INVESTIGATION OF IMPEDANCE-BASED FAULT LOCATION TECHNIQUES IN POWER SYSTEM NETWORK

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ABSTRACT

Power transmission network delivers the electrical power from one substation to another over long distance lines often passing through remote areas with limited accessibility. Identify the fault location accurately helps to restore the power supply in short period and reduce the economic loss due to prolonged rectification works and power outage. A number of one-ended impedance-based fault location methods have been developed to estimate the fault distance in transmission network. However it is widely reported that the accuracy of impedance-based fault location methods is influenced by a number of system parameters. As such, it is essential to understand the effect of system parameters on the accuracy of fault location methods when selecting the fault location method for transmission system. This research project presents the investigation on the effect of the 5 systems parameters on the accuracy of the 4 one-ended impedance-based fault location methods. 5 case studies represent the effect of 5 system parameters are simulated using the transmission network model developed in MATLAB SIMULINK. The simulated voltage and current waveforms are applied to the algorithms of 4 fault locations methods to compute the estimated fault distance. The estimated fault distances are evaluated using relative error based on total line length to determine the accuracy. The accuracy and performance of one-ended impedance-based fault location methods in the 5 case studies are discussed and compared in this report. The summary of results and the recommendations for one-ended impedance-based fault location methods are also provided in this report as reference for readers.

ABSTRAK

Rangkaian penghantaran kuasa menyalurkan kuasa elektrik dari satu pencawang ke yang lain dalam jarak jauh sering menempuhi kawasan terpencil yang sukar diakses. Pengenalpastian lokasi kerosakan yang tepat dapat membantu pemulihan bekalan kuasa dalam tempoh masa yang singkat dan dapat mengurangkan kerugian ekonomi yang diakibatkan oleh kerja pembetulan dan gangguan kuasa elektrik yang berpanjangan. Beberapa kaedah pengenalpastian lokasi kerosakan berasaskan impedans hujung tunggal telah diperkenalkan untuk pengangkaran jarak lokasi kerosakan dalam rangkaian penghantaran kuasa. Walau bagaimanapun, ia dilaporkan bahawa ketepatan kaedah pengenalpastian lokasi kerosakan berdasarkan impedans tersebut adalah dipengaruhi oleh beberapa parameter sistem. Oleh itu, pemahaman tentang pengaruh parameter sistem tersebut adalah penting untuk pemilihan kaedah pengenalpastian lokasi kerosakan bagi sistem penghantaran kuasa. Projek penyelidikan ini membentangkan penyiasatan mengenai pengaruh oleh 5 parameter sistem pada ketepatan 4 kaedah pengenalpastian lokasi kerosakan berdasarkan impedans hujung tunggal. 10 senario yang mewakili kesan 5 parameter sistem tersebut disimulasikan dengan menggunakan model rangkaian penghantaran kuasa yang dibangunkan dalam MATLAB SIMULINK. Algoritma 4 kaedah pengenalpastian lokasi kerosakan menggunakan gelombang voltan dan arus simulasi sebagai input untuk penggiraan anggaran jarak lokasi. Ketepatan anggaran jarak lokasi kerosakan tersebut dinilai dengan menggunakan ralat relatif berdasarkan jumlah panjang rangkaian. Ketepatan dan prestasi kaedah pengenalpastian lokasi kerosakan berdasarkan impedans hujung tunggal untuk 5 kajian kes tersebut telah dibincangkan dan dibandingkan dalam laporan ini. Ringkasan hasil dan saranan untuk kaedah pengenalpastian lokasi kerosakan berdasarkan impedans hujung tunggal juga dibentangkan dalam laporan ini sebagai rujukan.

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LIST OF SYMBOLS AND ABBREVIATIONS

β	Phase Angle of d_S (Degree)
ΔI_R	Pure Fault Current at Remote Terminal (V)
ΔI_S	Pure Fault Current at Local Terminal (V)
ΔV_R	Pure Fault Voltage at Remote Terminal (V)
ΔV_S	Pure Fault Voltage at Local Terminal (V)
A	Ampere
AC	Alternating Current
DC	Direct Current
d_S	Current distribution factor
HV	High Voltage
Hz	Hertz
IEEE	The Institution of Electrical and Electronic Engineering
I_F	Fault Current at Fault Point (A)
I_S	Line Current at Local Terminal During Fault (A)
I_{S0}	Zero Sequence Current at Local Terminal (V)
$I_{S1\ pre}$	Positive Sequence Pre-fault Current at Local Terminal (V)
I_{sup}	Superposition Current (A)
kA	kilo Ampere
kV	kilo Volt
m	Fault distance (pu)
MVA	Mega of Apparent Power
MVar	Mega of Reactive Power
MW	Mega Watts
pu	Per Unit
R_F	Fault Resistance (Ω)

$V_{F\,pre}$	Pre-fault Voltage at Fault Point (V)
V_R	Phase Voltage at Remote Terminal During Fault (V)
V_S	Phase Voltage at Local Terminal During Fault (V)
$V_{S1\,pre}$	Positive Sequence Pre-fault Voltage at Local Terminal (V)
X_{L1}	Positive Sequence Line Reactance (Ω)
Z_{L0}	Zero Sequence Line Impedance (Ω)
Z_{L1}	Positive Sequence Line Impedance (Ω)
Z_{Load}	Load Impedance (Ω)
Z_{R0}	Zero Sequence Source Impedance at Remote Terminal (Ω)
Z_{R1}	Positive Sequence Source Impedance at Remote Terminal (Ω)
Z_{S0}	Zero Sequence Source Impedance at Local Terminal (Ω)
Z_{S1}	Positive Sequence Source Impedance at Local Terminal (Ω)

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Project Background

Power transmission networks transport electrical power at extra high voltages over long distances from one substation to another as shown in Figure 1.1. Large numbers of transmission lines are passing through remote areas with limited accessibility in order to delivers the electrical power to nationwide. Transmission lines are often exposed to the unsafe conditions such as contact with flying object, animal or trees, insulation deterioration or breakdown, and illegal human access which lead to electrical fault and subsequently power interruption as protection tripping is activated. Hence, precisely locating the fault location of long transmission lines is essential to identify and clear the fault source in shortest time possible. This allows the power supply to be restored at minimum cost, time, and manpower to assure the security and stability of the power network.

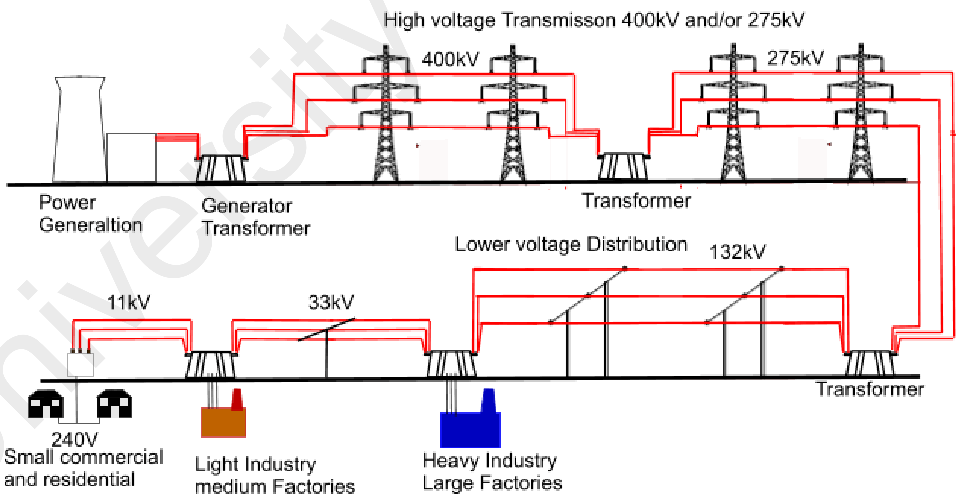


Figure 1.1: Electrical power transmission system (Fitzpatrick, 2012)

A series of impedance-based fault location algorithms have been introduced for transmission network applications in order to identify the fault location quickly and accurately. Impedance-based fault location techniques have become popular with the advent of microprocessor-based relay (Gheitasi, 2015). The waveforms of voltage and current can be captured to estimate the impedance between the measuring terminal and location of electrical fault occurrence. The various types of impedance-based fault location techniques are further discussed in Chapter 2.

The performance of impedance-based fault location algorithms is always inconsistent when they are applied to various types of transmission network configuration. The accuracy of impedance-based fault location algorithm is affected by multiple error contributors, for instance like distance to fault, fault resistance, source and load arrangement in the transmission system. Each of the fault location algorithms has its strengths and weaknesses. Users could have chosen an inefficient algorithm due insufficient understanding on the working principle of impedance-based fault location algorithms. As a result, the transmission system will fail to deliver accurate fault distance and delay the rectification work in order to restore the electrical power supply to customers. The power security and stability will no longer be secured in such cases.

<u>Key Statements:</u>

- The accuracy of impedance-based fault location algorithms is influenced by a number of system parameters.
- Insufficient understanding on working principle of impedance-based fault location algorithm results in selecting inappropriate fault location method for the network.

1.3 Objectives

This research project aims to study the performance of different impedance-based fault location methods and there are (3) objectives to be achieved in the end of this project, as follows:-

1. To review the various methods of one-ended impedance-based fault location algorithms
2. To develop the various methods of one-ended impedance-based fault location algorithms in simulation software
3. To determine the accuracy of the various methods of one-ended impedance-based fault location algorithms.

1.4 Scope and Limitations

The scope and limitations of the research project are:-

1) The scope in this project is limited to a 10km, 69kV, 60Hz transmission network.
2) Only 4 one-ended impedance-based fault location methods are considered in this research project, which are 1) simple reactance, 2) Takagi, 3) Eriksson, and 4) Novosel et al. methods.
3) Only single phase to ground fault is considered when simulating the fault in simulation model.
4) All simulations in this project are conducted using MATLAB SIMULINK R2014b.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

No transmission lines are invulnerable to electrical fault as transmission lines are exposed to multiple risks e.g. lightning strike, trees, animals, and etc. Fault is always unpredictable and unavoidable even with the best planning on the transmission system (Andrade & Leão, 2012). In fact, transmission lines made up 85-87% of power system faults (Singh, Panigrahi, & Maheshwari, 2011). Due to that, accurately estimating the fault distance is undeniably important to restore the power supply in the shortest time possible to avoid prolonged power interruption that cause losses to the customers (Roostaee, Thomas, & Mehfuz, 2017). Identifying fault distance for transmission lines is also important to safeguard electrical power system and provide timely and effective fault mitigation and rectification (Singh et al., 2011).

Technology has been improved and nowadays protection relays installed at transmission system terminals are utilized in conjunction with fault location estimating function by processing the measured signals by using various fault location methods (Gheitasi, 2015). There are 2 types of signal captured by the relays that is used for estimating fault location(Izykowski, Molag, Rosolowski, & Saha, 2006):-

1) Fundamental frequency (phasor) of voltages and currents
2) High frequency travelling waves generated by faults

There are 4 types of fault in 3 phase transmission system, which are phase to ground fault, phase to phase fault, double phase to ground fault, and three-phase fault (Anderson, 1973; Oswald & Panosyan, 2006). Single phase to ground fault is type of fault that most often happens in power system (Birajdar & Tajane, 2016).

2.2 Classification of Fault Location Methods

According to IEEE Guide ("IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines," 2015) number of fault location methods have been developed to estimate the fault location in transmission lines, which can be broadly classified into impedance-based methods, traveling wave methods, methods using synchronized phasors, and methods using time-tagging of the events .

The most common used fault location method is impedance-based fault location methods because it is simple and cheap in term of implementation (Andrade & Leão, 2012). This method is firstly used in 1923. It uses fundamental frequency or phasor of measured voltages and currents and line impedance to compute the fault distance (Zamora, Minambres, Mazon, Alvarez-Isasi, & Lazaro, 1996). Several impedance-based methods require source impedances as additional inputs for the respective algorithms (Lima, Ferraz, Filomena, & Bretas, 2013). Impedance-based methods can be divided into two categories, which are one-ended and two ended impedance-based fault location methods. One-ended impedance-based fault location methods are later elaborated more in this chapter.

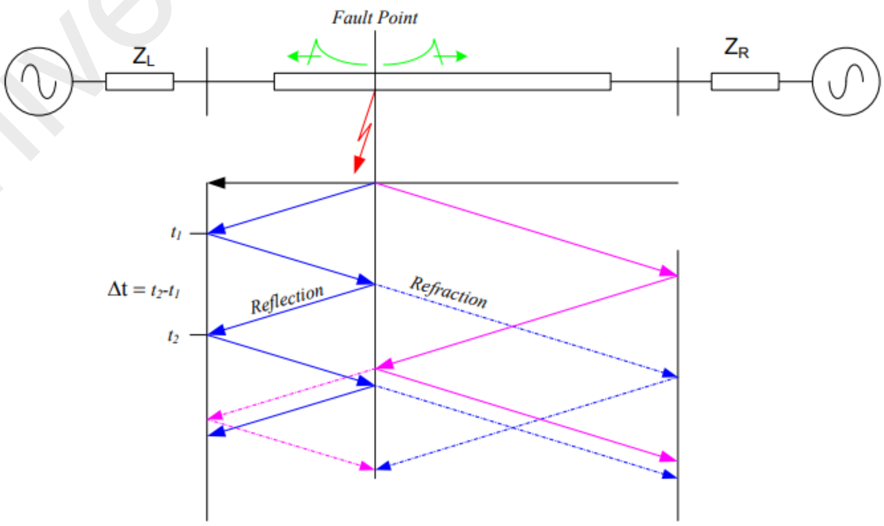


Figure 2.1: Travelling wave during fault in Lattice diagram

High frequency travelling wave is produced when fault occurs in transmission lines. The wave then travels in speed of light to both directions from the fault point to the terminals (Xun et al., 2017). The basis of travelling wave method is it detects the travelling impulse and uses that to measure the arrival time difference between first impulse waves and its reflection (Aoyu, Dong, Shi, & Bin, 2015). Figure 2.1 illustrated the working principle of travelling wave methods.

Apart from these, knowledge-based methods are also suggested in IEEE paper (Okada, Urasawa, Kanemaru, & Kanoh, 1988). It says the fault current is indefinite and behave differently at different line configurations and operational conditions. Therefore applying the same parameters for fault location estimation may create errors sometimes. In response, fuzzy logics are introduced to analyse the features of fault current distribution where it allows more accurate fault location estimation (Coleman, 1989). Exploratory, heuristic and Bayesian algorithms are some of the examples using fuzzy logics to detect fault (Nastac & Thatte, 2006).

The technology has progressed to utilise Global Positioning System (GPS) as assistance feature to estimation the fault location more accurately. Few studies using GPS have been carried out to improve the fault location calculation such as (Ying-Hong, Chih-Wen, & Ching-Shan, 2004) and (McNeff, 2002).

The discussed fault location methods can be summarised, as follows:-

1) Impedance-based methods
    1. One-ended impedance-based methods
    2. Two-ended impedance-based methods
2) Travelling wave methods
3) Methods using synchronized phasors
4) Methods using time-tagging of the events

5) Knowledge-based methods

This research project only studies and compares the performance of one-ended impedance-based methods. The rest of the methods are not are not considered in the study area of this research project.

2.3 One-ended Impedance-based Fault Location Methods

2.3.1 Principle of One-ended Impedance-based Methods

One-ended impedance-based location methods are developed on the basis of homogenous system. Homogenous transmission system is a transmission system where the line impedance, local and remote source impedances having the similar system angle (Razavi, Maaskant, Yang, & Viberg, 2015). In homogenous system, the conductor size of transmission line is presumed to be identical along the line as such the impedance of transmission line is uniformly distributed (Zimmerman & Costello, 2005). However in reality the transmission system is hardly be 100% homogenous due to non-ideal sources, loads and lines.

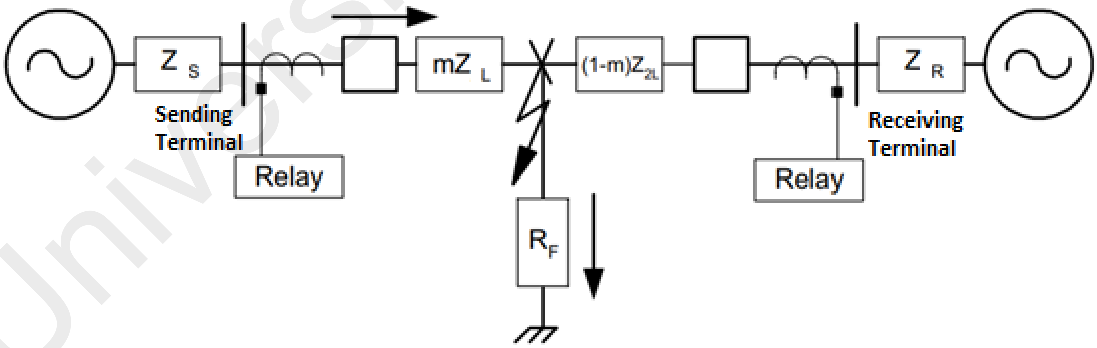


Figure 2.2: Single line schematic of transmission system with 2 terminals

Figure 2.2 shows the single line model of transmission system with 2 terminals, local and remote terminals. When fault happens at a distance, m from local terminal, the fault current is contributed from both sources at local and remote terminal. The relay at each terminal will measure and capture the voltage and current phase angles. The recorded values will be then computed using the impedance-based fault location algorithm to estimate the fault distance from local terminal (Gama & Lopes, 2017). One-ended fault location methods estimates the fault distance from one terminal end only unlike two-ended methods processes captured data from both terminal of the line which needs more cost to establish the communication between two terminals. It is noted that one-ended fault location methods use only the voltage and current readings recorded at either local or remote terminal (Das, Santoso, Gaikwad, & Patel, 2014).

Simplest form of the one-ended impedance-based method is derived one-ended transmission network using Kirchhoff's Laws. It approximates the distance from local terminal to the fault location using the voltage and current of the fault involved phase(s), the positive sequence line impedance, fault resistance, and fault current (Holbeck, 1944).

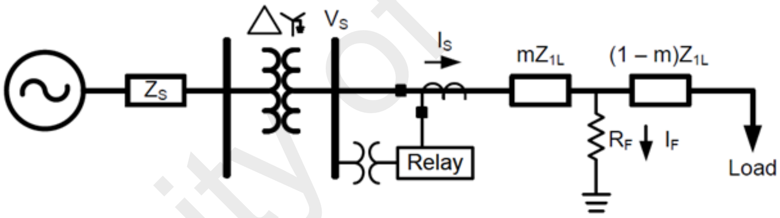


Figure 2.3: One-ended network for simple impedance calculation (M. M. Saha, 2002)

The one-ended network in Figure 2.3 can be converted into simplified circuit as shown in Figure 2.4.

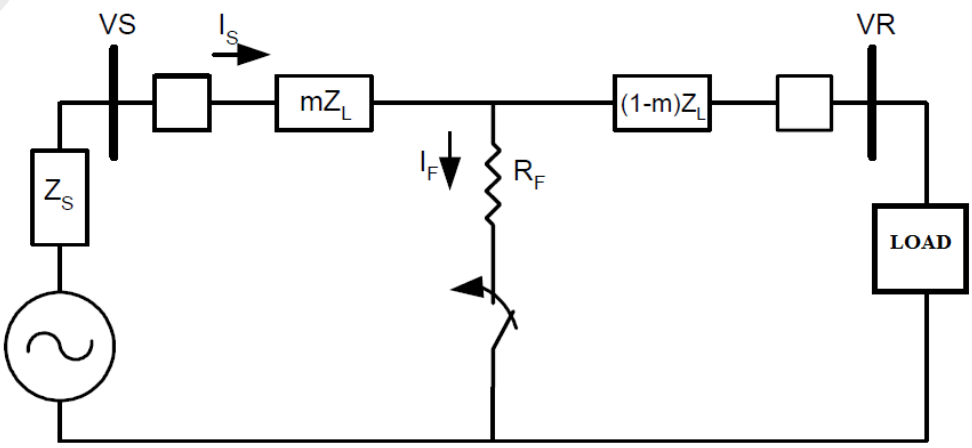


Figure 2.4: Representative simplified circuit for one-ended network (Zimmerman & Costello, 2005)

Applying Kirchhoff's Laws, the impedance method can be expressed with equation:

$$V_S = mZ_{1L}I_S + R_F I_F \tag{1}$$

Rearrange the equation, the fault distance, *m* is:

$$m = \frac{(V_S - R_F I_F)}{Z_{L1} I_S} \tag{2}$$

The relationship of the types of fault with the V_S, I_S, and ΔI_S is tabulated in Table 1. The formula in the table can be applied to one-ended impedance-based fault location techniques as the input parameters for fault distance estimation.

Table 2.1: Simple impedance equations for different fault types (Das et al., 2014)

Fault Type	V_G	I_G	ΔI_G
A-G	V_{AF}	$I_{AF} + kI_{G0}$	$I_{AF} - I_{Apre}$
B-G	V_{BF}	$I_{BF} + kI_{G0}$	$I_{BF} - I_{Bpre}$
C-G	V_{CF}	$I_{CF} + kI_{G0}$	$I_{CF} - I_{Cpre}$
AB, AB-G, ABC	$V_{AF} - V_{BF}$	$I_{AF} - I_{BF}$	$(I_{AF} - I_{Apre}) - (I_{BF} - I_{Bpre})$
BC, BC-G, ABC	$V_{BF} - V_{CF}$	$I_{BF} - I_{CF}$	$(I_{BF} - I_{Bpre}) - (I_{CF} - I_{Cpre})$
CA, CA-G, ABC	$V_{CF} - V_{AF}$	$I_{CF} - I_{AF}$	$(I_{CF} - I_{Cpre}) - (I_{AF} - I_{Apre})$
where $k = \frac{Z_{L0}}{Z_{L1}} - 1$			

2.3.2 Simple Reactance Method

Simple reactance method is developed based on the assumption that the fault resistance is always resistive in nature (Hashim, Ping, & Ramachandaramurthy, 2009). Thus simple reactance method eliminates the R_F from the Equation (2) by assuming the I_S and I_R is in phase. Simple reactance method uses simple calculation derived from simple impedance method and emphasizes only the imaginary values or phasor of the total impedance. It is useful and requires minimum input parameters for fault location calculation.

Divides the equation by I_S and ignores $\frac{(R_F I_F)}{I_S}$ with assumption ∠I_S = ∠I_F and computes only the imaginary part of the equation (Hashim et al., 2009; Surwase, Nagendran, & Patil, 2015):

$$Im\left(\frac{V_S}{I_S}\right) = Im(m.Z_{L1}) = m.X_{L1} \quad (3)$$

Solve for fault distance, *m* and the simple reactance equation is obtained:

$$m = \frac{Im\left(\frac{V_S}{I_S}\right)}{X_{L1}} \quad (4)$$

Figure 2.5 shows the reactance error when the network system is homogenous and non-homogenous. Fault location will be over-estimated when I_S lags I_F and under-estimated when I_S leads I_F.

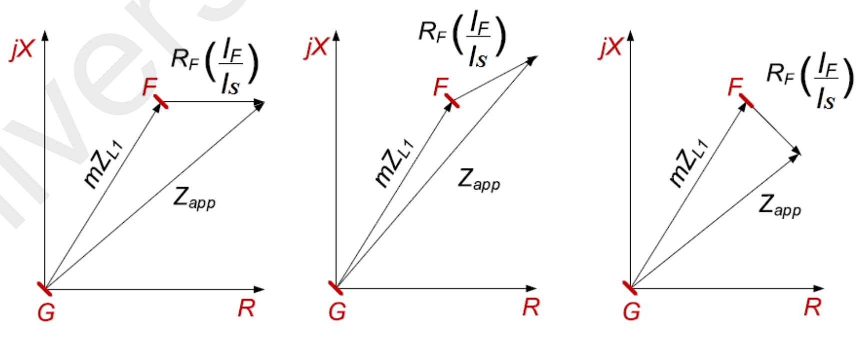


Figure 2.5: Reactance error in the simple reactance method (Das et al., 2014). (a) ∠I_S = ∠I_F. (b) I_S lags I_F. (c) I_S leads I_F.

2.3.3 Takagi Method

Takagi method subtracts the pre-fault load current from the total fault current to enhance the performance of simple reactance method by minimizing the impacts of load flow and R_F (Hashim et al., 2009). Transmission network that experiencing a fault can be broken down into pre-fault and pure fault networks by applying superposition theorem as shown in Figure 2.6.

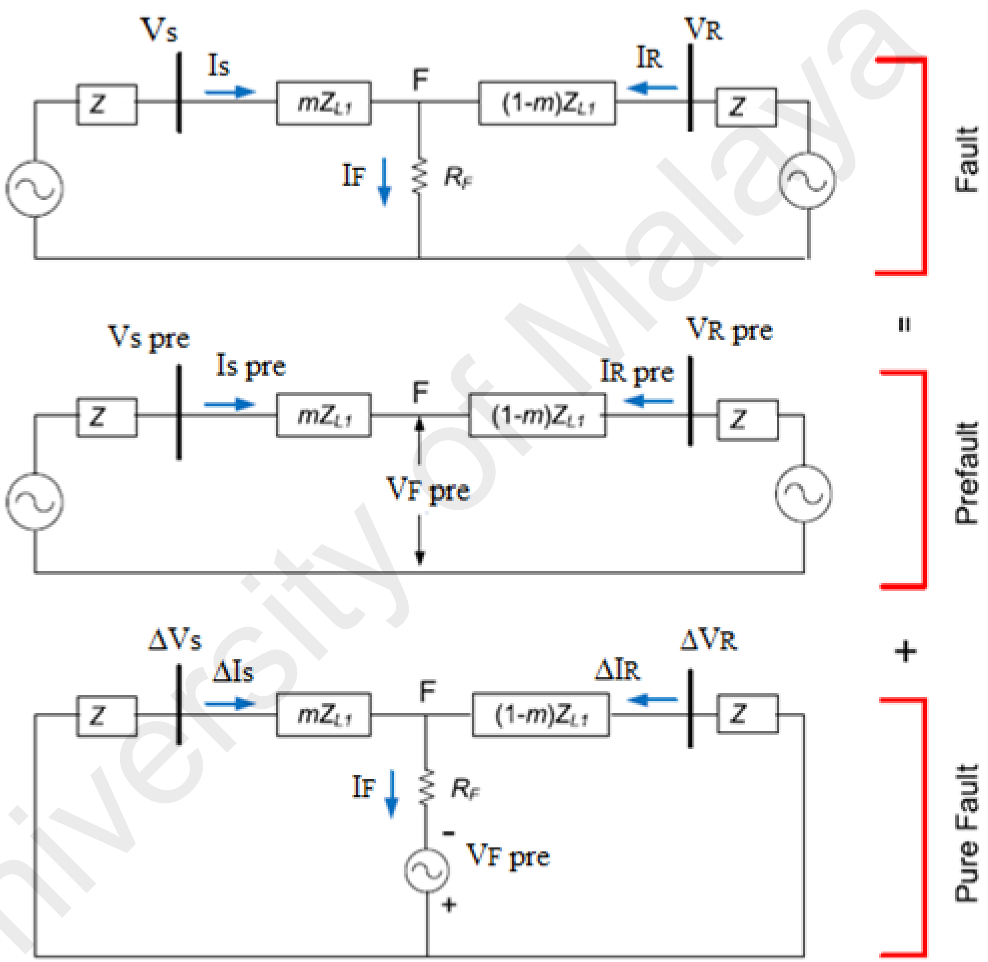


Figure 2.6: Fault transmission network is decomposed to per-fault and pure fault network using superposition principle (Das et al., 2014).

As superposition principle is applied, the pre-fault network consists only load current flowing in the network. Whereby, the sources in pure fault network is short circuited and V_F pre is placed at fault point. Superposition current is obtained in Equation (5):

$$I_{sup} = I_S - I_{S\,pre} \tag{5}$$

Mutiply conjugate of Isup, Isup* on the both sides of Equation (1) and extract imaginary part:

$$Im\left(V_S I_{sup}^*\right) = \text{m}.\, Im\left(Z_{L1} I_S I_{sup}^*\right) + R_F.\, Im\left(I_F I_{sup}^*\right) \tag{6}$$

Eliminate R_F and solve for fault distance, *m*:

$$m = \frac{Im\left(V_S . I_{sup}^*\right)}{Im\left(Z_{L1} . I_S . I_{sup}^*\right)} \tag{7}$$

Similarly like simple reactance method, the reactance error increases when the non-homogeneity is greater in the network (Marguet & Raison, 2014). Besides, the error may become greater when the load current is not being constant in the network (Das et al., 2014).

2.3.4 Eriksson Method

Eriksson method is a novel fault location algorithm uses source impedance as additional input parameters to reduce the reactance error resulted by non-homogenous system (Das et al., 2014; Eriksson, Saha, & Rockefeller, 1985).

Replacing I_F with $\left(\frac{Z_{S1}+Z_{L1}+Z_{R1}}{(1-m)Z_{L1}+Z_{R1}}\right)\Delta I_S$ in Equation (1):

$$V_S = mZ_{1L} I_S + R_F \left(\frac{Z_{S1} + Z_{L1} + Z_{R1}}{(1-m)Z_{L1} + Z_{R1}}\right)\Delta I_S \tag{8}$$

Equation (8) can be rearranged and simplified into Boolean expression:

$$m^2 - k_1 m + k_2 - k_3 R_F = 0 \tag{9}$$

where

$$k_1 = a + jb = 1 + \frac{Z_{R1}}{Z_{L1}} + \left(\frac{V_S}{(Z_{L1} \times I_S)}\right)$$

$$k_2 = c + jd = \frac{V_S}{Z_{L1} \times I_S} + \left(1 + \frac{Z_{R1}}{Z_{L1}}\right)$$

$$k_3 = e + jf = \frac{\Delta I_S}{Z_{L1} \times I_S} + \left(1 + \frac{Z_{R1} + Z_{S1}}{Z_{L1}}\right)$$

Solve Equation (8) using quadratic function to find fault distance, *m*:

$$m = \frac{\left(a - \frac{eb}{f}\right) \pm \sqrt{\left(a - \frac{eb}{f}\right)^2 - 4\left(c - \frac{ed}{f}\right)}}{2} \tag{10}$$

Quadratic function produces 2 values of *m*. The value which lies between 0 and 1 pu should be selected as the actual fault distance.

Eriksson method also has advantage to estimate fault resistance for root cause analysis of fault event using formula:

$$R_F = \frac{d - mb}{f} \tag{11}$$

The source impedance values at local and remote terminals shall be accurate for better fault location estimation of Eriksson method (Eriksson et al., 1985).

2.3.5 Novosel et al. Method

Novosel et al. method improves the Eriksson fault location algorithm and it is useful for computing the fault distance of a radial transmission network (D. Novosel, 1998; Das et al., 2014). Novosel et al. method replaced input parameter Z_{R1} with Z_{Load} in the Eriksson algorithm where Z_{Load} is the load impedance of remote terminal. Figure 2.7 illustrates the radial transmission network with load impedance at remote terminal.

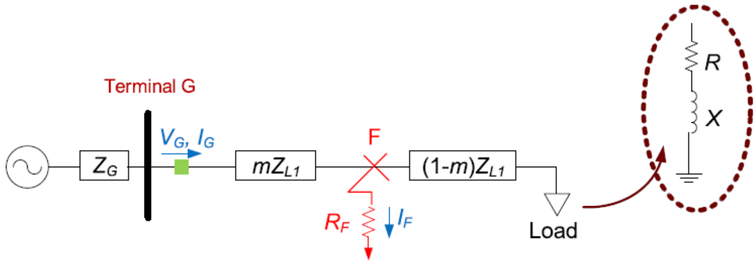


Figure 2.7: Radial transmission network with load impedance at remote terminal (Das et al., 2014)

Equation (12) shows the equation of Z_{Load}:

$$Z_{Load} = \frac{V_{S1\,pre}}{I_{S1\,pre}} - Z_{L1} \tag{12}$$

Replacing Z_{R1} with Z_{Load} in Equation (8) becomes:

$$V_S = mZ_{1L}I_S + R_F\left(\frac{Z_{S1} + Z_{L1} + Z_{Load}}{(1-m)Z_{L1} + Z_{Load}}\right)\Delta I_S \tag{13}$$

Rearrange and simplify Equation (9), and constant k_1, k_2, and k_3 are as follows:

$$k_1 = a + jb = 1 + \frac{Z_{Load}}{Z_{L1}} + \left(\frac{V_S}{(Z_{L1} \times I_S)}\right)$$

$$k_2 = c + jd = \frac{V_S}{Z_{L1} \times I_S} + \left(1 + \frac{Z_{Load}}{Z_{L1}}\right)$$

$$k_3 = e + jf = \frac{\Delta I_S}{Z_{L1} \times I_S} + \left(1 + \frac{Z_{Load} + Z_{S1}}{Z_{L1}}\right)$$

Similar to Eriksson, fault distance, *m* of Novosel et al. method is solved using quadratic function as stated in Equation (10) which *m* lies between 0 and 1 pu shall be selected as the fault distance. Novosel et al. method can also estimate the fault resistance using Equation (11) like Eriksson method.

2.3.6 Modified Takagi Method

Modified Takagi method improves the performance of Takagi method and removes the requirement of pre-fault current which might not available in some relay settings. Instead, modified Takagi method uses zero sequence current, zero sequence line impedance, and zero sequence source impedances of both terminals to compute the fault location.

Firstly, modified Takagi method makes assumption to identify preliminary fault distance (Das et al., 2014):

$$m = \frac{imag(V_S \times 3I_{0S}^*)}{imag(Z_{1L} \times I_S \times 3I_{0S}^*)} \tag{14}$$

Then, Equation 15 is used to compensate the non-homogeneity of the transmission system:

$$|d_S|\angle\beta = \frac{Z_{0S} + Z_{0L} + Z_{0R}}{(1-m)Z_{0L} + Z_{0R}} \tag{15}$$

Using Equation 15, β can be found and apply to Equation 16 to obtain the final fault distance:

$$m = \frac{imag\left(V_S \times 3I_{0S}^* \times e^{-j\beta}\right)}{imag(Z_{1L} \times I_S \times 3I_{0S}^* \times e^{-j\beta})} \tag{16}$$

Modified Takagi method is superior than Takagi method in accuracy however its accuracy will drop if the source impedance values are not accurate (Camarillo-Pefiaranda & Ramos, 2018).

2.4 Error Sources of Fault Location Methods in Transmission System

Many factors that may affect the accuracy of fault location estimation are not taken into account in the fault location algorithms. With refer to (Le & Petit, 2016), the underground transmission cables experiences reactance effect during fault. Capacitance of cable insulation will add to the fault resistance and alter its nature of being pure resistive. Thus it is advised to put cable insulation into algorithm when estimating fault location.

Another challenge to estimate fault location suggested by (Wei & Liu, 2012) is the difficulty to determine the fault location for high resistance fault. The peak value of voltage-second the recorded voltage is proposed to estimate the fault location in the paper. Inconsistency of soil resistivity along the transmission lines is also a factor that influences the fault resistance and zero sequence line impedance (Garcia-Osorio, Mora-Florez, & Perez-Londono, 2008). The paper conducted the test for few soil samples collected from transmission lines site to determine the actual fault resistance characteristic for better fault location estimation.

It is crucial to identify the fault type correctly for fault location estimation. Wrongly estimate the fault type can lead to error of fault locating (Tağluk, Mamiş, Arkan, & Ertuğrul, 2015). This paper analysed the applicability of extreme learning machine with the aspiration to identify the fault type and fault location correctly.

Mutual impedance of transmission coupling lines will affect the performance of protection relay typically the earth fault distance protection (Liu, Cai, & Hou, 2005). Zero sequence current and inter-tripping method are utilised as compensation factors to minimise the effect of mutual coupling.

(Kim, Lee, Radojevic, Park, & Shin, 2006) proposed new algorithm that adopted shunt capacitance effect and compare the fault locating performance with algorithm without shunt capacitance. It was proven the new algorithm has better capabilities in the aspects of accuracy and speed over the traditional algorithm.

Estimating location of fault at an unbalanced power system is also quite difficult where typically happens more in distribution lines. (Nunes & Bretas, 2011) suggested the coordination of downstream voltages and current with the upstream to overcome the modified fault current magnitude and phasor due to multiple generation sources.

2.5 Error Measurement of Fault Location Methods

Error calculation is needed in order to perform analysis and measure the accuracy of the fault location methods. In IEEE Guide ("IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines," 2015), 3 calculations are presented to measure the fault location error, namely absolute error, relative error, and relative error based on total line length as shown in below:

1) Absolute error

   Absolute error is expressed as:

$$error_a = |m_{actual} - m_{estimated}| \tag{17}$$

   where

   $error_a$ is the absolute error in percentage or per unit

   m_{actual} is the actual fault distance in percentage or per unit

   $m_{estimated}$ is the estimated fault distance in percentage or per unit

2) Relative error

   Relative error is expressed as:

$$error_r = \frac{|m_{actual} - m_{estimated}\,|}{m_{actual}} \tag{18}$$

   where

   $error_r$ is the relative error in percentage or per unit

3) Relative error based on total line length

   Relative error based on total line length is expressed as:

$$error_L = \frac{|m_{actual} - m_{estimated}|}{Total\ Line\ Length} \tag{19}$$

where

$error_L$ is the relative error based on total line length in percentage and per unit

According to IEEE Guide ("IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines," 2015), absolute error ignores the line length and only measures the difference between the actual fault and estimated fault. It is practically useful on giving sample error for the technical team to identify the actual fault location at the site to rectify the fault. Nonetheless it is not feasible to be applied on analysing the accuracy of the fault location method as it neglects the relation with the line length or fault distance from terminal.

Relative error calculation was popular to be used for determining the accuracy of fault location methods like those suggested by (Starr & Gooding, 1939) and (Gama & Lopes, 2017). However it is losing its popularity over relative error based on line length because the calculated error is not related to the length of the line. For example, a fault location method with 100m error for a 1km transmission line is significant because the fault location method mis-located 10% of the total line length. If the similar 100m error is recorded on a 100km transmission line, the fault location method is considered accurate because it only wrongly estimated 1%. Note that relative error is only applicable for one-ended fault location method because two-ended methods will have different perspectives on m_{actual} when viewing from each terminal.

Most of the recent research papers calculate the fault location error using relative error based on line length, for instances (Ö, Gürsoy, Font, & Ö, 2016), (Kyung Woo, Das, & Santoso, 2016), and (Muddebihalkar & Jadhav, 2015). Calculating the error based on line length is able to overcome the disadvantages of relative error and offer uniform error for the faults on the same line regardless the location along the line. Hence it can be used to measure the accuracy for both one-ended and two-ended fault location methods.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This research project presents the investigation on the performance of one-ended impedance-based fault location methods in the transmission network, which includes 1) simple reactance method, 2) Takagi method, 3) Eriksson method, and 4) Novosel et al. method,. A number of system parameters are varied to determine their effects and influences to the accuracy of one-ended impedance-based fault location methods in the transmission system. A MATLAB SIMULINK transmission network model and MATLAB coding script for one-ended impedance-based fault location algorithms are developed in this project in order to study the impact of these factors to the accuracy of one-ended impedance-based fault location methods. In this chapter, an overview of the project methods and procedures will be discussed. The methodology comprises of identification of system configuration of high voltage transmission network, system modeling, simulation scheme, measurement of voltage and current waveforms, percentage error calculation and as well as requirement of one-ended impedance-based fault location algorithms.

3.2 Identification of System Configuration of High Voltage Transmission Network

The simulation model is developed based on one of transmission system examples as recorded in IEEE Guide ("IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines," 2015) .

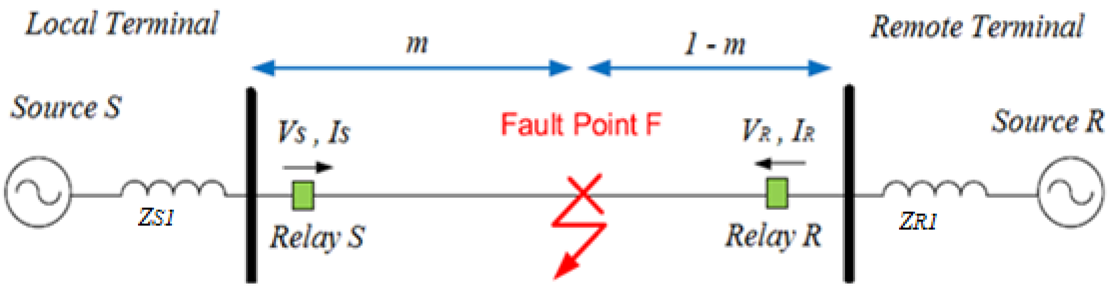


Figure 3.1 System configuration for the 69kV three-phase transmission network with 2 terminals

As shown in Figure 3.1, the transmission network is a 69kV three-phase system with two terminals, i.e. local terminal and remote terminal are used as simulation model in this project. Each terminal is connected to a 69kV source, namely Source S at local terminal and Source R at remote terminal. The positive sequence source impedances at local and remote terminals are Z_{S1} = 0.2616 + j3.7409 Ω and Z_{R1} = 2.0838 + j11.8177 Ω, respectively. Relays are located at both local and remote terminals to measure and record the voltage and current waveforms during normal operation and fault period. The transmission line length is 10km from local terminal to remote terminal where the total positive sequence line impedance is Z_{L1} = 1.1478 + j4.9713 Ω. The input parameters for this transmission system is listed in Table 3.1.

Table 3.1: Input parameters for transmission system of simulation model

Parameter	Value
Z_{S1}	0.2616 + j3.7409 Ω
Z_{R1}	2.0837 + j11.8177 Ω
Z_{L1}	1.1477 + j4.9713 Ω

3.3 System Modeling

MATLAB SIMULINK is a computer aided graphical programming tool developed by MathWorks for model-based design. It provides a modeling platform with graphical block diagramming tool and block libraries. The block libraries is featured with Simscape Electrical™ blocks for modeling, simulating, and analysing electrical power systems which includes but not limited to generation, transmission, and distribution systems. The simulation model for this research project is developed in MATLAB SIMULINK as illustrated in Appendix A.

3.3.1 Transmission Network Source Modeling

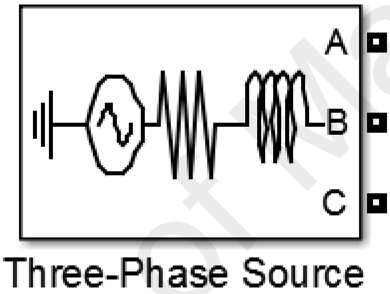


Figure 3.2: Three-phase source of transmission network

The transmission network source is developed using the three-phase voltage source in series with RL branch. It is set to feed 69kV to the transmission line, in accordance to example given in IEEE Guide ("IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines," 2015). Source models, namely Source S and Source R are used at local terminal and remote terminal respectively. The input parameters for transmission network source models are listed in Table 3.2.

Table 3.2: Input parameters for transmission network source model

Parameter	Value	
	Source S	**Source R**
Phase-to-phase RMS Voltage	69kV	69kV
Frequency	60Hz	60Hz
Internal Connection	Grounded Star	Grounded Star
Source Resistance	0.2616 Ω	2.0838 Ω
Source Inductance	$\left(3.7409 \times \frac{1}{2\pi 60}\right)$ $= 0.9923 \times 10^{-4} H$	$\left(11.8177 \times \frac{1}{2\pi 60}\right)$ $= 0.0313\ H$

3.3.2 Transmission Line Modeling

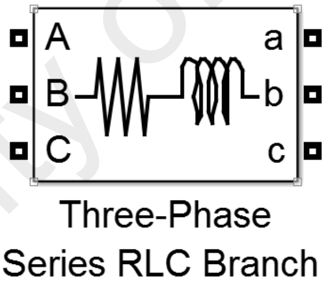


Figure 3.3: Three-phase series branch for transmission line modeling

Three-phase series RLC branch block as shown in Figure 3.3 is used to model transmission line. The complete 10km transmission line is developed using 2 blocks, where Block 1 represents fault distance, *m* and Block 2 represents the remaining distance, 1 – *m*. The total positive sequence line impedance is Z_{L1} = 1.1477 + j4.9713 Ω, therefore the line impedances of Block 1 and Block 2 are listed in Table 3.3.

Table 3.3: Input parameters for transmission line model

Parameter	Value	
	Block 1	**Block 2**
Resistance	(m).(1.1477) Ω	(1 – m).(1.1477) Ω
Inductance	$(m).\left(4.9713 \times \frac{1}{2\pi 60}\right)$ $= (m).(1.319 \times 10^{-2})$H	$(1 - m).\left(4.9713 \times \frac{1}{2\pi 60}\right)$ $= (1 - m).(1.319 \times 10^{-2})$

3.3.3 Load Modeling

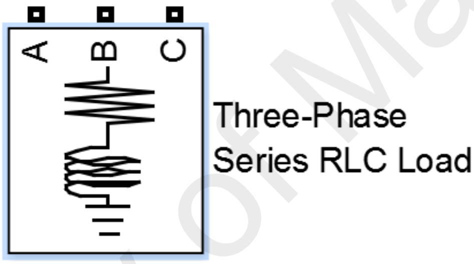


Figure 3.4: Three-phase series RLC load for load modeling

Three-phase series RLC load is inserted into simulation model to determine the response of the fault location methods when the load is connected at different locations. It is used to simulate constant load with unity power factor and 0.8 lagging power factor at local and remote terminals. Each terminal supports 250A current, therefore real power required for unity power factor load is $P = \sqrt{3} \times 69kV \times 250A \times 1 = 29.878MW$. Whereby, the real power for 0.8 lagging power factor is $P = \sqrt{3} \times 69kV \times 2500A \times 0.8 = 23.902MW$ and the reactive power is $Q = \sqrt{S^2 - P^2} = \sqrt{}((29.878MVA)^2 - (23.902MW)^2) = 17.927MVar$. The input parameters for Load Modeling is shown in Table 3.4.

Table 3.4: Input parameters for load modeling

Parameter	Value	
	Unity PF Load	**0.8 Lagging PF Load**
Active Power	29.878MW	23.902MW
Reactive Power	0MVar	17.927MVar

3.3.4 Fault Modeling

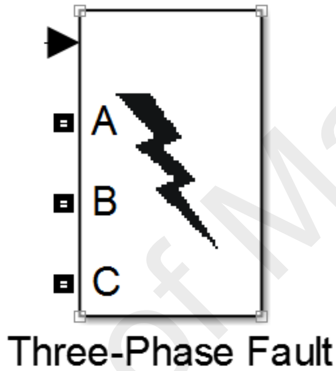


Figure 3.5: Three-phase fault block for fault modeling

The fault in between the transmission line is simulated using three-phase fault block in MATLAB SIMULINK. Single line-to-ground fault is applied for all fault simulations in this research project. The simulation is executed in normal operation to capture the pre-fault voltage and current waveforms before the fault is introduced at the transmission line. Table 3.5 shows the input parameters for three-phase fault block.

Table 3.5: Input parameters for three-phase fault block

Parameter	Value
Fault Between	Phase A and Ground
Fault Resistances	0.1Ω, 2.5Ω, 5Ω, 10Ω, 15Ω, 20Ω, or 25Ω

3.4 Simulation Scheme

3.4.1 System Parameters for Simulation

The MATLAB SIMULINK simulation model in Appendix A is developed to investigate the effects of system parameters i.e. 1) fault resistance, 2) fault distance, 3) location of the load, 4) load power factor, and 5) presence of remote source in-feed on the accuracy of the one-ended impedance-based fault location methods. The system parameters are listed in Table 3.6:

Table 3.6: System parameters used to investigate the accuracy of one-ended impedance-based fault location methods

System Parameters	Value or Description
Fault Resistance, R_F	1) $R_F = 0.1\Omega$ 2) $R_F = 2.5\Omega$ 3) $R_F = 5\Omega$ 4) $R_F = 10\Omega$ 5) $R_F = 15\Omega$ 6) $R_F = 20\Omega$ 7) $R_F = 25\Omega$
Fault Distance, m	1) m = 0.25pu 2) m = 0.50pu 3) m = 0.75pu 4) m = 1.00pu
Location of the Load	1) No load 2) Load at local terminal 3) Load at remote terminal
Load Power Factor	1) Power factor: 1 2) Power factor: 0.8 lagging
Remote Source In-feed	1) Without Source R at remote terminal 2) With Source R at remote terminal

3.4.2 Simulation Procedure

In this research project, sensitivity analysis is adopted to investigate the effects of these system parameters on the accuracy of the one-ended impedance-based fault location methods. 5 case studies are developed as below.

1) Case Study 1

Case Study 1 is proposed to investigate the effect of fault resistance on the accuracy of the one-ended impedance-based fault location methods. The simulation model in this case study shall be free from the influence of load and remote source in-feed to ensure the results solely reflect the effect of fault resistance.

The network configuration of Case Study 1 is as resembled in Appendix N – Transmission Network Model 1. The simulation is initiated with fault resistance 0.1Ω and constant fault distance value of 0.01pu. Then the simulation is repeated by changing the fault resistance to 2.5Ω, 5Ω, 10Ω, 15Ω, 20Ω, and 25Ω

2) Case Study 2

Case Study 2 is proposed to investigate the effect of fault distance on the accuracy of the one-ended impedance-based fault location methods. It uses the same configuration as Case Study 1 and repeats the simulation steps in Case Study 1 by changing the fault distance from 0.01pu to 0.25pu, 0.5pu, 0.75pu, and 1.0pu.

3) Case Study 3

Case Study 3 is proposed to investigate the effect of load location on the accuracy of the one-ended impedance-based fault location methods. A load will be connected to either local or remote terminal and the simulation steps are repeated as mentioned in Case Study 2. The load shall be unity power factor load (pure resistive) to omit the influence of load power factor.

The network configuration of Case Study 3 is as resembled in Appendix N – Transmission Network Model 2 and Transmission Network Model 3.

4) Case Study 4

Case Study 4 is proposed to investigate the effect of load power factor on the accuracy of the one-ended impedance-based fault location methods. The 0.8 lagging power factor load is used in this case study to determine the influence of inductive load when it is connected at either local or remote terminal.

The network configurations of Case Study 4 are as resembled in Appendix N – Transmission Network Model 4 and Transmission Network Model 5.

5) Case Study 5

Case Study 5 is proposed to investigate the effect of remote source in-feed on the accuracy of the one-ended impedance-based fault location methods.

The network configurations of Case Study 5 are as resembled in Appendix N – Transmission Network Model 6, 7, 8, 9, and 10.

Referring to the system parameters in Table 3.6, the simulation steps to study the effect of system parameters on the accuracy of the one-ended impedance-based fault location methods are listed below:

1. Initiate the simulation with one-ended transmission network that has only Source S connected at local terminal as resembled in Appendix N – Transmission Network Model 1. No load is connected to the network.
2. Simulate the voltage and current waveforms at 0.1Ω of fault resistance and 0.01pu of fault distance.
3. Compute the estimated fault distance using 4 one-ended impedance-based fault location methods.
4. Compute the percentage error of the estimated fault distance.
5. Repeat step 1 to 4 by changing the fault resistance to 2.5Ω, 5Ω, 10Ω, 15Ω, 20Ω, and 25Ω.
6. Repeat step 1 to 5 by changing the fault distance to 0.25pu, 0.5pu, 0.75pu, and 1.0pu.
7. Repeat step 2 to 5 by adding the unity power factor load at local terminal.

8. Repeat step 2 to 5 by adding the unity power factor load at remote terminal.
9. Repeat step 2 to 5 by adding the 0.8 lagging power factor load at local terminal.
10. Repeat step 2 to 5 by adding the 0.8 lagging power factor load at remote terminal.
11. Repeat step 2 to 10 by adding the remote source in-feed at remote terminal.

3.5 Measurement of Voltage and Current Waveforms

One-ended impedance-based fault location methods require the voltage and current magnitudes and phase angles at local terminal during the fault to compute the fault distance. During transient and sub-transient periods, the fault current is asymmetrical due to the DC component is contain in the waveform in the first few cycles. The RMS value of fault current fluctuates until the DC component is completely decayed before it can reach steady-state. The typical fault current waveform is shown in Figure 3.6.

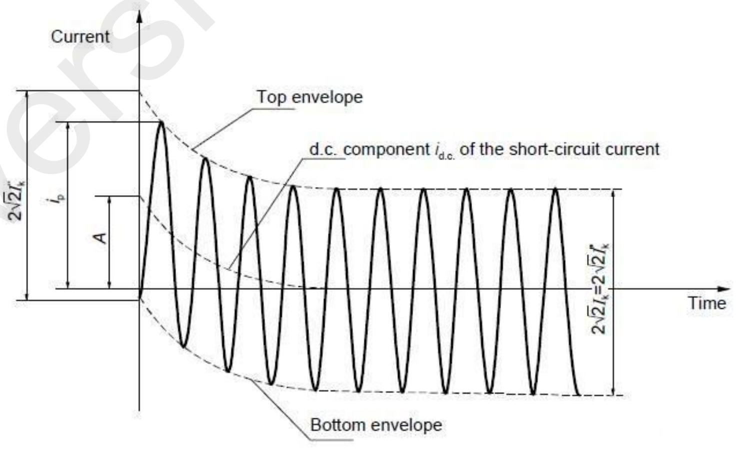


Figure 3.6: Typical asymmetrical fault current waveform

In order to omit the unwanted DC component of voltage and current waveforms during fault, 0.5 seconds is given to assure the waveforms reach steady-state. This is important to ensure the fault distance result is only affected by the system parameters described in Section 3.4.

3.6 Percentage Error Calculation

Relative error based on total line length is used in this research project to calculate the percentage error of estimated fault distance. The equation of relative error based on total line length is stated as follow:

$$Percentage\ Error\ (\%) = \frac{|Actual\ Fault\ Distance - Estimated\ Fault\ Distance|}{Total\ Line\ Length} \times 100\% \qquad (20)$$

3.7 Overall Percentage Error Calculation

The overall percentage error is used in this research project to determine the overall accuracy of one-ended impedance-based fault location methods in each case study. The equation of overall percentage error is shown in below:

$$Overall\ Average\ Percentage\ Error\ (\%) = \frac{|Sum\ of\ percentage\ error\ of\ all\ cases\ within\ a\ case\ study|}{Number\ of\ cases\ within\ a\ case\ study} \times 100\% \qquad (21)$$

3.8 Requirement of One-ended Impedance-based Fault Location Algorithms

The voltage and current magnitudes and phase angles obtained from the simulation is used to compute the fault distance. The required inputs parameters for one-ended impedance-based fault location algorithms are summarised in Table 3.7.

Table 3.7: Summary of required input parameters for one-ended impedance-based fault location algorithms

Input Parameter	Simple Reactance	Takagi	Eriksson	Novosel et al.
Pre-fault Voltage Phasor				✓
Pre-fault Current Phasor		✓	✓	✓
Fault Voltage Phasor	✓	✓	✓	✓
Fault Current Phasor	✓	✓	✓	✓
Positive Sequence Line Impedance	✓	✓	✓	✓
Zero Sequence Line Impedance	✓	✓	✓	✓
Positive Sequence Source Impedance (Source S)			✓	✓
Positive Sequence Source Impedance (Source R)			✓	
Type of Fault	✓	✓	✓	✓

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the 5 case studies as described in Section 3.4. The accuracy of each fault location method is measured based on the calculated fault distance generated from the simulation. The percentage errors are plotted into graphs and bar charts to compare and investigate the effect of system parameters on the accuracy of each method. In the last section, the sensitivity of each one-ended impedance-based fault location method corresponding to the effect of system parameters are discussed and summarized.

4.2 Results and Discussion of Case Study 1

This section presents and discusses the results of the effect of fault resistance on the accuracy of one-ended impedance-based fault location methods.

4.2.1 Results of Case Study 1

The results of Case Study 1 are plotted into graph as shown in Figure 4.1 to present the effect of fault resistance on the accuracy of one-ended impedance-based fault location methods.

Based on Figure 4.1, the percentage error of simple reactance, Takagi, and Novosel et al. methods is constant at 0% for all fault resistance values. Besides, the graph indicates the percentage error of the Eriksson gradually increases with increasing fault resistance values.

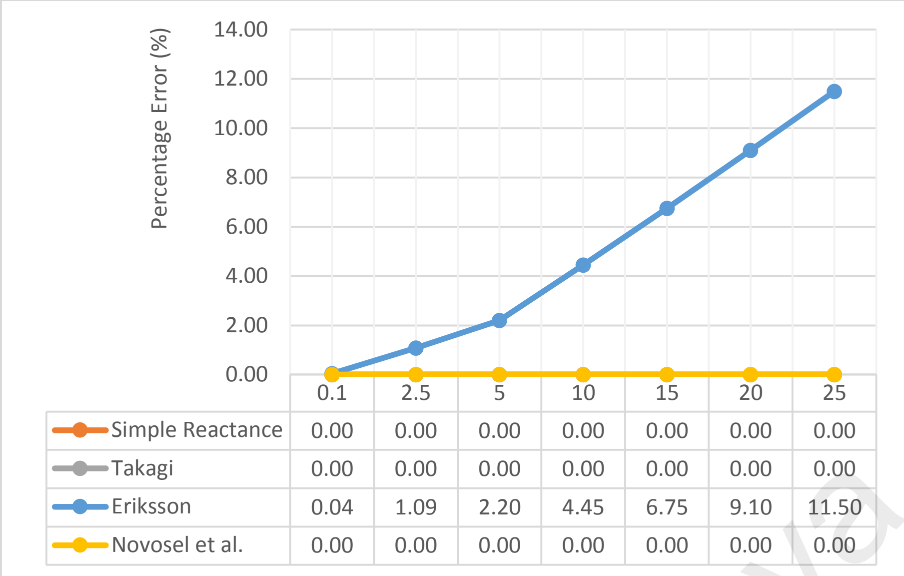


Figure 4.1: Graph of percentage error versus fault resistance at fault distance 0.01pu or 0.1km

The overall percentage error of all one-ended impedance-based fault location methods is plotted into bar chart as illustrated in Figure 4.2 to compare the overall accuracy of 4 fault location methods in Case Study 1. The overall percentage error is calculated by taking the average percentage error at all fault resistance values. From Figure 4.2, it clearly shows the simple reactance, Takagi, and Novosel et al. methods have perfect accuracy with zero percentage error, and followed by Eriksson method (5.02%).

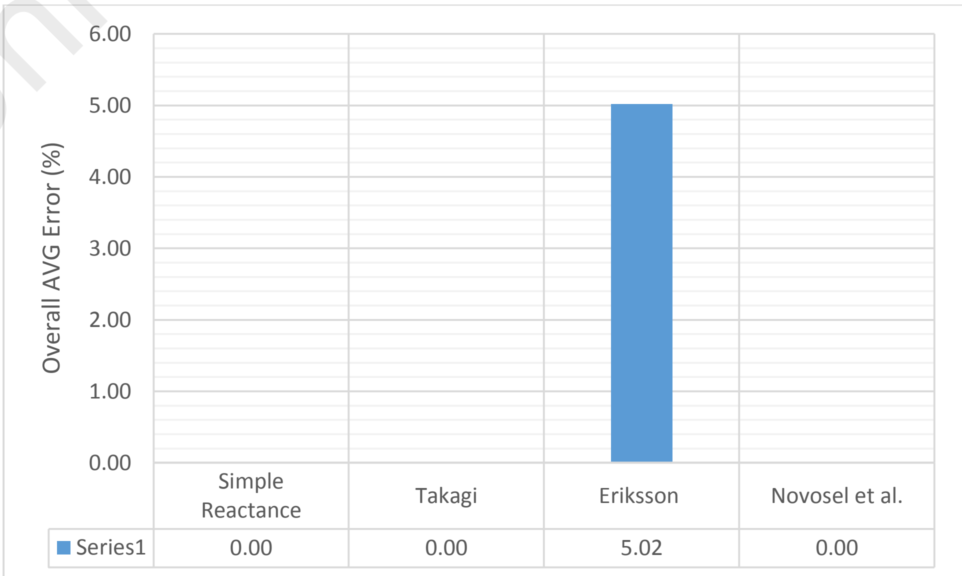


Figure 4.2: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 1

4.2.2 Discussion of Case Study 1

Case Study 1 investigates the effects of fault resistance on the accuracy of the one-ended impedance-based fault location methods. The configuration in this case study is a one-ended transmission line with no load or source connected at remote terminal. Due to this, the transmission system is homogenous with no influence from system parameters except the fault distance and fault resistance. Therefore the system contributes no reactance error because the fault resistance is purely resistive and the line impedance is homogenous. Apart from that, no load current is flowing in the transmission line during pre-fault and fault. As a result, no error is given by simple reactance, Takagi, and Novosel et al. methods at all fault resistances values.

Eriksson method uses the source impedance to calculate the estimated fault distance. However Z_{R1} is no longer true values when the Source R is not connected to remote terminal. The incorrect value of Z_{R1} causes Eriksson method to have overall percentage error 5.02% despite the transmission network is homogenous. The increasing trend of percentage error of Eriksson method indicates its accuracy deteriorates as fault resistance increases.

The effect of fault resistance on the accuracy of fault location methods in Case Study 1 is summarised in Table 4.1:

Table 4.1: Summary of Case Study 1

Case Study 1	
Fault Location Method	**Sensitivity to Fault Resistance**
Simple Reactance	No
Takagi	No
Eriksson	Yes, error increases with increasing of fault resistance
Novosel et al.	No

4.3 Results and Discussion of Case Study 2

This section presents and discusses the results of the effect of fault distance on the accuracy of one-ended impedance-based fault location methods.

4.3.1 Results of Case Study 2

The results of Case Study 2 are plotted into 5 graphs. Each graph represents the results at fault distance 0.01pu, 0.25pu, 0.50pu, 0.75pu and 1.0pu respectively.

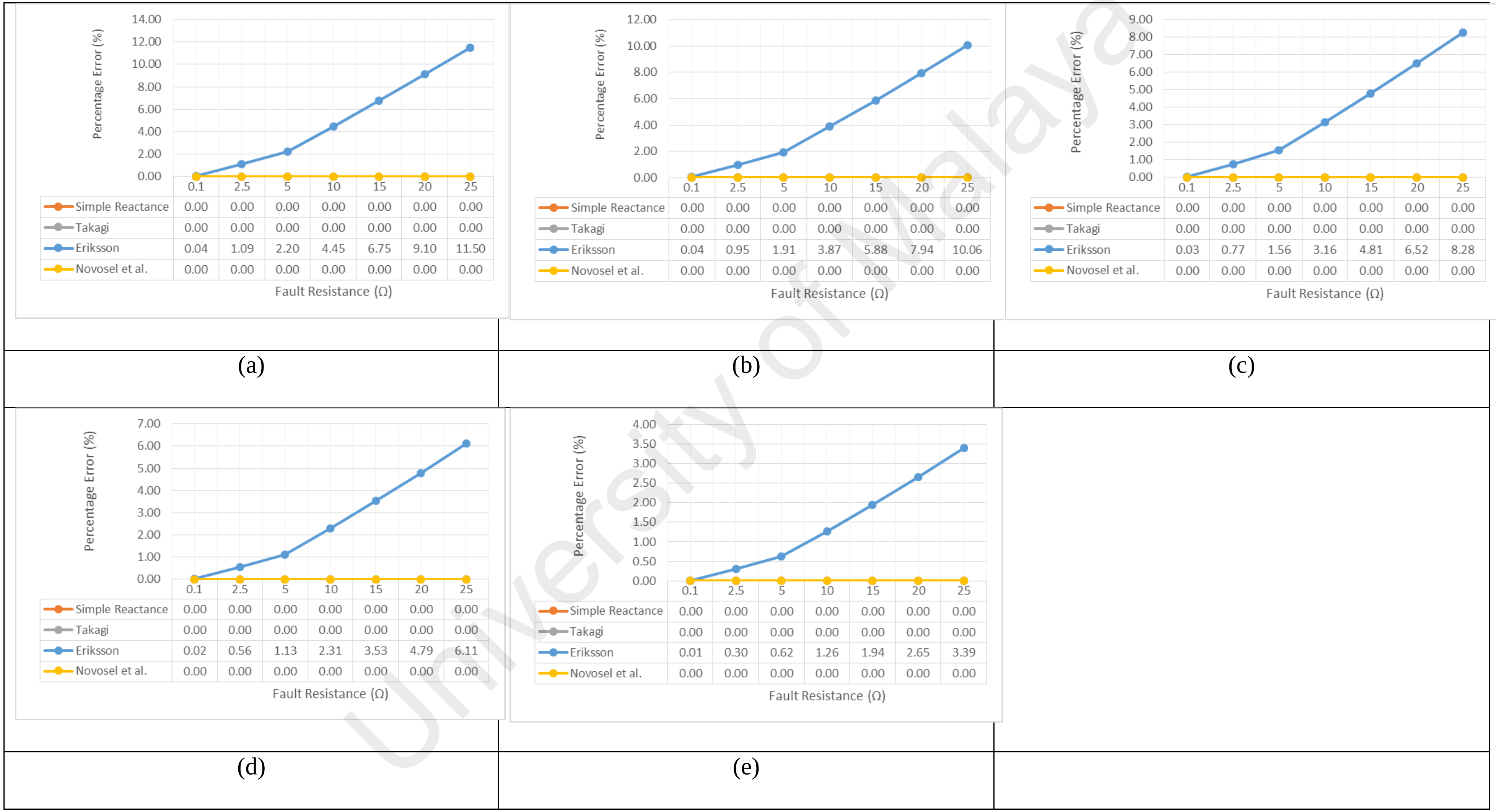


Figure 4.3: Graphs of percentage error vs fault resistance at fault distance a) 0.01pu b) 0.25pu c) 0.50pu d) 0.75pu e) 1.0pu for Case Study 2

Based on the graphs above, the percentage error of simple reactance, Takagi, and Novosel et al. methods maintain constant at 0% even when the fault distance increases from 0.01pu to 1.00pu. The percentage error of Eriksson method reduces as the fault distance increases, from highest recorded 11.50% in Figure 4.3 (a) to 3.39% in Figure 4.3 (e).

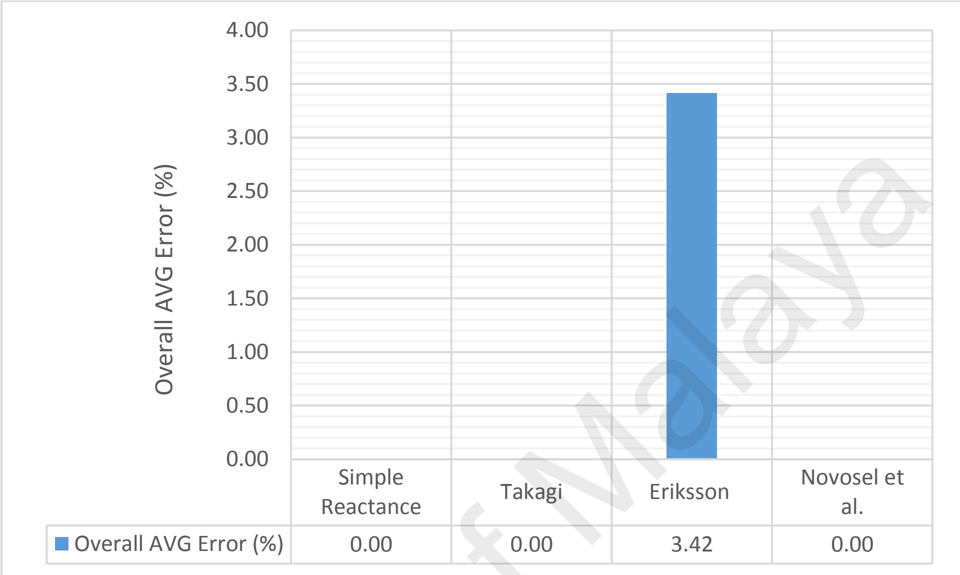


Figure 4.4: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 2

The overall percentage error of all one-ended impedance-based fault location methods is plotted into bar chart as illustrated in Figure 4.4 to compare the overall accuracy of 4 fault location methods in Case Study 2. The overall percentage error is calculated by taking the average of percentage error at all simulation cases. Based on Figure 4.4, the simple reactance, Takagi, and Novosel et al. methods have perfect accuracy with zero percentage error followed by Eriksson method (3.42%).

4.3.2 Discussion of Case Study 2

Case Study 2 investigates the effects of fault distance on the accuracy of the one-ended impedance-based fault location methods. The configuration in this case study is identical to Case Study 1. As such, the transmission network is homogenous and no error sources contribute to the reactance error. Therefore, the simple reactance, Takagi, and Novosel et al. methods maintain the 0% percentage error at all simulation case.

Similarly to explanation in Case Study 1's discussion, the Eriksson method produces error because Z_{R1} used in algorithms are not true values when Source R is not connect at remote terminal. The accuracy of Eriksson method improves when the fault distance from local terminal increases.

The effect of fault distance on the accuracy of fault location methods in Case Study 2 is summarized in Table 4.2:

Table 4.2: Summary of Case Study 2

Case Study 2	
Fault Location Method	**Sensitivity to Fault Distance**
Simple Reactance	No
Takagi	No
Eriksson	Yes, error decreases with increasing of fault distance
Novosel et al.	No

4.4 Results and Discussion of Case Study 3

The results of Case Study 3 in this section presents the effect of load location on the accuracy of one-ended impedance-based fault location methods. In Case Study 3, there are 2 samples of results as follows:

Case Study 3 (i): Unity power factor load is connected at local terminal

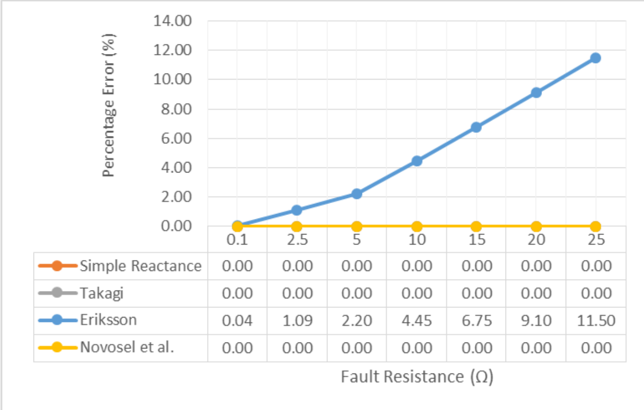
Case Study 3 (ii): Unity power factor load is connected at remote terminal

Each sample of results has 5 graphs, each graph represents the results of the sample at the particular fault distance.

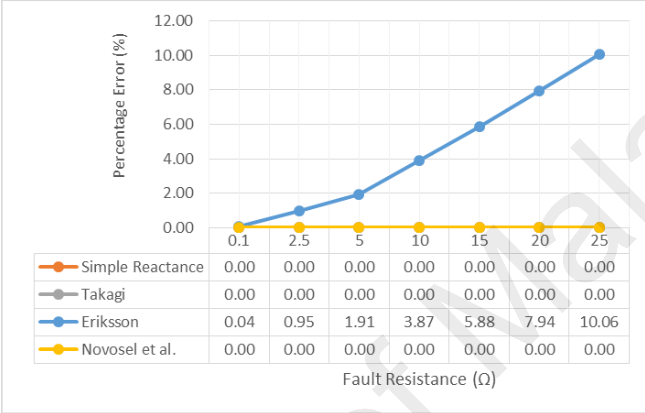
4.4.1 Results of Case Study 3 (i)

The results of Case Study 3 (i) are plotted into graphs as presented in Figure 4.5. As compared to results in Figure 4.3, there is no changes in the accuracy of all methods when the unity power factor load is connected at local terminal.

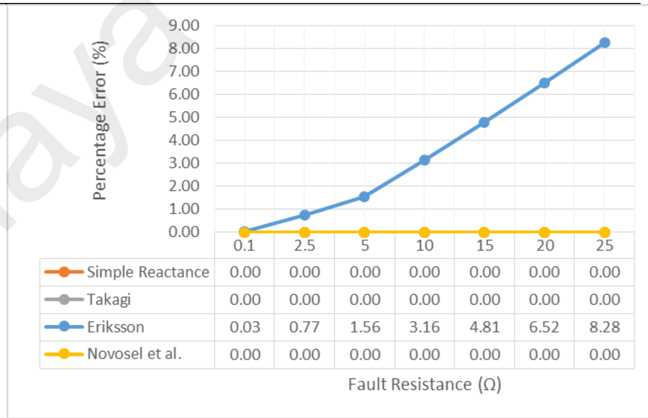
Similarly, the overall percentage error of all one-ended impedance-based fault location methods when unity power factor load is connected at local terminal is also identical to Case Study 2 as shown in Figure 4.6.



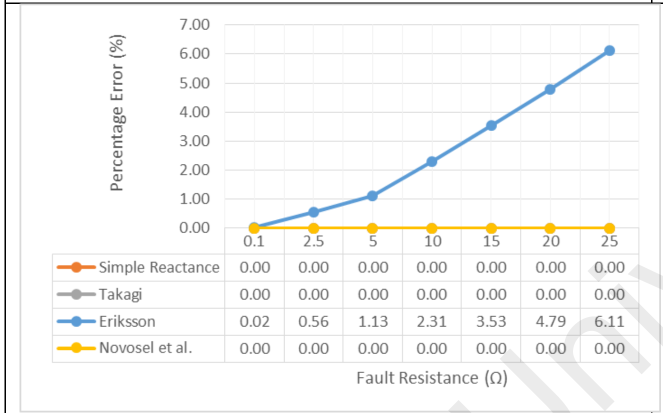
(a)



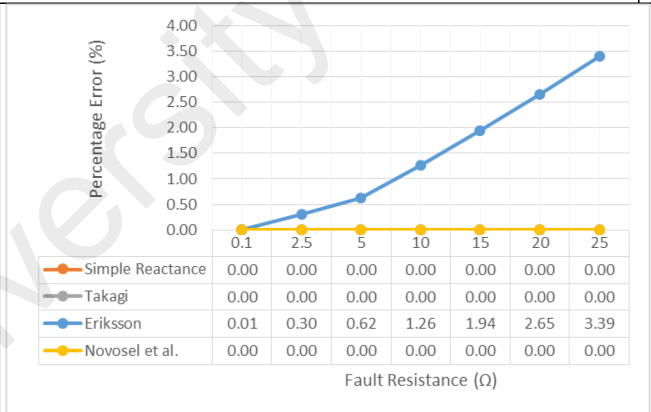
(b)



(c)



(d)



(e)

Figure 4.5: Graphs of percentage error vs fault resistance at fault distance a) 0.01pu b) 0.25pu c) 0.50pu d) 0.75pu e) 1.0pu for Case Study 3 (i)

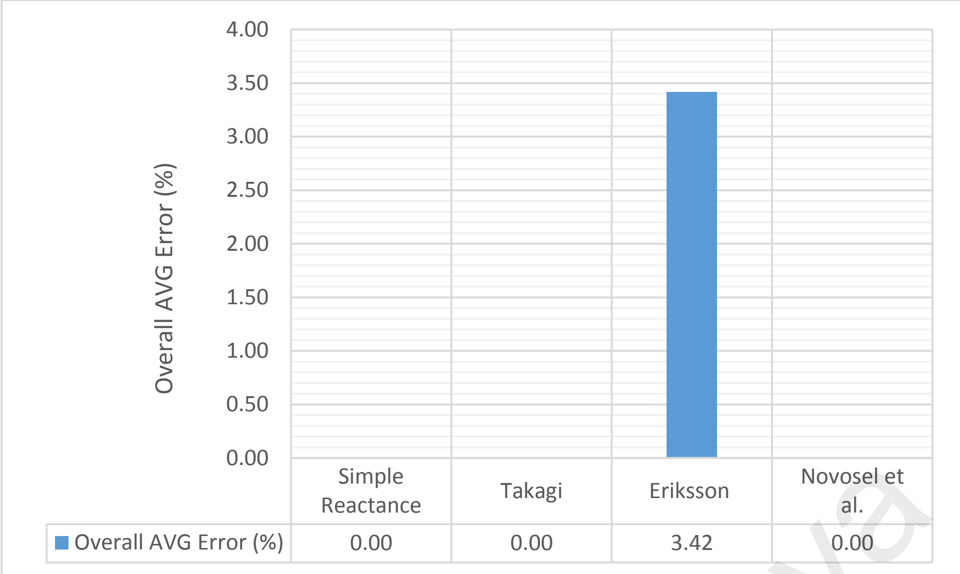


Figure 4.6: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 3 (i)

4.4.2 Discussion of Case Study 3 (i)

Case Study 3 (i) investigates the effect of unity power factor connected at local terminal on the accuracy of one-ended impedance-based fault location methods. The connected unity power factor load at local terminal does not change the results in Case Study 3 (i) as compared to Case Study 2 because the load and the measuring point of voltage and current waveforms are both located at local terminal. Before fault is initiated, there is no current flowing in the transmission line due to the open circuit at the remote terminal. During fault period, I_S is equal to I_F because remote terminal is open-ended and the I_S flows directly to the fault point as there is no alternative path. Adding load at local terminal does not affect the values of I_S and I_F because the measuring point is also location at same terminal. It will not "see" the increased current demand due to additional loading but only the outgoing current from the local terminal to the fault point. As a result, the voltage and current values obtained in Case Study 3 (i) are no difference with the values in Case Study 2 and subsequently, the fault location algorithms produced the results which is identical to Case Study 2.

The effect of unity power factor load connected at local terminal on the accuracy of fault location methods in Case Study 3 (i) in reference to Case Study 2 is summarized in Table 4.3:

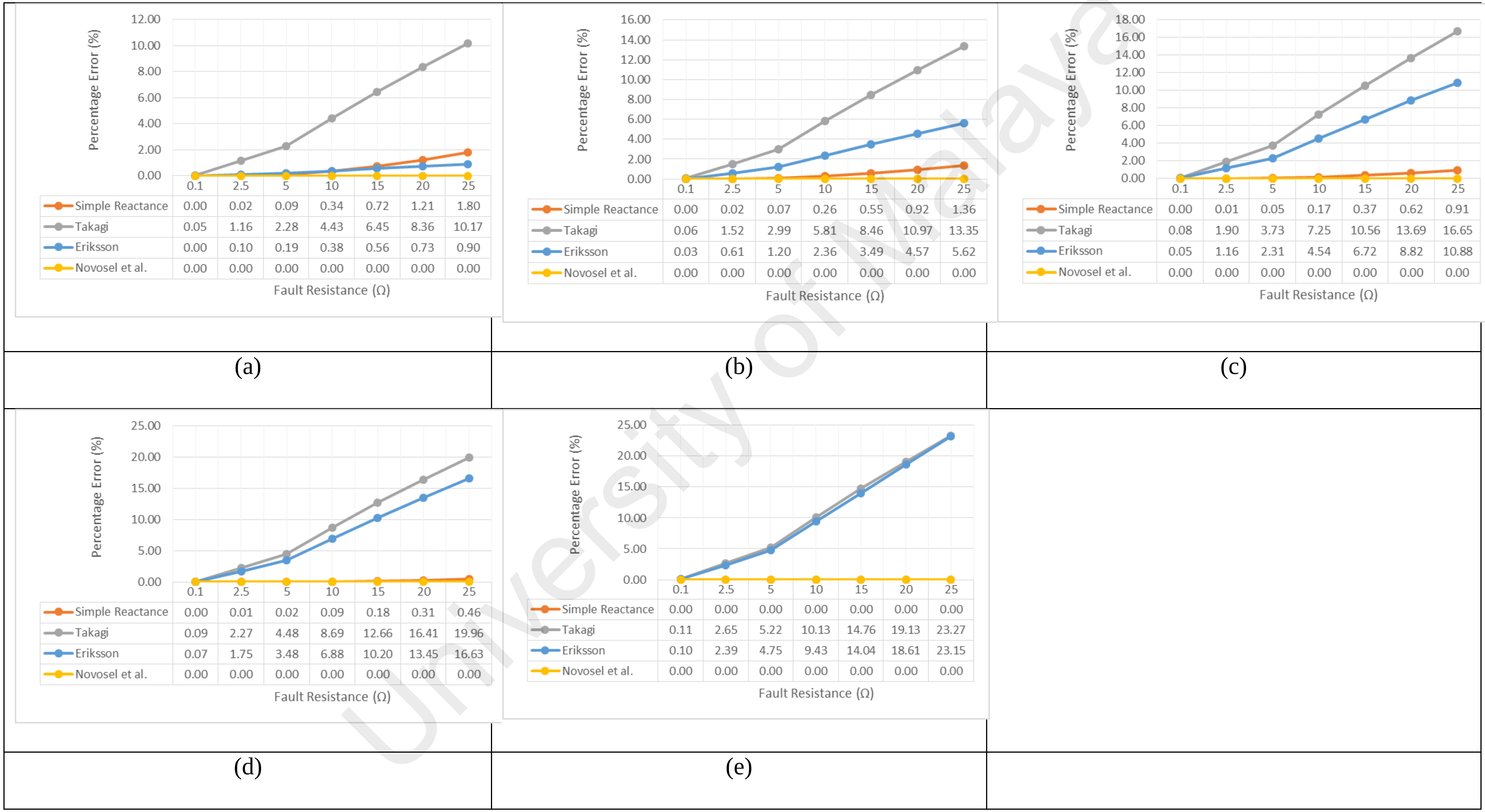
Table 4.3: Summary of Case Study 3 (i)

Case Study 3 (i)	
Fault Location Method	**Sensitivity to Unity Power Load Connected at Local Terminal**
Simple Reactance	No
Takagi	No
Eriksson	No
Novosel et al.	No

4.4.3 Results of Case Study 3 (ii)

The results of Case Study 3 (ii) are plotted into graphs as presented in Figure 4.7. It is observed that the simple reactance and Novosel et al. methods are not affected by the unity power factor load connected at remote terminal. The percentage error of these 2 methods persists nearly 0% at all fault resistance and fault distance. From Figure 4.7, it shows the percentage error of Takagi method increases with the increasing fault resistance and fault distance values after the unity power factor load is connected at remote terminal. On the other hand, the accuracy of Eriksson method drops as the fault distance from local terminal increases.

Based on Figure 4.8, the Novosel et al. methods has 0% overall percentage error, followed by simple reactance method (0.30), Eriksson method (5.15%), and Takagi method (7.71%).



(a)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.02	0.09	0.34	0.72	1.21	1.80
Takagi	0.05	1.16	2.28	4.43	6.45	8.36	10.17
Eriksson	0.00	0.10	0.19	0.38	0.56	0.73	0.90
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(b)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.02	0.07	0.26	0.55	0.92	1.36
Takagi	0.06	1.52	2.99	5.81	8.46	10.97	13.35
Eriksson	0.03	0.61	1.20	2.36	3.49	4.57	5.62
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(c)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.01	0.05	0.17	0.37	0.62	0.91
Takagi	0.08	1.90	3.73	7.25	10.56	13.69	16.65
Eriksson	0.05	1.16	2.31	4.54	6.72	8.82	10.88
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(d)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.01	0.02	0.09	0.18	0.31	0.46
Takagi	0.09	2.27	4.48	8.69	12.66	16.41	19.96
Eriksson	0.07	1.75	3.48	6.88	10.20	13.45	16.63
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(e)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Takagi	0.11	2.65	5.22	10.13	14.76	19.13	23.27
Eriksson	0.10	2.39	4.75	9.43	14.04	18.61	23.15
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 4.7: Graphs of percentage error vs fault resistance at fault distance a) 0.01pu b) 0.25pu c) 0.50pu d) 0.75pu e) 1.0pu for Case Study 3(ii)

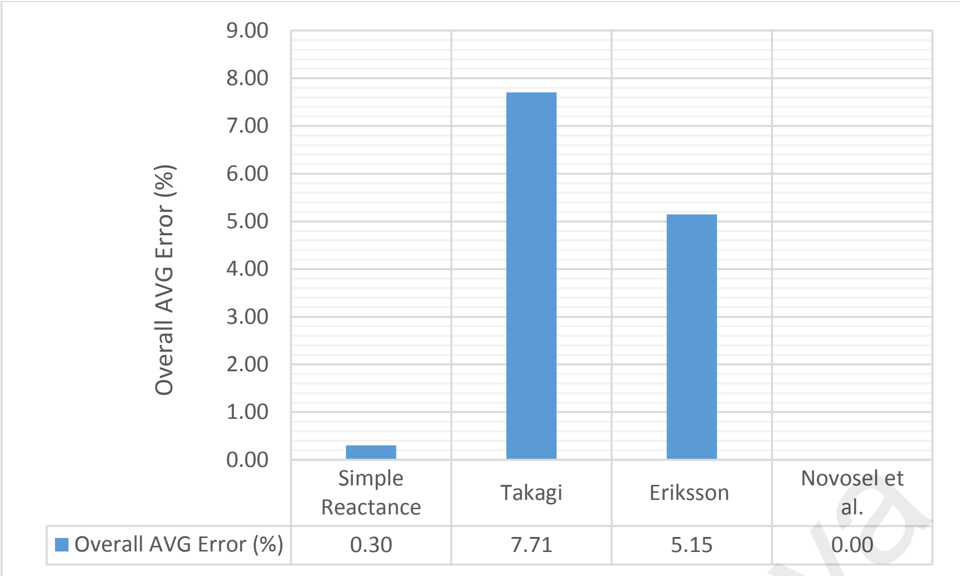


Figure 4.8: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 3 (ii)

4.4.4 Discussion of Case Study 3 (ii)

Case Study 3 (ii) investigates the effect of unity power factor connected at remote terminal on the accuracy of one-ended impedance-based fault location methods. Based on Figure 2.5, it is known that the magnitude of reactance error depends on the phase angle difference between I_F and I_S. The connected load is pure resistive and has little effect to the reactance of the transmission system and therefore the overall percentage error of simple reactance is only 0.30% which is comparatively small when compare to Takagi, Eriksson, and Novosel et al. methods.

In Case Study 3 (ii), the connected load is fully supplied by the Source S. Thus the calculated Z_{Load} using $V_{S1\ pre}$ and $I_{S1\ pre}$ for Novosel et al. method is very precise. Due to that the Novosel et al. method is robust to the reactance error caused by the load, fault resistance, and the fault location distance. This explains the reason why Novosel et al. method has perfect accuracy in the Case Study 3 (ii).

In this case study, the transmission system is shifted to non-homogenous system after the resistive load is connected at remote terminal. This causes the pre-fault current, $I_{S\,pre}$ leads the fault current, I_S and the phase angle difference between them is depending on the total fault impedance which including the fault line impedance and fault resistance. Takagi methods uses pure fault current by subtracting out the pre-fault current from the fault current. Therefore the greater the phase angle mismatch between pre-fault current and fault current, the higher the reactance error will produce. Hence the Takagi method is sensitive to fault resistance and fault distance when resistive load is connected at remote terminal.

Similar to previous explanation in Case Study 2, Eriksson method is sensitive to the change of fault distance and results in 5.15% overall percentage due to incorrect Z_{R1} as explained in Case Study 1's discussion.

The effect of unity power factor load connected at remote terminal on the accuracy of fault location methods in Case Study 3 (ii) in reference to Case Study 2 is summarized in Table 4.4:

Table 4.4: Summary of Case Study 3 (ii)

Case Study 3 (ii)	
Fault Location Method	**Sensitivity to Unity Power Factor Load Connected at Remote Terminal**
Simple Reactance	Yes, error increases
Takagi	Yes, error increases
Eriksson	Yes, error increases
Novosel et al.	No

4.5 Results and Discussion of Case Study 4

The results of Case Study 4 in this section presents the effect of power factor load on the accuracy of one-ended impedance-based fault location methods. In Case Study 4, there are 2 samples of results as follows:

Case Study 4 (i): 0.8 lagging power factor load is connected at local terminal

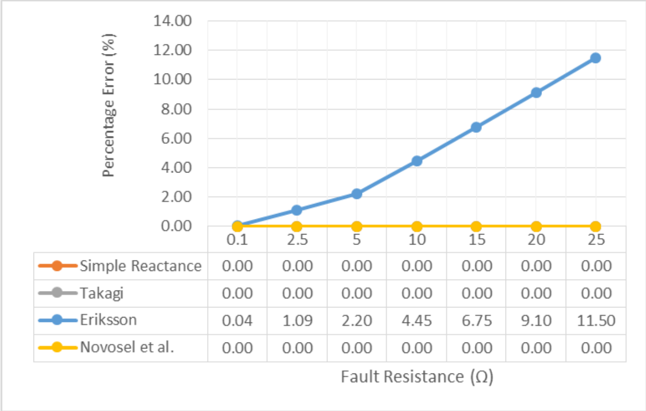
Case Study 4 (ii): 0.8 lagging power factor load is connected at remote terminal

Each sample of results has 5 graphs, each graph represents the results of the sample at the particular fault distance.

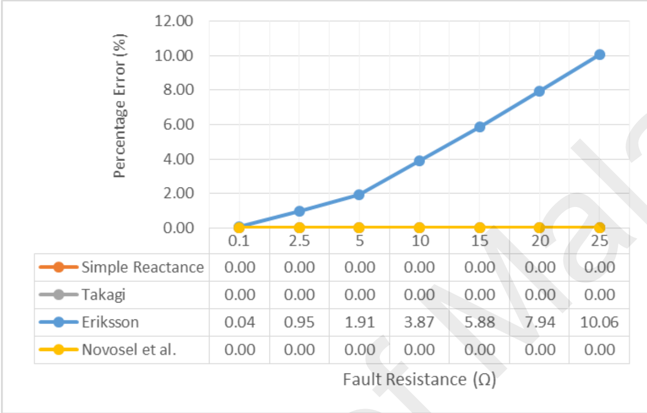
4.5.1 Results of Case Study 4 (i)

The results of Case Study 4 (i) are plotted into graphs as presented in Figure 4.9. It shows no changes in the accuracy of all methods when the 0.8 lagging power factor load is connected at local terminal as compared to the results in Case Study 2 and Case Study 3 (i).

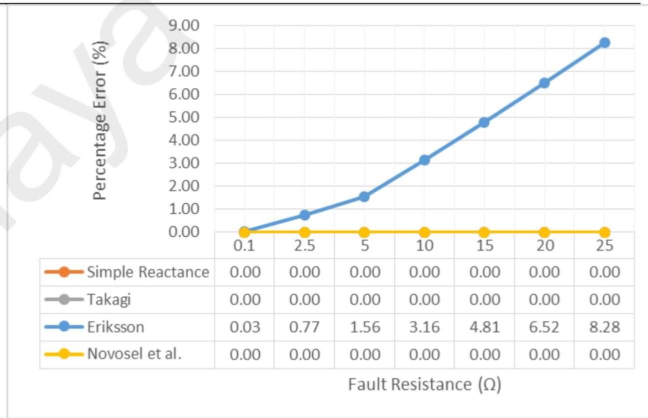
Besides, the overall percentage error of all one-ended impedance-based fault location methods as presented in Figure 4.10 is also identical to Case Study 2 and Case Study 3 (i).



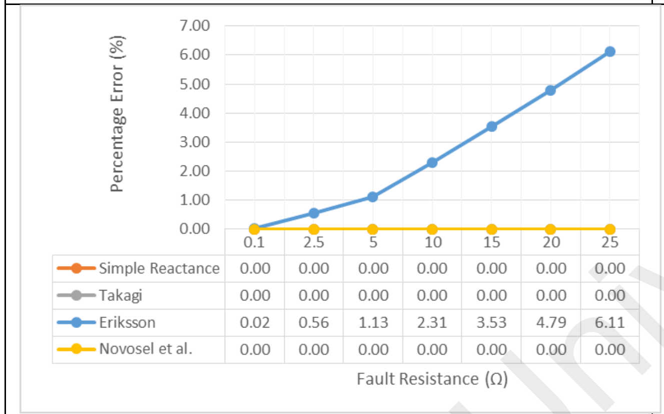
(a)



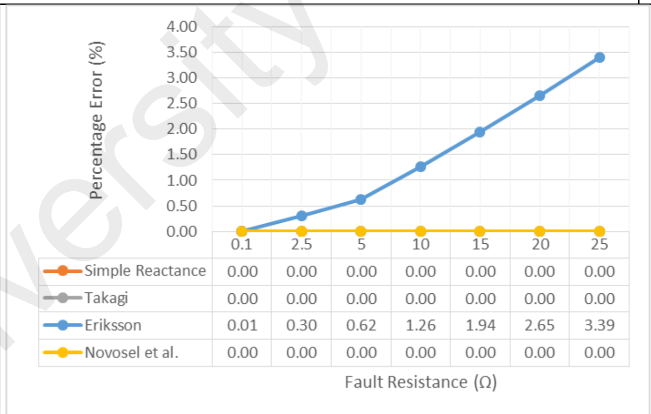
(b)



(c)



(d)



(e)

Figure 4.9: Graphs of percentage error vs fault resistance at fault distance a) 0.01pu b) 0.25pu c) 0.50pu d) 0.75pu e) 1.0pu for Case Study 4(i)

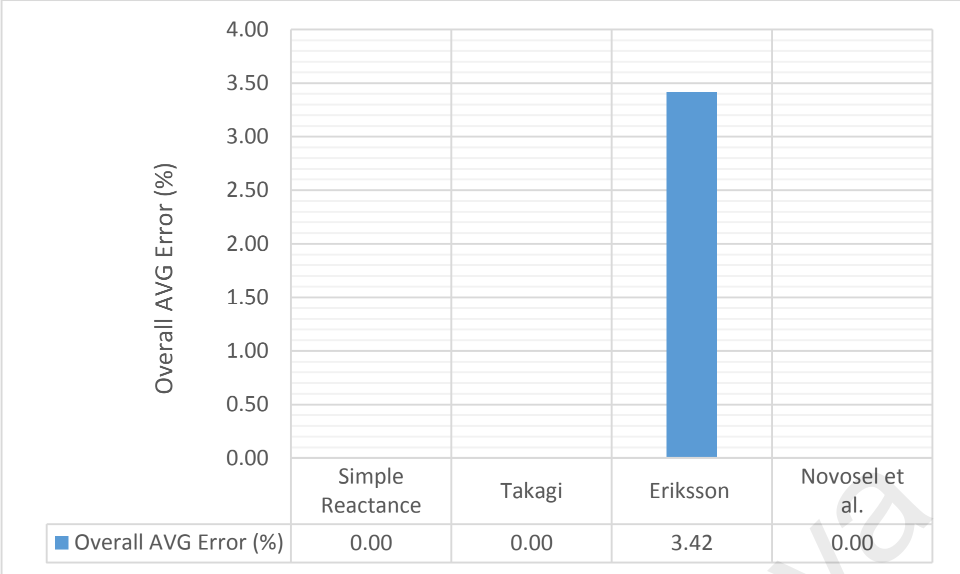


Figure 4.10: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 4 (i)

4.5.2 Discussion of Case Study 4 (i)

Case Study 4 (i) investigates the effect of 0.8 lagging power factor connected at local terminal on the accuracy of one-ended impedance-based fault location methods The explanation is similar to the discussion in Case Study 3 (i).

The effect of 0.8 lagging power factor load connected at local terminal on the accuracy of fault location methods in Case Study 4 (i) in reference to Case Study 3 (i) is summarized in Table 4.5:

Table 4.5: Summary of Case Study 4 (i)

Case Study 4 (i)	
Fault Location Method	**Sensitivity to 0.8 Lagging Power Factor Load Connected at Local Terminal**
Simple Reactance	No
Takagi	No
Eriksson	No
Novosel et al.	No

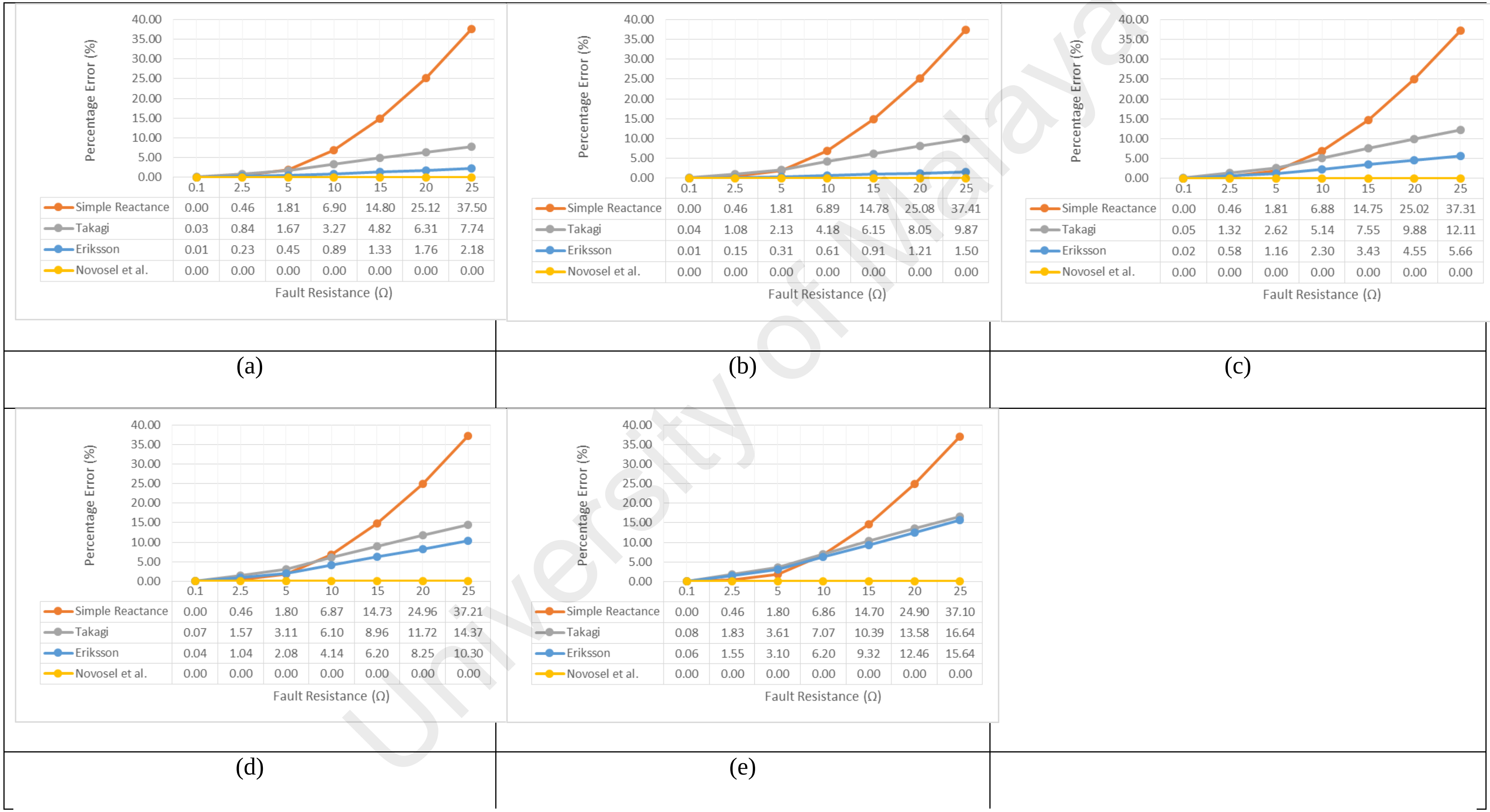
4.5.3 Results of Case Study 4 (ii)

The results of Case Study 4 (ii) are plotted into graphs as presented in Figure 4.11. Based on Figure 4.11, the simple reactance method is sensitive to the changes of fault resistance but robust to the changes of fault distance. The percentage error of simple reactance method increases as fault resistance increase but the increasing of fault distance only gives small increment of percentage error which is almost negligible.

The Takagi and Eriksson methods show their sensitivity to both fault resistance and fault distance when the 0.8 lagging power factor load is connected at remote terminal. Their percentage errors increase with the increasing of fault resistance or fault distance.

Novosel et al. method is not influenced by the connected 0.8 lagging power factor load and maintain 0% percentage error at all values of fault resistance and fault distance.

According to Figure 4.12, the accuracy in ascending order is simple reactance method (12.32%), Takagi method (5.54%), Eriksson method (3.13%), and Novosel et al. method (0%).



(a)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.46	1.81	6.90	14.80	25.12	37.50
Takagi	0.03	0.84	1.67	3.27	4.82	6.31	7.74
Eriksson	0.01	0.23	0.45	0.89	1.33	1.76	2.18
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(b)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.46	1.81	6.89	14.78	25.08	37.41
Takagi	0.04	1.08	2.13	4.18	6.15	8.05	9.87
Eriksson	0.01	0.15	0.31	0.61	0.91	1.21	1.50
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(c)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.46	1.81	6.88	14.75	25.02	37.31
Takagi	0.05	1.32	2.62	5.14	7.55	9.88	12.11
Eriksson	0.02	0.58	1.16	2.30	3.43	4.55	5.66
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(d)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.46	1.80	6.87	14.73	24.96	37.21
Takagi	0.07	1.57	3.11	6.10	8.96	11.72	14.37
Eriksson	0.04	1.04	2.08	4.14	6.20	8.25	10.30
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(e)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.00	0.46	1.80	6.86	14.70	24.90	37.10
Takagi	0.08	1.83	3.61	7.07	10.39	13.58	16.64
Eriksson	0.06	1.55	3.10	6.20	9.32	12.46	15.64
Novosel et al.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 4.11: Graphs of percentage error vs fault resistance at fault distance a)0.01pu b)0.25pu c)0.50pu d)0.75pu e)1.0pu for Case Study 4(ii)

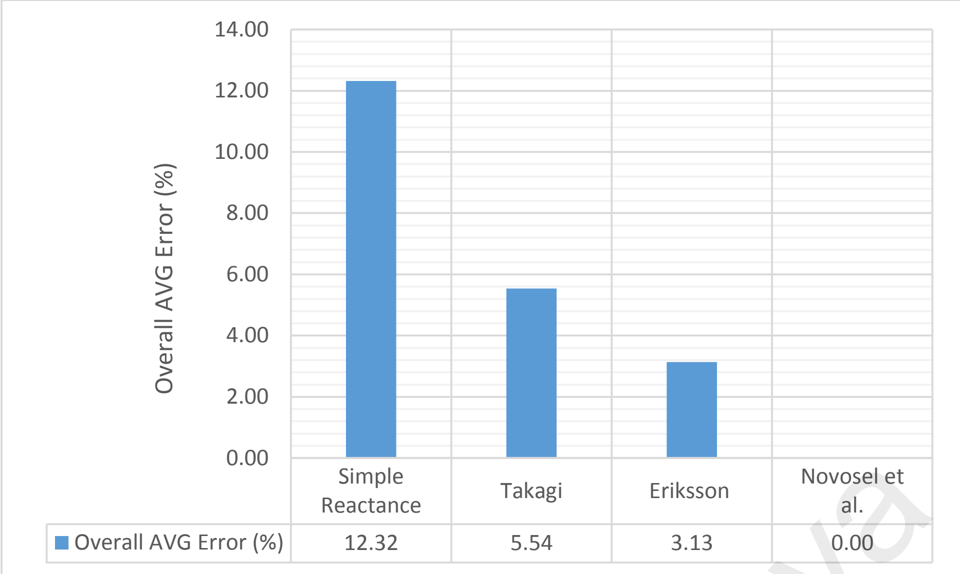


Figure 4.12: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 4 (ii)

4.5.4 Discussion of Case Study 4 (ii)

Case Study 4 (ii) investigates the effect of 0.8 lagging power factor connected at remote terminal on the accuracy of one-ended impedance-based fault location methods. The configuration of Case Study 4 (ii) is similar to Case Study 3 (ii) except the connected load at remote terminal is replaced with a 0.8 lagging power factor load (inductive load).

This inductive load causes I_F leads I_S and thus increases the phase angle mismatch between them. In addition, the reactance error of simple reactance method can be expressed as $R_F(I_F/I_S)$ according to (Das et al., 2014), where the reactance error is proportional to the fault resistance. As a result, the simple reactance method seems to have higher reactance error and sensitive to the fault resistance in this case study. Nevertheless, the changes of fault distance have very limited effect on the accuracy of simple reactance method in Case Study 4 (ii).

Results show that Takagi method has better accuracy when inductive load is connected at remote terminal as compared to Case Study 3 (ii). This is because the inductive load casued the pre-fault current to become more lagging and subsequently reduce the phase angle difference between $I_{S\,pre}$ and I_S. Even so, Takagi method remains the sensitivity to the fault distance and fault resistance similarly like Case Study 3 (ii).

Similar to Case Study 1, 2, and 3, the accuracy of Eriksson method is mainly affected by the incorrect Z_{R1} due to absence of Source R in the transmission system. It uses $I_{S\,pre}$ and I_S in the algorithm like Takagi method, therefore the accuracy of Eriksson method seems improved as compared to Case Study 3 (ii).

As discussed in Case Study 3 (ii), the Z_{Load} calculated using Novosel et al. algorithm is very precise because the connected load is fully supplied by the local source without influence from remote source in-feed. Therefore Novosel et al. method is also having 0% percentage error in this case study.

The effect of 0.8 lagging power factor load connected at remote terminal on the accuracy of fault location methods in Case Study 4 (ii) in reference to Case Study 3 (ii) is summarized in Table 4.6:

Table 4.6: Summary of Case Study 4 (ii)

Case Study 4 (ii)	
Fault Location Method	**Sensitivity to 0.8 Lagging Power Factor Load Connected at Remote Terminal**
Simple Reactance	Yes, error increases
Takagi	Yes, error decreases
Eriksson	Yes, error decreases
Novosel et al.	No

4.6 Results and Discussion of Case Study 5

The results of Case Study 5 in this section presents the effect of power factor on the accuracy of one-ended impedance-based fault location methods. In Case Study 5, there are 5 samples of results as follows:

Case Study 5 (i): Remote source (Source R) is added with no load connected

Case Study 5 (ii): Remote source (Source R) is added with unity power factor load connected at local terminal

Case Study 5 (iii): Remote source (Source R) is added with unity power factor load connected at remote terminal

Case Study 5 (iv): Remote source (Source R) is added with 0.8 lagging power factor load connected at local terminal

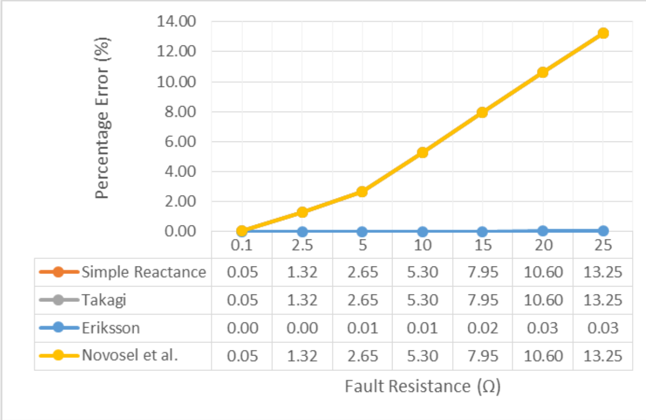
Case Study 5 (v): Remote source (Source R) is added with 0.8 lagging power factor load connected at remote terminal

Each sample of results has 5 graphs, each graph represents the results of the sample at the particular fault distance.

4.6.1 Results of Case Study 5 (i)

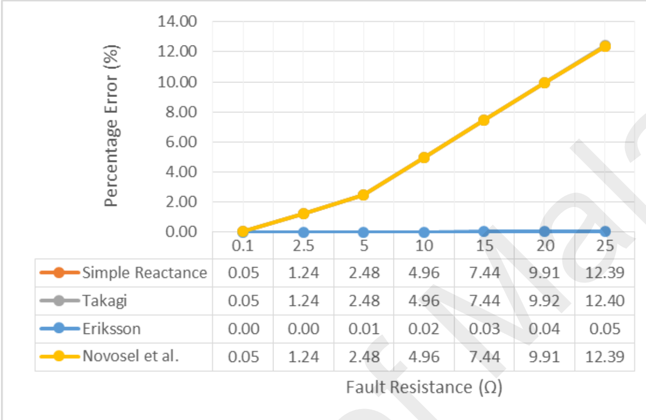
The results of Case Study 5 (i) are plotted into graphs as presented in Figure 4.13. Based on the figure, the simple reactance, Takagi, and Novosel et al. methods show identical results where the percentage error of these 3 methods reduces as the fault distance increases and increases when fault resistance increases. Eriksson shows nearly 0% percentage error and the percentage error is almost constantly stable at all fault distances and fault resistances.

The overall percentage errors in Figure 4.14 show the simple reactance, Takagi, and Novosel et al. methods have same accuracy in this case study with percentage error of 4.50%. Eriksson method has nearly perfect accuracy with only 0.03% of overall percentage error.



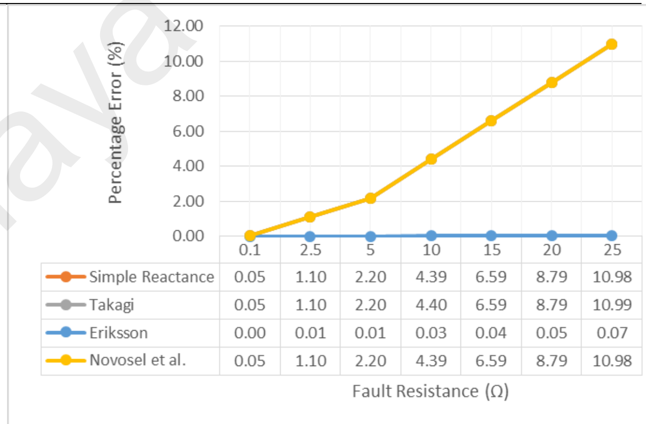
	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.32	2.65	5.30	7.95	10.60	13.25
Takagi	0.05	1.32	2.65	5.30	7.95	10.60	13.25
Eriksson	0.00	0.00	0.01	0.01	0.02	0.03	0.03
Novosel et al.	0.05	1.32	2.65	5.30	7.95	10.60	13.25

(a)



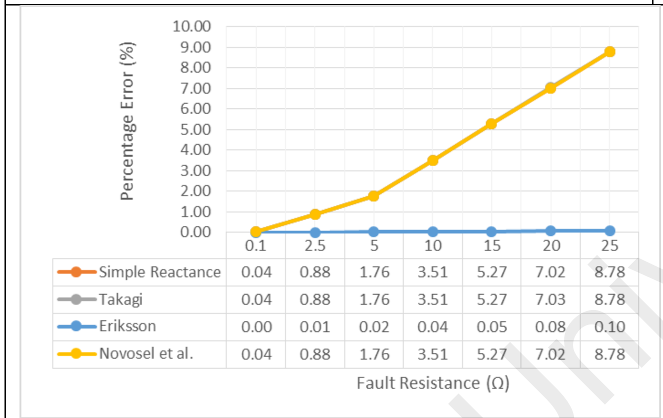
	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.24	2.48	4.96	7.44	9.91	12.39
Takagi	0.05	1.24	2.48	4.96	7.44	9.92	12.40
Eriksson	0.00	0.00	0.01	0.02	0.03	0.04	0.05
Novosel et al.	0.05	1.24	2.48	4.96	7.44	9.91	12.39

(b)



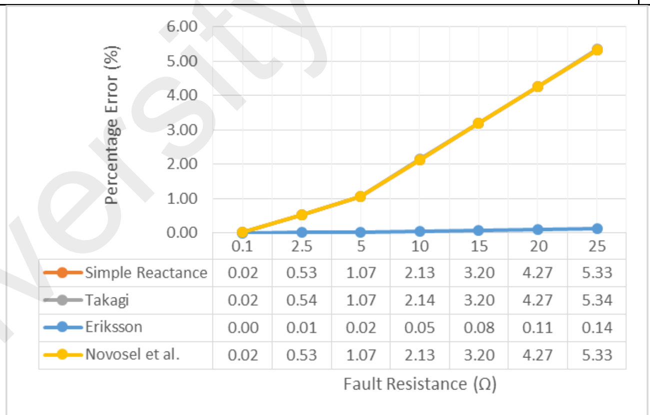
	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.10	2.20	4.39	6.59	8.79	10.98
Takagi	0.05	1.10	2.20	4.40	6.59	8.79	10.99
Eriksson	0.00	0.01	0.01	0.03	0.04	0.05	0.07
Novosel et al.	0.05	1.10	2.20	4.39	6.59	8.79	10.98

(c)



	0.1	2.5	5	10	15	20	25
Simple Reactance	0.04	0.88	1.76	3.51	5.27	7.02	8.78
Takagi	0.04	0.88	1.76	3.51	5.27	7.03	8.78
Eriksson	0.00	0.01	0.02	0.04	0.05	0.08	0.10
Novosel et al.	0.04	0.88	1.76	3.51	5.27	7.02	8.78

(d)



	0.1	2.5	5	10	15	20	25
Simple Reactance	0.02	0.53	1.07	2.13	3.20	4.27	5.33
Takagi	0.02	0.54	1.07	2.14	3.20	4.27	5.34
Eriksson	0.00	0.01	0.02	0.05	0.08	0.11	0.14
Novosel et al.	0.02	0.53	1.07	2.13	3.20	4.27	5.33

(e)

Figure 4.13: Graphs of percentage error vs fault resistance at fault distance a)0.01pu b)0.25pu c)0.50pu d)0.75pu e)1.0pu for Case Study 5(i)

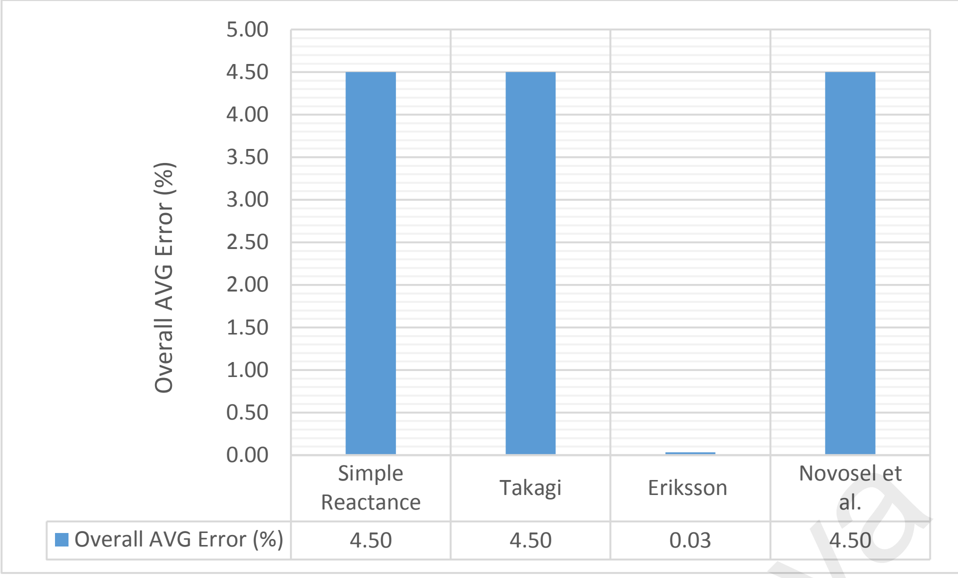


Figure 4.14: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 5(i)

4.6.2 Discussion of Case Study 5 (i)

Case Study 5 (i) investigates the effect of remote source in-feed on the accuracy of one-ended impedance-based fault location methods. The transmission network in Case Study 5 (i) is a typical two terminal transmission system that has source at both terminals without any system load connected as resembled in Appendix N – Transmission Network 6.

The remote source in-feed with source impedance alters the degree of homogeneity and the current phasor of the transmission network. Therefore, simple reactance, Takagi, and Novosel et al. methods are affected by remote source in-feed because their algorithms do not consider the remote source impedance like Eriksson method to reduce the effect of remote source in-feed to the transmission network. Due to this, the simple reactance, Takagi, and Novosel et al. methods have poor accuracy and sensitive to the changes of fault distance and fault resistance even though no system load is connected at either terminal.

Note that there is no system load connected in this case study. Therefore the effect of the pre-fault current and load current is almost negligible. As a result, the simple reactance, Takagi, and Novosel et al. methods have identical results as displayed in Figure 4.13.

Eriksson method shows superior result and gives the best fault location estimation with only 0.03% overall percentage error. This method uses source impedance parameters in the algorithm to minimize the effect of fault resistance, fault distance, and non-homogeneity. Unlike the previous case studies, the accuracy of Eriksson method is greatly improved because Source R is connected at remote terminal and Z_{R1} used is no longer an incorrect value.

The effect of remote source in-feed on the accuracy of fault location methods in Case Study 5 (i) in reference to Case Study 2 is summarized in Table 4.7:

Table 4.7: Summary of Case Study 5 (i)

Case Study 5 (i)	
Fault Location Method	**Sensitivity to Remote Source In-feed**
Simple Reactance	Yes, error increases
Takagi	Yes, error increases
Eriksson	Yes, error decreases
Novosel et al.	Yes, error increases

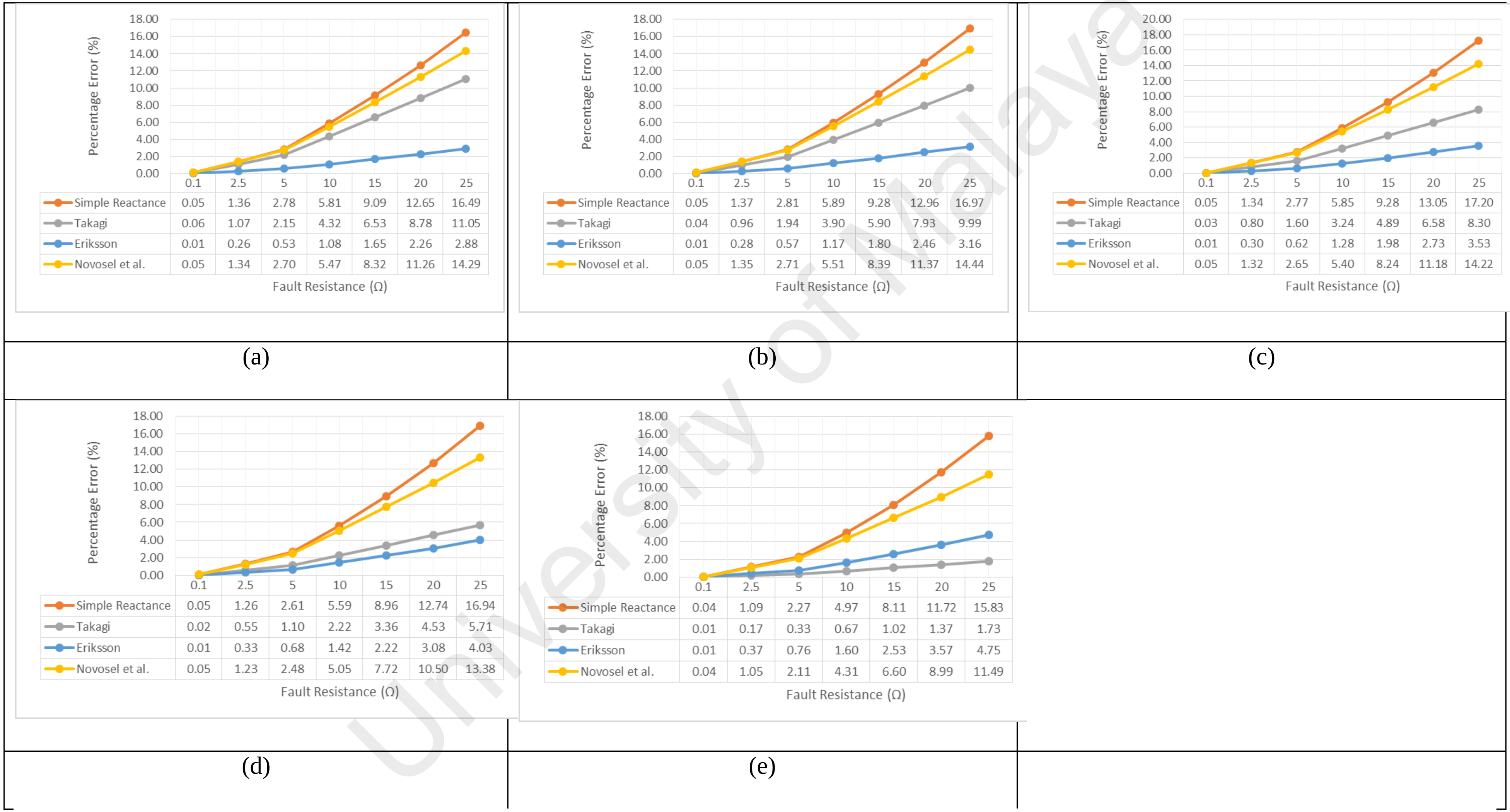
4.6.3 Results of Case Study 5 (ii)

The results of Case Study 5 (ii) are plotted into graphs as presented in Figure 4.15. As observed, the simple reactance method is robust to the influence of fault distance but sensitive to the fault resistance. The percentage error of simple reactance method increases with the increasing fault resistance value.

The accuracy of Takagi and Novosel et al. methods improves as the fault distance increases. They are also sensitive to fault resistance where the increasing of fault resistance increases the percentage error of these two methods.

Eriksson method is sensitive to both fault distance and fault resistance. The percentage error increases when fault distance or fault resistance increases.

Based on Figure 4.16, Eriksson method (1.54%) has the best accuracy in Case Study 5 (ii) followed by Takagi method (3.22%), Novosel et al. method (5.87%), and simple reactance method (6.84%).



(a)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.36	2.78	5.81	9.09	12.65	16.49
Takagi	0.06	1.07	2.15	4.32	6.53	8.78	11.05
Eriksson	0.01	0.26	0.53	1.08	1.65	2.26	2.88
Novosel et al.	0.05	1.34	2.70	5.47	8.32	11.26	14.29

(b)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.37	2.81	5.89	9.28	12.96	16.97
Takagi	0.04	0.96	1.94	3.90	5.90	7.93	9.99
Eriksson	0.01	0.28	0.57	1.17	1.80	2.46	3.16
Novosel et al.	0.05	1.35	2.71	5.51	8.39	11.37	14.44

(c)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.34	2.77	5.85	9.28	13.05	17.20
Takagi	0.03	0.80	1.60	3.24	4.89	6.58	8.30
Eriksson	0.01	0.30	0.62	1.28	1.98	2.73	3.53
Novosel et al.	0.05	1.32	2.65	5.40	8.24	11.18	14.22

(d)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.26	2.61	5.59	8.96	12.74	16.94
Takagi	0.02	0.55	1.10	2.22	3.36	4.53	5.71
Eriksson	0.01	0.33	0.68	1.42	2.22	3.08	4.03
Novosel et al.	0.05	1.23	2.48	5.05	7.72	10.50	13.38

(e)

Fault Resistance (Ω)	0.1	2.5	5	10	15	20	25
Simple Reactance	0.04	1.09	2.27	4.97	8.11	11.72	15.83
Takagi	0.01	0.17	0.33	0.67	1.02	1.37	1.73
Eriksson	0.01	0.37	0.76	1.60	2.53	3.57	4.75
Novosel et al.	0.04	1.05	2.11	4.31	6.60	8.99	11.49

Figure 4.15: Graphs of percentage error vs fault resistance at fault distance a)0.01pu b)0.25pu c)0.50pu d)0.75pu e)1.0pu for Case Study 5(ii)

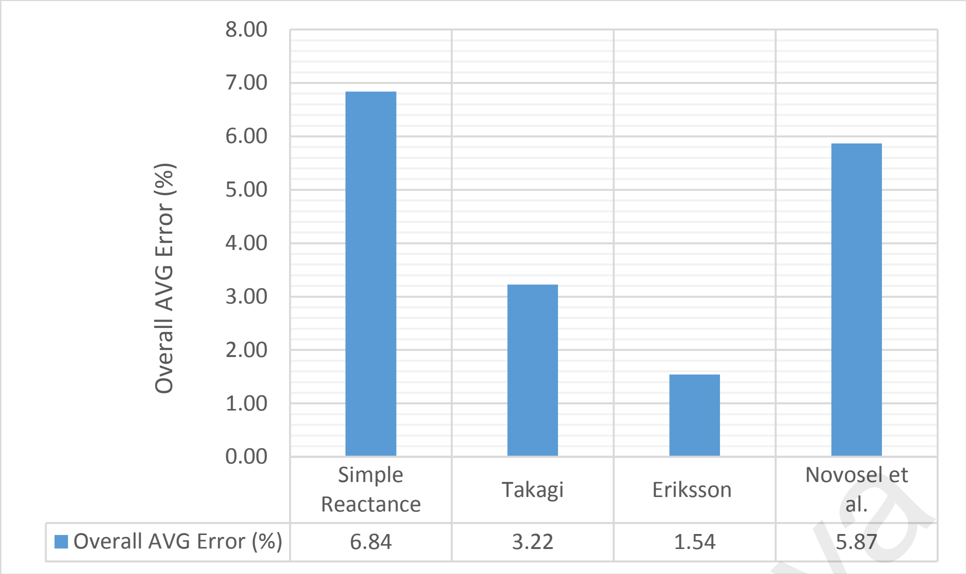


Figure 4.16: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 5 (ii)

4.6.4 Discussion of Case Study 5 (ii)

Case Study 5 (ii) investigates the effect of remote source in-feed on the accuracy of one-ended impedance-based fault location methods. The network configuration in this case study is similar to Case Study 3 (i) with additional remote source connected at the remote terminal.

The introduction of remote source turns the transmission network to a non-homogeneous system. As explained earlier, the reactance error is proportional to $R_F(I_F/I_S)$. The resistive load connected at local terminal and fault distance have little effect on the phase angle difference between I_F and I_S. Therefore the simple reactance method is robust to fault distance but sensitive to fault resistance in this case study.

Takagi method has better accuracy than simple reactance method because it uses the pure fault current in the algorithm to reduce the effect of remote source in-feed. Note that the resistive load is not connected at remote terminal, therefore the Takagi method can determine the pure fault current more accurately when the fault distance is closer to the remote terminal.

Eriksson uses source impedances at local and remote terminals to reduce the influence of system parameters. Therefore, the accuracy of Eriksson method improved as compared to Case Study 3 (i) after the remote source is connected where the source impedance values are defined.

The advantage of Novosel et al. method to estimate the fault distance using Z_{Load} is no longer valid in this case study because the load is connected at local terminal but not remote terminal. Furthermore, the accuracy of Novosel et al. method is also affected by remote source in-feed unlike in Case Study 3 (i) where the remote terminal is open-ended and free of in-feed influence. As a result, the Novosel et al. method has the second worst accuracy after simple reactance method.

The effect of remote source in-feed on the accuracy of fault location methods in Case Study 5 (ii) in reference to Case Study 3 (i) is summarized in Table 4.8:

Table 4.8: Summary of Case Study 5 (ii)

Case Study 5 (ii)	
Fault Location Method	**Sensitivity to Remote Source In-feed**
Simple Reactance	Yes, error increases
Takagi	Yes, error increases
Eriksson	Yes, error decreases
Novosel et al.	Yes, error increases

4.6.5 Results of Case Study 5 (iii)

The results of Case Study 5 (ii) are plotted into graphs as presented in Figure 4.17. The percentage error of simple reactance is observed increases when the fault resistance increases. However its accuracy improves when the fault distance increases.

Takagi and Eriksson methods are sensitive to both fault distance and fault resistance as their percentage error increases with the increasing of fault distance or fault resistance.

Novosel et al. method's percentage error increases as the fault resistance increases. On the other hand, its percentage error reduces with the increasing of fault distance.

Based on Figure 4.18, the Novosel et al. method (3.06%) is most accurate method among all in this case study, followed by simple reactance method (3.38%), Eriksson method (6.69%), and Takagi method (10.10%).

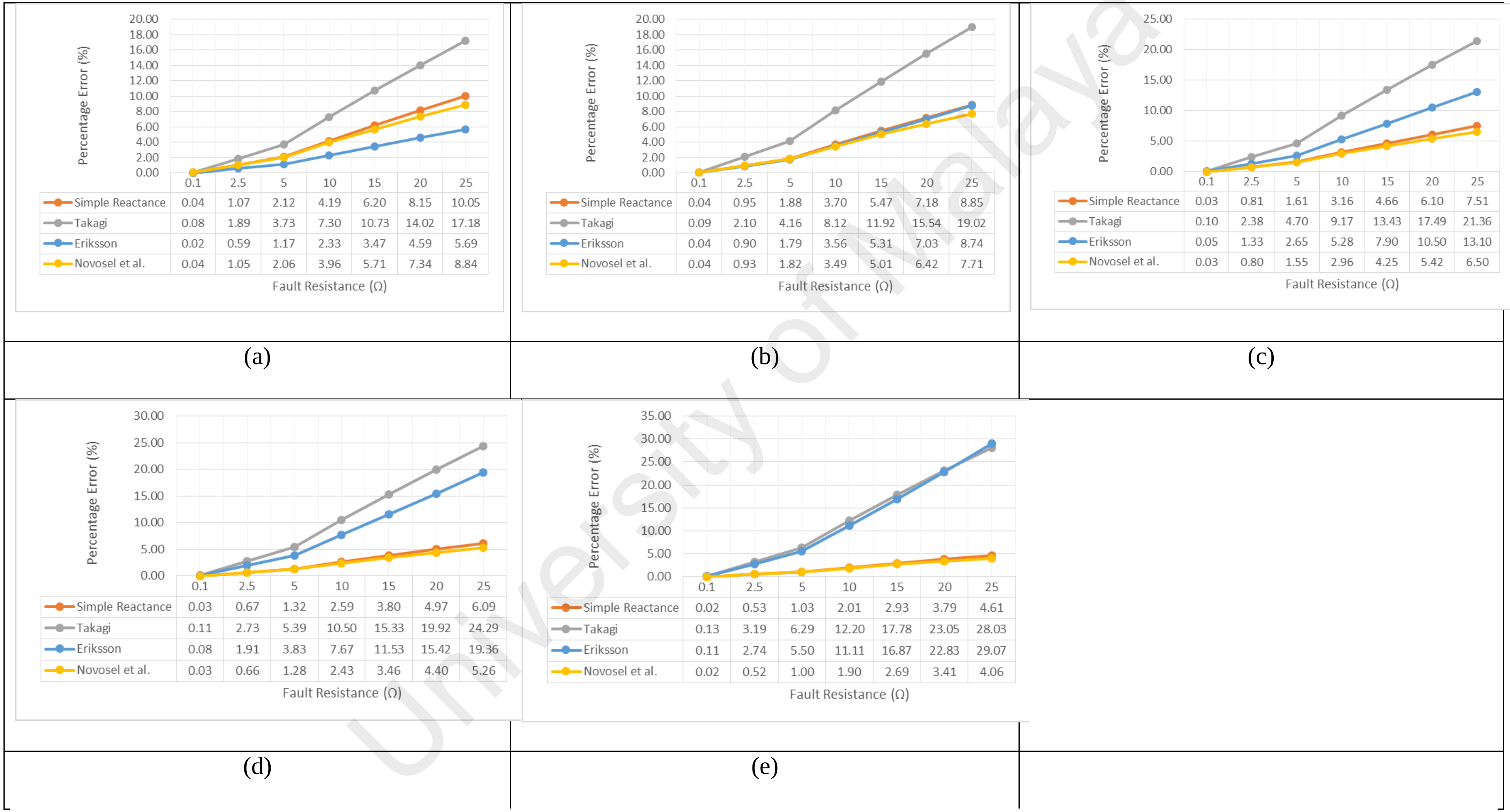


Figure 4.17: Graphs of percentage error vs fault resistance at fault distance a)0.01pu b)0.25pu c)0.50pu d)0.75pu e)1.0pu for Case Study 5(iii)

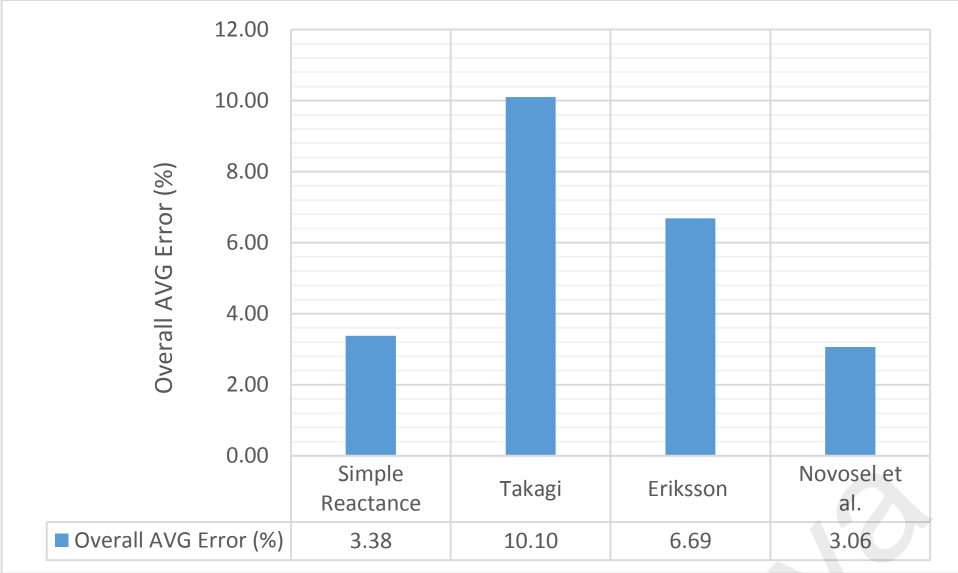


Figure 4.18: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 5 (iii)

4.6.6 Discussion of Case Study 5 (iii)

Case Study 5 (iii) investigates the effect of remote source in-feed on the accuracy of one-ended impedance-based fault location methods. The network configuration in this case study is similar to Case Study 3 (ii) with additional remote source connected at the remote terminal.

The simple reactance method has similar sensitivity to fault distance like Case Study 3 (ii). Its percentage error decreases with the increasing fault distance. It is also observed that the simple reactance method has poorer accuracy if compare to Case Study 3 (ii) due to the influence of remote source in-feed. However it has better accuracy as compared to Case Study 5 (ii) because the resistive load connected at remote terminal reduces the phase angle difference between the I_F and I_S.

Takagi method has the similar behaviour to the fault resistance and fault distance like Case Study 3 (ii). The remote source in-feed further increases the non-homogeneity in the transmission network and the phase angle difference between pre-fault current, $I_{S\,pre}$ and the fault current, I_S. This deteriorates the accuracy of Takagi method and resulted in the highest percentage error among all fault location methods similar to Case Study 3 (ii).

Eriksson method has bad accuracy in this case study even though Eriksson method uses source impedances to minimise the effects of fault distance and fault resistance. This is because it uses $I_{S\ pre}$ and I_S in the algorithm like Takagi method where the phase angle mismatch between $I_{S\ pre}$ and I_S are severely affected by the resistive load connected at the remote terminal. As a result, it has the worst accuracy after Takagi method in this case study.

Unlike Case Study 3 (ii), remote terminal not just only have the resistive load but added with a remote source. This remote source in-feed affects the precision of Novosel et al. algorithm on determining the Z_{Load}. Therefore Novosel et al. method no longer preserves its perfect accuracy due to the reactance error caused by the remote source in-feed. Despite, the Novosel et al. method is still the most accurate fault location method in this case study.

The effect of remote source in-feed on the accuracy of fault location methods in Case Study 5 (ii) in reference to Case Study 3 (ii) is summarized in Table 4.9:

Table 4.9: Summary of Case Study 5 (iii)

Case Study 5 (iii)	
Fault Location Method	**Sensitivity to Remote Source In-feed**
Simple Reactance	Yes, error increases
Takagi	Yes, error increases
Eriksson	Yes, error increases
Novosel et al.	Yes, error increases

4.6.7 Results of Case Study 5 (iv)

The results of Case Study 5 (iv) are plotted into graphs as presented in Figure 4.19. The percentage error of simple reactance is observed to have inconsistent pattern. It shows increasing trend when the fault resistance increases from 0.1Ω to 15Ω then changes to decreasing trend afterwards. This point of changing from increasing trend to decreasing trend happens at smaller fault resistance value as the fault distance increases.

The percentage error of Takagi and Novosel et al. methods shows the same pattern where it increases with the increasing of fault resistance but decreases with the increasing of fault distance.

Eriksson method's accuracy reduces as the fault resistance and fault distance increases. However the effect of fault distance seems to be little and almost negligible.

Based on Figure 4.20, it is observed that the Eriksson method recorded the least overall percentage error (1.21%) among all fault location methods, followed by simple reactance method (2.37%), Takagi method (3.49%), and Novosel et al. method (5.51%).

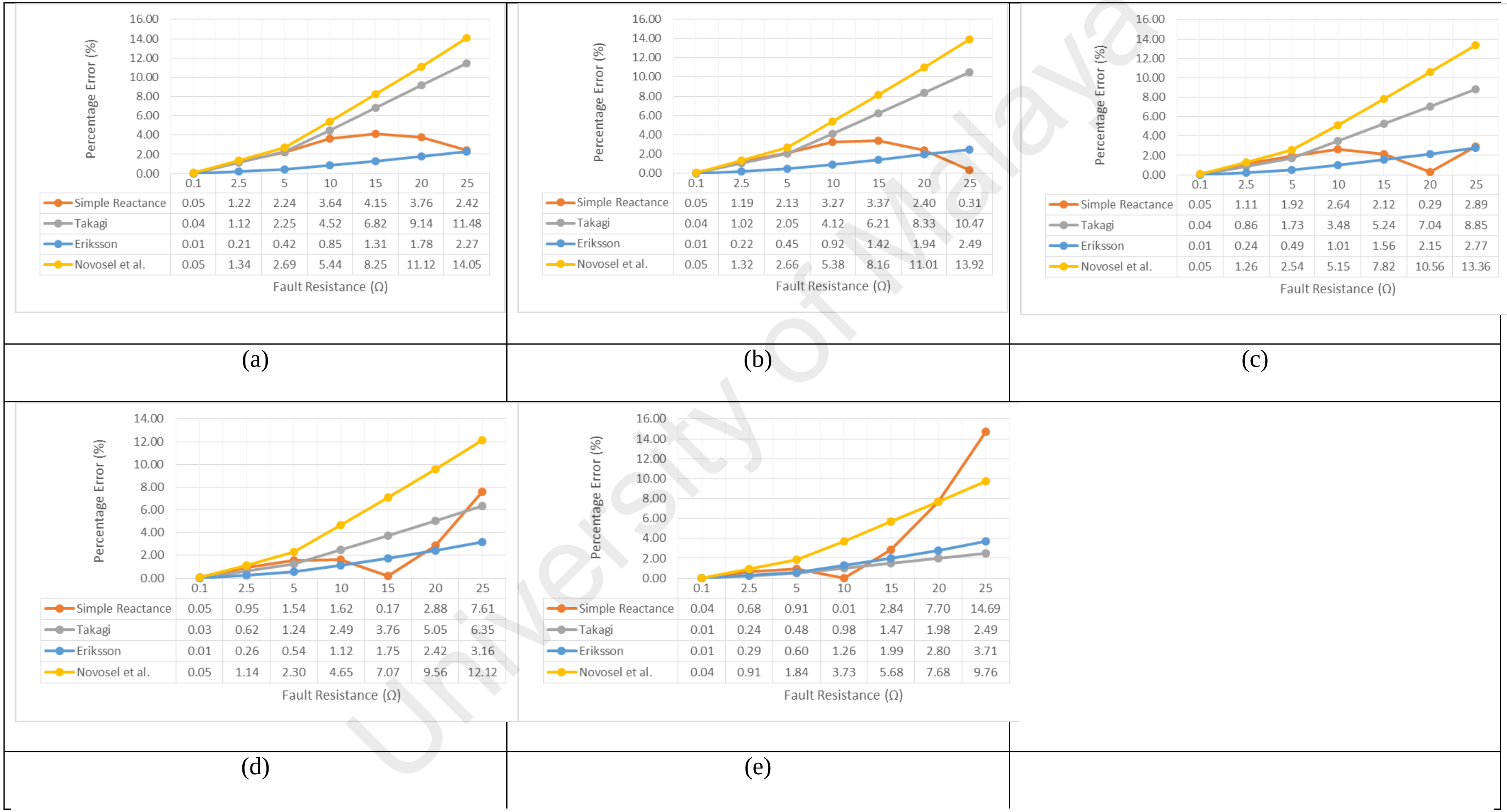


Figure 4.19: Graphs of percentage error vs fault resistance at fault distance a)0.01pu b)0.25pu c)0.50pu d)0.75pu e)1.0pu for Case Study 5(iv)

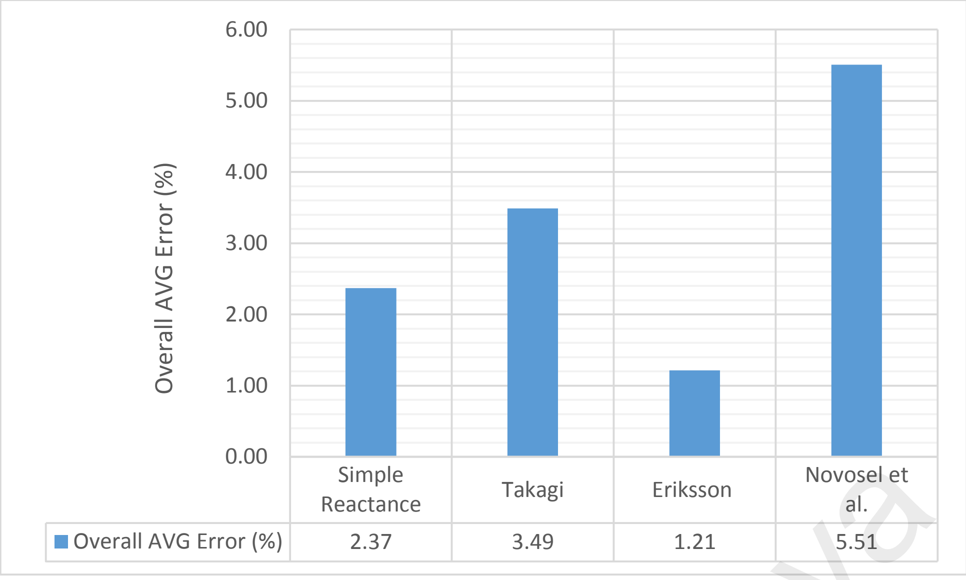


Figure 4.20: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 5 (iv)

4.6.8 Discussion of Case Study 5 (iv)

Case Study 5 (iv) investigates the effect of remote source in-feed on the accuracy of one-ended impedance-based fault location methods. The network configuration in this case study is similar to Case Study 4 (i) except a remote source is connected at remote terminal.

The introduction of inductive load at remote terminal has changed the total reactance at the local terminal. As a result, the I_F slowly leads the I_S as the fault resistance or fault distance increases. This can be observed from the results in Appendix L, it shows the simple reactance method over-estimates the fault distance at the lower values of fault resistance and fault distance. Then it becomes under-estimates the fault distance as the fault resistance and fault distance increases. Note that the reactance error is proportional to $R_F = I_F/I_S$ as explained earlier.

Takagi method was not able to offer perfect accuracy like Case Study 4 (i) due to the non-homogeneity caused by the remote source in-feed. Takagi method shows a similar sensitivity response with respect to fault resistance and fault distance as compared to Case Study 5 (ii) except the percentage error is slightly higher in this case study because the inductive load slightly increases the phase angle difference between $I_{S\,pre}$ and I_S. The good results of Takagi method in Case Study 3 (i), 4 (i), and 5 (ii) proves the Takagi method is useful to estimate the fault distance when the system load is connected at local terminal.

Like the previous case studies with remote in-feed, the accuracy of Eriksson method improves as compared to Case Study 4 (i) after the remote source impedance is defined. Compare to the results in Case Study 5 (ii), Eriksson method has the similar sensitivity response to the fault resistance and fault distance in this case study. Eriksson uses source impedances at local and remote terminals to reduce the influence of system parameters. Hence it has the best accuracy in this case study.

The accuracy of Novosel et al. method is also severely affected by the load connected at local terminal and remote source in-feed therefore it cannot maintain the perfect accuracy like Case Study 4 (i) as the Z_{Load} is not accurately determined.

The effect of remote source in-feed on the accuracy of fault location methods in Case Study 5 (iv) in reference to Case Study 4 (i) is summarized in Table 4.10:

Table 4.10: Summary of Case Study 5 (iv)

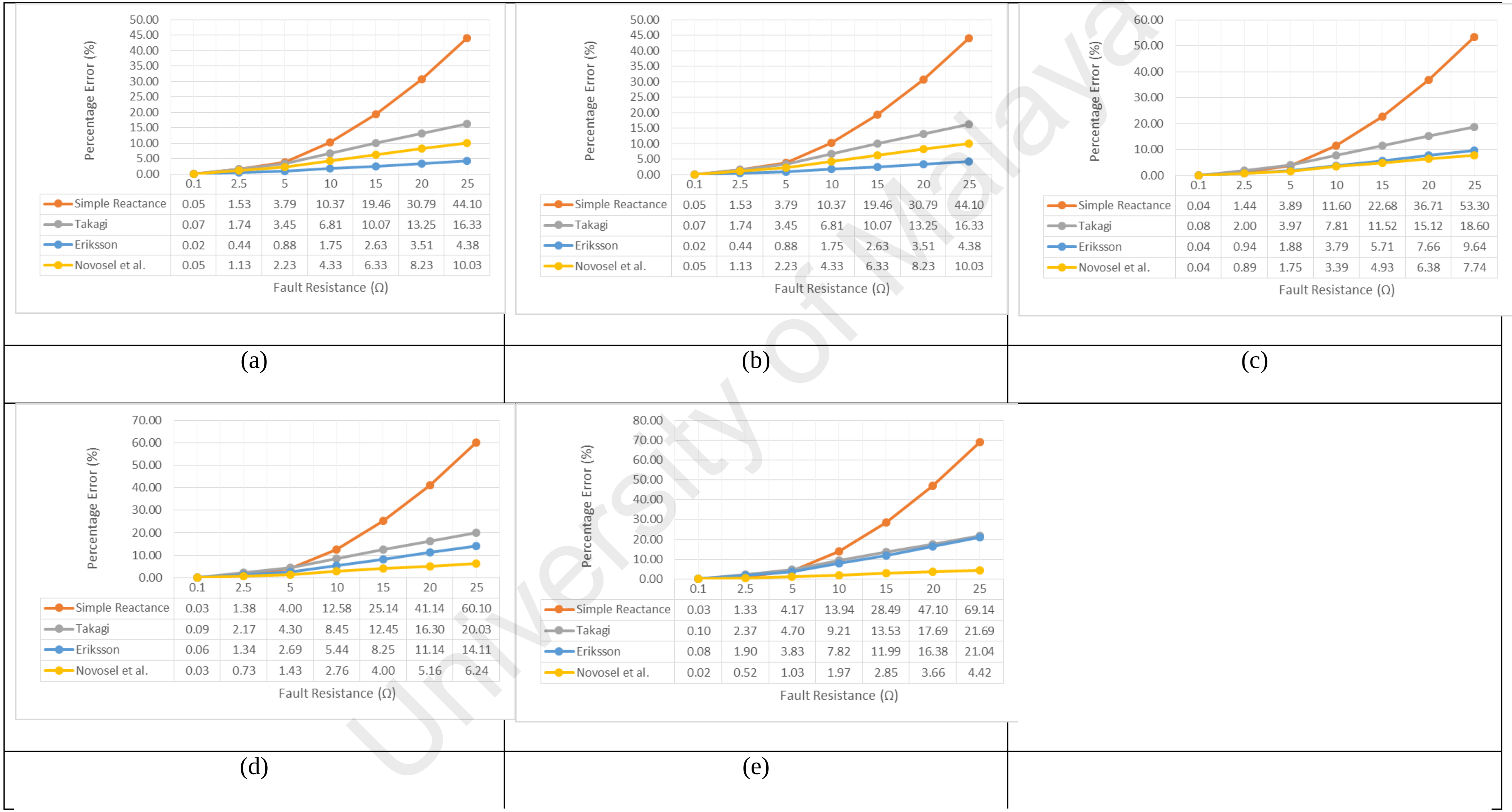
Case Study 5 (iv)	
Fault Location Method	**Sensitivity to Remote Source In-feed**
Simple Reactance	Yes, error increases
Takagi	Yes, error increases
Eriksson	Yes, error decreases
Novosel et al.	Yes, error increases

4.6.9 Results of Case Study 5 (v)

The results of Case Study 5 (v) are plotted into graphs as presented in Figure 4.21. The simple reactance, Takagi, and Eriksson methods are sensitive to both fault resistance and fault distance. The accuracy of these fault location methods decreases as the fault resistance or fault distance increases.

Novosel et al. method is less sensitive to fault resistance and fault distance if compare to the rest 3 fault location methods. The percentage error of Novosel et al. increases as the fault resistance increases or fault distance decreases.

Based on Figure 4.22, the Novosel et al. method is the most accurate method in this case study with 3.47% error, followed by Eriksson method (4.85%), Takagi method (8.54%), and simple reactance method (19.05%).



(a)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.53	3.79	10.37	19.46	30.79	44.10
Takagi	0.07	1.74	3.45	6.81	10.07	13.25	16.33
Eriksson	0.02	0.44	0.88	1.75	2.63	3.51	4.38
Novosel et al.	0.05	1.13	2.23	4.33	6.33	8.23	10.03

(b)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.05	1.53	3.79	10.37	19.46	30.79	44.10
Takagi	0.07	1.74	3.45	6.81	10.07	13.25	16.33
Eriksson	0.02	0.44	0.88	1.75	2.63	3.51	4.38
Novosel et al.	0.05	1.13	2.23	4.33	6.33	8.23	10.03

(c)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.04	1.44	3.89	11.60	22.68	36.71	53.30
Takagi	0.08	2.00	3.97	7.81	11.52	15.12	18.60
Eriksson	0.04	0.94	1.88	3.79	5.71	7.66	9.64
Novosel et al.	0.04	0.89	1.75	3.39	4.93	6.38	7.74

(d)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.03	1.38	4.00	12.58	25.14	41.14	60.10
Takagi	0.09	2.17	4.30	8.45	12.45	16.30	20.03
Eriksson	0.06	1.34	2.69	5.44	8.25	11.14	14.11
Novosel et al.	0.03	0.73	1.43	2.76	4.00	5.16	6.24

(e)

	0.1	2.5	5	10	15	20	25
Simple Reactance	0.03	1.33	4.17	13.94	28.49	47.10	69.14
Takagi	0.10	2.37	4.70	9.21	13.53	17.69	21.69
Eriksson	0.08	1.90	3.83	7.82	11.99	16.38	21.04
Novosel et al.	0.02	0.52	1.03	1.97	2.85	3.66	4.42

Figure 4.21: Graphs of percentage error vs fault resistance at fault distance a)0.01pu b)0.25pu c)0.50pu d)0.75pu e)1.0pu for Case Study 5(v)

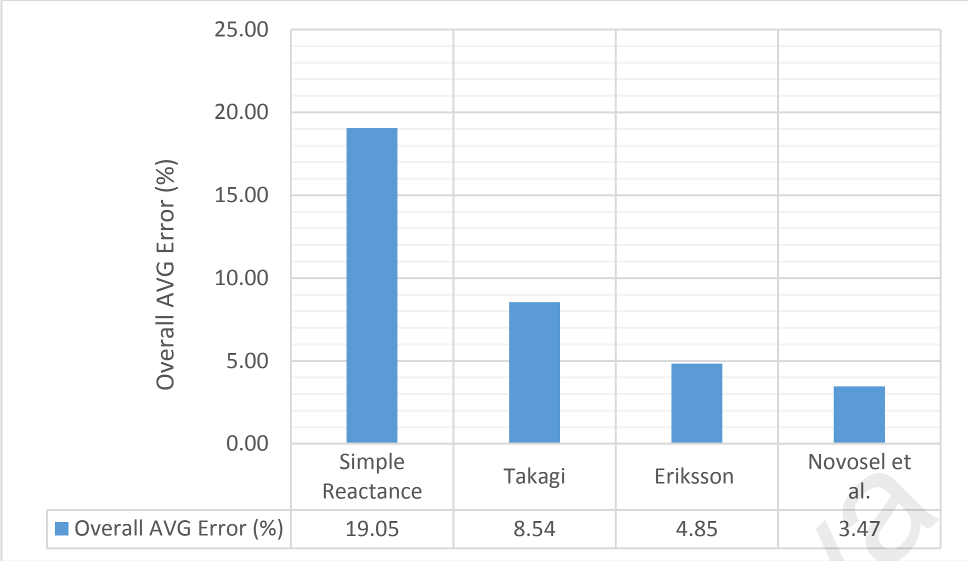


Figure 4.22: Overall percentage error of all one-ended impedance-based fault location methods in Case Study 5 (v)

4.6.10 Discussion of Case Study 5 (v)

Case Study 5 (v) investigates the effect of remote source in-feed on the accuracy of one-ended impedance-based fault location methods. The network configuration in this case study is similar to Case Study 4 (ii) except a remote source is connected at remote terminal.

By comparing the results between Case Study 4 (ii) and 5 (v), it is observed the simple reactance, Takagi, and Eriksson methods have the similar trend patterns in these two case studies. However the percentage error of these 3 fault location methods are higher in Case Study 5 (v) because the remote source in-feed further deteriorates the phase angle difference between I_F and I_S and also phase angle between $I_{S\,pre}$ and I_S.

The Z_{Load} calculated using Novosel et al. algorithm is no longer precise because the connected load is not fully supplied by the local source due to the influence from remote source in-feed. Regardless, the Novosel et al. method is still the most accurate method in this case study.

The effect of remote source in-feed on the accuracy of fault location methods in Case Study 5 (v) in reference to Case Study 4 (ii) is summarized in Table 4.11:

Table 4.11: Summary of Case Study 5 (v)

Case Study 5 (v)	
Fault Location Method	**Sensitivity to Remote Source In-feed**
Simple Reactance	Yes, error increases
Takagi	Yes, error increases
Eriksson	Yes, error increases
Novosel et al.	Yes, error increases

4.7 Overall Discussion

Based on the separate results and discussions from Case Study 1-5, the accuracy of one-ended impedance-based fault location methods is summarized and discussed as below. Table 4.12 shows the summary of accuracy and the effect of system parameters of one-ended impedance-based fault location methods for all case studies.

1) Simple reactance method

The accuracy of simple reactance method mainly affected by the reactance error due to the phase angle mismatch between I_S and I_F or can be represented as $R_F(\frac{I_F}{I_S})$. I_F is the sum product of I_S and I_R, therefore $\angle I_R$ shall be as close as possible to $\angle I_S$ to assure the accuracy of simple reactance method. The results in this research project show that the fault distance estimation of simple reactance method is sensitive to the system load as the load will affect the phase angle of I_S and I_R. For example when inductive load is connected at local terminal in Case Study 4 (i) where the I_R lags I_S, it increases the phase angle of I_S. As a result, the phase angle difference between I_R and I_S is reduced and therefore it improves the accuracy of simple reactance method. In contrast, when inductive load is connected at remote terminal in Case Study 4 (ii), it increases the phase angle of I_R and causes higher error in simple reactance method due to bigger phase angle mismatch between I_R and I_S. Hence, the total impedance including source impedance and load impedance at local and remote terminals shall be determined in order to identify the phase angle difference between them. Simple reactance method is only recommended to be applied when the phase angle difference between the total impedance at local terminal and remote terminal is small. However this is not always true because in reality the load impedance is not always constant. Moreover the phase angle of I_F is also affected by line impedance and fault resistance. Simple reactance also has excellent accuracy in Case Study 1, 2, 3 (i), and 4 (i) when the remote terminal in open-ended.

2) Takagi method

Takagi method subtracts out the pre-fault load current from the total fault current and assumes the transmission system is homogenous to calculate the fault distance in the algorithm. Therefore when the transmission system is not being homogenous it will cause error in the Takagi algorithm. The error can be represented as $R_F = 1/d_S$where it is proportional to the degree of non-homogeneity. Based on the results, Takagi method shows inferior accuracy when the system load is connected at remote terminal. Despites, Takagi method has excellent accuracy when the remote terminal in open-ended.

3) Eriksson method

Eriksson method includes source impedance parameters to reduce the error caused by the fault resistance, system load, fault distance or system non-homogeneity. The Z_{R1} shall be known to assure the accuracy of Eriksson method. Results show that Eriksson method is lack of accuracy when the Source R is not connected at the remote terminal because the Z_{R1} used in Eriksson algorithm does not hold true value under this circumstance. Despite, Eriksson method has superior accuracy in two terminal transmission system. However in Case Study 5 (iii) and 5 (v), the accuracy of Eriksson method dropped when the system load is connected at remote terminal.

4) Novosel et al. method

Novosel et al. method is a modified version of the Eriksson method which has excellent accuracy and robust to fault distance, fault resistance, and load in estimating the fault distance for radial transmission line. The superiority of Novosel et al. method is proven in the results of Case Study 1, 2, 3(i), and 4 (i) with 0% of percentage error at all fault distance and fault resistance. It is also showing best accuracy among all fault location methods in Case Study 5 (iii) and 5 (v) when the system load is connected at remote terminal. However the accuracy of Novosel et al. methods drastically dropped in Case Study 5 (ii) and 5 (iv) when the system load is connected at local terminal.

In conclusion, the simple reactance method is most straightforward of all fault location methods but its accuracy deteriorates due to fault distance, fault resistance, system load, and connected source at remote terminal. Takagi method is robust to system load but sensitive to the connected source at remote terminal and connected system load at local terminal. Eriksson method uses source impedances at local and remote terminals to minimize the influence of source at remote terminal but still will be affected by the connected load in the transmission network. Novosel et al. method has excellent performance when there is no remote in-feed and robust to the load connected at remote terminal.

Each impedance-based fault location algorithm uses certain assumption as computation basis and requires specific input parameters in order to calculate the fault distance. None of these fault location methods can assure the best performance out of the other in various types of network configurations because these assumptions may or may not hold true in that particular condition. Therefore there is no best impedance-based fault location method that suits all types of transmission network. It requires detailed study on the transmission network characteristics and working principles to select the most suitable impedance-based fault location technique.

Table 4.12: Summary of accuracy and the effect of system parameters on one-ended impedance-based fault location methods for Case Study 1 – 5

Case Study	Data	Simple Reactance	Takagi	Eriksson	Novosel et al.
1	Accuracy[1]	1	1	2	1
	Effect of Fault Resistance[2]	No	No	Increase	No
2	Accuracy	1	1	2	1
	Effect of Fault distance[3]	No	No	Decrease	No
3(i)	Accuracy	1	1	2	1
	Effect of Load Location[4]	No	No	No	No
3(ii)	Accuracy	2	4	3	1
	Effect of Load Location	Increase	Increase	Increase	No
4(i)	Accuracy	1	1	2	1
	Effect of Power Factor Load[5]	No	No	No	No
4(ii)	Accuracy	4	3	2	1
	Effect of Power Factor Load	Increase	Decrease	Decrease	No
5(i)	Accuracy	2	2	1	2
	Effect of Remote Source In-feed[6]	Increase	Increase	Decrease	Increase
5(ii)	Accuracy	4	2	1	3
	Effect of Remote Source In-feed	Increase	Increase	Decrease	Increase
5(iii)	Accuracy	2	4	3	1
	Effect of Remote Source In-feed	Increase	Increase	Increase	Increase
5(iv)	Accuracy	2	3	1	4
	Effect of Remote Source In-feed	Increase	Increase	Decrease	Increase
5(v)	Accuracy	4	3	2	1
	Effect of Remote Source In-feed	Increase	Increase	Increase	Increase

[1] 1 represents the highest accuracy, followed by 2, 3, 4 and 5. Methods may share similar number if having same accuracy.

[2] Effect of fault resistance on the percentage error of fault location methods when fault resistance increases.

[3] Effect of fault location distance on the percentage error of fault location methods when fault location distance increases.

[4] Effect of load location on the percentage error of fault location methods

[5] Effect of power factor load on the percentage error of fault location methods

[6] Effect of remote source in-feed on the percentage error of fault location methods

CHAPTER 5: CONCLUSION

5.1 Conclusion

This research project aims to compare and discuss the accuracies of the various methods of one-ended impedance-based fault location algorithms with respects to the influences of 5 system parameters which are 1) fault resistance, 2) fault distance, 3) load location, 4) power factor load, and 5) remote source in-feed in the transmission system. Typical two-terminal transmission network with the parameters proposed in IEEE Guide ("IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines," 2015) was used in this project.

In this project, literature review was carried out to identify the various methods of impedance-based fault location algorithms and review their working principles. The algorithms of each fault location methods were then converted into MATLAB coding script to compute the estimated fault distance using the voltage and current waveforms obtained from the simulation in MATLAB SIMULINK. As such, Objective 1 and 2 had been accomplished.

A methodology had been developed to determine the accuracy of the fault location methods under different case studies. Simulation case studies were developed and fault distance simulation was executed in MATLAB SIMULINK to generate the voltage and current waveforms as the inputs for fault distance computations. The results of fault distance for each fault location methods in each case study were compared and discussed. Hence, Objective 3 in this project had been achieved.

5.2 Contribution of Research

The results of this research presents the accuracy of each one-ended impedance-based fault location methods under different transmission network configurations and the influences of the selected system parameters. These data can be used as the reference for the users to determine the most adequate one-ended impedance-based fault location methods for different types of transmission networks.

5.3 Recommendation

This research project had compared and discussed the accuracy of one-ended impedance-based fault location methods with respect to the influence of the system parameters, i.e. fault resistance, fault distance, load location, load power factor, and remote source in-feed. However, the results obtained for the above used the steady state voltage and current waveforms as inputs did not consider the effect of DC components during the fault transient. In reality, the distance relay protection is initiated based on the first few cycles of the fault voltage and current waveforms in order to isolate the fault from the network within the shortest time. It is unrealistic to use the steady state waveforms to estimate the fault distance as the faulty lines are already disconnected from the terminal before the waveforms can reach steady state. Fourier transforms are recommended to be applied to filter the DC components because the calculation of the phasor quantities of the waveforms are complicated by the presence of the DC component. Hence, future research can be conducted by estimating the fault distance using the filtered asymmetrical transient waveforms to explore the effect of DC components on the accuracy of one-ended impedance-based location methods.

REFERENCES

Anderson, P. M. (1973). Analysis of Faulted Power Systems. *Iowa State University Press, Ames, IA.*

Andrade, L. d., & Leão, T. P. d. (2012, 7-10 May 2012). *Impedance-based fault location analysis for transmission lines.* Paper presented at the PES T&D 2012.

Aoyu, L., Dong, X., Shi, S., & Bin, W. (2015, 1-4 Sept. 2015). *A novel current travelling wave based single-ended fault location method for locating single-phase-to-ground fault of transmission line.* Paper presented at the 2015 50th International Universities Power Engineering Conference (UPEC).

Birajdar, A., & Tajane, S. (2016, 4-6 July 2016). *Modelling and simulation of transmission line to detect single line to ground fault location.* Paper presented at the 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES).

Camarillo-Pefiaranda, J. R., & Ramos, G. (2018, 23-27 Sept. 2018). *Effect of phase-angle jump in Impedance-based Fault Location Methods for Transmission and Distribution Systems.* Paper presented at the 2018 IEEE Industry Applications Society Annual Meeting (IAS).

Coleman, C. S. (1989, 20-20 April 1989). *The application of knowledge based systems within the proposed telecommunications management network (TMN) environment to support fault diagnosis.* Paper presented at the IEE Colloquium on Expert Systems for Fault Diagnosis in Engineering Applications.

D. Novosel, D. H., Y. Hu, and J. Myllymaki. (1998). System for locating faults and estimating fault resistance in distribution networks with tapped loads. *U.S. Patent 5 839 093, Nov*.

Das, S., Santoso, S., Gaikwad, A., & Patel, M. (2014). Impedance-based fault location in transmission networks: theory and application. *IEEE Access, 2*, 537-557. doi: 10.1109/ACCESS.2014.2323353

Eriksson, L., Saha, M. M., & Rockefeller, G. D. (1985). An Accurate Fault Locator With Compensation For Apparent Reactance In The Fault Resistance Resulting From Remore-End Infeed. *IEEE Transactions on Power Apparatus and Systems, PAS-104*(2), 423-436. doi: 10.1109/TPAS.1985.319058

Fitzpatrick, J. (2012). Smart Grid. 2018, from https://sites.google.com/site/ee5352012/john-fitzpatrick

Gama, J. R., & Lopes, F. V. (2017, 16-17 Nov. 2017). *On compensating synchronization errors in two-terminal based fault location approaches.* Paper presented at the 2017 Workshop on Communication Networks and Power Systems (WCNPS).

Garcia-Osorio, G., Mora-Florez, J., & Perez-Londono, S. (2008, 13-15 Aug. 2008). *Analysis of the ground effect in the single phase fault location for power distribution systems.* Paper presented at the 2008 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America.

Gheitasi, A. (2015, 15-18 Nov. 2015). *Evaluation of performance of distance relays in presence of series compensators.* Paper presented at the 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC).

Hashim, M. M. I., Ping, H. W., & Ramachandaramurthy, V. K. (2009, 23-26 Jan. 2009). *Impedance-based fault location techniques for transmission lines.* Paper presented at the TENCON 2009 - 2009 IEEE Region 10 Conference.

Holbeck, J. I. (1944). A simple method for locating ground faults. *Electrical Engineering, 63*(3), 89-92. doi: 10.1109/EE.1944.6440188

IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines. (2015). *IEEE Std C37.114-2014 (Revision of IEEE Std C37.114-2004)*, 1-76. doi: 10.1109/IEEESTD.2015.7024095

Izykowski, J., Molag, R., Rosolowski, E., & Saha, M. M. (2006). Accurate location of faults on power transmission lines with use of two-end unsynchronized measurements. *IEEE Transactions on Power Delivery, 21*(2), 627-633. doi: 10.1109/TPWRD.2005.858778

Kim, H. H., Lee, C. J., Radojevic, Z. M., Park, J. B., & Shin, J. R. (2006, 18-22 June 2006). *An improved two-terminal numerical algorithm for fault location estimation considering shunt capacitance.* Paper presented at the 2006 IEEE Power Engineering Society General Meeting.

Kyung Woo, M., Das, S., & Santoso, S. (2016, 3-5 May 2016). *Improved method for locating faults upstream from distributed generation.* Paper presented at the 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D).

Le, T. D., & Petit, M. (2016, 4-8 April 2016). *Earth fault location based on a Modified Takagi Method for MV distribution networks.* Paper presented at the 2016 IEEE International Energy Conference (ENERGYCON).

Lima, D. A. C., Ferraz, R. G., Filomena, A. D., & Bretas, A. S. (2013, 21-25 July 2013). *Electrical power systems fault location with one-terminal data using estimated remote source impedance.* Paper presented at the 2013 IEEE Power & Energy Society General Meeting.

Liu, W., Cai, Z., & Hou, R. (2005, 18-18 Aug. 2005). *Power System Fault Calculation under Special Circumstances and Corresponding Effect on Protective Relaying.* Paper presented at the 2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific.

M. M. Saha, R. D., P. Verho, and D. Novosel. (2002). Review of fault location techniques for distribution systems. *Proc. Power Syst. Commun. Infras-truct. Future*.

Marguet, R., & Raison, B. (2014, 27-31 July 2014). *Fault distance localization method for heterogeneous distribution networks.* Paper presented at the 2014 IEEE PES General Meeting | Conference & Exposition.

McNeff, J. G. (2002). The global positioning system. *IEEE Transactions on Microwave Theory and Techniques, 50*(3), 645-652. doi: 10.1109/22.989949

Muddebihalkar, S. V., & Jadhav, G. N. (2015, 30 Oct.-1 Nov. 2015). *Analysis of fault location algorithm for transmission line protection based on synchronized phasor measurement.* Paper presented at the 2015 International Conference on Energy Systems and Applications.

Nastac, L., & Thatte, A. A. (2006, 17-19 Sept. 2006). *A Heuristic Approach for Predicting Fault Locations in Distribution Power Systems.* Paper presented at the 2006 38th North American Power Symposium.

Nunes, J. U. N., & Bretas, A. S. (2011, 19-23 June 2011). *A impedance-based fault location technique for unbalanced distributed generation systems.* Paper presented at the 2011 IEEE Trondheim PowerTech.

Ö, A., Gürsoy, E., Font, A., & Ö, K. (2016, 19-22 Sept. 2016). *Travelling wave fault location on hybrid power lines.* Paper presented at the 2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE).

Okada, K., Urasawa, K., Kanemaru, K., & Kanoh, H. (1988, 25-27 May 1988). *Knowledge-based fault location system for electric power transmission lines with OPGW.* Paper presented at the Proceedings of the International Workshop on Artificial Intelligence for Industrial Applications.

Oswald, B. R., & Panosyan, A. (2006, 15-18 Aug. 2006). *A New Method for the Computation of Faults on Transmission Lines.* Paper presented at the 2006

IEEE/PES Transmission & Distribution Conference and Exposition: Latin America.

Razavi, A., Maaskant, R., Yang, J., & Viberg, M. (2015). Maximum Aperture Power Transmission in Lossy Homogeneous Matters. *IEEE Antennas and Wireless Propagation Letters, 14*, 175-178. doi: 10.1109/LAWP.2014.2358693

Roostaee, S., Thomas, M. S., & Mehfuz, S. (2017). Experimental studies on impedance based fault location for long transmission lines. *Protection and Control of Modern Power Systems, 2*(1), 16. doi: 10.1186/s41601-017-0048-y

Singh, M., Panigrahi, B. K., & Maheshwari, R. P. (2011, 23-24 March 2011). *Transmission line fault detection and classification.* Paper presented at the 2011 International Conference on Emerging Trends in Electrical and Computer Technology.

Starr, A. T., & Gooding, H. T. (1939). Localization of flashing faults in cables. *Journal of the Institution of Electrical Engineers, 84*(510), 699-709. doi: 10.1049/jiee-1.1939.0111

Surwase, P., Nagendran, M., & Patil, M. (2015, 17-20 Dec. 2015). *Comparative evaluation of phasor estimation for fault location in double end transmission system.* Paper presented at the 2015 Annual IEEE India Conference (INDICON).

Tağluk, M. E., Mamiş, M. S., Arkan, M., & Ertuğrul, Ö. F. (2015, 16-19 May 2015). *Detecting fault type and fault location in power transmission lines by extreme learning machines.* Paper presented at the 2015 23nd Signal Processing and Communications Applications Conference (SIU).

Wei, L., & Liu, Z. (2012, 15-20 Sept. 2012). *Identifying ground fault location in High Resistance Grounded systems for Adjustable Speed Drive at low speed.* Paper presented at the 2012 IEEE Energy Conversion Congress and Exposition (ECCE).

Xun, L., Shungui, L., Ronghui, H., Jingwen, A., Yunzhu, A., Ping, C., & Zhengxiang, X. (2017, 20-22 Oct. 2017). *Study on accuracy traveling wave fault location method of overhead line — Cable hybrid line and its influencing factors.* Paper presented at the 2017 Chinese Automation Congress (CAC).

Ying-Hong, L., Chih-Wen, L., & Ching-Shan, C. (2004). A new PMU-based fault detection/location technique for transmission lines with consideration of arcing fault discrimination-part I: theory and algorithms. *IEEE Transactions on Power Delivery, 19*(4), 1587-1593. doi: 10.1109/TPWRD.2004.832407

Zamora, I., Minambres, J. F., Mazon, A. J., Alvarez-Isasi, R., & Lazaro, J. (1996). Fault location on two-terminal transmission lines based on voltages. *IEE Proceedings - Generation, Transmission and Distribution, 143*(1), 1-6. doi: 10.1049/ip-gtd:19960112

Zimmerman, K., & Costello, D. (2005, 5-7 April 2005). *Impedance-based fault location experience.* Paper presented at the 58th Annual Conference for Protective Relay Engineers, 2005.