	0.56	0.04	0.58	0.02	0.58	0.02
	1.50	1.50	0.00	1.50	0.00	1.51	0.01	1.52	0.02
	2.40	2.44	0.04	2.44	0.04	2.45	0.05	2.45	0.05
3	0.60	0.61	0.01	0.61	0.01	0.60	0.00	0.60	0.00
	1.50	1.50	0.00	1.50	0.00	1.49	0.01	1.49	0.01
	2.40	2.40	0.00	2.40	0.00	2.38	0.02	2.39	0.01
4	0.60	0.60	0.00	0.60	0.00	0.61	0.01	0.61	0.01
	1.50	1.47	0.03	1.50	0.00	1.51	0.01	1.48	0.02
	2.40	2.41	0.01	2.40	0.00	2.42	0.02	2.39	0.01
5	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.39	0.01	2.41	0.01	2.41	0.01	2.39	0.01
10	0.60	0.59	0.01	0.60	0.00	0.60	0.00	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.39	0.01	2.40	0.00	2.41	0.01	2.40	0.00

Table 3.19 compares the fault location results of the four bus pairs using the double-ended method for 0.1 Ohm ABG fault on a single circuit sampled at 1 MHz, 2 MHz, 3

MHz, 4 MHz, 5 MHz and 10 MHz. As we increase the sampling rate there is not much change as the results are very accurate.

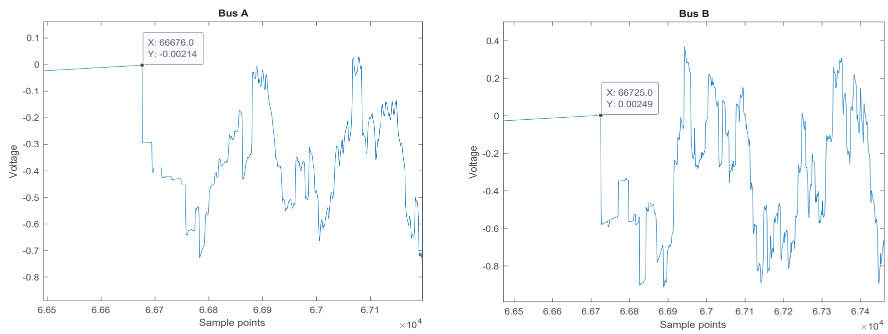

Figure 41: Time indexes for Bus 3 and Bus 5 pair with 0.1Ω ABG Fault at 0.60 km from Bus 3 on Single Circuit (4 MHz)

Example 37: Focusing on Bus 3 and Bus 5 pair at 0.60 km at 4 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 66676 (t_a) and the initial traveling wave for the fault to Bus 5 is 66725 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 4.5 + \frac{1}{2}(267880)\left(\frac{1}{4000000}\right)(66676 - 66725)}$$

$$\boldsymbol{X = 0.61\ km}$$

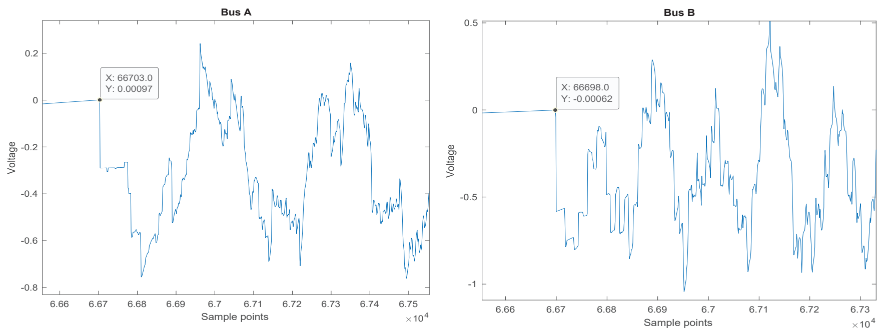

Figure 42: Time indexes for Bus 3 and Bus 5 pair with 0.1Ω ABG Fault at 2.40 km from Bus 3 on Single Circuit (4 MHz)

Example 38: Focusing on Bus 3 and Bus 5 pair at 2.40 km at 4 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 66703 (t_a) and the initial traveling wave for the fault to Bus 5 is 66698 (t_b). Plugging these values into the fault location equation gives us:

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

$$X = 4.5 + \frac{1}{2}(267880)\left(\frac{1}{4000000}\right)(66703 - 66698)$$

$$X = 2.42\ km$$

Table 3.20: Double-Ended Fault Location Results for 0.1 Ohm Three phase to Ground (ABCG) Fault on Single Circuit at Various Sampling Rates

		'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Sampling Rate (MHz)	Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
1	0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
	1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
	2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2	0.60	0.57	0.03	0.56	0.04	0.58	0.02	0.58	0.02
	1.50	1.50	0.00	1.50	0.00	1.51	0.01	1.52	0.02
	2.40	2.44	0.04	2.44	0.04	2.45	0.05	2.45	0.05
3	0.60	0.61	0.01	0.61	0.01	0.60	0.00	0.60	0.00
	1.50	1.50	0.00	1.50	0.00	1.49	0.01	1.49	0.01
	2.40	2.40	0.00	2.40	0.00	2.38	0.02	2.39	0.01
4	0.60	0.60	0.00	0.60	0.00	0.61	0.01	0.61	0.01
	1.50	1.47	0.03	1.50	0.00	1.51	0.01	1.48	0.02
	2.40	2.41	0.01	2.40	0.00	2.38	0.02	2.39	0.01
5	0.60	0.59	0.01	0.59	0.01	0.59	0.01	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.39	0.01	2.41	0.01	2.41	0.01	2.39	0.01
10	0.60	0.59	0.01	0.60	0.00	0.60	0.00	0.59	0.01
	1.50	1.50	0.00	1.50	0.00	1.50	0.00	1.50	0.00
	2.40	2.39	0.01	2.40	0.00	2.41	0.01	2.40	0.00

Table 3.20 compares the fault location results of the four bus pairs using the double-ended method for 0.1 Ohm ABCG fault on a single circuit sampled at 1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz and 10 MHz. As we increase the sampling rate there is not much change as the results are very accurate.

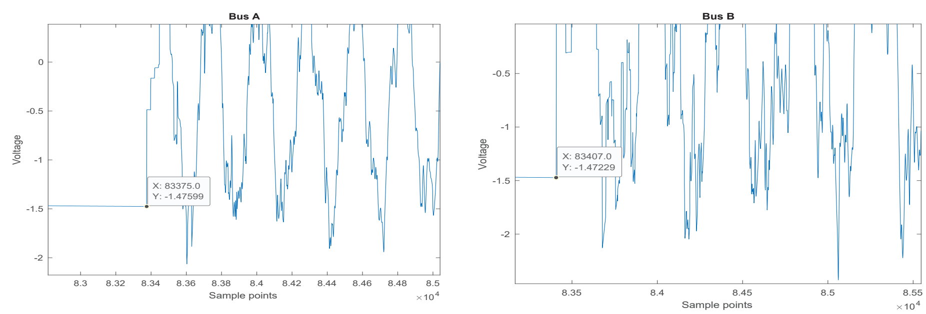

Figure 43: Time indexes for Bus 2 and Bus 5 pair with 0.1Ω ABCG Fault at 0.60 km from Bus 3 on Single Circuit (5 MHz)

Example 39: Focusing on Bus 2 and Bus 5 pair at 0.60 km at 5 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 83375 (t_a) and the initial traveling wave for the fault to Bus 5 is 83407 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$\boldsymbol{X = L + \frac{1}{2} v\, \tau\, (t_a - t_b) - Line\_Bus2\_3}$$

$$\boldsymbol{X = 6.1 + \frac{1}{2}(267880)\left(\frac{1}{5000000}\right)(83375 - 83407) - 1.6}$$

$$\boldsymbol{X = 0.59\ km}$$

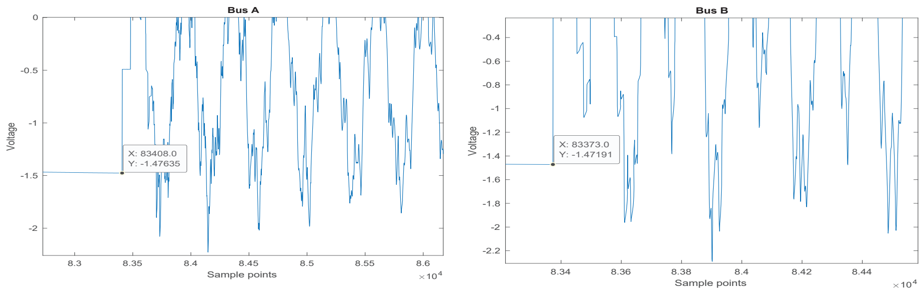

Figure 44: Time indexes for Bus 2 and Bus 5 pair with 0.1Ω ABCG Fault at 2.40 km from Bus 3 on Single Circuit (5 MHz)

Example 40: Focusing on Bus 2 and Bus 5 pair at 2.40 km at 5 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 83408 (t_a) and the initial traveling wave for the fault to Bus 5 is 83373 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$\boldsymbol{X = L + \frac{1}{2} v\, \tau\, (t_a - t_b) - Line\_Bus2\_3}$$

$$\boldsymbol{X = 6.1 + \frac{1}{2}(267880)\left(\frac{1}{5000000}\right)(83408 - 83373) - 1.6}$$

$$\boldsymbol{X = 2.39\ km}$$

3.3.3 Comparison of Fault and Ground Resistance

In this section, the double ended method fault location error results of the four bus pairs (‘Bus 2 & Bus 4’, ‘Bus 3 & Bus 4’, ‘Bus 3 & Bus 5’ and ‘Bus 2 & Bus 5’) are compared using different fault resistance (Ron) and ground resistance (Rg) relative to the fault type being analyzed. All testing was performed on the single circuit presented earlier in the chapter, with a sampling frequency of 1 MHz.

Table 3.21: Double-Ended Fault Location Results for Rg = 10 Ohm Single Phase to Ground (AG) Fault on Single Circuit (1MHz)

	‘Bus 2 & Bus 4’		‘Bus 3 & Bus 4’		‘Bus 3 & Bus 5’		‘Bus 2 & Bus 5’	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.30	0.00	0.29	0.01	0.24	0.06	0.24	0.06
0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
0.90	0.83	0.07	0.96	0.06	0.91	0.01	0.78	0.12
1.20	1.24	0.04	1.23	0.03	1.31	0.11	1.32	0.12
1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
1.80	1.77	0.03	1.78	0.02	1.85	0.05	1.85	0.05
2.10	2.04	0.06	2.04	0.06	2.12	0.02	2.12	0.02
2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2.70	2.71	0.01	2.71	0.01	2.65	0.05	2.66	0.04
Average		0.03		0.03		0.05		0.07

Table 3.21 compares the fault location results of the four bus pairs using the double-ended method for an AB fault on a single circuit sampled at 1 MHz with a ground resistance, Rg = 10 Ohm. All bus pairs performed well at all fault locations.

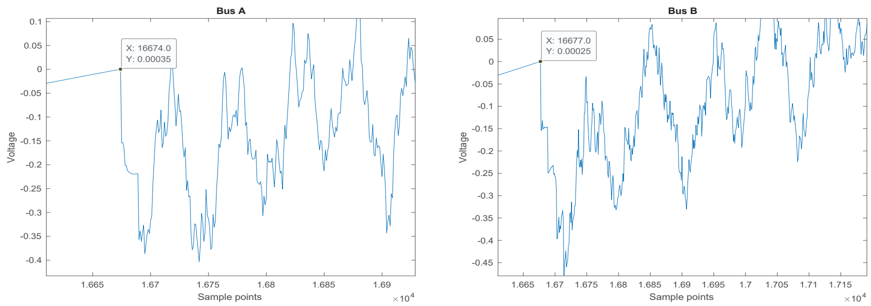

Figure 45: Time indexes for Bus 2 and Bus 4 pair with Rg = 10 Ω AG Fault at 0.30 km from Bus 3 on Single Circuit (1 MHz)

Example 41: Focusing on Bus 2 and Bus 4 pair at 0.30 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 16674 (t_a) and the initial traveling wave for the fault to Bus 4 is 16677 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$\boldsymbol{X = L + \frac{1}{2} v \, \tau \, (t_a - t_b) - Line\_Bus2\_3}$$

$$\boldsymbol{X = 4.6 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16674 - 16677) - 1.6}$$

$$\boldsymbol{X = 0.30\ km}$$

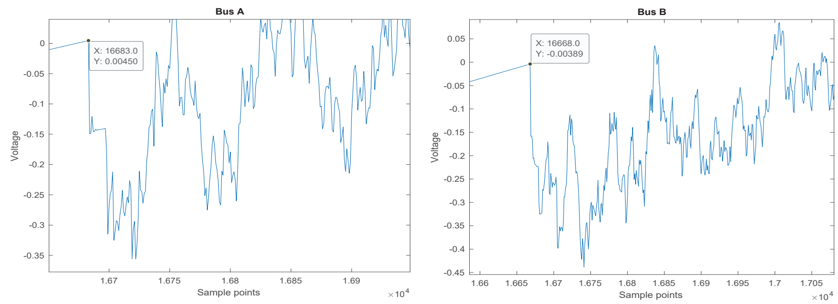

Figure 46: Time indexes for Bus 2 and Bus 4 pair with Rg = 10 Ω AG Fault at 2.70 km from Bus 3 on Single Circuit (1 MHz)

Example 42: Focusing on Bus 2 and Bus 4 pair at 2.70 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 16683 (t_a) and the initial traveling wave for the fault to Bus 4 is 16668 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$\boldsymbol{X = L + \frac{1}{2} v\, \tau\, (t_a - t_b) - Line\_Bus2\_3}$$

$$\boldsymbol{X = 4.6 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16683 - 16668) - 1.6}$$

$$\boldsymbol{X = 2.71\ km}$$

Table 3.22: Double-Ended Fault Location Results for Ron = 5 Ohm Double Line Ungrounded (AB) Fault on Single Circuit (1MHz)

	'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.30	0.00	0.29	0.01	0.24	0.06	0.24	0.06
0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
0.90	0.83	0.07	0.96	0.06	0.91	0.01	0.78	0.12
1.20	1.24	0.04	1.23	0.03	1.31	0.11	1.32	0.12
1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
1.80	1.77	0.03	1.78	0.02	1.85	0.05	1.85	0.05
2.10	2.04	0.06	2.04	0.06	2.12	0.02	2.12	0.02
2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2.70	2.71	0.01	2.71	0.01	2.65	0.05	2.66	0.04
Average		0.03		0.03		0.05		0.07

Table 3.22 compares the fault location results of the four bus pairs using the double-ended method for an AG fault on a single circuit sampled at 1 MHz with a fault resistance, Ron = 5 Ohm. All bus pairs performed well at all fault locations.

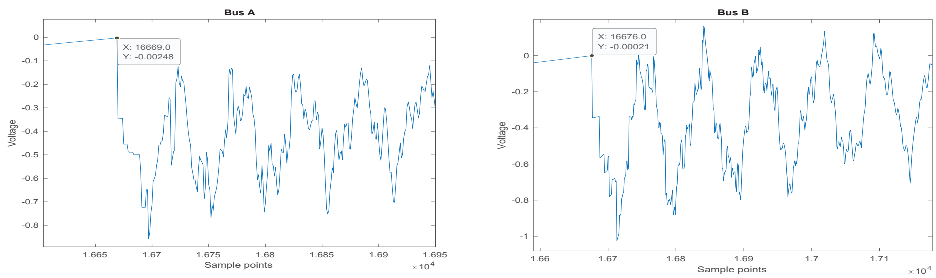

Figure 47: Time indexes for Bus 3 and Bus 4 pair with Ron = 5 Ω AB Fault at 0.60 km from Bus 3 on Single Circuit (1 MHz)

Example 43: Focusing on Bus 3 and Bus 4 pair at 0.60 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 16669 (t_a) and the initial traveling wave for the fault to Bus 4 is 16676 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3.0 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16669 - 16676)}$$

$$\boldsymbol{X = 0.56\ km}$$

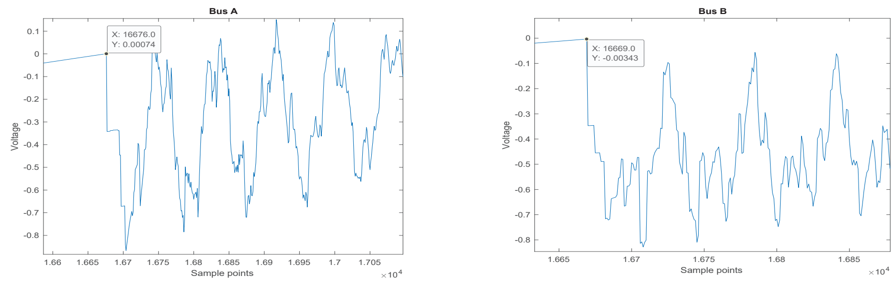

Figure 48: Time indexes for Bus 3 and Bus 4 pair with Ron = 5 Ω AB Fault at 2.40 km from Bus 3 on Single Circuit (1 MHz)

Example 44: Focusing on Bus 3 and Bus 4 pair at 2.40 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 16676 (t_a) and the initial traveling wave for the fault to Bus 4 is 16669 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 3.0 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16676 - 16669)}$$

$$\boldsymbol{X = 2.44\ km}$$

Table 3.23: Double-Ended Fault Location Results for Rg = 10 Ohm and Ron = 5 Ohm
Double Line to Ground (ABG) Fault on Single Circuit (1MHz)

	'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.30	0.00	0.29	0.01	0.24	0.06	0.24	0.06
0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
0.90	0.83	0.07	0.96	0.06	0.91	0.01	0.78	0.12
1.20	1.24	0.04	1.23	0.03	1.31	0.11	1.32	0.12
1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
1.80	1.77	0.03	1.78	0.02	1.85	0.05	1.85	0.05
2.10	2.04	0.06	2.04	0.06	2.12	0.02	2.12	0.02
2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2.70	2.71	0.01	2.71	0.01	2.65	0.05	2.66	0.04
Average		0.03		0.03		0.05		0.07

Table 3.23 compares the fault location results of the four bus pairs using the double-ended method for an ABG fault on a single circuit sampled at 1 MHz with a ground resistance, Rg = 10 Ohm and fault resistance, Ron = 5 Ohm. All bus pairs performed well at all fault locations.

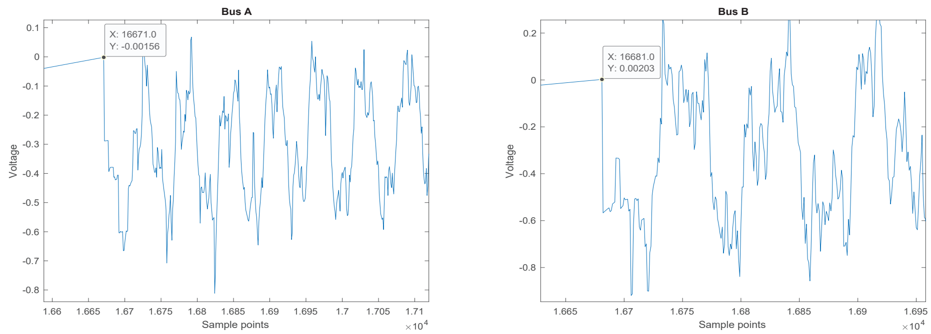

Figure 49: Time indexes for Bus 3 and Bus 5 pair with Rg = 10 Ohm and Ron = 5 Ohm ABG Fault at 0.90 km from Bus 3 on Single Circuit (1 MHz)

Example 45: Focusing on Bus 3 and Bus 5 pair at 0.90 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 16671 (t_a) and the initial traveling wave for the fault to Bus 5 is 16681 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 4.5 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16671 - 16681)}$$

$$\boldsymbol{X = 0.91\ km}$$

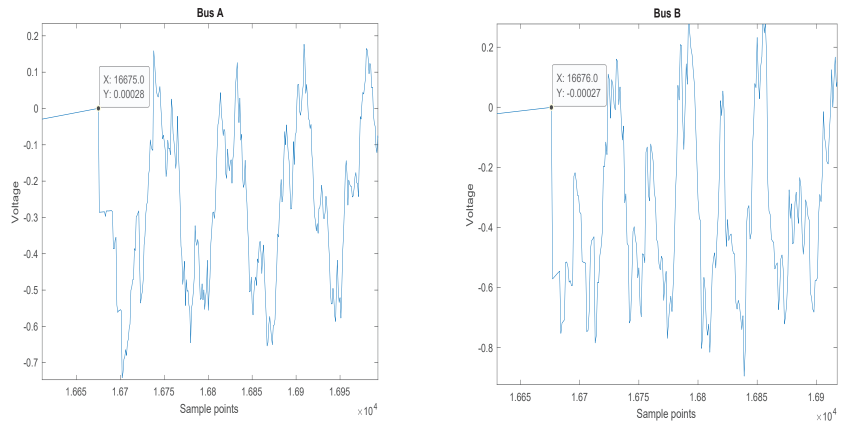

Figure 50: Time indexes for Bus 3 and Bus 5 pair with Rg = 10 Ohm and Ron = 5 Ohm ABG Fault at 2.10 km from Bus 3 on Single Circuit (1 MHz)

Example 46: Focusing on Bus 3 and Bus 5 pair at 2.10 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 3 is 16675 (t_a) and the initial traveling wave for the fault to Bus 5 is 16676 (t_b). Plugging these values into the fault location equation gives us:

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

$$\boldsymbol{X = 4.5 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16675 - 16676)}$$

$$\boldsymbol{X = 2.12\ km}$$

Table 3.24: Double-Ended Fault Location Results for Rg = 10 Ohm and Ron = 5 Ohm Three phase to Ground (ABCG) Fault on Single Circuit (1MHz)

	'Bus 2 & Bus 4'		'Bus 3 & Bus 4'		'Bus 3 & Bus 5'		'Bus 2 & Bus 5'	
Actual (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)	Estimate (km)	Error (km)
0.30	0.30	0.00	0.29	0.01	0.24	0.06	0.24	0.06
0.60	0.57	0.03	0.56	0.04	0.51	0.09	0.51	0.09
0.90	0.83	0.07	0.96	0.06	0.91	0.01	0.78	0.12
1.20	1.24	0.04	1.23	0.03	1.31	0.11	1.32	0.12
1.50	1.50	0.00	1.50	0.00	1.58	0.08	1.58	0.08
1.80	1.77	0.03	1.78	0.02	1.85	0.05	1.85	0.05
2.10	2.04	0.06	2.04	0.06	2.12	0.02	2.12	0.02
2.40	2.44	0.04	2.44	0.04	2.38	0.02	2.39	0.01
2.70	2.71	0.01	2.71	0.01	2.65	0.05	2.66	0.04
Average		0.03		0.03		0.05		0.07

Table 3.24 compares the fault location results of the four bus pairs using the double-ended method for an ABCG fault on a single circuit sampled at 1 MHz with a ground resistance, Rg = 10 Ohm and fault resistance, Ron = 5 Ohm. All bus pairs performed well at all fault locations.

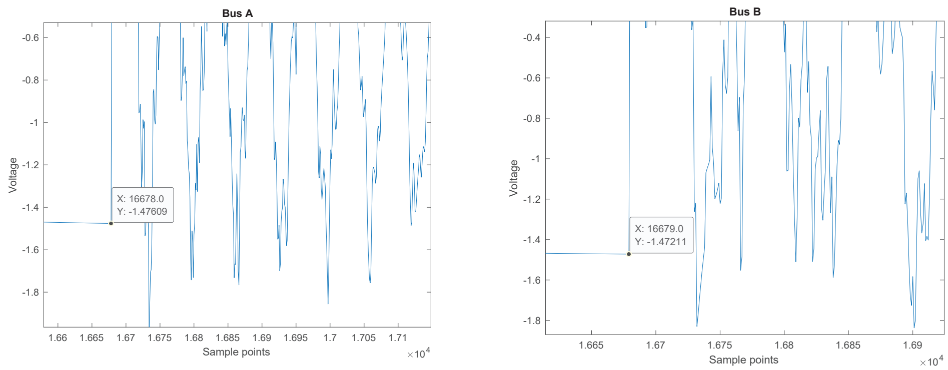

Figure 51: Time indexes for Bus 2 and Bus 5 pair with Rg = 10 Ohm and Ron = 5 Ohm ABCG Fault at 1.20 km from Bus 3 on Single Circuit (1 MHz)

Example 47: Focusing on Bus 2 and Bus 5 pair at 1.20 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 16678 (t_a) and the initial traveling wave for the fault to Bus 5 is 16679 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$\boldsymbol{X = L + \frac{1}{2} v\, \tau\, (t_a - t_b) - Line\_Bus2\_3}$$

$$\boldsymbol{X = 6.1 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16678 - 16679) - 1.6}$$

$$\boldsymbol{X = 1.32\ km}$$

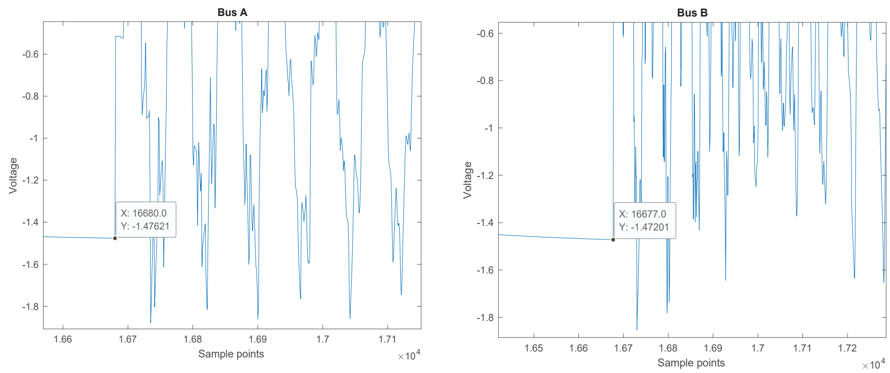

Figure 52: Time indexes for Bus 2 and Bus 5 pair with Rg = 10 Ohm and Ron = 5 Ohm ABCG Fault at 1.80 km from Bus 3 on Single Circuit (1 MHz)

Example 48: Focusing on Bus 2 and Bus 5 pair at 1.80 km at 1 MHz.

The index for the initial traveling wave for the fault to Bus 2 is 16680 (t_a) and the initial traveling wave for the fault to Bus 5 is 16677 (t_b). Since there is a line of length 1.6km connecting Bus 2 and Bus 3, we need to subtract that length from the final solution. Plugging these values into the fault location equation gives us:

$$\boldsymbol{X = L + \frac{1}{2} v\, \tau\, (t_a - t_b) - Line\_Bus2\_3}$$

$$\boldsymbol{X = 6.1 + \frac{1}{2}(267880)\left(\frac{1}{1000000}\right)(16680 - 16677) - 1.6}$$

$$\boldsymbol{X = 1.85\ km}$$

CHAPTER 4. CONCLUSION

The motivation for this project was to explore the topic of fault location in more complex distribution systems using the traveling wave fault location method. A simulation study was conducted in MATLAB SIMULINK showing results when using both the single-ended and double-ended method with faults evaluated at 0.3 km increments over a 3.0 km line.

Results from the single-ended method analysis when the signals are compared show that they all perform fairly similar, however careful analysis is needed in order to determine the timestamp of the reflected wave for the AB and ABCG faults in the second half of the line. Increasing the sampling rate and varying the fault and ground resistance also shows similar results. However, as we increase the sampling rate, we see that the error reduces and at high enough sampling rates we get results that are as accurate as the double-ended method.

In the double-ended method analysis, four different voltage bus pairs are compared. These bus pairs are compared consistently across fault types, sampling rates and fault resistance.

Results from the double-ended method analysis when the bus pairs are compared show that they all perform similarly regardless of what fault type scenario is simulated at any point in the line. Increasing the sampling rate and varying the fault resistance also shows similar results in terms of fault location. The conclusion from this is that the double-ended method gives more accurate and consistent results as it is easier to locate the incident waves at both bus terminals than locating the reflected/refracted waves in the single-ended method however the results become near identical when sampling at a high frequency.

The results and conclusions from this study are in line with the literature in regard to the traveling wave fault location method.

For future work,

- When the fault resistance is small, the single-ended method for the AB and ACBG fault types needs more careful examination of the wave polarity to identify the wavefronts to use for fault location. More research on automated identification of the wavefronts to use is desirable.
- Establishing an optimization algorithm that can detect fault type and select 'best-fit' parameters with which to calculate fault location.

APPENDIX

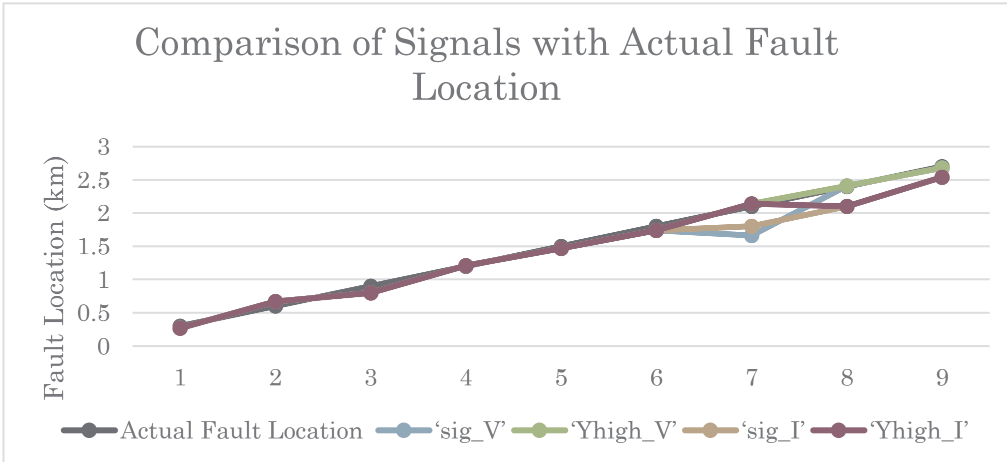

Figure A1: Comparison of signals using the single-ended method.

This figure above shows the comparison between the four different signals for the single ended method for a 0.1 Ohm AB fault on a single circuit with a sampling rate of 1 MHz and how closely each signal follows the actual location of the fault.

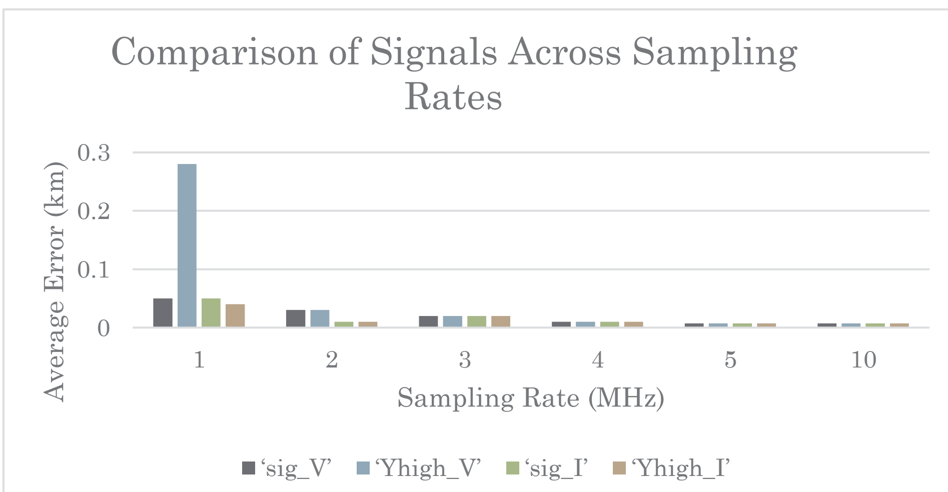

Figure A2: Comparison of signals across sampling rates using the single ended method.

This figure shows the comparison between the four different signals for the single ended method for a 0.1 Ohm ABG fault on a single circuit and how the average error between the simulated fault location and the actual fault location changes due to the sampling rate.

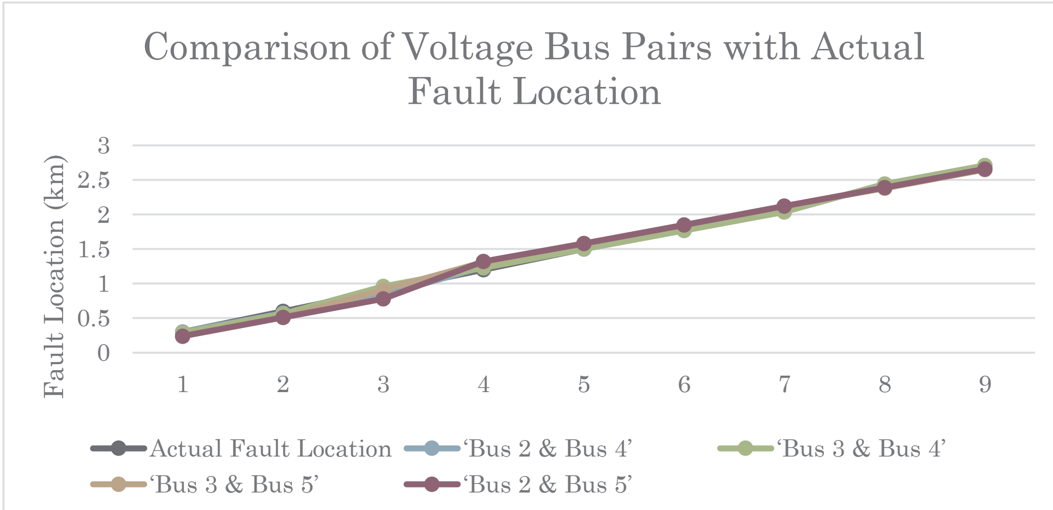

Figure A3: Comparison of voltage bus pairs using the double-ended method.

This figure shows the comparison between the four different voltage bus pair signals for the double ended method for a 0.1 Ohm AB fault on a single circuit with a sampling rate of 1 MHz and how closely each signal follows the actual location of the fault.

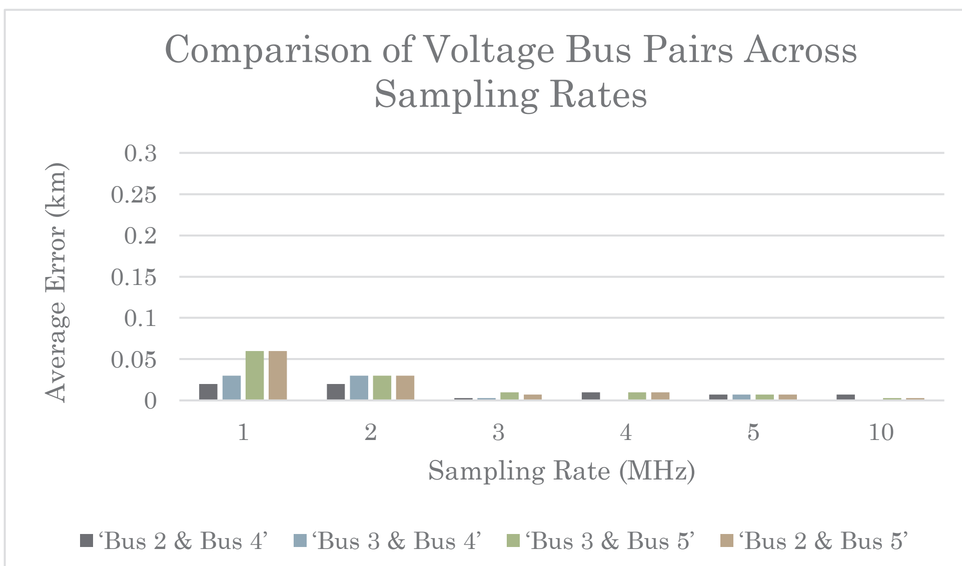

Figure A4: Comparison of voltage bus pairs across sampling rates using the double-ended method.

This figure shows the comparison between the four different voltage bus pair signals for the double ended method for a 0.1 Ohm ABG fault on a single circuit and how the average error between the simulated fault location and the actual fault location changes due to the sampling rate.

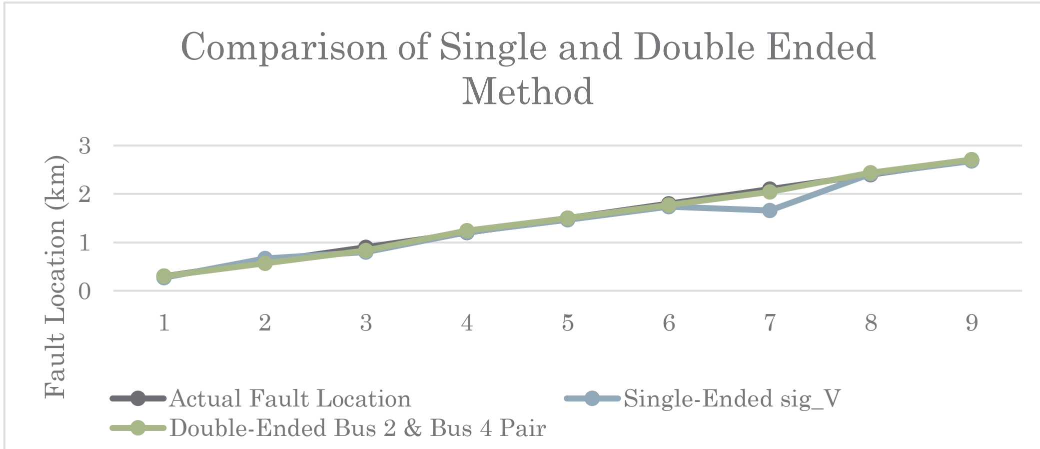

Figure A5: Comparison between the voltage signal from the single ended method and the voltage bus pair for the double ended method.

This figure shows the comparison between the voltage signal from the single ended method and the voltage bus pair for the double ended method for a 0.1 Ohm AB fault on a single circuit with a sampling rate of 1 MHz and how closely each method follows the actual location of the fault.

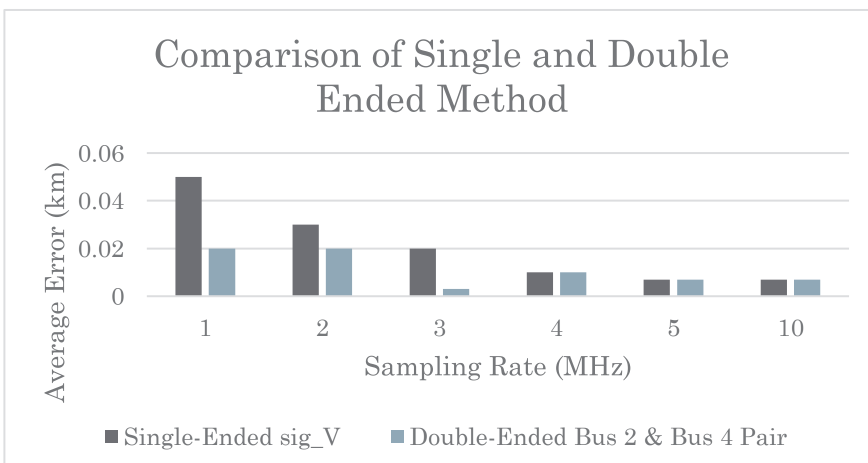

Figure A6: Comparison between the voltage signal from the single ended method and the voltage bus pair across sampling rates using the double ended method.

This figure shows the comparison between the voltage signal from the single ended method and the voltage bus pair across sampling rates using the double ended method for a 0.1 Ohm ABG fault on a single circuit and how the average error between the simulated fault location and the actual fault location changes due to the sampling rate.

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