

**Frequency Domain Transient Modeling of
Multiconductor Transmission Lines Based
On Analytical Impedance Equation**

BY

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This dissertation is dedicated to my parents and my son Elyas

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	vi
LIST OF TABLES	x
LIST OF FIGURES	xii
LIST OF ABBREVIATIONS	xvii
ABSTRACT (ENGLISH)	xviii
ABSTRACT (ARABIC)	xx
CHAPTER 1 INTRODUCTION	1
1.1 Motivation and Problem Statement	2
1.2 Dissertation Objectives	4
1.3 Dissertation Contributions	7
1.4 Dissertation Organization	10
CHAPTER 2 LITERATURE REVIEW	12
2.1 MTL modeling	12
2.2 Adaptive Protection	17
CHAPTER 3 THE PROPOSED TRANSIENT MODELING OF MULTICONDUCTOR TRANSMISSION LINES	24
3.1 Vector Fitting	26
3.2 Wave Characteristics On Finite Transmission Lines	27

3.3	Transmission Line Frequency Response Analysis (FRA) measurements	32
3.4	Parameters of Transmission Line Impedance Equation	39
3.5	Obtaining transmission line parameters of Z_{12} , Z_{13} and Z_{23}	48
3.6	Developed algorithm for a more accurate fitting	57
3.7	Frequency dependency of transmission line parameters	61
CHAPTER 4 FITTING OF THE IMPEDANCE FREQUENCY RE-		
SPONSE USING THE PROPOSED MTL MODEL		62
4.1	Simulations and Results	62
4.1.1	Case1: Test for 10KHz frequency rang:	67
4.1.2	Case2: Test for 100KHz frequency range	70
4.1.3	Case3: Test for 1MHz frequency range :	72
4.1.4	Case4: Test for different transmission line lengths for 1MHz frequency range :	73
4.2	Computational time comparison between the proposed model and VF .	75
4.3	Remarks on the proposed model	76
4.3.1	Features of the proposed model	79
CHAPTER 5 APPLICATIONS OF THE PROPOSED MTL MODEL		
AND IMPLEMENTATION IN RTDS		82
5.1	Introduction	83
5.2	Implementation of the proposed MTL model in RTDS	84
5.3	Voltage measurement during transient scenarios using the proposed model	90
5.3.1	The proposed model transient response during a fault	90
5.3.2	Test transient response during line energization (Switching) . .	96
5.4	Distance protection	98
5.5	Impedance of MTL	100
5.6	Mho impedance relay and the Setting-less impedance relay	102
CHAPTER 6 CONCLUSION		115

APPENDIX A RESONANCE EQUATIONS DERIVATION	119
REFERENCES	130
VITAE	145

LIST OF TABLES

3.1	Reactance of Short-Circuited Line	31
3.2	Reactance of Open-Circuited Line	32
3.3	Transmission Line Parameters	33
3.4	Transmission Line Parameters	36
3.5	Transmission Line Calculated Parameters for Z_{11}	46
3.6	Transmission Line Calculated Parameters for Z_{12} , Z_{13} and Z_{23}	54
3.7	Transmission Line Calculated and Fitted Parameters of the proposed model for Z_{11}	59
3.8	Transmission Line Calculated and Fitted Parameters of the proposed model for Z_{12}	59
3.9	Transmission Line Calculated and Fitted Parameters of the proposed model for Z_{23}	60
4.1	Transmission Line Calculated Parameters for Z_{11}	64
4.2	Transmission Line Calculated Parameters for Z_{12}	65
4.3	Transmission Line Calculated Parameters for Z_{11}	66
4.4	Computer specs	76
4.5	Computational Time	76
4.6	Transmission Line Parameters	79
5.1	Proposed Model Parameters for Z_{11} , Z_{22} , and Z_{33}	84
5.2	Proposed Model Parameters for Z_{12} , Z_{21} , Z_{31} , and Z_{13}	86
5.3	Proposed Model Parameters for Z_{23} , and Z_{32}	88
5.4	Transmission Line Parameters	91

5.5	System A (Source) Parameters.	91
5.6	System B (Source) Parameters.	92
5.7	Distance relay setting.	103
5.8	Detection time of Mho relay and the proposed sitting less impedance relay during L-G fault.	105
5.9	Detection time of Mho relay and the proposed sitting less impedance relay during LL-G fault.	107
5.10	Detection time of Mho relay and the proposed sitting less impedance relay during LLL-G fault.	109
5.11	Detection time of Mho relay and the proposed sitting less impedance relay during two phases fault.	111
5.12	Detection time of Mho relay and the proposed sitting less impedance relay during three phases fault.	113

LIST OF FIGURES

1.1	Transmission line imaginary impedance (Z_{11}) with different sampling rates.	8
3.1	A segment of transmission Line Distributed Parameters.	28
3.2	Reactance of Short-Circuited Line.	30
3.3	Reactance of Open-Circuited Line.	32
3.4	RTDS circuit Line Diagram of FRA measurements.	34
3.5	FRA measurements of transmission line impedance imaginary part of Z_{11}	35
3.6	FRA measurements of transmission line impedance real part.	35
3.7	FRA measurements of transmission line impedance imaginary part when $Z_0 = Z_1$	37
3.8	FRA measurements of transmission line impedance real part when $Z_0 = Z_1$	37
3.9	FRA measurements of transmission line impedance.	42
3.10	FRA measurements of transmission line real impedance of Z_{11}	43
3.11	Impedance Frequency response measurements and the proposed model calculation of the real part of Z_{11}	47
3.12	Impedance Frequency response measurements and the proposed model calculation of the imaginary part of Z_{11}	48
3.13	Impedance Frequency response measurements of the real part of Z_{11} and Z_{12}	50
3.14	Impedance Frequency response measurements of the imaginary part of Z_{11} and Z_{12}	51

3.15	Impedance Frequency response measurements and the proposed model calculation of the real part of Z_{12}	56
3.16	Impedance Frequency response measurements and the proposed model calculation of the imaginary part of Z_{12}	56
3.17	Developed Algorithm for an accurate model.	58
4.1	The magnitude of the measured impedance and the proposed model impedance, $ Z_{11} $, $ Z_{12} $, and $ Z_{23} $	68
4.2	The angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$	68
4.3	The magnitude of the measured impedance and the VF impedance, $ Z_{11} $, $ Z_{12} $, and $ Z_{23} $	69
4.4	The angle of the measured impedance and the VF impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$	69
4.5	The magnitude of the measured impedance and the proposed model impedance, $ Z_{11} $, $ Z_{12} $, and $ Z_{23} $	70
4.6	The Angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$	71
4.7	The magnitude of the measured impedance and the VF impedance, $ Z_{11} $, $ Z_{12} $, and $ Z_{23} $	71
4.8	The angle of the measured impedance and the VF impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$	72
4.9	The magnitude of the measured impedance and the proposed model impedance, $ Z_{11} $, $ Z_{12} $, and $ Z_{23} $	73
4.10	The angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$	73
4.11	The magnitude of the measured impedance and the proposed model impedance, $ Z_{11} $, $ Z_{12} $, and $ Z_{23} $	74
4.12	The angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$	75

4.13	The angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$.	80
5.1	Implementation of Z_{11} in RTDS.	85
5.2	Implementation of Z_{12} in RTDS.	87
5.3	Implementation of Z_{23} in RTDS.	89
5.4	Tested power system.	90
5.5	Voltages and current measurements in RTDS.	93
5.6	Voltage measurement and voltage calculation using the proposed model of Phase a.	95
5.7	Voltage measurement and voltage calculation using the proposed model of Phase b.	95
5.8	Voltage measurement and voltage calculation using the proposed model of Phase c.	96
5.9	Voltage measurement and voltage calculation using the proposed model of Phase a.	97
5.10	Voltage measurement and voltage calculation using the proposed model of Phase b.	97
5.11	Voltage measurement and voltage calculation using the proposed model of Phase c.	98
5.12	Impedance traces during Line to Ground fault.	104
5.13	Fault duration and Mho detection time during a phase to ground fault.	104
5.14	Fault duration and the proposed setting less impedance relay detection time during a phase to ground fault.	105
5.15	Fault duration and Mho detection time during two phases to ground fault.	106
5.16	Fault duration and the proposed setting less impedance relay detection time during two phases to ground fault.	107
5.17	Fault duration and Mho detection time during three phases to ground fault.	108

5.18	Fault duration and the proposed setting less impedance relay detection time during three phases to ground fault.	109
5.19	Fault duration and Mho detection time during two phases fault during two phases fault.	110
5.20	Fault duration and the proposed setting less impedance relay detection time during during two phases fault.	111
5.21	Fault duration and Mho detection time during three phases fault. . . .	112
5.22	Fault duration and he proposed setting less impedance relay detection time during three phases fault.	113

LIST OF ABBREVIATIONS

FDCM	Frequency-Dependent Cable Model
FDTD	Finite-Difference Time-Domain
FDTLM	Frequency-Domain Transmission-Line Matrix
MTL	Multiconductor Transmission lines
MVF	Model Vector Fitting
NULs	Nonuniform Lines
PUL	Per Unit Length
RMTL	Revised Multiconductor Transmission Line
TDFE	Time-Domain Finite-Element
VF	Vector Fitting

DISSERTATION ABSTRACT

NAME: Hosam Alharbi

TITLE OF STUDY: Frequency Domain Transient Modeling of Multiconductor Transmission Lines Based on Analytical Impedance Equation

MAJOR FIELD: Electrical Engineering

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In this Ph.D dissertation, a frequency domain transient modeling of Multiconductor transmission lines (MTL) based on the impedance analytical equation of transmission line is presented. The proposed model is a function of the transmission line length since it is based on the analytical impedance equation of a finite transmission line. The proposed MTL model is developed from the impedance frequency response measurement. Therefore, by fitting the proposed model with the impedance frequency response measurement, an accurate representation of MTL is derived. The frequency response of a transmission line impedance is measured using a real-time digital simulator (RTDS). The parameters of the proposed model were calculated using derived resonance equations from the proposed model. The calculated proposed model parameters are within a

1% of error compared to the fitted parameters. Further more, an algorithm is developed to obtain a more accurate fit of MTL impedance frequency response. The implemented algorithm take the derivative of each of the proposed model parameters of the proposed complex nonlinear equation to minimize the error between the fitted and the measured impedance frequency response. To test the accuracy of the proposed model, a comparison between the proposed model and vector fitting is carried out. Once the parameters of a transmission line are obtained, changing the length of the line will not effects the proposed transient modeling. This is because the transient modeling is based on the finite transmission line impedance equation. In addition, the proposed model is developed to be implemented in practical application. Therefore, the proposed model is implemented in an adaptive protection for microgrid. The proposed model can be used to calculate the voltages and currents throughout the length of the transmission line which is a key feature of the proposed model. Moreover, a second feature of the proposed model is an ease of implementation. Therefore, the proposed model is implemented in RTDS to compare the proposed model calculation to direct measurement during transient simulations in RTDS, such as fault and line switching. In addition, the proposed model is used as a setting-less impedance relay for adaptive microgrid protection. Moreover, the proposed model-based relay (setting-less impedance relay) has a faster fault detection time compared to Mho relay.

ملخص الرسالة

الاسم: حسام سالم الحربي

عنوان الدراسة: نموذج لحظي في المجال الترددي لخطوط النقل الكهربائية المتعددة الموصلات بناء

على معادلة المعاوقة الكهربائية التحليلية

التخصص: الهندسة الكهربائية

تاريخ الدرجة العلمية: رمضان 1443

في أطروحة الدكتوراه هذه ، تم تقديم نموذج لحظي لمعاوقة خطوط النقل الكهربائية المتعددة الموصلات في المجال الترددي بناءً على معادلة المعاوقة التحليلية لخط النقل. النموذج المقترح هو دالة في طول خط النقل لأنه بني على أساس معادلة المعاوقة التحليلية لخط نقل محدود. تم تطوير نموذج لخطوط النقل الكهربائية المتعددة الموصلات المقترح من قياس استجابة تردد المعاوقة. بناءً على ذلك ، من خلال مطابقة النموذج المقترح مع قيم استجابة المقاومة الترددية ، تم اشتقاق تمثيل مطابق لتردد لخطوط النقل الكهربائية المتعددة الموصلات . بالإضافة لذلك ، تم قياس استجابة التردد لمقاومة خطوط النقل باستخدام جهاز محاكاة رقمي في الوقت الحقيقي (RTDS) ومن القيم المقاسة والمعادلات المشتقة في حالة الرنين لخطوط النقل تم حساب معاملات النموذج المقترح. تقع معاملات النموذج المقترحة المحسوبة في حدود خطأ 1 % مقارنة بالمعاملات المطابقة. علاوة على ذلك ، تم تطوير خوارزمية للحصول على معاملات أكثر دقة لاستجابة تردد مقاومة. لإختبار دقة النموذج المقترح ، تم عرض مقارنة بين النموذج المقترح وتركيب المنتج. بالإضافة إلى ذلك ، تم تطوير النموذج المقترح ل يتم تنفيذه في التطبيق العملي. لذلك ، تم تنفيذ النموذج

المقترح كحماية تكييفية للشبكة المصغرة. يمكن استخدام النموذج المقترح لحساب الجهود و للتيارات على طول خط النقل والتي تعد سمة أساسية للنموذج المقترح. علاوة على ذلك ، يتميز النموذج المقترح بسهولة التنفيذ. لذلك ، تم تنفيذ النموذج المقترح في RTDS لمقارنة النموذج المقترح بالقيم المقاسة أثناء عمليات المحاكاة العابرة في RTDS ، مثل الخطأ أو الفصل. بالإضافة إلى ذلك ، يتم استخدام النموذج المقترح كمرحل مقاومة بدون إعدادات لحماية الشبكة المصغرة التكييفية. علاوة على ذلك ، يتميز المرحل المستند إلى النموذج المقترح بسرعة استجابة في اكتشاف الأخطاء مقارنة بمرحل Mho.

CHAPTER 1

INTRODUCTION

A transmission line is one of the major electrical components in a power grid. Transmission lines are power guide components to deliver electric power from the source to the load. One characteristic of a transmission line that differs from any other electrical component is that transmission lines may cover long distances from the source to the load. Due to the length of a transmission line, a standing wave in a transmission line may occur. In addition, a wide range of different transient phenomena may affect transmission lines, such as lightning discharge, switching, and faults. Therefore, developing an accurate transient model of a transmission line is essential to predict the behavior of transmission lines in different transient scenarios.

Developing a transient model of transmission lines is quite difficult, considering the electric and magnetic coupling between the lines in addition to the distributed parameters of the transmission line along their length. Nevertheless, many different transient modeling of the transmission lines have been developed, and each has its advantages and disadvantages. Still, the need for less computational time and power, an accurate and reliable model is needed. With the advances made in computational pro-

cessors, the transmission line transient model in electromagnetic transient simulation has become more sophisticated to acquire an accurate model.

The transmission line transient modeling can be classified into two major groups: the time domain model and the frequency domain model. The frequency-domain model is based on frequency modeling of the transmission line at different frequency points within a specific frequency range. While in the time domain, the developed model obtained a transmission line solution by integrating discrete time intervals (Δt). The conversion of the frequency domain model to the time domain is difficult because the transmission lines parameters are frequency-dependent elements.

1.1 Motivation and Problem Statement

Frequency domain transient modeling of multiconductor transmission lines (MTL) plays an important role in understanding the transient behaviors of a transmission line. Many transient behaviors occur on transmission lines during operation, such as lightning, switching, and faults. Furthermore, due to the long length of the transmission line, a standing wave may occur. Therefore, accurate transient modeling is essential in understanding the transient behavior of the transmission line. There are many different transient modeling for MTL in research that can be classified into two main groups: time-domain transient modeling and frequency domain transient modeling. This ph.D. dissertation research will be focused on the frequency domain transient modeling.

There are many different frequency domain transient modelings in the research,

but most if not all of them are based on a mathematical function which is not related to the transmission line impedance equation. The mathematical function, such as rational function approximation, can fit the transient behavior of the transmission line impedance to a very high degree of accuracy. On the other hand, it required a high number of approximation to achieve a high level of accuracy. This will result in a high computing power requirement to implement in practical applications. In addition, the rational approximation function is not based on the transmission line impedance, and it is not a function of transmission line length. Therefore, changing the length of the transmission line will required retaking the impedance frequency response of the transmission line. Moreover, calculating the voltages and currents throughout the transmission line length is not applicable since the rational function turns the transmission line model into a two-port model.

Therefore, in this Ph.D. dissertation, a frequency domain transient modeling of Multiconductor Transmission lines (MTL) based on the analytical equation of transmission line impedance is presented. The proposed model is a function of the transmission line length since it is based on the analytical impedance equation of a finite transmission line. Moreover, a comparison between the proposed model and vector fitting Vector Fitting (VF) is carried out to ensure the accuracy of the proposed model. The proposed MTL model has two key features over different frequency-domain models. The first feature is that the proposed model is based on transmission line length. This feature will allow for voltage and current measurement throughout the transmission line length. The second feature is the ease of implementation of the proposed model in practical application. Therefore, an implementation of the proposed model in

RTDS is carried out to compare the proposed model during transient scenarios to the measurements. Furthermore, an implementation of the proposed model as a setting-less impedance relay is carried out. These applications demonstrate the advantages of the proposed model.

1.2 Dissertation Objectives

The objectives of this Ph.D. dissertation are:

- Develop a transient frequency domain multiconductor transmission line (MTL) model based on analytical impedance equation: The proposed MTL transient model will be based on the impedance equation of a transmission line. The key feature of the transmission line impedance equation is that the impedance of the transmission line is a function of transmission line length. Therefore, developing a transient frequency domain model for MTL based on the analytical impedance equation will have many advantages and applications. There are many frequency domain MTL models in the research. Some are based on the rational function approximation, which has a high fitting curve and low errors. Nevertheless, all of the developed frequency-domain models for MTL are not a function of transmission line length. The only available frequency-domain model, which is a function of transmission line length, is for a single-phase transmission line. Therefore, changing the length of the transmission line for most of the available models required retaking the frequency response measurements and obtaining a new frequency domain model for the transmission line.

- Derivation of resonance equations from the proposed impedance model and the frequency response measurement of the MTL: To fit the proposed impedance equation for MTL, the parameters of the equations must be obtained. To obtain the parameters of the proposed MTL impedance, an analysis of the transient frequency response impedance measurements must be carried away. Therefore, developing sets of equations that describe and govern the behavior of MTL impedance response during resonance of the transmission line is essential to obtain the proposed model. After obtaining sets of equations that describe the transient behavior of MTL impedance, the parameters of the proposed MTL impedance can be calculated. The transient frequency response impedance measurement obtained from real-time digital simulator (RTDS) is essential in calculating the proposed frequency-domain MTL equations parameters.
- Develop an algorithm for more accurate fitting of the proposed model: An algorithm is developed to minimize the error between the measured and the fitted impedance frequency response. The algorithm takes the partial derivative of transmission line parameters (R , L , and C) from a complex nonlinear equation and changes those parameters to minimize the error. Therefore, the developed algorithm will fit the the proposed model to the frequency response impedance measurement to high degree of accuracy.
- Comparison between the proposed model and an existing model (VF): A simulation of the MTL model is carried out to compare the proposed model with the frequency response transient measurement. The obtained frequency re-

sponse impedance measurements are measured using a real-time digital simulator (RTDS). In addition, a comparison between the proposed model and the vector fitting method is presented. Furthermore, since the proposed model is based on the analytical impedance equation and is a function of transmission line length, changing the length of the line will not effects the proposed model. Thus, the simulation results are presented to show that the model will remain effective even the length of the transmission line is changed. Moreover, Once the model is obtained, there is no need to retake the frequency response measurement of the transmission line if the length of the line is changed, unlike the other available MTL frequency-domain model.

- Implementing the MTL proposed model in RTDS: One of the key feature of the proposed model is ease of implementation in practical application. This due to the limited number of parameters and equations required to model a MTL. The vector fitting model required high number of approximation to fit the impedance frequency response to very high degree of accuracy. In addition, the number of approximation required by VF to fit the impedance frequency response will increases with the frequency range. In contrast, the proposed model have a set of constant parameters and few equations to fit the impedance frequency response for a wide frequency ranges.
- Testing the proposed model during transient scenarios: To verify the model accuracy, a comparison between the voltage measurement and the proposed model calculation is carried out. The proposed model is a transient frequency domain

model. Therefore, the proposed model must give an accurate representation of MTL during transient scenarios. A solid line to ground fault is introduced to the power system while a direct measurement of the phases voltages are compared to the proposed model voltages calculation. In addition, the proposed model is tested during line energizing (switching) to ensure the accurate representation of the proposed MTL model. Since the proposed model is based on finite transmission line impedance equation. Therefore, in both transient scenarios, switching and fault, the measurements were taking at mid point of the line even though the model is developed for the entire length of the line. In contrast, VF method model the transmission line as a two ports system. Therefore, any measurement throughout the transmission line length will not be possible.

- Develop a setting less impedance relay based on the proposed model: The impedance of transmission line is effected by the mutual coupling of the lines, the self impedance of the lines, and the currents in the lines. Therefore, the impedance of the line is changing in different operation conditions and during transient scenarios. Since the developed lumped MTL model is an accurate representation of the transmission line impedance in the frequency domain. Therefore, the proposed model can be implemented as setting less impedance relay.

1.3 Dissertation Contributions

This dissertation work leads to the following contributions in the development of MTL transient frequency domain model:

1. Develop MTL transient model based on the analytical impedance equation:

Many different fitting methods can fit a set of data to a very high degree of accuracy with minimum error. The fitting is achieved through a set of mathematical equations which may not be correlated to the fitted data. In addition, if the sampling number of the fitted data is small, then the obtained fitted curve, even though fitted to a very high degree, will not give accurate values of the data. For example, Figure 1.1 shows two different sampling rates of a transmission line impedance (200 and 200K). This problem manifests itself when taking the frequency response for a high-frequency range while being limited by a set of the sampling rate. Due to the low sampling rate of the data, the fitted curve does not reflect the correct values. In contrast, using the analytical solution which

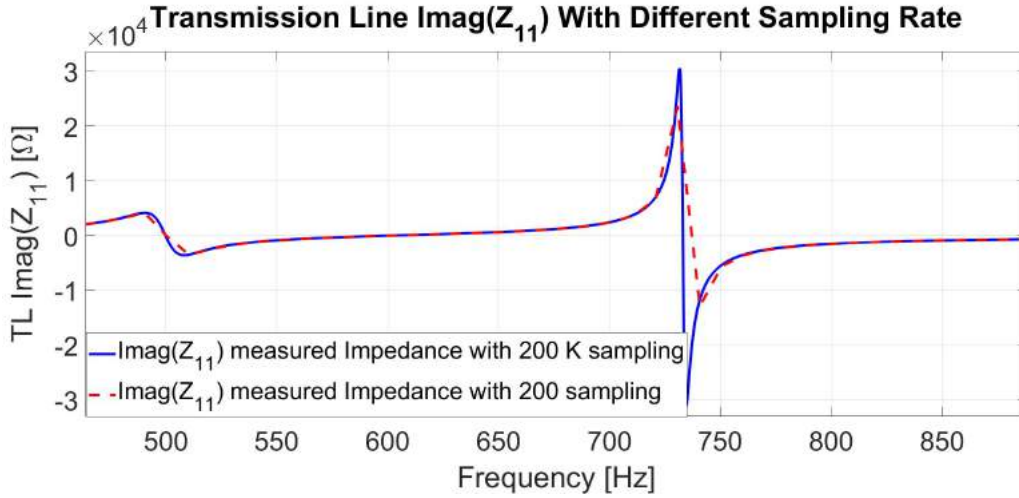


Figure 1.1: Transmission line imaginary impedance (Z_{11}) with different sampling rates.

describes the impedance of the transmission line even with fewer sampling rates will result in a better representation of a transmission line impedance.

2. Develop MTL transient model, which is a function in transmission line length:

The proposed method is based on finite transmission line impedance, which is a function of the transmission line length. Therefore, changing the length of the transmission line will not require any changes in the model. Unlike different fitting methods, which required retaking the frequency response of the transmission line and a generate new parameters for a mathematical function.

3. Easy implementation of the proposed MTL transient model in practical application:

Curve fitting methods require a high number of approximations to fit the impedance curve of the transmission line for a high-frequency range, which in turn reflects in the high number of terms the mathematical function required to fit the curve. Moreover, the higher number of approximations will require more computational power to fit the impedance curve. In contrast, the proposed analytical solution has a constant set of terms and parameters which will not change with the frequency range.

4. Develop a MTL model which allow for voltage measurement through out the transmission line length:

VF method convert MTL into two ports system and any measurement throughout the transmission line length is not allowed. In contrast, the proposed model is based on the analytical impedance equation of finite transmission line length. Therefore, the proposed model allow for voltage calculation throughout the transmission line length. In addition, voltages calculation through the trans-

mission line length during transient scenarios such as fault and switching is presented.

5. Develop a setting less impedance relay based on the MTL model:

The impedance of MTL changes with different operation conditions. In addition, the impedance is effected by the self impedance of the line, the mutual coupling of the lines and the current in the lines. Therefore, the impedance of MTL changes during transient scenarios. The proposed model is a transient frequency domain model of MTL. Therefore, the proposed model is implemented as a setting less impedance relay. A comparison between the proposed setting less impedance relay and Mho impedance relay is carried out for different fault types.

1.4 Dissertation Organization

The 2nd chapter will present the literature review of MTL transient modeling. In addition, a comprehensive literature review on adaptive protection is presented as well. The 3rd chapter will present the vector fitting method and how the proposed model is developed. A detail mathematical derivation of the resonance equations and the calculation of the proposed model parameters are shown. The 4th chapter presents the complete proposed model and its parameters of MTL. A comparison between the proposed model and the vector fitting method is presented. The 5th chapter will present two applications of the proposed model. The first application is the implementation of the model to measure the voltage along the length of the transmission line during transient scenarios, such as fault and line switching. The

results of the proposed model calculation of transmission line voltage measurement is directly compared to the bus voltage measurement in RTDS. The second presented application of the proposed model is the implementation of the proposed model as a setting-less impedance relay. In addition, a comparison between the proposed model based relay and the tradition impedance relay, Mho, is presented. Finally, The 6th chapter is the conclusion chapter where the findings and the conclusion of this Ph.D. dissertation work is presented.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a comprehensive literature review is conducted on MTL transient modeling. In addition, the proposed model is used in adaptive microgrid protection. Therefore, a literature review on microgrid protection is presented as well.

2.1 MTL modeling

Transmission lines are subject to a variety of transients behavior during operation, such as switching, fault, and lightning. In addition, the transmission line extended over a wide area, which arise to the standing wave phenomena. Therefore, transient modeling for the transmission line is essential for the reliable operation of the power system. Developing a transient model of transmission lines is quite difficult, considering the electric and magnetic coupling between the lines in addition to the distributed parameters of the transmission line along their length. Nevertheless, many different transient modeling of the transmission lines have been developed, and each with its own advantages and disadvantages. Still, the need for an accurate

and reliable model still exists. With the advances in computational processors and software, the transmission line transient model in electromagnetic transient simulation has become more sophisticated to acquire an accurate model.

One of the most known and widely used transmission line models is the π model. It is one of the simplest transient models usually used for short transmission lines under 100 Km. This model is used for steady-state analysis [1]. Another model is the lossless model, where the resistance and the conductance of the transmission line are set to zero ($R=0$, $G=0$) [2].

Vector fitting uses a rational function approximation method to fit measured data to the rational function,[3]. In [4], [5], and [6], Gustavsen and Semlyen presented a transient model of multiconductor transmission lines (MTL) using vector fitting. Vector fitting is a fast and robust method for rational fitting of frequency domain responses. In [7], time-domain modeling of partial discharge on medium voltage cables using the Vector Fitting Method is presented. The proposed model uses the vector fitting method to incorporate the skin effects and dielectric losses into the state matrices. In [8], a fast realization of the modal Model Vector Fitting (MVF) is presented. MVF has a faster pole and residue identification step and a lower number of iterations required to obtain the state-space model. In[9], a hybrid phase domain transmission line transient model is introduced, which utilizes the transpose of a transmission line to have a lower computational time without loss of accuracy. In [10], a Frequency-Dependent Cable Model (FDCM) is presented, which solves

an issue associated with the eigenvalues by reducing the rank of the propagation matrix to obtain a smooth fitting model. In [11] a new computationally efficient Frequency-Domain Transmission-Line Matrix (FDTLM) method is presented. The introduced approach combines features of both the time- and the frequency domain transmission-line matrix (TLM). The proposed FDTLM has the advantage of being able to extract all the frequency-domain information in the frequency range of interest from a single simulation. In [12], transient modeling of lossy multiconductor transmission lines (MTLs) using the Finite-Difference Time-Domain (FDTD) method is introduced. The proposed model is integrated with lumped loads at the transmission line terminal to study the behavior of electrified railway systems for protection and insulation coordination studies. In [13] frequency-dependent line model is developed, which utilizes the concept of frequency-adaptive simulation of transients in which the Fourier spectra are adaptively shifted in the frequency domain to reduce the discretization time-steps in the time domain. In [14] a transmission line frequency-dependent model based on the finite differences method is presented. The proposed model is complementary to the existing traveling wave-based approaches and better suited for distributed sources. In [15] A new Frequency-Dependent Line Model (FDLM) is proposed based on the Revised Multiconductor Transmission Line (RM TL) equations. The proposed model postulated the physical constraint that the voltage and current waves should travel collocated.

Some of the research papers focused more on the low-frequency range or DC transient modeling. In [16], an enhanced fitting technique for the transient response

of the transmission line is presented. The method is used to obtain an accurate DC transient response of the lines. The proposed model uses low-order fitting of a function error for every line parameter to obtain an accurate DC transient model of transmission lines. Moreover, a frequency domain transient transmission line model is presented in [17], emphasizing low-frequency transient response. The proposed transient model consists of two-stage modeling, a low-frequency model and a high-frequency model. The proposed model focuses on minimizing the error of a curve fitting in the low-frequency range. In [18] a frequency-domain model for the transient response of transmission lines/underground cables due to switching operations is presented. The presented model uses a fast Fourier transform-generated switching matrix where the on/off times are included. In [19] an enhanced fitting to obtain accurate transients, DC response of transmission lines is introduced. The proposed improved fitting method of the transmission line parameters emphasizes on the DC transient response for a wide range of frequencies. The proposed model uses the rational function approximation to fit the transient response of transmission line impedance.

Many papers address a more specific transient phenomenon to integrate into the transient modeling of transmission lines. Gunawardana, and Kordi, in [20], address the issue of the transient behavior of transmission lines crossing. The developed model utilizes the electromagnetic scattering theory to calculate space varying Per Unit Length (PUL) parameter matrices close to the conductor crossing. The proposed model takes into account different crossing angles for lossless and

frequency-independent transmission lines. While in [21], accurate transient modeling of skin effect of multiconductor transmission lines is proposed. This paper takes into account the transient behavior of transmission line skin effects.

In addition to the frequency domains model, many different time-domain models have been presented in the research. For instance, in [22], a transient model of multiconductor transmission lines (MTLs) using the Time-Domain Finite-Element (TDFE) method is presented. The proposed model is used for lossy MTLs with frequency-dependent parameters to simulate the transient behavior of MTLs. In addition, a real-time Optimized transient modeling of a transmission line is presented in [23]. The developed method subdivided the transmission line modeling (TLM) into individual nonlinear elements to reduce the simulation time. Moreover, a time-domain model of multiphase nonuniform lines Nonuniform Lines (NULs) is introduced in [24]. The proposed model is based on traveling waves and takes into account the frequency dependence of the line parameters. In [25], a transient time-domain model is developed using phase coordinates to avoid the problems associated with frequency-dependent transformation matrices. The proposed model converted to the time domain by synthesizing the circuit from the rational function approximation. In [26] a time-domain macromodeling method for the transient responses of underground cables is presented. The frequency-dependent variables are modeled using frequency response then converted to the time domain transient model. In [27], a nonuniform single-phase transmission lines frequency domain model is introduced. The proposed model assumes the line parameters vary exponentially. The model obtained a frequency model from a set of two ports equations based on

frequency-dependent functions. Then the frequency model is converted to a time model by synthesizing the obtained rational functions.

An estimation algorithm for mutually coupled transmission line parameters is developed in [28]. The presented model deals with the mutually coupled transmission line as a black box and measures the voltages and the currents at the sending end during a transient event. Then, the proposed algorithm obtains the unknown transmission line parameters during the transient event from the measured voltages and currents. In [29] a transmission line transient time-domain model based on scattering parameters is introduced. The model combines the scattering matrix and the nonlinear impedance functions. In [30] Frequency domain transient analysis of nonuniform transmission lines with incident field excitation is presented. The analysis is carried away using the cascaded connection of chain matrices of uniform line segments and a space-variant linear system. In[31] A wavelet transform-based method for improved modeling of transmission lines is introduced. the proposed wavelet-based frequency-dependent transmission line model is integrated into the overall network transients simulation.

2.2 Adaptive Protection

With the immense efforts in expanding microgrids and renewable energy sources penetration in the electric power grid due to the significant benefits associated

with operation cost, many challenges have been raised to efficiently design, control, and operate microgrids. Due to the different short-circuit levels of renewable inverter-based sources in microgrids, the distribution protective devices cannot reliably protect microgrids. In addition, the lack of specially designed commercially available microgrid relay, the existing options for reliable microgrid protection remain the sub-transmission and transmission system protective devices, as shown in [32].

In a microgrid, the power flow can change its direction through the transmission lines. Therefore, protecting the transmission line will be more difficult since the distance relays are not an inherently directional element. One of the solutions presented in the research is by studying the harmonics of a microgrid during fault and normal operation, and when the microgrid is in an islanded mode or connected to the utility grid, in [33], and [34].

The protection of a microgrid has its own challenges, one of these challenges is a microgrid network topology, whether it is a radial or looped network. Therefore, a communication-based relay is essential to identify the microgrid network connection configuration. As a result, the setting values of the relays must accommodate the changing of the microgrid network configuration. Therefore, in [35], a new microprocessor directional relay to protect microgrids for low-voltage microgrids is presented. On the other hand, in [36], a differential protection scheme using the spectral energy content of the time-frequency response for microgrid protection is presented. Moreover, By utilizing Cuckoo optimization algorithm(COA) and linear

programming algorithm, in [37], the optimization of protection coordination of renewable energy sources in microgrids is presented.

To overcome the problem of microgrid bidirectional power flow, a new directional element using the magnitude and angle of the negative-sequence impedance for microgrid protection is presented in [38]. While in [39], an innovative directional element for inverter-based microgrids that utilize unique features of zero-sequence components is presented. In addition, relay coordination to enhance the microgrid protection scheme plays an essential role in the protection scheme of a microgrid. Therefore, in [40], a novel optimal overcurrent relay coordination with constraint and non-standard characteristics to enhance the microgrid protection scheme is presented. Moreover, a solution is proposed to solve some of the distributed generators (DGs) integration problems in [41], by the usage of distance relays for distribution protection and current-based protection relays for feeders.

One of the most recent solutions to microgrid protection is adaptive relays and communication-based relays. In [42], In [43], and [44], a communication-based adaptive relay design is presented as a solution for the microgrid's different fault current level when it operates in an islanded mode or when it connected to the grid. While in [45], a hybrid microgrid protection concept is proposed, based on the integration of a traditional differential protection scheme with an adaptive microgrid protection scheme. In [46], an integration between control coordination strategy and different protection schemes for different microgrid operation modes is presented. In [47],

the authors presented a ring distribution microgrid architecture protection scheme that is capable of identifying the fault location and isolating it during the different modes of operations. A directional overcurrent protection scheme is used in [5], which is capable of identifying different fault currents levels in a different direction in a microgrid. In [48], an integration of fuse with an overcurrent protection scheme for a microgrid with distributed generators is presented. The proposed adaptive protection combines the technical and economic advantages of fuses and adaptive relays in a microgrid. Since all of the adaptive protection schemes require a different setting for the microgrid when it is connected to the grid and when it is operating in an islanded mode, then the adaptive relays of the microgrid depend heavily on communication. In [49], shows the communication failure impacts on microgrid protection schemes and utilizes the energy storage as a backup for power loss. Furthermore, in [50], the author proposes the integration of micro-phasor measurement units with overcurrent relays using communication-based as a solution for the microgrid protection scheme. The adaptive overcurrent relaying (AOCR) is heavily dependent on the renewable energy sources in a microgrid. Therefore, in [51] dynamic adaptive protection for different microgrid operation modes is presented with less communication overhead by utilizing external controllers to estimate relay pickup. While in [52], the authors presented an adaptive protection scheme for microgrid protection based on machine learning for reliable protection. The current fault level of photovoltaic (PV) power plants and the fault resistance could cause a high probability of failure in operation and unwanted operation of distance relay. Therefore, in [53], the authors proposed protection scheme to obtain the phase angle of fault current, which is the key

to calculating adaptive setting impedance. Distributed Generations are usually connected to the ac grid through HVDC transmission systems. Therefore, in [54] the authors proposed an adaptive distance protection scheme for a microgrid by controlling the current level of the renewable energy sources and adjusting the setting of the impedance relay of the microgrid.

The protection of microgrid has its challenges; one of these challenges is the different fault current levels of the microgrid when it is operated in an islanded mode or when it is connected to the utility grid. Due to the different fault current levels of the microgrid when it is connected to the grid and when it is in an islanded mode operation, a solution to limit the fault current by utilizing Fault Current Limiter (FLC) at the point of common coupling between the utility grid and the microgrid is presented in [55], and [56]. While in [57],[58], and [59] show the impact of utilizing a superconductor as fault current limiter, which has a lower power loss compared to using a conductor. The microgrid is exposed to utility grid common power quality disturbances when they are connected. Therefore, in [60], two current-limiting algorithms are presented and tested to increase the reliability of a microgrid.

Due to different fault current levels in a microgrid, the protection of the microgrid becomes more complicated. Different protection schemes are proposed in research papers to overcome microgrid protection issues in [61], and [62]. While in [63], a protection scheme is presented by monitoring the voltage level of the microgrid to differentiate between fault current and loading current in an islanded mode operation

of a microgrid. A different protection scheme is presented in [64],[65], and [66] by utilizing a traveling wave with low-bandwidth communication to identify the fault and the operation modes of a microgrid. A communication less fault detection protection scheme based on indirect impedance measurement is proposed in [67] for a looped microgrid. Another solution for an island microgrid protection scheme based on an adaptive microprocessor relay is presented in [68]. In [69], a solution to the microgrid protection coordination problem is presented by determining the optimal relay settings considering $N-1$ contingency. Due to the low fault current level of inverters-based microgrids, the conventional overcurrent protection relays can not be implemented effectively. Therefore, in [70], an inverter-based microgrid protection scheme for microgrid operated in an islanded Mode is presented. A mathematically based optimization algorithm for a microgrid protection scheme that is capable of identifying different fault types in different microgrid operation modes is presented in [71]. To enhance grid resilience, in [72], a reliable protection scheme for inverter-based microgrids using a real-time validation ensemble classifier method is proposed. The formulated proposed scheme can simultaneously identify the microgrid mode of operation and determine the fault location. Coordination between protective relays in microgrid and renewable energy sources plays a vital role in microgrid stability in avoiding nuisance tripping of DG, as shown in [73]. With the increasing penetration of renewable energy sources into the distribution network protection, the selectivity and reliability of microgrid protection will be affected. Therefore, in [74], and [75] microgrid protection coordination scheme for renewable energy sources is presented by modifying an existing characteristic curve of overcurrent relays. An adaptive

protection method using zero sequence components to identify the fault for different microgrid operation conditions is presented in [76].

In [77] and [78], the authors presented the advantages and disadvantages of different protection schemes. In [79], the authors presented a more recent and comprehensive review on adaptive protection for microgrids based on communications. In addition, the article present the authors perspective on the future of 5G wireless systems communication deployments for adaptive protection.

CHAPTER 3

THE PROPOSED TRANSIENT MODELING OF MULTICONDUCTOR TRANSMISSION LINES

A transmission line is one of the major electrical components in a power grid. Transmission lines are power guide components to deliver electric power from the source to the load. One characteristic of a transmission line that differs from any electrical component is that transmission lines may cover long distances from the source to the load. Due to the length of a transmission line, a standing wave in a transmission line may occur. In addition, a wide range of different transient phenomena may affect transmission lines, such as lightning discharge, switching, and faults. Therefore, developing an accurate transient model of a transmission line

is essential to predict the behavior of transmission lines in different transient scenarios.

Developing a transient model of transmission lines is quite difficult, considering the electric and magnetic coupling between the lines in addition to the distributed parameters of the transmission line along their length. Nevertheless, many different transient modeling of the transmission lines have been developed, and each has its advantages and disadvantages. Still, the need for less computational time and power, an accurate and reliable model is needed. With the advances made in computational processors, the transmission line transient model in electromagnetic transient simulation has become more sophisticated to acquire an accurate model.

The transmission line transient modeling can be classified into two major groups: the time domain model and the frequency domain model. The frequency-domain model is based on frequency modeling of the transmission line at different frequency points within a specific frequency range. While in the time domain, the developed model obtained a transmission line solution by integrating discrete time intervals (δt). The conversion of the frequency domain model to the time domain is difficult because the transmission lines parameters are frequency-dependent elements.

In the next section, an introduction to a well known and developed method, Vector Fitting (VF) is presented. VF is widely used to fit the impedance frequency response of a transmission line. The later sections of this chapter will be dedicated to the proposed model where it present the development of the proposed model. In addition,

the calculation of the proposed model parameters for a complex nonlinear equation is carried out. A comparison between VF and the MTL model will be presented in chapter 4.

3.1 Vector Fitting

VF is a methodology used to fit the impedance frequency response measurement of electrical equipment or network using a rational function approximation. In addition, a different method of frequency response measurement is presented. This is essential in developing the proposed model and comparing the proposed model with a well-known and developed fitting method, VF.

In [80], Gustavsen and Semlyen introduced VF, which is an approach to fit the impedance frequency response measurement of electrical equipment or network using a rational function approximation. The presented described methodology, which is known as a vector fitting, has the advantage of obtaining a more accurate transient response for a higher frequency response. The obtained transient space model can be synthesized into a two-port circuit model. The obtained circuit model must be passive, which means that the generated circuit model from the frequency response can not generate energy. In addition, the transient synthesized circuit is stabilized by enforcing passivity on the obtained circuit model.

To design a transient model of electric equipment or a network, a frequency response must be measured and analyzed. Then a two ports model can be developed from the measured data. The model is derived from the rational function obtained

from the fitted measured data. There are different approaches used in fitting a rational function approximation, such as inverse fast Fourier transform (IFFT) [81]. IFFT is a time-consuming process compared to the vector fitting method [80]. Gustavsen and Semlyen developed Vector Fitting (VF), which is a rational function approximation method.

The rational function approximation can be expressed as

$$f(s) = \sum_{n=1}^N \frac{c_n}{s - a_n} + d + s.h \quad (3.1)$$

where, C_n : Residues, a_n : poles, and d, h : real numbers.

The state-space model, which can be obtained from rational function approximation, can be utilized to develop a circuit model. The obtained circuit model has an identical frequency response as the measured data of an electric equipment or a network. The obtained circuit model can be simulated to ensure the same frequency response as the measured data.

3.2 Wave Characteristics On Finite Transmission Lines

The transmission lines can be represented by distributed circuit parameters through the length of the line, as shown in Figure 3.1. The physical dimensions of the transmis-

sion line could be many wavelengths long or a substantial fraction of the wavelength. Therefore, a standing wave may exist in a transmission line depending on the length of the transmission line and the operating frequency of the line, [82] and [83].

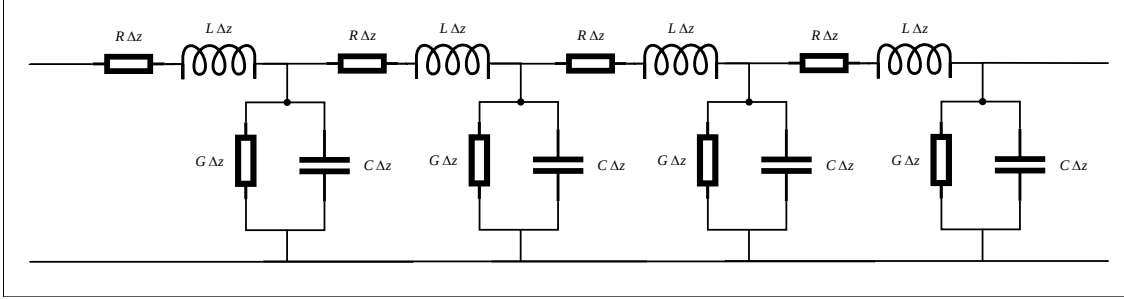


Figure 3.1: A segment of transmission Line Distributed Parameters. [84].

The wave characteristics of finite transmission lines is governed by the impedance of the transmission line. The impedance of the transmission line is given by [82]:

$$Z = Z_0 \frac{Z_L + Z_0 \times \tanh(\gamma l)}{Z_0 + Z_L \times \tanh(\gamma l)} \quad (3.2)$$

For short-circuit transmission line where the load impedance $Z_L = 0$:

$$Z = Z_0 \times \tanh(\gamma l) \quad (3.3)$$

For an open-circuit transmission line where the load impedance $Z_L = \infty$:

$$Z = \frac{Z_0}{\tanh(\gamma l)} \quad (3.4)$$

Where the characteristic impedance of the line is given by:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (3.5)$$

and, the propagation constant is given by:

$$\gamma_1 = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (3.6)$$

where:

- α , attenuation constant, in Np/m.
- β , phase constant, in rad/m.
- R , resistance per unit length, in Ω/m .
- L , inductance per unit length, in H/m.
- G , conductance per unit length, in S/m.
- C , capacitance per unit length, in F/m.
- l , length of the transmission line, in m.

For lossless transmission line:

$$Z_0 = R_0 = \sqrt{\frac{L}{C}} \quad (3.7)$$

Where R_0 is the characteristic resistance of lossless line.

$$\gamma_1 = j\beta = j\omega\sqrt{LC} \quad (3.8)$$

$$\tanh(\gamma l) = \tanh(j\beta l) = j \tan(\beta l) \quad (3.9)$$

Therefore, the impedance of a lossless short-circuited transmission line is given by ($Z_L = 0$):

$$Z = jR_0 \tan(\beta l) \quad (3.10)$$

Figure 3.2 shows the impedance of short-circuited transmission line as described by equation 3.10. The impedance of short-circuited transmission line is oscillating between inductive and capacitive depending of the value of βl , which is frequency dependant, see Table 3.1.

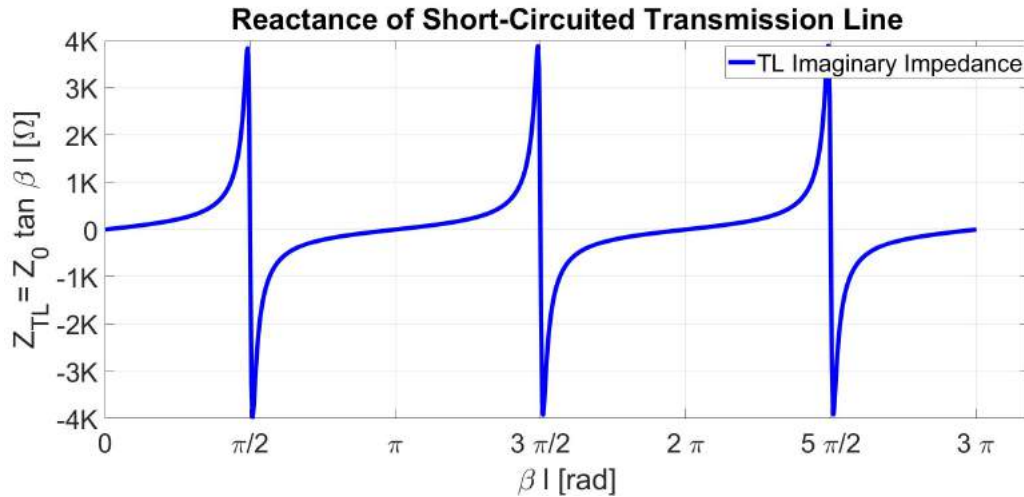


Figure 3.2: Reactance of Short-Circuited Line.

Table 3.1: Reactance of Short-Circuited Line

l	βl	Z_{TL}
$(n-1)\frac{\lambda}{2} < l < (2n-1)\frac{\lambda}{4}$	$(n-1)\frac{\pi}{4} < \beta l < (2n-1)\frac{\pi}{2}$	Inductive
$(2n-1)\frac{\lambda}{4} < l < n\frac{\lambda}{2}$	$(2n-1)\frac{\pi}{2} < \beta l < n\pi$	Capacitive
$n\frac{\lambda}{2}$	$n\pi$	0
where n= 1,2,3,...		

While the impedance of a lossless open-circuited transmission line is given by ($Z_L = \infty$):

$$Z = -jR_0 \cot(\beta l) \quad (3.11)$$

Figure 3.3 shows the impedance of the Open-circuited transmission line as described by equation 3.11. The impedance of short-circuited transmission line is oscillating between capacitive and inductive depending on the value of βl , which is frequency dependant, see Table 3.2.

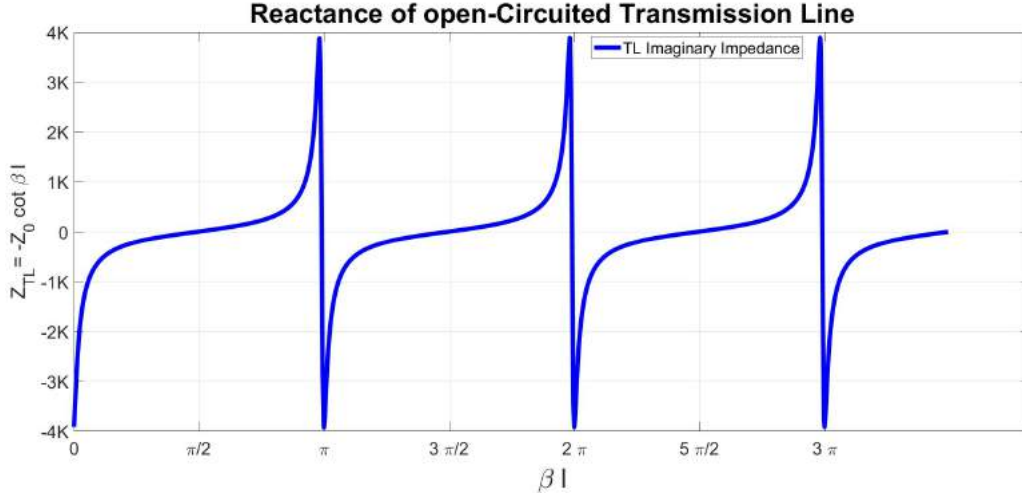


Figure 3.3: Reactance of Open-Circuited Line.

Table 3.2: Reactance of Open-Circuited Line

l	βl	Z_{TL}
$(n-1)\frac{\lambda}{2} < l < (2n-1)\frac{\lambda}{4}$	$(n-1)\frac{\pi}{4} < \beta l < (2n-1)\frac{\pi}{2}$	Capacitive
$(2n-1)\frac{\lambda}{4} < l < n\frac{\lambda}{2}$	$(2n-1)\frac{\pi}{2} < \beta l < n\pi$	Inductive
$(2n-1)\frac{\lambda}{4}$	$(2n-1)\frac{\pi}{2}$	0
where $n = 1, 2, 3, \dots$		

3.3 Transmission Line Frequency Response Analysis (FRA) measurements

In the previous section, the impedance frequency response of short-circuited transmission line has been shown using the analytical solution, see equation 3.10. Frequency

Response Analysis (FRA) is a methodology used to measure the frequency response of an impedance function or a transfer function. A similar tool in Real-Time Digital Simulator (RTDS) called frequency scan ”_rtds_FREQSCAN” is used to obtain the impedance frequency response of short-circuited transmission line over a wide range of frequencies. The frequency scan has a maximum range of 1MHz. The frequency scan output a text file containing all the impedance matrices at their measured frequencies. Therefore, the Real-Time Digital Simulator (RTDS) is used to obtain the FRA impedance measurements of a short-circuited transmission line. The data of the transmission line, which will be modeled and studied, is shown in Table 3.3. Figure 3.4 shows the circuit diagram of FRA measurement in RTDS.

Table 3.3: Transmission Line Parameters

Model	Bergeron (RLC Data Entry)
Line Length	100 [Km]
Frequency	60 [Hz]
Ground Resistivity	100 [Ω -m]
Number of Phases	3
Positive Sequence Series Resistance	0.018547 [Ω /Km]
Positive Sequence Series Ind. Reactance	0.37661 [Ω /Km]
Positive Sequence Shunt Cap. Reactance	0.22789 [Meaga Ω *Km]
Zero Sequence Series Resistance	0.3618376[Ω /Km]
Zero Sequence Series Ind. Reactance	1.227747 [Ω /Km]
Zero Sequence Shunt Cap. Reactance	0.34513 [Meaga Ω *Km]

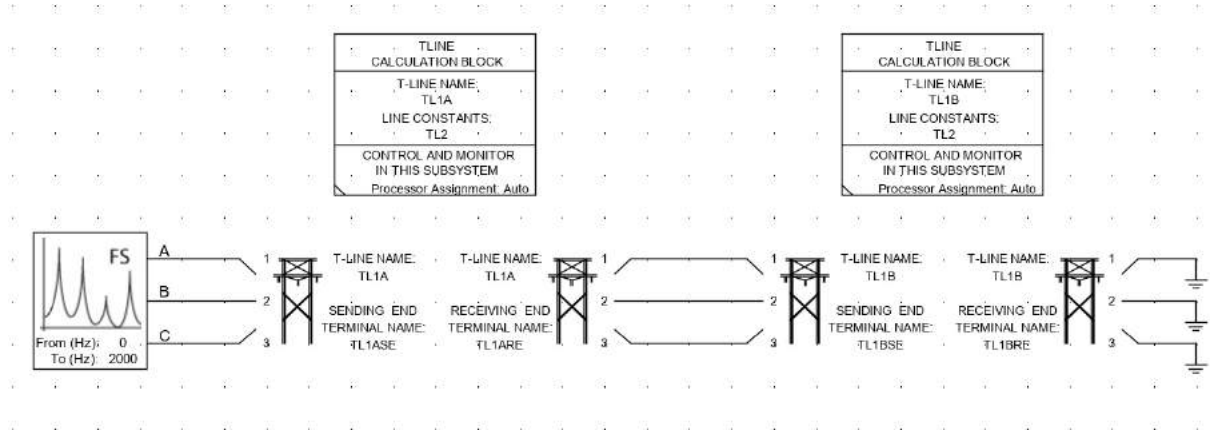


Figure 3.4: RTDS circuit line diagram of FRA measurements.

The FRA measurements of transmission line impedance are obtained in a symmetrical matrices format from RTDS. The impedance matrix of the transmission line at every frequency point is measured in the form of :

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \quad (3.12)$$

The impedance matrices of the transmission line are measured at different frequency points in a defined frequency range. To obtain a higher sampling rate and present clear graphs, the shown measurements were taken up to 2 kHz with 200001 samplings. The imaginary and real values of the transmission line impedance measurements of Z_{11} are shown in Figures 3.5 and 3.6 respectively.

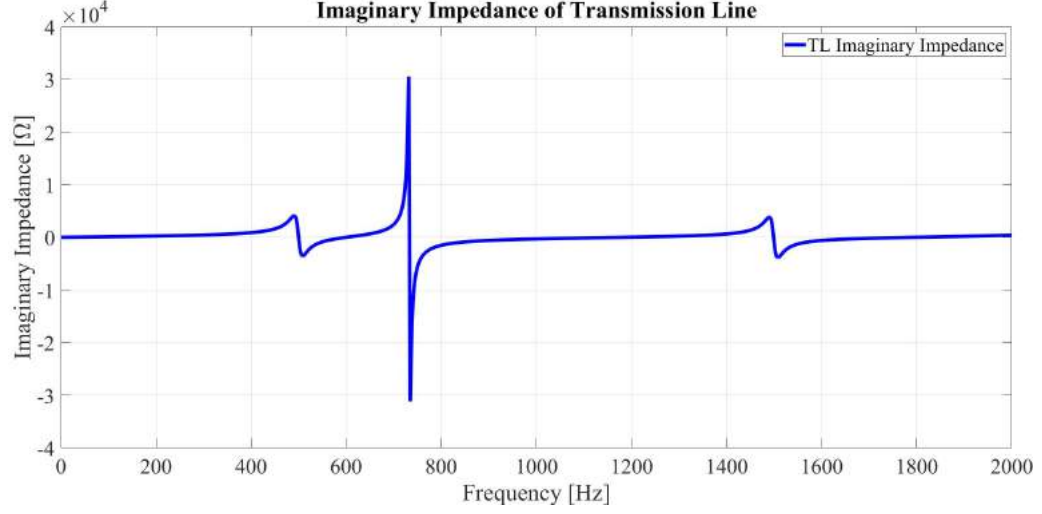


Figure 3.5: FRA measurements of transmission line impedance imaginary part of Z_{11} .

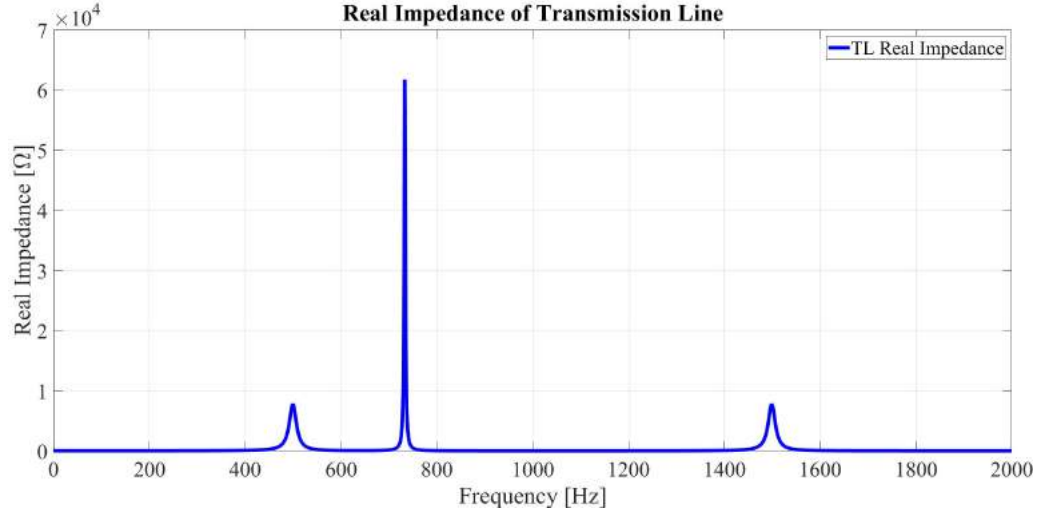


Figure 3.6: FRA measurements of transmission line impedance real part of Z_{11} .

Figure 3.5 shows sharp changes in the imaginary part of the transmission line impedance from maximum positive to minimum negative values (inductive to capacitive) at $f_{o1}=500$ Hz and $f_{o2}=733$ Hz, and slower changes from capacitive to inductive

at 600 Hz and 1200 Hz. Since the sharp changes from inductive to capacitive or vice versa (f_{o1} and f_{o2}) are associated with high real impedance values, then it will be considered as the resonance frequency of the transmission line. By analyzing Figures 3.5 and 3.6, we can see that the resonance frequencies take place when the imaginary part of the transmission line impedance is equal to zero, and the real part of the transmission line impedance is at maximum. Moreover, Figures 3.5 show two sets of resonance frequencies, while Figure 3.2 shows only one resonance. This is because equation 3.3 is for a single-phase transmission line, while FRA impedance measurement shown in Figures 3.5 and 3.6 are for a mutually coupled multiconductor transmission line. Therefore, by changing the number of phases to one and maintaining the same parameters, see Table 3.4, a single repeated resonance will appear as shown in Figures 3.7 and 3.8.

Table 3.4: Transmission Line Parameters

Model	Bergeron (RLC Data Entry)
Line Length	100 [Km]
Frequency	60 [Hz]
Ground Resistivity	100 [Ω -m]
Number of Phases	1
Positive Sequence Series Resistance	0.018547 [Ω /Km]
Positive Sequence Series Ind. Reactance	0.37661 [Ω /Km]
Positive Sequence Shunt Cap. Reactance	0.22789 [Meaga Ω *Km]

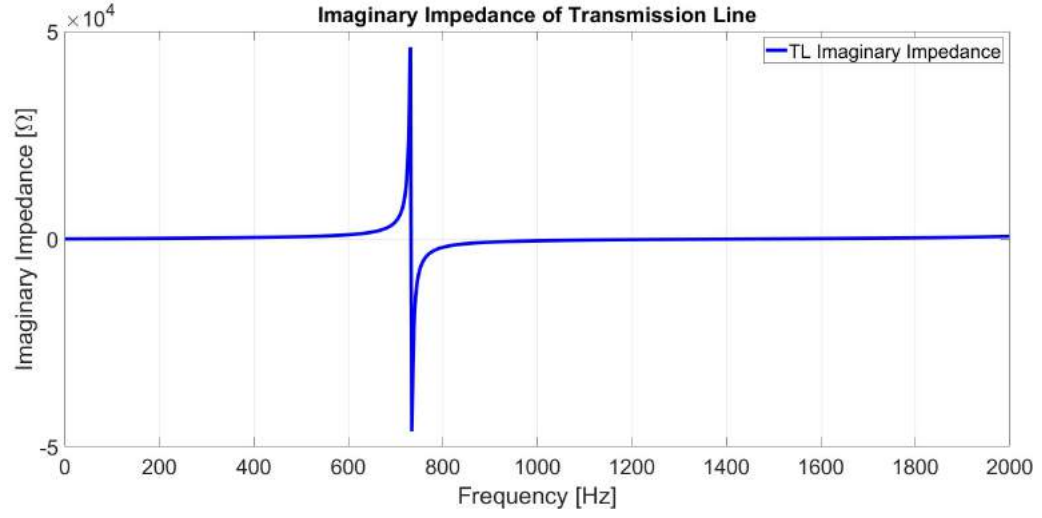


Figure 3.7: FRA measurements of transmission line impedance imaginary part when $Z_0 = Z_1$.

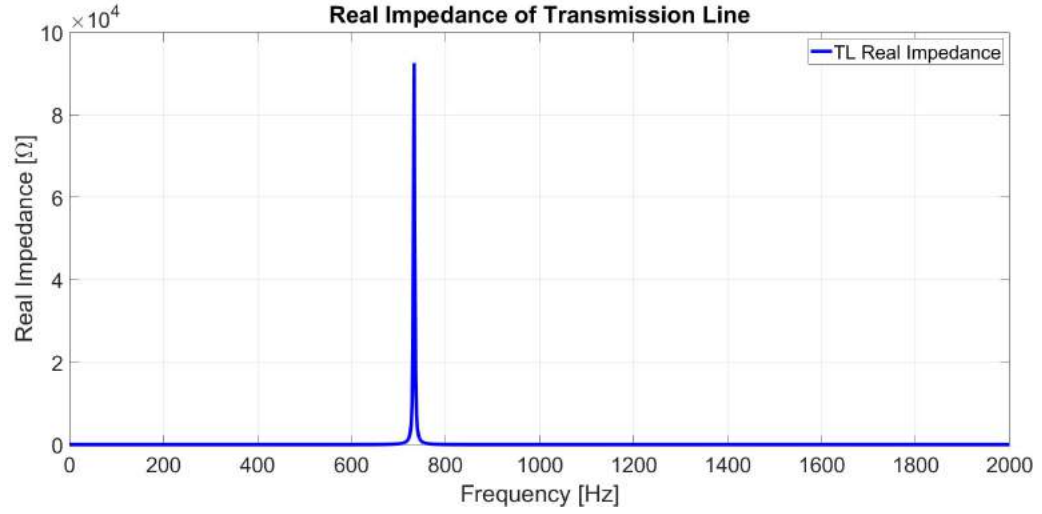


Figure 3.8: FRA measurements of transmission line impedance real part when $Z_0 = Z_1$.

Therefore, due to all the different parameters of transmission line of mutual coupling between the phases and between the phases and the ground wires, and the self

impedance parameters of different lines, then a more accurate representation of a multiconductor mutually coupled transmission line impedance equation (in the case Z_{11}) will be:

$$Z_{11} = Z_{o1} \times \tanh \gamma_1 l + Z_{o2} \times \tanh \gamma_2 l \quad (3.13)$$

let

$$Z_1 = Z_{o1} \times \tanh \gamma_1 l \quad (3.14)$$

$$Z_2 = Z_{o2} \times \tanh \gamma_2 l \quad (3.15)$$

Where:

Z_1 is the lumped mutual coupling impedance of the transmission line.

Z_2 is the lumped self impedance of the transmission line.

Z_{o1} is the characteristic impedance of the self impedance of the transmission line.

Z_{o2} is the characteristic impedance of the mutual coupling impedance of the transmission line.

Equation 3.13 will be used to model the MTLs impedance instead of equation 3.3. The added second term in equation 3.13, is because the transient frequency response of MTLs impedance (for Z_{11}) has a second resonance, and due to the similarity and nature of both resonances, the same function ($\tanh$) is used. In the next section, the parameters of the proposed model equation 3.13 will be calculated using derived resonance equations and the frequency response of a transmission line impedance.

3.4 Parameters of Transmission Line Impedance

Equation

To obtain the parameters of the proposed transmission line impedance equation (in this case for Z_{11}), a set of equations must be derived from the complex nonlinear transmission line impedance equation:

$$Z_{11} = Z_1 + Z_2 \quad (3.16)$$

$$Z_{11} = Z_{o1} \times \tanh \gamma_1 l + Z_{o2} \times \tanh \gamma_2 l \quad (3.17)$$

where

$$Z_{o1} = \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \quad (3.18)$$

$$Z_{o2} = \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \quad (3.19)$$

$$\gamma_1 = \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} \quad (3.20)$$

$$\gamma_2 = \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} \quad (3.21)$$

- R_1 and R_2 are the resistance per unit length for the mutual impedance and the self impedance respectively, in Ω/m .

- L_1 and L_2 are the inductance per unit length for the mutual impedance and the self impedance respectively, in H/m.
- G_1 and G_2 are the conductance per unit length for the mutual impedance and the self impedance respectively, in S/m.
- C_1 and C_2 are the capacitance per unit length for the mutual impedance and the self impedance respectively, in F/m.

Therefor, the transmission line impedance of Z_{11} :

$$\begin{aligned} & \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} + \\ & \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} = Z_{11} \end{aligned} \quad (3.22)$$

Since the air resistance between phases and between phase and ground is very high ($10^9 \frac{\Omega}{m}$), then we can initially assume:

$$G_1 = G_2 = 10^{-9} [S] \quad (3.23)$$

Since the capacitance in μF and the measured impedance frequency range is 10^{-6} Hz to 2 MHz, then at low frequency

$$\tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} = \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} \quad (3.24)$$

$$\tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} = \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} \quad (3.25)$$

Therefore, equation 3.22 at low frequency can be simplified:

$$R_1 + R_2 + j\omega(L_1 + L_2) = Z_{11} \quad (3.26)$$

Let,

$$R_T = R_1 + R_2 \quad (3.27)$$

$$R_T = \text{Real}(Z_{11})_{at 10^{-6} Hz} \quad (3.28)$$

$$L_T = L_1 + L_2 \quad (3.29)$$

$$L_T = \frac{\text{Im}(Z_{11})_{at 10^{-6} Hz}}{\omega} \quad (3.30)$$

Where R_T and L_T are the total resistance and inductance, respectively obtained from transmission line FRA measurement at 10^{-6} Hz. Since we have two resonances ($f_{01} = 500$ and $f_{02} = 733$) as shown in figure 3.9 where the real part of the transmission line impedance peaks at, then equation 3.22 must be written in rectangular complex format (real and imaginary) to obtain the transmission line parameters. From equating the imaginary part of equation 3.22 to zero and the real part by the relative maximum values, a set of equations are derived, see Appendix A for resonance equations derivation:

$$Z_{R1} = \frac{2L_1}{C_1 R_1} \quad (3.31)$$

$$Z_{R2} = \frac{2L_2}{C_2 R_2} \quad (3.32)$$

$$\frac{\pi^2}{4\omega^2} = L_1 C_1 \quad (3.33)$$

$$\frac{\pi^2}{4\omega_2^2} = L_2 C_2 \quad (3.34)$$

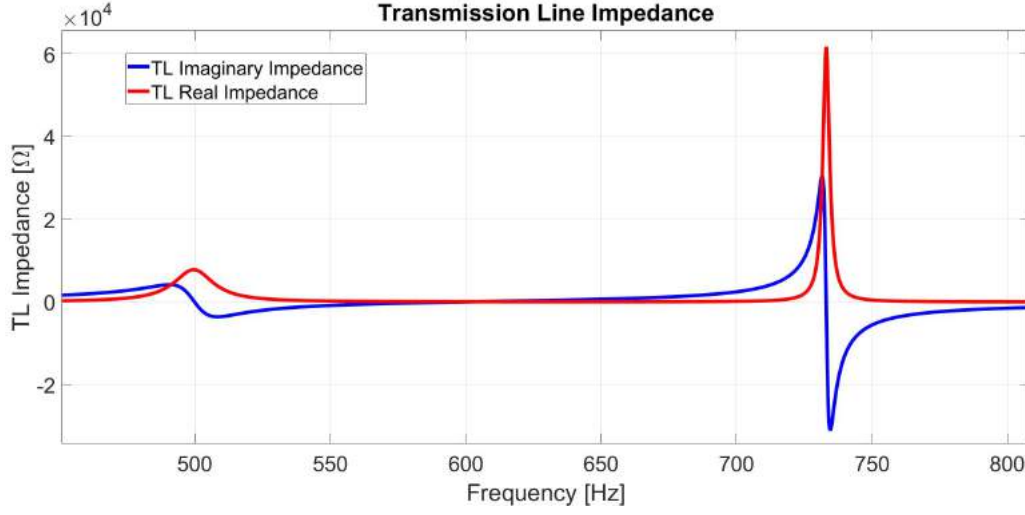


Figure 3.9: FRA measurements of transmission line impedance.

Equations 3.31 and 3.35, and Figure 3.10, shows that the maximum real impedance of transmission line (Z_{11}) at resonance is dependent on transmission line parameters (R, L, and C) and not on the frequency.

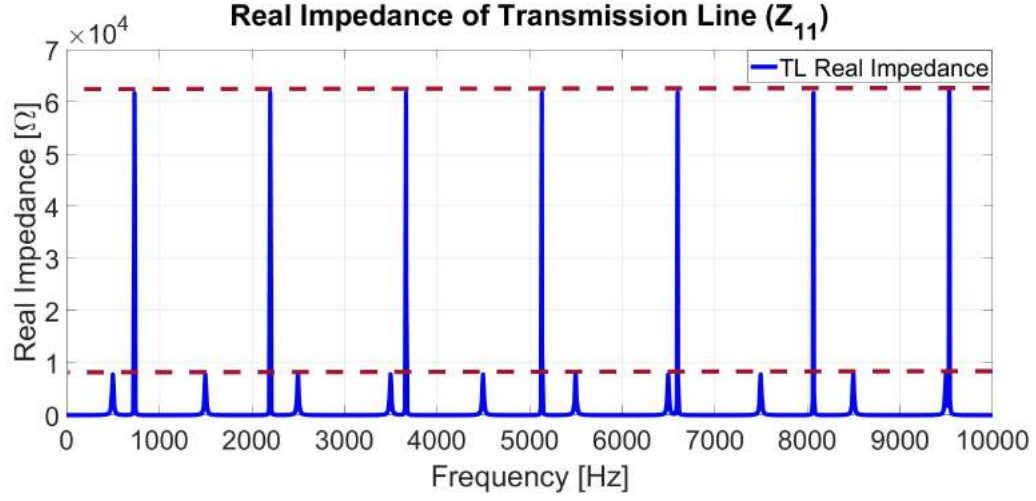


Figure 3.10: FRA measurements of transmission line real impedance of Z_{11} .

Through mathematical derivation and the measured frequency response of transmission line impedance, six equations were obtained with six unknowns:

$$R_T = R_1 + R_2 \quad (3.35)$$

$$L_T = L_1 + L_2 \quad (3.36)$$

where

$$R_T = \text{Real}(Z_{11})_{at 10^{-6} Hz} \quad (3.37)$$

$$L_T = \text{Im}(Z_{11})_{at 10^{-6} Hz} \quad (3.38)$$

$$L_1 C_1 = \frac{\pi^2}{4\omega_1^2} \quad (3.39)$$

$$L_2 C_2 = \frac{\pi^2}{4\omega_2^2} \quad (3.40)$$

$$Z_{R1} = \frac{2L_1}{C_1 R_1} \quad (3.41)$$

$$Z_{R2} = \frac{2L_2}{C_2 R_2} \quad (3.42)$$

Where

Z_{R1} is the maximum peak of the real part of the transmission line impedance at f_{o1} .

Z_{R2} is the maximum peak of the real part of the transmission line impedance at f_{o2} .

substituting equation 3.39 in 3.41, we get:

$$Z_{R1} = \frac{2L_1^2 4\omega_1^2}{\pi^2 R_1} \quad (3.43)$$

$$Z_{R1} \pi^2 R_1 = 2L_1^2 4\omega_1^2 \quad (3.44)$$

substituting equation 3.35

$$Z_{R1} \pi^2 (R_T - R_2) = 2L_1^2 4\omega_1^2 \quad (3.45)$$

substituting equation 3.42

$$Z_{R1} \pi^2 \left(R_T - \frac{2L_2}{C_2 Z_{R2}} \right) = 2L_1^2 4\omega_1^2 \quad (3.46)$$

$$Z_{R1} \pi^2 R_T = 2L_1^2 4\omega_1^2 + \frac{2L_2}{C_2 Z_{R2}} Z_{R1} \pi^2 \quad (3.47)$$

$$Z_{R1} \pi^2 R_T C_2 Z_{R2} = 2L_1^2 4\omega_1^2 C_2 Z_{R2} + 2L_2 Z_{R1} \pi^2 \quad (3.48)$$

$$C_2(Z_{R1}\pi^2 R_T Z_{R2} - 2L_1^2 4\omega_1^2 Z_{R2}) = 2L_2 Z_{R1}\pi^2 \quad (3.49)$$

substituting equation 3.40

$$\frac{\pi^2}{4\omega_2^2}(Z_{R1}\pi^2 R_T Z_{R2} - 2L_1^2 4\omega_1^2 Z_{R2}) = 2L_2^2 Z_{R1}\pi^2 \quad (3.50)$$

$$\frac{\pi^2}{4\omega_2^2} Z_{R1}\pi^2 R_T Z_{R2} - \frac{\pi^2}{4\omega_2^2} 2L_1^2 4\omega_1^2 Z_{R2} = 2L_2^2 Z_{R1}\pi^2 \quad (3.51)$$

$$2L_2^2 Z_{R1}\pi^2 + \frac{\pi^2}{4\omega_2^2} 2L_1^2 4\omega_1^2 Z_{R2} - \frac{\pi^2}{4\omega_2^2} Z_{R1}\pi^2 R_T Z_{R2} = 0 \quad (3.52)$$

substituting equation 3.36

$$2L_2^2 Z_{R1}\pi^2 + \frac{\pi^2 \omega_1^2}{\omega_2^2} (L_T - L_2)^2 2Z_{R2} - \frac{\pi^4}{4\omega_2^2} Z_{R1} R_T Z_{R2} = 0 \quad (3.53)$$

$$2L_2^2 Z_{R1}\pi^2 + L_T^2 2\frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} + L_2^2 2\frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} - 2L_2 L_T 2\frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} - \frac{\pi^4}{4\omega_2^2} Z_{R1} R_T Z_{R2} = 0 \quad (3.54)$$

$$L_2^2 (2Z_{R1}\pi^2 + 2\frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2}) - L_2 (L_T 4\frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2}) + L_T^2 2\frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} - \frac{\pi^4}{4\omega_2^2} Z_{R1} R_T Z_{R2} = 0 \quad (3.55)$$

$$a = 2Z_{R1}\pi^2 + 2\frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} \quad (3.56)$$

$$b = -4L_T \frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} \quad (3.57)$$

$$c = 2L_T^2 \frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} - \frac{\pi^4}{4\omega_2^2} Z_{R1} R_T Z_{R2} \quad (3.58)$$

Since Z_{11} at 1^{-6} Hz:

$$Z_{11} = 13.29772 + 0.0000011i \Omega \quad (3.59)$$

Then,

$$R_T = 13.29772 \, \Omega \quad (3.60)$$

$$L_T = 0.17504 \, H \quad (3.61)$$

$$Z_{R1} = 7.81585 \, k\Omega \quad (3.62)$$

$$Z_{R2} = 61.71053 \, k\Omega \quad (3.63)$$

$$f_{o1} = 499.55 Hz \quad (3.64)$$

$$f_{o2} = 733.15 Hz \quad (3.65)$$

$$\omega_1 = 2\pi f_{o1} \quad (3.66)$$

$$\omega_2 = 2\pi f_{o2} \quad (3.67)$$

By solving the second order equation, the transmission line parameters of Z_{11} can be obtained:

Table 3.5: Transmission Line Calculated Parameters for Z_{11}

Transmission Line Parameters	Calculation
R_1	12.07079 $[\Omega]$
L_1	0.108695 $[H]$
C_1	2.30425 $[\mu F]$
R_2	1.22693 $[\Omega]$
L_2	0.06635 $[H]$
C_2	1.75258 $[\mu F]$

From the calculated transmission line parameters in Table 3.5, and by using equation:

$$\sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} + \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} = Z_{11} \quad (3.68)$$

The measured and the fitted impedance can be presented. The real and imaginary impedance, Z_{11} , of the transmission line are shown in Figures 3.11 and 3.12 respectively.

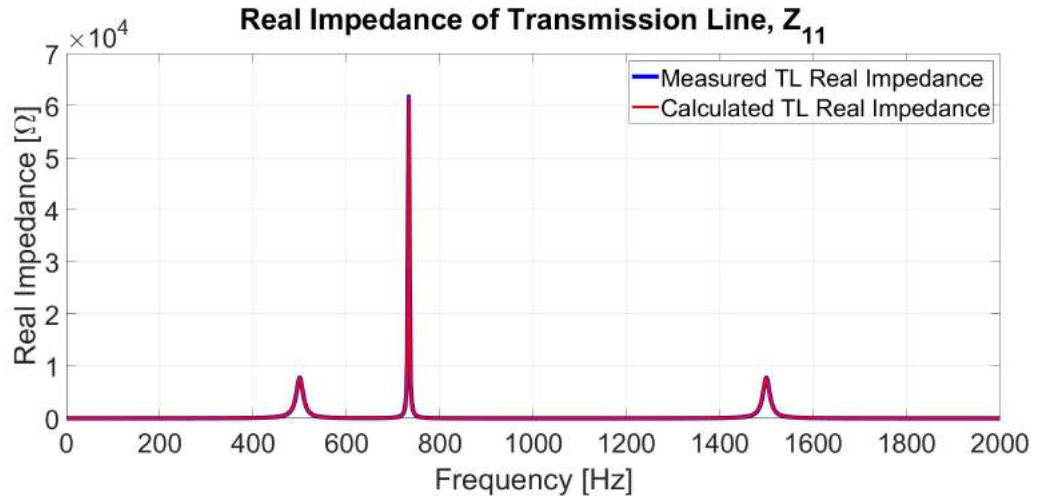


Figure 3.11: Impedance Frequency response measurements and the proposed model calculation of the real part of Z_{11} .

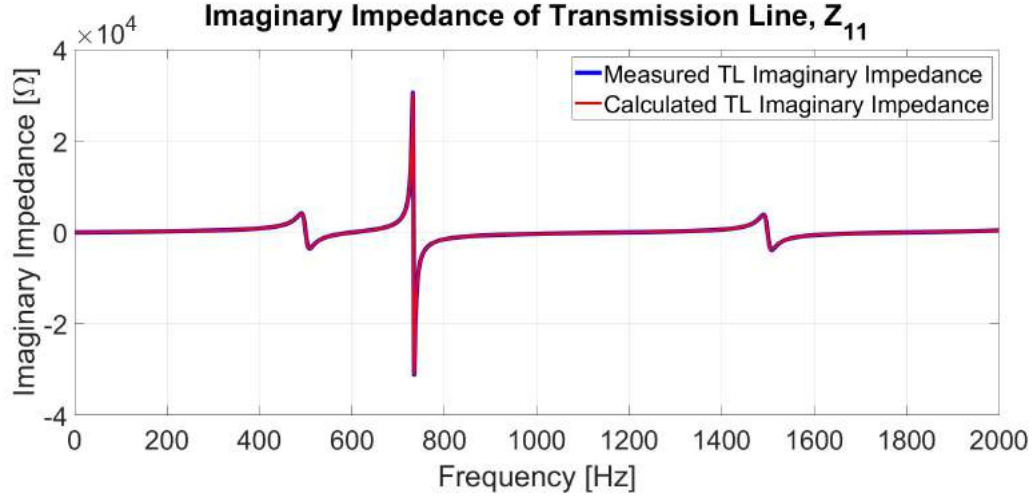


Figure 3.12: Impedance Frequency response measurements and the proposed model calculation of the imaginary part of Z_{11} .

3.5 Obtaining transmission line parameters of Z_{12} , Z_{13} and Z_{23}

The FRA measurements of transmission line impedance are obtained in a symmetrical matrices format from RTDS. The impedance matrix of the transmission line at every single measured frequency point is in the form:

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \quad (3.69)$$

From the measured impedance matrices we find that

$$Z_{12} = Z_{21} = Z_{13} = Z_{31} = Z_{23} = Z_{32} \quad (3.70)$$

and

$$Z_{11} = Z_{22} = Z_{33} \quad (3.71)$$

Therefore, to obtain the parameters of Z_{12} , we can apply the same mathematical formula derived in the last section using Z_{12} FRA measurements. Figures 3.13 and 3.14 show the FRA of transmission line impedance of Z_{11} and Z_{12} for both real and imaginary parts, respectively. Therefore, by comparing Z_{11} and Z_{12} in Figures 3.13 and 3.14, we find that the first resonance, $f_{o1} = 500Hz$, both the real and imaginary part of Z_{11} and Z_{12} have the same values. In contrast, in the second resonance, $f_{o2} = 733Hz$, both the real and imaginary part of Z_{11} and Z_{12} have different values with opposite signs. Therefore, by comparing both Figures 3.13 and 3.14 we can derive the impedance equation which describe Z_{12} . Therefore, since

$$Z_{11} = Z_{o1} \times \tanh \gamma_1 l + Z_{o2} \times \tanh \gamma_2 l \quad (3.72)$$

Which is simplified to

$$Z_{11} = Z1 + Z2 \quad (3.73)$$

Then for Z_{12} ,

$$Z_{12} = Z3 - Z4 \quad (3.74)$$

and since both of Z_{11} and Z_{12} have the same real and imaginary values for the first resonance f_{o1} then,

$$Z_3 = Z_1 \quad (3.75)$$

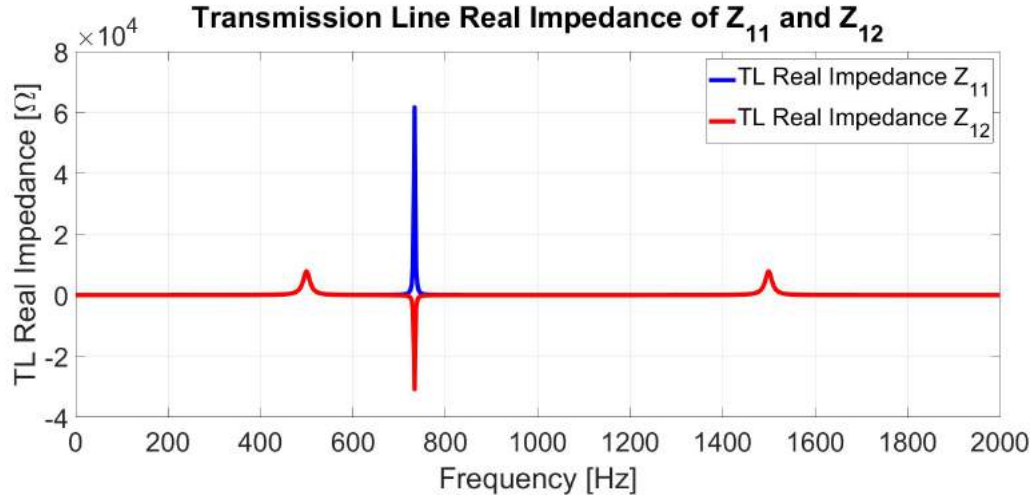


Figure 3.13: Impedance Frequency response measurements of the real part of Z_{11} and Z_{12} .

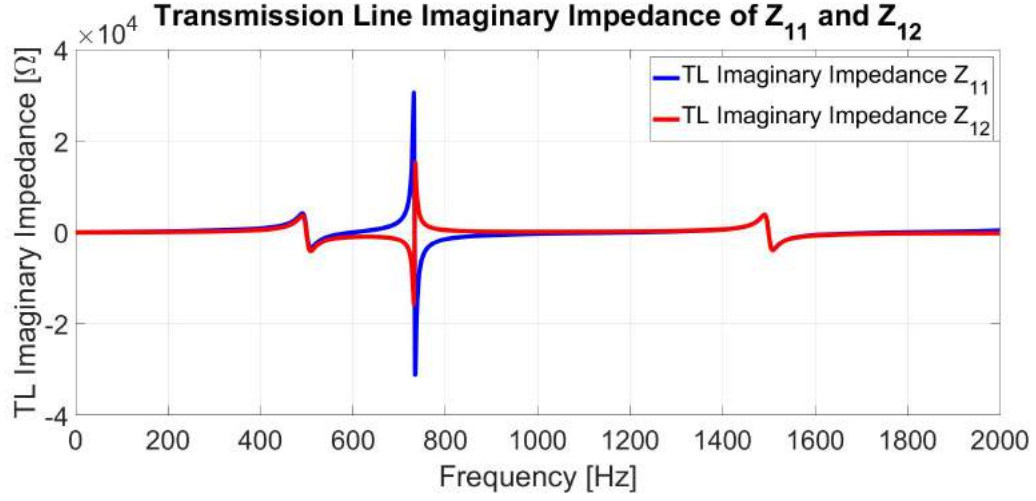


Figure 3.14: Impedance Frequency response measurements of the imaginary part of Z_{11} and Z_{12} .

Therefore, to obtain the parameters of Z_{12} , we change the equations 3.35 and 3.36 to:

$$R_T = R_1 - R_2 \quad (3.76)$$

$$L_T = L_1 - L_2 \quad (3.77)$$

where

$$R_T = \text{Real}(Z_{11})_{at 10^{-6} Hz} \quad (3.78)$$

$$L_T = \text{Im}(Z_{11})_{at 10^{-6} Hz} \quad (3.79)$$

$$L_1 C_1 = \frac{\pi^2}{4\omega_1^2} \quad (3.80)$$

$$L_2 C_2 = \frac{\pi^2}{4\omega_2^2} \quad (3.81)$$

$$Z_{R1} = \frac{2L_1}{C_1 R_1} \quad (3.82)$$

$$Z_{R2} = \frac{2L_2}{C_2 R_2} \quad (3.83)$$

$$Z_{R1} = \frac{2L_1^2 4\omega_1^2}{\pi^2 R_1} \quad (3.84)$$

$$Z_{R1} \pi^2 R_1 = 2L_1^2 4\omega_1^2 \quad (3.85)$$

$$Z_{R1} \pi^2 (R_T + R_2) = 2L_1^2 4\omega_1^2 \quad (3.86)$$

$$Z_{R1} \pi^2 (R_T + \frac{2L_2}{C_2 Z_{R2}}) = 2L_1^2 4\omega_1^2 \quad (3.87)$$

$$Z_{R1} \pi^2 R_T = 2L_1^2 4\omega_1^2 - \frac{2L_2}{C_2 Z_{R2}} Z_{R1} \pi^2 \quad (3.88)$$

$$Z_{R1} \pi^2 R_T C_2 Z_{R2} = 2L_1^2 4\omega_1^2 C_2 Z_{R2} - 2L_2 Z_{R1} \pi^2 \quad (3.89)$$

$$C_2 (Z_{R1} \pi^2 R_T Z_{R2} - 2L_1^2 4\omega_1^2 Z_{R2}) = -2L_2 Z_{R1} \pi^2 \quad (3.90)$$

$$\frac{\pi^2}{4\omega_2^2} (Z_{R1} \pi^2 R_T Z_{R2} - 2L_1^2 4\omega_1^2 Z_{R2}) = -2L_2^2 Z_{R1} \pi^2 \quad (3.91)$$

$$\frac{\pi^2}{4\omega_2^2} Z_{R1} \pi^2 R_T Z_{R2} - \frac{\pi^2}{4\omega_2^2} 2L_1^2 4\omega_1^2 Z_{R2} = -2L_2^2 Z_{R1} \pi^2 \quad (3.92)$$

$$2L_2^2 Z_{R1} \pi^2 - \frac{\pi^2}{4\omega_2^2} 2L_1^2 4\omega_1^2 Z_{R2} + \frac{\pi^2}{4\omega_2^2} Z_{R1} \pi^2 R_T Z_{R2} = 0 \quad (3.93)$$

$$2L_2^2 Z_{R1} \pi^2 - \frac{\pi^2 \omega_1^2}{\omega_2^2} (L_T + L_2)^2 2Z_{R2} + \frac{\pi^4}{4\omega_2^2} Z_{R1} R_T Z_{R2} = 0 \quad (3.94)$$

$$2L_2^2 Z_{R1} \pi^2 - L_T^2 2 \frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} - L_2^2 2 \frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} - 2L_2 L_T 2 \frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} + \frac{\pi^4}{4\omega_2^2} Z_{R1} R_T Z_{R2} = 0 \quad (3.95)$$

$$L_2^2 (2Z_{R1} \pi^2 - 2 \frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2}) - L_2 (L_T 4 \frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2}) - L_T^2 2 \frac{\pi^2 \omega_1^2}{\omega_2^2} Z_{R2} + \frac{\pi^4}{4\omega_2^2} Z_{R1} R_T Z_{R2} = 0 \quad (3.96)$$

Since Z_{12} at 1^{-6} Hz:

$$Z_{12} = 11.44302 + 0.00000047i\Omega \quad (3.97)$$

Then,

$$R_T = 11.44302 \Omega \quad (3.98)$$

$$L_T = 0.07515 H \quad (3.99)$$

$$Z_{R1} = 7.81024 k\Omega \quad (3.100)$$

$$Z_{R2} = 30.84093 k\Omega \quad (3.101)$$

$$f_{o1} = 499.55 Hz \quad (3.102)$$

$$f_{o2} = 733.14 Hz \quad (3.103)$$

$$\omega_1 = 2\pi f_{o1} \quad (3.104)$$

$$\omega_2 = 2\pi f_{o2} \quad (3.105)$$

By solving the second order equation, the transmission line parameters of Z_{12} can be obtained:

Table 3.6: Transmission Line Calculated Parameters for Z_{12} , Z_{13} and Z_{23}

Transmission Line Parameters	Calculation
R_1	12.06897 [Ω]
L_1	0.10865 [H]
C_1	2.30525 [μF]
R_2	0.62594 [Ω]
L_2	0.0335 [H]
C_2	3.4709 [μF]

Table 3.6 shows that R_1 , L_1 , and C_1 of Z_{12} have the same values as R_1 , L_1 , and C_1 of Z_{11} from Table 3.5. Therefore, the calculation carried out to find all the parameters were not necessary but to shows that the values of $Z1$ and $Z3$ are the same in equation 3.75. Since the values of R_1 , L_1 , and C_1 are already obtained in Table 3.5, then equations (3.76, 3.77, and 3.83) can be used to obtain R_2 , L_2 , and C_2 for Z_{12} .

Moreover, another method to obtain the line parameters for $Z2$, is by taking the ratio of Z_{R2} of Z_{11} from equation 3.63 to Z_{R2} of Z_{12} from equation 3.101. Therefore, let

$$\alpha = \frac{Z_{R2}}{Z_{R2}} = 2.000930040924867 \approx 2 \quad (3.106)$$

To maintain the same resonance at f_{o2} , and reduce the value of Z_{R2} from equation 3.63 by α , then

$$L_2 = \frac{L_2}{\alpha} \quad (3.107)$$

$$C_2 = C_2\alpha \quad (3.108)$$

$$R_2 = \frac{R_2}{\alpha} \quad (3.109)$$

Once these sets of equations (3.107, 3.108, and 3.109) are met, then the resonance frequency will remain the same (equation 3.81) while the magnitude of Z_{R2} will drop to match the measured value of Z_{12} (equation 3.83). By comparing the vales of R_2 , L_2 , and C_2 from Table 3.6 with Table 3.5, we find that the values of R_2 and L_2 were halfed while the value of C_2 was doubled. Therefore, the impedance of Z_{12} , equation 3.74, can be written using the parameters of Z_{11} :

$$Z_{12} = Z3 - Z4 = Z1 - \frac{Z2}{\alpha} \quad (3.110)$$

Equation 3.110 is an indication that all the impedance equations (Z_{12} , Z_{13} , and Z_{23}) of the impedance matrix can be derived using the initial obtain parameters of Z_{11} . Therefore, by analyzing and comparing different impedance waveforms (Z_{12} , Z_{13} , and Z_{23}) with Z_{11} the remaining impedance equations of Z_{12} , Z_{13} , and Z_{23} can be derived.

From the calculated transmission line parameters in Table 3.6, and by using equation:

$$\begin{aligned} & \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} - \\ & \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} = Z_{12} \end{aligned} \quad (3.111)$$

The measured and the fitted impedance can be plotted. The real and imaginary impedance, Z_{12} , of the transmission line are shown in Figures 3.15 and 3.16 respectively.

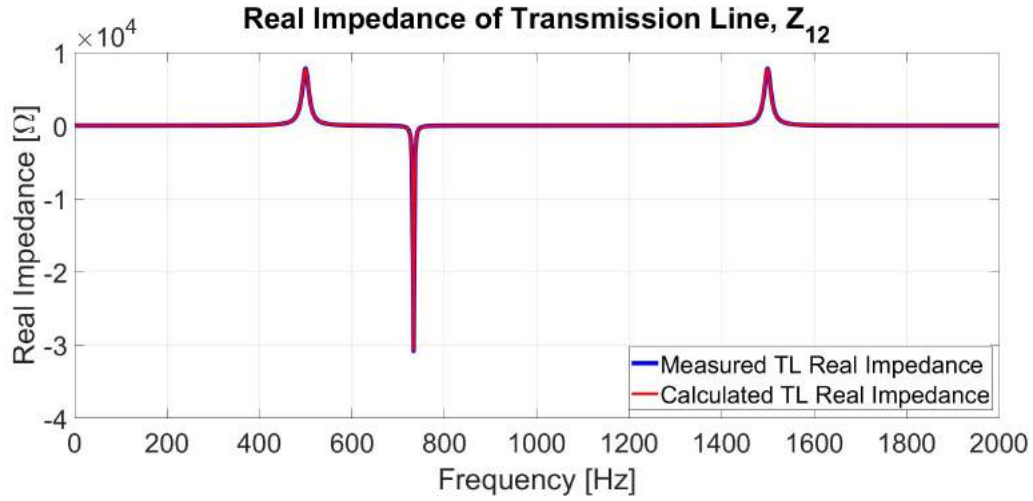


Figure 3.15: Impedance Frequency response measurements and the proposed model calculation of the real part of Z_{12} .

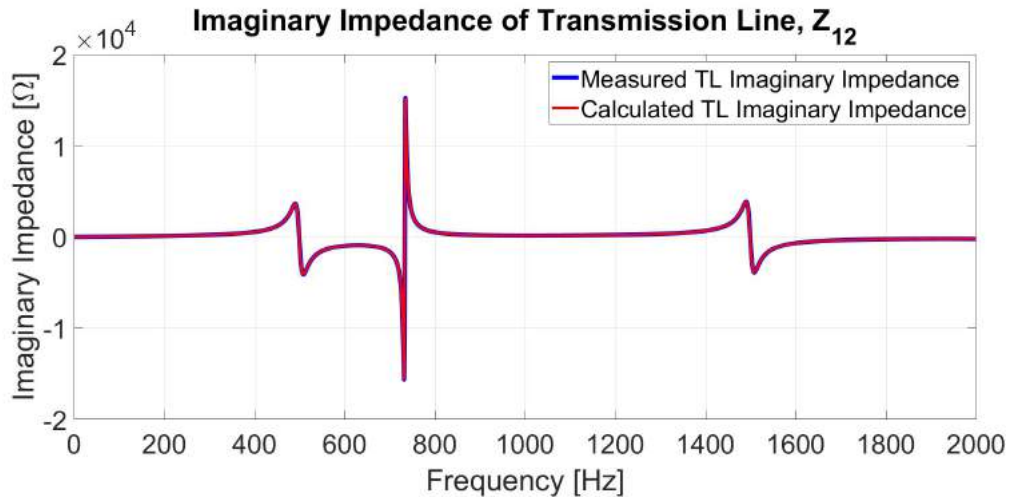


Figure 3.16: Impedance Frequency response measurements and the proposed model calculation of the imaginary part of Z_{12} .

3.6 Developed algorithm for a more accurate fitting

An algorithm is developed to minimize the error between the measured impedance and the analytically proposed model. The derived analytical model has some initial approximation to obtain the initial transmission line parameters. Therefore, the proposed algorithm use the calculated initial parameters values and keep updating the transmission line parameters (R_1 , L_1 , C_1 , R_2 , L_2 , and C_2) to minimize the error and obtain a more accurate model parameters. The proposed algorithm is shown in Figure 3.17

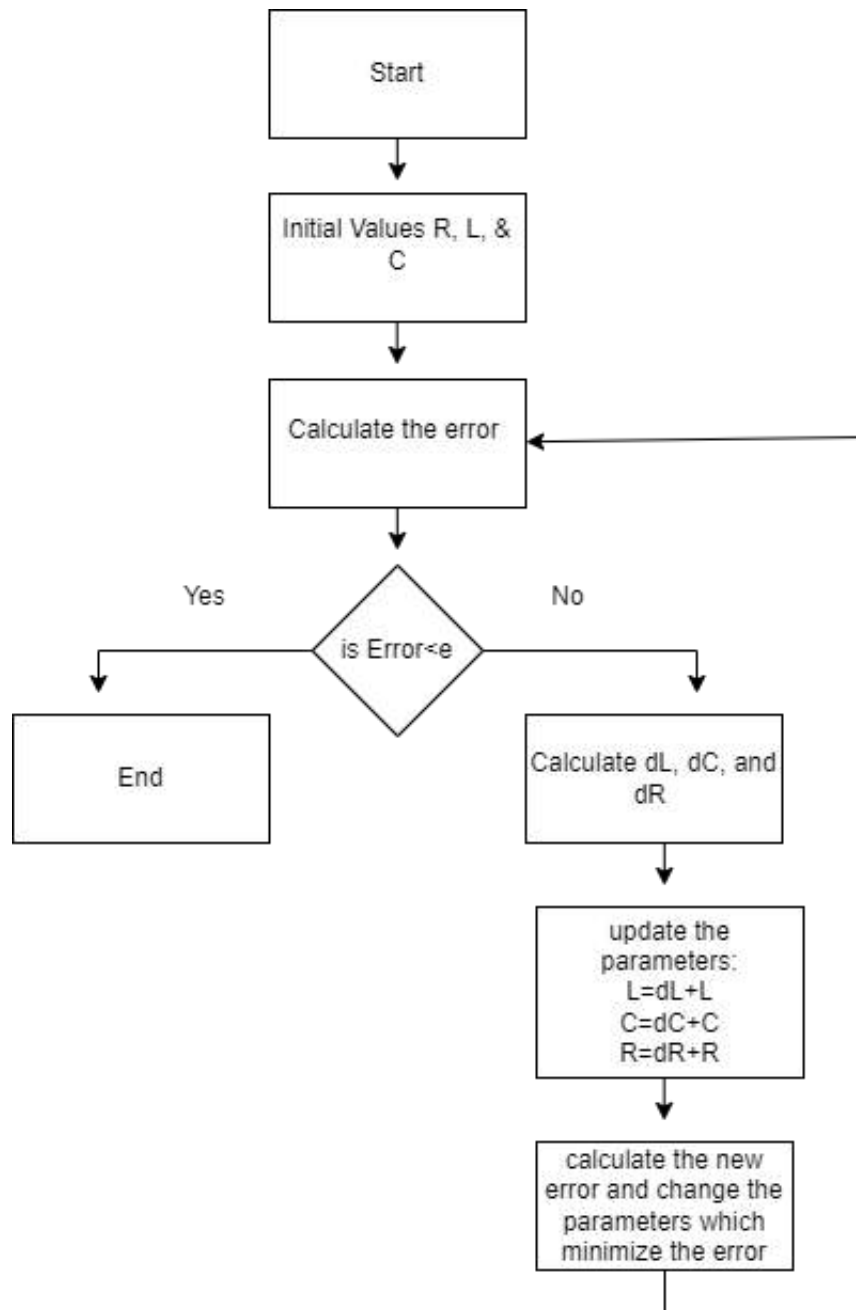


Figure 3.17: Developed Algorithm for an accurate model.

The transmission line parameters which fit the measured impedance of Z_{11} , Z_{12} , and Z_{23} more accurately are shown in Tables 4.3, 3.8, and 3.9 respectively.

Table 3.7: Transmission Line Calculated and Fitted Parameters of the proposed model for Z_{11} .

TL Parameters	Calculated	Fitted	Error %
R_1	12.0708 [Ω]	12.06 [Ω]	0.0895
L_1	0.10869 [H]	0.10854 [H]	0.1371
C_1	2.30425 [μF]	2.30594 [μF]	0.0735
R_2	1.22693 [Ω]	1.23772 [Ω]	0.8719
L_2	0.06635 [H]	0.06659 [H]	0.3678
C_2	1.75258 [μF]	1.74613 [μF]	0.3696

Table 3.8: Transmission Line Calculated and Fitted Parameters of the proposed model for Z_{12} .

TL Parameters	Calculated	Fitted	Error %
R_1	12.06897 [Ω]	12.06 [Ω]	0.0743
L_1	0.10865 [H]	0.10855 [H]	0.0944
C_1	2.30525 [μF]	2.30596 [μF]	0.0309
R_2	0.62594 [Ω]	0.61886 [Ω]	1.1447
L_2	0.0335 [H]	0.03329 [H]	0.6179
C_2	3.4709 [μF]	3.49224 [μF]	0.6110

Table 3.9: Transmission Line Calculated and Fitted Parameters of the proposed model for Z_{23} .

TL Parameters	Calculated	Fitted	Error %
R_1	12.06897 [Ω]	12.06 [Ω]	0.0743
L_1	0.10865 [H]	0.10855 [H]	0.0944
C_1	2.30525 [μF]	2.30596 [μF]	0.0309
R_2	0.62594 [Ω]	0.61886 [Ω]	1.1447
L_2	0.0335 [H]	0.03329 [H]	0.6191
C_2	3.4709 [μF]	3.49228 [μF]	0.6122

Tables 4.3, 3.8, and 3.9 shows the error between the calculated and the fitted parameters, (R_1 , L_1 , C_1 , R_2 , L_2 , and C_2). Even though some approximation was made to solve the transmission line impedance equations, yet the maximum error between the fitted and the calculated transmission line parameters is within 1%. The parameters obtained from the algorithm are shown in Tables 4.3, 3.8, and 3.9. The obtained transmission line parameters are used to fit the impedance of the multiconductor mutually coupled transmission line for a 1 MHz range.

The parameters of Z_{23} and the frequency response impedance measurements are slightly different than Z_{12} and Z_{13} . This difference is in the impedance measurement obtained from RTDS. Therefore, To have a more accurate fit for the proposed model, the algorithm is used for Z_{23} as well. Comparing the tables 3.8, and 3.9, show that the difference between the parameters of Z_{23} and Z_{12} is very small.

3.7 Frequency dependency of transmission line parameters

The per unit length parameters of transmission line are frequency dependent and can be used as constant parameters for a lumped transmission line model in the frequency domain. In addition, the lumped transmission line model can accurately model the transmission line for high frequency range in the frequency domain. However, modeling the transmission line in the time domain requires including the frequency effects on the parameters. This is because a single pulse in the time domain contains a continuum of sinusoidal components[85]. Since the proposed model is a lumped MTL model in the frequency domain, then the parameters of the proposed model can be constants.

CHAPTER 4

FITTING OF THE IMPEDANCE FREQUENCY RESPONSE USING THE PROPOSED MTL MODEL

In this chapter the complete proposed model and its parameters are presented. The proposed model is compared with a well known and developed fitting method, vector fitting. The proposed model and the vector fitting method will be tested for different frequency ranges.

4.1 Simulations and Results

To ensure the accuracy of the proposed model, a well-known and developed fitted method is used, vector fitting. Vector Fitting (VF) is a powerful tool which imple-

ment the rational function approximation to fit the mathematical function to the measured data. VF is a general procedure to fit the measured impedance frequency response of MTL to rational function approximation. VF has been used to model the transient behavior of transmission lines and underground cables. The rational function approximation of Vector fitting is given by:

$$f(s) = \sum_{n=1}^N \frac{c_n}{s - a_n} + d + s.h \quad (4.1)$$

where:

C_n : Residues.

a_n : Poles.

d and h : Real numbers.

n : The number of approximation.

Therefore, to have a better fit of the measured data, the number of approximation (n) must have a higher value.

The presented model in this research is based on the analytical analysis of the finite transmission line impedance equation. The proposed model takes into account the mutual coupling and self-impedance of a three-phase transmission line. Therefore, the presented model uses the obtained transmission line parameters and sets of the equation to describe the transmission line impedance for different frequencies range. The presented model and vector fitting method will be tested for different frequency ranges. For the proposed analytical model, the parameters

and the equations will be fixed under different frequency ranges. The impedance of the three-phase transmission line will be presented For both models. Since this model is based on the impedance of the transmission line, then for the vector fitting method, we will plot the impedance instead of the admittance. In addition, to give a more accurate representation of both models, the error instead of the deviation will be calculated for the absolute and the angle of the impedance for both models.

Proposed model For Z_{11} , Z_{22} , and Z_{33} :

The parameters:

Table 4.1: Transmission Line Calculated Parameters for Z_{11}

Transmission Line Parameters	Values
R_1	12.06 $[\Omega]$
L_1	0.10855 $[H]$
C_1	2.30594 $[\mu F]$
G_1	1e-9 $[S]$
R_2	1.23772 $[\Omega]$
L_2	0.06659 $[H]$
C_2	1.74613 $[\mu F]$
G_2	1e-9 $[S]$

The equations:

$$Z_{11} = Z_{22} = Z_{33} = Z_1 + Z_2 \quad (4.2)$$

where:

$$Z1 = \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} \quad (4.3)$$

$$Z2 = \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} \quad (4.4)$$

Proposed model For Z_{12} , Z_{21} , Z_{13} , and Z_{31} :

The parameters:

Table 4.2: Transmission Line Calculated Parameters for Z_{12}

Transmission Line Parameters	Values
R_1	12.06 $[\Omega]$
L_1	0.10855 $[H]$
C_1	2.30596 $[\mu F]$
G_1	1e-9 $[S]$
R_2	0.61886 $[\Omega]$
L_2	0.03329 $[H]$
C_2	3.49224 $[\mu F]$
G_2	1e-9 $[S]$

The equations:

$$Z_{12} = Z_{21} = Z_{31} = Z_{13} = Z_1 - Z_2 \quad (4.5)$$

where:

$$Z1 = \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} \quad (4.6)$$

$$Z2 = \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} \quad (4.7)$$

Proposed model For Z_{23} , and Z_{32} :

The parameters:

Table 4.3: Transmission Line Calculated Parameters for Z_{11}

Transmission Line Parameters	Values
R_1	12.06 $[\Omega]$
L_1	0.10855 [H]
C_1	2.30596 $[\mu F]$
G_1	1e-9 [S]
R_2	0.61886 $[\Omega]$
L_2	0.03329 [H]
C_2	3.49228 $[\mu F]$
G_2	1e-9 [S]

The equations:

$$Z_{23} = Z_{32} = Z_1 - Z_2 \quad (4.8)$$

where:

$$Z1 = \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} \quad (4.9)$$

$$Z2 = \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} \quad (4.10)$$

4.1.1 Case1: Test for 10KHz frequency rang:

In this case, the tested frequency range is 1^{-6} to 10kHz. The number of approximations used for the vector fitting is set to 50 (n=50). Figures 4.1 and 4.2 show the magnitude and the angle of the proposed model and the measurement of the transmission line impedance, respectively. The green line in Figures 4.1 shows the error between the measured and fitted impedance of the three-phase transmission line using the proposed model with a maximum error of 0.1111 %.

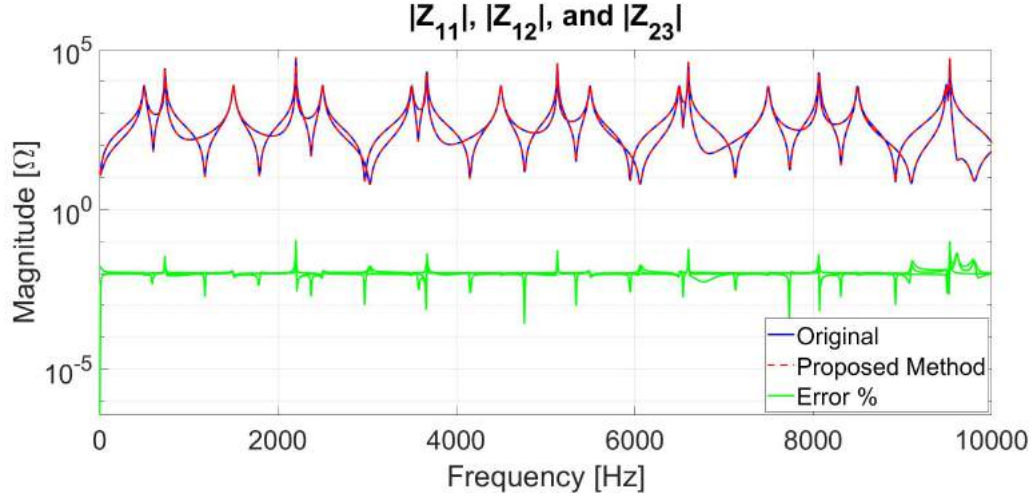


Figure 4.1: The magnitude of the measured impedance and the proposed model impedance, $|Z_{11}|$, $|Z_{12}|$, and $|Z_{23}|$.

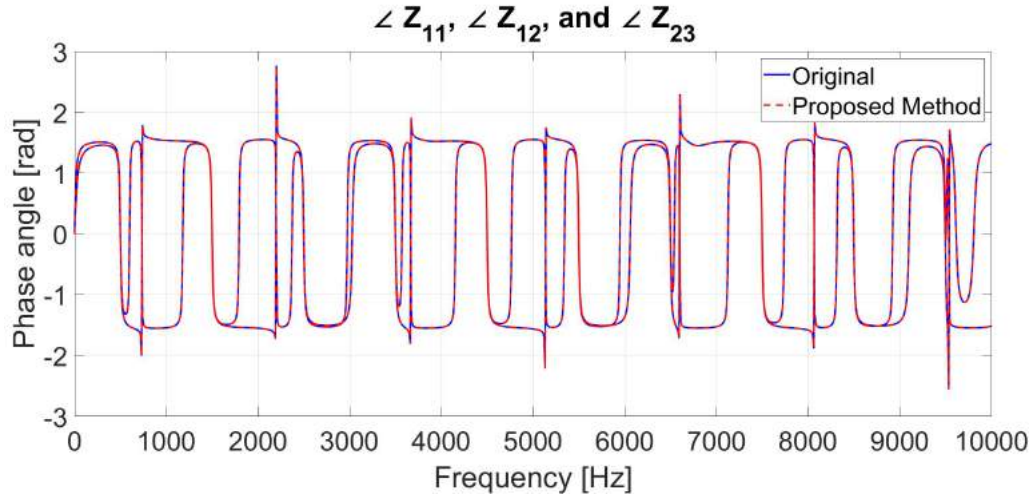


Figure 4.2: The angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$.

Figures 4.3 and 4.4 show the magnitude and the angle of the VF method and the measurement of the transmission line impedance, respectively. The green line

in Figures 4.3 shows the error between the measured and fitted impedance of the three-phase transmission line using the VF method with a maximum error of 0.0222 %.

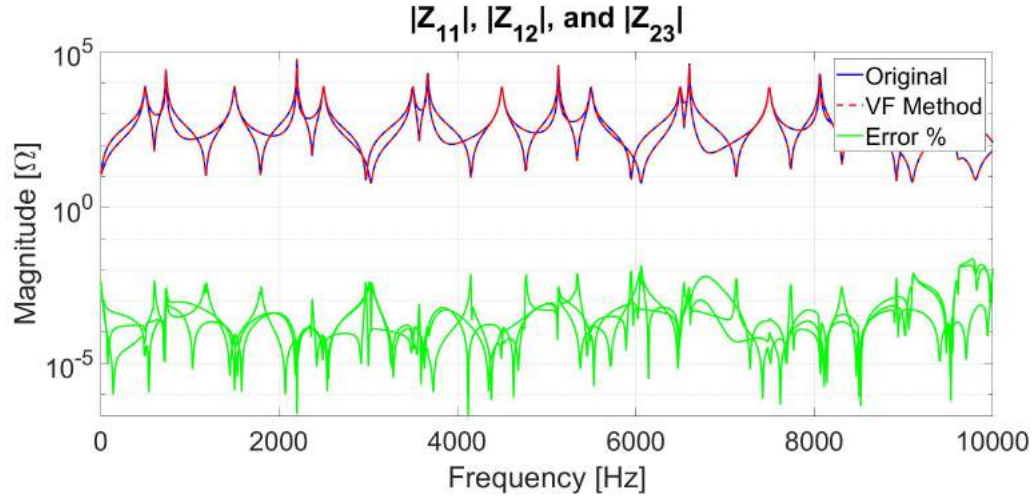


Figure 4.3: The magnitude of the measured impedance and the VF impedance, $|Z_{11}|$, $|Z_{12}|$, and $|Z_{23}|$.

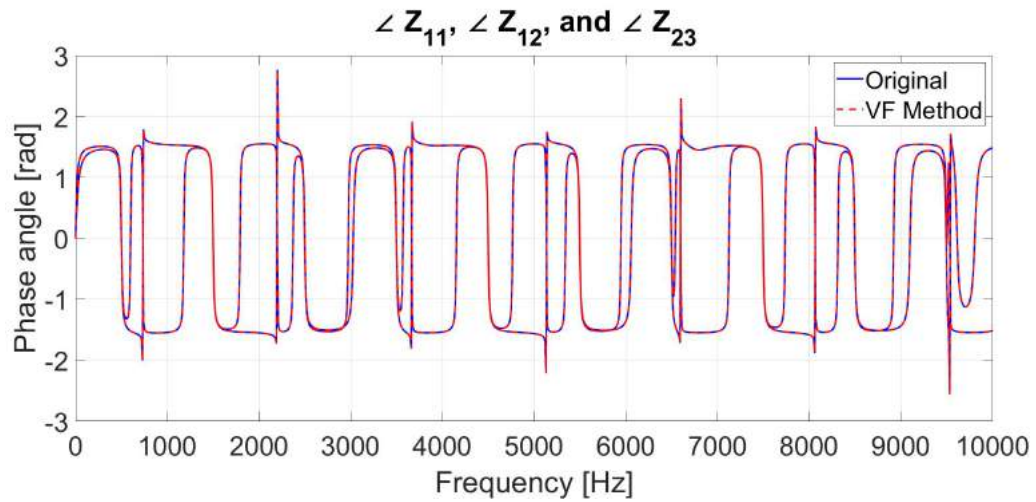


Figure 4.4: The angle of the measured impedance and the VF impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$.

4.1.2 Case2: Test for 100KHz frequency range

In this case, the tested frequency range is up to 100kHz. The number of approximations for the vector fitting is set to 750 ($n=750$). Figures 4.5 and 4.6 show the magnitude and the angle of the proposed model and the measurement of the transmission line impedance, respectively. The green line in Figures 4.5 shows the error between the measured and fitted impedance of the three-phase transmission line using the proposed model with a maximum error of 0.1309 %.

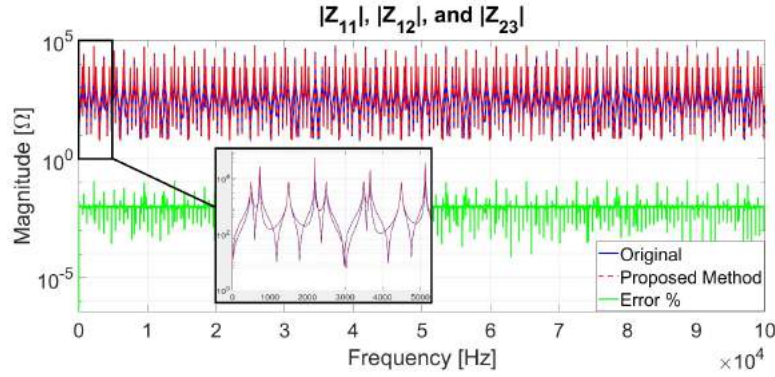


Figure 4.5: The magnitude of the measured impedance and the proposed model impedance, $|Z_{11}|$, $|Z_{12}|$, and $|Z_{23}|$.

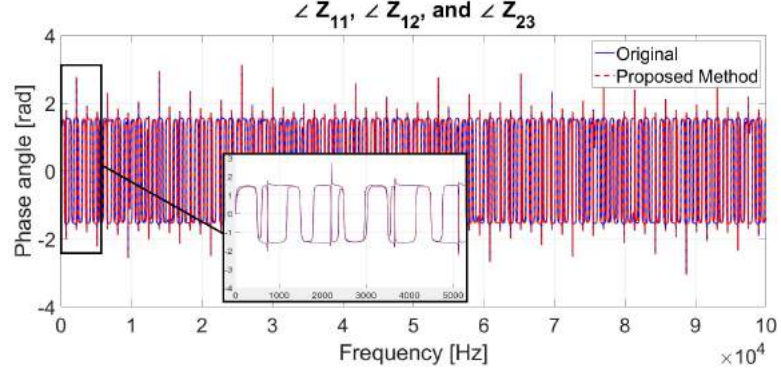


Figure 4.6: The Angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$.

Figures 4.7 and 4.8 show the magnitude and the angle of the VF method and the measurement of the transmission line impedance, respectively. The green line in Figures 4.7 shows the error between the measured and fitted impedance of the three-phase transmission line using the VF method with a maximum error of 0.1039 %.

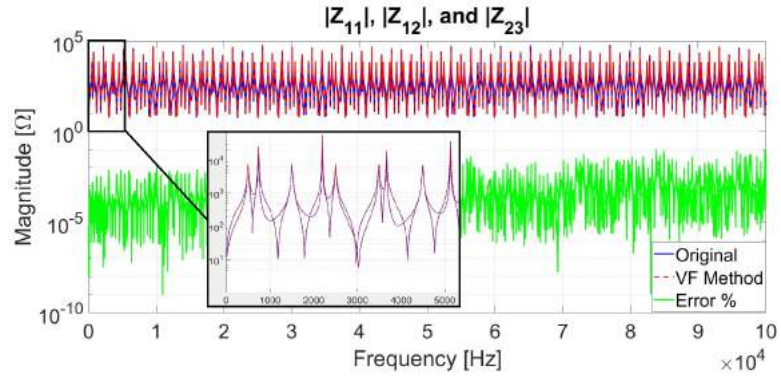


Figure 4.7: The magnitude of the measured impedance and the VF impedance, $|Z_{11}|$, $|Z_{12}|$, and $|Z_{23}|$.

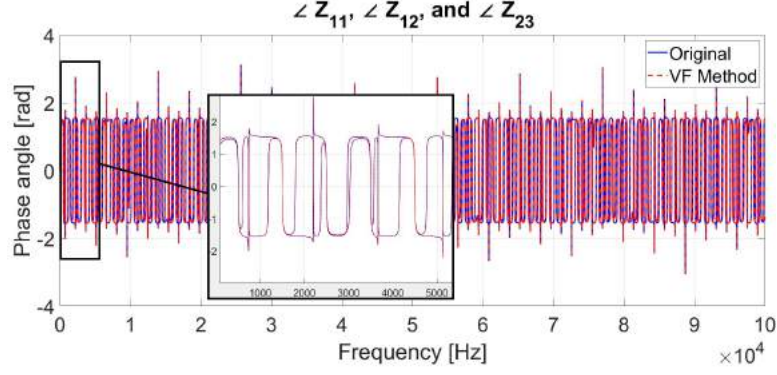


Figure 4.8: The angle of the measured impedance and the VF impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$.

4.1.3 Case3: Test for 1MHz frequency range :

In this case, the tested frequency range is up to 1MHz. Assuming a linear relationship between the frequency range and the number of approximation (n) from the previous cases, then the number of approximations required to fit the impedance curve using vector fitting for the 1 MHz range is 11250. Simulating this high number of approximations is highly computational costly. Therefore, for cases 3 and 4, only the proposed model results will be shown. Figures 4.11 and 4.13 show the magnitude and the angle of the proposed model and the measurement of the transmission line impedance, respectively. The green line in Figures 4.11 shows the error between the measured and fitted impedance of the three-phase transmission line using the proposed model with a maximum error of 0.1530 %.

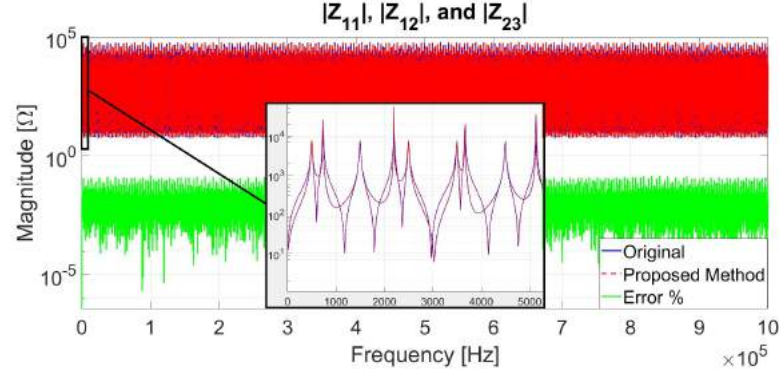


Figure 4.9: The magnitude of the measured impedance and the proposed model impedance, $|Z_{11}|$, $|Z_{12}|$, and $|Z_{23}|$.

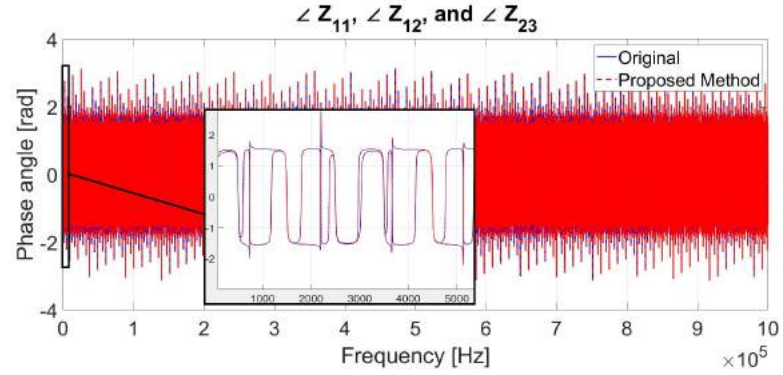


Figure 4.10: The angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$.

4.1.4 Case4: Test for different transmission line lengths for 1MHz frequency range :

Since the proposed model is based on the analytical impedance equation of the transmission line, then the model must correlate to the transmission line length. Therefore,

changing the length of the line should not increase the error level between the measured and calculated transmission line impedance. The new length of the simulated transmission line is (300 Km). Since the added length of the line is half of the original length, then all the parameters of Z_{11} , Z_{12} , and Z_{23} in Tables 4.3, 3.8, and 3.9 are multiplied by (1.5). Figures 4.11 and 4.13 show the magnitude and the angle of the proposed model and the measurement of the transmission line impedance, respectively. The green lines in Figures 4.11 show the error between the measured and fitted impedance of the three-phase transmission line using the proposed model with a maximum error of 0.1660 %.

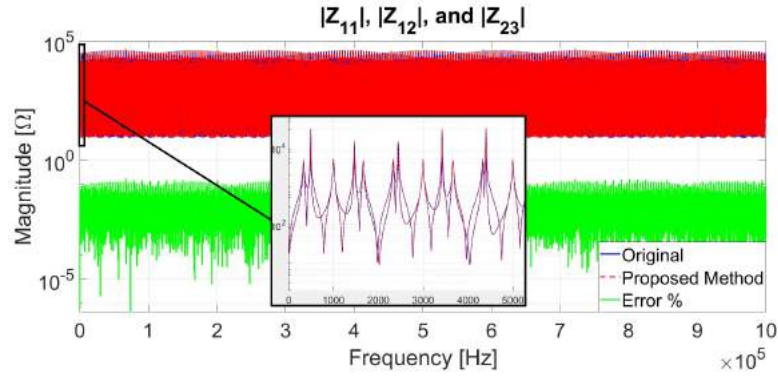


Figure 4.11: The magnitude of the measured impedance and the proposed model impedance, $|Z_{11}|$, $|Z_{12}|$, and $|Z_{23}|$.

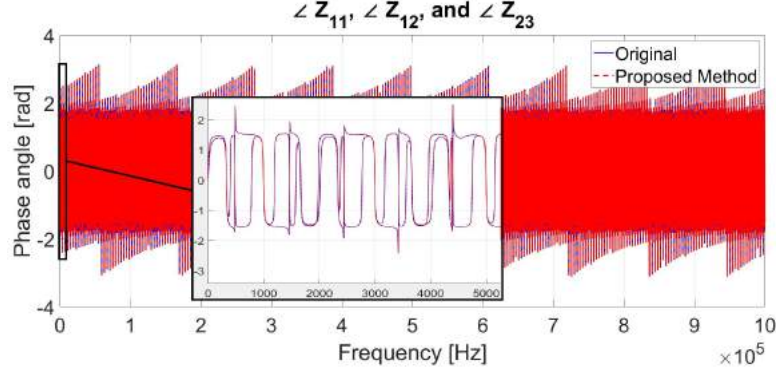


Figure 4.12: The angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$.

4.2 Computational time comparison between the proposed model and VF

In this section, the computational time comparison between the proposed model and VF method is presented. The MTL model using VF method was not obtained due to the high computational power requirement. Therefore, the conducted comparison is under the assumption of a linear relation between the measured time for a lower approximation number of vector fitting and the required approximation number to fit the impedance curve. The specs of the used computer is shown in Table 4.4. Table 4.5, show the approximation computational time for VF and the proposed model.

Table 4.4: Computer specs

Computer	Specs
RAM	32 GB, 3200MHz
CPU	i7-11700F
Operating system	Windows 11

Table 4.5: Computational Time

Method	Computational time [S]
VF	8774.33
Proposed Model	516.75

4.3 Remarks on the proposed model

The proposed model is based on the finite transmission line impedance equation. If we simplify the model by equating ignore the slight difference between Z_{23} and Z_{12} , we can obtain the impedance equation for multiconductor mutually coupled transmission line:

$$\begin{bmatrix} (Z_1 + Z_2) & (Z_1 - \frac{Z_2}{\alpha}) & (Z_1 - \frac{Z_2}{\alpha}) \\ (Z_1 - \frac{Z_2}{\alpha}) & (Z_1 + Z_2) & (Z_1 - \frac{Z_2}{\alpha}) \\ (Z_1 - \frac{Z_2}{\alpha}) & (Z_1 - \frac{Z_2}{\alpha}) & (Z_1 + Z_2) \end{bmatrix} \quad (4.11)$$

where:

$$Z1 = \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} \quad (4.12)$$

$$Z2 = \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} \quad (4.13)$$

Where:

α : is the ratio between the maximum peaks of $\text{Real}(Z_{11})$ to the maximum peaks of $\text{Real}(Z_{12})$ at the resonance f_{02} .

From the matrix impedance of three phase mutually coupled symmetrical transmission line:

$$\begin{bmatrix} (Z_S) & (Z_m) & (Z_m) \\ (Z_m) & (Z_S) & (Z_m) \\ (Z_m) & (Z_m) & (Z_S) \end{bmatrix} \quad (4.14)$$

By comparing equation with equation we find that:

$$Z_S = Z_1 + Z_2; \quad (4.15)$$

$$Z_m = Z_1 - \frac{Z_2}{\alpha} \quad (4.16)$$

Since the zero, positive, and negative sequence impedance given by

$$Z_0 = Z_S + 2Z_m; \quad (4.17)$$

$$Z_{+ve} = Z_S - Z_m \quad (4.18)$$

$$Z_{-ve} = Z_S - Z_m \quad (4.19)$$

Then, according to the derived equations of multiconductor transmission line impedance, the sequence impedance of the transmission line should be:

$$Z_0 = 3Z_1 + \frac{\alpha - 2}{\alpha} Z_2 = 3 \times Z_{o1} \times \tanh \gamma_1 l + \frac{\alpha - 2}{\alpha} \times Z_{o2} \times \tanh \gamma_2 l \quad (4.20)$$

$$Z_{+ve} = Z_{-ve} = \frac{\alpha + 1}{\alpha} Z_2 = \frac{\alpha + 1}{\alpha} \times Z_{o2} \times \tanh \gamma_2 l \quad (4.21)$$

since $\alpha \approx 2$ in the presented example then :

$$Z_0 = 3 \times Z_1 \quad (4.22)$$

$$Z_{+ve} = Z_{-ve} = \frac{3}{2} \times Z_2 \quad (4.23)$$

Using the previous equation, we can calculate the positive and zero sequences impedance of the transmission line and compare it with the sequence impedance of the simulated transmission line (RTDS values), see Table 4.6.

Table 4.6: Transmission Line Parameters

Bergeron (RLC Data Entry)	RTDS (Values)	Calculated	Error%
Positive Sequence Series Resistance	0.018547	0.018772	1.2
Positive Sequence Series Ind. Reactance	0.37661	0.378657	0.54
Zero Sequence Series Resistance	0.3618376	0.370561	2.41
Zero Sequence Series Ind. Reactance	1.227747	1.241079	1.09

In addition, the voltages and current can be calculated through the transmission line length, since the equation is dependant on the transmission line length then,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} (Z_1 + Z_2) & (Z_1 - \frac{Z_2}{\alpha}) & (Z_1 - \frac{Z_2}{\alpha}) \\ (Z_1 - \frac{Z_2}{\alpha}) & (Z_1 + Z_2) & (Z_1 - \frac{Z_2}{\alpha}) \\ (Z_1 - \frac{Z_2}{\alpha}) & (Z_1 - \frac{Z_2}{\alpha}) & (Z_1 + Z_2) \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (4.24)$$

4.3.1 Features of the proposed model

Many different fitting methods have the capability of fitting a set of data to a very high degree of accuracy with minimum error. The fitting is achieved through a set of mathematical equations which may not be correlated to the fitted data. In addition, if the sampling number of the fitted data is small, then the obtained fitted curve, even though fitted to a very high degree, will not give accurate values of the data. For instance, Figure shows two different sampling rates of a transmission line impedance (200 and 200K). This problem manifests when taking the frequency response for a

high-frequency range while being limited with a set of the sampling rate. Due to the low sampling rate of the data, the fitted curve does not reflect the correct values.

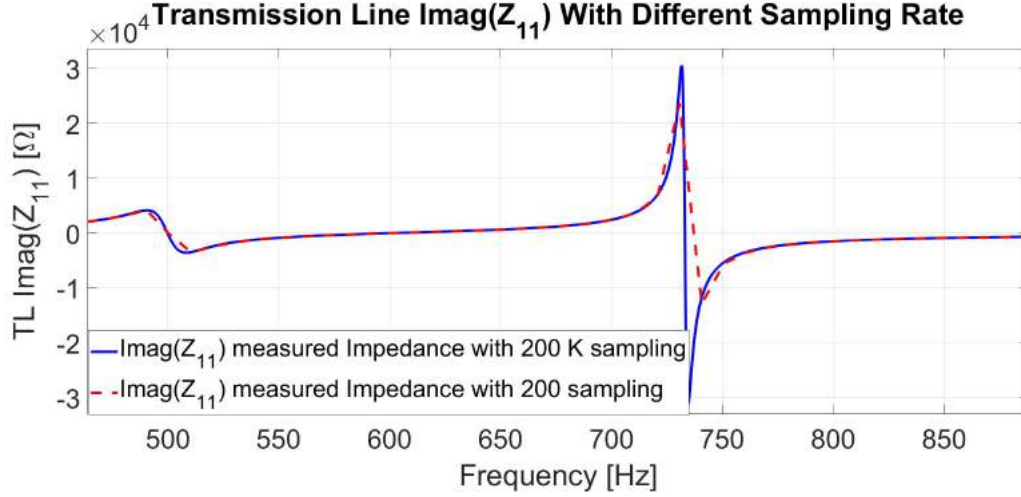


Figure 4.13: The angle of the measured impedance and the proposed model impedance, $\angle Z_{11}$, $\angle Z_{12}$, and $\angle Z_{23}$.

In contrast, using the analytical solution which describes the impedance of the transmission line even with fewer sampling rates will result in a better representation of a transmission line impedance.

In addition, the proposed method is based on finite transmission line impedance, which is a function of the transmission line length. Therefore, changing the length of the transmission line will not require any changes in the model, as shown in Case 4. Unlike different fitting methods, which required retaking the frequency response of the transmission line and a generate a new set of mathematical equations and parameters to describe it.

Moreover, since the proposed multiconductor impedance equations are a function of transmission line length, then they allow for voltages and the currents calculations through the transmission line length. In contrast, the fitted mathematical model will not permit such calculation since it fit the curve as a set of mathematical equations which are not correlated to the length of the line.

In addition, curve fitting methods required a high number of approximations to fit the impedance curve of the transmission line for a high-frequency range, see case 3, which in turn reflects in the high number of terms the mathematical function required to fit the curve. Moreover, the higher number of approximations will require more computational power to fit the impedance curve. In contrast, the proposed analytical solution has a constant set of terms and parameters that will not change with the frequency range.

CHAPTER 5

APPLICATIONS OF THE PROPOSED MTL MODEL AND IMPLEMENTATION IN RTDS

In this chapter, two applications of the proposed MTL model in the frequency domain are presented. The proposed model is based on the analytical impedance equation of a finite transmission line. Therefore, the proposed model will allow for voltage measurement at any point on the transmission line length. Therefore, the first application is a direct measurement of the MTL voltages during transient scenarios, such as switching and fault. The calculated voltages of MTL using the proposed model are compared to the direct measurement using RTDS. This will demonstrate an application of the proposed model as well as the implementation of the model in RTDS. The second application is the setting-less distance protection of MTL based on the proposed model. Both of the applications are presented to demonstrate the ease of implementation

of the proposed model and its accuracy compared to the direct measurement from RTDS.

5.1 Introduction

The electric power system has different and integrated electric power equipment such as generators, transformers, and transmission lines to deliver electric power to the loads. These electric power equipment may fail due to malfunctions or faults and disrupt the power flow from the source to the loads. Therefore, protective relays are designed to protect the electrical equipment from severe damage and isolate the faulted part from the electric grid. Thus, the arts and the sciences of protection are developed.

Protective relaying is an indispensable part of electrical power systems. In terms of modern technology, a revolution has taken place in the development and application of microprocessor-based multifunction relays (MMPRs). The single-function electromechanical relays are now outdated, and these are being replaced with MMPRs in many industrial and utility systems. In modern times, the advancement of protection relay is being governed by microprocessor-based multifunction relays (MMPRs). Protective relaying is an essential part of the electrical system, which is considered in the power system design. Furthermore, smart grids, integration of wind and solar generation, and microgrids are also the driving aspects of fast changes and innovations in protective relaying. Cybersecurity is a growing concern for grid systems with more advanced and adaptive relaying and communication-based relays.

5.2 Implementation of the proposed MTL model in RTDS

One of the main advantages of the proposed model is the ease of implementation. The rational function approximation, as shown in the previous chapter, required a high number of approximation to implement the model, which in turn resulted in a high computational power requirement. In contrast, the proposed model required a set of constants parameters and three equations.

Table 5.1: Proposed Model Parameters for Z_{11} , Z_{22} , and Z_{33}

Transmission Line Parameters	Values
R_1	12.06 [Ω]
L_1	0.10855 [H]
C_1	2.30594 [μF]
G_1	1e-9 [S]
R_2	1.23772 [Ω]
L_2	0.06659 [H]
C_2	1.74613 [μF]
G_2	1e-9 [S]

$$\begin{aligned}
& \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} + \\
& \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh \sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)} = Z_{11}
\end{aligned} \tag{5.1}$$

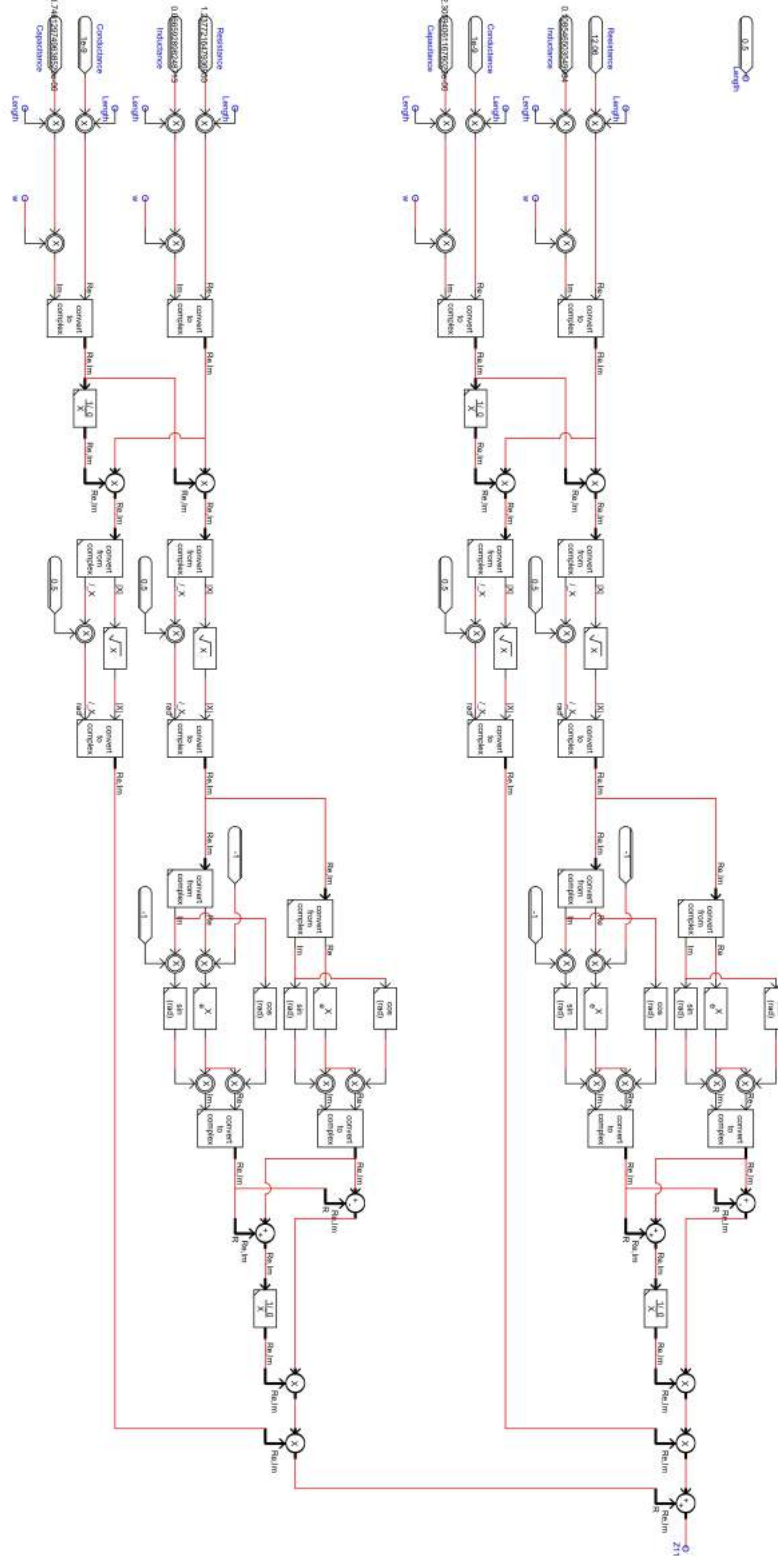


Figure 5.1: Implementation of Z_{11} in RTDS.

For the elements Z_{11} , Z_{22} , and Z_{33} in the impedance matrix, Table 5.1 shows the proposed model constant parameters and Equation 5.1 is the proposed model to calculate the impedance of Z_{11} , Z_{22} , and Z_{33} . Figure 5.1 shows the implemented model in RTDS for Z_{11} , Z_{22} , and Z_{33} .

For the elements Z_{12} , Z_{21} , Z_{31} , and Z_{13} in the impedance matrix, Table 5.2 shows the proposed model constant parameters and Equation 5.14 is the proposed model to calculate the impedance of Z_{12} , Z_{21} , Z_{31} , and Z_{13} . Figure 5.2 shows the implemented model in RTDS for Z_{12} , Z_{21} , Z_{31} , and Z_{13} .

Table 5.2: Proposed Model Parameters for Z_{12} , Z_{21} , Z_{31} , and Z_{13}

Transmission Line Parameters	Values
R_3	12.06 [Ω]
L_3	0.10855 [H]
C_3	2.30596 [μF]
G_3	1e-9 [S]
R_4	0.61886 [Ω]
L_4	0.0333 [H]
C_4	3.49224 [μF]
G_4	1e-9 [S]

$$\sqrt{\frac{R_3 + j\omega L_3}{G_3 + j\omega C_3}} \times \tanh \sqrt{(R_3 + j\omega L_3)(G_3 + j\omega C_3)} - \sqrt{\frac{R_4 + j\omega L_4}{G_4 + j\omega C_4}} \times \tanh \sqrt{(R_4 + j\omega L_4)(G_4 + j\omega C_4)} = Z_{12} \quad (5.2)$$

Z12_Z_Relay_Model_step1

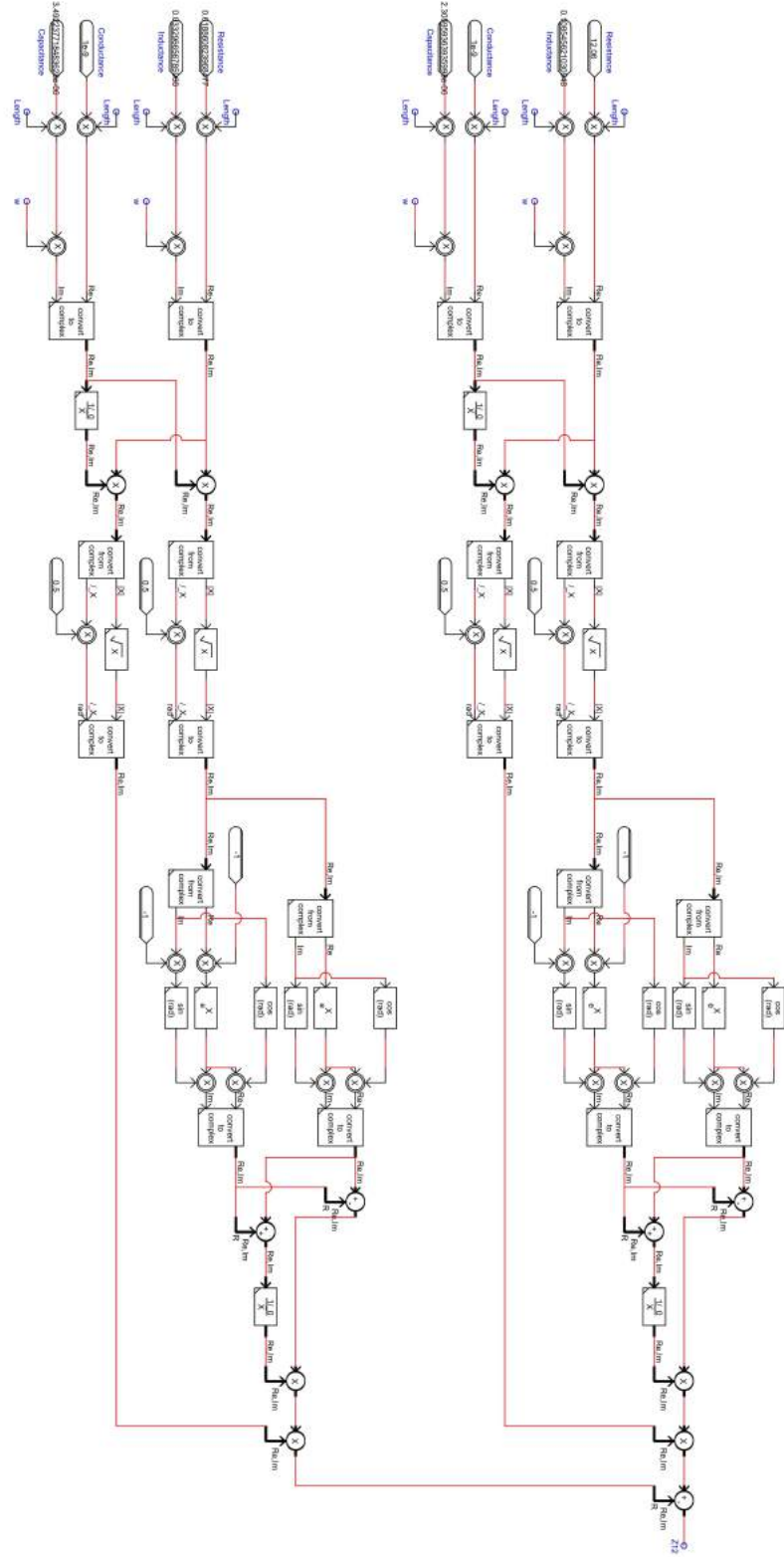


Figure 5.2: Implementation of Z_{12} in RTDS.

For the elements Z_{32} , and Z_{23} in the impedance matrix, Table 5.3 shows the proposed model constant parameters and Equation 5.28 is the proposed model to calculate the impedance of Z_{32} , and Z_{23} . Figure 5.3 shows the implemented model in RTDS for Z_{32} , and Z_{23} .

Table 5.3: Proposed Model Parameters for Z_{23} , and Z_{32}

Transmission Line Parameters	Values
R_5	12.06 [Ω]
L_5	0.10855 [H]
C_5	2.30596 [μF]
G_5	1e-9 [S]
R_6	0.61886 [Ω]
L_6	0.0333 [H]
C_6	3.49228 [μF]
G_6	1e-9 [S]

$$\begin{aligned}
& \sqrt{\frac{R_5 + j\omega L_5}{G_5 + j\omega C_5}} \times \tanh \sqrt{(R_5 + j\omega L_5)(G_5 + j\omega C_5)} - \\
& \sqrt{\frac{R_6 + j\omega L_6}{G_6 + j\omega C_6}} \times \tanh \sqrt{(R_6 + j\omega L_6)(G_6 + j\omega C_6)} = Z_{23}
\end{aligned} \tag{5.3}$$

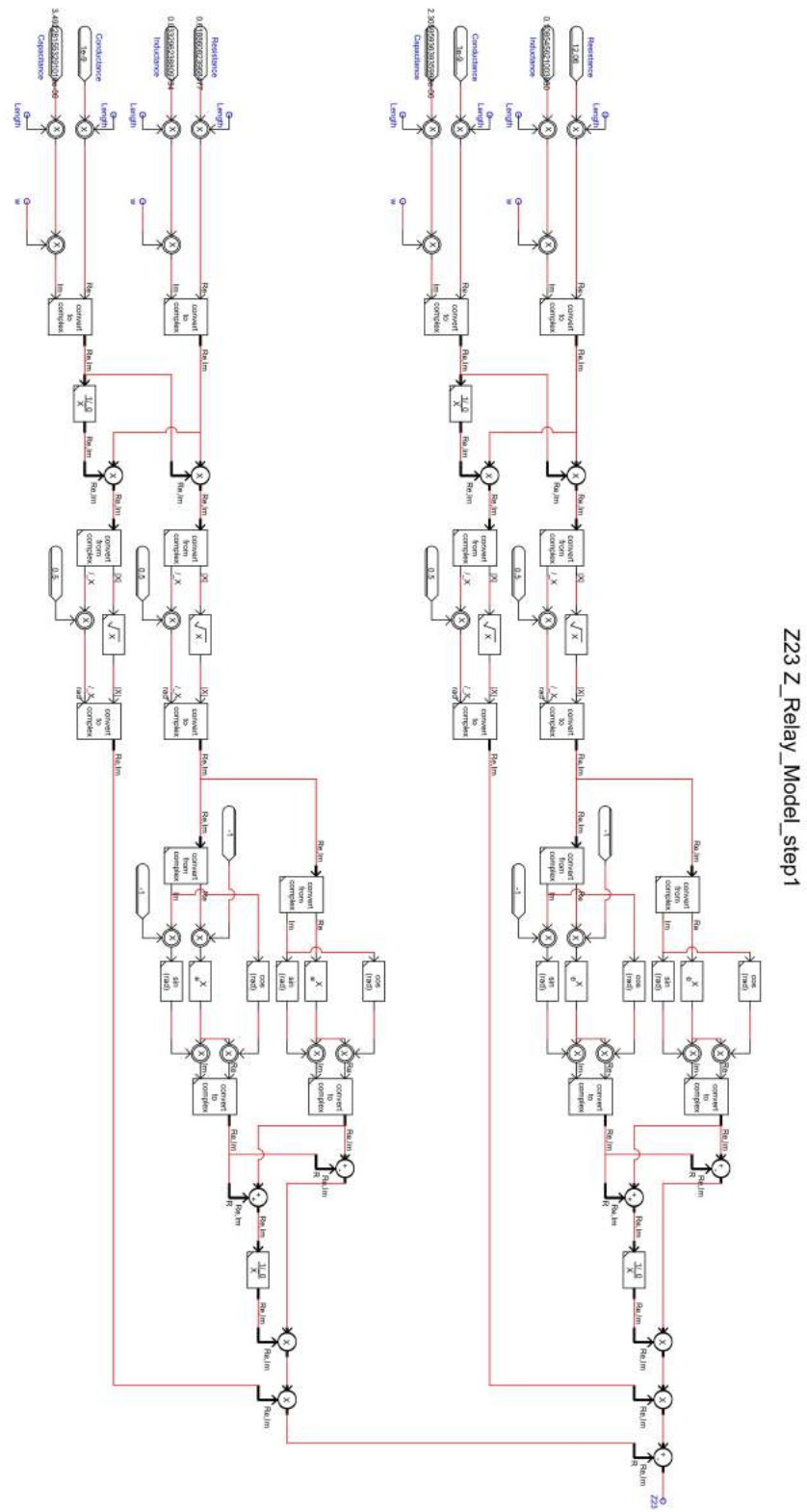


Figure 5.3: Implementation of Z_{23} in RTDS.

5.3 Voltage measurement during transient scenarios using the proposed model

After implementing the proposed model in RTDS, a voltage calculation using the proposed model and a direct voltage measurement during transient scenarios is conducted in this section.

5.3.1 The proposed model transient response during a fault

In this case, a comparison between the measured voltages and the calculated voltages using the proposed model during a fault is presented. Figure 5.4 show the power system under study. The proposed transmission line model lumped parameters are shown in Table 5.4. Tables 5.5 and 5.6, show the data of the power system sources under study.

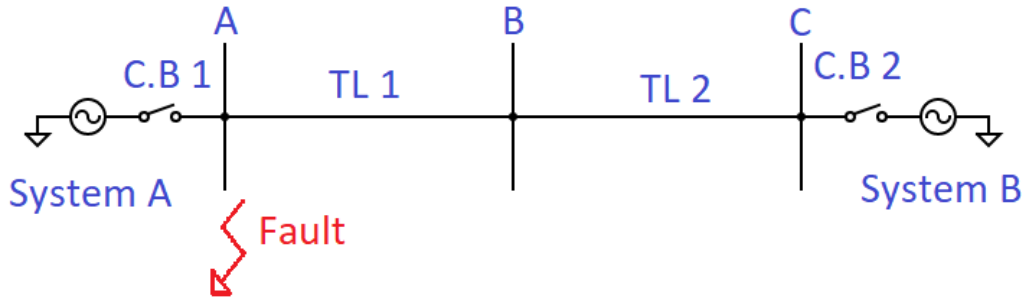


Figure 5.4: Tested power system.

Table 5.4: Transmission Line Parameters

Model	Bergeron (RLC Data Entry)
Line Length	100 [Km]
Frequency	60 [Hz]
Ground Resistivity	100 [Ω -m]
Number of Phases	3
Positive Sequence Series Resistance	0.018547 [Ω /Km]
Positive Sequence Series Ind. Reactance	0.37661 [Ω /Km]
Positive Sequence Shunt Cap. Reactance	0.22789 [Meaga Ω *Km]
Zero Sequence Series Resistance	0.3618376[Ω /Km]
Zero Sequence Series Ind. Reactance	1.227747 [Ω /Km]
Zero Sequence Shunt Cap. Reactance	0.34513 [Meaga Ω *Km]

Table 5.5: System A (Source) Parameters.

System A (Source)	Values
Initial Source Magnitude (L_L, RMS)	231.900170 [kV]
Initial Frequency	60 [Hz]
Initial Phase	10.391918 [degree]
Z_1	2.6+j52.724 [Ω]
Z_0	50.68+j171.88 [Ω]

Table 5.6: System B (Source) Parameters.

System B (Source)	Values
Initial Source Magnitude (L_L, RMS)	223.011472 [kV]
Initial Frequency	60 [Hz]
Initial Phase	-21.162421 [degree]
Z_1	2.6+j52.724 [Ω]
Z_0	50.68+j171.88 [Ω]

During normal operation, a solid Line-Ground fault is induced on phase a at Bus A as shown in Figure 5.4. The fault started at 0.055 S and was removed at 0.275 S. The three-phase voltages measurements at Bus B are compared with the proposed model measurements. The currents and voltages measurements of the three-phase system are carried out by first taking the analog signal sampling then using Discrete Fourier Transform (DFT) to extract the fundamental values in the frequency domain, see Figure 5.6.

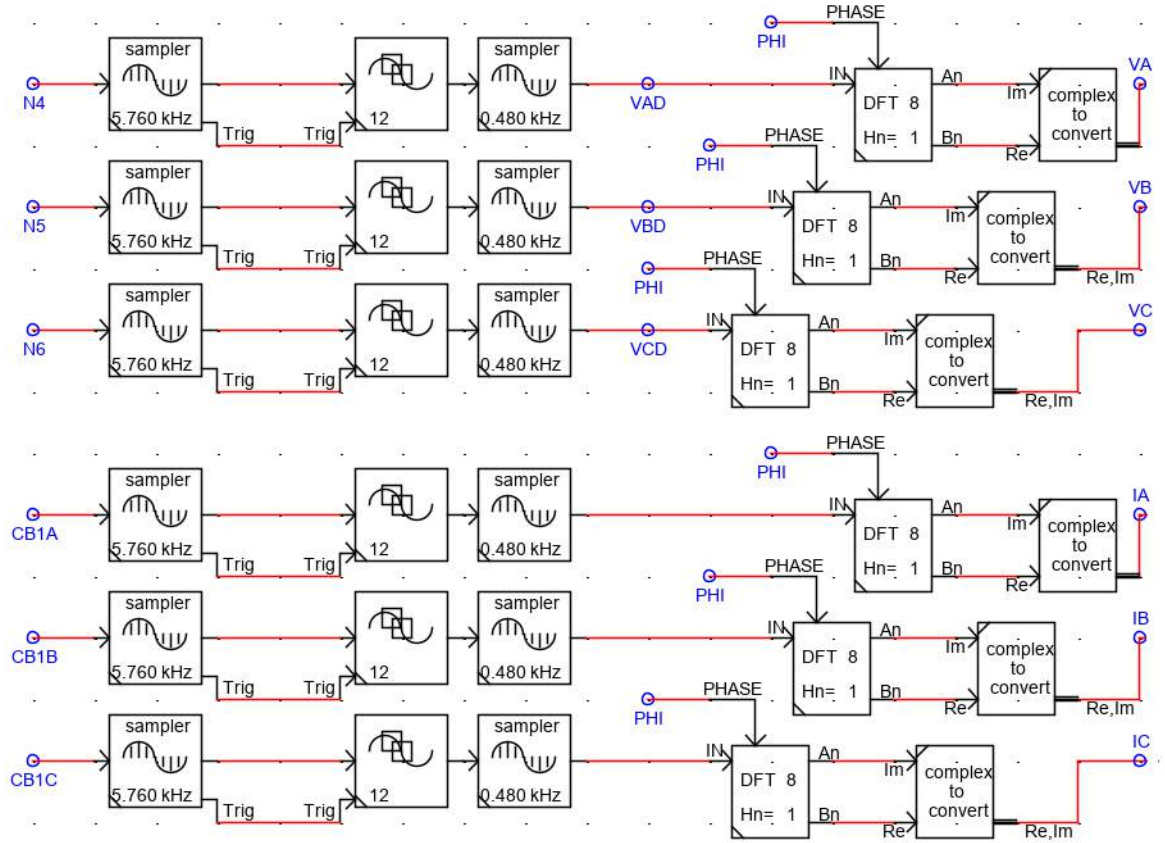


Figure 5.5: Voltages and Current Measurements in RTDS.

The three-phase voltage measurements were chosen at Bus B to show that even though the presented model is for the total length of the line, yet the voltage measurement at the length (l) of the line can be calculated using the proposed model. Since the length of the line (100 Km) is half of the original length (200 Km), then the parameters of the line in Tables 4.3, 3.8, and 3.9 must be multiplied by (0.5). To calculate the three phases voltages at bus B, first, the voltages and the currents at Bus C must be measured then by subtracting the voltage drop on the TL2 using the proposed model, the three phases voltages at Bus B can be calculated. Since the

voltage drop is given by:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (5.4)$$

where

$$Z_{12} = Z_{21} = Z_{13} = Z_{31} \quad (5.5)$$

$$Z_{23} = Z_{32} \quad (5.6)$$

$$Z_{11} = Z_{22} = Z_{33} \quad (5.7)$$

Then the Voltage at Bus B is given by:

$$\begin{bmatrix} V_{a[B]} \\ V_{b[B]} \\ V_{c[B]} \end{bmatrix} = \begin{bmatrix} V_{a[C]} \\ V_{b[C]} \\ V_{c[C]} \end{bmatrix} - \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (5.8)$$

Figures 5.6, 5.7, and 5.8 shows the three phase voltages (phase a, b, and c respectively) at Bus B during a fault. The red line is the voltage calculated using the proposed model while the blue line is the direct measurement of the voltage at Bus B.

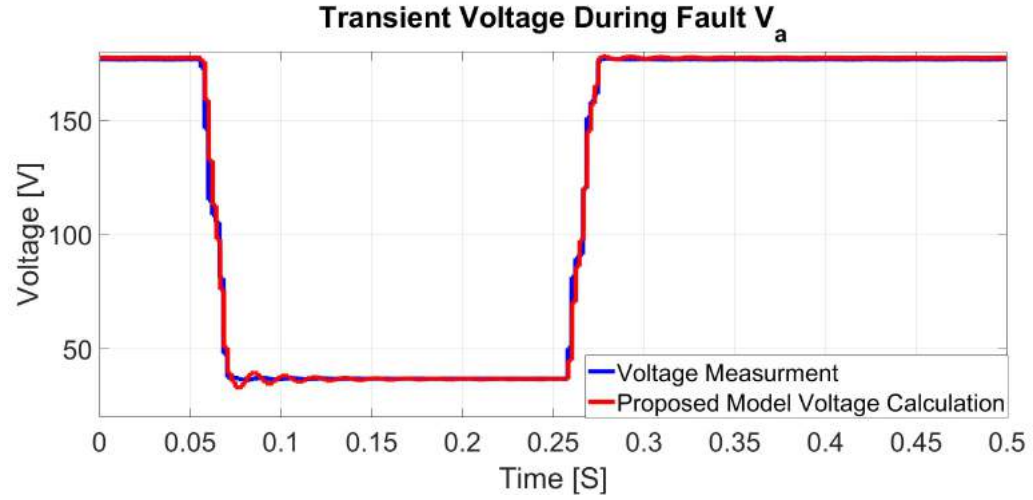


Figure 5.6: Voltage measurement and voltage calculation using the proposed model of Phase a.

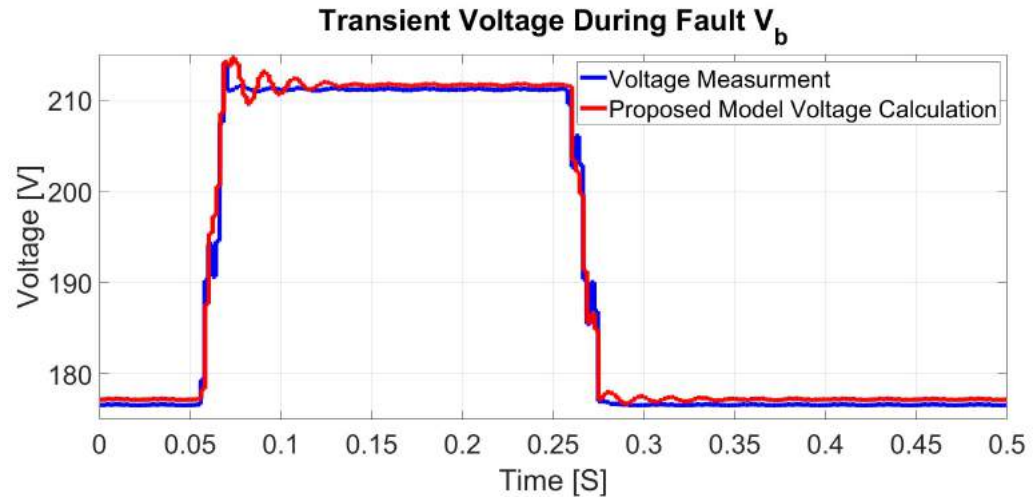


Figure 5.7: Voltage measurement and voltage calculation using the proposed model of Phase b.

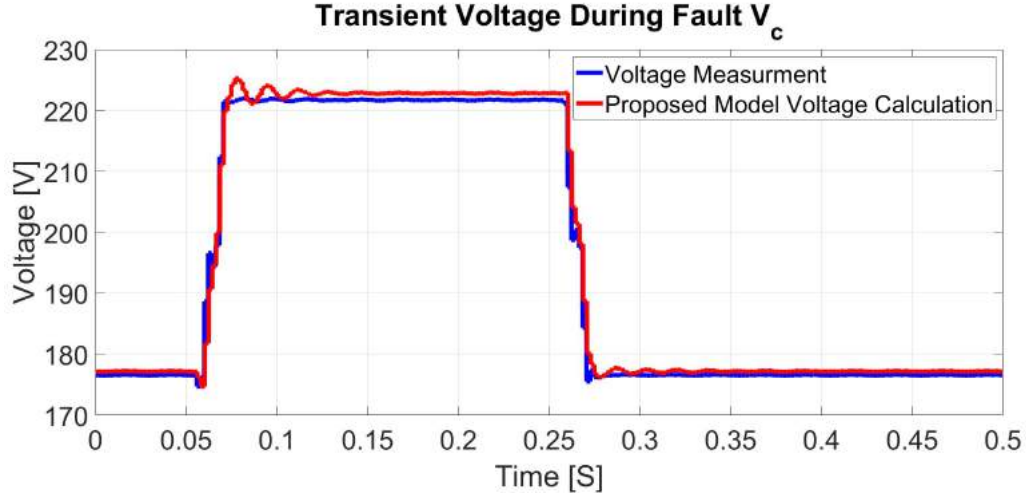


Figure 5.8: Voltage measurement and voltage calculation using the proposed model of Phase c.

5.3.2 Test transient response during line energization (Switching)

In this case, the transient behavior of the line during energization (Switching) will be presented. The tested power system is shown in Figure 5.4. In this case, the circuit breaker (C.B 1) will be connected, and the voltage at Bus B will be directly measured and calculated using the proposed model. Figures 5.9, 5.10, and 5.11 shows the three-phase voltages (phase a, b, and c respectively) at Bus B during energization. The red line is the voltage calculated using the proposed model, while the blue line is the direct measurement of the voltage at Bus B.

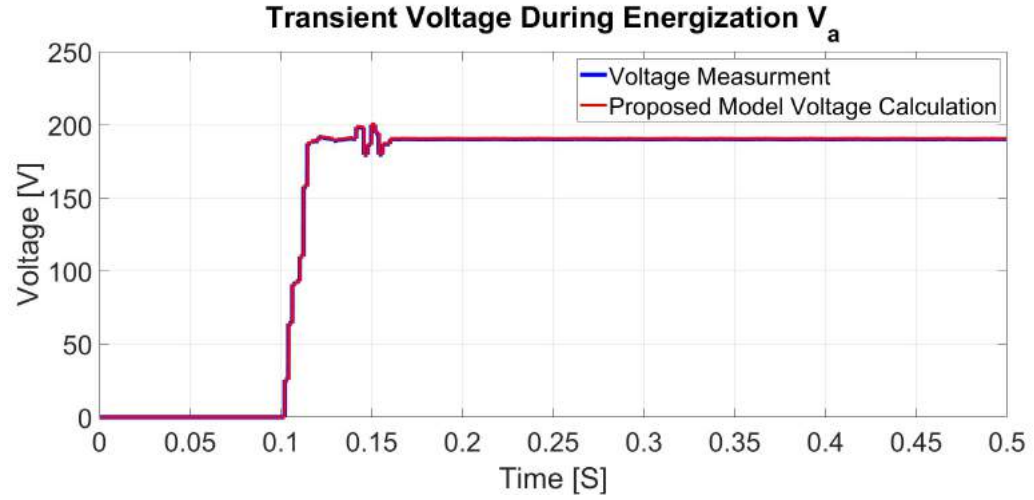


Figure 5.9: Voltage measurement and voltage calculation using the proposed model of Phase a.

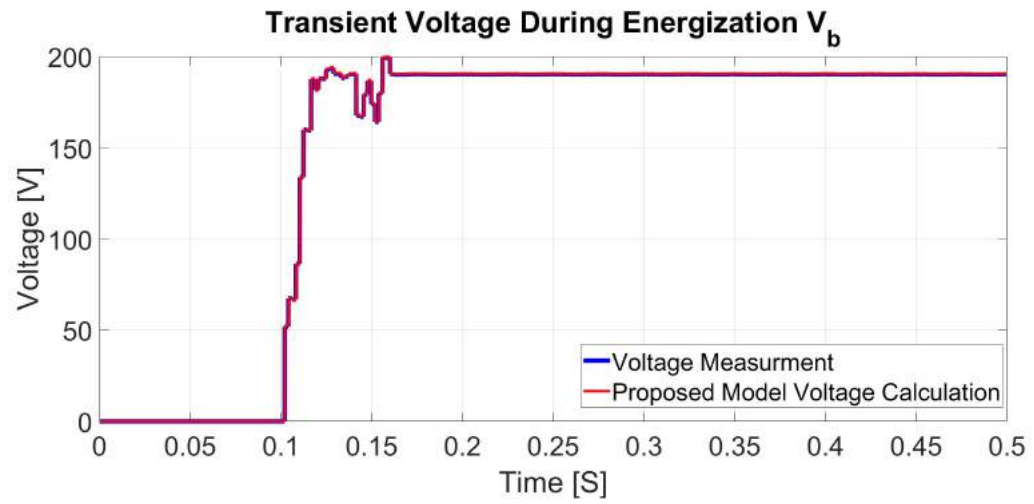


Figure 5.10: Voltage measurement and voltage calculation using the proposed model of Phase b.

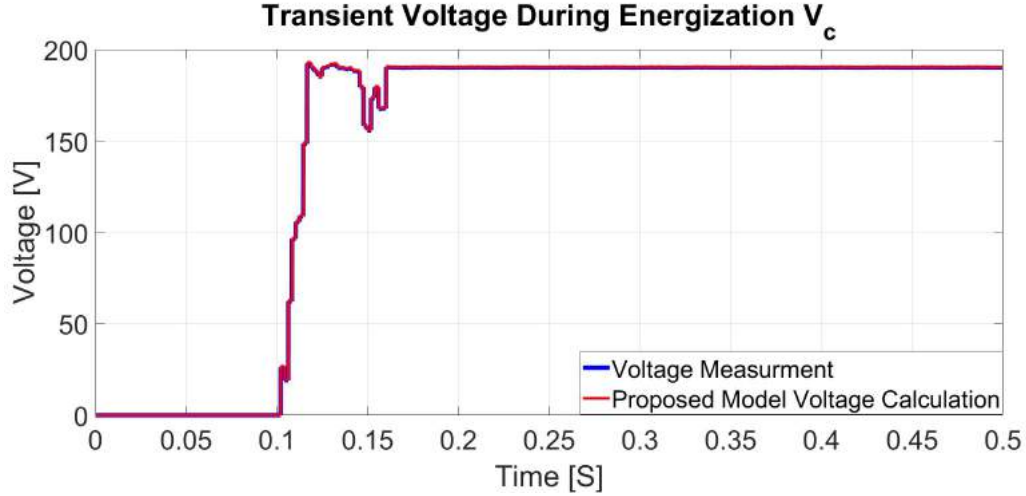


Figure 5.11: Voltage measurement and voltage calculation using the proposed model of Phase c.

5.4 Distance protection

One of the major parts of an electric power delivery system is the transmission lines. The transmission line can extend for long distances from the source to the load. Thus, identifying the location of a fault and fast clearance of the faulty part from the power grid is essential for reliable power system operation. Therefore, the distance relays or impedance relays play an important role in transmission line protection. In addition, Distance relays are used as backup protection for a generator and loss of excitation of a generator. Distribution lines usually is protected by an overcurrent relay. Therefore, in [86] an adaptive distance relay for distribution lines is presented. The proposed method utilize the positive and negative sequence impedance of a PV source to determine the distance relay setting. While in [87], an adaptive distance relay under

unbalanced fault for photovoltaic power plant is presented. Furthermore, in [88], an adaptive impedance relay is presented which calculate the phase angle of fault current by determining the fault impedance of the system after a fault occur. The mutual coupling impedance of a transmission lines may lead to maloperation of the distance relay if it was not considered. Therefore, in [89], the impedance of a mutually coupled transmission lines which are not terminated at the same substation is presented. The presented study proposed a compensation model for the transmission line impedance based on the system equivalent sequential networks. In [90], a distance relay based on travelling wave for transmission lines is presented. The proposed impedance relay is a one terminal travelling wave which only need to detect the first incident of travelling wave, thus eliminating the challenges of detecting the wave front reflecting from the fault point.

Distance protection is a non-unit system of protection offering significant economic and technological advantages. One of the technical advantages of distance relay is that its protected impedance zone is independent of the source impedance. Distance protection is relatively simple to implement and utilize. In addition, it has the advantage of fast operation for faults located in the protected zone. Moreover, it can be used as both primary protection and backup protection in a single protection scheme.

In the case of line to ground fault, a current compensation factor is introduced to match the zero-sequence impedance of the line and allow for the direct measurement of the positive impedance of the line.

$$Z_{L1} = \frac{V_a}{I_{ac}} \quad (5.9)$$

where:

$$V_a = (I_1 + I_2)Zl_1 + I_0Zl_0 \quad (5.10)$$

and the compensated current is

$$I_{ac} = I_1 + I_2 + I_0K_0 \quad (5.11)$$

where K_0 is the compensation factor which is given by

$$K_0 = \frac{Zl_0 - Zl_1}{K \times Zl_1} \quad (5.12)$$

The value of K is dependent on the relay design and manufacturer and can have either a value of 1 or 3.

5.5 Impedance of MTL

The impedance of a single phase of multiconductor transmission lines, even though it is measured as a single complex value, it takes the self impedance of the line and the mutual impedance between the lines into account. For MTL :

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (5.13)$$

$$V_a = Z_{11}I_a + Z_{12}I_b + Z_{13}I_c \quad (5.14)$$

$$\frac{V_a}{I_a} = Z_{11} + Z_{12}\frac{I_b}{I_a} + Z_{13}\frac{I_c}{I_a} \quad (5.15)$$

Therefore,

$$Z_a = Z_{11} + Z_{12}\frac{I_b}{I_a} + Z_{13}\frac{I_c}{I_a} \quad (5.16)$$

$$Z_b = Z_{21}\frac{I_a}{I_b} + Z_{22} + Z_{23}\frac{I_c}{I_b} \quad (5.17)$$

$$Z_c = Z_{31}\frac{I_a}{I_c} + Z_{32}\frac{I_b}{I_c} + Z_{33} \quad (5.18)$$

To calculate the impedance between two phases:

$$V_a = Z_{11}I_a + Z_{12}I_b + Z_{13}I_c \quad (5.19)$$

$$V_b = Z_{12}I_a + Z_{22}I_b + Z_{23}I_c \quad (5.20)$$

$$V_c = Z_{31}I_a + Z_{32}I_b + Z_{33}I_c \quad (5.21)$$

by subtracting equation 5.19 from equation 5.20

$$V_a - V_b = Z_{11}I_a + Z_{12}I_b + Z_{13}I_c - Z_{21}I_a - Z_{22}I_b - Z_{23}I_c \quad (5.22)$$

$$V_a - V_b = (Z_{11}I_a + Z_{12}I_b + Z_{13}I_c - Z_{21}I_a - Z_{22}I_b - Z_{23}I_c) \left(\frac{I_a - I_b}{I_a - I_b} \right) \quad (5.23)$$

$$\frac{V_a - V_b}{I_a - I_b} = \left(\frac{I_a}{I_a - I_b} \right) (Z_{11} - Z_{21}) + \left(\frac{I_b}{I_a - I_b} \right) (Z_{12} - Z_{22}) + \left(\frac{I_c}{I_a - I_b} \right) (Z_{13} - Z_{23}) \quad (5.24)$$

Therefore,

$$Z_{AB} = \left(\frac{I_a}{I_a - I_b} \right) (Z_{11} - Z_{21}) + \left(\frac{I_b}{I_a - I_b} \right) (Z_{12} - Z_{22}) + \left(\frac{I_c}{I_a - I_b} \right) (Z_{13} - Z_{23}) \quad (5.25)$$

$$Z_{BC} = \left(\frac{I_a}{I_b - I_c} \right) (Z_{21} - Z_{31}) + \left(\frac{I_b}{I_b - I_c} \right) (Z_{22} - Z_{32}) + \left(\frac{I_c}{I_b - I_c} \right) (Z_{23} - Z_{33}) \quad (5.26)$$

$$Z_{CA} = \left(\frac{I_a}{I_c - I_a} \right) (Z_{31} - Z_{11}) + \left(\frac{I_b}{I_c - I_a} \right) (Z_{32} - Z_{12}) + \left(\frac{I_c}{I_c - I_a} \right) (Z_{33} - Z_{13}) \quad (5.27)$$

By implementing equations 5.16, 5.17, 5.18, 5.25, 5.26, and 5.27 in RTDS, the impedance of the MTL can be calculated.

5.6 Mho impedance relay and the Setting-less impedance relay

In this section, a comparison between the mho impedance relay and the proposed setting-less impedance relay is presented. Both models will be compared in the case of line to ground fault, two lines to ground fault, three lines to ground fault, the line to line fault, and three lines fault. By implementing equations in RTDS, the impedance of the transmission line can be calculated. Both models are set to 80% due to the error in the CT and PT and the digital relay. Therefore, the impedance relay will only protect 80% of the line for zone 1 and 125 % of the line in zone 2. The compensation factor is where it is calculated by:

$$K = \frac{Z_0 - Z_1}{3Z_1} \quad (5.28)$$

The setting of the distance relay is shown in Table 5.7

Table 5.7: Distance relay setting.

Parameters	Setting
Line impedance (Z_{reach})	$6.032\angle 87.18$
Compensation Factor	$0.81\angle -19.1$
Zone 1	80 %
Zone 2	125 %

Line to ground fault

In this case, a line to ground fault is induced at different points on the transmission line. The impedance traces are plotted on the characteristic mho as shown in figure 5.12. Figure 5.13 shows the the mho relay's fault duration and detection time. Figure 5.14 show the proposed setting less impedance relay's fault duration and detection time. Table 5.8 shows the fault detection time for the Mho relay, the proposed setting-less impedance relay, and the time reduction percentage.

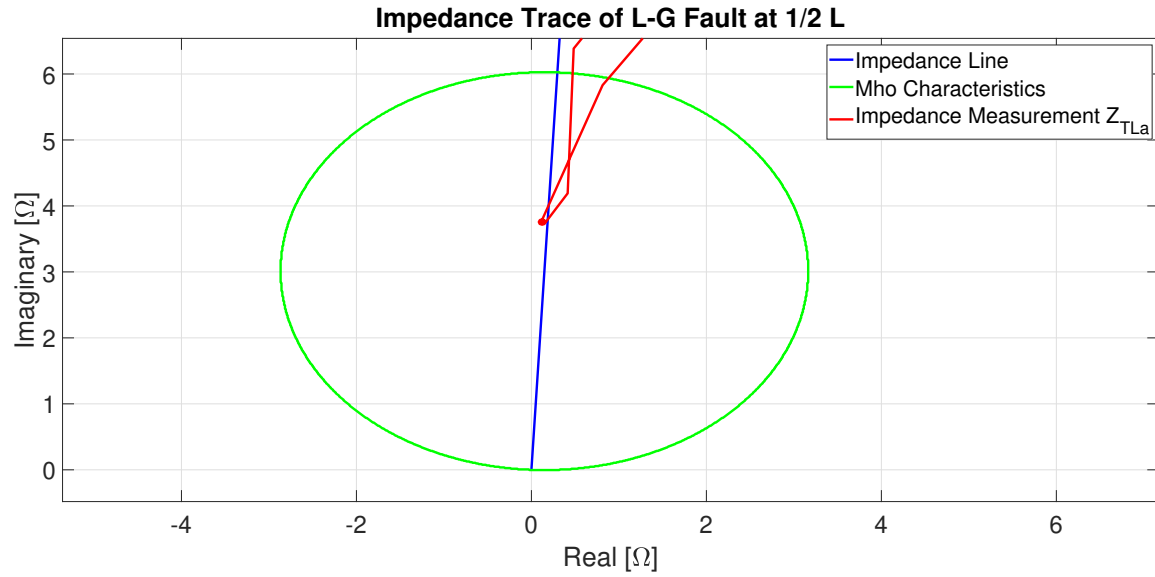


Figure 5.12: Impedance traces during Line to Ground fault.

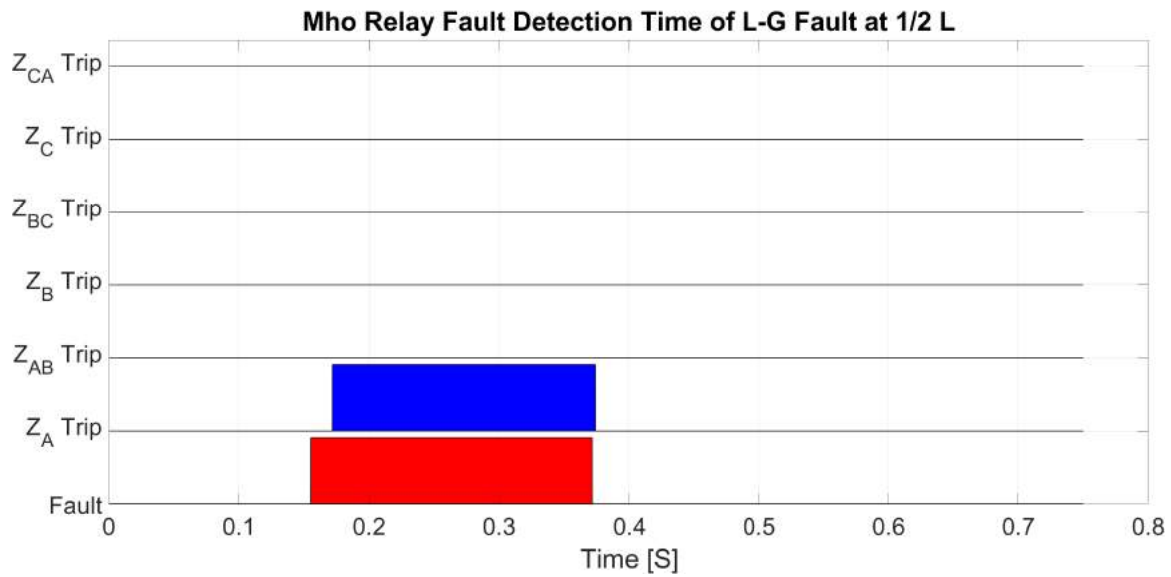


Figure 5.13: Fault duration and Mho detection time during a phase to ground fault.

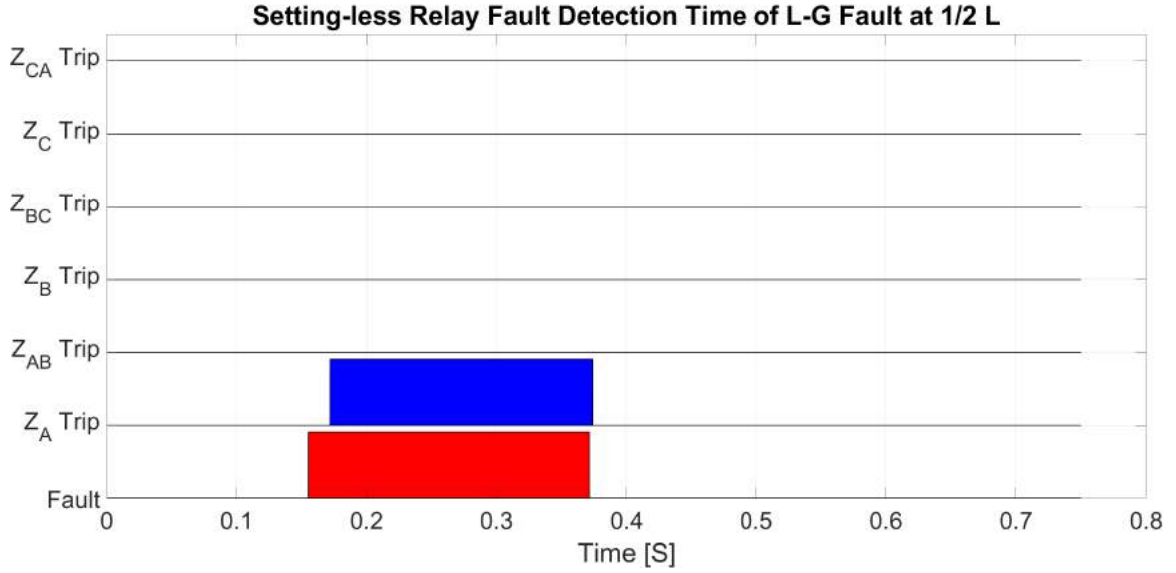


Figure 5.14: Fault duration and the proposed setting less impedance relay detection time during a phase to ground fault.

Table 5.8: Detection time of Mho relay and the proposed sitting less impedance relay during L-G fault.

Zone	Zone 1				Zone 2	
Fault Location (% of line length)	50 %	60 %	70 %	80 %	90 %	100 %
Mho Detection Time [ms]	16.6	16.6	16.6	18.7	16.6	16.6
Proposed Model Detection Time [ms]	16.7	16.7	16.7	18.8	14.6	16.7
Percent of Time Reduction [%]	-	-	-	-	12	-

In the case of the L-G fault, there is no significant difference between the proposed setting-less relay and the Mho relay except at 90 % of the transmission line length, where the proposed setting-less relay has a 12 % time reduction compared to the Mho relay.

Two lines to ground fault

In this case, two lines to ground fault are induced at different points on the transmission line. Figure 5.15 shows the the mho relay's fault duration and detection time. Figure 5.16 show the proposed setting less impedance relay's fault duration and detection time. Table 5.9 shows the fault detection time for the Mho relay, the proposed setting-less impedance relay, and the time reduction percentage.

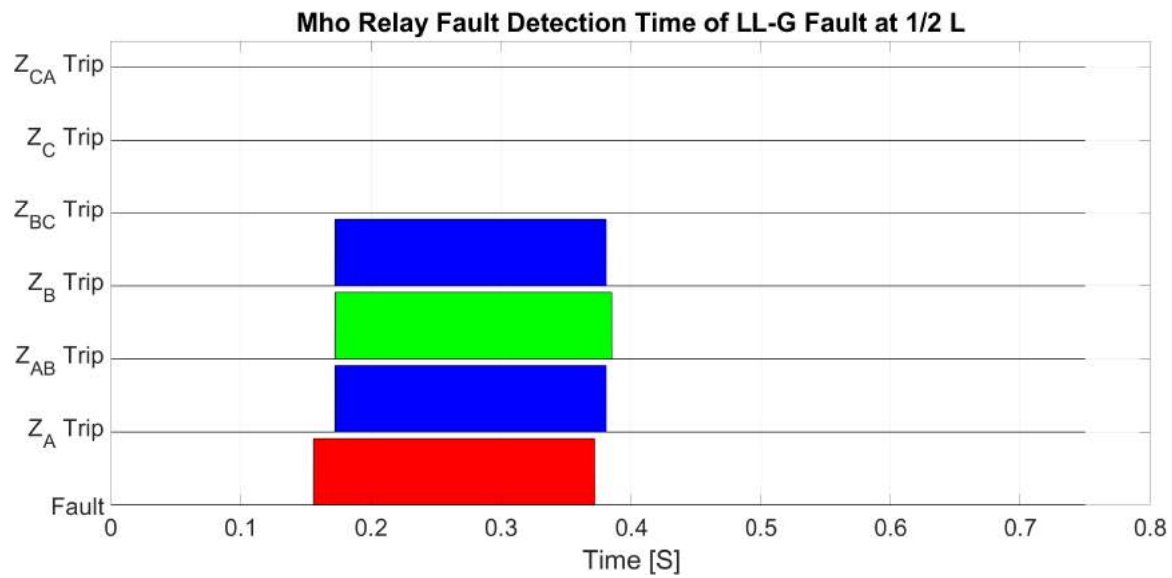


Figure 5.15: Fault duration and Mho detection time during two phases to ground fault.

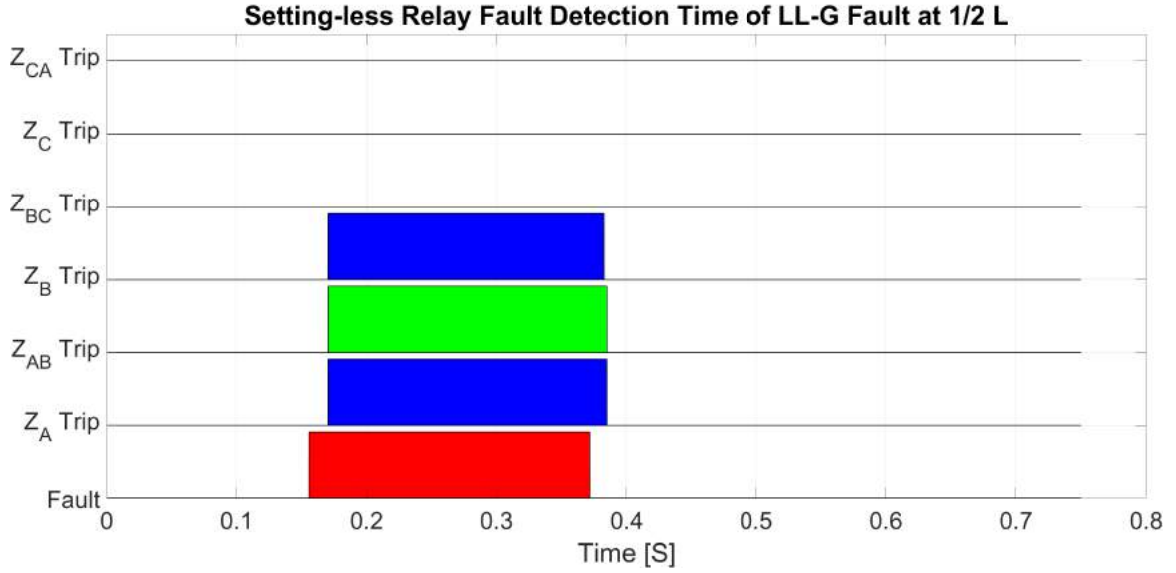


Figure 5.16: Fault duration and the proposed setting less impedance relay detection time during two phases to ground fault.

Table 5.9: Detection time of Mho relay and the proposed setting less impedance relay during LL-G fault.

Zone	Zone 1				Zone 2	
Fault Location (% of line length)	50 %	60 %	70 %	80 %	90 %	100 %
Mho Detection Time [ms]	16.6	16.6	16.6	18.7	16.6	16.6
Proposed Model Detection Time [ms]	14.7	14.7	14.6	18.8	14.7	14.6
Percent of Time Reduction [%]	11.4	11.4	12	-	11.4	12

In the case of the LL-G fault, there is a significant difference between the proposed setting-less relay and the Mho relay. The proposed setting-less relay has an 11.4 % time reduction in detecting the fault compared to the Mho relay. In addition, both relays indicate a fault in phases A, B, and AB.

Three lines to ground fault

In this case, three lines to ground fault are induced at different points on the transmission line. Figure 5.17 shows the the mho relay's fault duration and detection time. Figure 5.18 show the proposed setting less impedance relay's fault duration and detection time. Table 5.10 shows the fault detection time for the Mho relay, the proposed setting-less impedance relay, and the time reduction percentage.

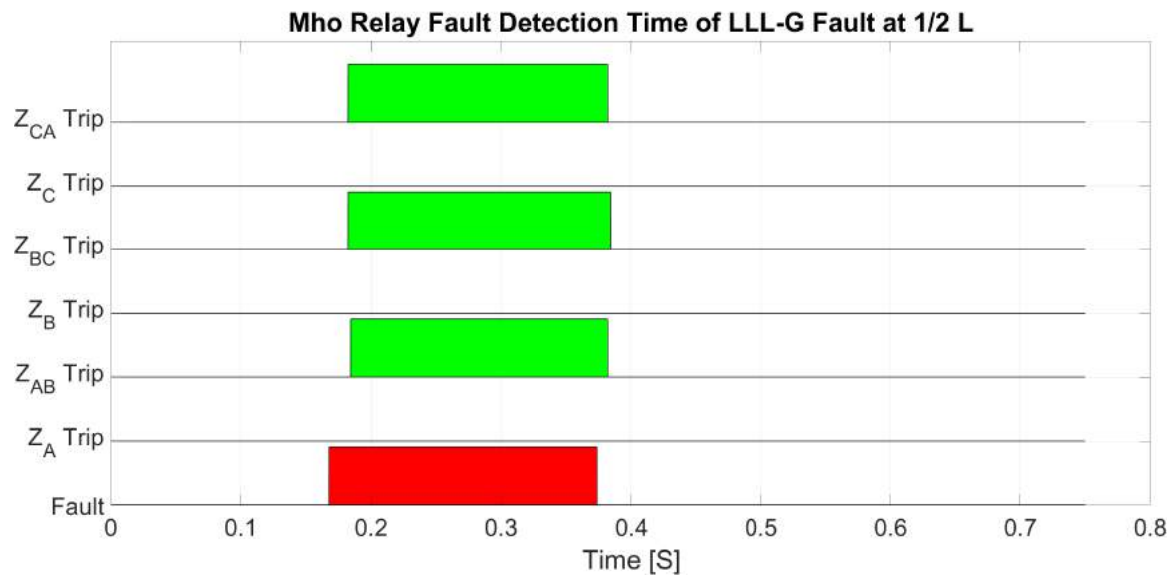


Figure 5.17: Fault duration and Mho detection time during three phases to ground fault.

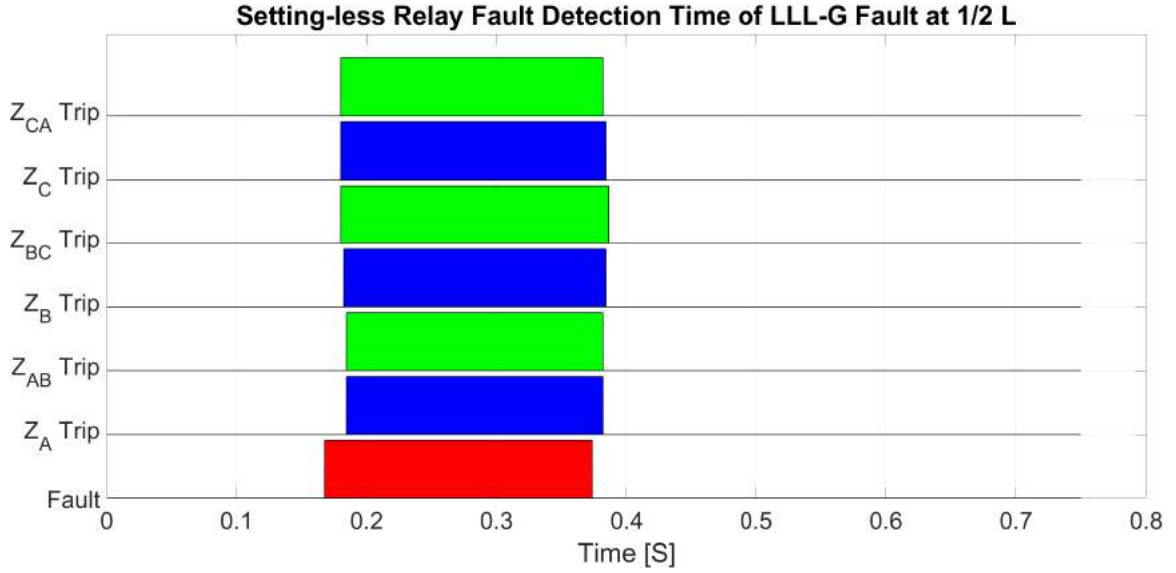


Figure 5.18: Fault duration and the proposed setting less impedance relay detection time during three phases to ground fault.

Table 5.10: Detection time of Mho relay and the proposed sitting less impedance relay during LLL-G fault.

Zone	Zone 1				Zone 2	
Fault Location (% of line length)	50 %	60 %	70 %	80 %	90 %	100 %
Mho Detection Time [ms]	14.6	14.5	16.6	16.6	14.5	14.5
Proposed Model Detection Time [ms]	12.6	12.6	14.6	16.7	12.6	12.5
Percent of Time Reduction [%]	13.7	13.1	12	-	13.1	13.8

In the case of the LLL-G fault, there is a significant difference between the proposed setting-less relay and the Mho relay. The proposed setting-less relay has a 12 % time reduction in detecting the fault compared to the Mho relay. In addition, the proposed relay indicates faults in phases A, B, C, AB, BC, and CA, while the Mho relay does

not indicate faults in phases A, B, and C even though the three lines are shorted to the ground.

line to line fault

In this case, the line-to-line fault is induced at different points on the transmission line.

Figure 5.19 shows the the mho relay's fault duration and detection time. Figure 5.20

show the proposed setting less impedance relay's fault duration and detection time.

Table 5.11 shows the fault detection time for the Mho relay, the proposed setting-less impedance relay, and the time reduction percentage.

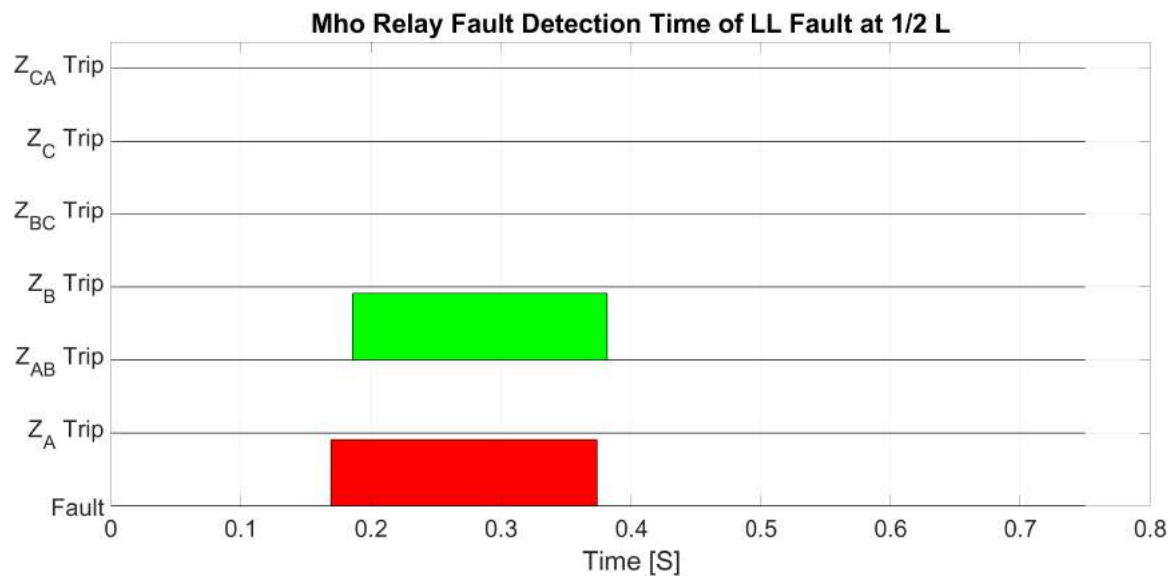


Figure 5.19: Fault duration and Mho detection time during two phases fault during two phases fault.

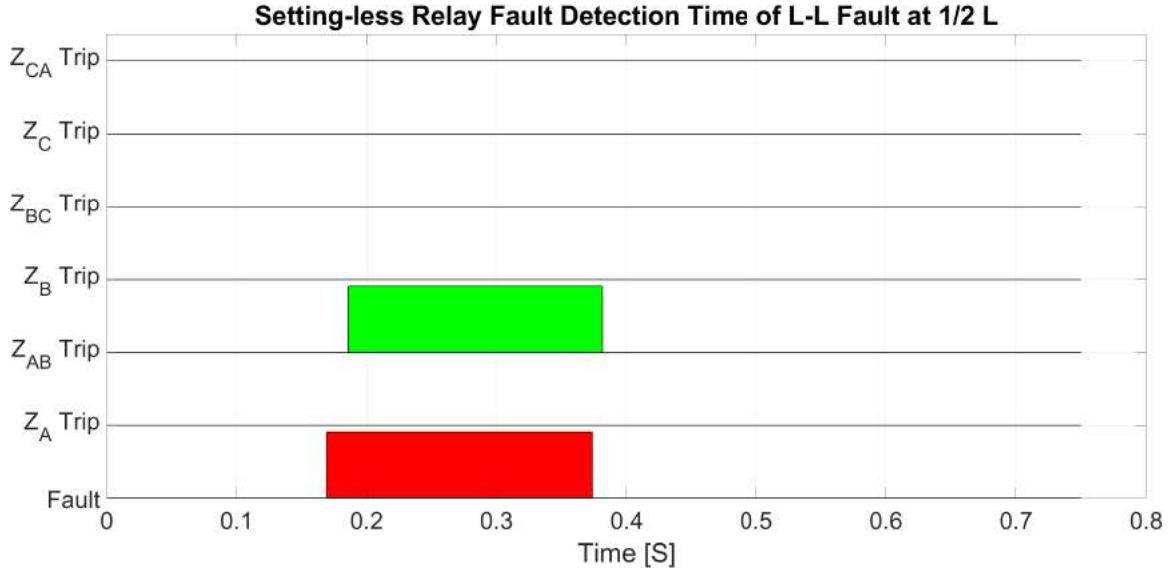


Figure 5.20: Fault duration and the proposed setting less impedance relay detection time during during two phases fault.

Table 5.11: Detection time of Mho relay and the proposed sitting less impedance relay during two phases fault.

Zone	Zone 1				Zone 2	
Fault Location (% of line length)	50 %	60 %	70 %	80 %	90 %	100 %
Mho Detection Time [ms]	16.6	16.6	16.6	20.7	16.6	16.6
Proposed Model Detection Time [ms]	16.7	16.7	16.7	20.8	14.6	16.7
Percent of Time Reduction [%]	-	-	-	-	12	-

In the case of the LL fault, there is no significant difference between the proposed setting-less relay and the Mho relay except at 90 % of the transmission line length, where the proposed setting-less relay has a 12 % time reduction compared to the Mho relay.

Three phases fault

In this case, the three lines fault is induced at different points on the transmission line. Figure 5.21 shows the the mho relay's fault duration and detection time. Figure 5.22 show the proposed setting less impedance relay's fault duration and detection time. Table 5.12 shows the fault detection time for the Mho relay, the proposed setting-less impedance relay, and the time reduction percentage.

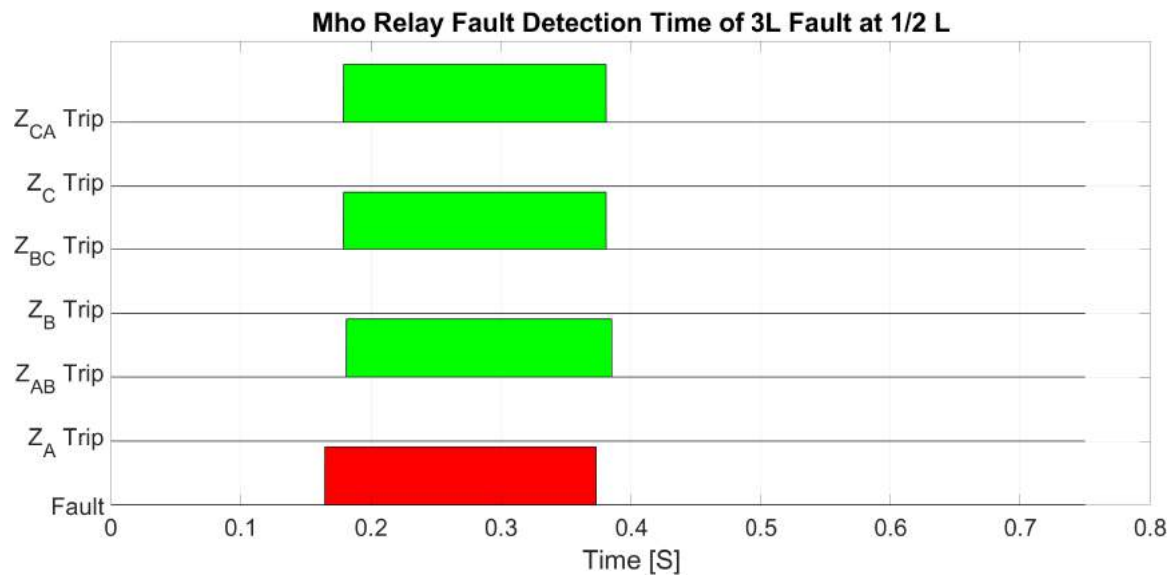


Figure 5.21: Fault duration and Mho detection time during three phases fault.

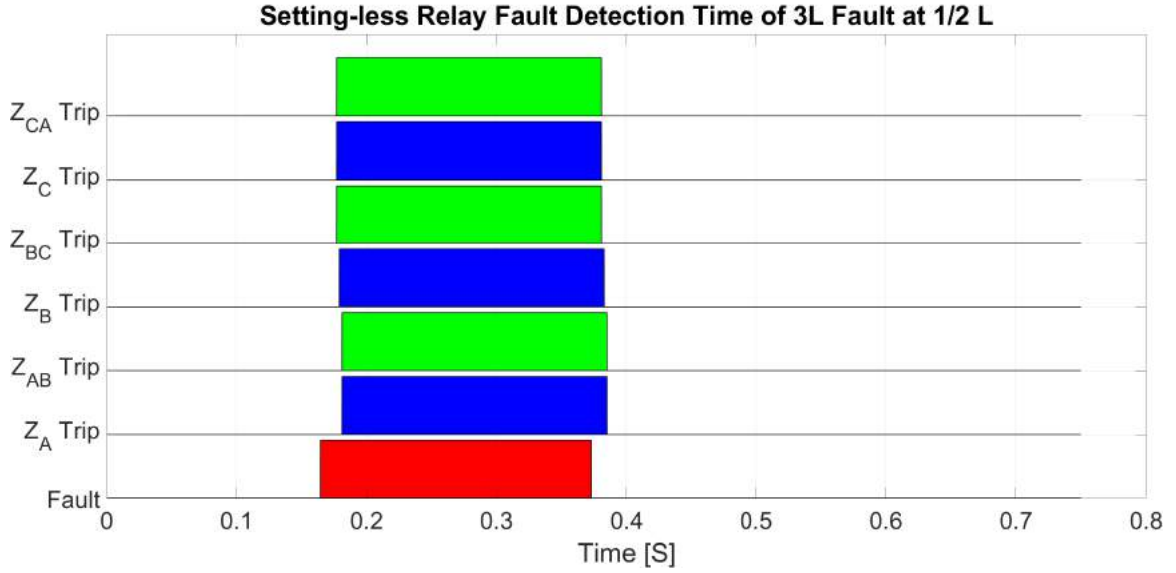


Figure 5.22: Fault duration and the proposed setting-less impedance relay detection time during three phases fault.

Table 5.12: Detection time of Mho relay and the proposed setting-less impedance relay during three phases fault.

Zone	Zone 1				Zone 2	
Fault Location (% of line length)	50 %	60 %	70 %	80 %	90 %	100 %
Mho Detection Time [ms]	14.5	14.5	16.6	16.6	14.5	14.6
Proposed Model Detection Time [ms]	12.6	12.5	14.6	16.7	12.6	12.6
Percent of Time Reduction [%]	13.1	13.8	12	-	13.1	13.7

In the case of three lines faults, there is a significant difference between the proposed setting-less relay and the Mho relay. The proposed setting-less relay has a minimum 12 % time reduction in detecting the fault compared to the Mho relay. In addition, the proposed relay indicates a fault in phases A, B, C, AB, BC, and CA,

while the Mho relay does not indicate faults in phases A, B, and C. The impedance of the line will change since the fault take place in the mid of the line, yet the Mho relay could not detect the change in the line impedance due to the implementation of the compensation factor. This will help in identifying the type of fault between three lines fault and three lines to ground fault, but it has a slow detection time compared to the proposed model.

CHAPTER 6

CONCLUSION

In this Ph.D. dissertation, a frequency domain transient modeling of MTLs based on the impedance analytical equation of the transmission line is presented. The main achievements of this Ph.D. dissertation can be summarized as follow:

1. A modified version of transmission line impedance can be implemented to fit the impedance frequency response of multiconductor transmission line, as shown in chapter 3. The proposed model is based on the analytical impedance equation of transmission line impedance which is crucial in depicting the behaviour of transmission line impedance. In contrast, using the rational function approximation method as in vector fitting may result in a fitted to a very high degree but will not reflect the behaviour of a transmission line impedance. This problem manifests when taking the frequency response for a high-frequency range while being limited by a set of the sampling rate. Due to the low sampling rate of the data, the fitted curve does not reflect the correct values.
2. The proposed method is based on finite transmission line impedance, which is

a function of the transmission line length. This is a key feature of the proposed model over different fitting method. Therefore, changing the length of the transmission line will not require any changes in the model as shown in case 4 chapter 4. Unlike different fitting methods, which required retaking the frequency response of the transmission line and a generate new parameters for a mathematical function.

3. The proposed model has a second key feature over different fitting method which is easy of implementation in practical application. Curve fitting methods require a high number of approximations to fit the impedance curve of the transmission line for a high-frequency range, which in turn reflects in the high number of terms the mathematical function required to fit the curve. Moreover, the higher number of approximations will require more computational power to fit the impedance curve. In contrast, the proposed analytical solution has a constant set of terms and parameters which will not change with the frequency range.
4. A complete mathematical derivation of resonance equations to obtain the parameter for the proposed model is presented in chapter 3, and the Appendix,. The parameters of the proposed model were calculated using derived resonance equations from the proposed model and the direct measurement from RTDS. The calculated proposed model parameters are within a 1% of error compared to the fitted parameters.
5. The proposed model allows for taking the measurement through the transmission line length as shown in chapter 5. This is the first direct implementation of the

proposed model during transient scenarios in practical application. Moreover, the implementation of the proposed model is compared to the direct measurement from RTDS in during transient scenarios. In contrast, different fitting method which converts the transmission line model into a two port system and any measurement through the transmission line length is not allowed. This feature allow for voltage and current measurement through the transmission line length which allow for monitoring the grid in the frequency domain.

6. A second implementation of the proposed model in practical application is shown in chapter 6, where the proposed model is implemented as a setting-less impedance relay. The presented relay based model shown a faster detection time than the traditional impedance relay with 11.4 % percent time reduction compared to the impedance relay.

In this Ph.D. dissertation, a frequency domain transient modeling of MTLs based on the impedance analytical equation of the transmission line is presented. The proposed model is a function of the transmission line length since it is based on the analytical impedance equation of a finite transmission line. The proposed MTL model is developed from the impedance frequency response measurement. By fitting the proposed model with the impedance frequency response measurement, an accurate representation of MTL is derived. The frequency response of a transmission lines impedance is measured using a real-time digital simulator (RTDS). The parameters of the proposed model were calculated using derived resonance equations from the proposed model. The calculated proposed model parameters are within a 1% of error

compared to the fitted parameters. Furthermore, an algorithm is developed to obtain a more accurate fit of MTL impedance frequency response. To test the accuracy of the proposed model, a comparison between the proposed model and vector fitting is shown. Once the parameters of a transmission line are obtained, changing the length of the line will not effects the proposed transient modeling. This is because the transient modeling is based on the finite transmission line impedance equation, see case 4, chapter 5. In addition, the proposed model is implemented as adaptive protection for a microgrid. The proposed model can be used to calculate the voltages and currents through the length of the transmission line, unlike different MTL models that deal with the transmission line as a two-port system or require high computational power to be implemented in practical application, see chapter 6 section 4. Moreover, an implementation of the proposed model in RTDS is carried out to compare the proposed model to measurement during transient simulations in RTDS, as shown in chapter 6. In addition, the proposed model is used as a setting-less impedance relay for adaptive microgrid protection. The proposed relay has a faster response time during LL-G fault, LLL-G fault, and LLL fault, as shown in chapter 6.

APPENDIX A

RESONANCE EQUATIONS DERIVATION

To obtain the parameters of the proposed transmission line impedance equation (in this case for Z_{11}), a set of equations must be derived from the complex nonlinear transmission line impedance equation at the resonance, ($f_{01} = 500$ and $f_{02} = 733$). Since the imaginary part of Z_{11} equals to zero at resonance ($f_{01} = 500$ and $f_{02} = 733$) then,

$$\begin{aligned} &Im\left(\sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh\sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} + \right. \\ &\left. \sqrt{\frac{R_2 + j\omega L_2}{G_2 + j\omega C_2}} \times \tanh\sqrt{(R_2 + j\omega L_2)(G_2 + j\omega C_2)}\right) = 0 \end{aligned} \quad (\text{A.1})$$

First we take the first part of equation A.1,

$$Im\left(\sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \times \tanh\sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)}\right) \quad (\text{A.2})$$

let,

$$\gamma_1 = \sqrt{(R_1 + j\omega L_1)(G_1 + j\omega C_1)} \quad (\text{A.3})$$

Using De Moivre's theorem:

$$r = \sqrt{\sqrt{(R_1 G_1 - \omega^2 L_1 C_1)^2 + (\omega L_1 G_1 + \omega C_1 R_1)^2}} \quad (\text{A.4})$$

$$\theta = \frac{1}{2} \tan^{-1} \left(\frac{\omega L_1 G_1 + \omega C_1 R_1}{R_1 G_1 - \omega^2 L_1 C_1} \right) \quad (\text{A.5})$$

Therefore,

$$\gamma_1 = -r \sin \theta + i r \cos \theta \quad (\text{A.6})$$

Similarly

$$Z_{01} = \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} = \sqrt{\frac{(R_1 + j\omega L_1)(G_1 + j\omega C_1)}{(G_1 + j\omega C_1)(G_1 + j\omega C_1)}} \quad (\text{A.7})$$

Let

$$A = \frac{1}{G_1^2 + \omega^2 C_1^2} \quad (\text{A.8})$$

Then

$$\begin{aligned} Z_{01} = & (-AG_1 r \sin \theta + \omega AC_1 r \cos \theta) + \\ & i(AG_1 r \cos \theta + \omega AC_1 r \sin \theta) \end{aligned} \quad (\text{A.9})$$

Let

$$h = (-AG_1 r \sin \theta + \omega AC_1 r \cos \theta) \quad (\text{A.10})$$

$$k = (AG_1 r \cos \theta + \omega AC_1 r \sin \theta) \quad (\text{A.11})$$

$$a = -r \sin \theta \qquad b = r \cos \theta \qquad (\text{A.12})$$

Then

$$Z_{01} = h + i k \qquad \gamma_1 = a + i b \qquad (\text{A.13})$$

Therefore

$$Z_1 = (h + i k) \tanh(a + i b) \qquad (\text{A.14})$$

Since

$$\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \qquad (\text{A.15})$$

$$Z_1 = (h + i k) \frac{e^{a+ib} - e^{-a-ib}}{e^{a+ib} + e^{-a-ib}} \qquad (\text{A.16})$$

Solving for the numerator first

$$Z_1 = (h + i k) (e^a e^{ib} - e^{-a} e^{-ib}) \qquad (\text{A.17})$$

Let

$$A_1 = e^a \qquad A_2 = e^{-a} \qquad (\text{A.18})$$

Then

$$Z_1 = (h + i k) [(A_1 - A_2) \cos b + i (A_1 + A_2) \sin b] \qquad (\text{A.19})$$

Let

$$x = (A_1 - A_2)\cos b \qquad y = (A_1 + A_2)\sin b \qquad (\text{A.20})$$

Therefore,

$$Z_1 = (hx - ky) + i(hy + kx) \qquad (\text{A.21})$$

$$\begin{aligned} hy + kx = AG_1rA_1\cos(\theta + b) - AG_1rA_2\cos(\theta - b) + \\ \omega AC_1rA_1\sin(\theta + b) - \omega AC_1rA_2\sin(\theta - b) \end{aligned} \qquad (\text{A.22})$$

$$\begin{aligned} hx - ky = -AG_1rA_1\sin(\theta + b) + AG_1rA_2\sin(\theta - b) + \\ \omega AC_1rA_1\cos(\theta + b) - \omega AC_1rA_2\cos(\theta - b) \end{aligned} \qquad (\text{A.23})$$

Let the real parts of the equation equal to:

$$A_5 = AG_1r(A_2\sin(\theta - b) - A_1\sin(\theta + b)) \qquad (\text{A.24})$$

$$A_6 = \omega AC_1r(A_1\cos(\theta + b) - A_2\cos(\theta - b)) \qquad (\text{A.25})$$

Let the imaginary parts of the equation equals to:

$$A_7 = AG_1r(A_1\cos(\theta + b) - A_2\cos(\theta - b)) \qquad (\text{A.26})$$

$$A_8 = \omega AC_1r(A_1\sin(\theta + b) - A_2\sin(\theta - b)) \qquad (\text{A.27})$$

Let,

$$\gamma = \theta - b \qquad \qquad \beta = \theta + b \qquad \qquad (A.28)$$

For the denominator

$$e^{a+ib} + e^{-a-ib} = A_1 \cos b + A_2 \cos b + i(A_1 \sin b - A_2 \sin b) \qquad (A.29)$$

Multiplying by the complex conjugate, the denominator will be

$$D = [(A_1 + A_2) \cos b]^2 + [(A_1 - A_2) \sin b]^2 \qquad (A.30)$$

Multiplying the numerators (equations A.24,A.25,A.26, and A.27) by the complex conjugate of the denominator:

$$A_1 \cos b + A_2 \cos b - i(A_1 \sin b - A_2 \sin b) \qquad (A.31)$$

We get:

$$\begin{aligned} Real_{11} = AG_1 r (A_1^2 \sin(-\theta) - A_1 A_2 \sin(\theta + 2b) + \\ A_1 A_2 \sin(\theta - 2b) + A_2^2 \sin(\theta)) \end{aligned} \qquad (A.32)$$

$$\begin{aligned} Real_{22} = \omega AC_1 r (A_1^2 \cos(-\theta) - A_2 A_1 \cos(\theta - 2b) + \\ A_1 A_2 \cos(\theta + 2b) - A_2^2 \cos(\theta)) \end{aligned} \qquad (A.33)$$

Therefore

$$Real(Z_1) = \frac{Real_{22} + Real_{11}}{D} \quad (A.34)$$

For the imaginary part:

$$Im_{11} = AG_1r(A_1^2\cos(-\theta) - A_2A_1\cos(\theta - 2b) + A_1A_2\cos(\theta + 2b) - A_2^2\cos(\theta)) \quad (A.35)$$

$$Im_{22} = \omega AC_1r(A_1^2\sin(\theta) - A_2A_1\sin(\theta - 2b) + A_1A_2\sin(\theta + 2b) - A_2^2\sin(\theta)) \quad (A.36)$$

$$Im(Z_1) = \frac{Im_{22} + Im_{11}}{D} \quad (A.37)$$

$$Z_1 = Z_{o1} \times \tanh\gamma_1 l = \frac{Real_{22} + Real_{11}}{D} + j \frac{Im_{22} + Im_{11}}{D} \quad (A.38)$$

Similarly for the second part of equation A.1:

$$Z_2 = Z_{o2} \times \tanh\gamma_2 l = \frac{Real_{33} + Real_{44}}{D_1} + j \frac{Im_{33} + Im_{44}}{D_1} \quad (A.39)$$

At the resonance frequency the imaginary value goes to zero while the real value will be at maximum, therefore:

$$\frac{Im_{22} + Im_{11}}{D} + \frac{Im_{33} + Im_{44}}{D_1} = 0 \quad (A.40)$$

Since Im_{11} and Im_{33} is multiplied by G_1 and G_2 respectively (where both are equal

to 10^{-9}), then equation A.40 will be:

$$Im_{22}D_1 + Im_{44}D = 0 \quad (\text{A.41})$$

Since $\omega AC_1 r D_1$ can't be zero then

$$A_1^2 \sin(\theta) - A_2 A_1 \sin(\theta - 2b) + A_1 A_2 \sin(\theta + 2b) - A_2^2 \sin(\theta) = 0 \quad (\text{A.42})$$

To make equation A.42 equals to zero then,

$$\theta = 0 \quad b = \frac{\pi}{2} \quad (\text{A.43})$$

One characteristic of the transmission line imaginary impedance is the sharp change at resonance; this is due to the tanh function. Solving for a single-phase transmission line impedance will result in Im_{22} equals to zero at resonance. Therefore, by adding a second term $Im_{44}D$, the resonance frequency will increase or decrease by a small value due to the sharp change at resonance. In addition, the peak to peak value of the first term of equation A.41 at the first resonance compared to the impedance of the second term is very high. The second characteristic is that the resonance of both terms is repeated according to $(2n+1)$ since it is a tanh function. Therefore the two resonance will come close and separate apart at different frequency points through the frequency range. Therefore, the effects of the second resonance on the first resonance will change through the frequency range. Thus, taking the measurement of the resonance location with minimum effects from the second resonance will give an accurate result. This will

not effects the derived equations later but how to take the measurement of the first resonance frequencies and the maximum real peaks for both terms of the transmission line impedance. Therefore, the second part of equation A.41 is forced to be zero, assuming no effects on the first resonance. Since

$$b = r \cos(\theta) = \frac{\pi}{2} \quad (\text{A.44})$$

Then,

$$r = \sqrt{\sqrt{(R_1 G_1 - \omega^2 L_1 C_1)^2 + (\omega L_1 G_1 + \omega C_1 R_1)^2}} = \frac{\pi}{2} \quad (\text{A.45})$$

$$L_1^2 = \frac{\frac{\pi^4}{16} - \omega^2 C_1^2 R_1^2 - R_1^2 G_1^2}{\omega^4 C_1^2 + \omega^2 G_1^2} \quad (\text{A.46})$$

Since G has very small value, then:

$$L_1^2 = \frac{\frac{\pi^4}{16} - \omega^2 C_1^2 R_1^2}{\omega^4 C_1^2} \quad (\text{A.47})$$

Since the value of C is in μF , and the first resonance take place under 1kHz, then

$$\frac{\pi^4}{16} \gg \omega^2 C_1^2 R_1^2 \quad (\text{A.48})$$

Then

$$L_1^2 \omega^4 C_1^2 = \frac{\pi^4}{16} \quad (\text{A.49})$$

$$\frac{\pi^2}{4\omega^2} = L_1 C_1 \quad (\text{A.50})$$

Similarly for the second resonance:

$$\frac{\pi^2}{4\omega_2^2} = L_2 C_2 \quad (\text{A.51})$$

Solving for the real part, we can ignore the real part associated with Z_2 to solve for Z_1 and vice versa. This is due to the high real part impedance value of Z_1 at resonance (f_{o1}) compared to the real value of Z_2 at f_{o1} . Since the real part of Z_1 will equal to a maximum at f_{o1} when θ equals zero and b equals to $\pi/2$, then

$$Real(Z_1) = \frac{Real_{22} + Real_{11}}{D} \quad (\text{A.52})$$

Since $Real_{11}$ is multiplied by G_1 , then

$$Real_{11} \approx 0 \quad (\text{A.53})$$

Since θ equals zero and b equals to $\pi/2$

$$\begin{aligned} Real_{22} = \omega AC_1 r (A_1^2 \cos(-\theta) - A_2 A_1 \cos(\theta - 2b) + \\ A_1 A_2 \cos(\theta + 2b) - A_2^2 \cos(\theta)) \end{aligned} \quad (\text{A.54})$$

Then

$$Real_{22} = \omega AC_1 r (A_1^2 - A_2^2) \quad (\text{A.55})$$

$$D = (A_1 - A_2)^2 \quad (\text{A.56})$$

Let the maximum impedance of the real part be equal to:

$$Real(Z_1) = Z_{R1} \quad (A.57)$$

$$Z_{R1} = \omega AC_1 r \frac{(A_1^2 - A_2^2)}{(A_1 - A_2)^2} \quad (A.58)$$

$$Z_{R1} = \omega AC_1 r \frac{(A_1^2 - A_2^2)}{(A_1^2 + A_2^2 - 2)} \quad (A.59)$$

$$Z_{R1} = \omega AC_1 r \frac{e^{-2r \sin(\theta)} - e^{2r \sin(\theta)}}{e^{-2r \sin(\theta)} + e^{2r \sin(\theta)} - 2} \quad (A.60)$$

Since

$$- \coth\left(\frac{1}{2}x\right) = \frac{e^{-x} - e^x}{e^{-x} + e^x - 2} \quad (A.61)$$

Then,

$$Z_{R1} = -\omega AC_1 r \coth\left(\frac{1}{2}2r \sin(\theta)\right) \quad (A.62)$$

$$\coth(x) = \frac{\cosh(x)}{\sinh(x)} \quad (A.63)$$

Since the angle θ is very small at resonance then,

$$\cosh(x) = 1 \quad \sinh(x) = x \quad (A.64)$$

Therefore

$$Z_{R1} = \omega AC_1 r \frac{1}{r \sin(\theta)} \quad (A.65)$$

Since

$$A = \frac{1}{G_1^2 + \omega^2 C_1^2} \quad (\text{A.66})$$

And the values of G and θ are small, then

$$Z_{R1} = -\frac{1}{\omega C} \frac{1}{\theta} \quad (\text{A.67})$$

Where,

$$\theta = \frac{1}{2} \tan^{-1} \left(\frac{\omega L_1 G_1 + \omega C_1 R_1}{R_1 G_1 - \omega^2 L_1 C_1} \right) \quad (\text{A.68})$$

Initially the value of θ made to equal zero to solve for the imaginary part. Substituting θ by zero in equation A.67 will result in infinity. Since equation A.68 can not equals to zero due to the summation of two positive number in the numerator, then the value of θ should be small (close to zero). Since G_1 has a small value as well as $(\frac{\omega L_1 G_1 + \omega C_1 R_1}{R_1 G_1 - \omega^2 L_1 C_1})$ at resonance, then

$$\theta = \frac{1}{2} \left(\frac{\omega C_1 R_1}{-\omega^2 L_1 C_1} \right) \quad (\text{A.69})$$

$$\theta = \frac{R_1}{-2\omega L_1} \quad (\text{A.70})$$

Therefore, the real part of the impedance at the crossover frequency will be:

$$Z_{R1} = \frac{2L_1}{C_1 R_1} \quad (\text{A.71})$$

Similarly for the second resonance,

$$Z_{R2} = \frac{2L_2}{C_2 R_2} \quad (\text{A.72})$$

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